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J. Olek, P. J. Tikalsky, and R. L. Carrasquillo

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16. Abstract

The need for more cost efficient construction materials for highway applications and the problem of waste disposal of fly ash have prompted the study presented herein. This study addresses some of themajor concerns of resident highway engineers about concrete containing fly ash for highway applications, which include: curing conditions, setting times, strength development, and durability.

This report summarizes the experimental observations and conclusions from a research program investigating the properties of both fresh and hardened pavement concrete containing fly ash. Tests were performed to establish guidelines for the selection of materials and trial mix design procedures for producing quality concrete containing fly ash. The study investigated freeze-thaw resistance, flexural and compressive strength characteristics, mixing conditions and procedures, and curing conditions such as temperature, humidity, and curing methods. Types A and B fly ashes were used in this study as a replacement for 0, 15, 25, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type A fly ash was used.

The results of this study show that concrete containing fly ash can be designed and proportioned to meet present Texas SDHPT specifications for highway applications. In addition, this study reveals that an optimum mix design for concrete containing fly ash is both technically and economically advantageous to the Texas SDHPT.

This report provides the resident engineer with recommendations to ensure the production of quality concrete containing fly ash for highway applications.

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by

J. Olek

P. J. Tikalsky

and

R. L. Carrasquillo

Research Report No. 364-2

Production of Concrete Containing Fly Ash

Research Project 3-9-84-364

Conducted for

Texas
State Department of Highways and Public Transportation
in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

May 1986

PREFACE

This is the second report in a series of four reports which summarizes the effect of fly ash on the production of concrete containing fly ash. The first report in the series summarizes the effect of fly ash on the production of structural concrete. The second report summarizes the effect of fly ash on concrete used for highway pavement applications. The third report of the series summarizes the effects of fly ash on the durability of concrete containing fly ash. The fourth and final report of the series outlines a mix proportioning procedure for concrete containing fly ash. The last report uses the results of the previous three reports to develop a mix design procedure which results in a concrete mix that meets all applicable Texas State Department of Highways and Public Transportation specifications.

This work is part of Research Project 3-9-84-364, entitled "Production of Concrete Containing Fly Ash." The studies described were conducted jointly between the Center for Transportation Research, Bureau of Engineering Research, and the Phil M. Ferguson Structural Engineering Laboratory at the University of Texas at Austin. The work was co-sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration. The studies were performed in cooperation with the Texas State Department of Highways and Public Transportation, Materials and Testing Division through contact with Mr. Fred Schindler.

The overall study was directed and supervised by Dr. Ramon L. Carrasquillo.

SUMMARY

The need for more cost efficient construction materials for highway applications and the problem of waste disposal of fly ash have prompted the study presented herein. This study addresses some of the major concerns of resident highway engineers about concrete containing fly ash for highway applications, which include: curing conditions, setting times, strength development, and durability.

This report summarizes the experimental observations and conclusions from a research program investigating the properties of both fresh and hardened pavement concrete containing fly ash.

Tests were performed to establish guidelines for the selection of materials and trial mix design procedures for producing quality concrete containing fly ash. The study investigated freeze-thaw resistance, flexural and compressive strength characteristics, mixing conditions and procedures, and curing conditions such as temperature, humidity, and curing methods. Types A and B fly ashes were used in this study as a replacement for 0, 15, 25, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type A fly ash was used.

The results of this study show that concrete containing fly ash can be designed and proportioned to meet present Texas SDHPT specifications for highway applications. In addition, this study reveals that an optimum mix design for concrete containing fly ash is both technically and economically advantageous to the Texas SDHPT.

This report provides the resident engineer with recommendations to ensure the production of quality concrete containing fly ash for highway applications.

IMPLEMENTATION

This report summarizes some of the findings of an extensive experimental investigation of concrete containing fly ash. Specific recommendations for the resident engineer are presented to ensure adequate quality pavement concrete containing fly ash.

This study shows that pavement concrete containing fly ash can be produced under adverse environmental conditions provided proper concrete production procedures are followed. In addition, concrete containing fly ash can be produced more economically than plain portland cement concrete.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Chapter Page

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure Page

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

CHAPTER 1

INTRODUCTION

1.1 General

The search for more efficient construction materials and the problem of industrial waste disposal have been combined in the development of uses for fly ash produced by coal fired power generating stations. Since the pioneering work of R.E. Davis and his associates on cement and concrete containing fly ash [1] in 1937, much time and effort have been devoted to evaluating the effects of this pozzolan on concrete.

Much of the research on fly ash concrete is apparently repetitious, but this repetition is justified and even necessitated by the nonuniformity of the material. Fly ash is the product of a relatively uncontrolled burning process and, as a result, its chemical and physical properties vary widely from source to source.

1.2 Problem Statement

Roads, large consumers of materials of all kinds, are among those civil engineering projects with which the builder can take the most technical risks; innovation in road building is therefore constant and progresses from the laboratory to practical use very rapidly.

Increased highway construction costs, coupled with decreasing revenues, are spurring the continuing development of more cost effective construction methods and materials. One set of materials being given serious consideration in Texas is locally available fly ash.

It is estimated that the current annual production of fly ash in Texas exceeds five million tons, making fly ash readily available within the state as a potential highway material.

The beneficial effects of fly ash in concrete are well known [2,3,4]; however, at present, although fly ash consumption has increased steadily throughout the world, with several countries producing standard specifications for its use in concrete [5,6], its consumption in concrete is still very small. There are a number of reasons for the resistance to more widespread use of fly ash, one of which is the inadequacy of the methods of proportioning concrete incorporating fly ash.

The mix proportioning procedure of concrete can significantly affect its properties and cost effectiveness and consequently, in the case of fly ash, the attitude towards its incorporation in concrete as a cementitious material. This report contains the results of tests on the use of two types of fly ash as a replacement for part of the cement in concrete and examines their effect on the mix design procedure. This information will constitute the first step in the development of the needed concrete mix design procedure which can be followed by field engineers for safe, economical and efficient use of fly ash in concrete for highway application.

1.3 Scope and Objective of the Research

The scope of work in this study involved the evaluation of the performance in concrete mixes of two fly ashes produced in Texas. The methods of fly ash inclusion as a cementitious material in concrete can be divided into two categories: 1) the use of a blended cement containing fly ash, and 2) the introduction of fly ash as an additional component in concrete. The first method is simple, free from most batching errors, and existing mix proportioning procedures apply, but it could be inefficient for some structural applications where early age strengths are a major design criterion.

The main advantage of the second method is its flexibility, allowing the cement/fly ash proportions to be determined by the requirements of the concrete and the properties of the materials. This permits the most effective utilization of fly ash by taking into account different variables influencing the performance of fly ash concrete. The following variables have been studied:

1. Trial mix design procedure for proportioning concrete mixes containing fly ash to meet Texas State Department of Highways and Public Transportation (SDHPT) Standard Specification for Concrete Pavement, Item 360 [10];

2. Moist curing time required for concrete to meet strength requirements;

3. Mixing water demand for concrete containing different amounts of fly ash at two fresh concrete temperatures, 70-75°F and 100-105°F, including measurement of slump loss up to 1-1/2 hr of mixing time;

4. The effect of different curing conditions and curing methods on strength development of concrete containing fly ash at 7 and 28 days, namely

    a. moist curing for 1, 3, and 7 days followed by air drying at 40°F and 100°F until testing;

    b. spraying with curing compound after casting followed by air drying at 75°F and 100°F until testing;

5. Effectiveness of air-entraining admixture in concrete containing fly ash;

6. Freeze-thaw resistance of concrete containing fly ash; and

7. Comparison of the performance of concrete produced using cement containing fly ash (blended Type IP portland-pozzolan cement) with concrete produced using Type I cement with fly ash added as a mineral admixture to the fresh concrete.

As mentioned earlier, two types of fly ash, Types A and B have been used in this study. Two series of concrete batches were produced using 5.5 and 6.5 sacks of cement in the basic mix respectively and then substituting 15, 25 and 35% fly ash for portland cement by weight.

All mixing was done based on the required slump of the fresh concrete. Testing of the fresh concrete included slump, air content, unit weight and temperature. Flexural beam strength and compression cylinder strength tests were performed on hardened concrete at different ages such as 7, 28, 56 and 90 days.

The main objectives of this study are summarized as follows:

1. Establish guidelines for the selection of materials and trial mix design procedures for producing good quality concrete containing fly ash;

2. Conduct laboratory tests to provide information on freeze-thaw resistance of fly ash concrete; and

3. Study the effect of different curing conditions, temperature, humidity, and curing method, on the rate of strength gain of concrete containing fly ash.

1.4 Definitions

This section contains the basic terms and definitions frequently used in the text of this report except terms which are obvious and commonly known among practicing engineers.

1. Fly Ash -- Finely divided residue that results from the combustion of ground or powdered coal [7];

2. Type A Fly Ash -- Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this type as given in Texas SDHPT Material Specification for Fly Ash D-9-8900 [73]. This type of fly ash has pozzolanic properties.

3. Type B Fly Ash -- Fly ash normally produced from lignite or subbituminous coal that meets the applicable requirements for this type as given in Texas SDHPT Specification D-9-8900. This type of fly ash, in addition to having pozzolanic properties, also has cementitious properties. The lime content in this fly ash is typically higher than 10% [73].

4. Pozzolans -- Siliceous or siliceous and aluminous materials which in themselves possess 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 [7].

5. Portland-Pozzoland Cement -- A hydraulic cement consisting of an intimate and uniform blend of portland cement and fine pozzolan [8].

6. Cement Factor -- The number of sacks of cement used to produce one cubic yard of concrete. The symbol "CF" is used to signify the cement factor [9].

7. Coarse Aggregate Factor -- The dry rodded volume of coarse aggregate in a unit volume of concrete. The symbol "CAF" is used to signify the coarse aggregate factor [9].

8. Water/Cement + Fly Ash Ratio -- The ratio of the weight of water in one cubic yard of concrete to the weight of all cementitious materials, cement or cement plus fly ash, used in the same volume of concrete.

The American Society of Testing and Materials classifies fly ash in ASTM C618-84, Standard Specification for Fly Ash and Raw Calcinated Natural Pozzolan For Use as a Mineral Admixture in Portland Cement Concrete [7] as Class C or F as presented in Table 1.1. In general, Texas SDHPT Type A fly ash corresponds to ASTM Class F and Texas SDHPT Type B fly ash corresponds to ASTM Class C.

Table 1.1 Fly Ash Chemical Composition Requirements According to Different Specifications

Fly Ash Chemical Composition Requirements

	ASTM 618-84		Texas DSHPT D-9-8900	
	Class C	Class F	Type A	Type B
Si+Al+Fe oxides minimum %	50	70	65	50
Ca oxide maximum %	-	-	*	*
Mg oxide maximum %	-	-	5.0	5.0
Sulfate maximum %	5.0	5.0	5.0	5.0
Available Alkalies as Na oxide maximum %	1.5	1.5	1.5	1.5
Loss on Ignition maximum %	6.0	6.0	3.0	3.0
Moisture maximum %	3.0	3.0	2.0	2.0
Fineness #325 maximum retained	34	34	30	30
Pozzolanic Activity	75	75	75	75
Shrinkage maximum %	.03	.03	.03	.03

* 4% maximum variation from previous ten samples

CHAPTER 2

PROPERTIES OF FLY ASH

2.1 The Nature of Fly Ash

Fly ash is a byproduct of the burning of pulverized coal in power plants. It is removed from the combustion gases by mechanical collectors or electrostatic precipitators as fine particles before they are discharged into the atmosphere. Electrostatic precipitators capture the preferable, finer-sized particles that escape mechanical collectors [11].

Fly ash is classified as a pozzolan, a siliceous or aluminous material which, in finely divided form and in the presence of moisture, will react with calcium hydroxide to form compounds possessing cementitious properties. Certain fly ashes from lignite and subbituminous coals have sufficiently high calcium oxide contents to have hydraulic properties similar to portland cement.

The characteristics of fly ash from a single source may be uniform or quite variable, depending on factors such as the source of coal, degree of coal pulverization, design of boiler unit, loading and firing conditions, collection, and storage methods. By far the most influential factor of the fly ash produced is the coal source [12]. The variable composition of coal is distinctive as it relates to the composition of the resulting fly ash produced through combustion. Fly ashes with high variability in their composition are of little value for use in concrete due to the unpredictable nature they can impart to the hardened concrete properties.

2.2 Types of Fly Ash

Based on the differences in mineralogical composition and physical properties, fly ash can be divided into two groups, which differ from each other mainly in their calcium content. The first group, containing usually less than 10% analytical CaO, is generally a byproduct of the combustion of anthracite and bituminous coals. The second group, containing usually 15 to 35% analytical CaO, is generally a byproduct of the combustion of lignite and subbituminous coals.

The Texas SDHPT Material Specification for Fly Ash does not differentiate fly ash on the basis of calcium content, although this objective is achieved indirectly by requiring a minimum of 70% of major noncalcium oxides (silica + alumina + iron oxide) for Type A fly ash, and 50% for Type B fly ash, since the latter is high in calcium.

2.3 Chemical and Mineral Composition

The chemical and mineral composition of coal ash depends largely on the geologic and geographic factors related to the coal deposit, the combustion conditions, and the removal efficiency of air pollution control devices. The inorganic constituents of fly ash are those typical of rock and soils, primarily Si, Al, Fe and Ca; the oxides of these four elements comprise 95 to 99% of the composition of fly ash. Fly ash also contains smaller amounts (0.5 to 3.5%) of Mg, Ti, S, Na and K [13].

The low calcium Type A fly ash, consists principally of aluminosilicate glass. Researchers, including Diamond [14] and Mortureux et al. [15], have confirmed that the principal crystalline minerals in low calcium fly ash are quartz, mullite, sillimanite, hematite, and magnetite. Since these crystalline minerals are nonreactive at ordinary temperatures in the portland cement solution phase, their presence in large proportions reduces the reactivity of low calcium fly ash. According to Mehta [3], the assumption in the ASTM Specification C618-84 that all silica, alumina and iron oxide present in pozzolans are potentially reactive with lime is incorrect since, in most fly ashes, substantial amounts of these oxides occur as nonreactive crystalline minerals; for example, silica as quartz, mullite and sillimanite; alumina as mullite and sillimanite; and iron as hematite and magnetite.

The principal crystalline mineral in high calcium Type B fly ash is generally C_3A which is the most reactive mineral present in portland cement. In some high calcium fly ash, Mehta [3] has detected crystalline C_4A_3S, CS and Free CaO which, in addition to C_3A readily react to form cementitious calcium aluminate and sulfoaluminate hydrates. Unlike low calcium fly ash, many of the crystalline minerals in a high calcium fly ash are reactive and capable of imparting cementitious characteristics to the fly ash. In fact, quick setting behavior of some Texas SDHPT Type B fly ash due to rapid formulation of C_4AH_{13}, C_4ASH_{18}, and ettringite has been observed by Mehta as well as other researchers [3].

2.4 Physical Properties

The physical properties of fly ash depend mainly on the composition of the coal, the degree of coal pulverization, the rate and efficiency of combustion, the type of combustion equipment, and the fly ash collection system.

Physical properties of fly ash have a greater influence on the performance of fresh concrete than does the chemical composition. Variables such as water content, workability, bleeding, and unit weight are dependent primarily on the shape, weight and fineness of the fly ash particles rather than on their chemical composition [16].

2.4.1 Particle Shape and Size. In general, fly ash consists of glassy spheres of sizes varying from under 0.00004-in. to as large as 0.006-in., although typical particle size distribution shows that most of the material is under 0.0008 in. in diameter [3].

On the basis of optical and scanning electron microscope observations, Fisher et al. [17] and Lauf [18] have proposed several morphological categories of fly ash which may be summarized as follows:

1. Most of the fly ash particles occur as solid glass spheres, which are mostly transparent but may be partially devitrified;
2. Large irregular masses may exist either as agglomerates of small silicate glass spheres or porous particles of partially burnt carbonaceous matter;
3. Magnetite and hematite occur as opaque spheres in high-ion fly ash; and
4. Low calcium fly ash may contain a small amount, up to 5% by weight of hollow spheres which are either completely empty (cenospheres) or filled with smaller spheres (plerospheres).

Large concentrations of cenospheres are not desirable in ash used for concrete since they are lighter than water and tend to float during the finishing operation. This produces dark colored streaks on the concrete surface and leaves the appearance of excessive bleeding.

2.4.2 Fineness. Fineness of fly ash is important as it affects the rate of pozzolanic activity and the workability of the concrete. Finer fly ashes are generally preferable as a component of concrete because they tend to reduce the water necessary for a given consistency. The reduction of water will depend on the mix proportioning, shape of the fly ash particles as well as the shape of the aggregate. Lane et al. [16] reported that fly ashes with over 95% passing the No. 325 sieve may require an increase in water over that of a control mixture by 1 to 3%, especially in high strength, low water mixtures with high cementitious material contents. Greater fineness of fly ash may increase the demand for air-entraining admixture.

2.4.3 Specific Gravity. Some controversy exists over the significance of the specific gravity of fly ash. Several researchers [16, 21] have concluded that it has little, if any, effect on the properties of concrete except that it may indicate the particle sizes present in fly ash. Fine ashes tend to have a higher specific gravity than coarse fly ashes due to the greater density of the fine particles. The proportions of the constituents of iron, silicon, aluminum and carbon in the fly ash can also affect the specific gravity. High iron content is generally associated with a high specific gravity, whereas high alumina, silica and carbon contents tend to lower the specific gravity.

There are other researchers who claim a strong correlation exists between specific gravity, fineness and carbon content [12, 19, 20]. The specific gravity is relevant to mix proportioning because variations in specific gravity significantly alter the volume proportions of the mix. Major changes in specific gravity should therefore be compensated for by adjusting batch weights to maintain the yield.

2.4.4 Color. The color of fly ash may range from light tan to dark gray, depending on the type and quality of the coal and on the boiler operation. Aside from carbon, other elements such as iron affect color. A high carbon content changes the color to gray or black, while a high iron content produces a tan colored fly ash. Most low calcium ashes are similar in appearance to portland cement. As the color can reflect the amount of carbon, it is sometimes used as a colorimetric indicator of carbon [12].

2.5 Principles of Behavior

By adding fly ash, many aspects of concrete can be favorably influenced, some by chemical effects such as pozzolanic and cementitious reactions, and others by physical effects associated with the small size of fly ash particles which are generally finer than those of portland cement. Both types of effects are briefly discussed below.

2.5.1 Chemical Phenomena. Strength and permeability of hardened concrete, resistance to thermal cracking, alkali-silica expansion, and sulfate attack are the main effects associated with the pozzolanic and cementitious reactions. A direct relationship has been established between the pozzolanic activity of fly ash and the percentages of silica, alumina and iron oxides. As reported by Lane et al. [16], the total percentage of these materials is not as critical to fly ash performance as are the relative types and proportions of constituents present and whether they are present in the fine or coarse fraction of the ash. When the siliceous and aluminous materials are present in noncrystalline form and as finely divided particles, they can hydrate at a slow rate in alkaline solution to furnish silica and alumina for reaction with lime released during the hydration of portland cement. This leads to the formation of secondary cementitious compounds and contributes to the development of compressive strength in the concrete. Magnesium oxide hydrates similar to lime, however its hydration occurs slower and can be accompanied by disruptive expansion in the concrete [22]. Sulphur trioxide is added to portland cement in the form of gypsum to slow the fast setting action of hydrating aluminate; therefore, the soluble portion of the SO_3 content of fly ash must be limited to avoid excessive delays in setting and perhaps lowering of resulting compressive strength [21].

The presence of alkalies also has an effect upon setting times of concrete. High alkali contents reduce the retarding action of lime and can contribute to flash setting without adequate SO_3 levels [21]. Available alkalies such as Na_2O in fly ash also have the potential to react with cetain siliceous aggregates which can cause disruptive expansions in the finished product well after construction is complete.

The addition of predetermined amounts of fly ash can be used to mitigate such alkali-aggregate reactions because the finely divided amorphous silica reacts with the alkalies in the cement and fly ash [12, 21]. However, if high quantities of alkali are present in the fly ash itself, the mitigating effect can be reduced.

Unburned carbon particles, whose presence is indicated by loss on ignition, can be considered inert as far as cementitious reactions are concerned [12]. However, the carbon particles in fly ash have been shown to demonstrate an adverse effect on the air content in concrete due to adsorption of air-entraining admixture. The effect of this adsorption is a significant reduction in the amount and character of the air void system within the hardened concrete.

2.5.2 Physical Phenomena. Concrete mix proportions, rheological behavior of plastic concrete, and degree of hydration of portland cement are among the physical effects associated with the addition of fly ash to concrete mixes.

The spherical shape of the fly ash particles contributes to the workability of concrete by reducing the friction of the aggregate-paste interface producing a ball-bearing effect at the point of aggregate contact. As the specific gravity of a fly ash is smaller than that of portland cement, an obvious benefit of the use of fly ash is an increased paste volume which leads to improved cohesion and plasticity. The use of a fly ash as a partial cement replacement may reduce the water content of concrete at equal consistency. As reported by Mehta [3], the use of a coarse fly ash caused an increase in the water requirement instead of reducing it. The presence of fly ash between the aggregate particles helps to reduce bleeding by compensating for a deficiency of fines in a fine aggregate and breaking the continuity of bleed water channels in the concrete mix. Kobayashi and Sato [23] showed that by helping to separate and disperse the flocculated structure of particles of portland cement more efficiently, the presence of fine particles of fly ash increases the early hydration of cement. Thus, strength of concrete at a given cement content to which a fly ash was added, as fine aggregate replacement, was increased as early as at seven days when compared to the plain concrete.

CHAPTER 3

METHODS OF DETERMINATION OF THE QUALITY OF FLY ASH

In a report prepared for the Office of Recycled Materials, Frohnsdorff and Clifton [24] projected that about 18 million tons of fly ash could be consumed every year by the cement and concrete industry, provided there is adequate quality control and a better understanding of the technical requirements for satisfactory performance of the materials. Currently, only about three million tons are used annually in U.S. cement and concrete products.

According to Butler [25], ASTM C618-84 is probably the most demanding specification for fly ash, with comprehensive provisions for both chemical and physical tests. However, the time delays involved and the cost of testing are often out of proportion to the benefits derived. Meininger [26] states that "there is general dissatisfaction concerning the Classes C and F designations used in ASTM Specification C618-84."

In portland cement, there is a close relationship between chemical and mineralogical composition; however, this is not the case with fly ash which may contain large amounts of noncrystalline or glassy matter and are usually subject to greater variations in thermal history during the production process. Since no direct relationship exists between chemical and mineralogical composition, which controls the reactivity of these materials at room temperature, the standard specifications emphasizing chemical requirements may not serve a useful purpose. Therefore, Mehta [3] proposed a classification of fly ash in which closer attention is paid to the mineralogical rather than to the chemical analysis. This classification is presented in Table 3.1

Based on American and foreign specifications as well as on his own experience, Manz [5] has proposed the following recommendations related to the use of fly ash in concrete:

1. No reference should be made to the type of coal. Separation between Types A and B, or lime-richness, is as follows: Type A exhibits no hydraulic properties unless in the presence of a solution saturated with $Ca(OH)_2$, and Type B having hydraulic properties;

2. Require a simple performance test involving strength of cubes containing fly ash but no cement. Perhaps a standard of 500 psi at 3 days for Type B, and if less, Type A;

3. A further designation of percent retained on the No. 325 sieve and loss on ignition will further qualify the fly ash for use

TABLE 3.1 Classification, Composition and Particle Characteristics of Fly Ash for Concrete [3]

Classification	Chemical and Mineralogical Composition	Particle Characteristics
I. Cementitious and Pozzolanic high calcium fly ash	Mainly silicate glass containing calcium, magnesium, aluminum, and alkalies. The small quantity of crystalline matter present generally consists of quartz and C_3A; free lime and periclase may be present; CS and C_4A_3S may be present in the case of high sulphur coals. Unburnt carbon is usually less than 2% of the total composition.	Powder consisting of particles 10-15% larger than 45mm in diameter. Most particles are solid spheres with a diameter less than 20 mm. Particle surface is generally smooth but not as clean as in low calcium fly ash.
II. Pozzolanic low calcium fly ash	Mainly silicate glass containing aluminum, iron, and alkalies. The small quantity of crystalline matter present consists generally of quartz, mullite, sillimanite, hematite, and magnetite. Unburnt carbon is usually less than 5% but may be as high as 10% of the total composition.	Powder consisting of particles 15-30% larger than 45mm in diameter. Most particles are solid spheres with an average diameter of 20mm. Cenospheres and plerospheres may also be present. Particles have a smooth texture.

in concrete. The finer and the lower loss on ignition, the more desirable; and

4. Fly ash of similar mineralogical composition, glass content, and free lime as well as similar particle size distribution should have similar properties when used as a component of cement or concrete.

According to Meininger [26], the development of better rapid tests and their proper application can aid in the process of fly ash selection and reduce variation of material shipped for use in concrete. He proposes the following reasonably quick tests:

1. Monitoring changes in color of fly ash;
2. Measurement of loss on ignition or carbon content (a Leco rapid carbon apparatus is available); and
3. Measurement of percent retained on the No. 325 sieve (an Alpine air-jet sieve is available which is faster than the normal procedure using water, used for cement and pozzolans).

Other rapid tests which might be adapted for fly ash control purposes include:

1. Particle size distribution by rapid instrument (L&M Microtrac is an example);
2. Measurement of specific surface by air permeability techniques; and
3. Density or specific gravity checks on the fly ash.

There are two rapid tests available for determination of the free lime content: (1) measurement of temperature rise of a fly ash in a 10% HCl mixture, according to a Polish method [27]; or (2) measurement of pH of a fly ash mixture as reported by Dodson et al. [28].

McKerall et al. [21] developed a theoretical model for predicting properties of a fly ash. Using this model these approximations of fineness, CaO content, and specific gravity can be quickly obtained from the No. 200 sieve and CaO heat evaluation tests.

CHAPTER 4

THE EFFECT OF FLY ASH ON THE PROPERTIES OF CONCRETE: A LITERATURE REVIEW

4.1 General

Published literature contains many excellent papers including state-of-the-art reviews by numerous authors [1-3,14,16,24-30] which provide a wealth of information on the composition and properties of fly ash and its influence on the properties of concrete. The following is a survey of technical publications which address this subject. Properties of fresh and hardened concrete as well as durability aspects are discussed.

4.2 Properties of Fresh Concrete

Fresh concrete should be readily placed, compacted, and finished with a minimum of segregation. The addition of fly ash may produce changes in some of the properties of the mixture. The small size and essentially spherical form of fly ash particles contribute to the workability of concrete and will usually reduce the water content of concrete for a given consistency. Berry and Malhotra [2] cite two cases in which 30% fly ash substitution for cement was found to reduce the water requirement by about 7% at constant slump. Similarly, Lane and Best [16] reported 5 to 10% reduction of water in mortars of equal consistency when 33, 67 and 133% fly ash by weight of cement was added.

Replacement of cement in concrete by an equal weight of fly ash, a less dense material, produces an increase in the paste volume which leads to better cohesiveness and workability. In his review of the subject, Abdun-Nur [19] considered improved workability to be "almost axiomatic" when fly ash is used in properly adjusted concrete mixes. However, the literature does contain some conflicting data.

Brink and Halstead [31] reported that some fly ashes, generally of higher carbon content, increased the water requirements of test mortars. Berry and Malhotra [2] cited two other cases where adding a fly ash to the concrete mix caused an increase in the water requirement instead of reducing it.

Davis et al. [1] had concluded as early as 1937 that fly ash cement mixtures set more slowly than corresponding cements but the setting times were within the usual specification limits. The experiences of Lane and Best [16] with fly ashes generally confirms this. Also, according to Lane [32] the rate of slump loss is not affected by the addition of fly ash, except to the extent that initial setting time is slightly increased. It may be pointed out, however, that the observations of Davis et al. and Lane and Best pertain to low calcium fly ash. The high calcium fly ash which are generally low in carbon and high in reactive constituents sometimes exhibit a slightly faster setting time.

Covey [33] reported that concrete containing high calcium fly ash showed a faster setting tendency. Also, Welsh and Burton [34] reported loss of slump and flow for concrete made with some Australian fly ashes used to partially replace cement.

Concrete using fly ash is generally reported [2] to show reduced segregation and bleeding and to be more satisfactory when placed by pumping than plain concrete placed under the same circumstances.

The hydration reaction of cement is accompanied by the evolution of heat which causes a temperature rise in the concrete.

In mass concrete, the differential in temperature between the surface and the interior of the concrete structure will produce thermal gradients which may result in concrete stresses exceeding the tensile strength of concrete at early ages. Data cited by Berry and Malhotra [2] confirm that the use of fly ash generally reduces the amount of cement in the concrete mixture and, consequently, reduces both the amount and rate of temperature rise.

Many laboratory investigations [35-38] and field uses have demonstrated that frequently some sources of Texas SDHPT Type A, low CaO content, fly ash caused an increase in the quantity of the air-entraining agent required to produce a given content of entrained air. This is mainly due to the fact that fly ash carbon has a capacity for the selective adsorption of the organic compounds composing common air-entraining agents.

4.3 Strength

It is not easy to summarize the large volume of published data on the effect of fly ash on concrete strength. Both the rate of strength development and the ultimate strength depend on the water/cement plus fly ash ratio and are specific to certain fly ashes and certain concrete designs and production processes. This is because strength development is a function of the pore-filling process [3] which takes place with the formation of hydration products and is therefore influenced by variations in the mineralogical composition and particle characteristics of the fly ash, composition of the portland cement, curing temperature, humidity, and concrete mix proportions. The following general observations can be made in regard to this subject. Much research has shown that any percentage replacement of portland cement in concrete by fly ash on a one-for-one basis (either by volume or by weight) results in lower compressive and flexural strength up to about three months of curing [2,39]. It was found, however, [2,16,40] that addition of fly ash to cement combined with a decrease in fine aggregate content to produce proper yield generally gives increased strength in concrete at any ages. Improvements were small at seven days but the mixes containing fly ash achieved substantially higher strength at later ages when compared to portland cement mixes.

If the volume of cementitious material in a concrete mixture is constant and part of the cement is replaced by fly ash, the compressive strength may decrease with increasing fly ash contents [16]. Some authors [3,41] have found that with high calcium fly ash, a significant contribution to strength can be expected even at early ages. Many of the crystalline minerals in a high calcium fly ash are reactive; therefore, cementitious and pozzolanic activity may start as early as three days after hydration [3]. The pozzolanic reactions consume calcium hydroxide and thereby strengthen the material, principally through pore refinement during the early stage of hydration and later by improving the strength of the transition phase.

4.4 Permeability and Corrosion

Although permeability of concrete is not directly related to porosity, it is affected by numerous variables including cementitious material content, water content, aggregate grading, and interconnected void spaces. The pozzolanic reaction of fly ash in concrete, which produces calcium silicate hydrate, tends to fill these unoccupied spaces to form a product with decreased permeability. From this it is clear that the permeability of the concrete will be directly related to the quantity of hydrated cementitious material at any given time. Manmohan and Mehta [44] found that in the case of cements containing 10, 20, or 30% fly ash, the pore-size refinement and drastic drop in permeability of the cement paste, from 13×10^{-11} to 1×10^{-11} cm/sec, occurred during the 28 to 90 days curing period. This is consistent with the results of Davis, cited by Berry and Malhotra [2] on permeability of a pipe made of fly ash concrete, which was higher than plain concrete at 28 days, but substantially lower after six months of curing.

However, pozzolanic reaction consumes Ca(OH) , reducing the alkalinity of concrete. In plain concrete a reduction of alkalinity of the cement paste by carbonation from atmospheric carbon dioxide is the first step in the process of corrosion of steel in concrete. According to Mehta [3], this has caused some concern among construction engineers who feel that due to the reduced alkalinity the addition of fly ash to reinforced and prestressed concrete would present a danger for corrosion of steel.

According to Massazza [42], the resistance to carbonation of concrete does not appear to be related to the amount of calcium hydroxide in the pore solution since many researchers including Diamond [43] have reported that the pore solutions in mature portland cement pastes contain little or no calcium. He concluded, therefore, that the danger due to carbonation should not be of concern in concrete containing fly ash. Berry and Malhotra [2] have reported that in a recent study by Larsen et al. corrosion protection is increased by the inclusion of fly ash in concrete.

In conclusion, the pozzolanic and cementitious reactions associated with fly ash while reducing the free lime present in the cement paste, on one hand, also decrease the permeability of the concrete system.

4.5 Freeze-Thaw Resistance

Some controversy exists surrounding the effects of fly ash in concrete subject to freezing and thawing. Early research [19] indicated that bituminous fly ash reduced freeze-thaw resistance; however, these efforts often failed to account for the slower strength gains and higher sensitivity to air entrainment found in fly ash concrete in which the fly ash had significant quantities of carbon, high loss on ignition.

Larson [45] in presenting his work on the use of fly ash in air-entrained concrete and in reviewing the work of other investigators [46-51] concluded that the primary effect of fly ash was upon air-entraining agent demand, rather than upon the air entrainment system.

Research sponsored by the Department of Energy has shown that fly ash mixes of equal strength and entrained air content demonstrated comparable freeze-thaw performance compared to 100 percent portland cement concrete [52]. In conclusion, there are no apparent differences in freeze-thaw durability between fly ash and non-fly-ash concrete of equal strength and equal air contents. Fly ash does not affect the air entrainment system as such, but rather the air-entraining agent demand, as discussed earlier.

4.6 Chemical Resistance

The chemical resistance of concrete depends on two groups of factors: 1) physical--the quality of concrete, mainly permeability, uniformity, shape and size of the element, etc., and 2) chemical--the resistance of the binder itself. Depending on the quality and intensity of the aggressive environment, either of these two groups may be of primary importance. Fly ash, used as a replacement for portland cement, has an indirect influence on both groups of factors [2].

The main causes of concrete deterioration by chemical action are leaching of calcium hydroxide, acidic dissolution of cementitious hydrates, the action of atmospheric and dissolved carbon dioxide, and the reactivity of cement components with a variety of aggressive agents. Fly ash reduces such deterioration by reducing the long-term permeability of the concrete and, through the pozzolanic reaction, by tying up the calcium hydroxide chemically.

A study by the U.S. Bureau of Reclamation [53] established that fly ash in concrete under melting and drying conditions greatly improves the sulfate resistance of concrete made with all types of cement. Also, the effectiveness of fly ash in improving sulfate resistance was found to increase proportionally with the severity of the exposure to sulfate [16].

4.7 Other Properties

4.7.1 Creep, Modulus of Elasticity and Drying Shrinkage. Some studies have shown [16] that fly ash increases the creep of concrete. However, those investigations involved direct replacements of fly ash for cement and produced lower strength at loading. Since creep is dependent on both compressive strength and modulus of elasticity, lower strengths should be expected to lead to higher creep. Lothia et al. [54] have reported that the rate of creep with time is quite similar for plain concrete and concrete with fly ash contents of 15% or less. However, at fly ash contents higher than 15%, slightly higher creep occurs. If concrete mixes containing fly ash are proportioned to produce equal strength at or before the time of loading, creep would not increase. Some laboratory studies [16] have shown that fly ash concrete produces less creep at ages beyond 100 days.

Fly ash properties controlling the compressive strength of concrete also influence the modulus of elasticity but to a lesser extent. The modulus of elasticity, like compressive strength, is lower at early strength and higher at ultimate strength when compared with concrete without fly ash [19]. As concluded by Lane and Best [16], cement and aggregate characteristics have a much greater effect on the modulus of elasticity than the addition of fly ash.

Fly ash in commonly used proportions does not generally influence the drying shrinkage of concrete significantly. However, since drying shrinkage is a function of the paste volume and since the addition of fly ash usually increases paste volume, the drying shrinkage may be increased by a small amount if the water content remains constant. The study by Davis [1] indicates no apparent difference in drying shrinkage between concrete with low fly ash content and concrete without fly ash. Also, the study by the TVA [24] showed that the drying shrinkage of plain and fly ash concrete bars is essentially the same after 400 days.

4.7.2 Alkali-Aggregate Reactions. Sodium and potassium alkalis in certain cements react with the siliceous constituents of certain aggregates to form products of greater volume than the combined volumes of the reactive materials. This expansion leads to cracking and spalling.

Fly ash has been found to be effective in reducing expansions due to alkali-aggregate reactivity in concrete [22,56-60]. The alkalies released by the cement preferentially combine with the reactive silica in the fly ash rather than in the aggregate. When a part of the portland cement is replaced by fly ash, the available alkali in the system is reduced by the amount of fly ash present, provided the latter does not contain "soluble alkali." A further reduction in alkalinity may also occur with the progress of the pozzolanic reactions [3].

It should be noted, however, that the addition of some high calcium fly ash containing large amounts of soluble alkali sulfates might increase rather than decrease the alkali-aggregate reactivity. Such a phenomena has been reported by Mehta [61] and also by Diamond [62]. Both investigators have pointed out that it is the soluble alkali and not the total alkali present in a fly ash which plays a role in increasing the alkali-aggregate reactivity.

4.7.3 <u>Chemical Admixtures</u>. Investigations by Sumarin and Ryan [67] showed that fly ash can be used successfully with water-reducing agents. Compared with non-fly-ash mixes, such concrete provides higher 90-day strength, less bleeding in lean mixes, higher 28-day tensile strengths, and setting times 1 to 2 hours longer.

From an extensive laboratory study of the combined use of fly ash with superplasticizers, Lane [68] has concluded that slightly more sand is usually used in mix proportioning with these materials than in conventional concrete. He also reported that superplasticizers in fly ash mixes do not seem to improve compressive strength as much as in plain concrete. Similarly, shorter periods of increased plasticity and smaller reductions in the required water were observed.

CHAPTER 5

REVIEW OF FLY ASH CONCRETE MIX PROPORTIONING METHODS

Even a cursory review of the literature reveals the controversy which exists today concerning the role of fly ash in concrete. Fly ash has been viewed as an admixture, as a partial replacement for portland cement and, in a few instances, as a partial replacement for sand. These different viewpoints have resulted in different mix design methods.

5.1 Simple Replacement Methods

The principal method used by most mix designers for proportioning fly ash concrete is to substitute fly ash for cement. This substitution is generally made on a one-for-one basis either by weight or by volume in order to make sense out of the existing water-cement requirements of specifications. Fly ash concrete mixes proportioned by this method will usually have lower strengths than their control mixes at ages up to 28 days, but frequently equal or higher after 28 days.

The equal replacement approach to mix proportioning is suitable for most concrete applications, where early strength is not a prime requirement. The main drawback of this method is that the pattern of strength development, and workability will fluctuate considerably depending on the nature of the cement and fly ash, the water demand and pozzolanic activity of the fly ash, as well as the percentage cement replacement [69].

5.2 Modified Replacement Methods

All these methods have one common feature. The amount of fly ash put into the mix is greater than the amount of cement removed, the difference being accommodated by a change in the aggregate proportions.

Lovewell and Washa [70] showed that the actual quantity of fly ash in excess is dependent on the cement content of the original mix, with the extra amount of fly ash required increasing as the cement content decreased.

Modified replacement methods permit a fixed amount of cement reduction within a certain range, irrespective of the original cement content in the corresponding plain concrete mix. However, the use of fly ash in mixes of certain strength ranges may not be economical due to the cement/fly ash cost ratio [69].

5.3 Rational Methods

Smith [71] was probably the first to develop a rational approach to fly ash concrete mix proportioning. This method if based on the assumption that every fly ash possesses a unique cementing efficiency (k) such that a mass (F) of fly ash would be equivalent to a mass (kF) of cement. The required strength and workability of fly ash concrete comparable to plain concrete are obtained by applying Abrams' relationship between strength and water/cement (W/(c+kF)) ratio and by controlling the volume ratios of cementitious particles to water and aggregate.

ACI 211.1-81, Standard Practice for Proportioning Normal, Heavyweight and Mass Concrete, gives proportioning procedures in mass concrete containing pozzolans. Significant cement reductions can be achieved by adding fly ash to mass concrete in quantities greater than the amount replaced. In addition, fly ash will reduce the heat of hydration in mass concrete. The ratio of fly ash to cement will vary depending on the pozzolanic activity and job specifications.

The method applied by the Tennessee Valley Authority (TVA) [72] for proportioning fly ash concrete is essentially based on ACI 211.1-81. Modifications to this standard serve to adjust mixture performance due to the addition of fly ash. The increased workability obtained with fly ash allows for lower water contents than those proposed in ACI 211.1-81. As the cement content is reduced by using fly ash, the water-cement ratio by weight is no longer valid. Consequently, a water-cement plus pozzolan ratio was adopted by TVA several years ago and proposed by ACI Committee 211 [16].

CHAPTER 6

EXPERIMENTAL PROGRAM

6.1 Materials

All materials utilized in this study, except the fly ash and Type IP cement, were typical of material presently used in the manufacture of portland cement pavement concrete in the Houston, Texas area.

Two types of cement were used in this project. The Type I as defined in ASTM Specification C150 was produced by General Portland, Inc., Trinity South Division, at a facility located near New Braunfels, Texas. The ASTM C595 Type IP cement was produced by Texas Industries, Inc., Cement Division, at the plant located in Midlothian, Texas and contained 20% Type A fly ash by weight. Chemical and physical properties of cements used in this study are presented in Tables A.1 and A.2 of Appendix A.

Fly ash used in the study was obtained from two sources. Low calcium fly ash, designated Class F according to ASTM C618-84 and as Type A by Texas SDHPT Material Specification D-9-8900, was from the Big Brown plant near Fairfield, Texas. High calcium fly ash, Class C according to ASTM C618 and Type B according to Texas SDHPT Materials Specification D-9-8900, was obtained from the Welch Plant at Cason, Texas. The chemical and physical test results of the fly ashes presented in Table A.3 indicate that they complied with the requirements of the ASTM C618-80 and Texas SDHPT D-9-8900 specifications in relation to their physical properties and chemical composition.

The coarse aggregate used was partially crushed, 1-in. maximum size river gravel. The fine aggregate was natural sand. Both aggregates were from local Texas sources. Tables A.4 and A.5 summarize the properties of these aggregates. The aggregates were used in partially saturated states, and their moisture content was determined prior to mixing. Preliminary tests showed that the absorption of these aggregates was relatively low and amounted to 0.77 percent and 0.40 percent for coarse and fine aggregate, respectively.

Two types of chemical admixtures were used in all the mixes. The water reducer-retarder was Pozzolith 300R. The amount used in the concrete was 33 oz/yd^3. The air-entraining admixture was MB-VR, used in the amount of 1/2 oz/sack of cement. Tap water was used in all mixes. The unit weight of water was taken to be 62.5 lb/cu.ft. and the temperature was about 75°F±5°F during mixing.

6.2 Mix Design

The basic concrete mix proportions used in this study were obtained from those used by the Texas SDHPT in District 12, Houston, for concrete pavements. The original design called for 1-1/2 in. THD Grade No. 2 coarse aggregate, coarse aggregate factor (CAF) of 0.80, and a cement factor (CF) of 5.5 sks/cu.yd. The preliminary mixes based on this original design had poor workability and uniformity caused mainly by the small capacity of the mixer used (6 cu.ft.) and relatively large size of coarse aggregate. Therefore, after a series of trial mixes, a 1.0 in. max THD Grade No. 4 coarse aggregate was selected for further mixes and a new CAF equal to 0.77 was established accordingly. The other parameters for the original mix were not altered. The design work sheets of an original and re-designed concrete mix are shown in Appendix B. The basic mix design was proportioned according to Texas SDHPT Construction Bulletin C-11.

For the mixes containing fly ash, portions of the cement were removed from the basic mix and replaced by an equal weight of fly ash. Thus, the solid volume of cementitious material added was increased because of the difference between specific gravities. Cement replacements with fly ash of 15, 25, and 35% were used.

A parallel series of tests was conducted with mixes having the CF increased from an original 5.5 sks/cu.yd. to 6.5 sks/cu.yd. The design work sheet for this mix is included in Appendix B.

Similar to the previously described mixes, those mixes also had 15, 25, and 35% of cement replaced by fly ash. A control mix of both types, just using cement and no fly ash replacement, was made for control purposes. An additional mix of similar proportions was made using Type IP cement.

The proportions of the basic mix designs are shown in Appendix B as per the Texas SDHPT 1982 Standard Specifications for Construction of Highways, Streets and Bridges, Item 360 and Construction Bulletin C-11. All mixing was done based on the slump of fresh concrete which was held between three to four inches. All mixes were air-entrained and a retarding admixture was used in all of them.

6.3 Mixing Procedures and Testing of Fresh Concrete

All the mixes used in this study were made using a 6 cu.ft. max capacity Essex drum mixer at a mixing speed of 30 rev./min. The mixer was moistened thoroughly first and then the aggregate with about 50% of the water containing the retarder was put in and mixed for 5 minutes. The cement or cement plus fly ash was added next, and then the remainder of the water and the air-entraining admixture was added as required to reach the desired slump after 5 min of mixing. The mixer was then stopped for 5 min and 3 min of additional mixing followed. More water was added at this stage if required to attain the desired slump of 3-1/2 ± 1/2 in. In general, mixing was completed in about 15 minutes from the time the first materials were added to the mixer. A similar mixing procedure was followed for the mixes used to study the effect of high temperatures on the properties of concrete containing fly ash, referred to hereafter as hot weather mixes. In this case, however, the aggregate was preheated overnight to a temperature of 100°F. Also, in order to maintain a high temperature during mixing time, hot tap water at a temperature of about 105°F was continuously run over the mixer drum.

Slump tests were conducted according to ASTM 143-78, Standard Test Method for Slump of Portland Cement Concrete, and Tex-415-A, Slump of Portland Cement Concrete. The unit weight of every fresh mix was measured according to ASTM C138-81, Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete, using a 0.25 cu.ft. container. Yield of the mix was calculated on the basis of batch weights and specific gravities.

In addition, the amount of air in every mix was measured according to ASTM C231-82 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method using a PRESS-UR-METER. The temperature of every mix was also recorded.

For the hot weather mixes, the mixing times were 90 min with slump readings taken after 30, 60, and 90 min of mixing, respectively. After 60 and 90 min, the slump was adjusted if necessary by adding water. At the same time, flexure and compressive test specimens were cast.

6.4 Casting and Curing of Specimens

Twelve standard, 6 x 12 in., compressive strength cylinders and 12 standard, 6 x 6 x 20 in. flexural beams were cast from each mix. The concrete was placed inside the molds in layers and consolidated using a steel rod. The placing and consolidating were done according to current ASTM and Texas SDHPT methods.

For the purpose of freeze-thaw testing, 3 x 4 x 16 in. beam specimens were cast. In all, 60 series of mixes were made with a total of about 1500 specimens cast. This included repeat mixes made throughout the project as a check on repeatability of procedures and results.

After casting, the specimens were covered with wet burlap and kept in the molds for 24 hr. They were then demolded and transferred to the appropriate curing room. Depending on the type of test scheduled, the specimens were exposed to one or a combination of the following curing conditions:

1. Moist curing in standard laboratory curing room conditions, +74°F and 98% relative humidity;
2. Cold curing, +40°F and 55% relative humidity;
3. Hot curing, +100°F and 33% relative humidity; and
4. Lab curing, +75°F and 54% relative humidity.

The length of exposure to the particular curing conditions depended on the test series. The details of each individual test series are given in Chapter 8.

6.5 Testing of Hardened Concrete

The following specifications were followed for compressive, flexural, and freeze-thaw resistance testing; ASTM C39-81, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Tex-420-A, Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), ASTM C666-80 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Method B.

Compressive tests were performed using a SATEC 400 kip compression testing machine. Flexure testing was carried out on a Rainhart hydraulic, hand-operated center point loading beam tester having a 12 kip capacity.

All compressive strength specimens were capped using Forney's high-strength capping compound.

CHAPTER 7

TEST RESULTS

This chapter contains the raw data obtained from various tests which were conducted in the course of this investigation. Due to the high variability and complexity of the test results, it was decided in most cases to present the results in graphical form rather than in tabular form. Only the freeze-thaw test data are presented in both graphical and tabular forms. A detailed discussion and analysis of all data is presented in Chapter 8 of this report.

7.1 Properties of Fresh Concrete

Immediately following discharge from the mixer, the slump, concrete temperature, air content and unit weight of the concrete were measured according to the methods described in Sec. 6.3. The design of the mixes was based on a constant slump of the fresh concrete in the range of three to four inches. The unit weight of the freshly mixed concrete varied between 140 to 144 pcf and the temperature was in the range of 40 to 100°F.

7.1.1 Air Content. The measured air content in all the fresh concrete mixes with different cement and fly ash proportions are shown in Figs. 7.1 through 7.4. All mixes had a constant dosage of air entraining admixture. As can be seen from Figs. 7.1 and 7.2, the amount of air in the mixes containing Type A fly ash decreases for increasing fly ash content. The decrease is almost linear and the amount of air varies from about 5 to 7% for mixes without fly ash to between 2.5 to 3% for mixes with 35% fly ash content.

A similar trend can be observed for 5.5 sks concrete mixes containing Type B fly ash, but in this case the drop in the amount of air due to the addition of fly ash was smaller. For 6.5 sks concrete mixes containing Type B fly ash, no significant changes in the amount of air were observed due to the addition of fly ash, as shown in Fig. 7.4.

7.1.2 Water/Cement Plus Fly Ash Ratio. Plots of water to cement plus fly ash ratios needed to maintain a constant slump when the amount of fly ash in the mixture was increased are presented in Figs. 7.5 through 7.8.

The observed slight reduction in w/c+p ratio, if any, implies a reduced water content in some fly ash concrete mixes. This can be attributed to the lubricating effect of the glassy fly ash spheres. However, the overall amount of water is influenced by the mix proportion and physical as well as chemical characteristics of the components, mainly the fly ash.

The concrete mixes analyzed in this study had a relatively low percentage of sand (34 to 39% of a total aggregate), and the addition of fines

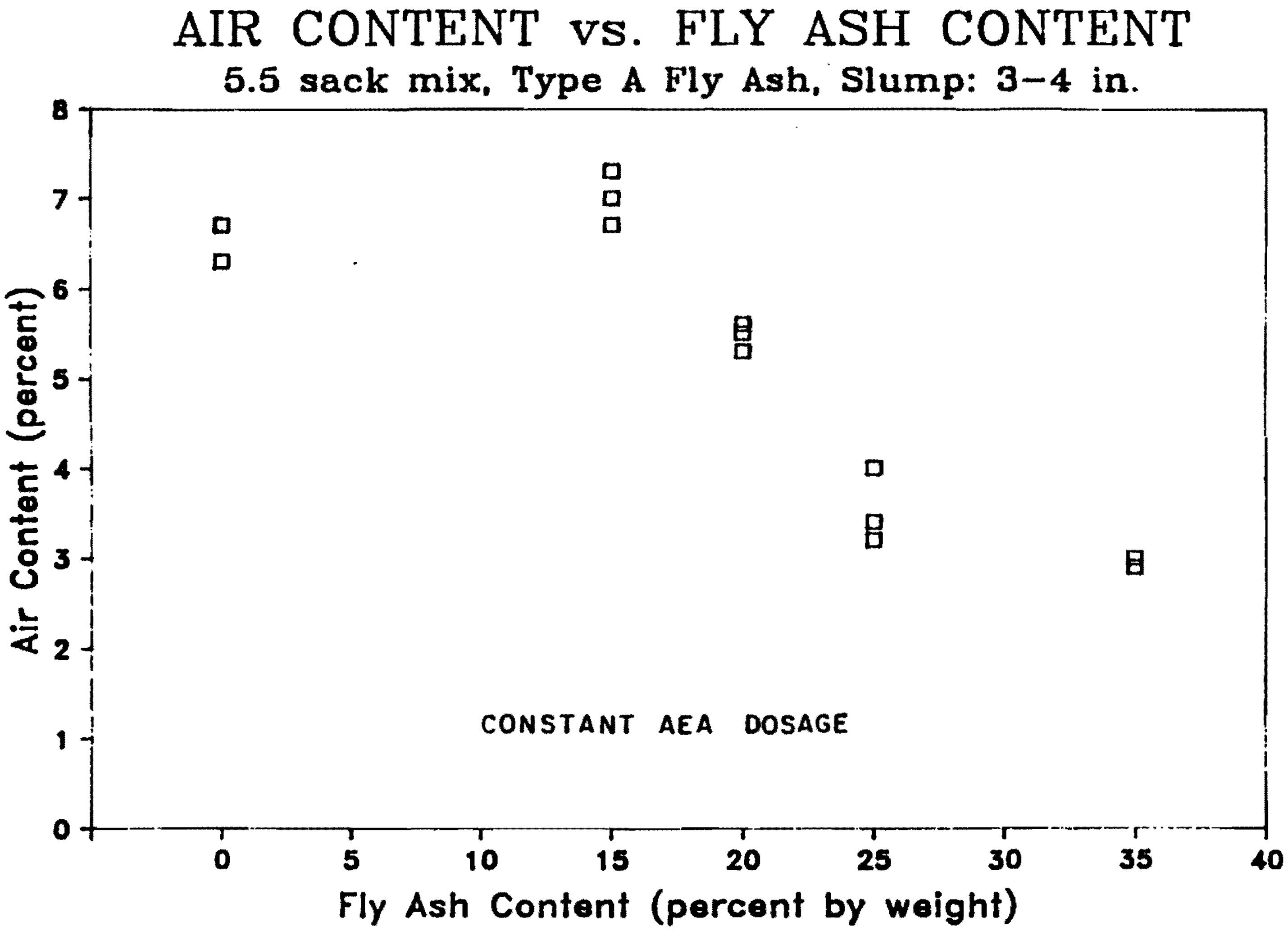

Fig. 7.1 Effect of Type A fly ash content on air content of 5.5 sks concrete mixes

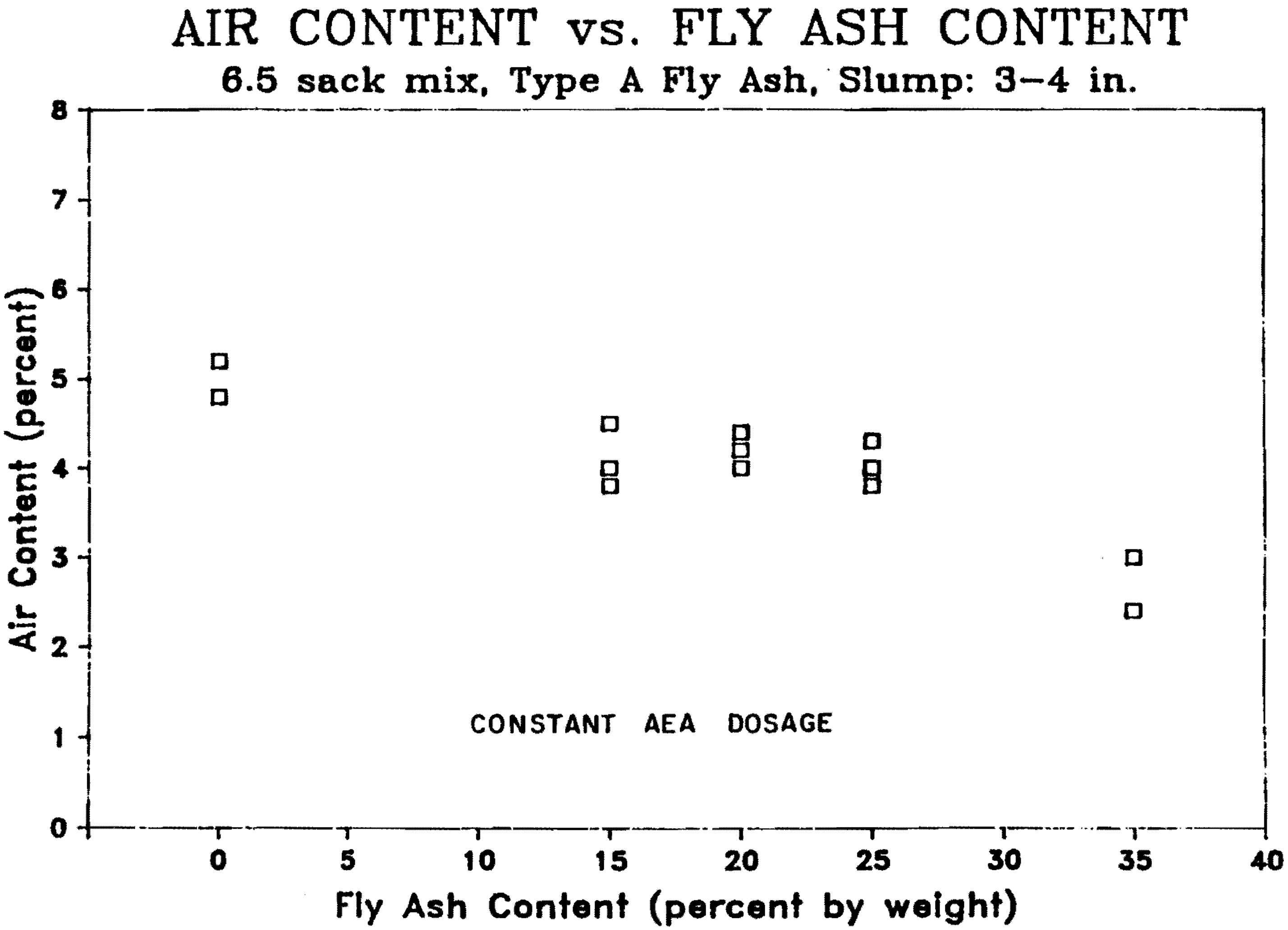

Fig. 7.2 Effect of Type A fly ash content on air content of 6.5 sks concrete mixes

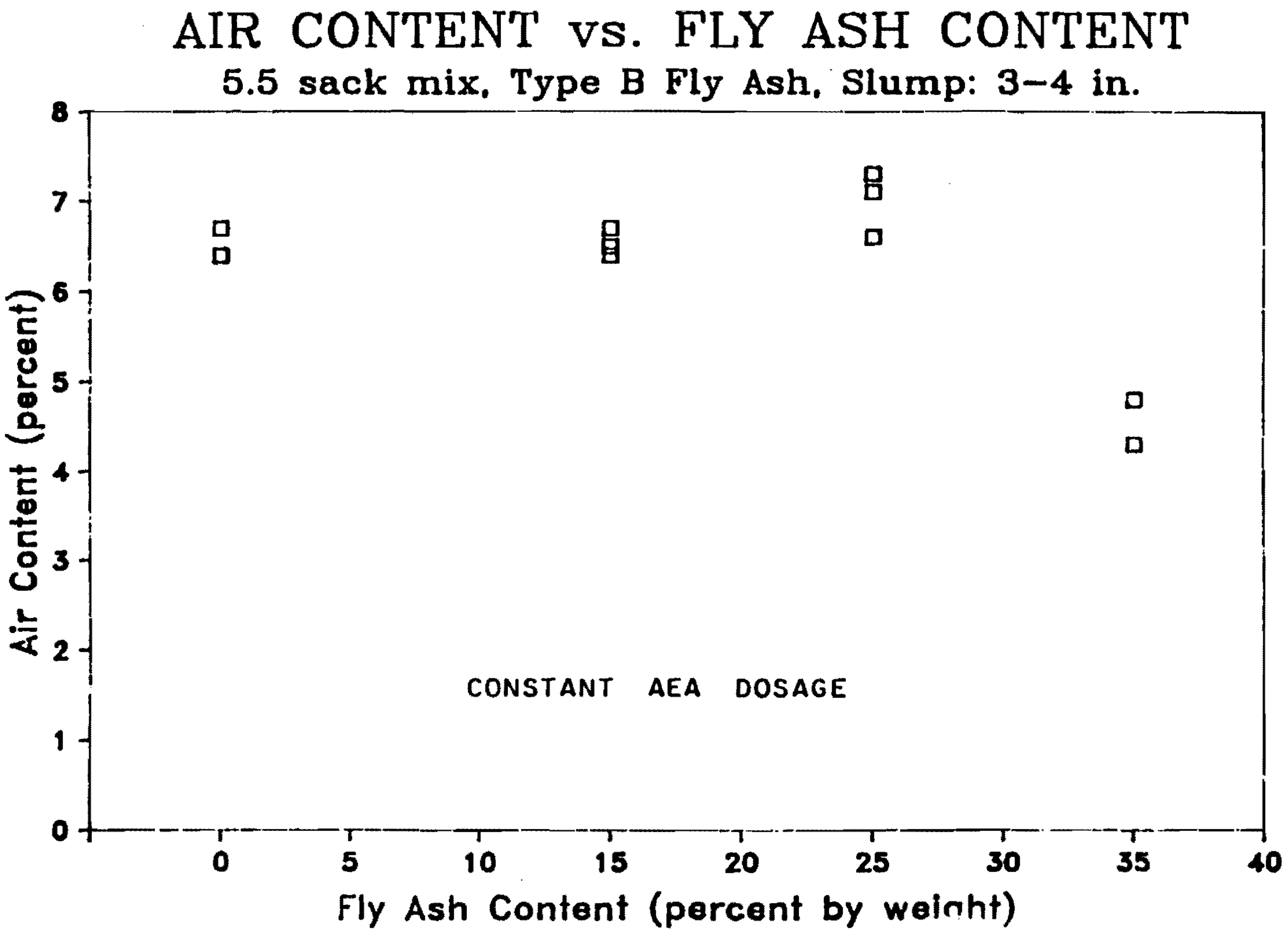

Fig. 7.3 Effect of Type B fly ash content on air content of 5.5 sks concrete mixes

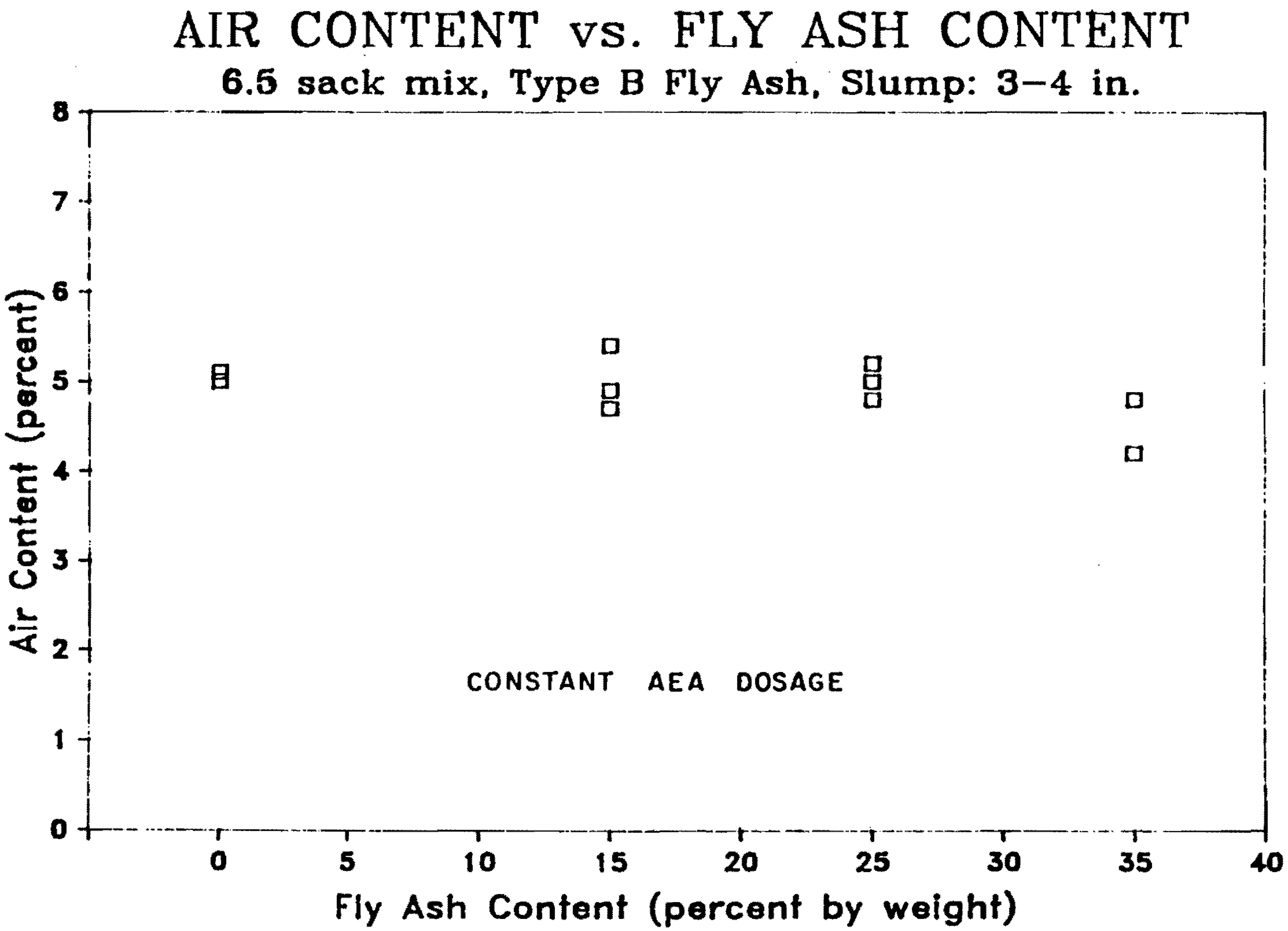

Fig. 7.4 Effect of Type B fly ash content on air content in 6.5 sks concrete mixes

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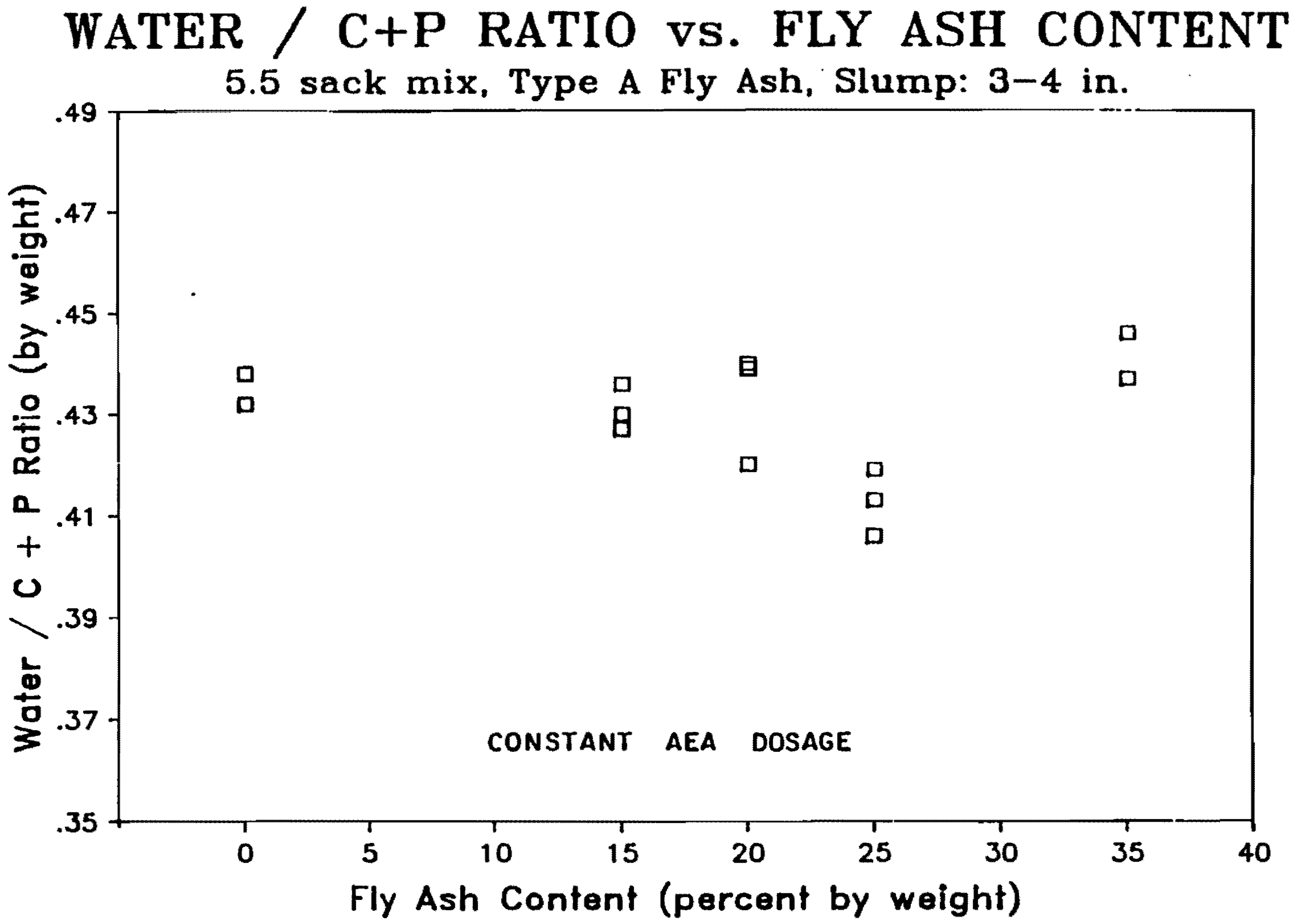


Fig. 7.5 Effect of fly ash content on the water/C+P ratio of 5.5 sks concrete mixes containing Type A fly ash

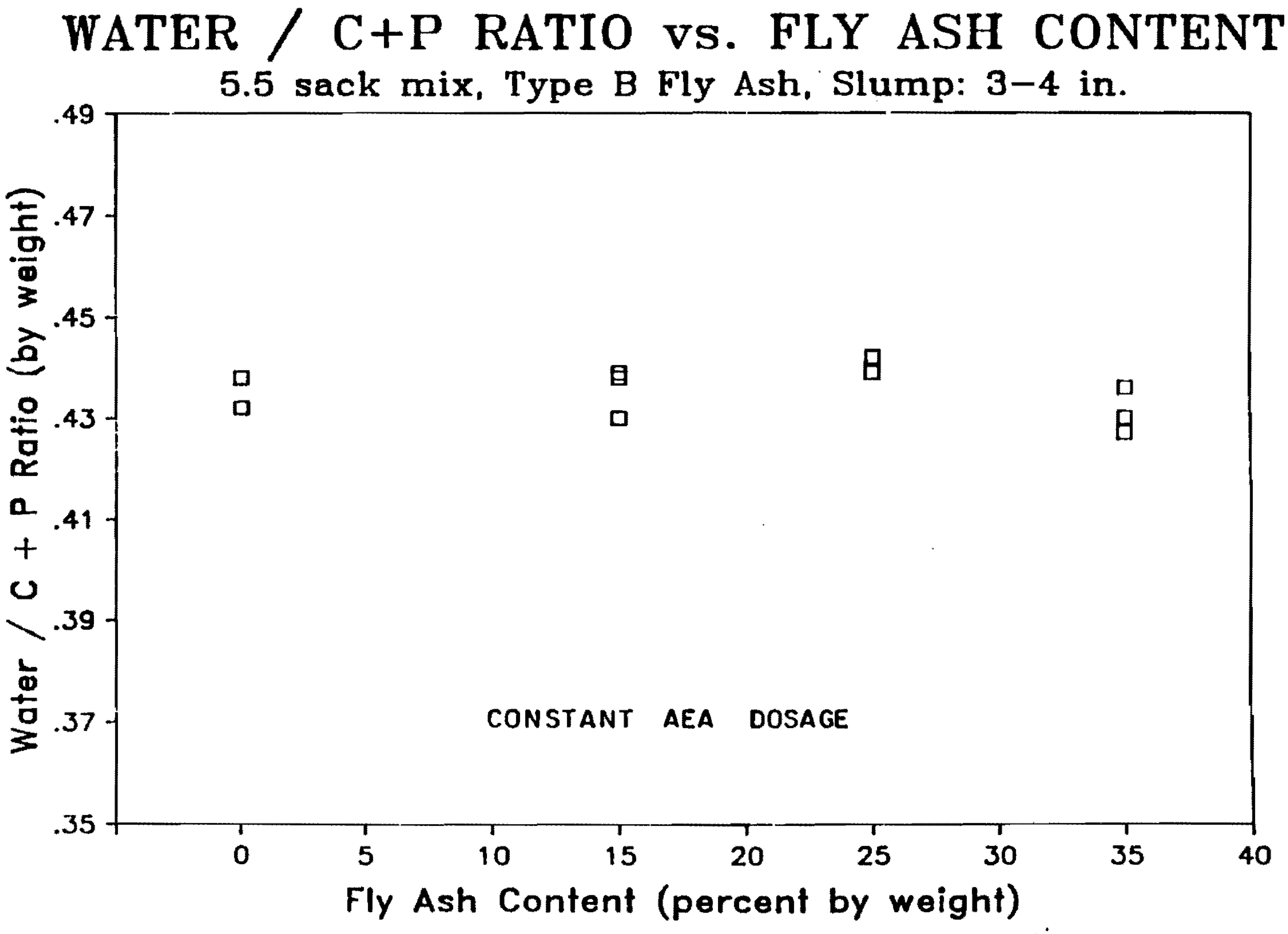


Fig. 7.6 Effect of Type B fly ash content on the water/C+P ratio of 5.5 sks concrete mixes

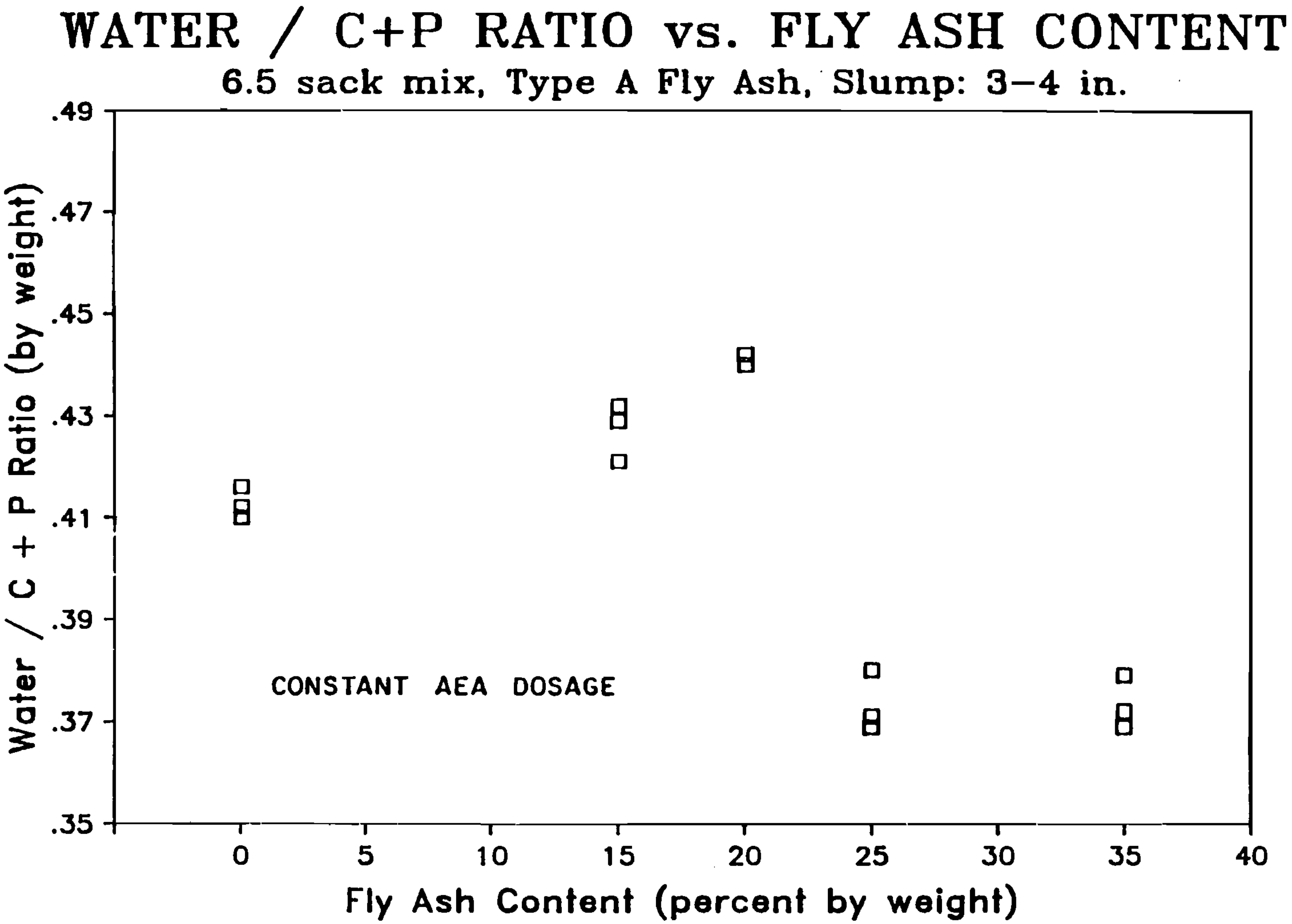


Fig. 7.7 Effect of Type A fly ash content on the water/C+P ration of 6.5 sks concrete mixes

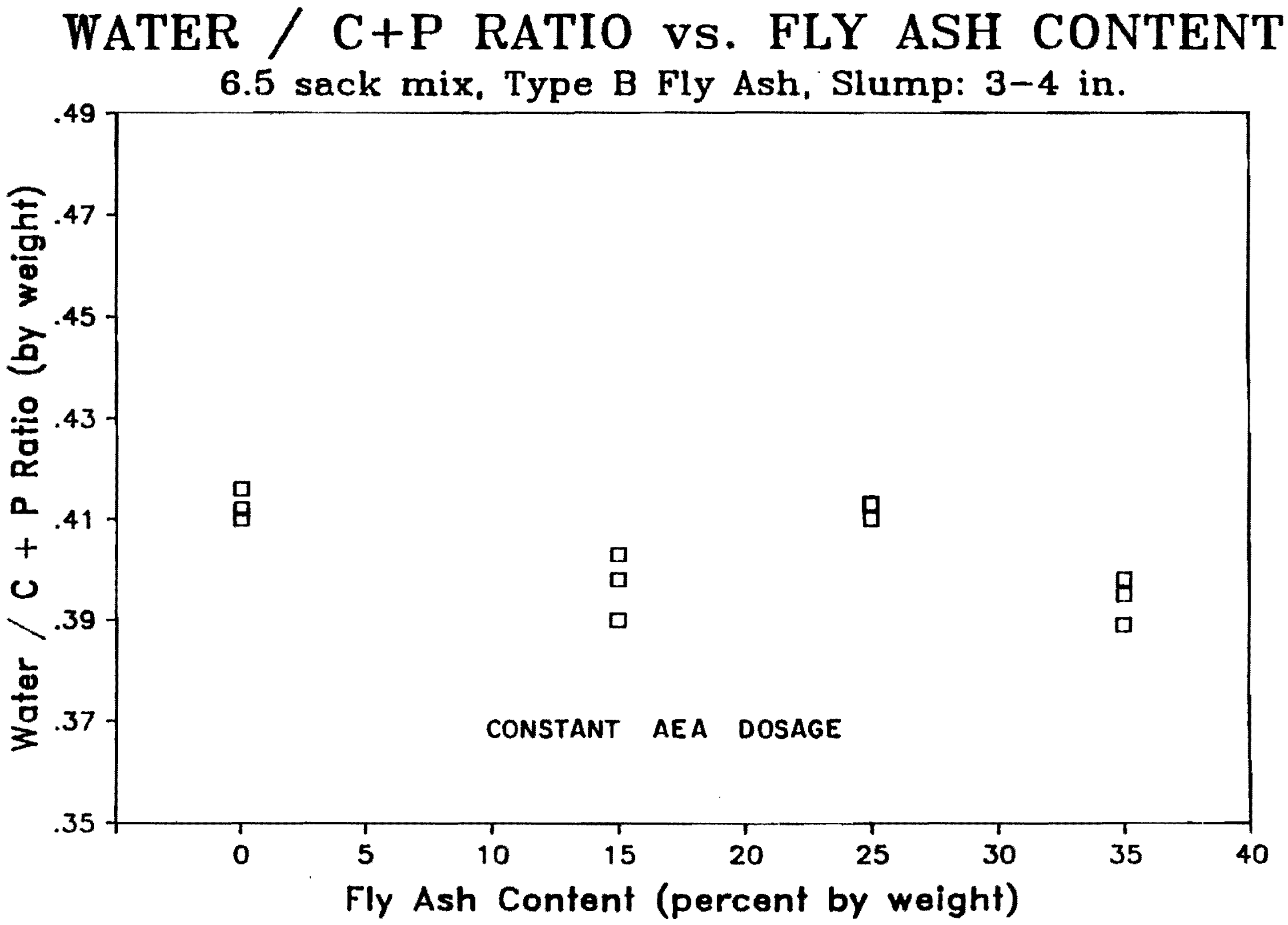


Fig. 7.8 Effect of Type B fly ash content on the water/C+P ratio of 6.5 sks concrete mixes

in the form of fly ash improved the workability without necessarily resulting in a decrease in the water requirements.

However, it should be noted that the effect of fly ash on the mixing water requirement for a given slump was more noticeable in the higher sack content mixes, especially in the Type A fly ash mix.

7.2 Flexural Strength

Texas SDHPT specifications [10] require that the concrete mix produce a minimum average flexural strength of 650 psi at the age of 7 days. One of the main objectives of this research was to determine the effect of cement replacement with fly ash on the flexural strength of the concrete. In addition, the effect of prolonged curing time on the flexural strength gain was studied by testing some specimens after 28 days of curing. 6 x 6 x 20 in. beam specimens tested at an 18-in. span were used for flexural tests. The molds were stripped 24 hr after casting and the specimens were moist cured in a curing room until tested.

The seven-day flexural strength for various cement and fly ash contents are shown in Figs. 7.9 through 7.12. As shown in Figs. 7.9 and 7.10 for 5.5 sks mixes there were several test results which had fallen below the specification limit of 650 psi.

For the 6.5 sks mix shown in Figs. 7.11 and 7.12, the results were almost entirely above the limit except a few test results at higher, 25 and 35%, fly ash replacement.

Companion specimens were cast with the seven-day flexural beams, stored in a moist curing room for 28 days, and then tested. The test results obtained at 28 days are shown in Figs. 7.13 through 7.16. Comparing these results with those obtained for seven-day specimens, it could be seen that the 28-day flexural strengths are all higher than 650 psi.

Detailed comparisons of flexural strengths values are presented in Sec. 8.2 of this report.

7.3 Compressive Strength

The compressive strength results gathered from specimens at various ages and with different fly ash contents are plotted in Figs. 7.17 through 7.32. For simplicity of analysis, the results are divided into four groups, according to the age of specimen at testing. Four groups were analyzed: 7, 28, 56 and 90 days. Prior to testing, all specimens were stored in a curing room as described in Sec. 6.4.

7.3.1 Compressive Strength at Seven Days. The compressive strength results at seven days, shown in Figs. 7.17 through 7.20, indicate that the

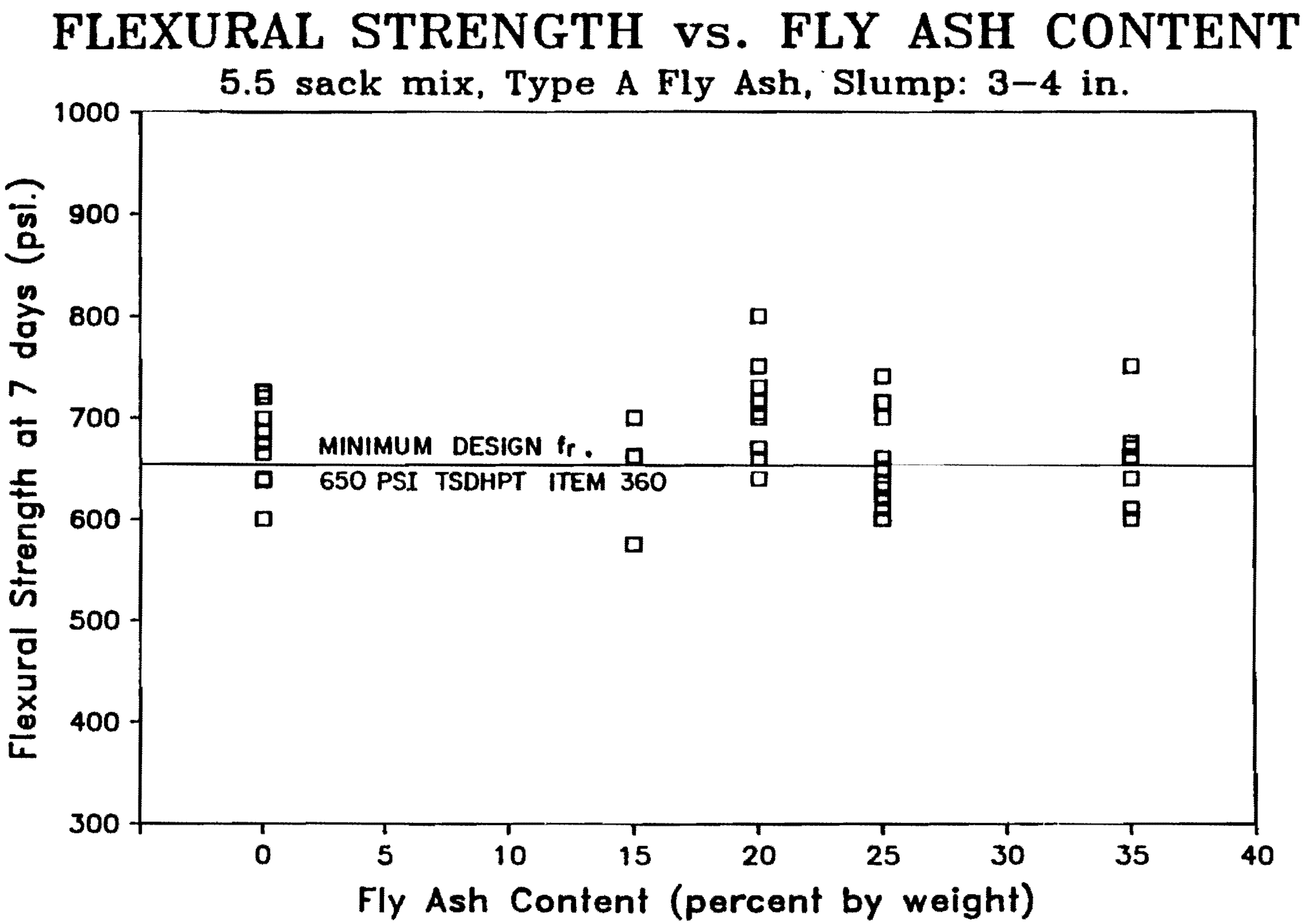


Fig. 7.9 Effect of Type A fly ash content on flexural strength of 5.5 sks concrete mixes

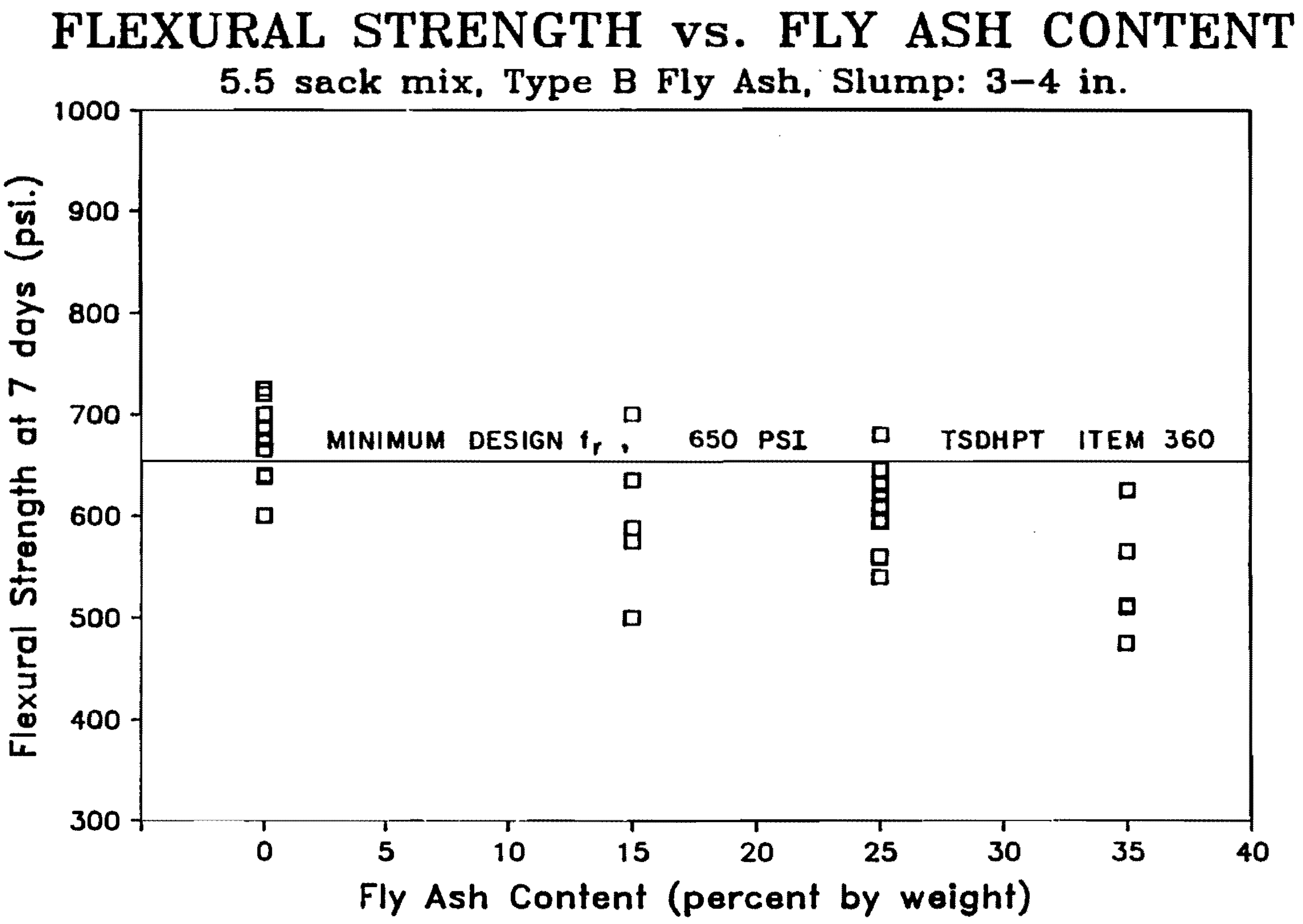


Fig. 7.10 Effect of Type B fly ash on flexural strength of 5.5 sks concrete mixes

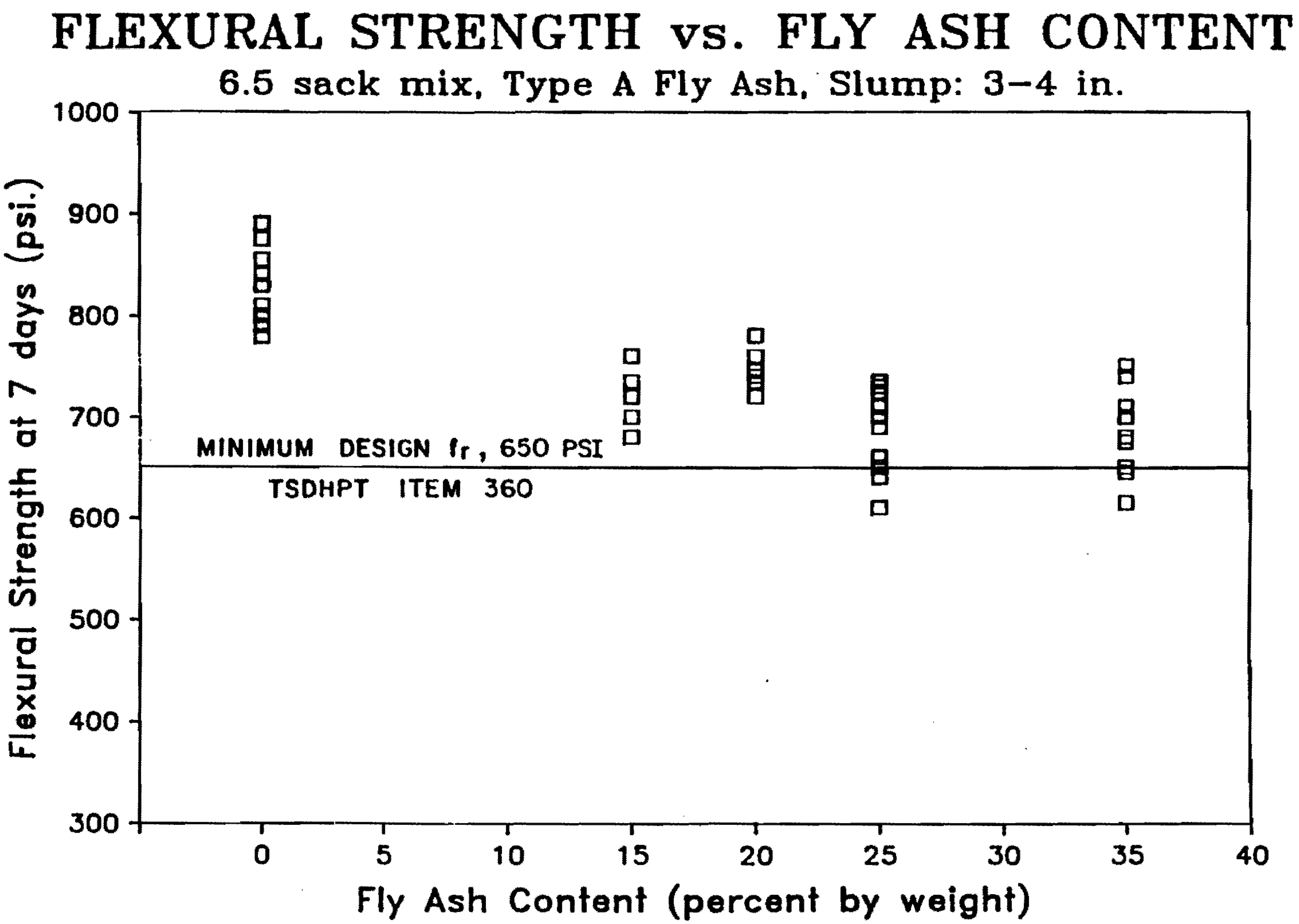


Fig. 7.11 Effect of Type A fly ash content on flexural strength of 6.5 sks concrete mixes

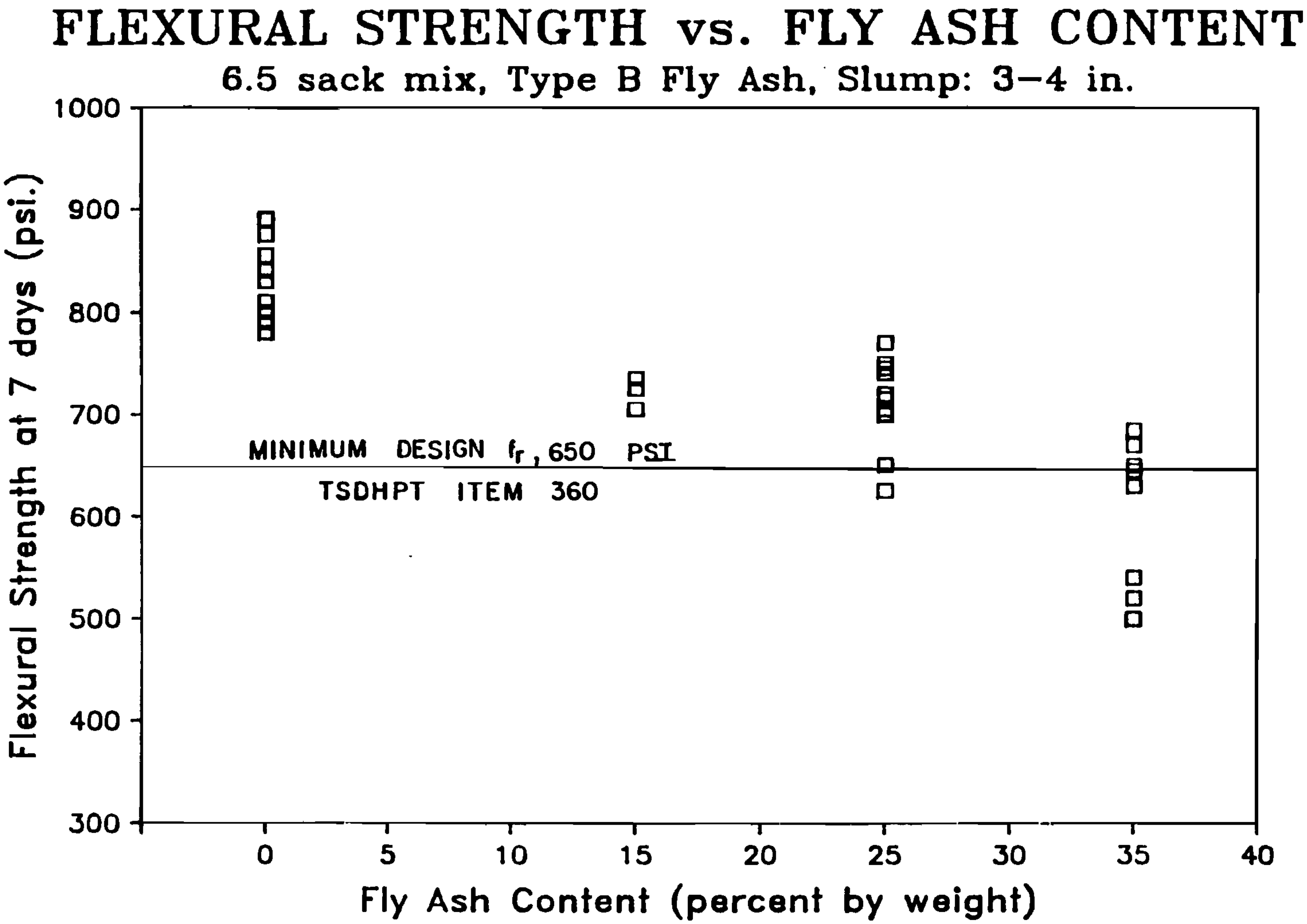


Fig. 7.12 Effect of Type B fly ash oontent on flexural strength of 6.5 sks concrete mixes

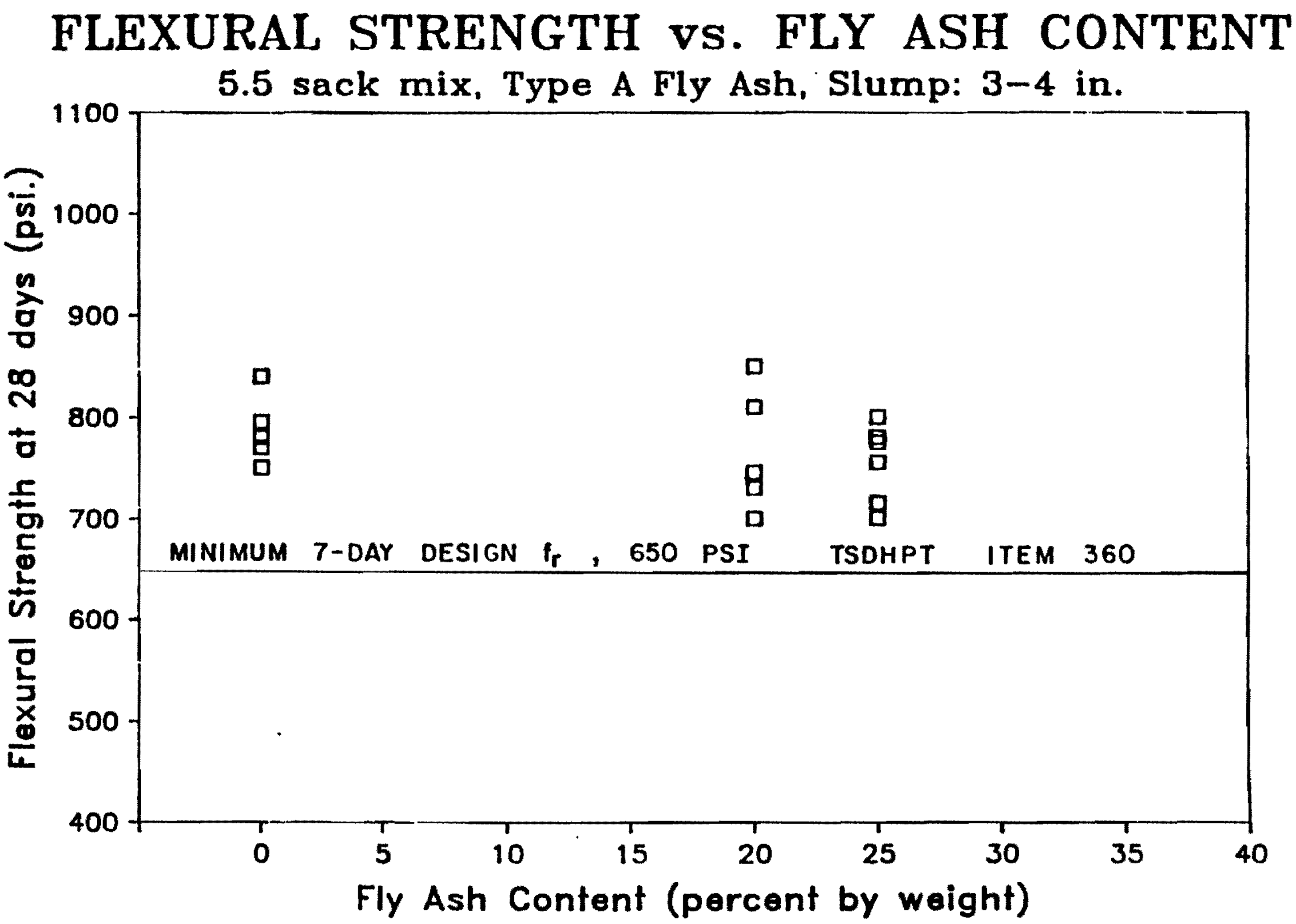


Fig. 7.13 Effect of Type A fly ash on flexural strength of 5.5 sks concrete mixes at 28 days

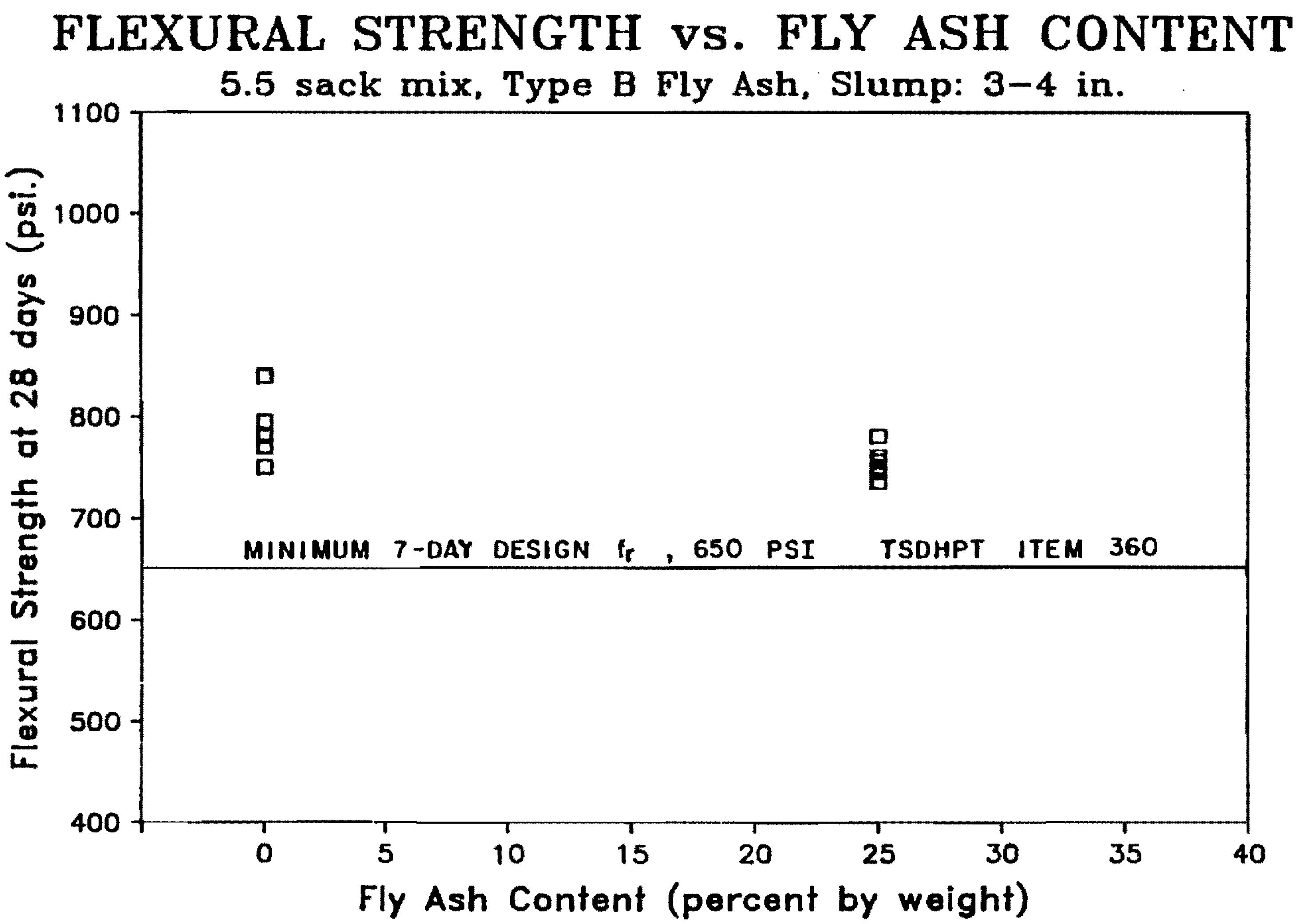


Fig. 7.14 Effect of Type B fly ash on flexural strength of 5.5 sks concrete mixes at 28 days

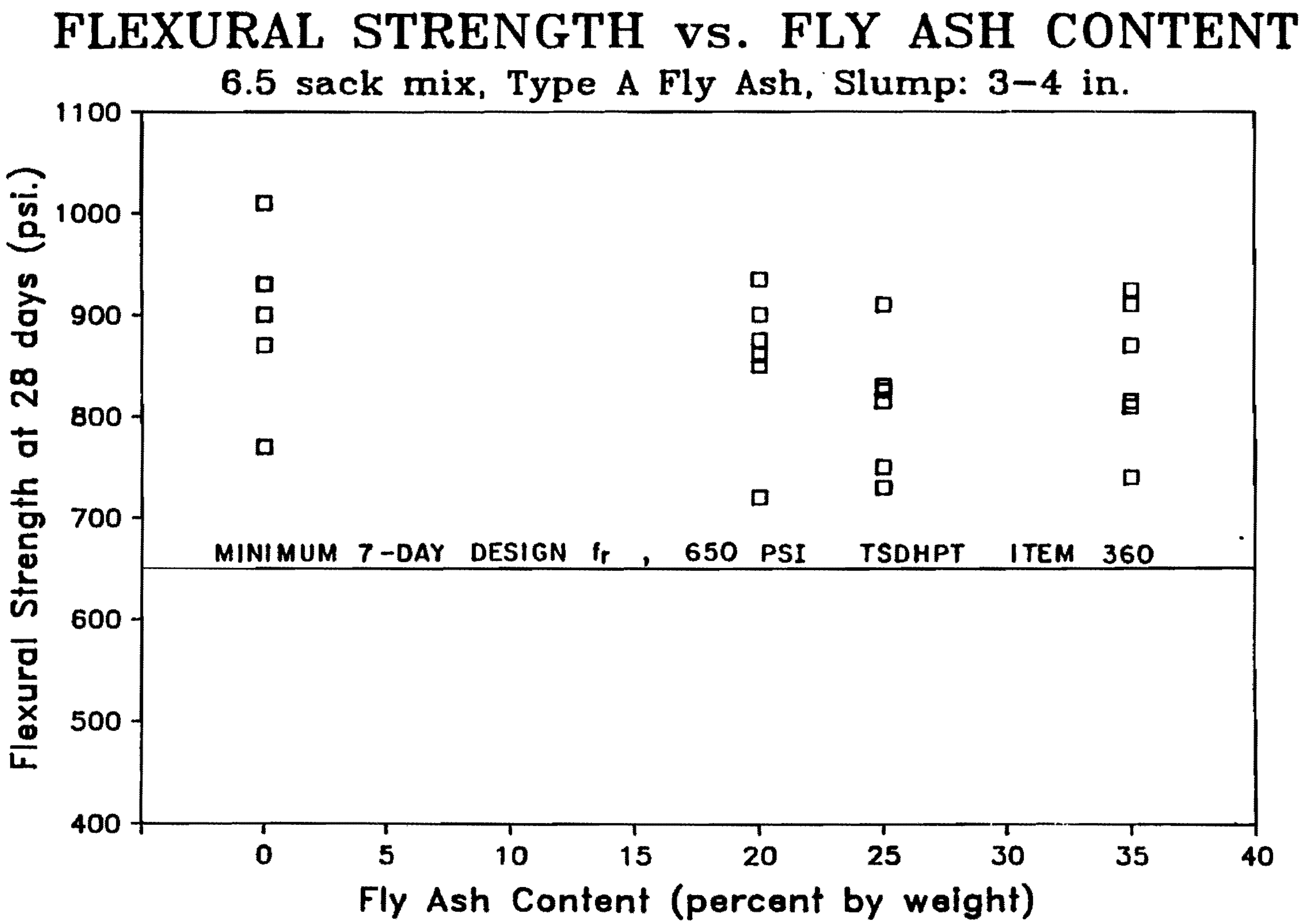


Fig. 7.15 Effect of Type A fly ash on flexural strength of 6.5 sks concrete mixes at 28 days

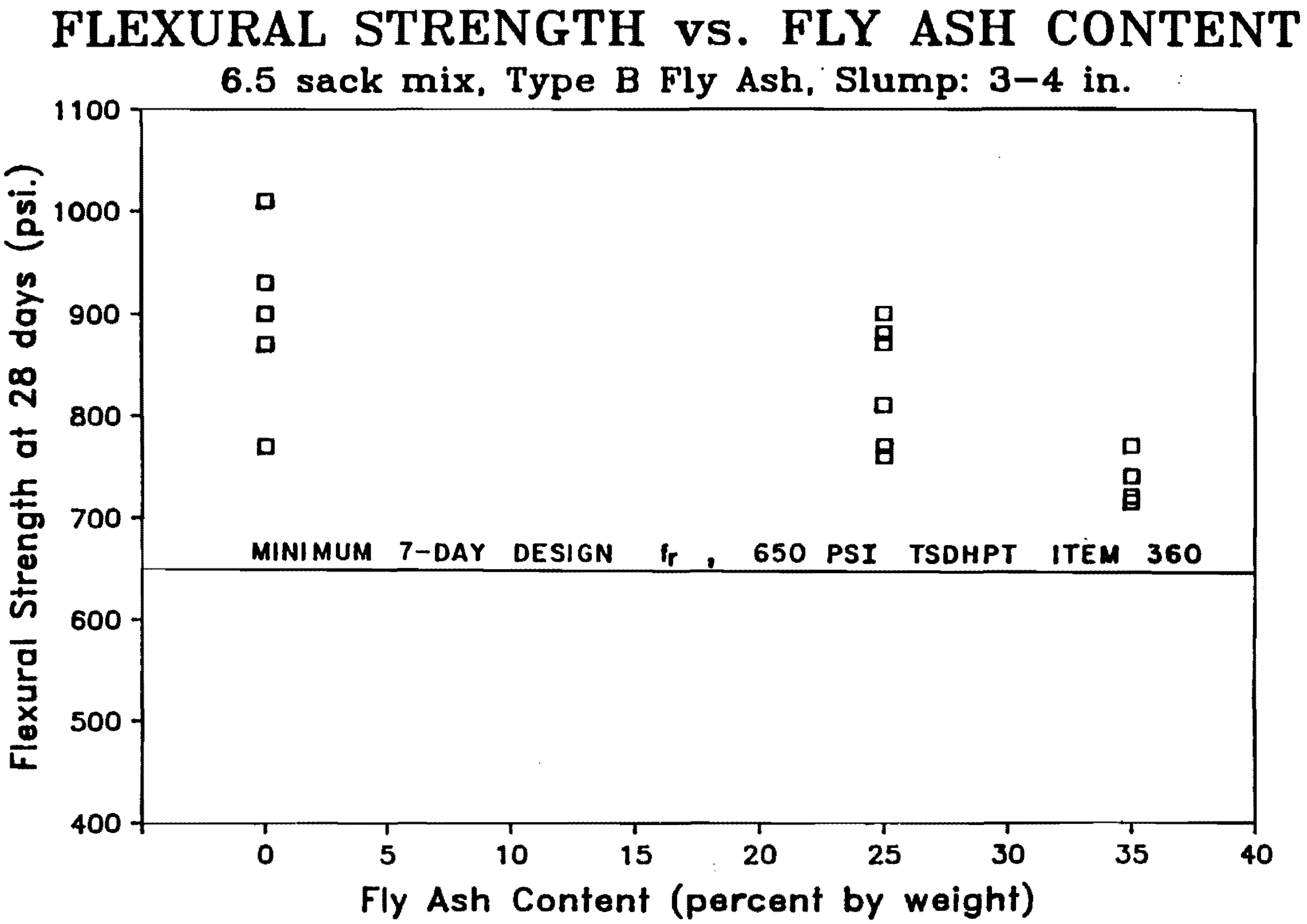


Fig. 7.16 Effect of Type B fly ash on flexural strength of 6.5 sks concrete mixes at 28 days

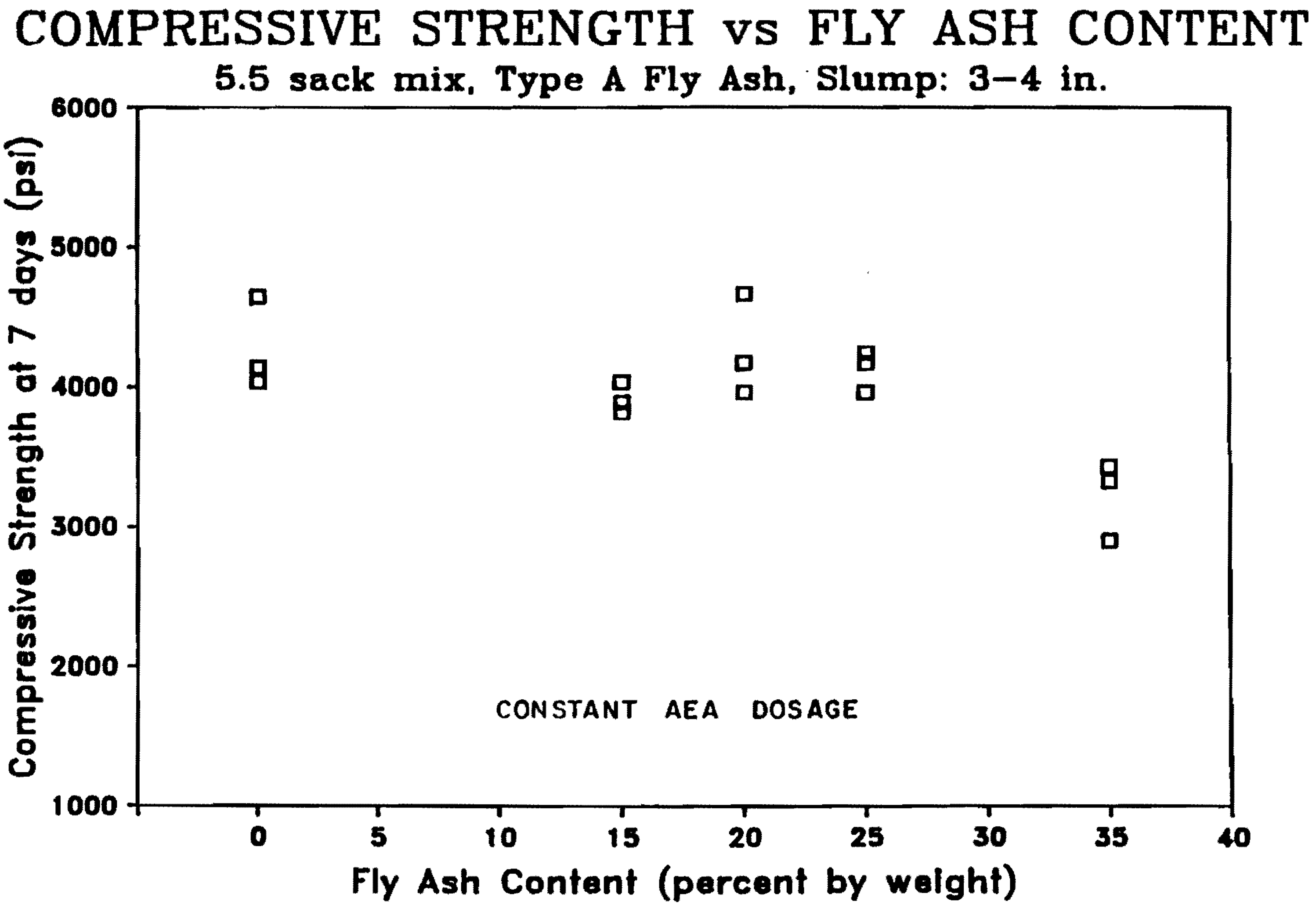


Fig. 7.17 7-day compressive strength of 5.5 sks concrete mix with various Type A fly ash contents

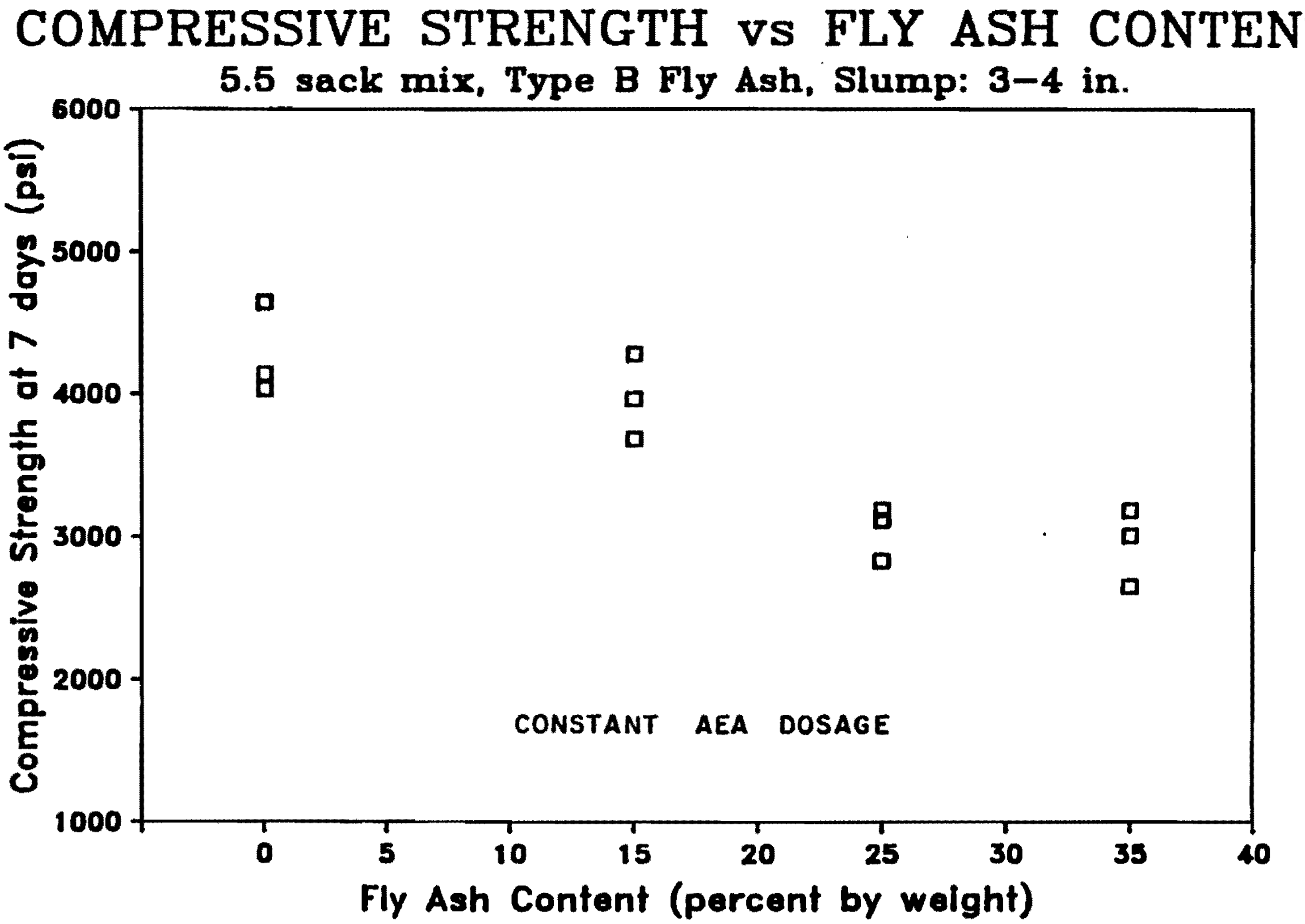


Fig. 7.18 7-day compressive strength of 5.5 sks concrete mix with various Type B fly ash contents.

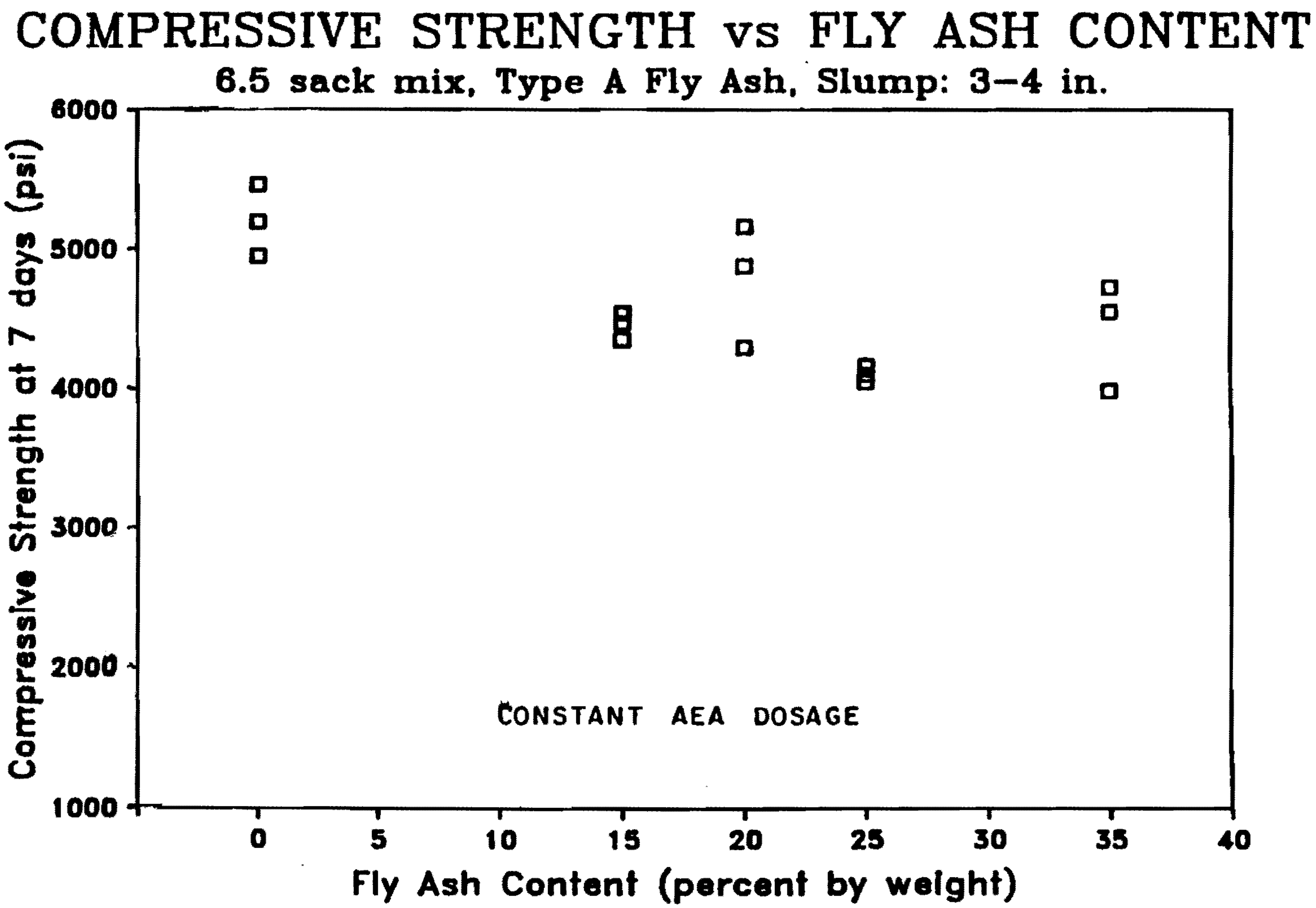


Fig. 7.19 7-day compressive strength of 6.5 sks concrete mix with various Type A fly ash contents.

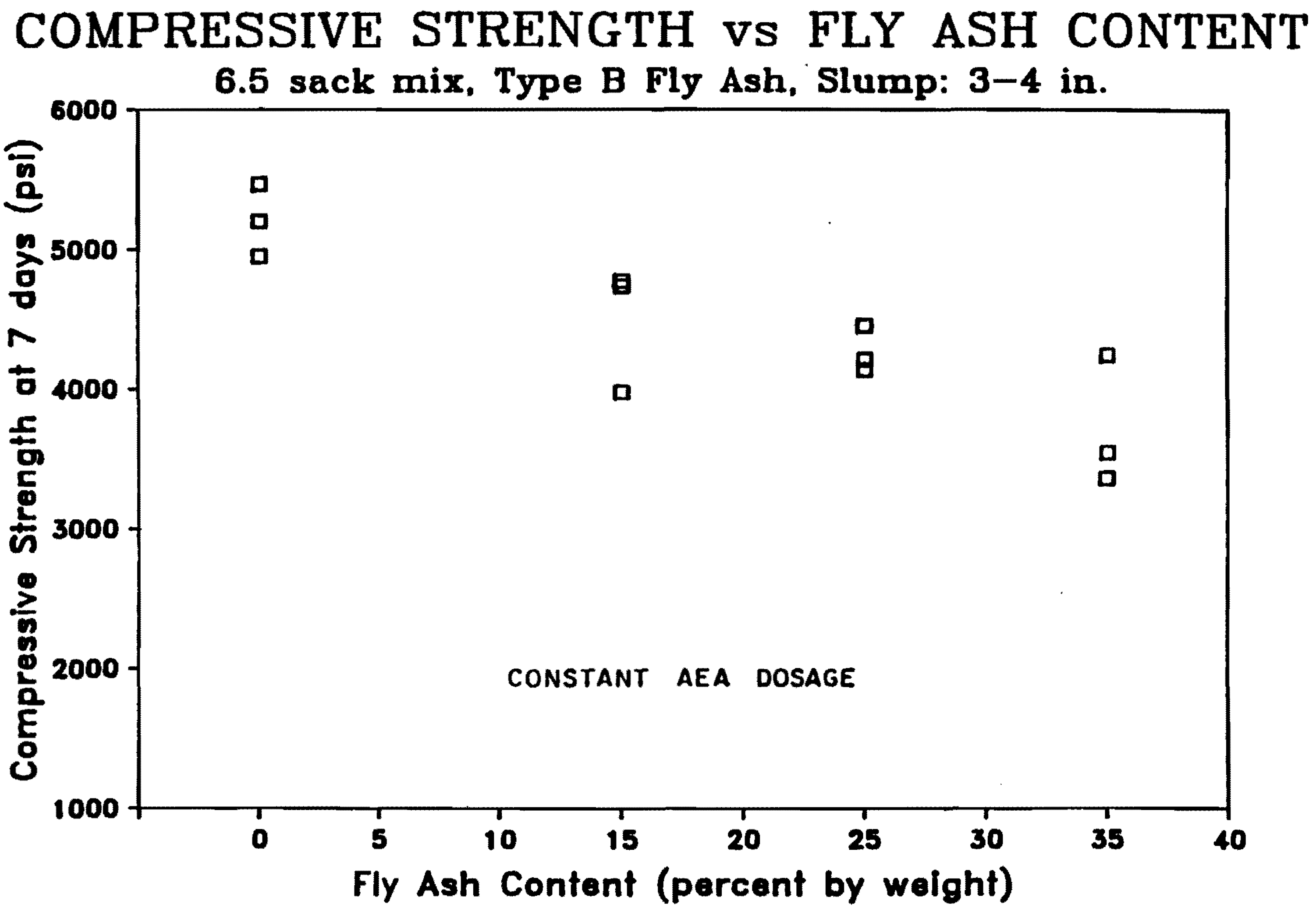


Fig. 7.20 7-day compressive strength of 6.5 sks concrete mix with various Type B fly ash contents.

incorporation of fly ash into the mix will cause a reduction in strength regardless of the type and the amount of fly ash used. Only the specimens produced with Type IP cement had strengths comparable with the strength of plain concrete.

7.3.2 Compressive Strength at 28 Days. A review of the data presented in Figs. 7.21 through 7.24 shows that 28 days compressive strength tends to increase with increased fly ash content. Those trends were more noticeable for concrete with Type A fly ash.

7.3.3 Compressive Strength at 56 Days. Similar trends were observed on 56-day compressive strength as on 28-day compressive strength for all mixes, as can be seen by comparing Figs. 7.21 through 7.24 with Figs. 7.25 through 7.28. Again, an increase in strength with increase fly ash content can be observed over the range of fly ash contents investigated.

7.3.4 Compressive Strength at 90 Days. Figures 7.29 through 7.32 are plots of compressive strength results after 90 days of curing. The distribution of the results is similar to that for 28 and 56 days with individual data being of higher value. The general discussion of all compressive strength results is presented in Sec. 8.3.

7.4 Effect of Temperature and Mixing Time

The effects of high temperature and mixing time on slump and strength of concrete with and without fly ash were studied. Six series of tests were conducted; three of them at room temperature, 72±3°F, and three at high temperatures, 102±3°F. Each series included a plain, 6.5 sks reference concrete mix, and mixes in which 25 and 35% of cement were replaced by equal weight of Type B fly ash. The mix proportions are given in Table 7.1.

The mixing time was 90 min with slump readings taken after 15, 30, 60, and 90 min of mixing. After 60 and 90 min of mixing retempering water was added to every mix in order to restore the initial slump of 3-1/2 in. The slump readings are summarized in Table 7.2 and presented graphically in Figs. 7.33 and 7.34 in the form of time plots and in Figs. 7.35 through 7.38 in the form of histograms for the test time intervals.

Approximately after 15 min of mixing as well as after 60 and 90 min, flexural strength and compressive strength specimens were cast using the 3-1/2-in. slump concrete. The strength results are given in Table 7.1 and are shown in Fig. 7.39 and 7.40.

Presented in Fig. 7.37 are the effects of temperature and mixing time on water/cement plus fly ash ratio, whereas Fig. 7.38 shows the influence of those parameters on water demand for various fly ash contents.

7.4.1 Slump Loss. The results indicate that of the fly ashes used, Type B had a significant effect on slump loss. For the series batched

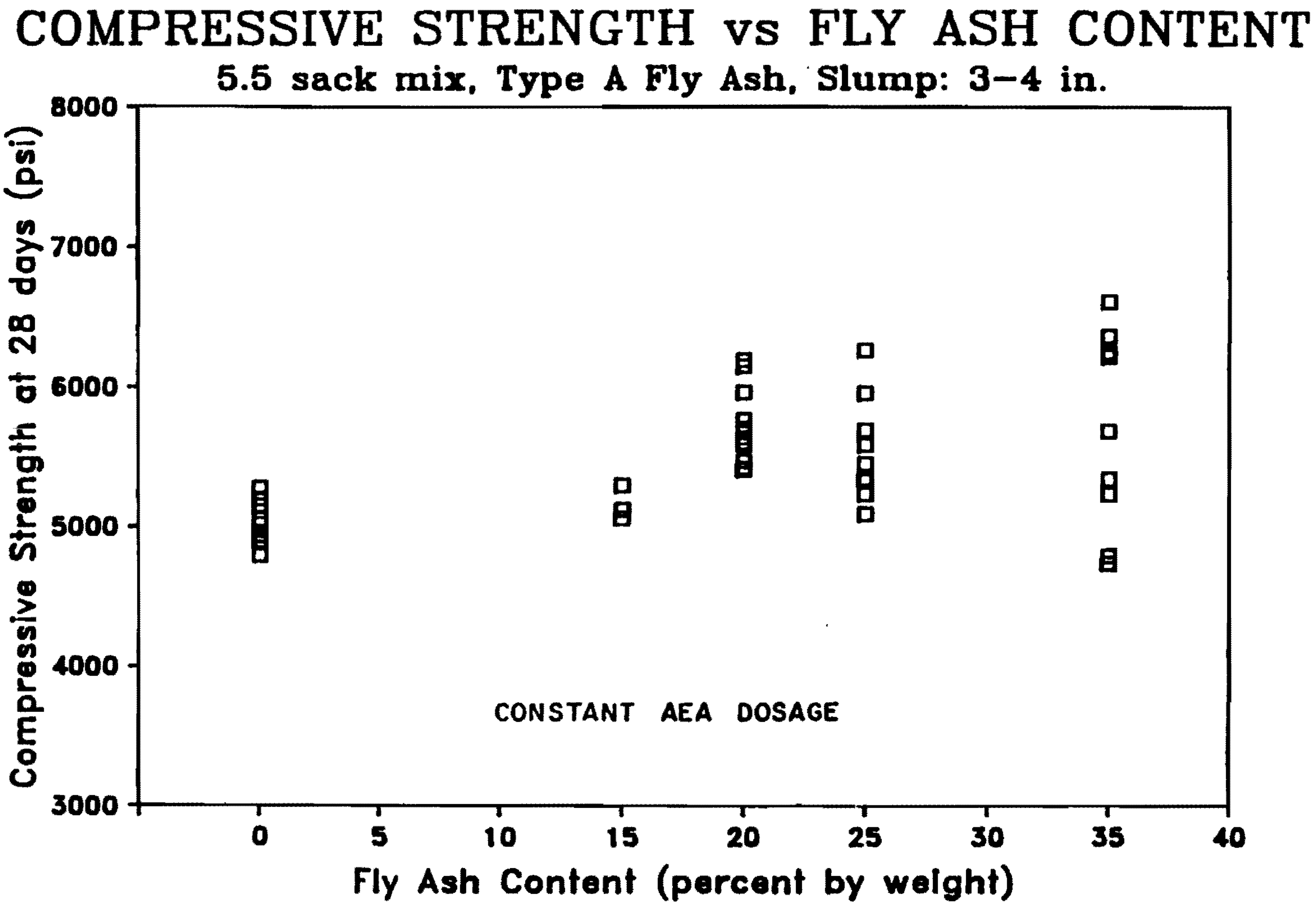


Fig. 7.21 28-day compressive strength of 5.5 sks concrete mix with various Type A fly ash contents.

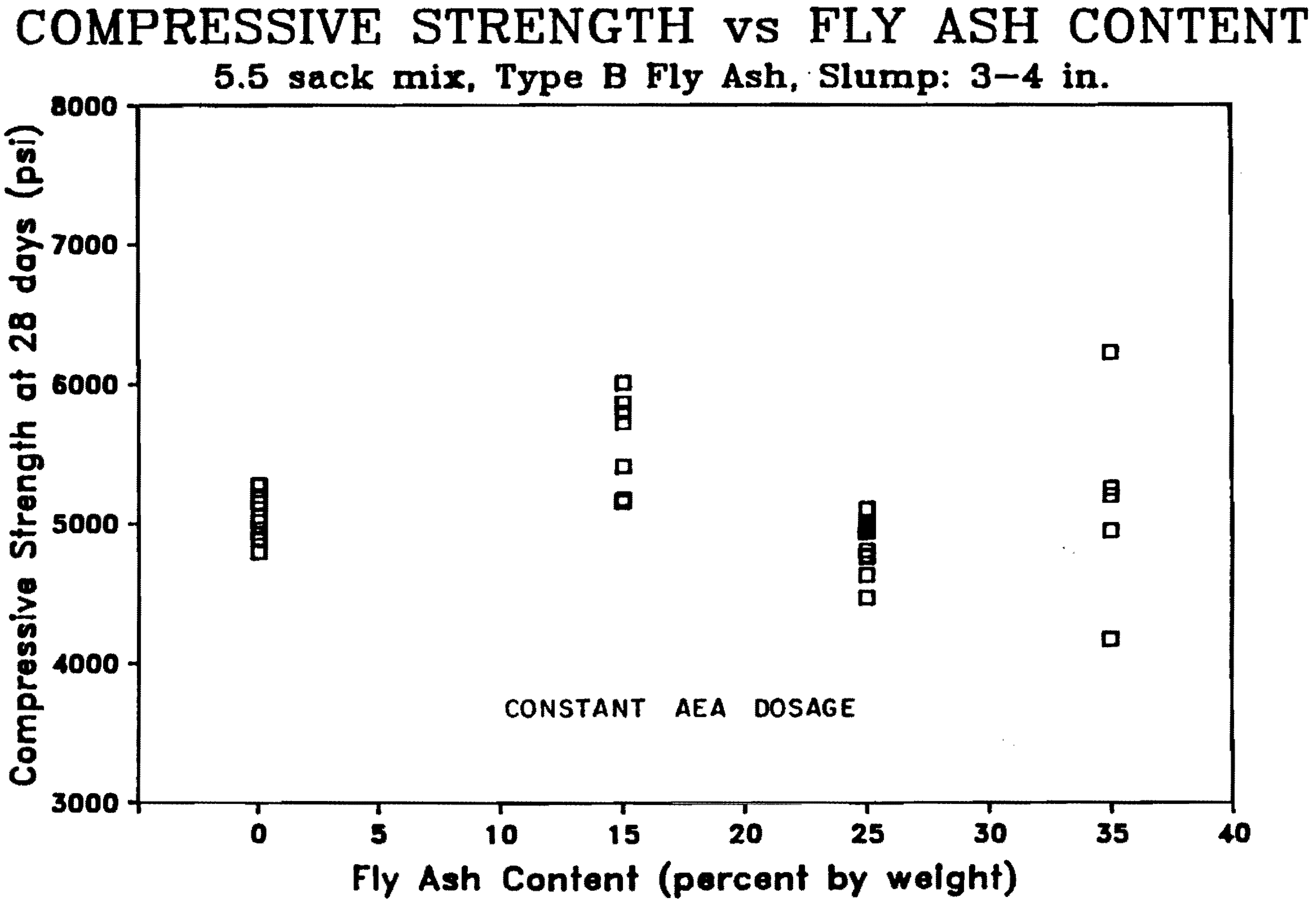


Fig. 7.22 28-day compressive strength of 5.5 sks concrete mix with various Type B fly ash contents.

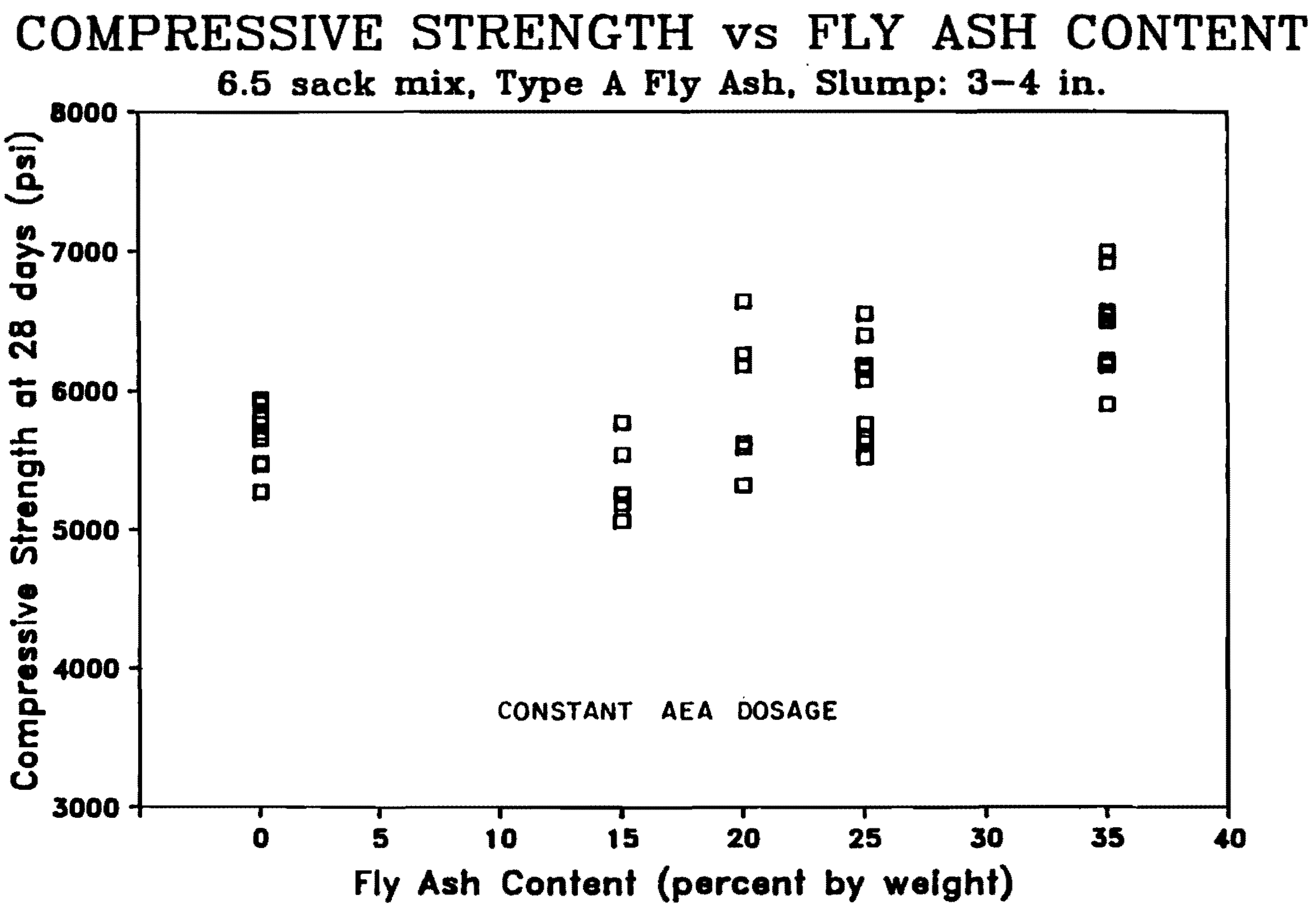


Fig. 7.23 28-day compressive strength of 6.5 sks concrete mix with various Type A fly ash contents.

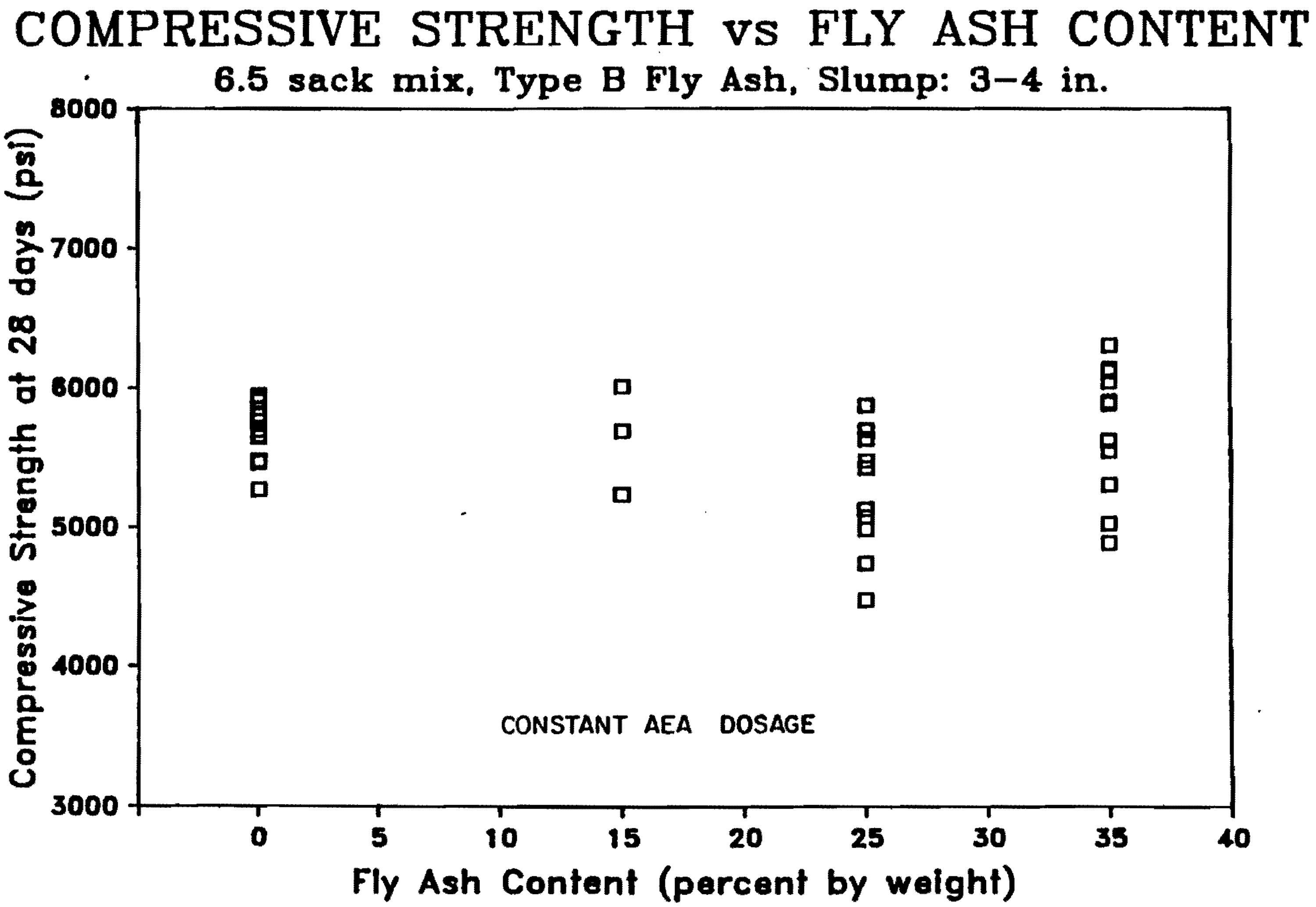


Fig. 7.24 28-day compressive strength of 6.5 sks concrete mix with various Type B fly ash contents.

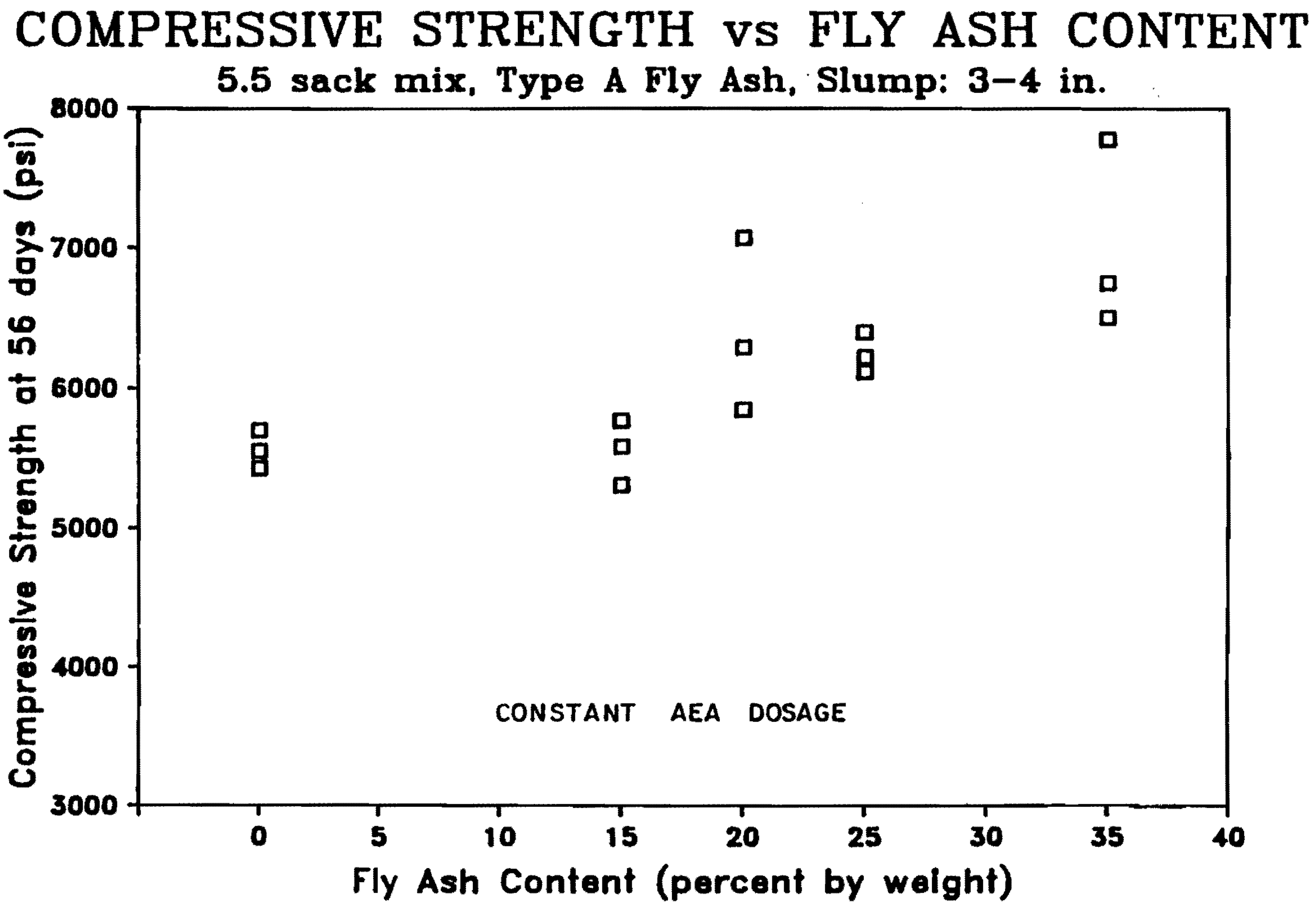


Fig. 7.25 56-day compressive strength of 5.5 sks concrete mix with various Type A fly ash contents.

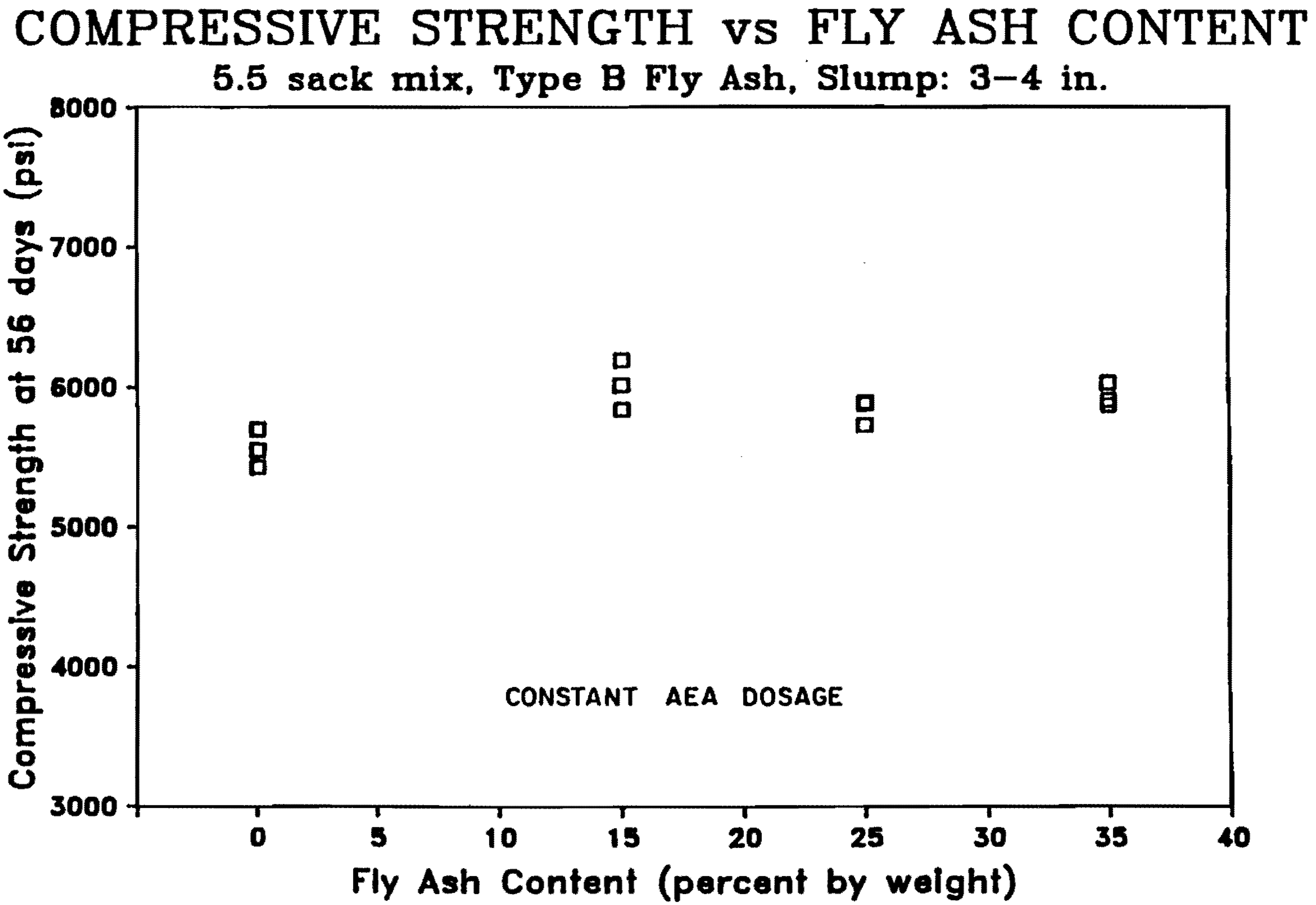


Fig. 7.26 56-day compressive strength of 5.5 sks concrete mix with various Type B fly ash contents.

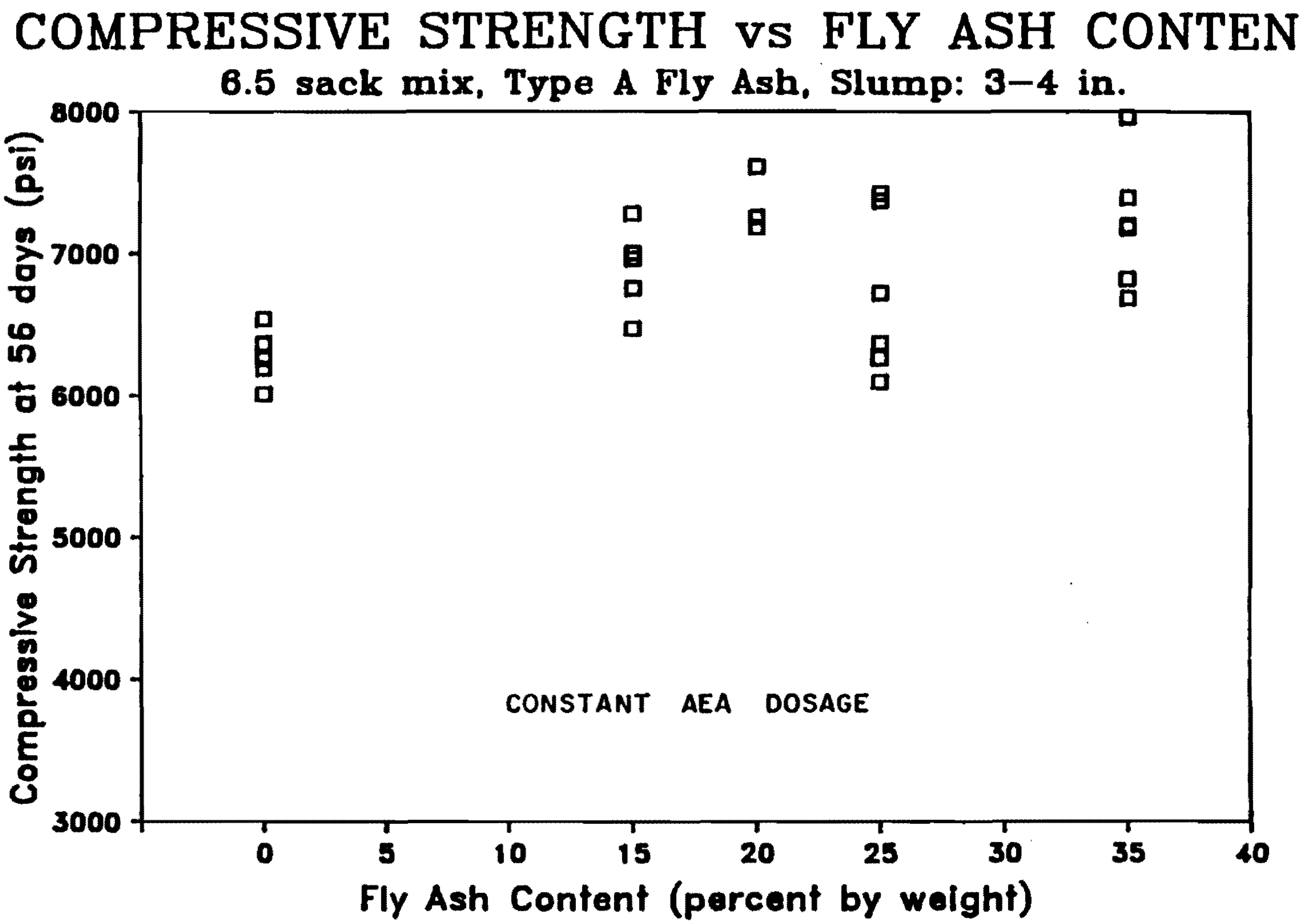


Fig. 7.27 56-day compressive strength of 6.5 sks concrete mix with various Type A fly ash contents

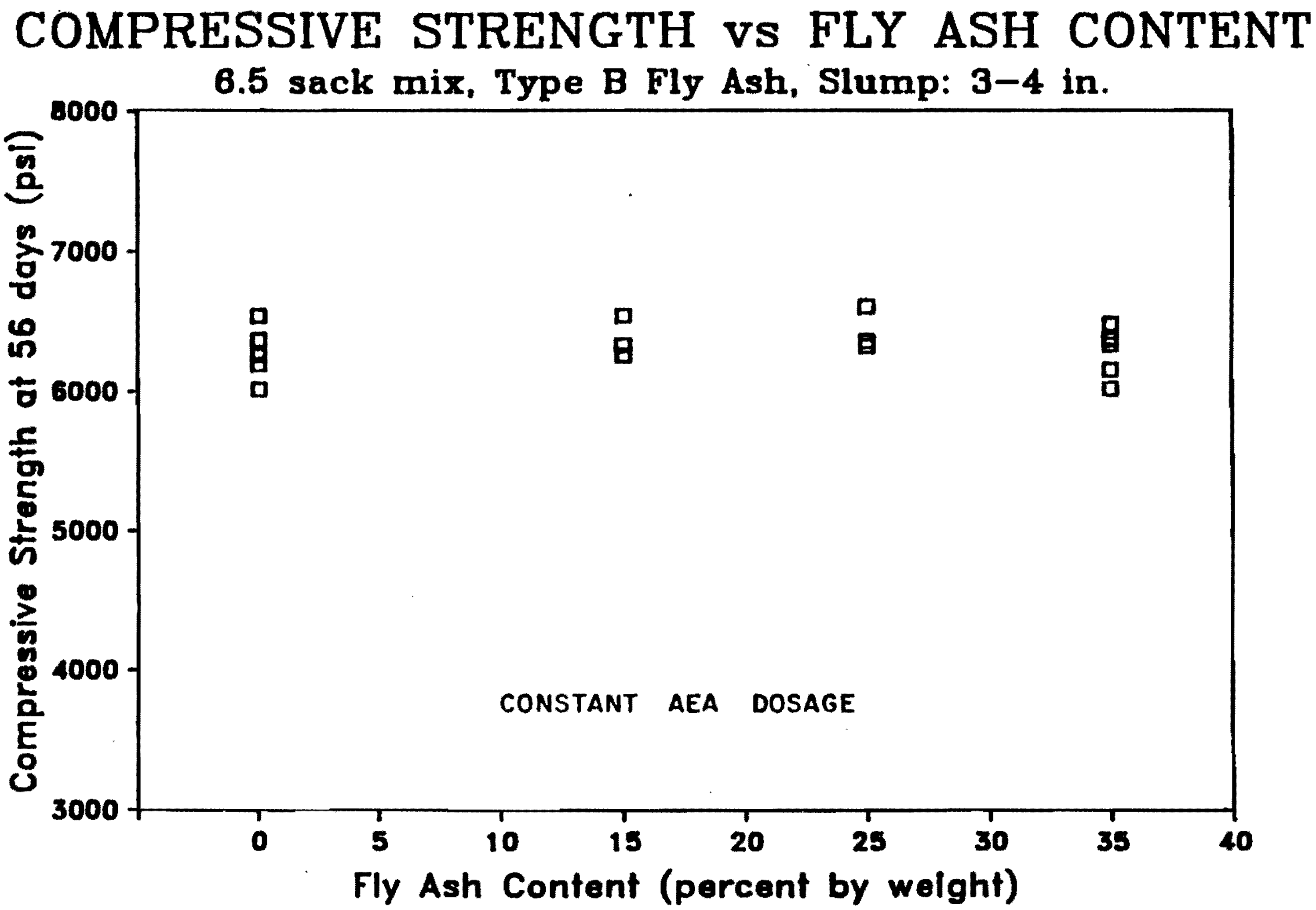


Fig. 7.28 56-day compressive strength of 6.5 sks concrete mix with various Type B fly ash contents

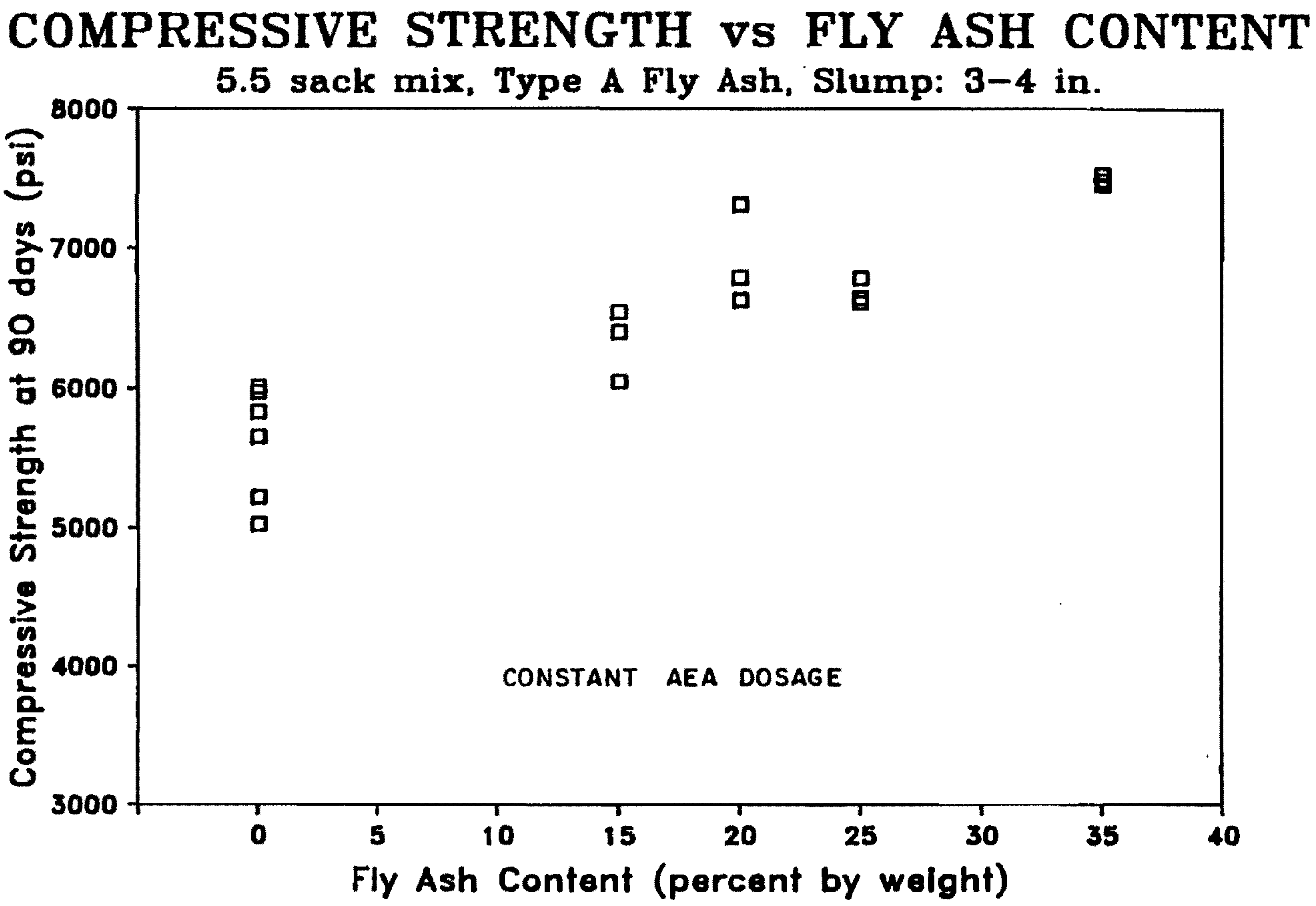


Fig. 7.29 90-day compressive strength of 5.5 sks concrete mix with various Type A fly ash contents

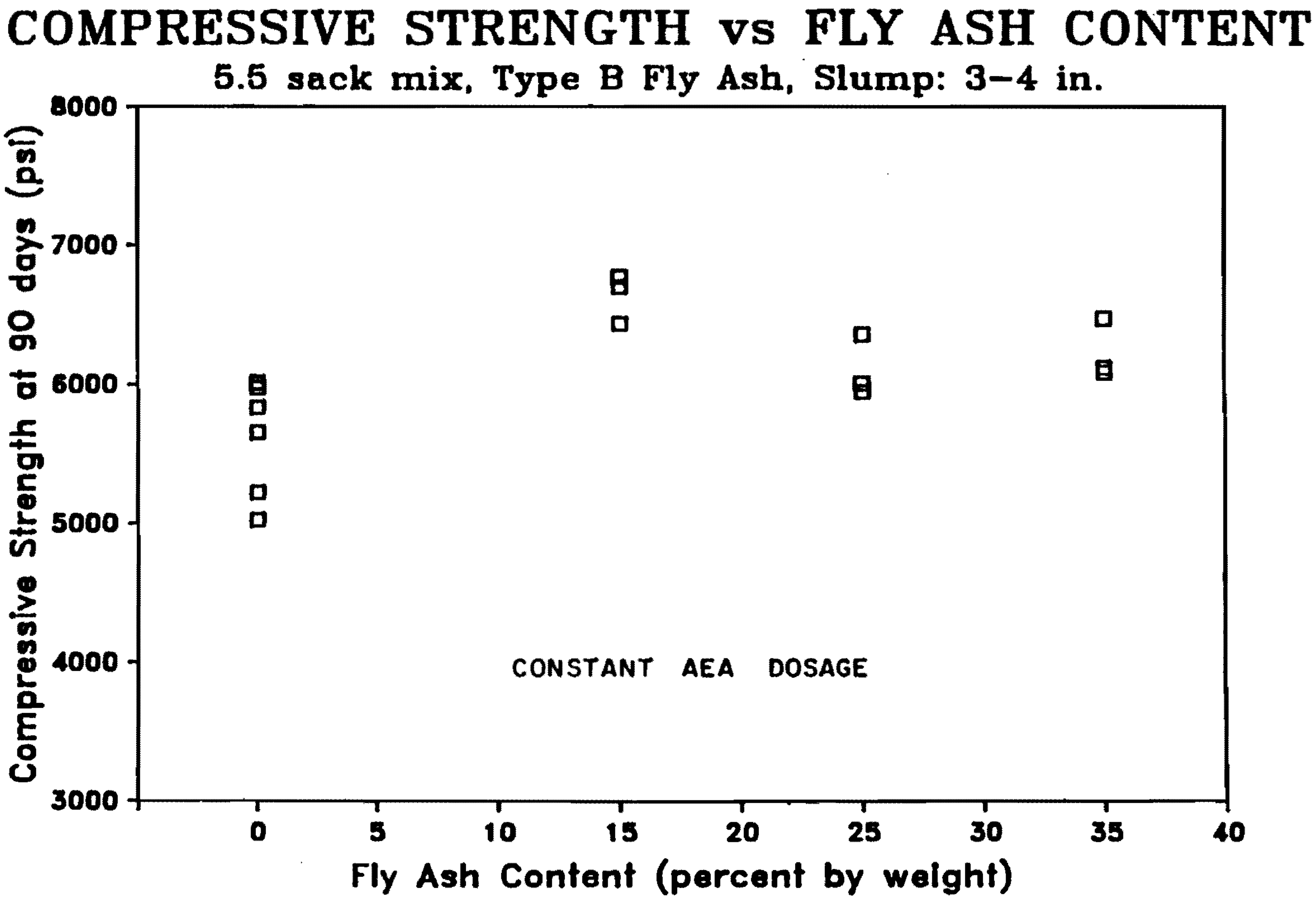


Fig. 7.30 90-day compressive strength of 5.5 sks concrete mix with various Type B fly ash contents

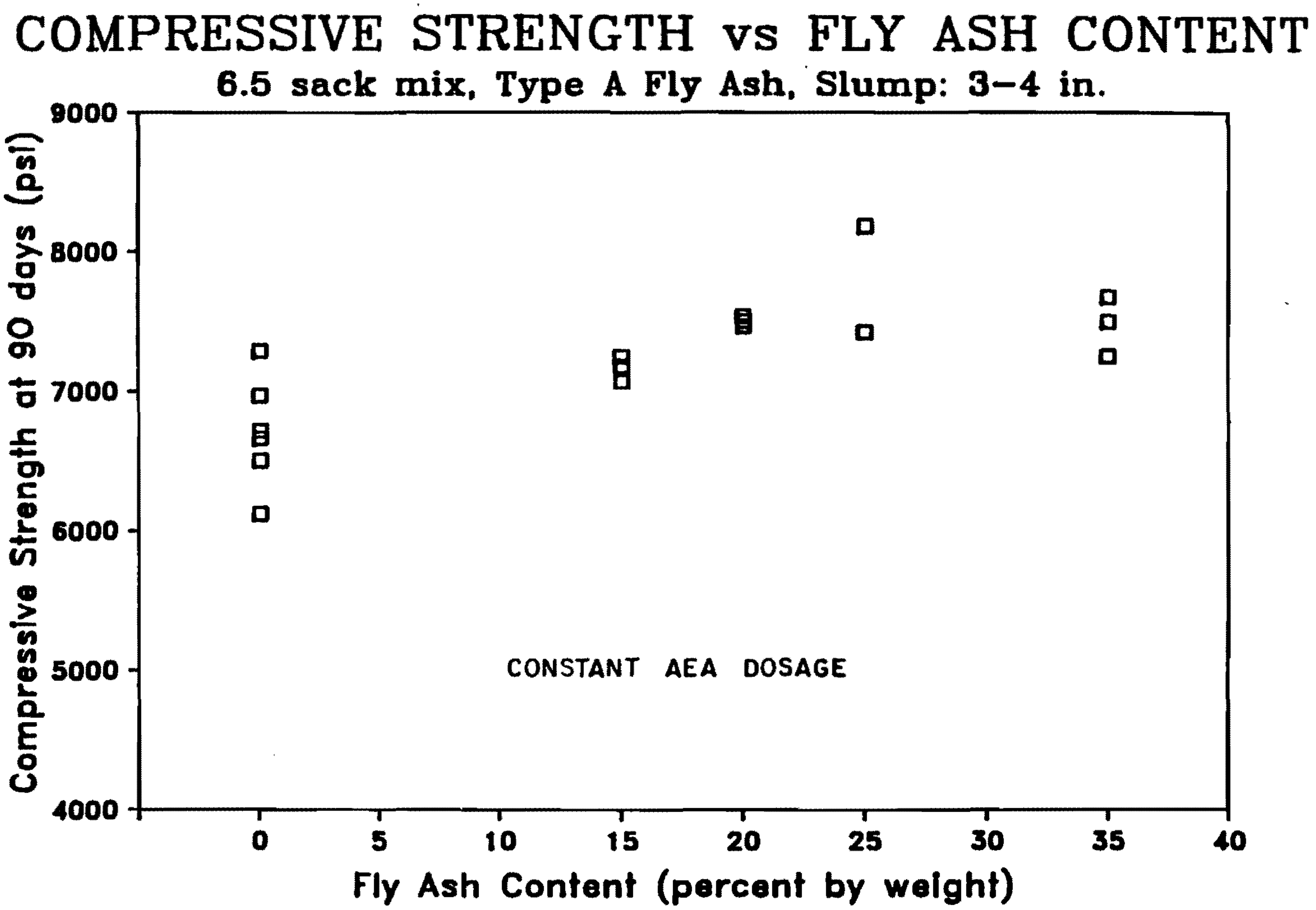


Fig.7.31 90-day compressive strength of 6.5 sks concrete mix with various Type A fly ash contents

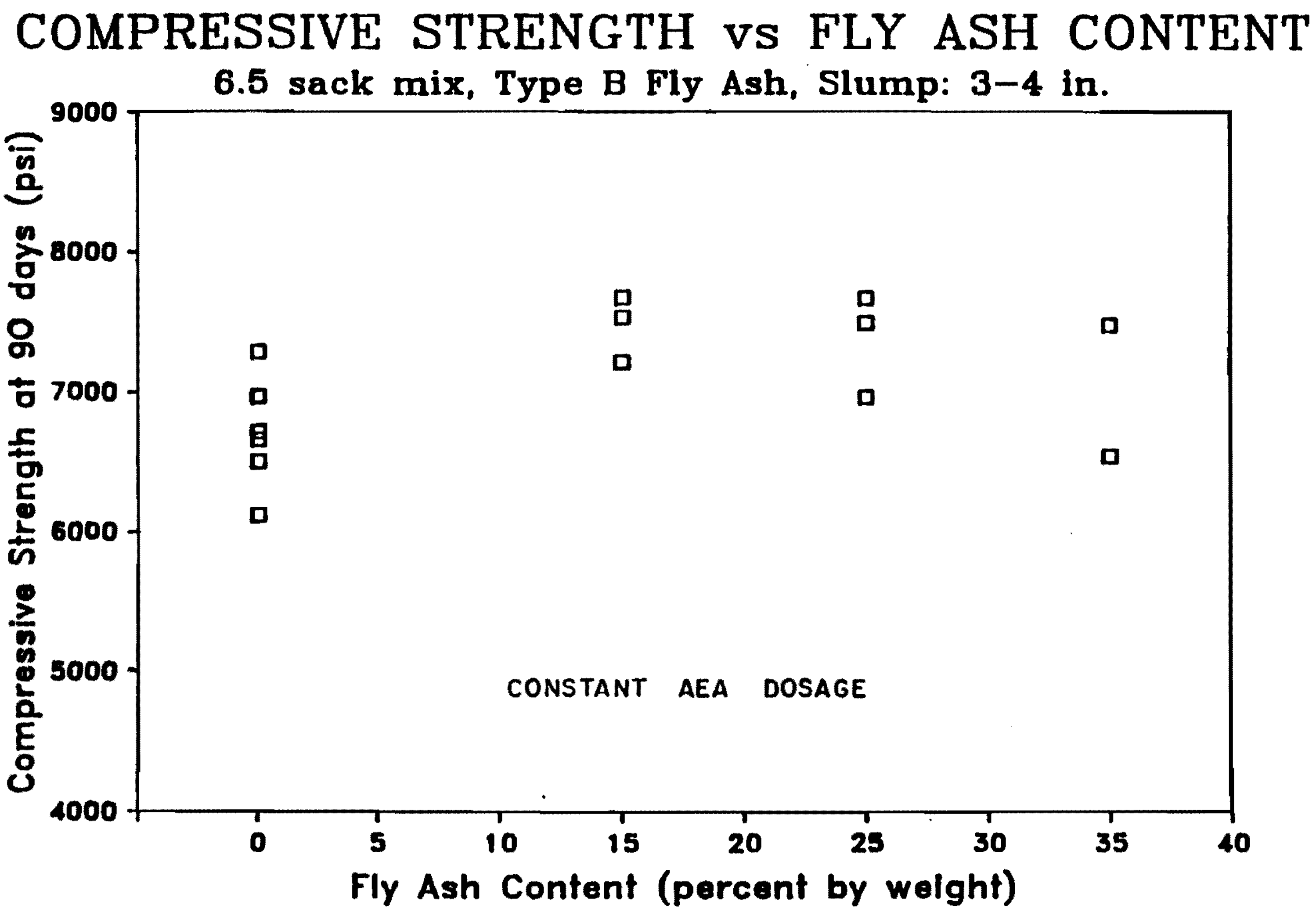


Fig. 7.32 90-day compressive strength of 6.5 sks concrete mix with various Type B fly ash contents

TABLE 7.1a Effect of Mixing Time at 72°F on Concrete Properties

	Mixing Time (min)								
	0	60	90	0	60	90	0	60	90
Type I Cement (lb/cu.yd.)	594	611	598	459	452	454	403	396	396
Type B Fly Ash (lb/cu.yd.)	-	-	-	153	151	151	216	213	213
Cement plus Fly Ash Content (lb/cu.yd.)	594	611	598	612	603	605	619	609	609
Fly Ash Content, (%)	0	0	0	25	25	25	35	35	35
Coarse Aggregate (lb/cu.yd.)	1949	2005	1963	2005	1978	1986	2034	2001	2000
Fine Aggregate (lb/cu.yd.)	986	1014	993	1014	1000	1004	1028	1012	1011
Retarder (oz)	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Air Entrainer (oz)	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Water (lb/cu.yd.)	258	278	275	225	260	269	203	246	252
Water/Cement plus Fly Ash Ratio	0.43	0.45	0.46	0.37	0.43	0.44	0.33	0.40	0.41
Flexural Strength @ 7 days (psi)	720	695	642	710	627	615	655	610	550
Compressive Strength @ 28 days (psi)	5706	5230	5168	5811	5706	5492	6109	5945	5662

TABLE 7.1b Effect of Mixing Time at 102°F on Concrete Properties

	Mixing Time (min)								
	0	60	90	0	60	90	0	60	90
Type I Cement (lb/cu.yd.)	594	611	601	466	451	443	402	386	381
Type B Fly Ash (lb/cu.yd.)	-	-	-	156	151	148	216	207	205
Total Cementitious Content (lb/cu.yd.)	594	611	601	622	602	591	618	593	586
Fly Ash Content, (%)	0	0	0	25	25	25	35	35	35
Coarse Aggregate (lb/cu.yd.)	1949	2004	1974	2042	1972	1934	2028	1946	1922
Fine Aggregate (lb/cu.yd.)	986	1013	998	1033	998	981	1026	984	972
Retarder (oz)	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Air Entrainer (oz)	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Water (lb/cu.yd.)	258	280	302	229	294	313	238	289	319
Water/Cement plus Fly Ash	0.43	0.46	0.50	0.37	0.49	0.53	0.39	0.49	0.54
Flexural Strength @ 7 days (psi)	820	805	780	690	555	505	650	520	400
Compressive Strength @ 28 Days (psi)	6466	6113	5627	6155	5732	5176	5742	4576	3745

TABLE 7.2 Slump and Temperature Readings

Mixing Time (min)	Temperature	Fly Ash Content		
		0%	25%	35%
			Slump (in.)	
15	72±3°F	3.5	3.5	3.5
30	for	2.4	1.2	1.1
60	all	2.0/3.5	1.0/3.5	1.0/3.5
90	mixes	2.8/3.5	2.8/3.5	3.1/3.5
			Slump (in.)	
15	102±3°F	3.5	3.5	3.5
30	for	1.0	0.6	0.5
60	all	1.0/3.5	0.5/3.5	0.5/3.5
90	mixes	2.8/3.5	2.7/3.5	2.8/3.5

Note: Retempting water was added to each mix after 60 and 90 min of mixing in order to restore the original slump of 3.5 in.

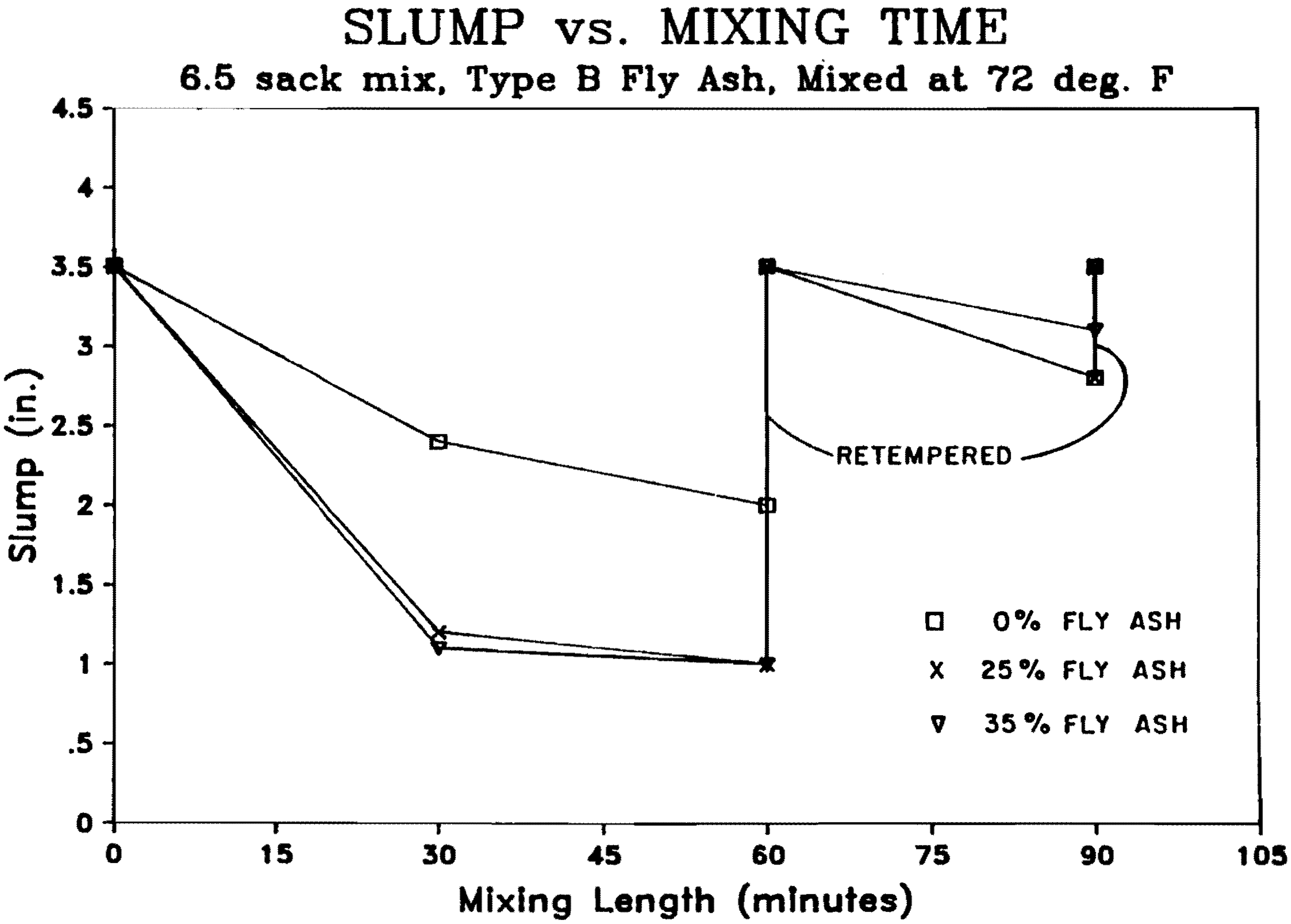


Fig. 7.33 Slump variation after 30,60, and 90 min of mixing. Mixes with 0, 25 and 35% of cement replaced by an equal weight of Type B fly ash mixed at room temperature (72°F)

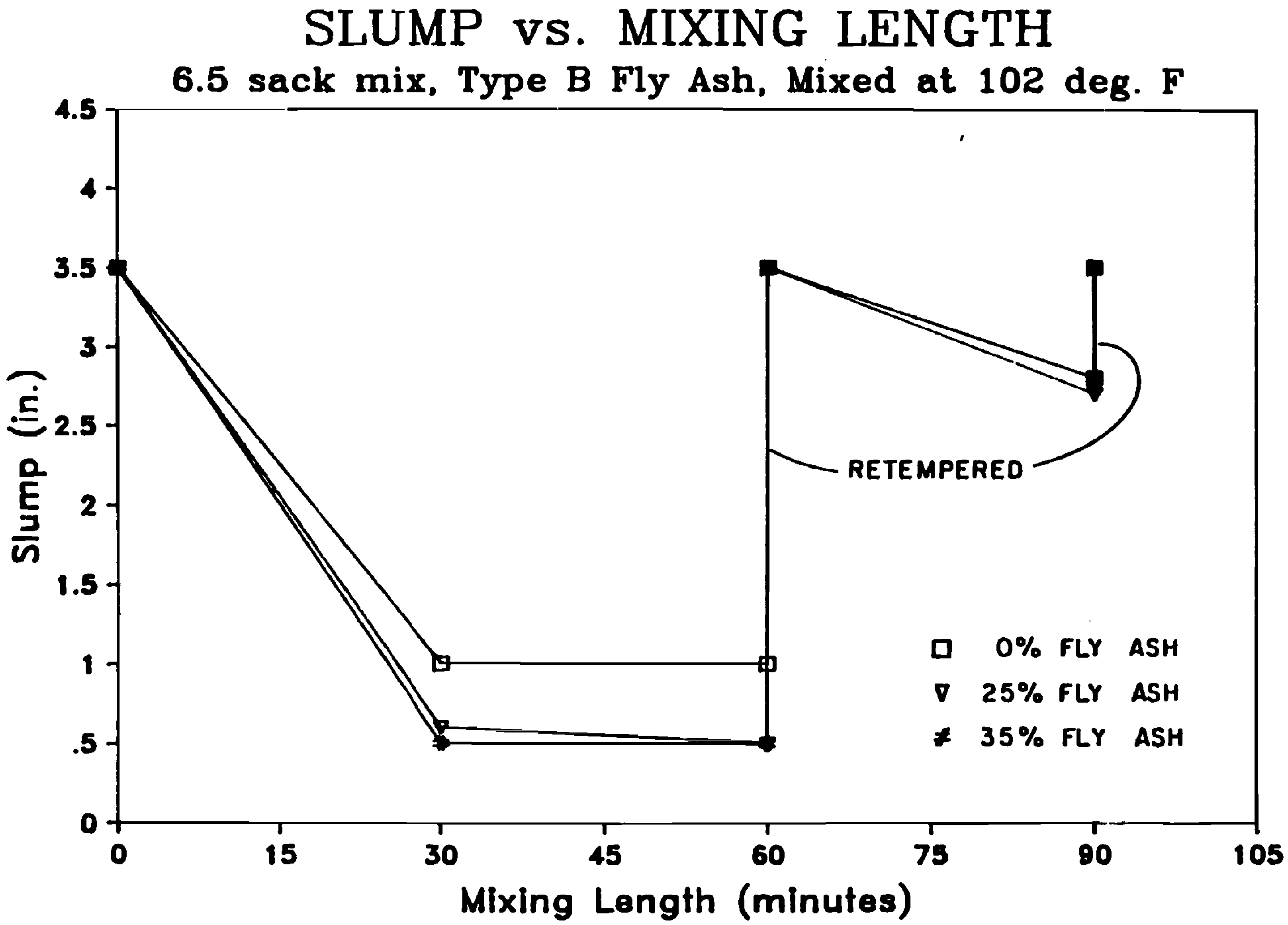


Fig. 7.34 Slump variation after 30, 60 and 90 min of mixing. Mixes with 0, 25 and 35% of Type B fly ash mixed at high temperatures (102°F)

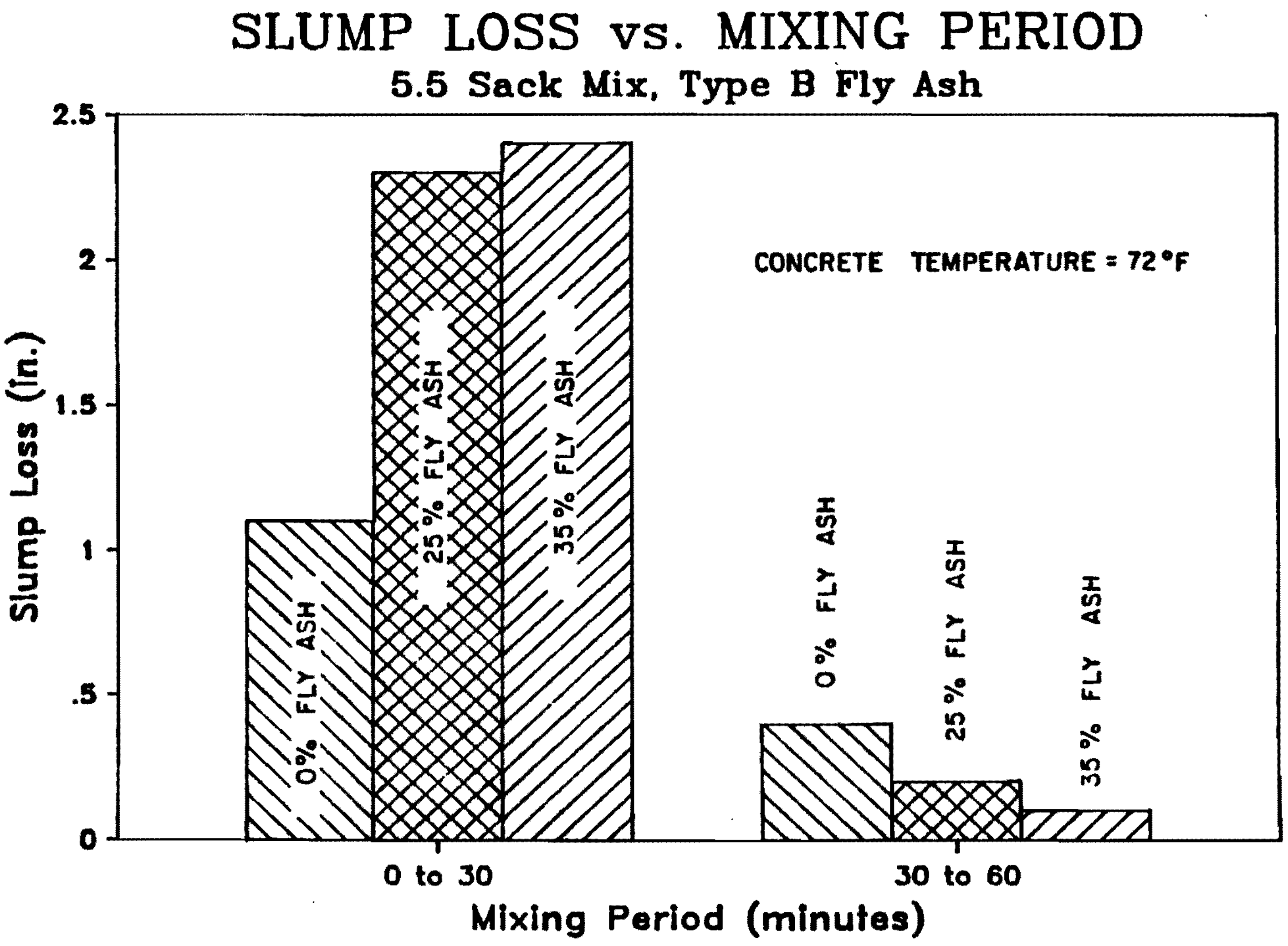


Fig. 7.35 Slump loss during mixing intervals of 0 to 30 min and 30 to 60 min. Mixes with 0, 25 and 35% of cement replaced by an equal weight of Type B fly ash mixed at room temperature (72°F)

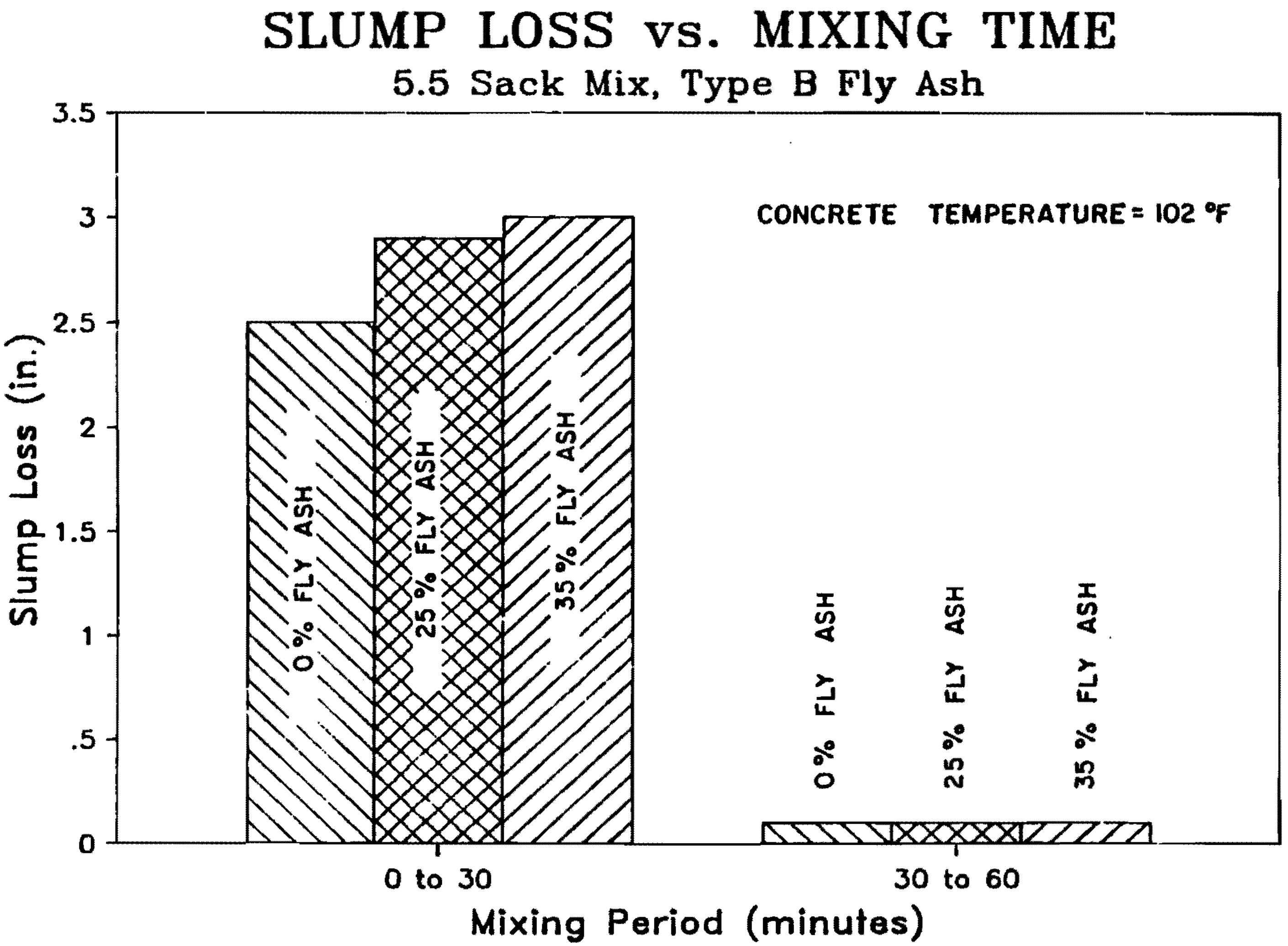


Fig. 7.36 Slump loss during mixing intervals of 0 to 30 min and 30 to 60 min. Mixes with 0, 25 and 35% of cement replaced by an equal amount of Type B fly ash, mixed at high temperature (102°F)

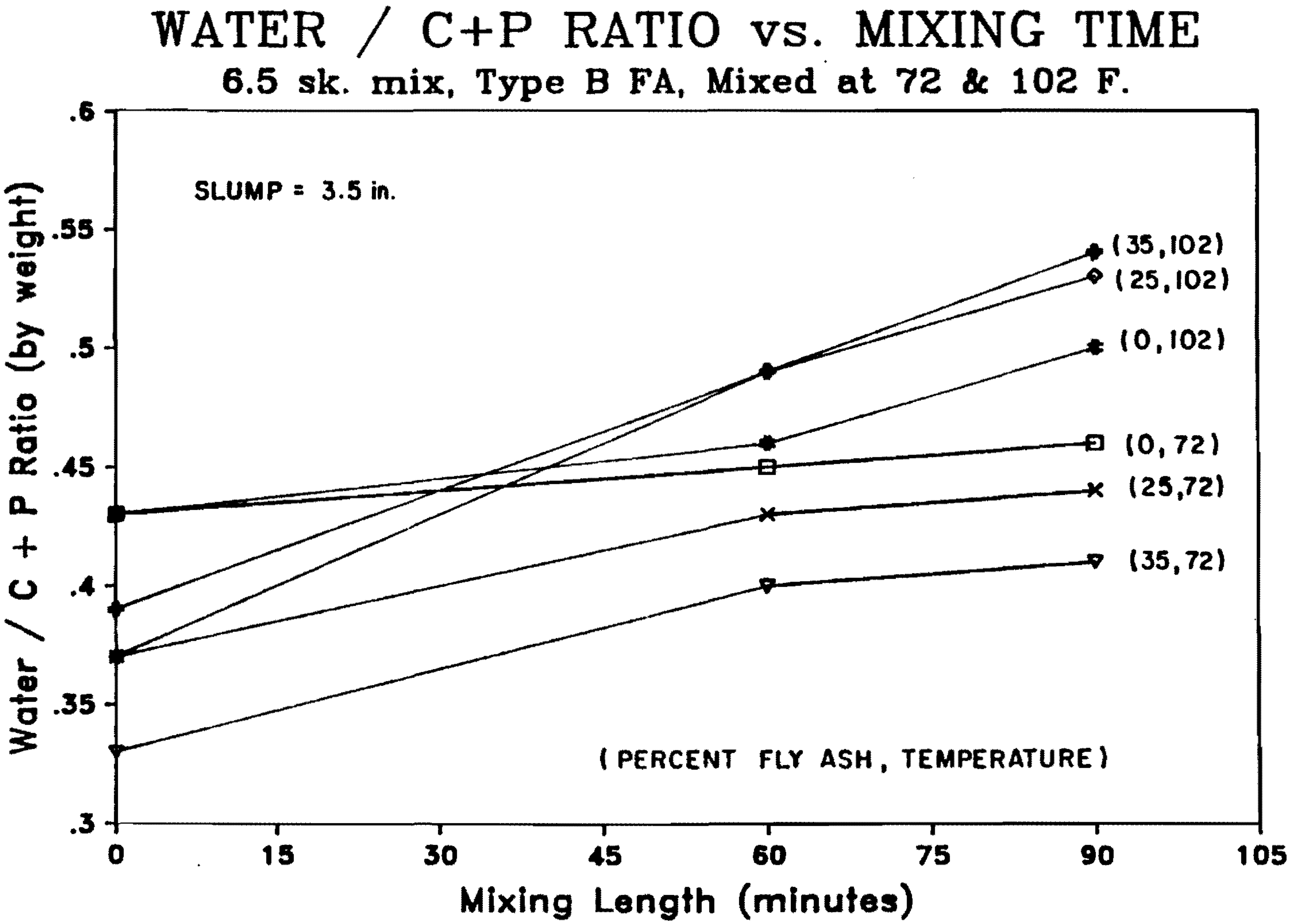


Fig. 7.37 Effect of temperature and mixing time on water/C+P ratio

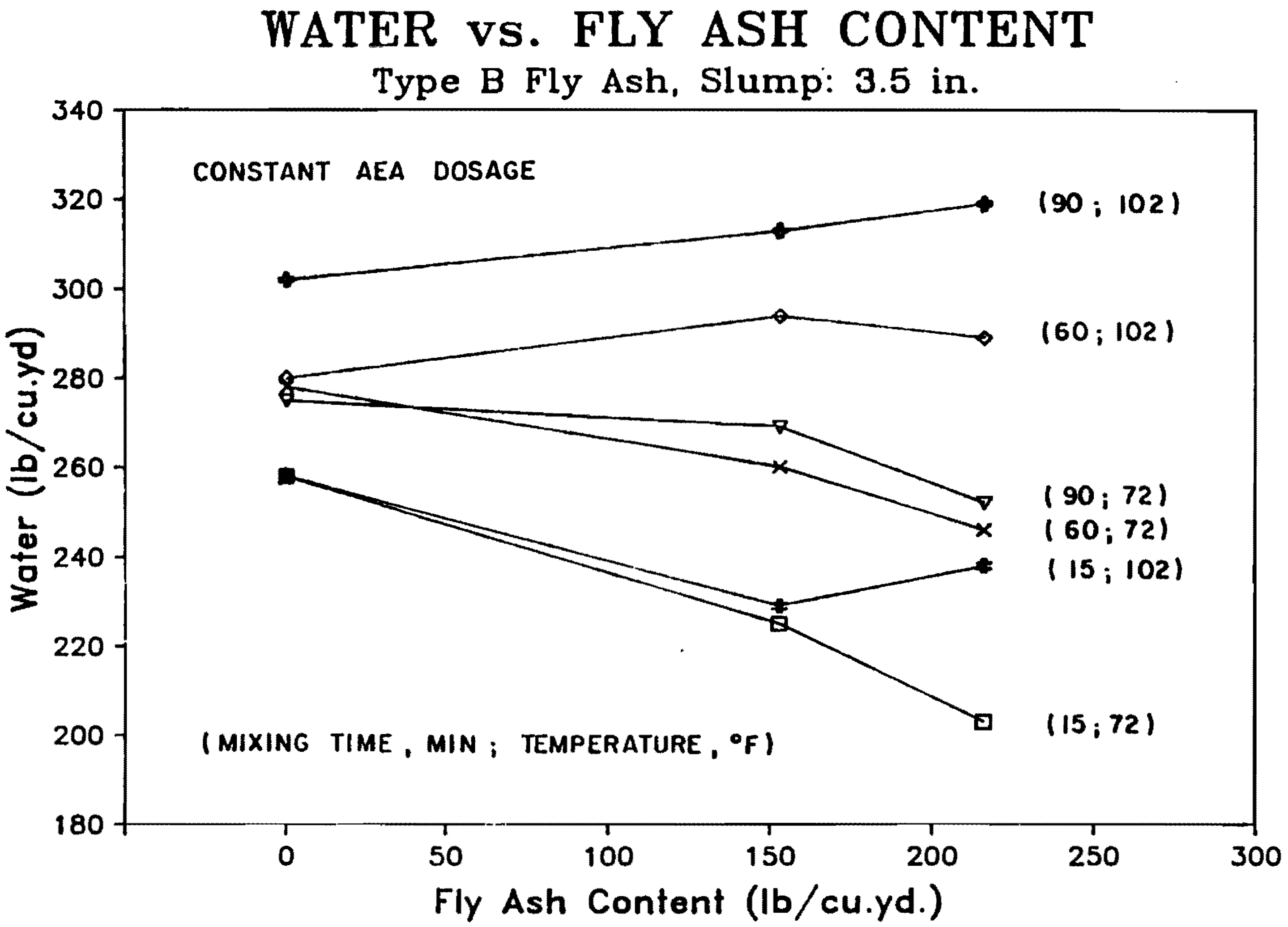


Fig. 7.38 Effect of temperature and mixing time on water demand for various fly ash contents

at room temperature, the mixes containing fly ash showed higher slump loss as compared to the mix without fly ash. This phenomenon was less pronounced in the series mixed at high temperature. The slump loss was not significantly influenced by the percentage of cement replacement, however, slump loss was greater for high temperature mixes. As shown on the histograms in Figs. 7.35 and 7.36, a major portion of the slump loss occurs during the first 30 min of mixing; thus indicating that under hot weather conditions, slump loss may become a problem mainly with regard to transportation, handling, and placing of the mix.

7.4.2 Water/Cement Plus Fly Ash Ratio and Mixing Water Demand. The water/cement plus fly ash ratio (w/c+p), where cement plus fly ash refers to the total weight of cement and Type B fly ash, was found to be influenced by both temperature and mixing time. The data presented in Table 7.1 and in Fig. 7.37 indicates that for a concrete of a constant slump, the w/c+p ratio increases as the mixing time increases, regardless of the mixing temperature. For the room temperature mixes, it was observed that the w/c+p ratios decreased with increased percentages of fly ash for any duration of mixing time. However, in the case of high temperature mixes containing fly ash, the w/c+p ratios increased over that of the plain concrete mix when subjected to mixing times in excess of 15 min.

The water requirements for a given slump of concrete, as shown in Fig. 7.38, were higher for longer mixing times. For the room temperature mixes, the water demand was lower for higher fly ash contents. However, in the case of high temperatures, the mixing water demand increased as the amount of fly ash in the mix increased, especially for the mixing times longer than 15 min. For any mixing period, the mixes batched at higher temperatures showed higher water demand.

7.4.3 Flexural and Compressive Strength. The effect of mixing time, temperature, and fly ash content on 7-day flexural strength of concrete is shown graphically in Fig. 7.39. The flexural strength of all concretes tested decreased with increased mixing time. The rate of strength loss was generally higher for high temperature mixes.

The 28-day compressive strength of corresponding concretes are shown in Fig. 7.40. Mixing time and temperature generally show the same effect on the 28-day compressive strength as on 7-day flexural strength for all mixes as can be seen by comparing Fig. 7.39 and 7.40. In this case however, the mixes batched at room temperature and containing fly ash showed higher strengths than plain concrete mixes.

7.5 Effect of Curing Compound

In field curing of concrete, it is often common practice to apply curing compounds to the concrete surface to prevent moisture loss and assure proper strength development of the hardening concrete.

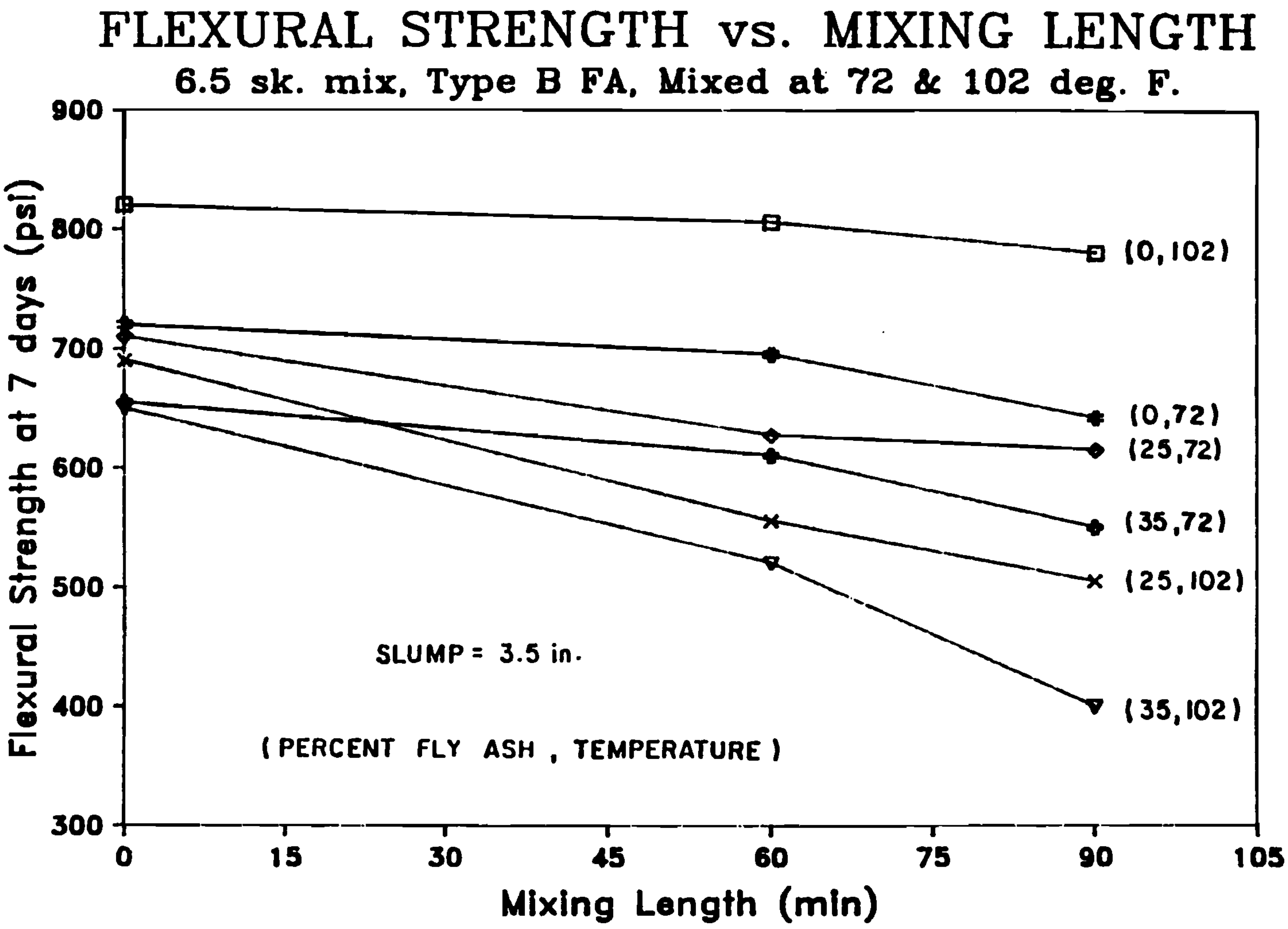


Fig. 7.39 Effect of temperature and mixing time on flexural strength at 7 days

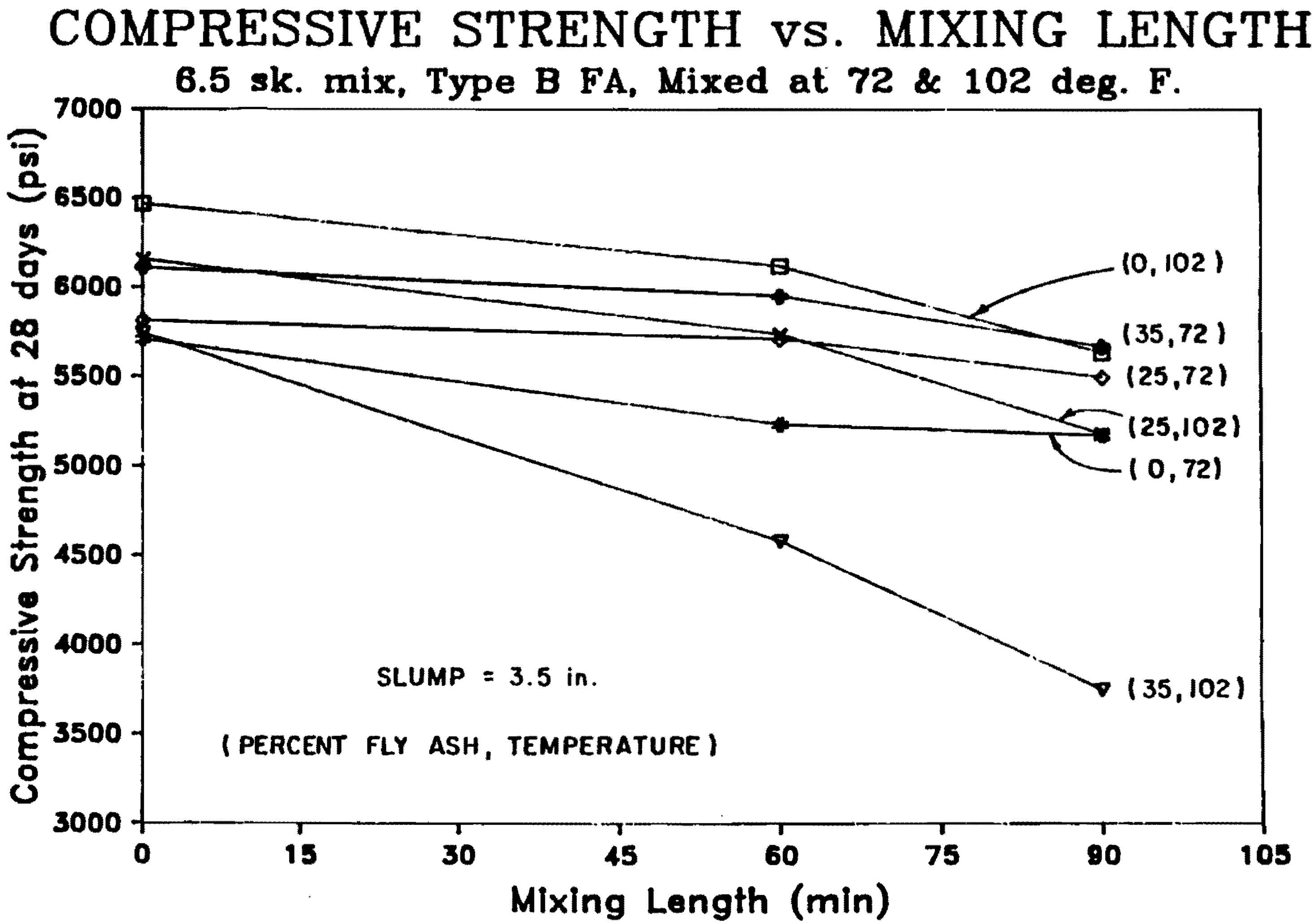


Fig. 7.40 Effect of temperature and mixing time on compressive strength of concrete at 28 days

In order to test the effectiveness of a curing compound on the strength development of fly ash concretes three series of specimens were cast. The basic mix used for this purpose was the 6.5 sks mix in which 25 and 35% of cement was subsequently replaced by Type B fly ash.

A total of 15 beams and 15 cylinders were cast. After 24 hours, following removal from the forms, specimens were coated with a curing compound meeting TEX-218-F Specification of the Texas SDHPT. Following the curing compound application, three of each set of five beams and five cylinders were placed in an environmental chamber, where they were subjected to a temperature of 100±2°F and a relative humidity of about 33%. The remaining two beams and two cylinders were kept in the laboratory room in which the temperature was +75±4°F and the relative humidity ranged from 50 to 60%.

Flexural tests were carried out on the beams after 7 days and cylinders were tested in compression after 28 days. The results of the flexural as well as compressive strength tests performed on these three mixes are shown in Table 7.3 and in Figs. 7.41 and 7.42.

7.6 Effect of Curing Conditions

Presented in this section are the effects of cold and hot curing conditions on the strength of concrete having varying percentages and types of fly ash.

Cold curing conditions are defined as the combination of low temperature, +40°F, and a relative humidity of 55%. Hot curing conditions are defined as the combination of high temperature, +100°F, and a low relative humidity of 33%.

As mentioned in Sec. 6.4, the specimens were cured under moist conditions, +74°F, 98% relative humidity, for the specified amount of time, which was 1, 3 or 7 days for flexural beams and 1, 3, 7, or 28 days for compressive cylinders. After the prescribed moist curing period, the specimens were placed in cold or hot environmental chambers accordingly, where they were kept until the test time. The flexural beams were tested at 7 days and the compressive strength cylinders at 28 days. Specimens subjected to the above procedure were therefore cured in cold or hot rooms for the following periods of time:

- beams 6 or 4 days

- cylinders 27, 25, or 21 days

The specimens kept in the moist room for the full length of 7 or 28 days served as a reference for flexural and compressive strengths, respectively.

TABLE 7.3 Flexural and Compressive Test Results of Specimens Subjected to Different Curing Methods

Mix	Fly Ash Replacement		Flexural Strength at 7 Days (psi)	Compressive Strength at 28 Days (psi)	Curing Conditions
	Type of Fly Ash	Weight of Cement Replaced (%)			
1		0	523	5241	Coated with curing compound; 6 or 27 days at +100±2°F. Relative humidity about 33%
2	B	25	430	4841	Same as above
3	B	35	388	4016	Same as above
4		0	590	5654	Coated with curing compound; 6 or 27 days at +75±4°F. Relative humidity about 55%
5	B	25	555	5141	Same as above
6	B	35	532	4160	Same as above
7		0	545	5199	Not coated; 6 or 27 days at 100±2°F. Relative humidity about 33%
8	B	25	455	4624	Same as above
9	B	35	395	3360	Same as above
10		0	816	5741	Not coated; 6 or 27 days at moist room temp. 74°F. Relative humidity 98%
11	B	25	715	6164	Same as above
12	B	35	651	6027	Same as above

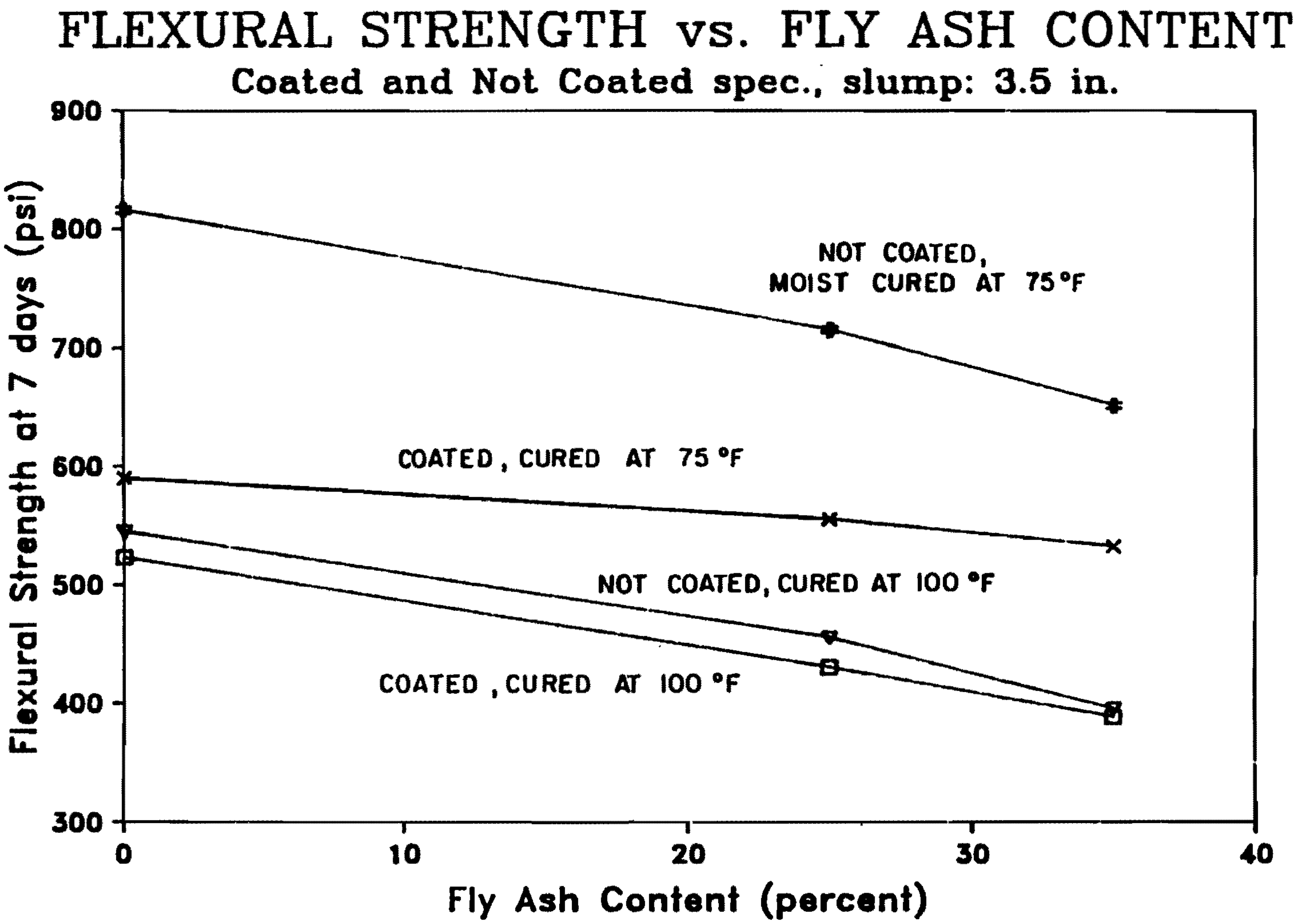


Fig. 7.41 Effect of curing compound and curing temperature on flexural strength of concrete with varying fly ash contents

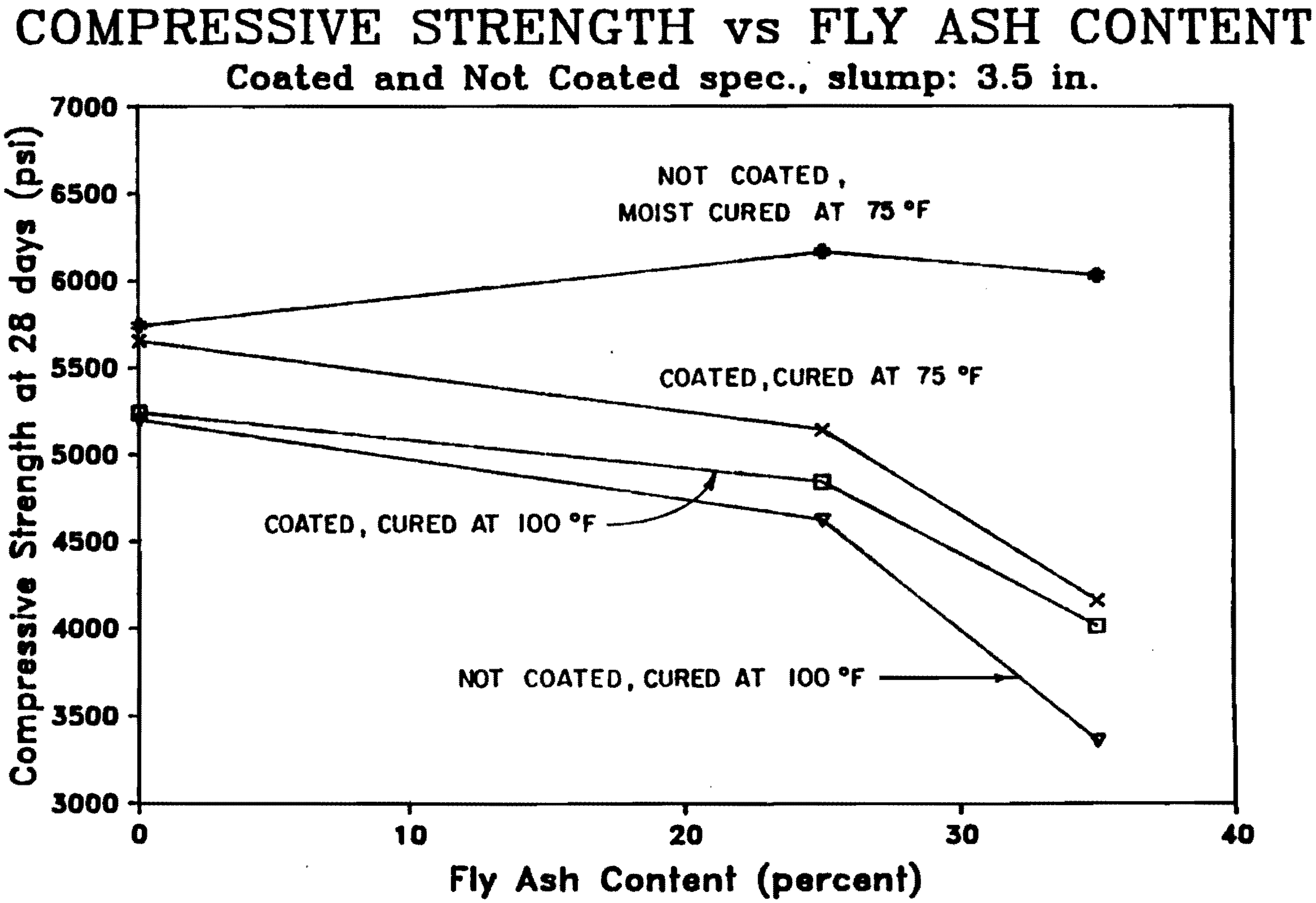


Fig. 7.42 Effect of curing compound and curing temperature on compressive strength of concrete with varying fly ash contents

7.6.1 Cold Curing. The flexural strength test results for cold cured mixes are presented in Figs. 7.43 through 7.46. It could be seen that the results are influenced by the length of moist curing before transfer to the cold room as well as by the cement content of the original mix and type of fly ash used.

In Figs. 7.47 through 7.50 the compressive strength results for cold cured mixes are presented. The discussion and analysis follow in Sec. 8.6.1.

7.6.2 Hot Curing. Figs. 7.51 through 7.54 show the flexural strength results for hot cured mixes. Similar to that of the cold cured mixes, the hot cured mixes were influenced by the length of initial moist curing and the type of fly ash used.

The age-compressive strength relationships for the different hot cured mixes are shown in Figs. 7.55 and 7.58. The general rate of strength development of the concrete containing fly ash is similar to that of plain portland cement concrete.

A discussion and analysis of hot cured mixes is presented in Sec. 8.6.2. Section 8.6.3 provides a general comparison between cold- and hot cured mixes.

7.7 Freezing and Thawing

ASTM C666-80, procedure A, Rapid Freezing and Thawing in Water Test was carried out on a total of about 50 specimens. Evaluation of the freeze-thaw resistance of concrete was carried out by measuring the fundamental transverse frequency before freezing and after approximately every 30 cycles of freeze-thaw. The change in the dynamic modulus of elasticity was determined from the fundamental transverse frequency readings.

The results of these tests are presented in Appendix C. These tables give the average dynamic modulus of elasticity, frequency and durability factor for each set of specimens after each increment of freeze-thaw cycles. The results will be discussed from the standpoint of changes in dynamic modulus of elasticity, reduction in the durability factor and change in physical appearance.

The dynamic modulus of elasticity is defined as the square of the fundamental transverse frequency of the beam:

$$DE = n^2 \text{ (psi)}$$

The durability factor of the concrete is expressed as the ratio of a YDE to the square of the fundamental transverse frequency of the beam before testing begins:

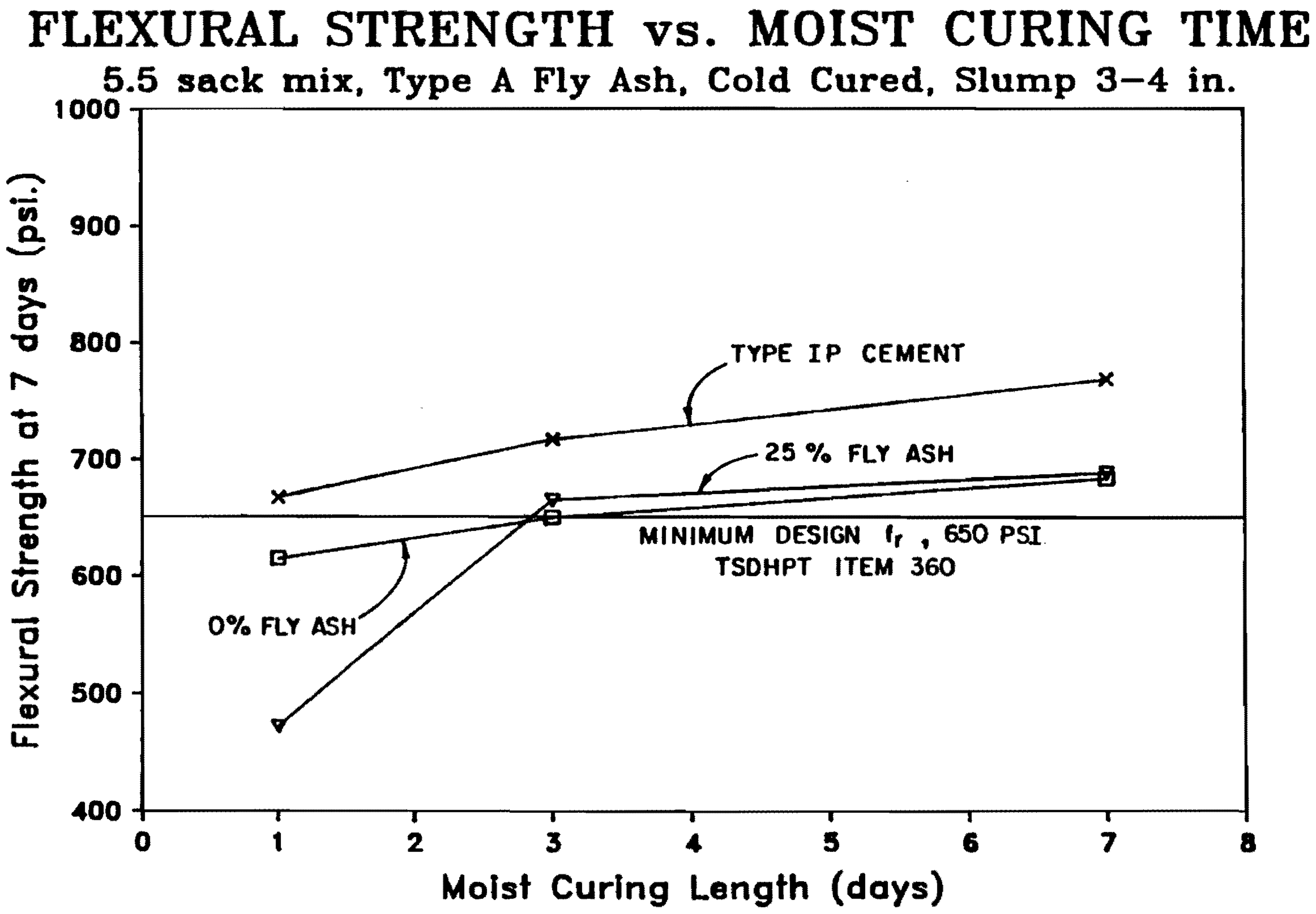


Fig. 7.43 Flexural strength of "cold" cured, 5.5 sks concrete mixes containing Type A fly ash

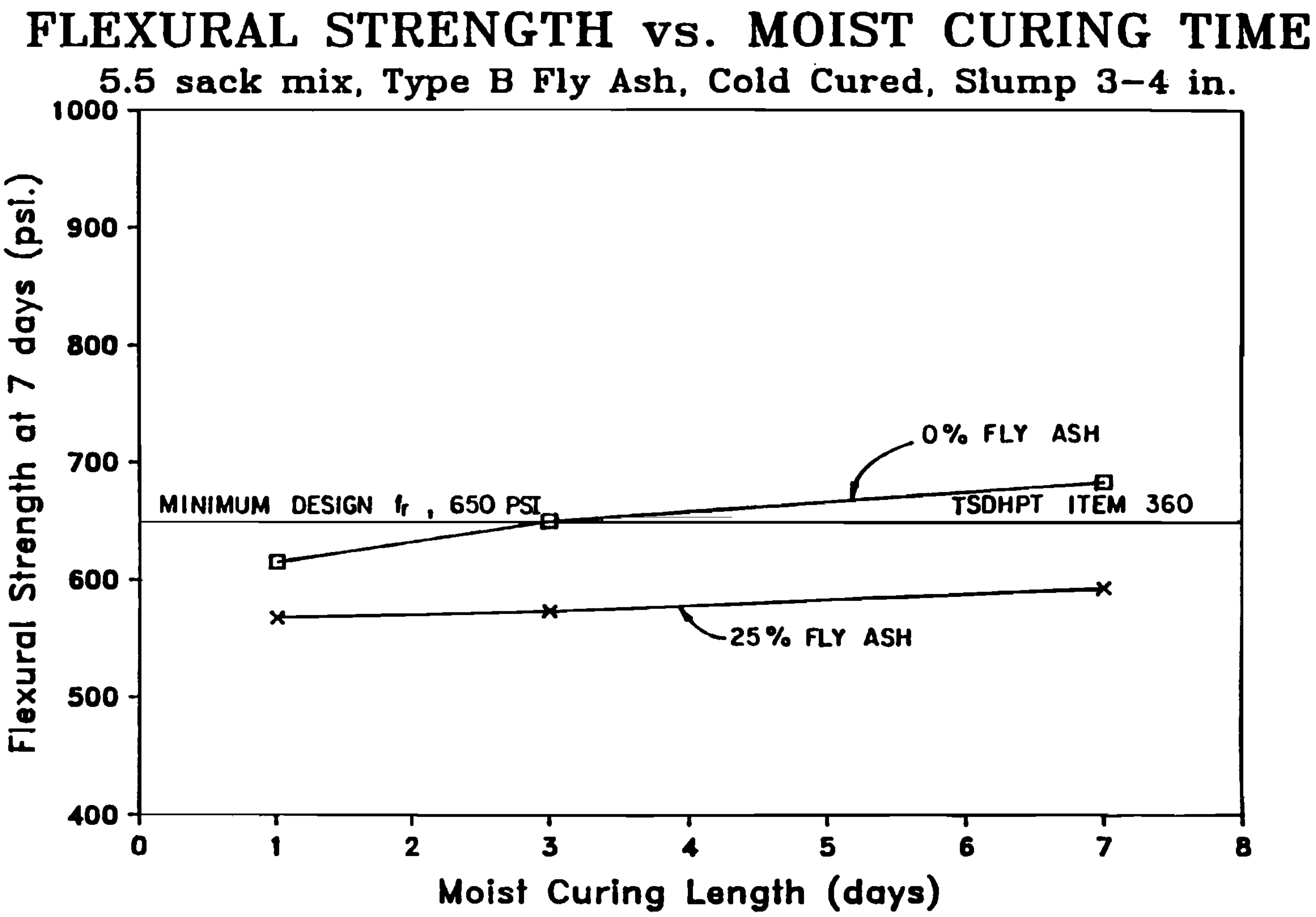


Fig. 7.44 Flexural strength of "cold" cured, 5.5 sks concrete mixes containing Type B fly ash

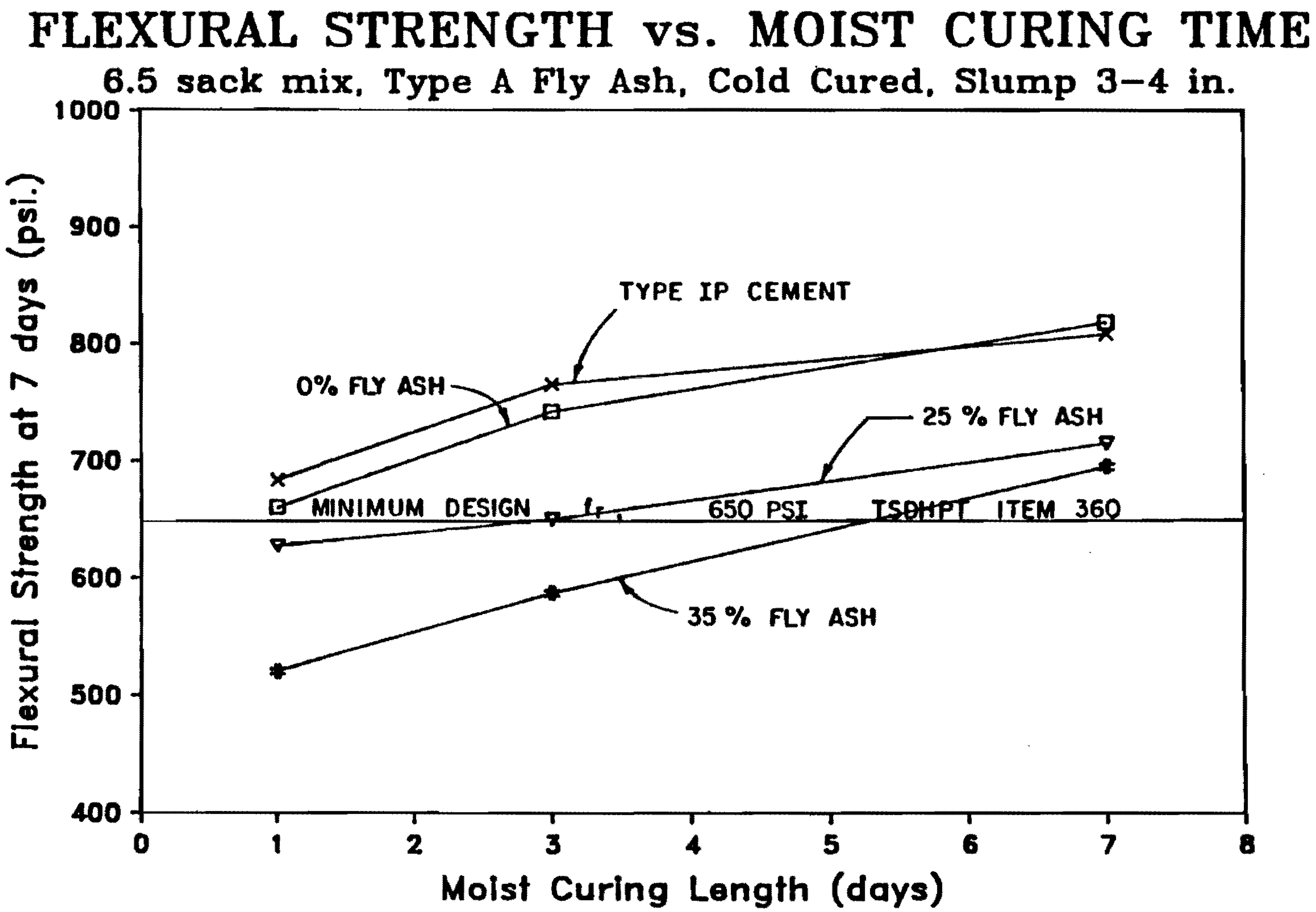


Fig. 7.45 Flexural strength of "cold" cured, 6.5 sks concrete mixes containing Type A fly ash

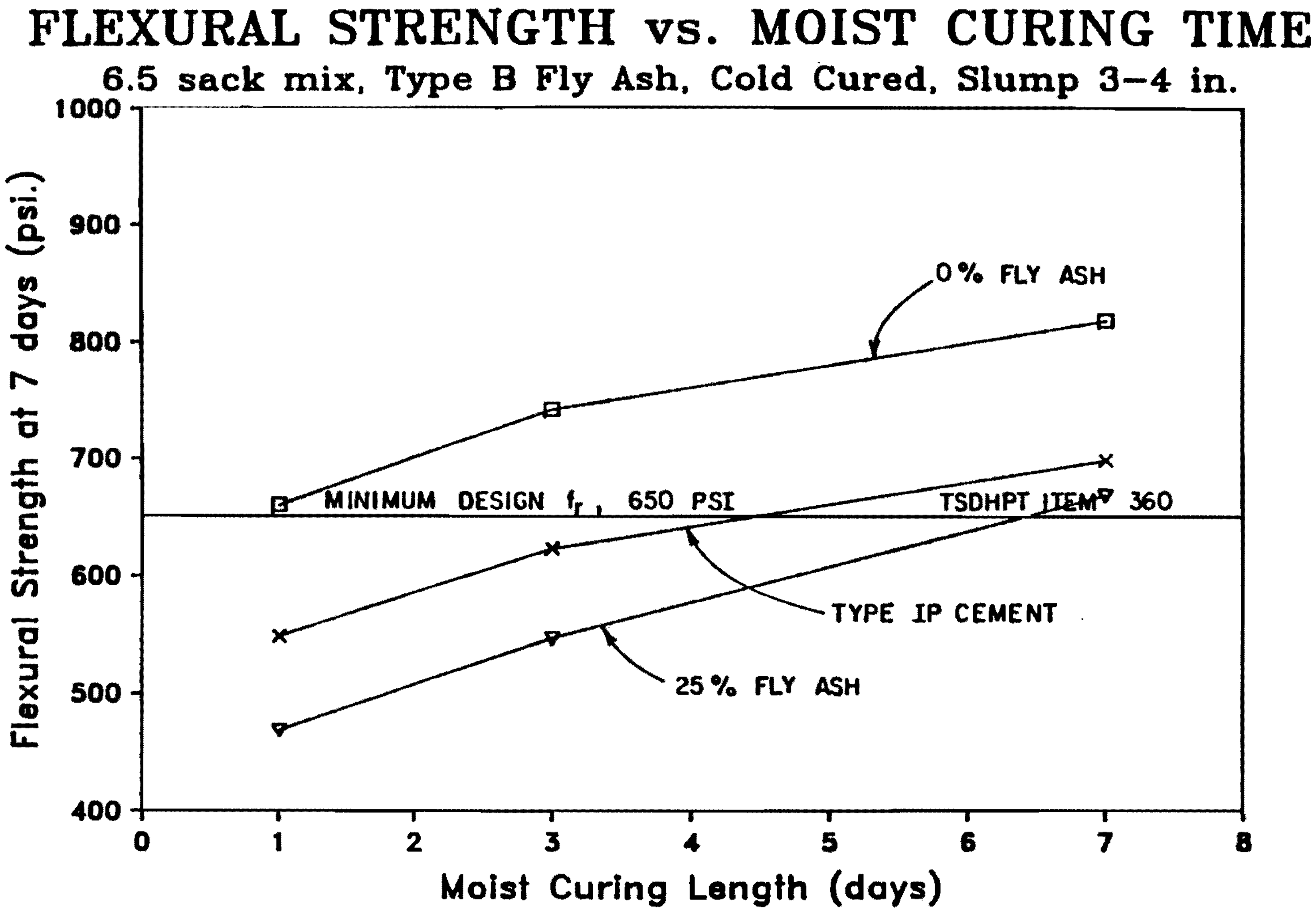


Fig. 7.46 Flexural strength of "cold" cured, 6.5 sks concrete mixes containing Type B fly ash

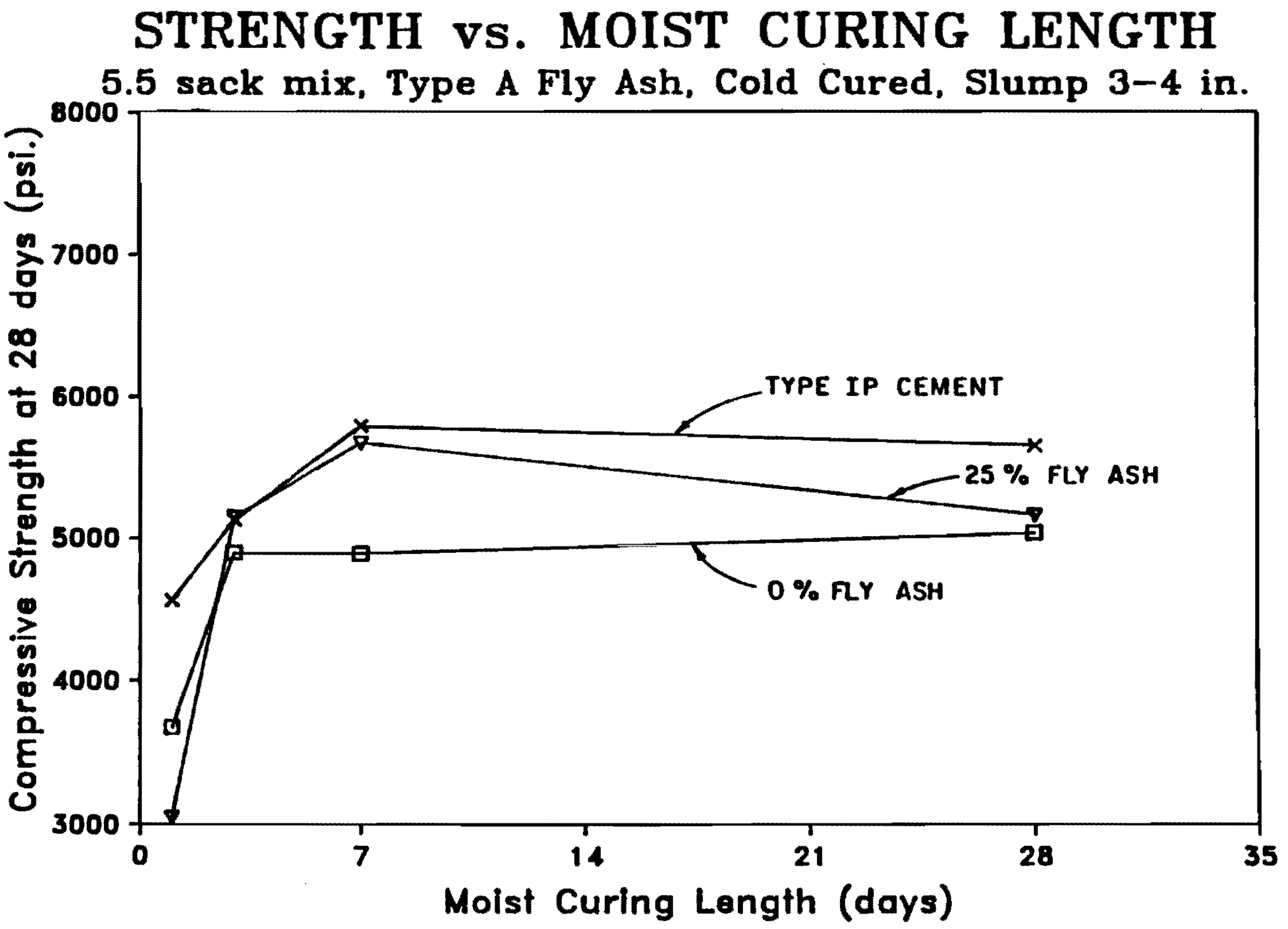


Fig. 7.47 Compressive strength of "cold" cured, 5.5 sks concrete mixes containing Type A fly ash

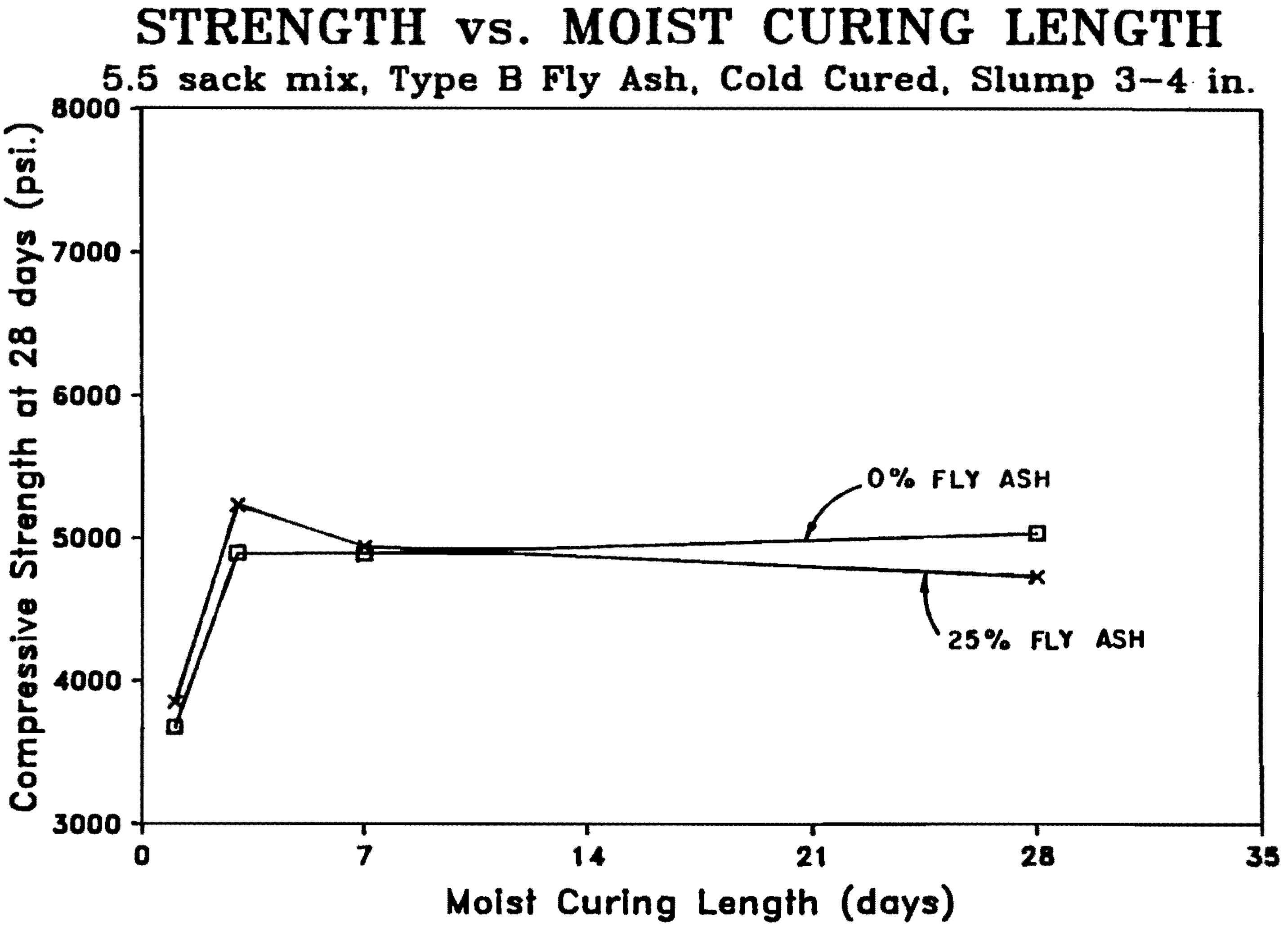


Fig. 7.48 Compressive strength of "cold" cured, 5.5 sks concrete mixes containing Type B fly ash

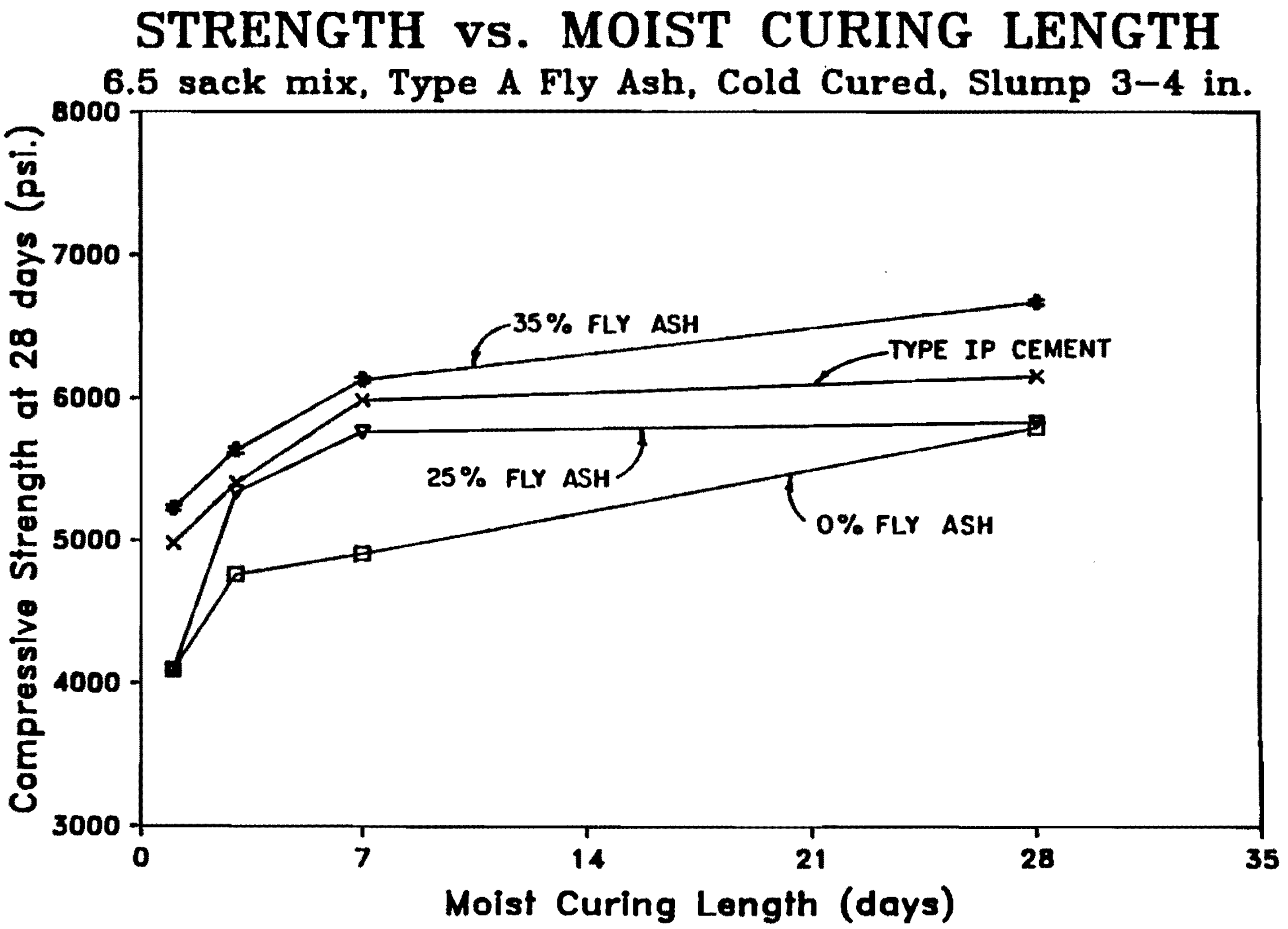


Fig. 7.49 Compressive strength of "cold" cured, 6.5 sks concrete mixes containing Type A fly ash

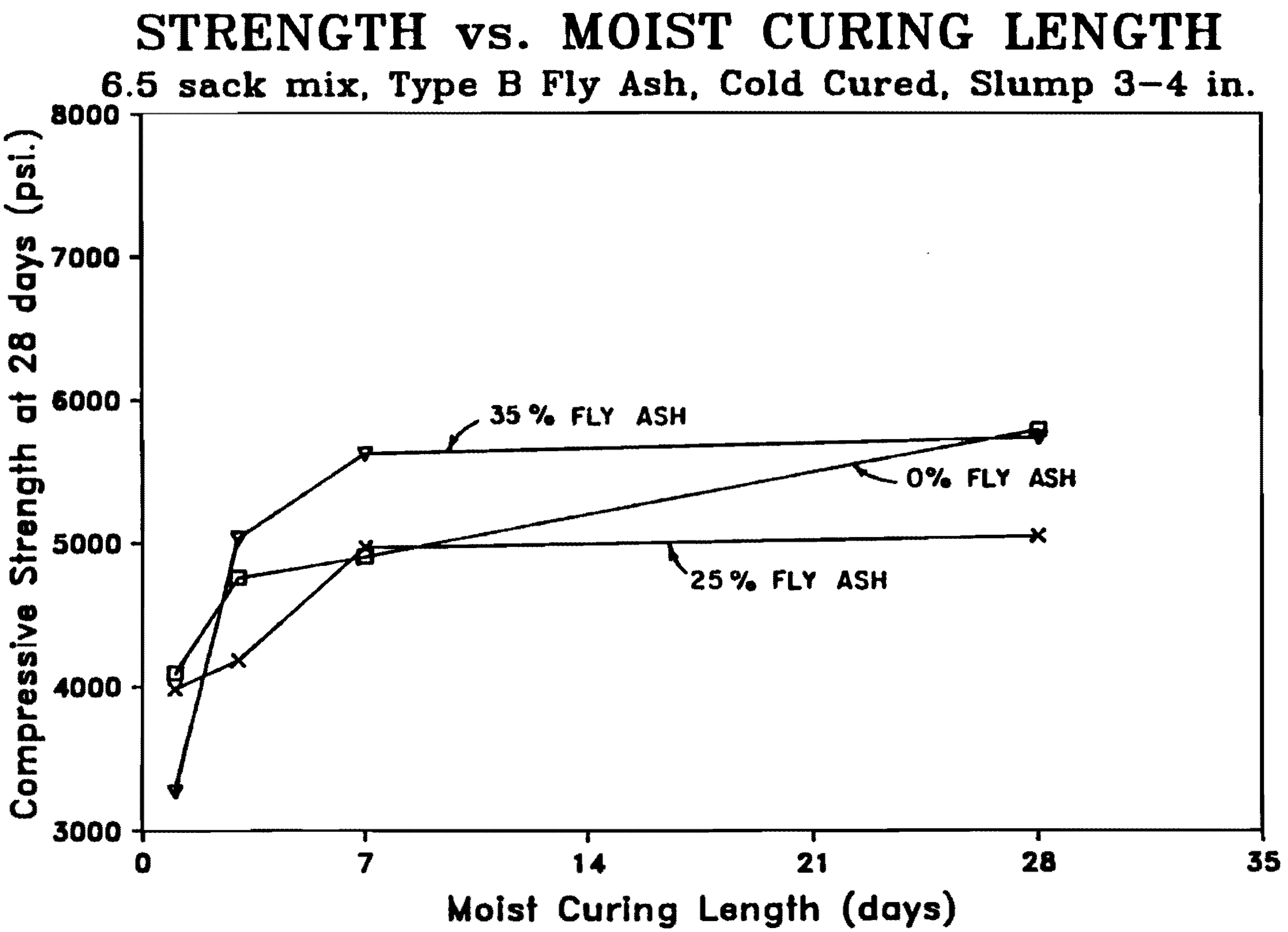


Fig. 7.50 Compressive strength of "cold" cured, 6.5 sks concrete mixes containing Type B fly ash

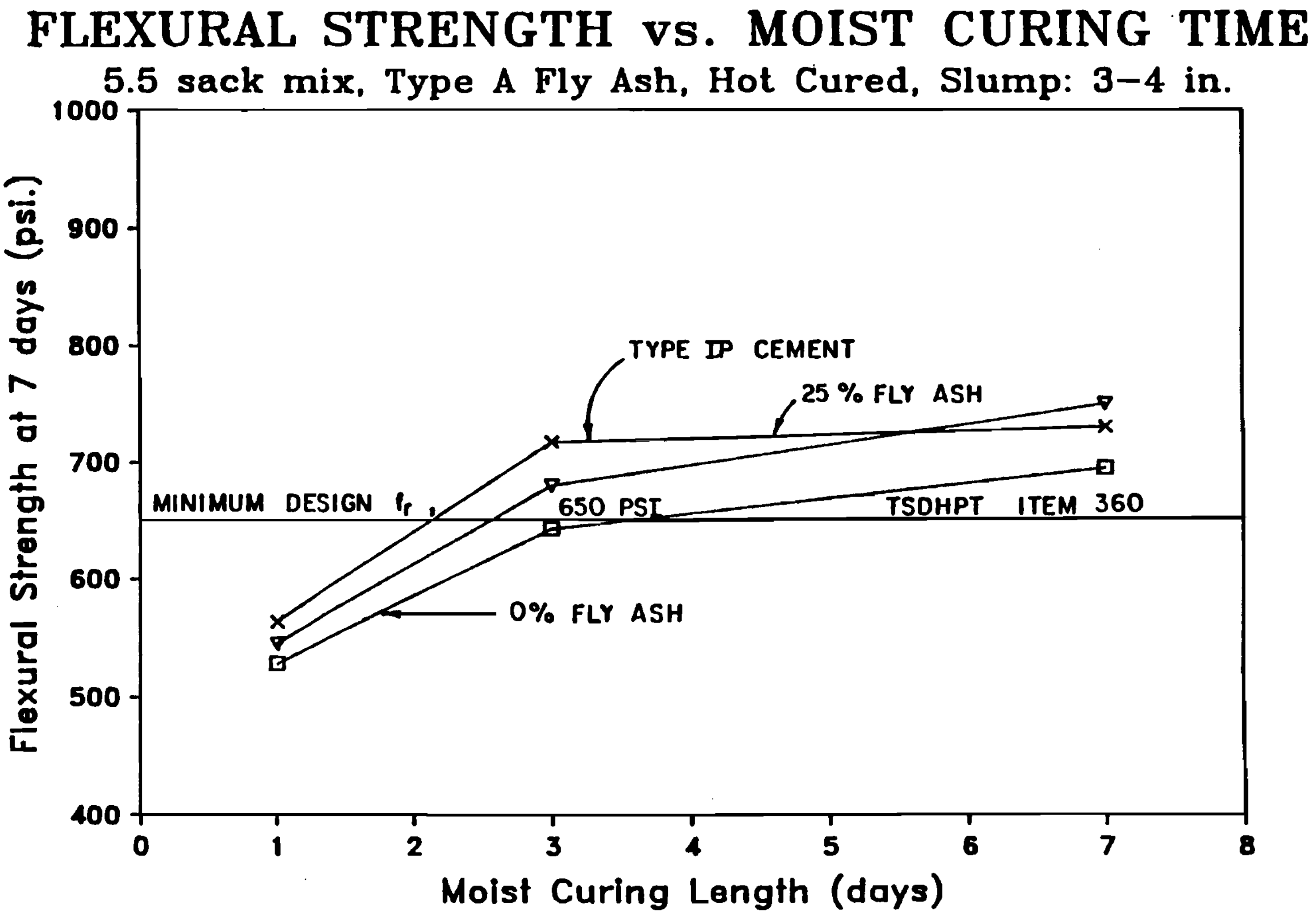


Fig. 7.51 Flexural strength of "hot"cured, 5.5 sks concrete mixes containing Type A fly ash

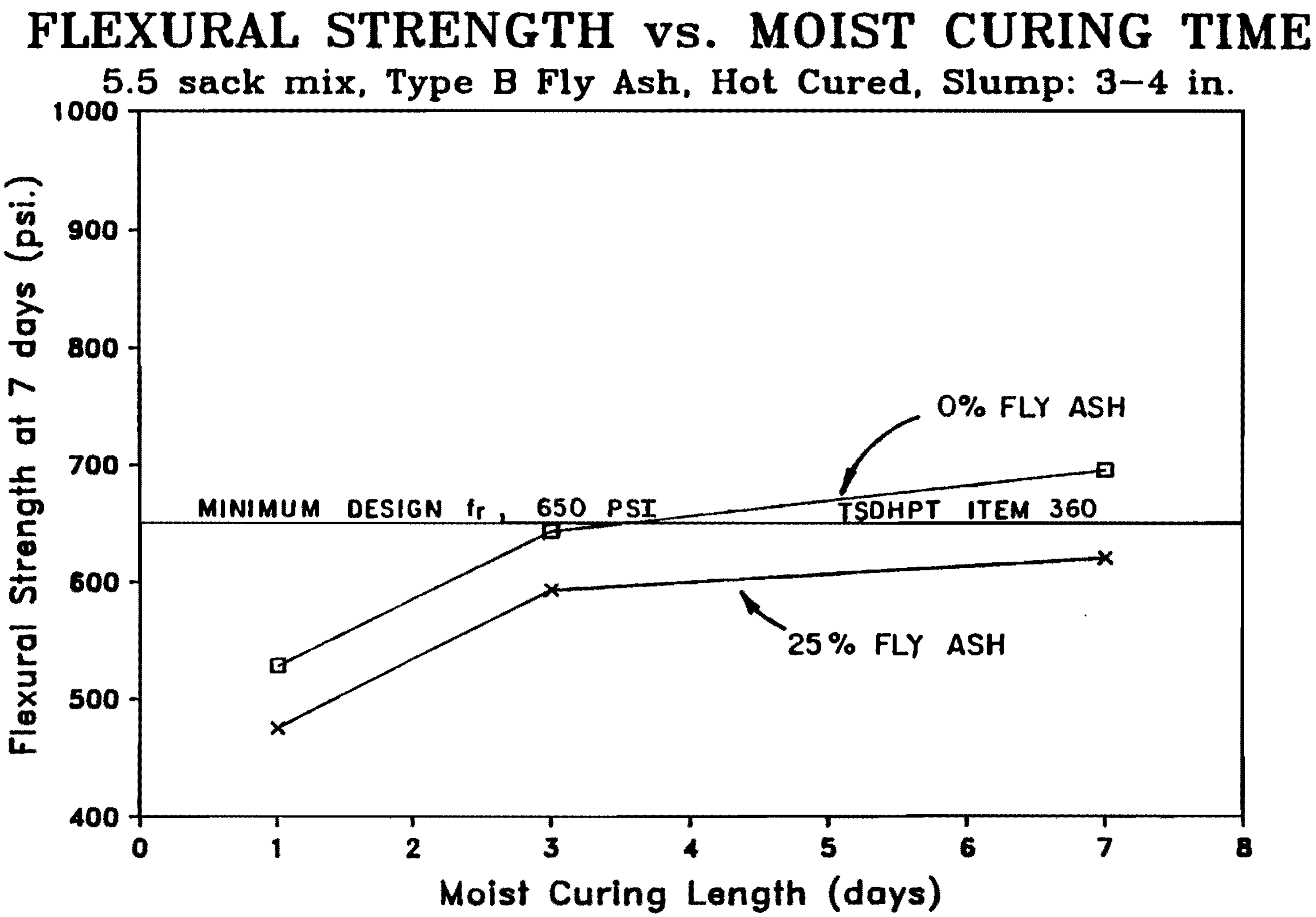


Fig. 7.52 Flexural strength of "hot" cured, 5.5 sks concrete mixes containing Type B fly ash

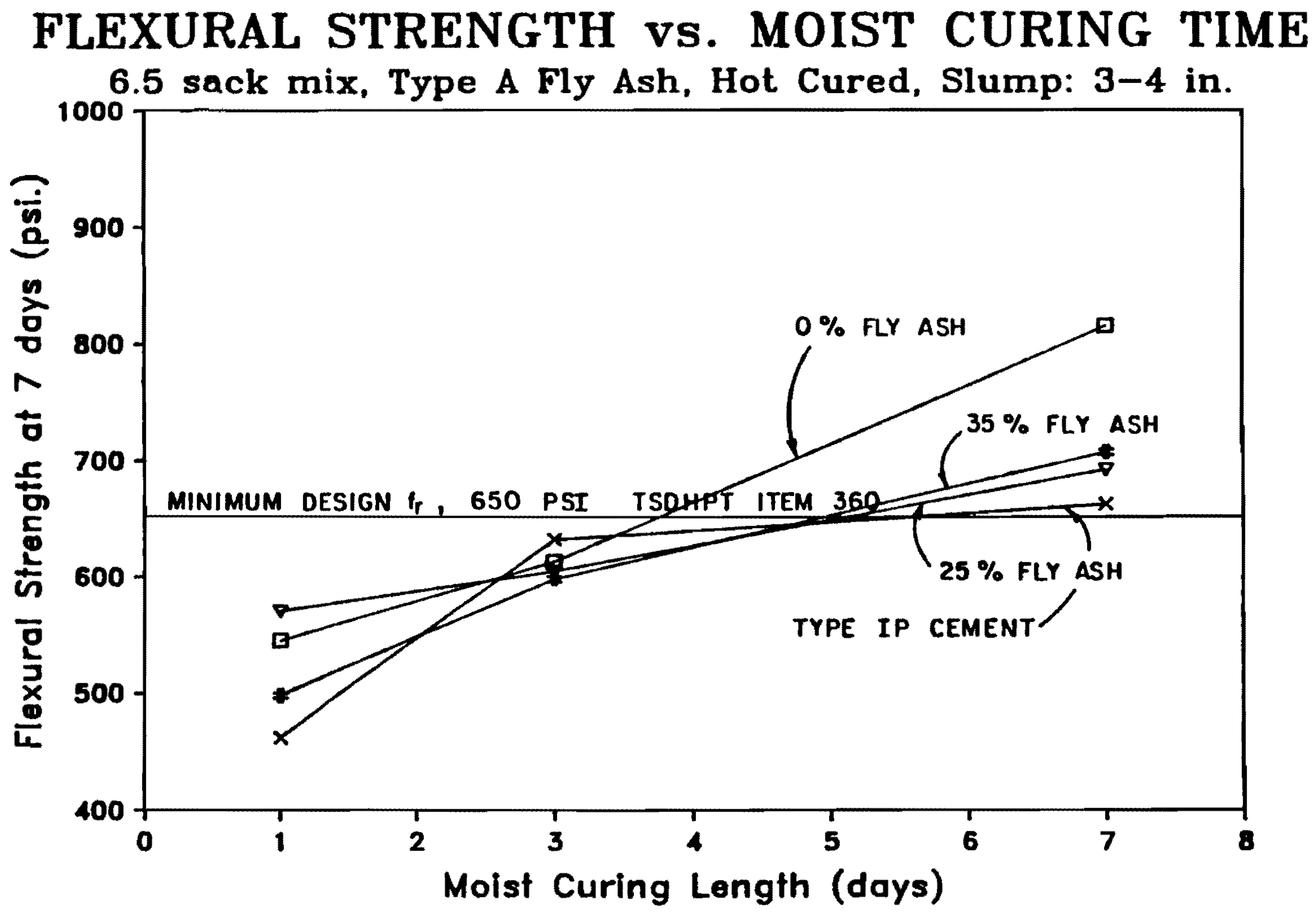


Fig. 7.53 Flexural strength of "hot" cured, 6.5 sks concrete mixes containing Type A fly ash

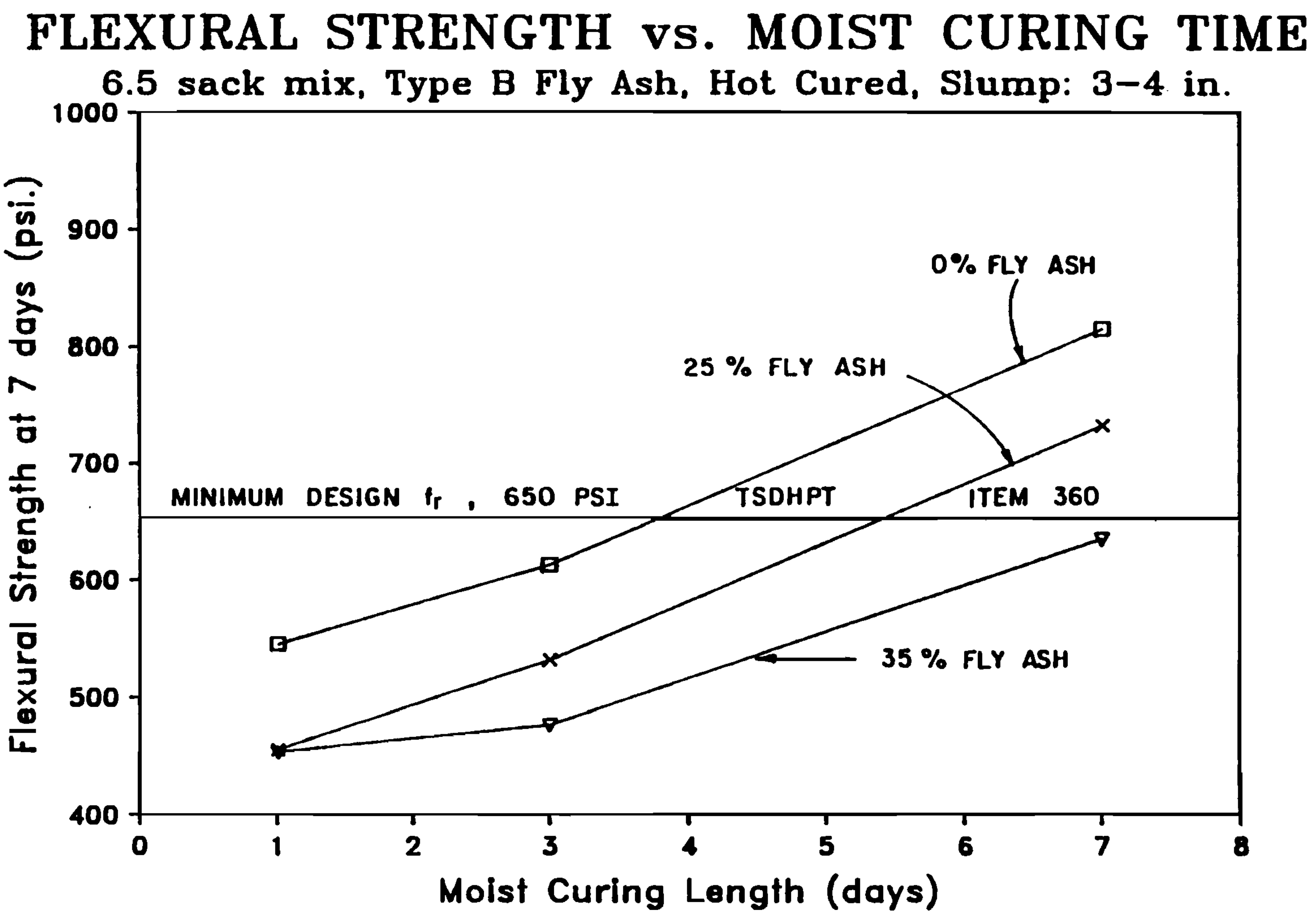


Fig. 7.54 Flexural strength of "hot" cured, 6.5 sks concrete mixes containing Type B fly ash

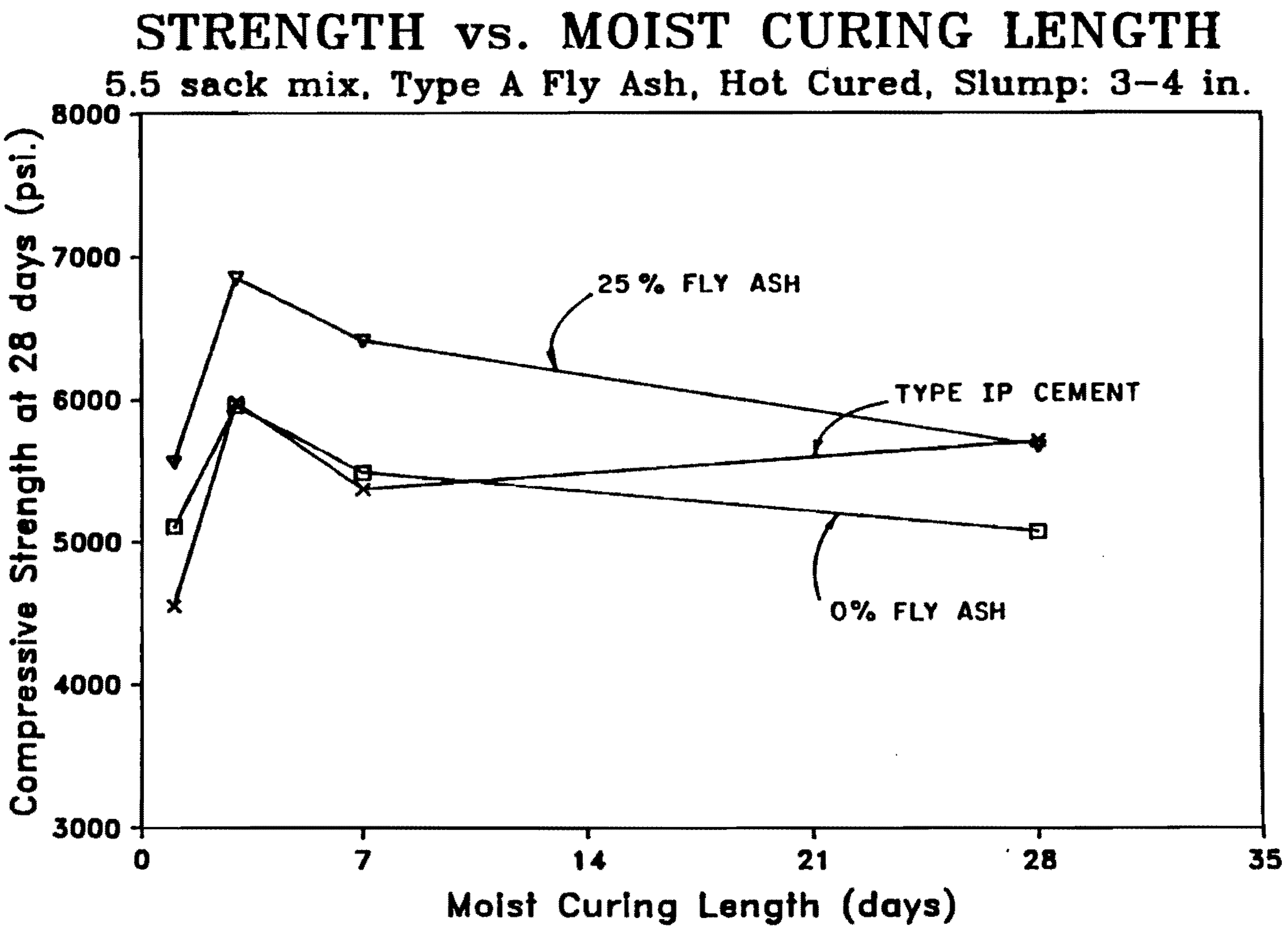


Fig. 7.55 Compressive strength of "hot" cured, 5.5 sks concrete mixes containing Type A fly ash

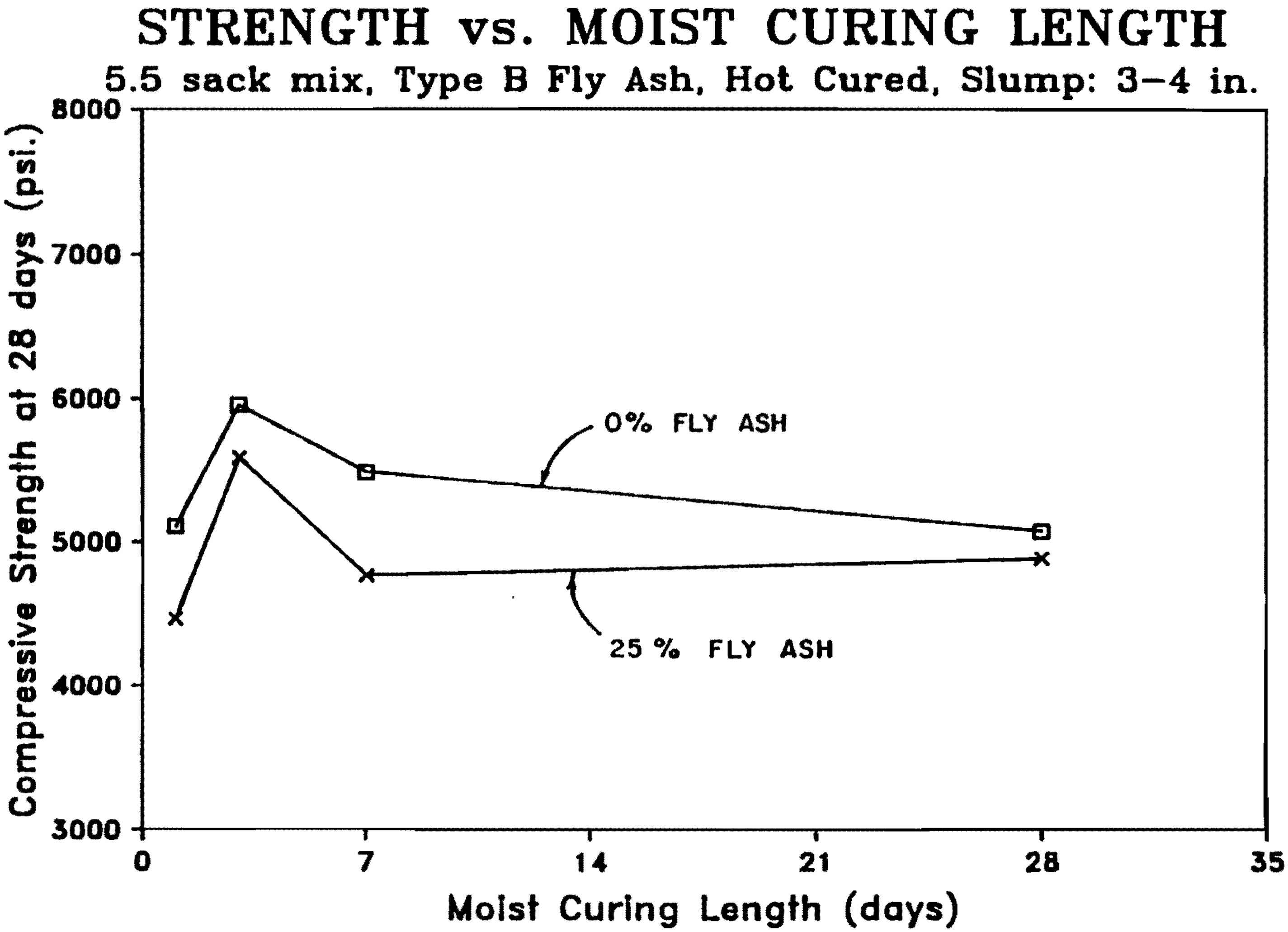


Fig. 7.56 Compressive strength of "hot" cured, 5.5 sks concrete mixes containing Type B fly ash

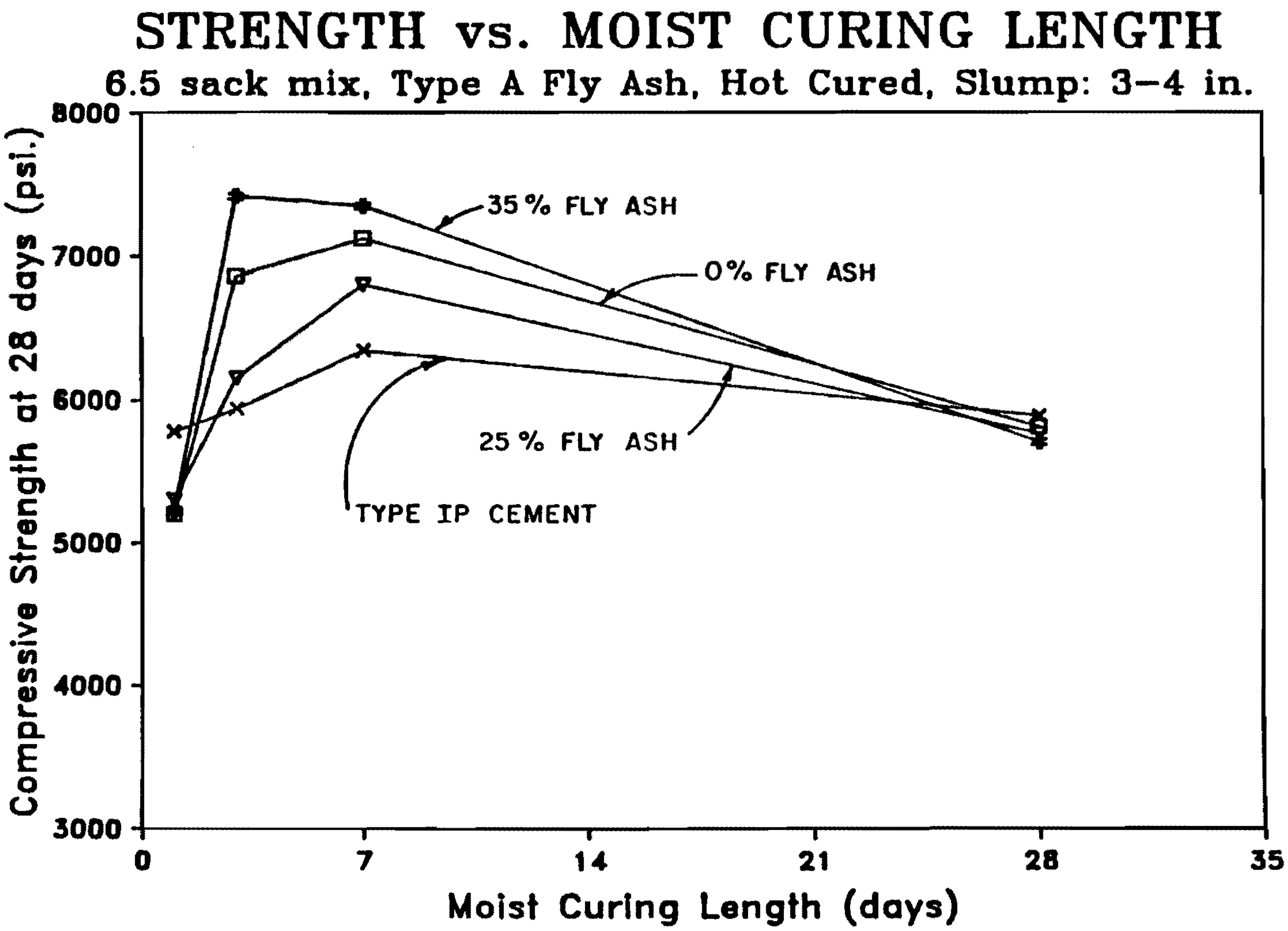


Fig. 7.57 Compressive strength of "hot" cured, 6.5 sks concrete mixes containing Type A fly ash

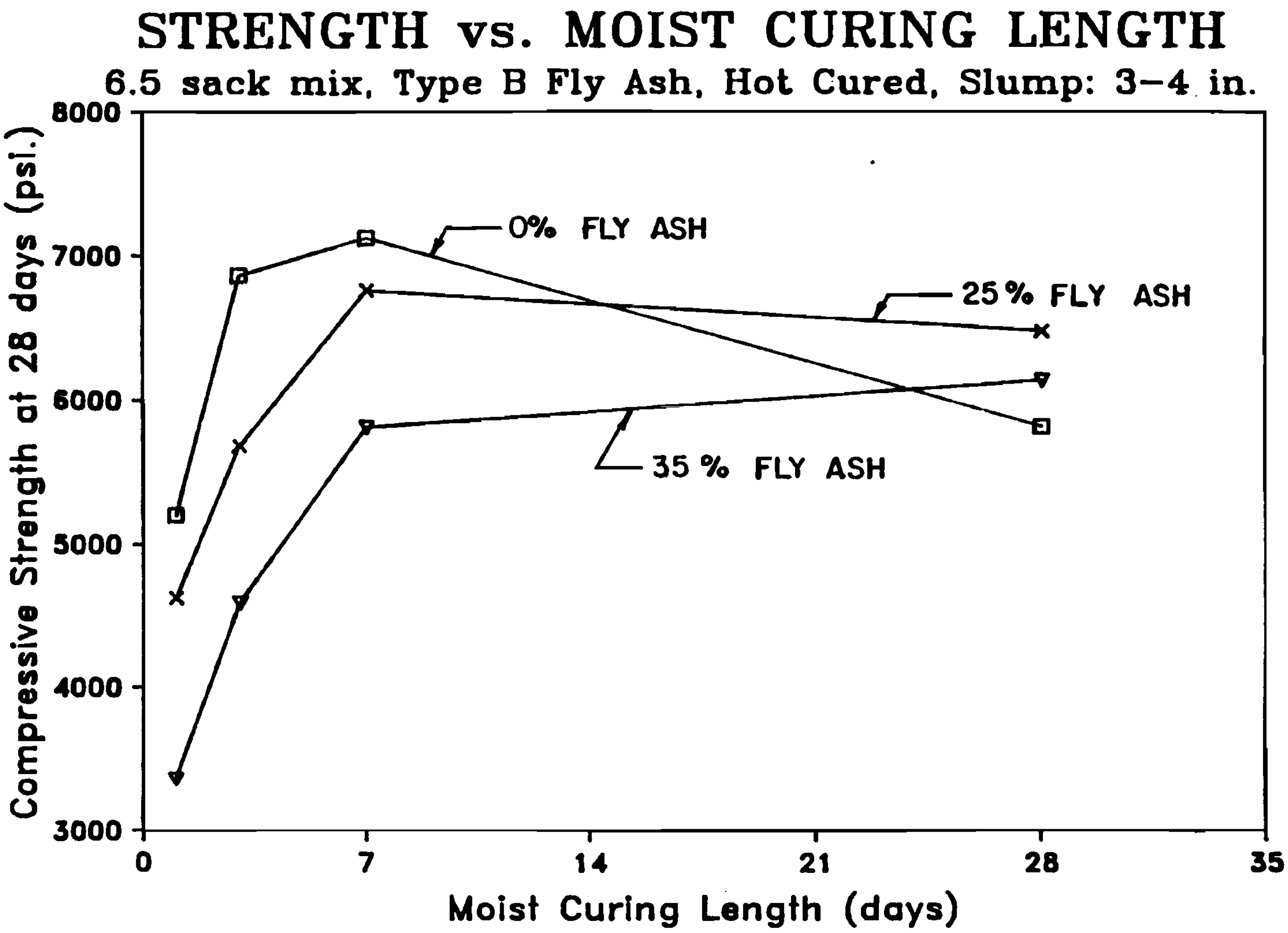


Fig. 7.58 Compressive strength of "hot" cured, 6.5 sks concrete mixes containing Type B fly ash

$$DF = P_c N/M$$

where:

$P_c = n_c^2/n^2 \times 100\%$

n_c = fundamental transverse frequency of resonance after c cycles of freezing and thawing;

n = fundamental transverse frequency of resonance at zero cycles of freezing and thawing;

N = number of freeze-thaw cycles at which P_c reaches the specified minimum value (60%) for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less.

M = specified number of cycles (300) at which the exposure is to be terminated.

ASTM C666-80 requires measurements to be carried out to 300 freeze-thaw cycles, unless the concrete deteriorates below a specified level before this number has been reached. All but two of the concrete specimens performed well enough for the test program to continue to 300 cycles. For these two cases the durability factor was calculated according to ASTM C666-80.

7.7.1 Reduction in Dynamic Modulus of Elasticity. The primary method of evaluation of distress caused by freeze-thaw cycling is the reduction in the dynamic modulus of elasticity. Measurements of the reduction of the dynamic modulus of elasticity due to freezing and thawing showed significant variations among the different concrete mixes. The variations in the dynamic modulus of elasticity for the concrete containing fly ash, as well as, the plain concrete mixes are shown in Figs. 7.59 through 7.62.

The 6.5 sks concrete mixes containing fly ash performed exceedingly well in this regard, the maximum reduction in the dynamic modulus for all but two sets of specimens being less than 3% after 300 freeze-thaw cycle as shown in Figs. 7.59 and 7.60. Although in the case of the 6.5 sks mix containing 25% Type A fly ash, the reduction in the dynamic modulus was as high as 20%. This still yields a durability factor of 80% after 300 cycles.

The reduction of the dynamic modulus in 5.5 sks concrete mixes was typically slightly greater than that of the 6.5 sks mixes, as shown in Figs. 7.61 and 7.62. Particularly large variations in the measured response of the dynamic modulus to freezing and thawing occurred in the 5.5 sks concrete mixes containing 25 and 35% of Type A fly ash, as shown in Fig. 7.61. In these two cases the dynamic modulus dropped below the recommended failure level of 60% of the starting value at about 100 freeze-thaw cycles.

The reduction in the dynamic modulus of the 5.5 sks concrete mixes containing Type B fly ash is shown in Fig. 7.62. Only the mix containing 35%

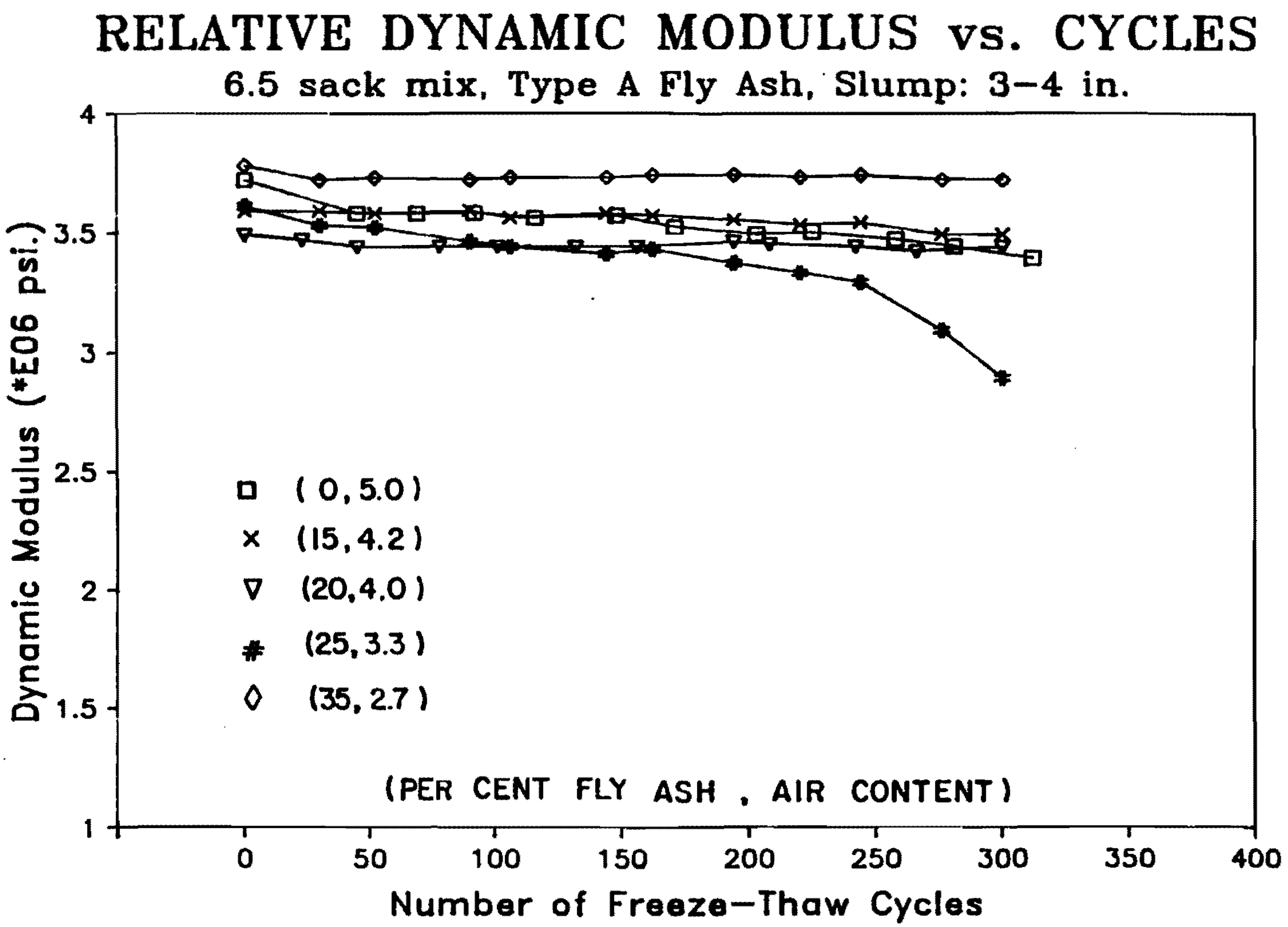


Fig. 7.59 Comparison of dynamic modulus of freeze-thaw specimens containing Type A fly ash

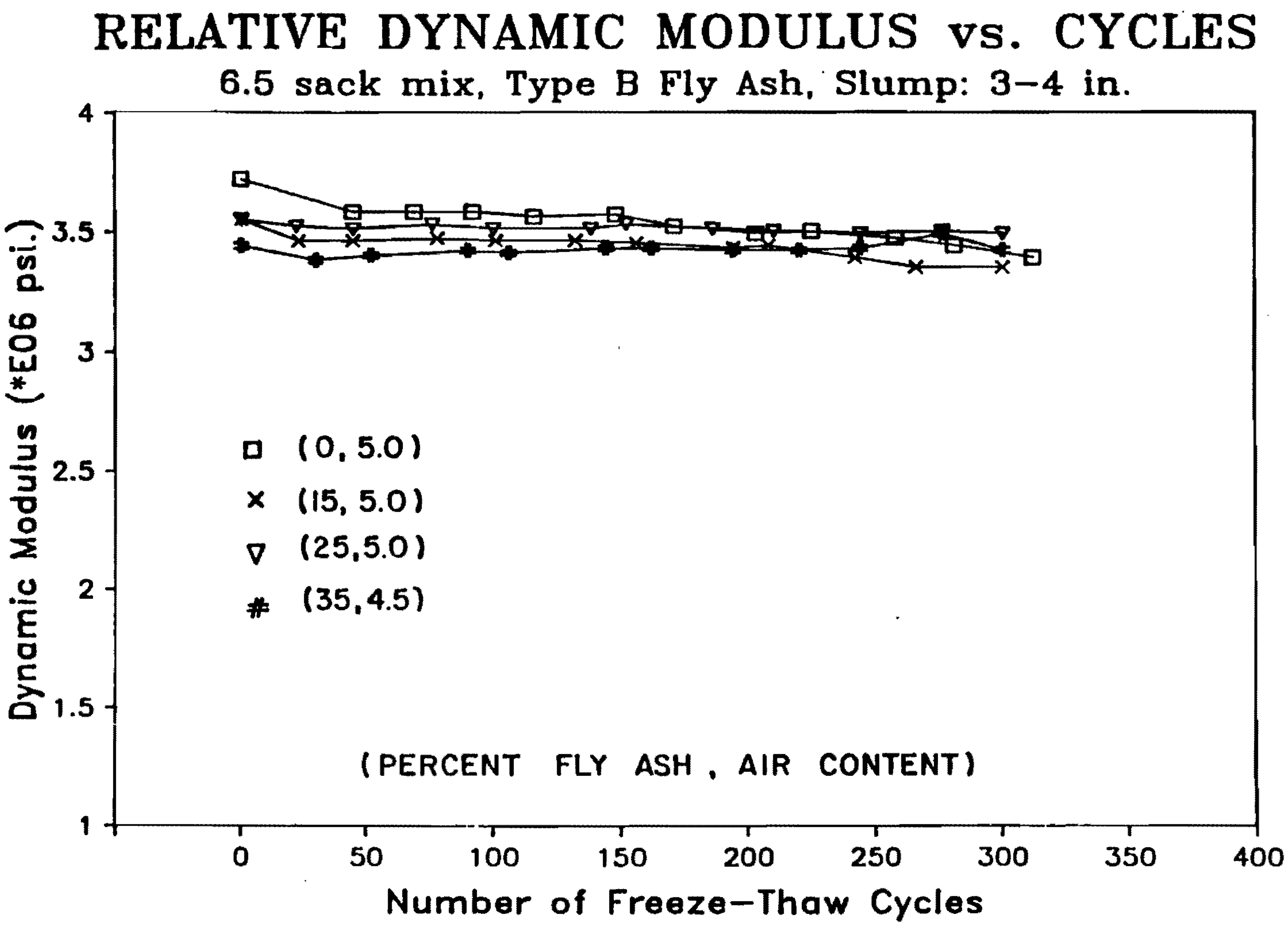


Fig. 7.60 Comparison of dynamic modulus of freeze-thaw specimen containing Type B fly ash

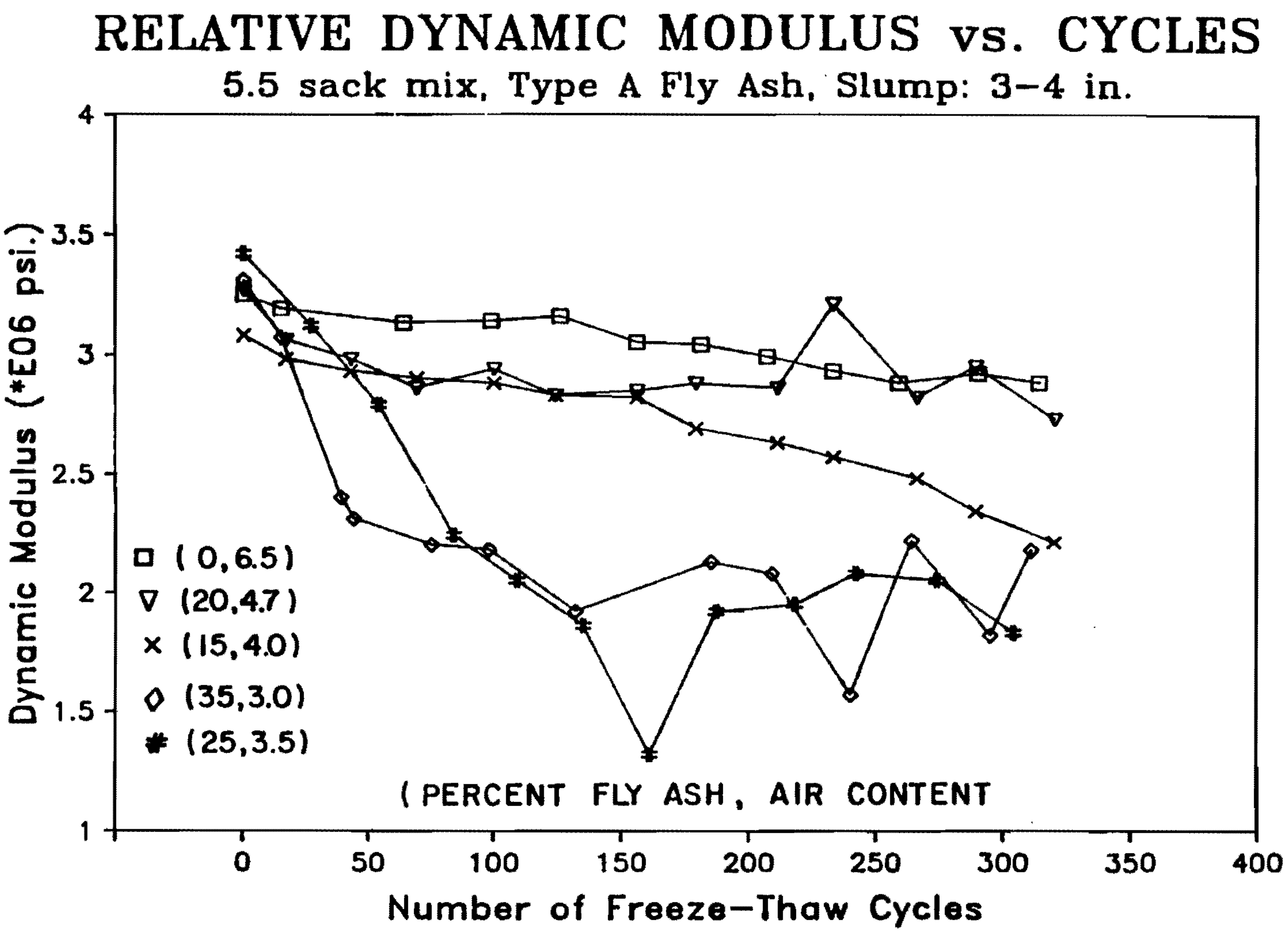


Fig. 7.61 Comparison of dynamic modulus of freeze-thaw specimens containing Type A fly ash

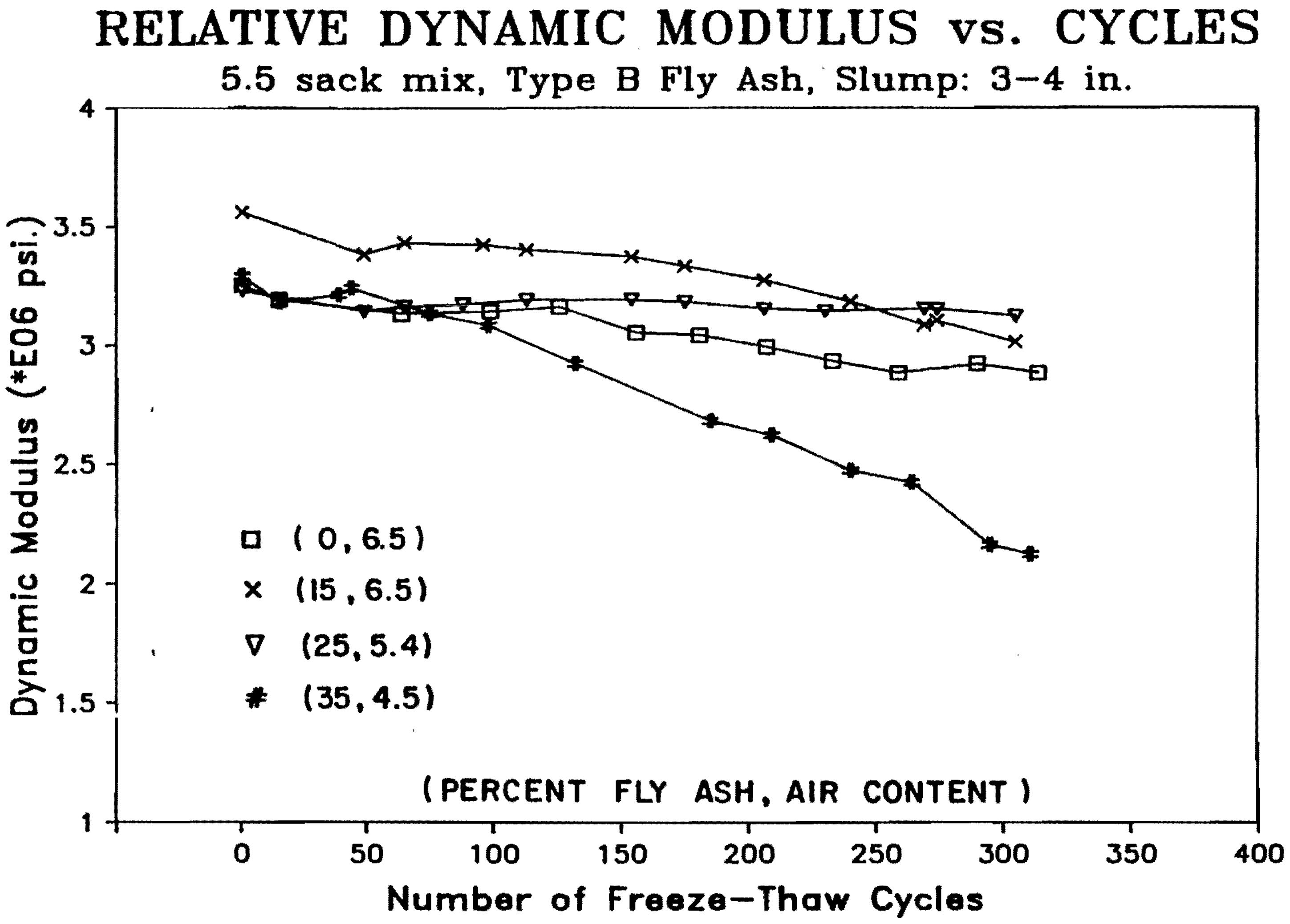


Fig.7.62 Comparison of dynamic modulus, freeze-thaw specimens containing Type B fly ash

fly ash showed rather sharp drop in the value of the dynamic modulus, but it continued past 300 freeze-thaw cycles retaining about 65% of its original dynamic modulus.

In summary, for 5.5 sks concrete mixes the influence of the type and the amount of fly ash or the freeze-thaw resistance of concrete was more pronounced than for the 6.5 sks mixes. Concretes with higher amount of Type A fly ash experienced a greater loss in the dynamic modulus.

7.7.2 Durability factor. The durability factors computed in accordance with ASTM Designation C666-80, Resistance of Concrete to Rapid Freezing and Thawing are shown in Figs. 7.63 through 7.66. For 6.5 sks concrete mixes, the durability factor in all but one case was higher than 90% as shown in Figs. 7.63 and 7.64.

The behavior of concrete with 25% Type A fly ash was discussed in Sec. 7.7.1. Figures 7.65 and 7.66 indicate that for 5.5 sks concrete mixes, the durability tends to decrease with the increased fly ash content. However, as indicated on the figures the air content was lower in mixes with higher fly ash contents, and freeze-thaw durability is directly related to the entrained air system.

From the air contents shown in Figs. 7.63 through 7.66, it is evident that mixes with higher amounts of Type A fly ash have a lower air content than corresponding mixes with Type B fly ash. For concrete with 6.5 sks of cement this influence on the durability is not as significant as in the 5.5 sks mixes.

7.7.3 Change in Physical Appearance. Illustrations of the apearance of typical specimens of different mixes after 300 cycles are provided in Figs. 7.67 through 7.74. Changes in physical appearance resulting from the freeze-thaw cycles were very noticeable for the 5.5 sks concrete mixes. For these mixes, as the fly ash content increases so does the surface deterioration. It is also apparent from Figs. 7.67 through 7.72 that when the same percentage of fly ash was used, the deterioration was more severe for the specimens which contained Type A fly ash. The specimens containing 35% of Type A fly ash show considerable surface distress as shown in Fig. 7.72.

Little difference was observed in physical appearance of specimens made of 6.5 sks concrete mixes. Regardless of the type of fly ash used, no surface damage was observed after 300 freeze-thaw cycles, even for concrete with 35% fly ash replacement, as compared between Figs. 7.73 and 7.74.

The apparent difference in appearance of the upper surfaces horizontal sides of the specimens as compared with the remaining sides was observed. In nearly every case the appearance of the cast upper surface was not affected by the repeated freezing and thawing exposure.

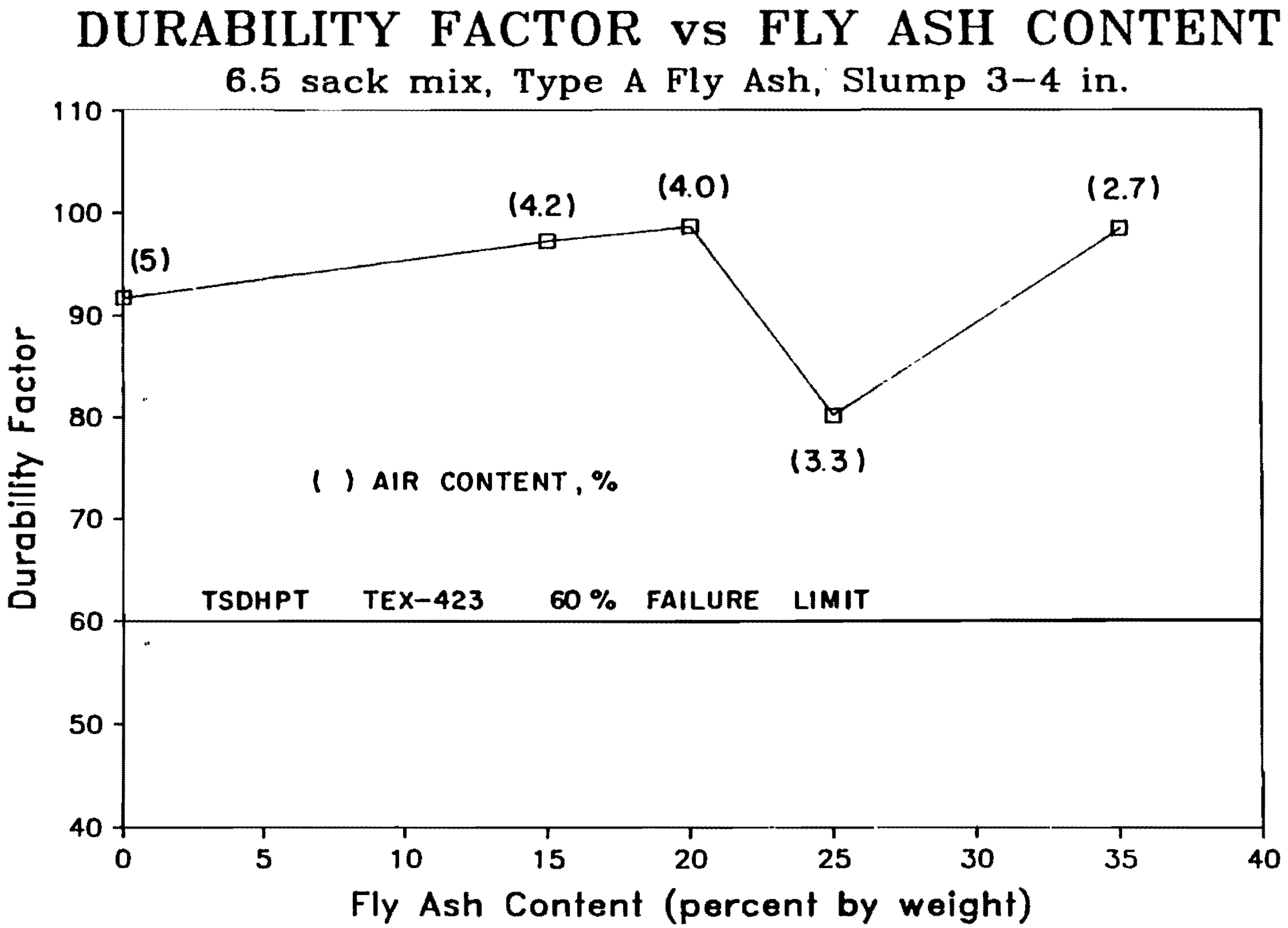


Fig. 7.63 Durability factors of concrete containing Type A fly ash in 6.5 sks mixes

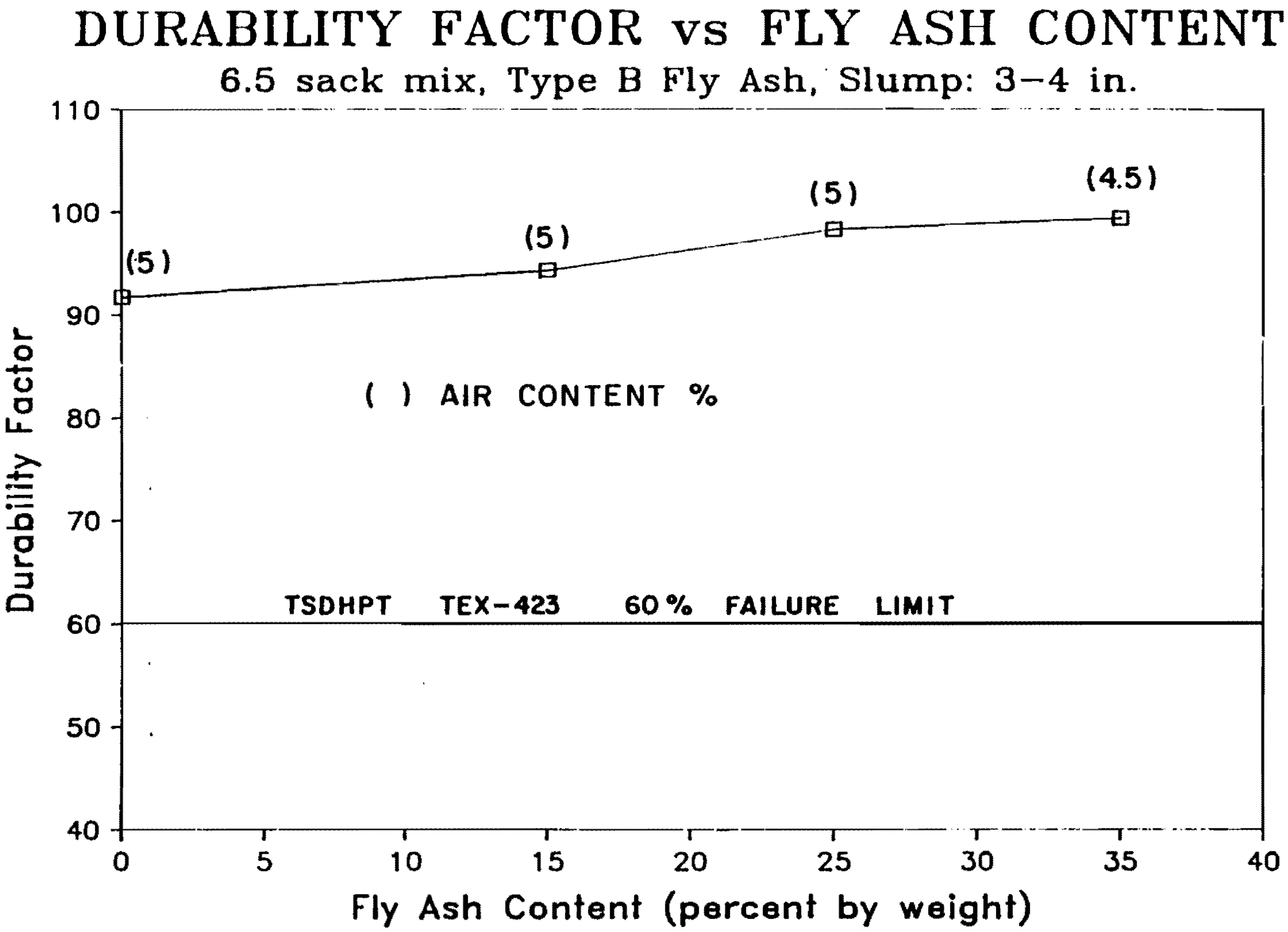


Fig. 7.64 Durability factors of concrete containing Type B fly ash in 6.5 sks mixes

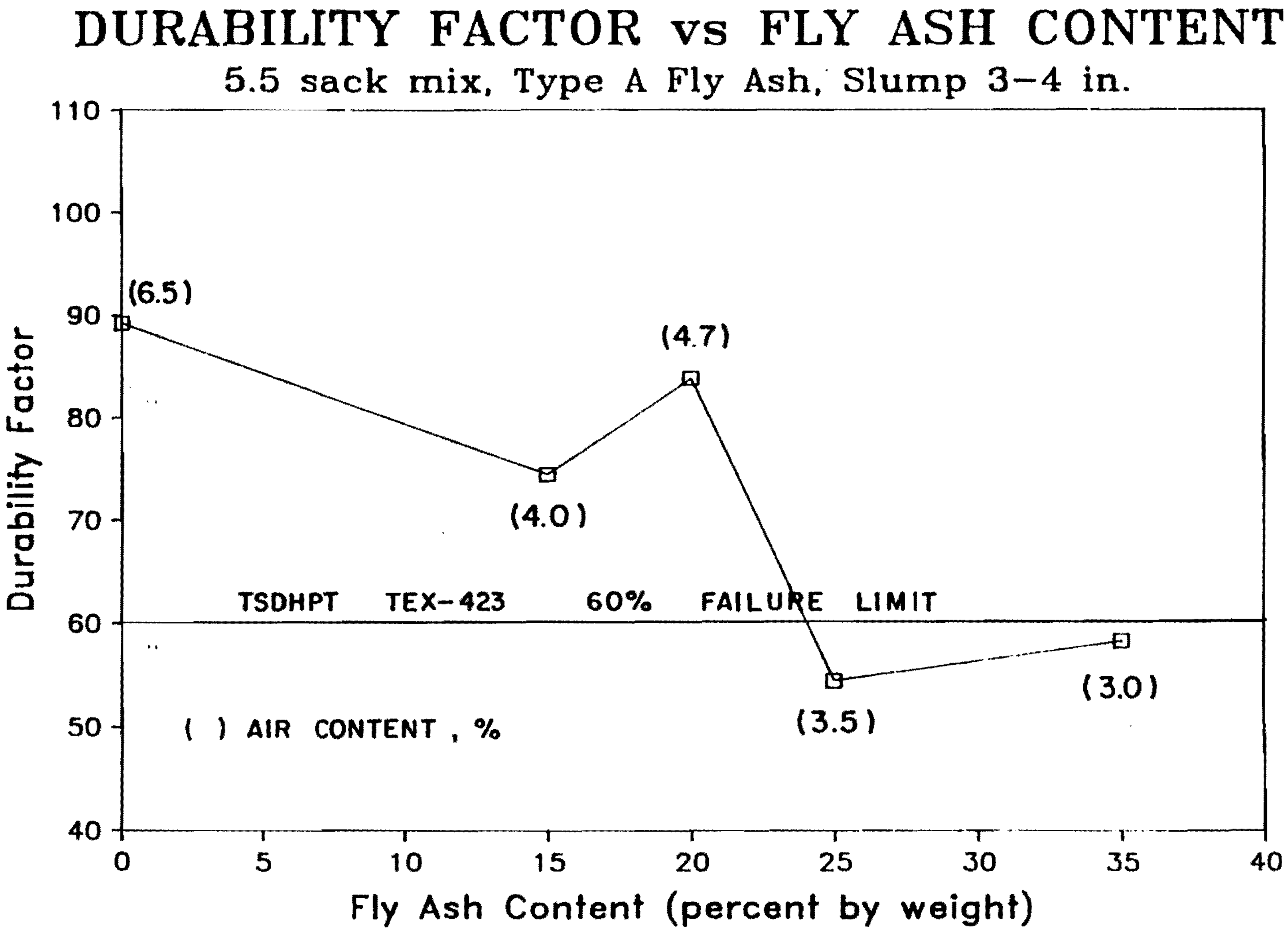
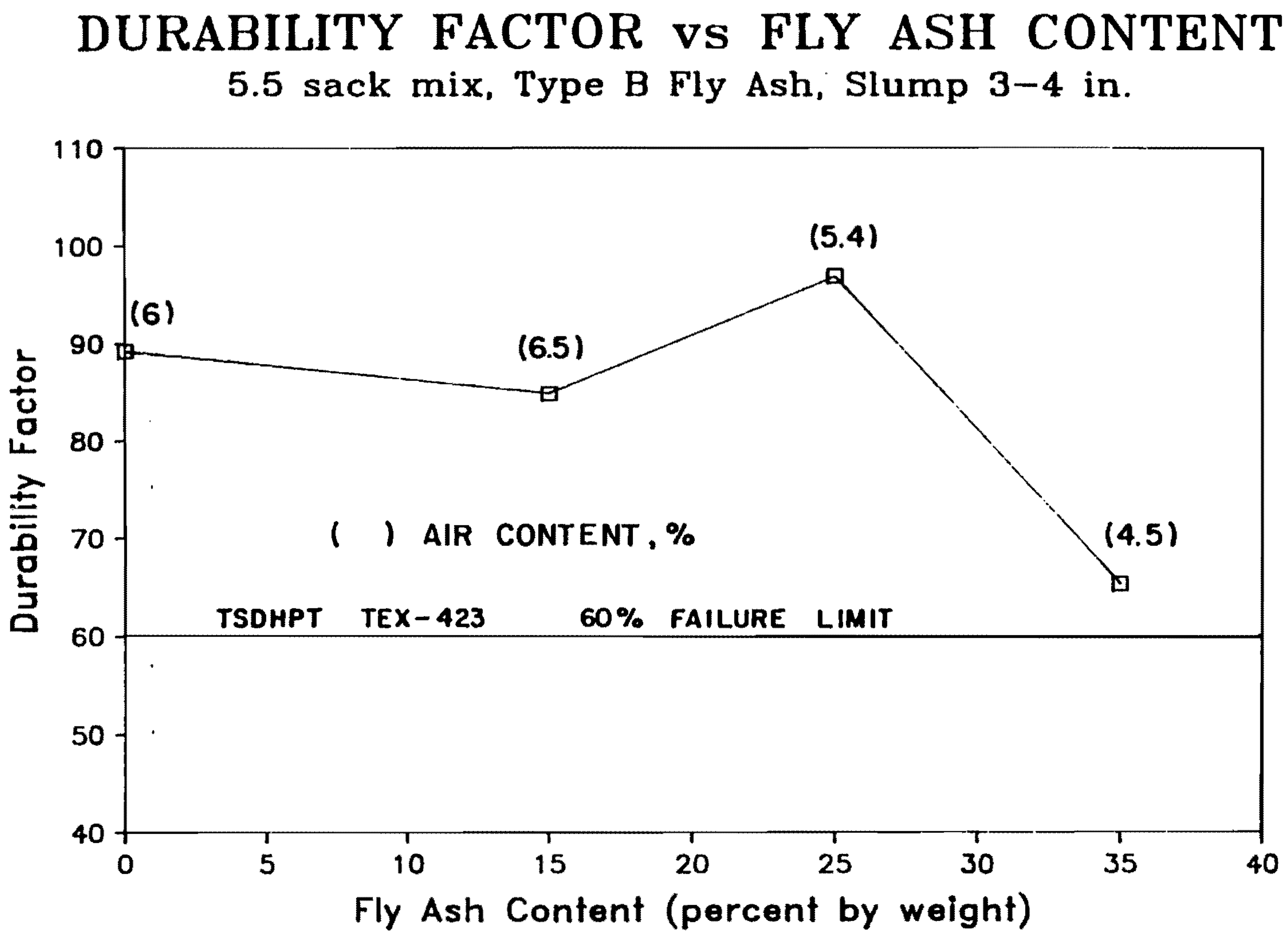


Fig.7.65 Durability factors of concrete containing Type A fly ash in 5.5 sks mixes



DURABILITY FACTOR vs FLY ASH CONTENT

5.5 sack mix, Type B Fly Ash, Slump 3–4 in.

Fig. 7.66 Durability factors of concretes containing Type B fly ash in 5.5 sks mixes

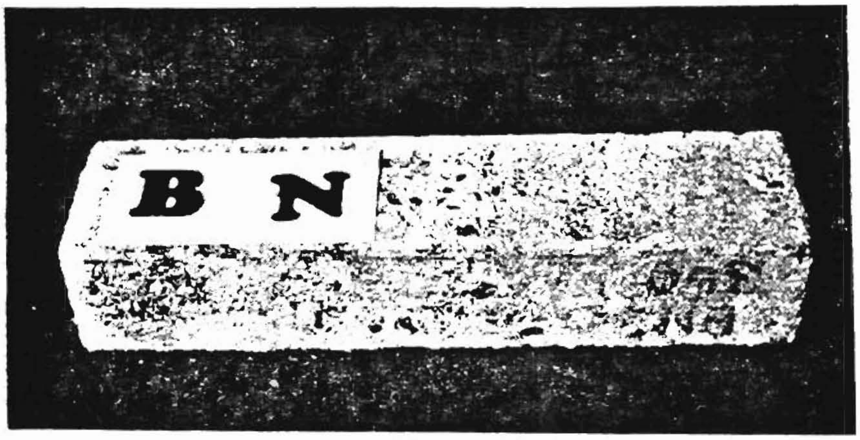


Fig. 7.67 Physical appearance of concrete containing 15% Type B fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

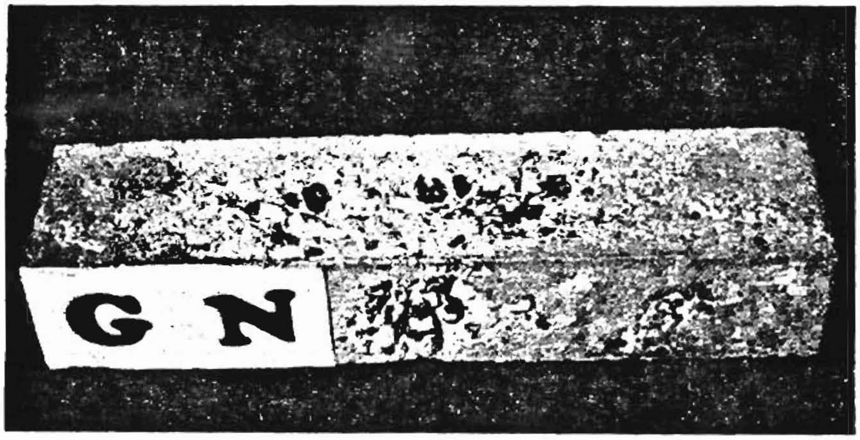


Fig. 7.68 Physical appearance of concrete containing 15% Type A fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

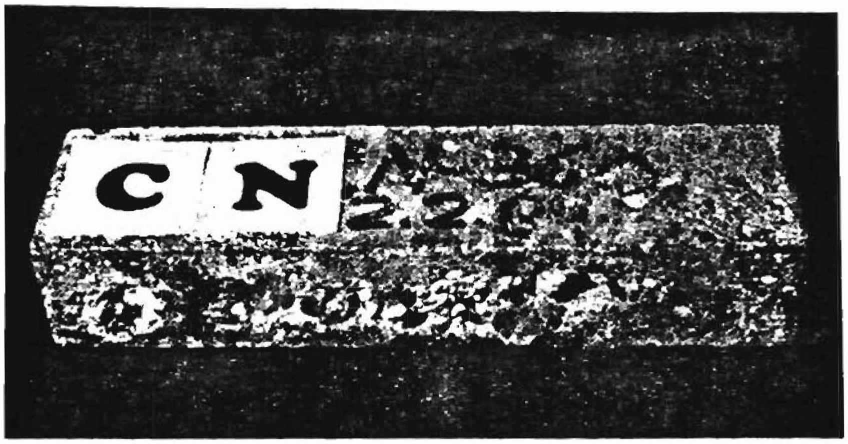


Fig. 7.69 Physical appearance of concrete containing 25% Type B fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

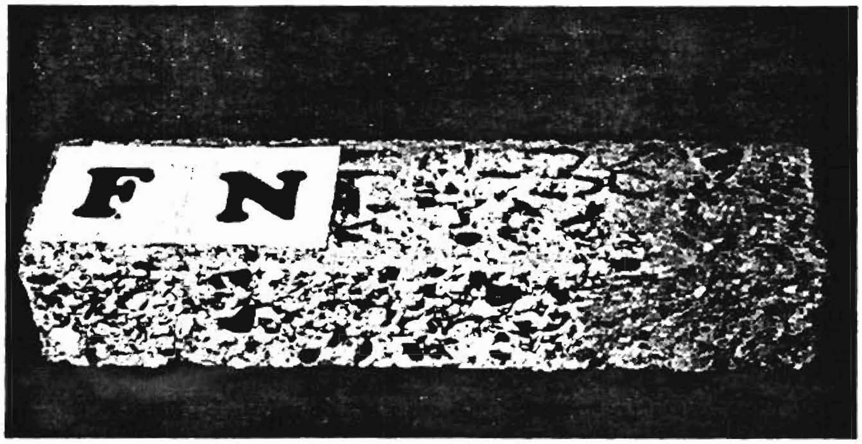


Fig. 7.70 Physical appearance of concrete containing 25% Type A fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

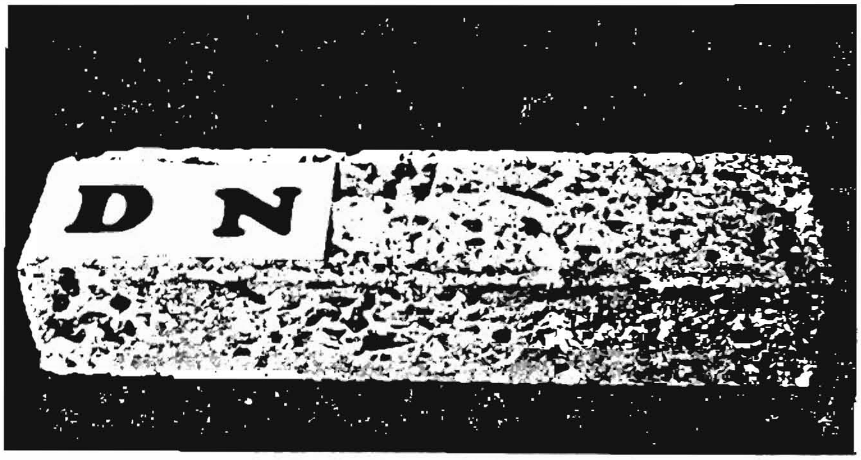


Fig. 7.71 Physical appearance of concrete containing 35% Type B fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

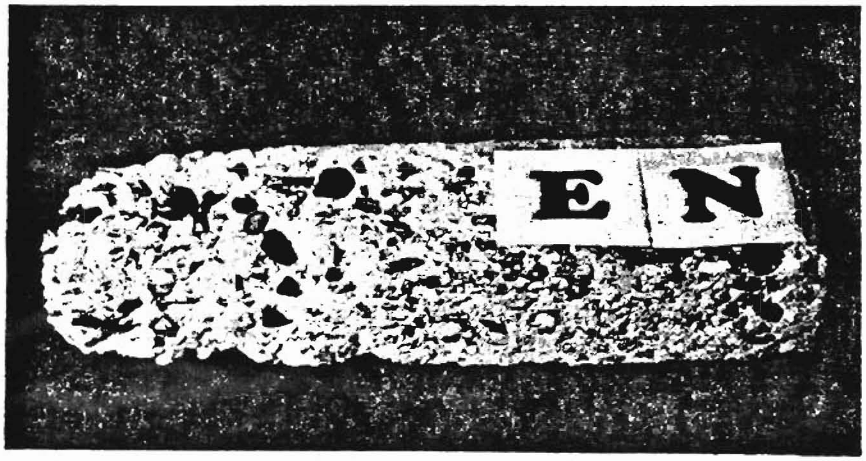


Fig. 7.72 Physical appearance of concrete containing 35% Type A fly ash in a 5.5 sks mix, after 300 freeze-thaw cycles

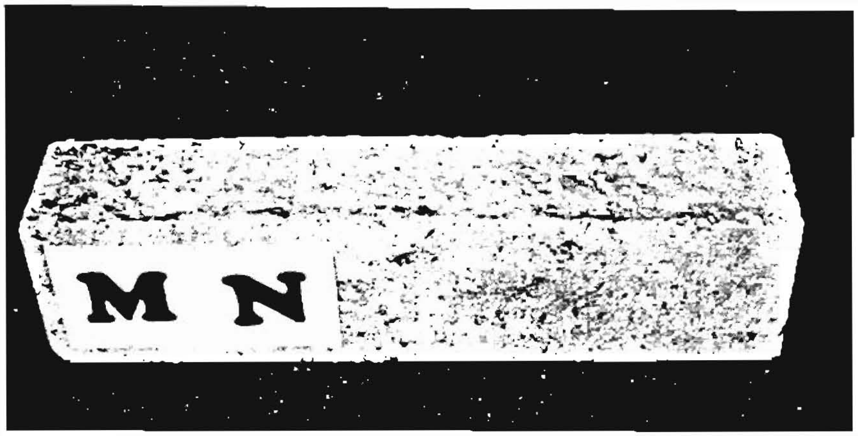


Fig. 7.73 Physical appearance of concrete containing 35% Type B fly ash in a 6.5 sks mix, after 300 freeze-thaw cycles

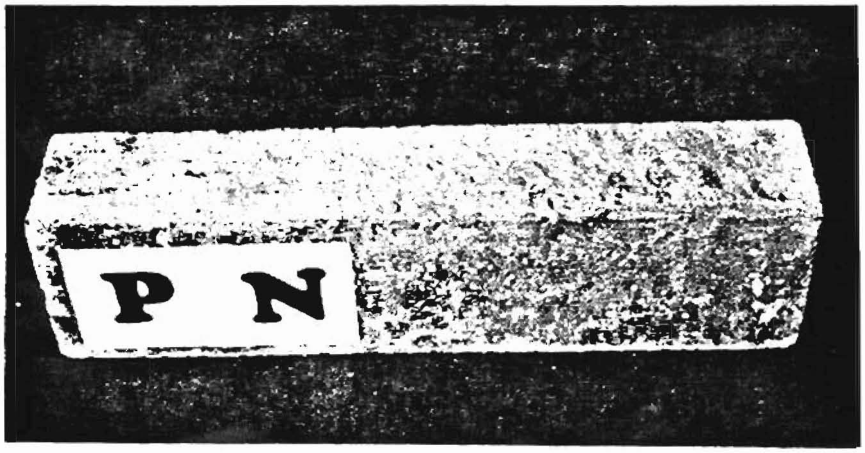


Fig. 7.74 Physical appearance of concrete containing 35% Type A fly ash in a 6.5 sks mix, after 300 freeze-thaw cycles

CHAPTER 8

DISCUSSION OF TEST RESULTS

A detailed analysis and discussion of all the results obtained during this study is presented in this chapter. The chapter is divided into sections, each having a counterpart in Chapter 7 where the corresponding test results are presented.

8.1. Properties of Fresh Concrete

Type and amount of fly ash used was observed to have a significant influence on the properties of fresh concrete. Some detailed information concerning the slump and setting time were discussed in Secs. 4.2 and 7.4 for Type B fly ash. The overall findings in general terms can be summarized as follows:

1. Substituting fly ash for an equal weight of cement increases the paste-aggregate ratio due to the lower specific gravity of the fly ash. This provides better cohesion and plasticity. Due to the spherical shape of fly ash particles, it also improves the workability. It was observed, however, that the plastic properties were extremely sensitive to small changes in the amount of mixing water.

2. A strong correlation was observed between the content of Type A fly ash and the amount of entrained air. At a constant air entraining admixture dosage, air content decreased proportionally with Type A fly ash content;

3. In cases where 35% Type A fly ash was used, additional set retardation was observed. This phenomenon was not investigated in this study, however, the delayed pozzolanic reaction of Type A fly ash is believed to be the cause of the retardation. In addition, the water-reducing admixture dosage used was held constant throughout the study. The pozzolanic nature of Type A fly ash does not require a water reducer-retarder to delay its setting time, therefore only the cement fraction of the binder material is directly affected by the water-reducing admixture. By maintaining a constant admixture dosage the cement may actually be overretarded by as much as 50% with a 35% replacement with Type A fly ash. In most cases, however final setting times were only slightly longer than those of plain concrete mixes;

4. When the average values of water/cement plus fly ash ratios are compared in Figs. 8.1 and 8.2, it is apparent that the lower ratios were associated with 6.5 sks mixes. This is especially

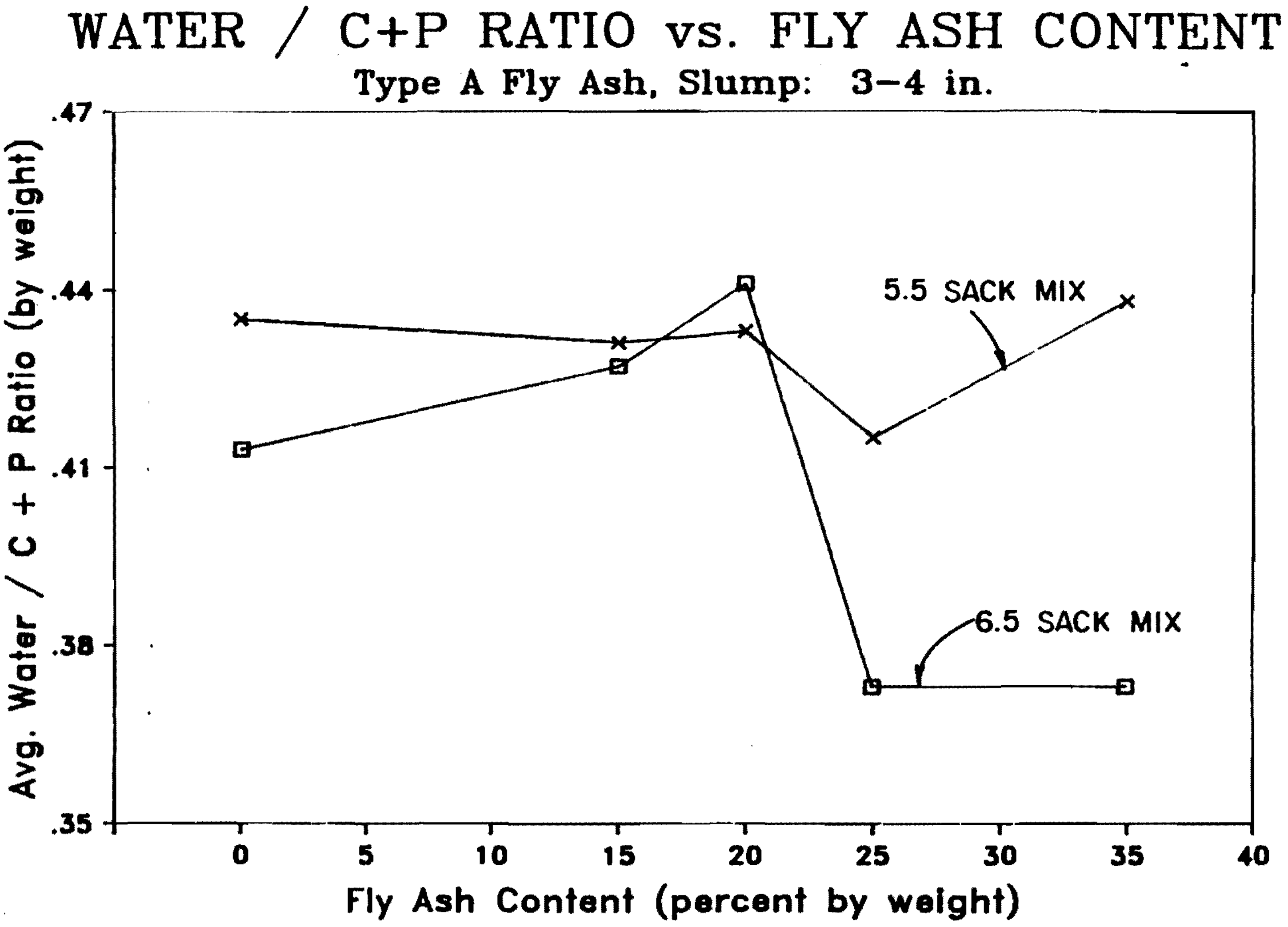


Fig. 8.1 Average water/C+P ratios for concrete containing Type A fly ash

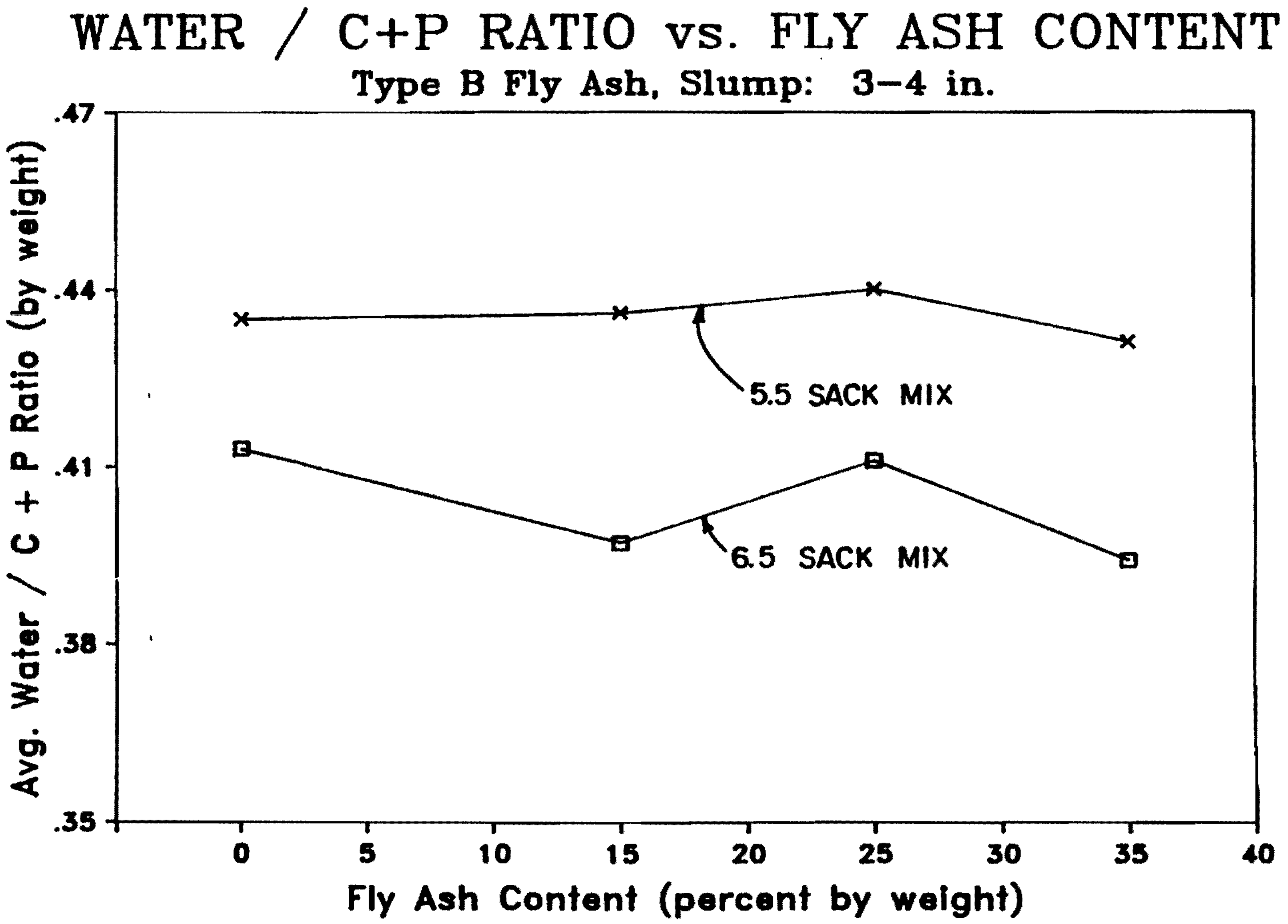


Fig. 8.2 Average water/C+P ratios for concrete containing Type B fly ash

true for mixes containing Type B fly ash. From this, it can be seen that fly ash affects the properties of concrete differently depending on the proportions of the concrete mixture, having a more pronounced effect in richer mixtures.

5. By comparing Figs. 8.1 and 8.2, one may conclude that the influence of the type of fly ash on the water/cement plus fly ash ratio depends on the cement plus fly ash content in the mix.

8.2 Flexural Strength

The fly ash concrete showed lower flexural strength at 7 and 28 days when compared to the corresponding control concrete containing no fly ash, as shown in Figs. 8.3 through 8.6. The decrease in flexural strength was generally greater at 7 days than it was at 28 days, indicating that some pozzolanic reaction had occurred during prolonged curing period.

For all mixes analyzed, the reduction in flexural strength was greater for higher fly ash contents. The type of fly ash used seems to be particularly important at early ages. The flexural strength of concrete with Type B fly ash decreased more rapidly than those made with Type A fly ash, mainly due to the effect on the air content of the concrete. The average 7-day flexural strengths obtained for 5.5 sks mixes containing Type B fly ash were all below 650 psi, which was the minimum required by Texas SDHPT Specification Item 360 [10]. The 5.5 sks mixes containing Type A fly ash all had average flexural strengths above the 650 psi limit. At 28 days the values of flexural strength, obtained for concrete containing Type B fly ash were similar to those obtained for concrete made with Type A fly ash, and above 700 psi.

The greater reduction in the 7-day flexural strength of concrete containing Type B fly ash as compared to Type A fly ash may be due to the following considerations:

1. The water/cement plus fly ash ratio of the mixes containing Type B fly ash was higher, as shown in Figs. 8.1 and 8.2, and therefore the strength was lower;

2. The difference in the specific gravities of the fly ashes yields a larger volume of paste in the concrete containing Type A fly ash, which may lead to better strength development characteristics.

3. The air content of concrete containing Type A fly ash is lower for equal AEA dosages as compared to concrete containing Type B fly ash. This is especially true for high percentages of replacement. The reduced air content would increase the strength of the concrete.

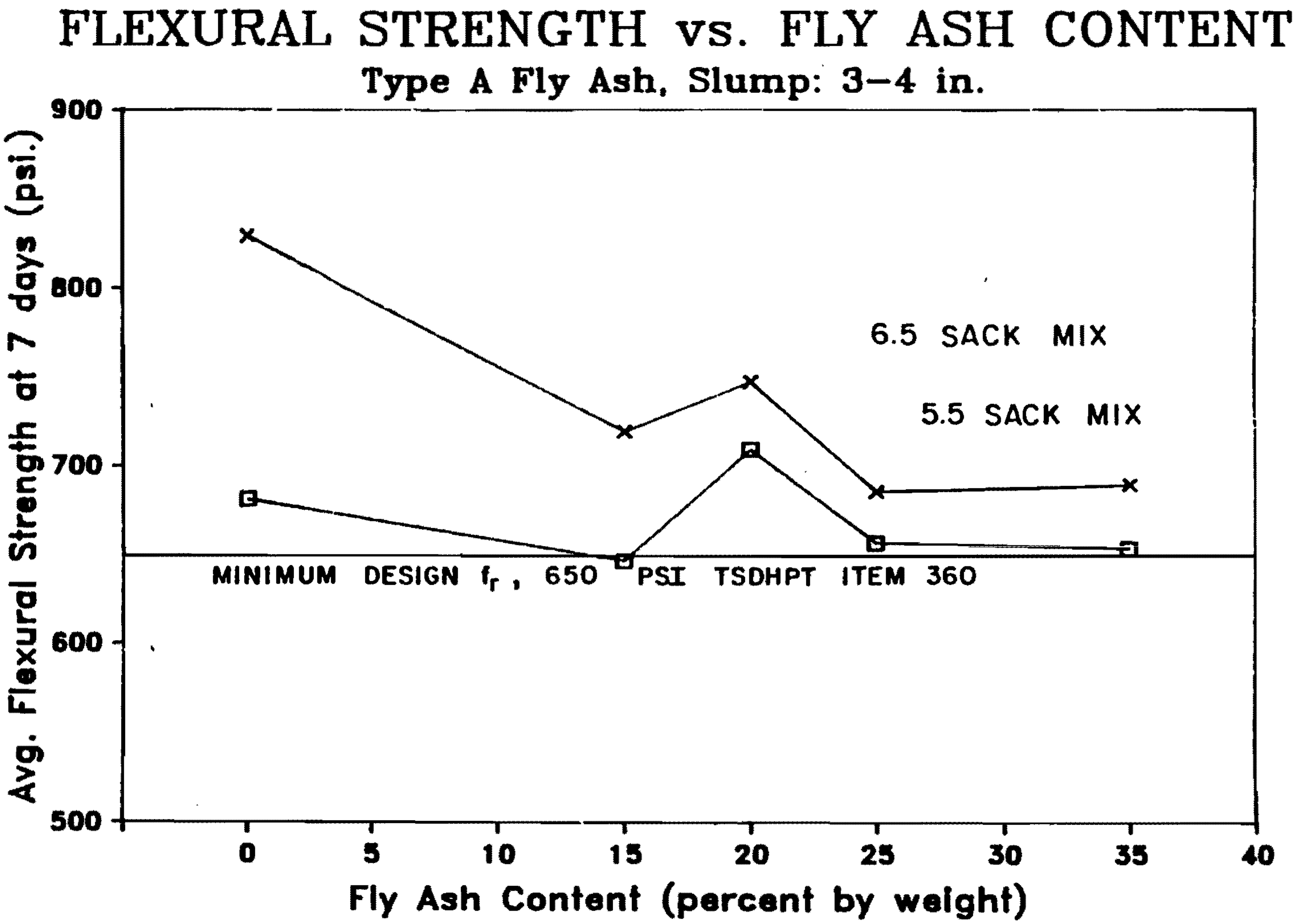


Fig. 8.3 Average flexural strength values for concrete containing Type A fly ash

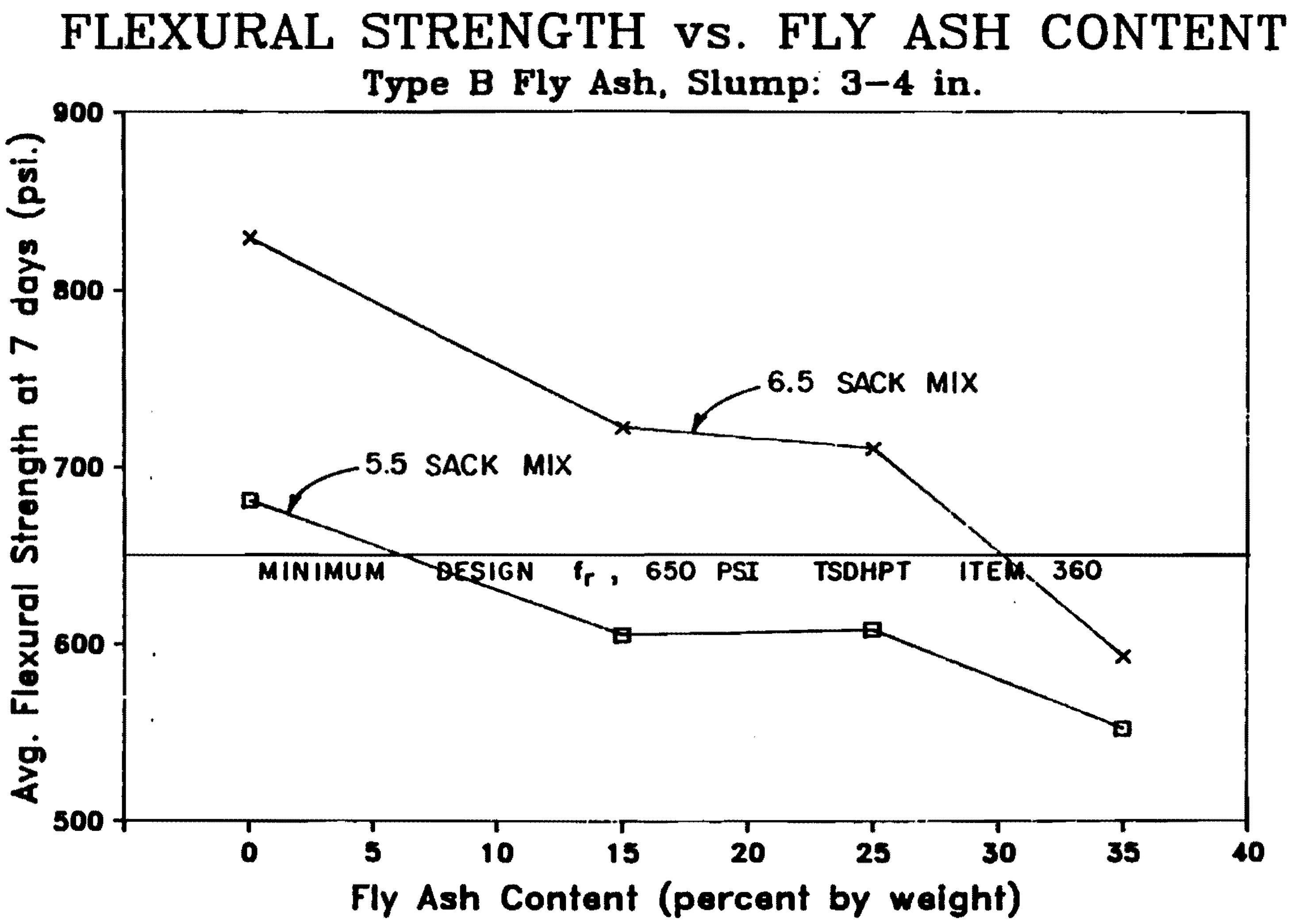


Fig. 8.4 Average flexural strength values for concrete containing Type B fly ash

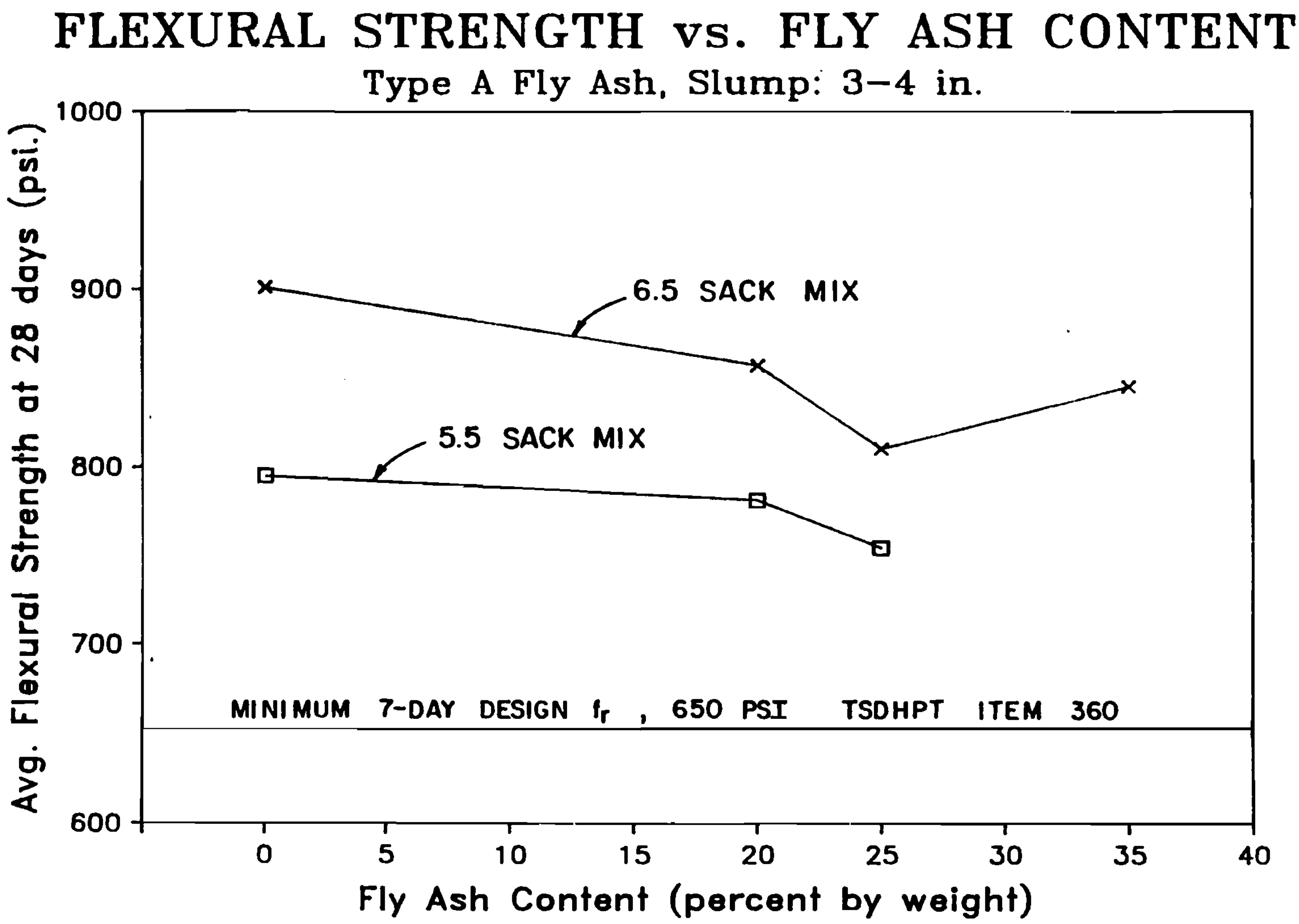


Fig. 8.5 Average flexural strength at 28 days of concrete containing Type A fly ash

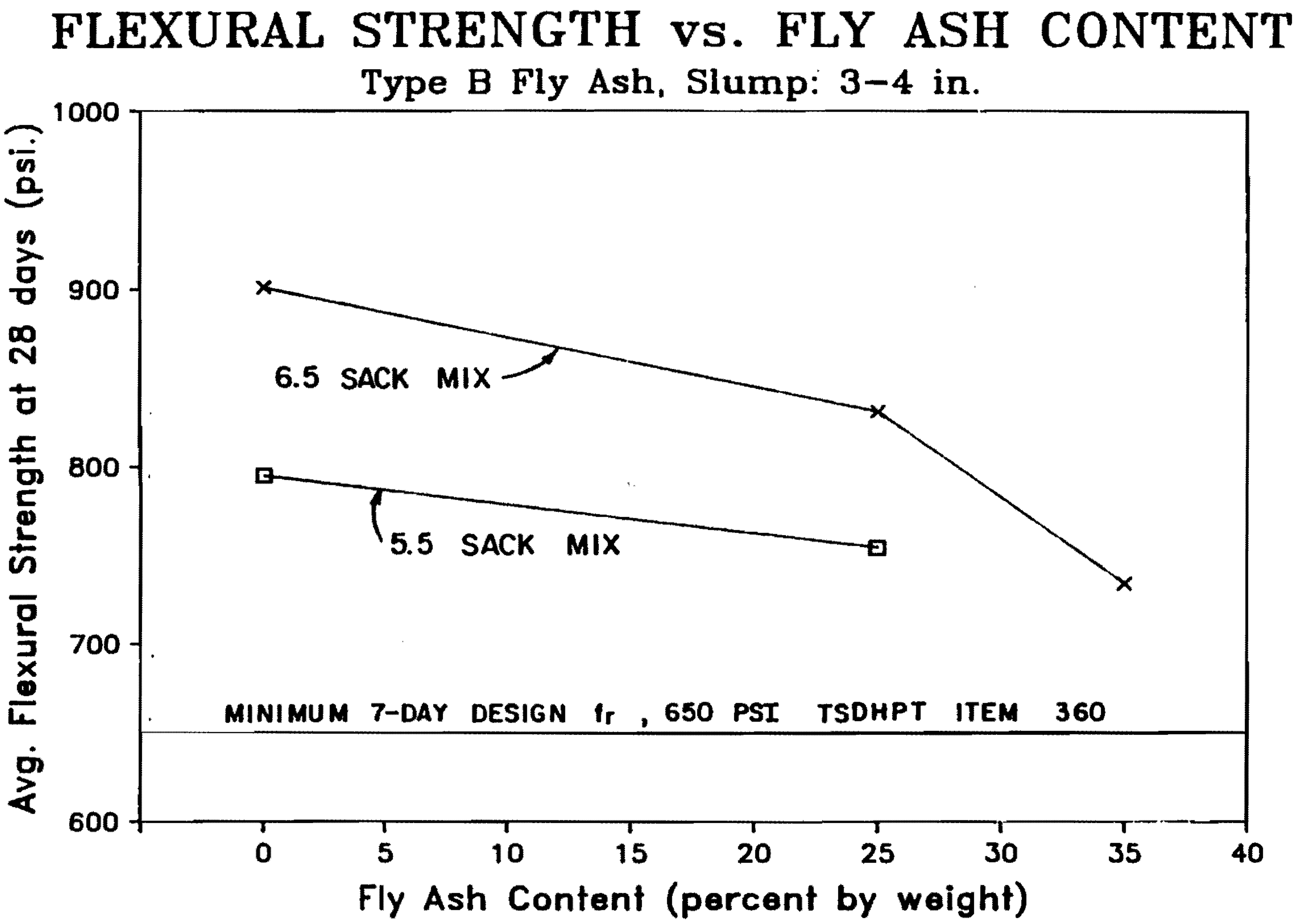


Fig. 8.6 Average flexural strength at 28 days of concrete containing Type B fly ash

The use of a blended Type IP cement, containing 20% Type A fly ash was beneficial in early strength development. No significant differences in strength between concrete made with Type IP cement or concrete having fly ash added at the time of mixing were observed after 28 days of curing as shown in Fig. 8.5.

On the average, the increase in flexural strength between 7 to 28 days is on the order of 13% for concrete without fly ash and about 18% for concrete containing 25% fly ash, either Type A or B.

8.3 Compressive Strength

Figures 8.7 and 8.8 show that the 7-day compressive strength of all fly ash concretes decreases as the fly ash content increases. Concrete containing Type A fly ash shows a less severe decrease in early compressive strength than Type B fly ash mixes, as shown in Fig. 8.7.

The average values of 28-day compressive strength, shown in Figs. 8.9 and 8.10, increased with increased fly ash content. The increase was much greater for concrete containing Type A fly ash than for Type B. The results for Type A fly ash show little strength increase for 15% replacement but realize higher compressive strengths at 25 and 35% replacement than those of concrete without fly ash. Concrete containing Type B fly ash produced compressive strengths nearly equal to those of plain concrete without fly ash after 28 days. rising strength were observed.

Similar trends can be observed in Figs. 8.11 and 8.12 where the results of 56-day compressive strength are presented. Again, an increase in compressive strength for Type A fly ash concrete and nearly equal strengths for Type B fly ash concrete, when compared to concrete without fly ash.

The tendency for large increases in compressive strength for Type A fly ash concrete is well pronounced in Fig. 8.13 where the average values of 90-day strengths are shown. The results for Type B fly ash concrete, presented in Fig. 8.14, are less clear. In rich concrete mixes the high percentage of Type B fly ash replacement had negligible effect on the 90-day compressive strength, whereas lower fly ash contents showed substantial strength increases.

The results for the Type B fly ash indicate that there is an optimum replacement content, which will yield the greatest long term strength benefit for a given mix design.

At every age the strengths for concrete made with Type IP cement showed significantly higher values than plain Type I cement. This indicates that fly ash incorporated in the cement undergoes a quicker and more complete pozzolanic reaction.

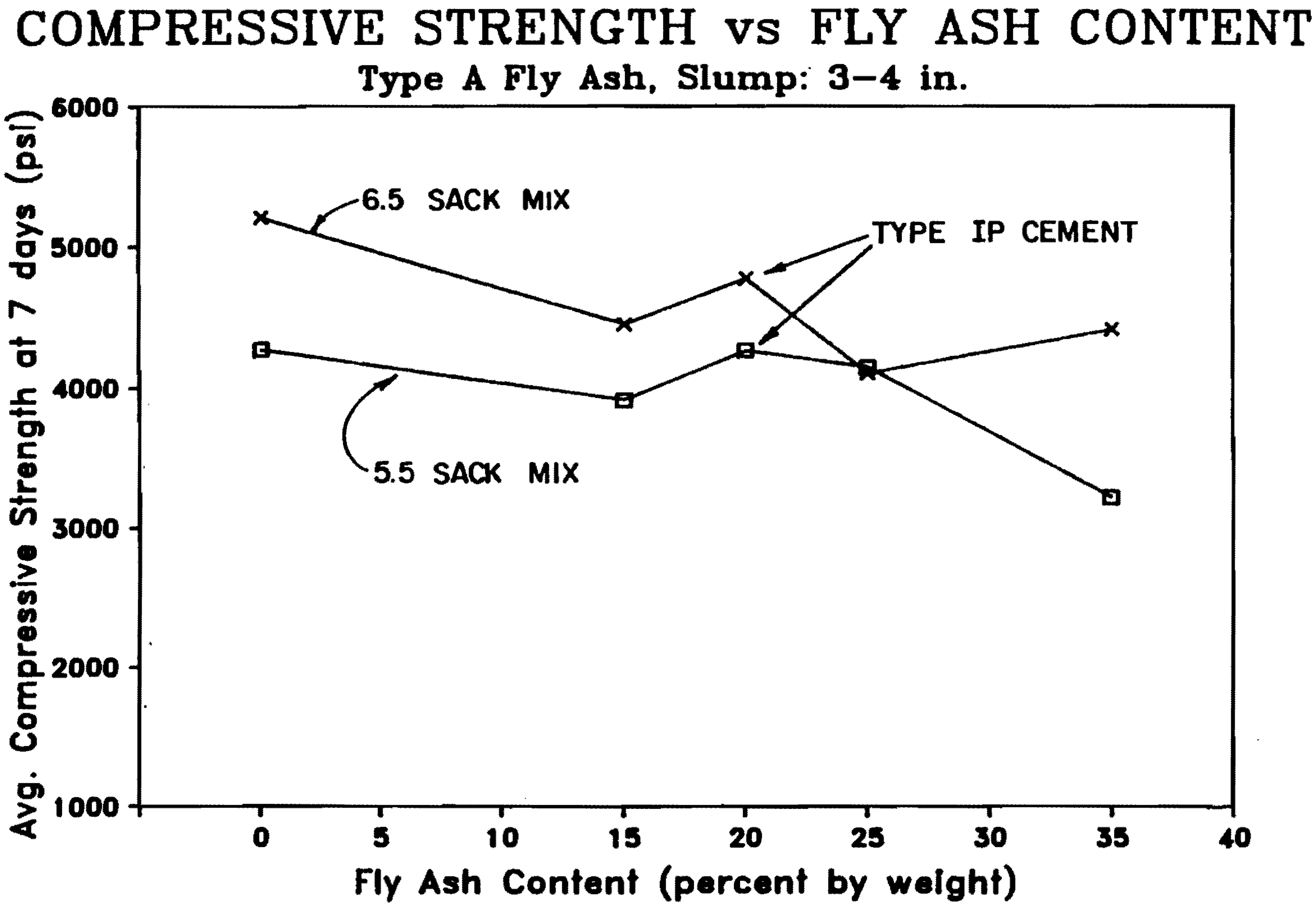


Fig. 8.7 Average compressive strength at 7 days of concrete containing Type A fly ash

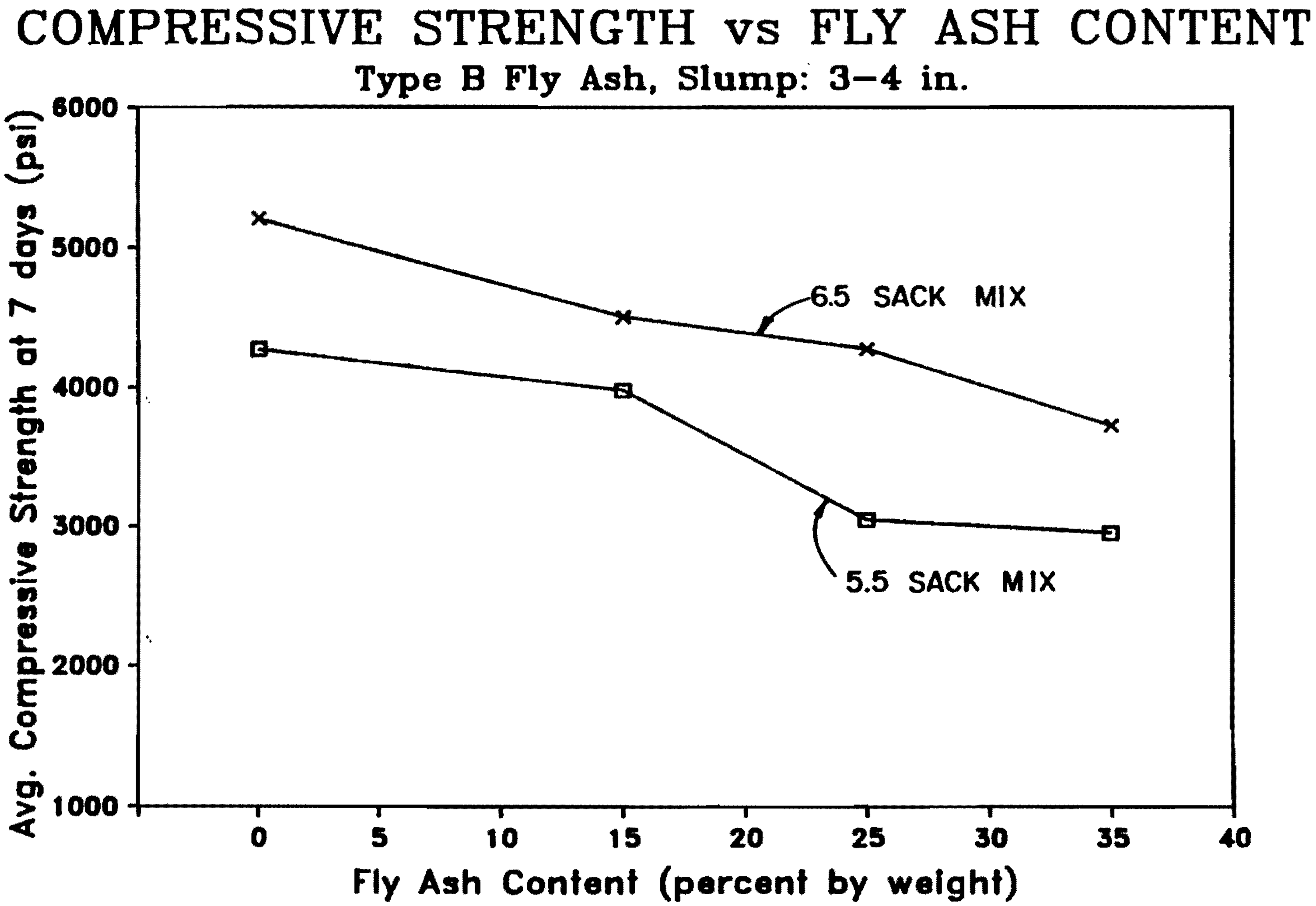


Fig. 8.8 Average compressive strength at 7 days of concrete containing Type B fly ash

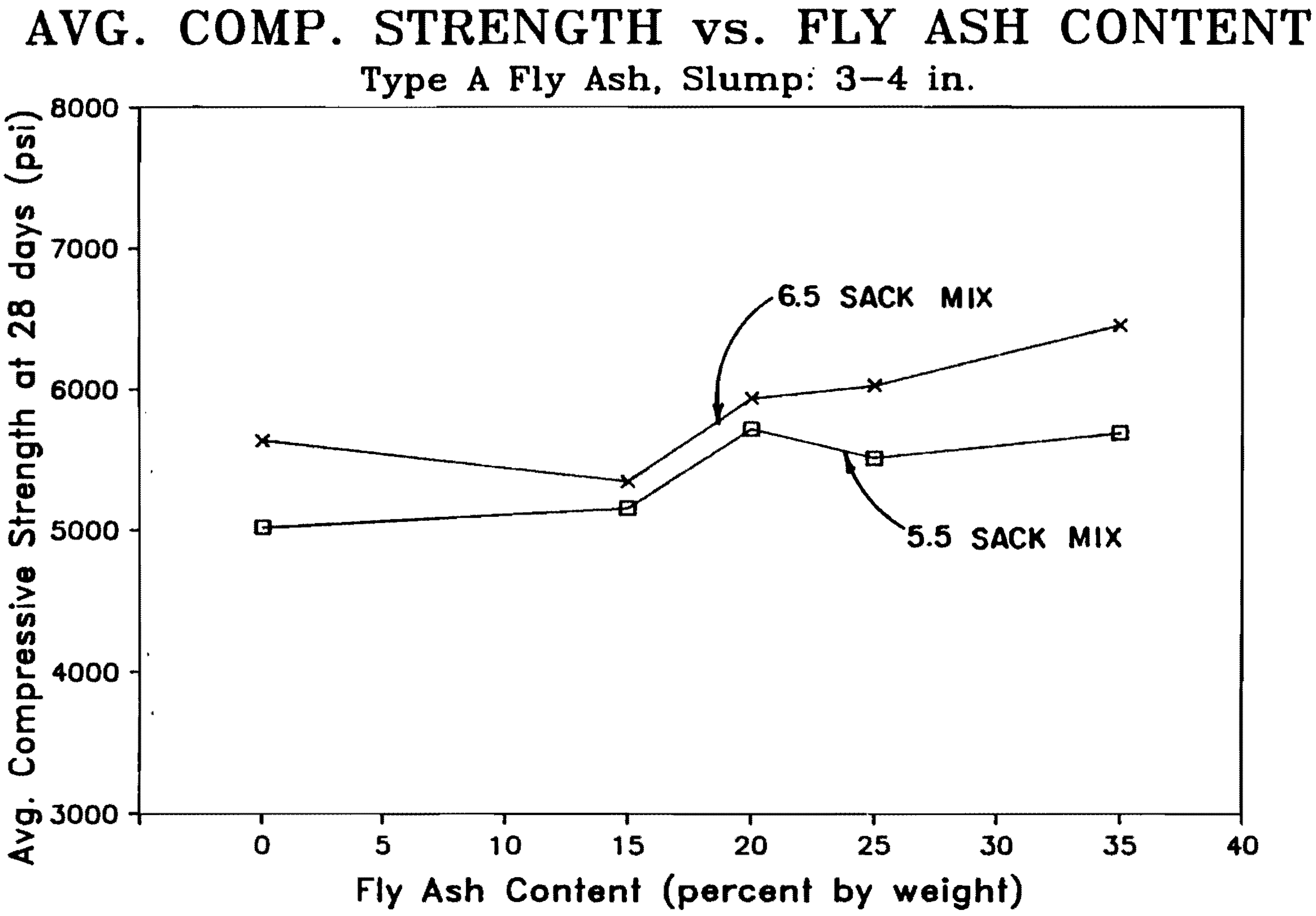


Fig. 8.9 Average compressive strength of concrete containing Type A fly ash

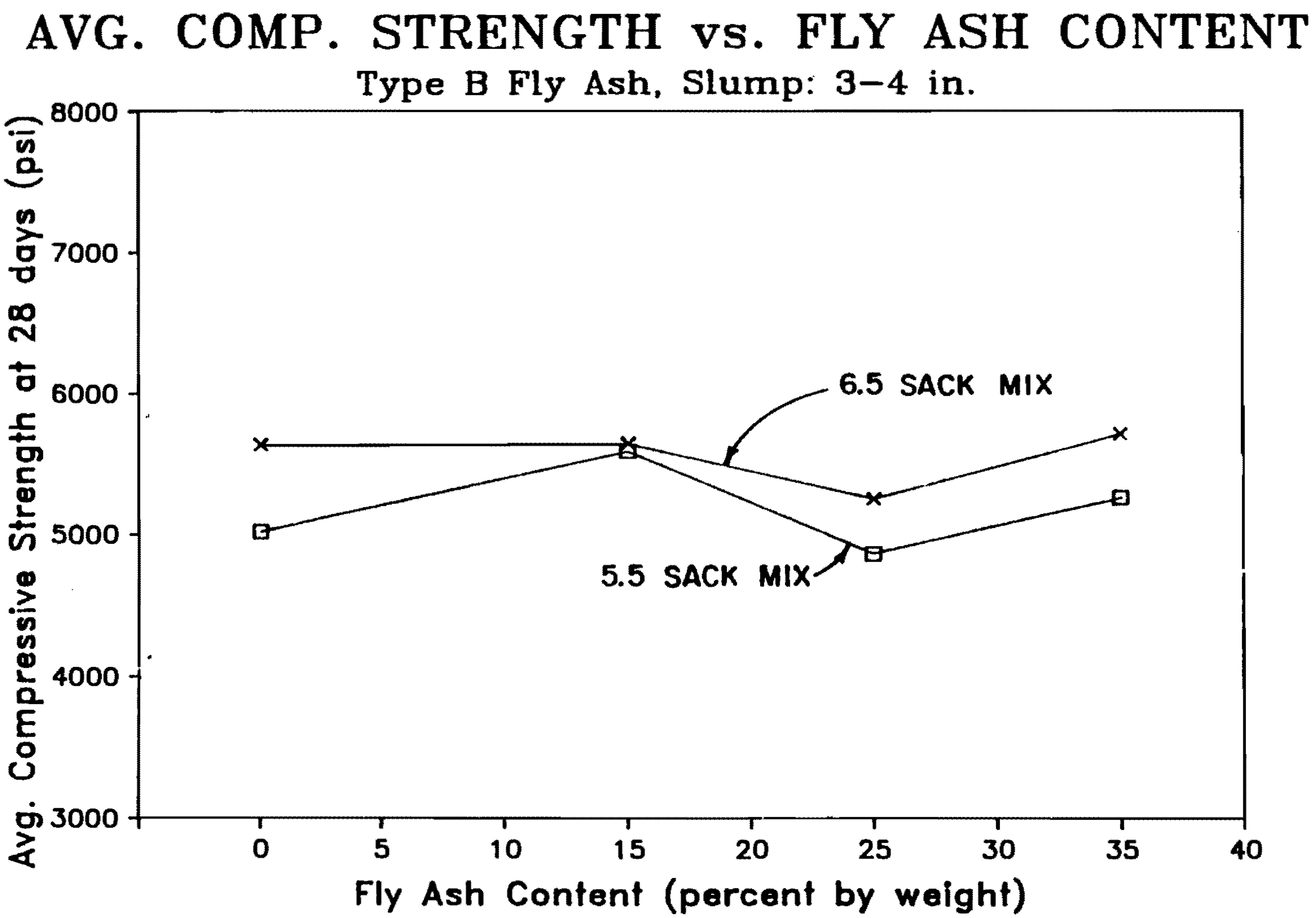


Fig. 8.10 Average compressive strength of concrete containing Type B fly ash

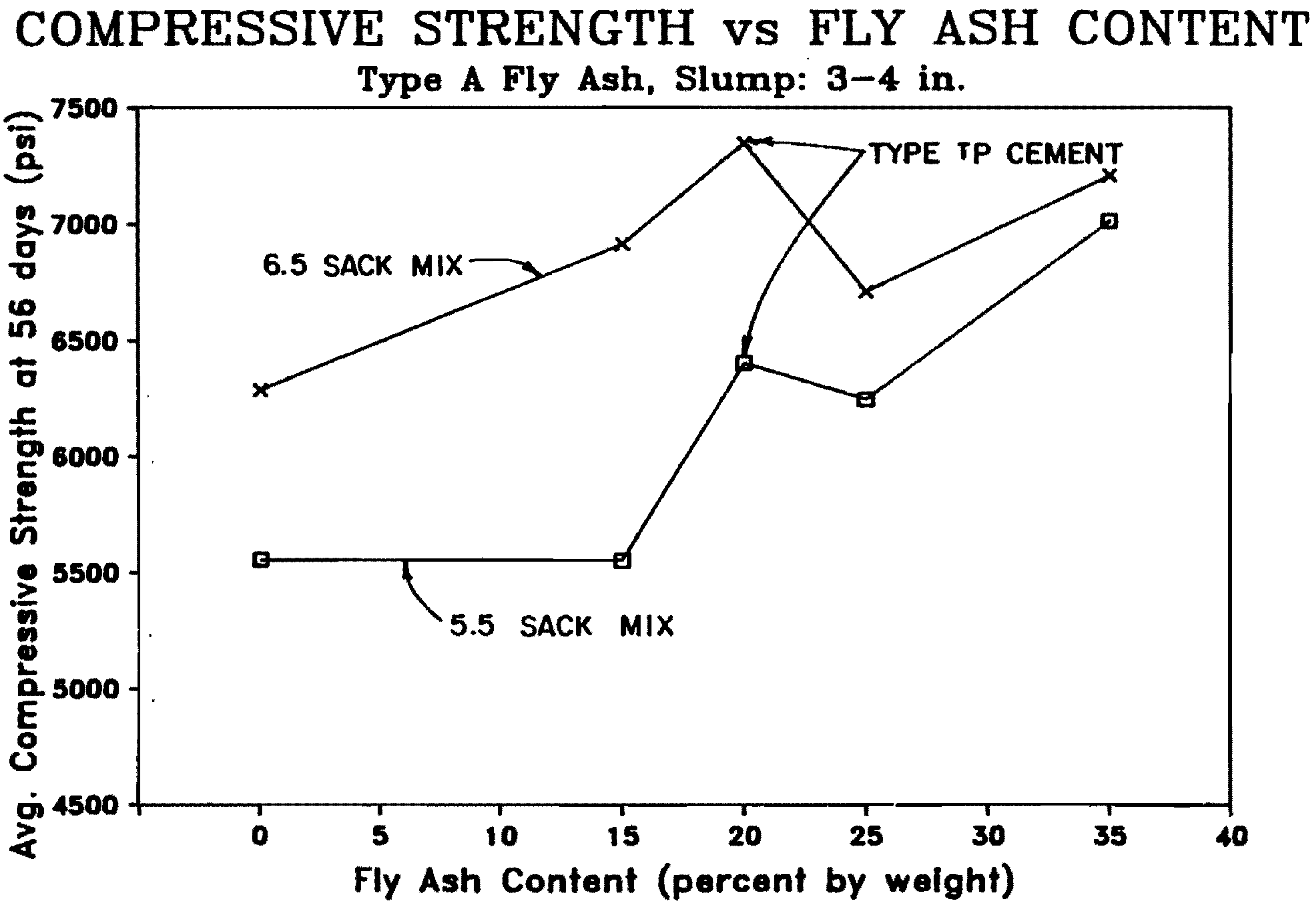


Fig. 8.11 Average compressive strength at 56 days of concrete containing Type A fly ash

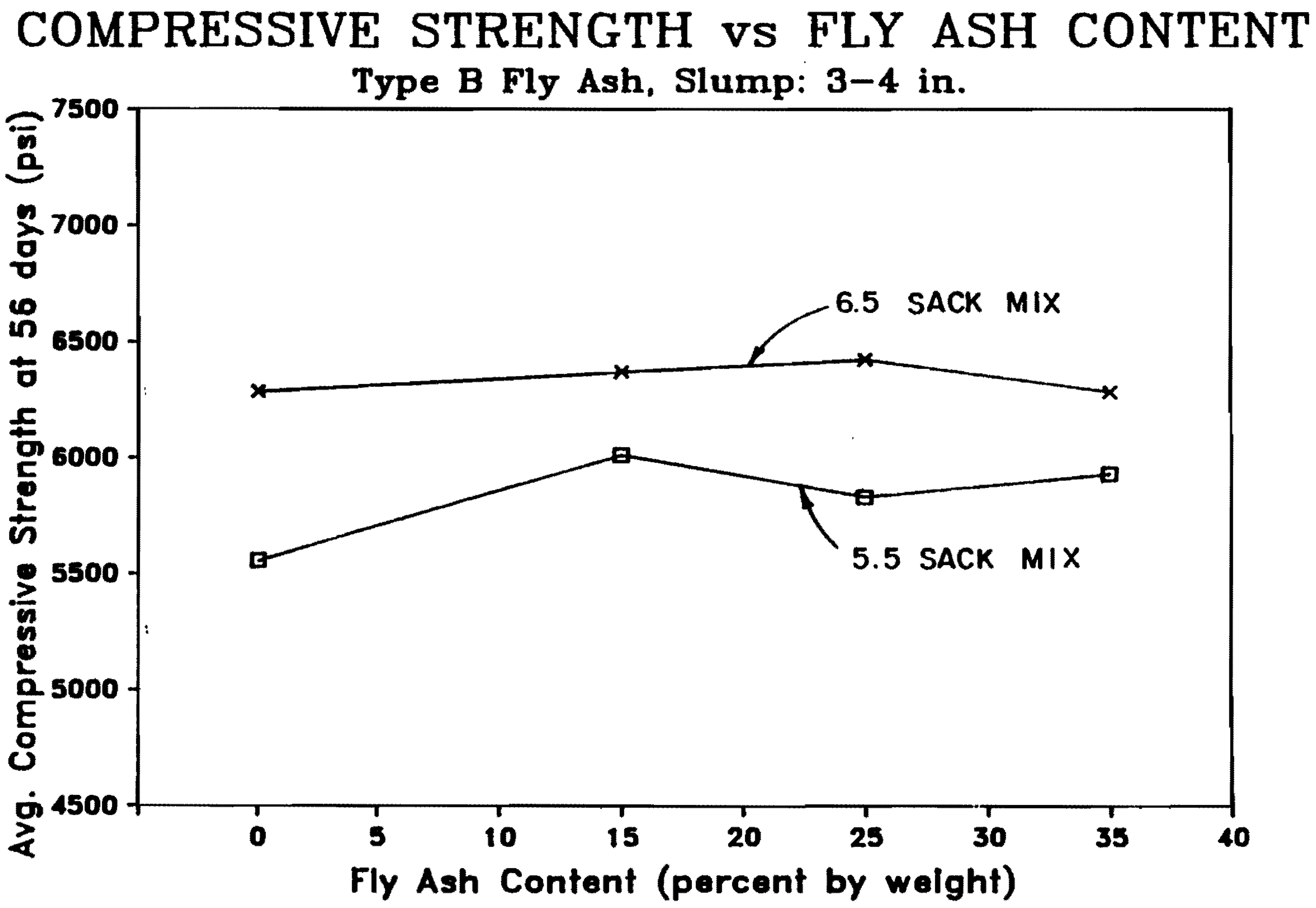


Fig. 8.12 Average compressive strength at 56 days of concrete containing Type B fly ash

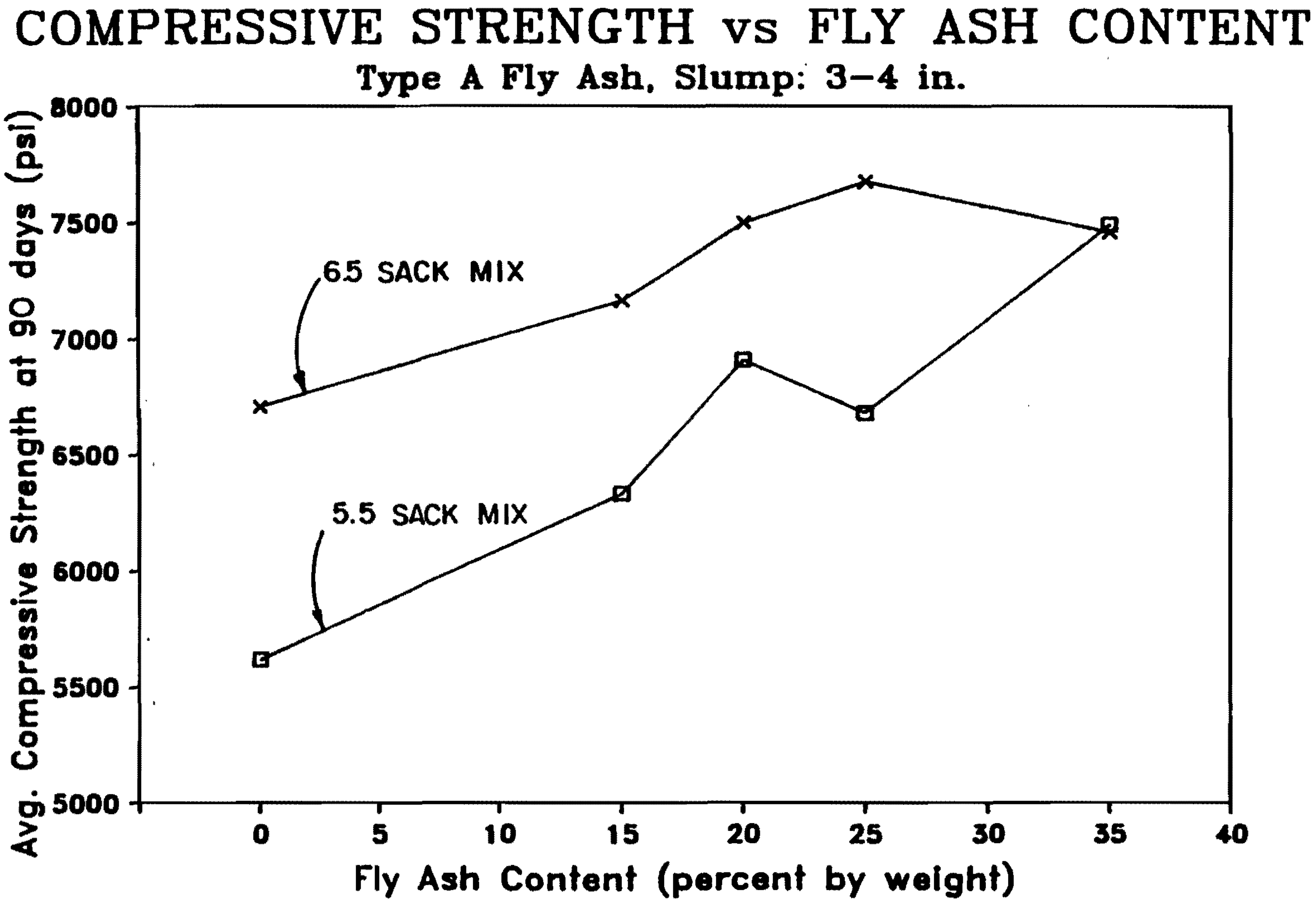


Fig. 8.13 Average compressive strength at 90 days of concrete containing Type A fly ash

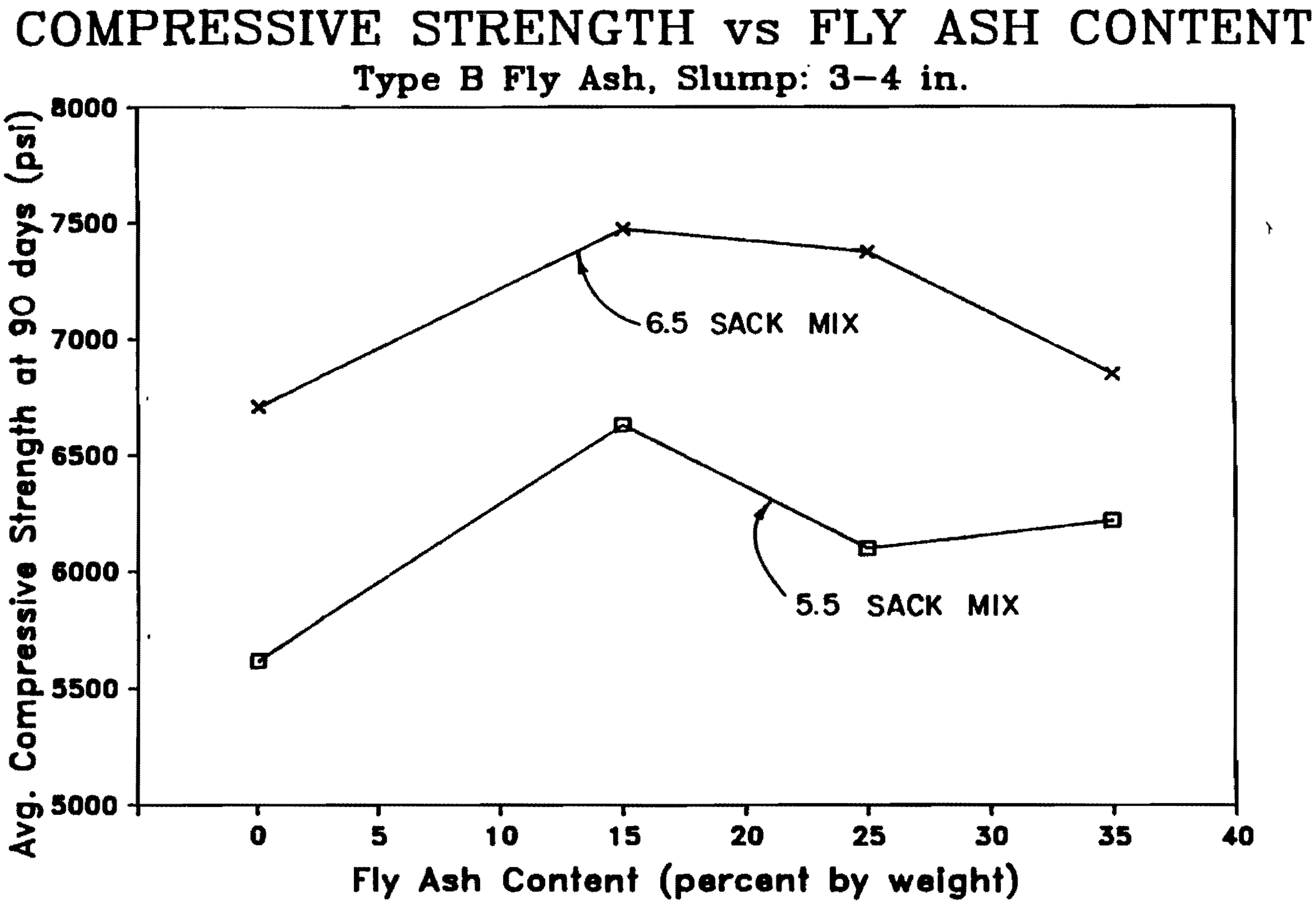


Fig. 8.14 Average compressive strength at 90 days of concrete containing Type B fly ash

As shown in Figs. 8.15 through 8.18, there is a continuous and significant strength development beyond 28 days in concrete containing fly ash. The rate of strength gain between 7 and 28-days is relatively steep, reflecting the fact that early strength of fly ash concrete was lower than the strength of equivalent portland cement concrete. At 28 days, all but a few values of the fly ash concrete strengths are higher than the plain concrete strength. There is no exception at 90 days where all strength values of fly ash concrete, regardless of type or amount of fly ash used, are higher than those of the plain concrete control mix. In some cases the increase in strength is significant.

This increase in strength gain is better shown in Figs. 8.19 through 8.22 where the relative compressive strength values are presented for different ages and fly ash contents in relation to 28-day.

The relative decrease in strength at early age dues to the use of fly ash varies from about 0.55 to about 0.82 depending on the amount and type of fly ash used. The relative increase in strength is greater after a prolonged curing time. Again, the increase in strength depends on type and amount of fly ash used but it could be as high as 40% in some cases.

In summary, although it seems to be obvious that the rate of strength variations depends on the age of concrete as well as type and amount of fly ash used, one should remember that it is also strongly dependent on the consistency of the fresh concrete, the w/c+p ratio and the air content. The results indicate only the general trends, in order to be more conclusive, further research is needed with stringent control on consistency, water, and air contents.

8.4 Effect of Temperature and Mixing Time

The data presented in Chapter 7.4 demonstrates clearly that Type B fly ash may increase the slump loss of concrete made at 72°F. The total slump loss is not significantly influenced by the percentage of cement replacement. Slump loss is rapid during the first 30 min and relatively minor thereafter. The amount of mixing water needed for a given slump in the hot temperature mixes tended to increase for increased fly ash contents. This, in combination with its slower rate of strength gain, reduces the early strength of concrete containing Type B fly ash. The slower initial strength gain did not influence the 28-day compressive strength as long as the fly ash replacement was below 25%.

Mixes containing fly ash are more sensitive to the effects of prolonged mixing than are plain concrete mixes. The increased sensitivity may be due to the reduced initial w/c+p ratio which is shown in Table 7.1. Excessive mixing of fly ash concrete may cause severe workability, handling, and placing problems.

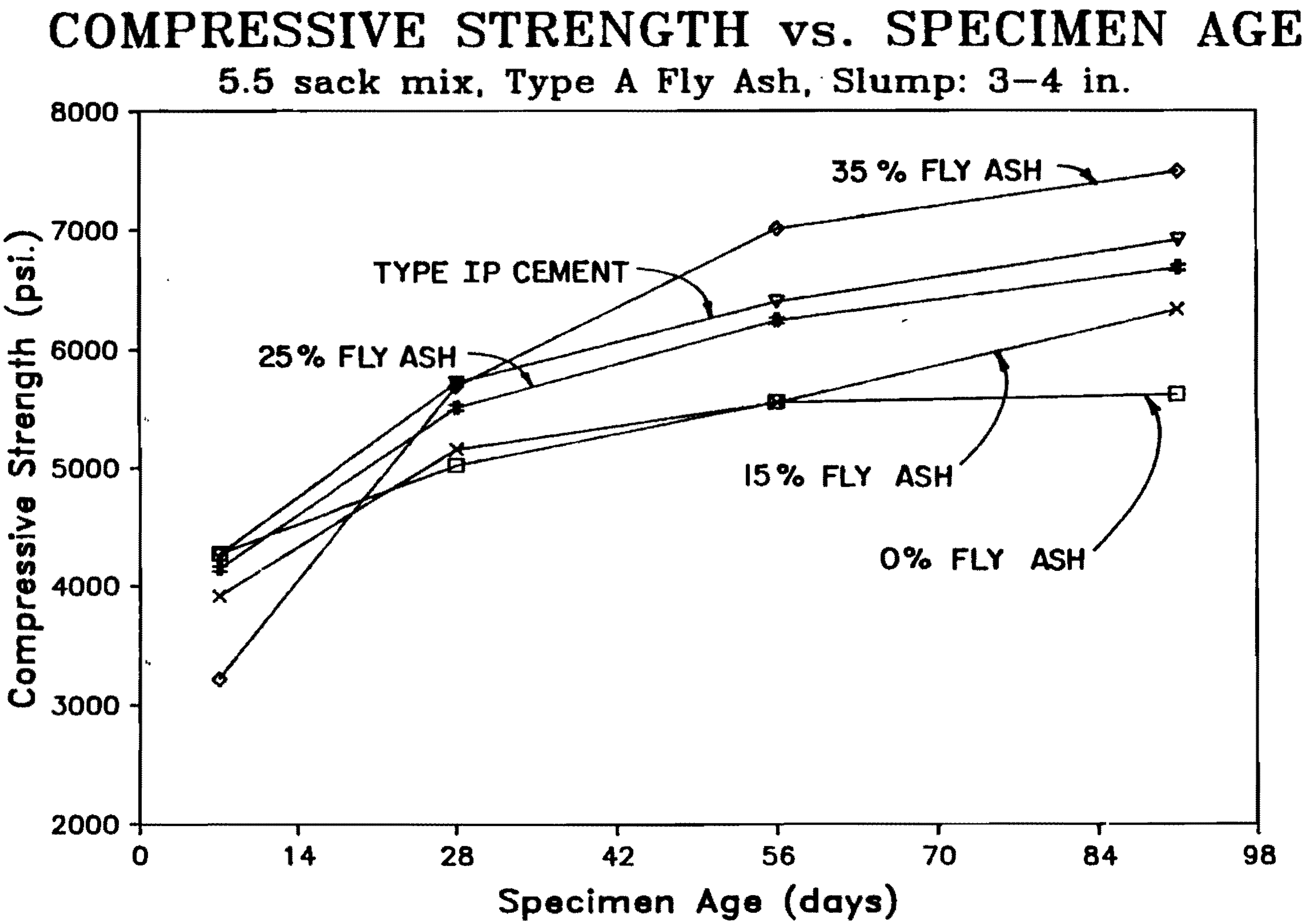


Fig. 8.15 Strength gain relationship for 5.5 sks concrete mixes containing Type A fly ash

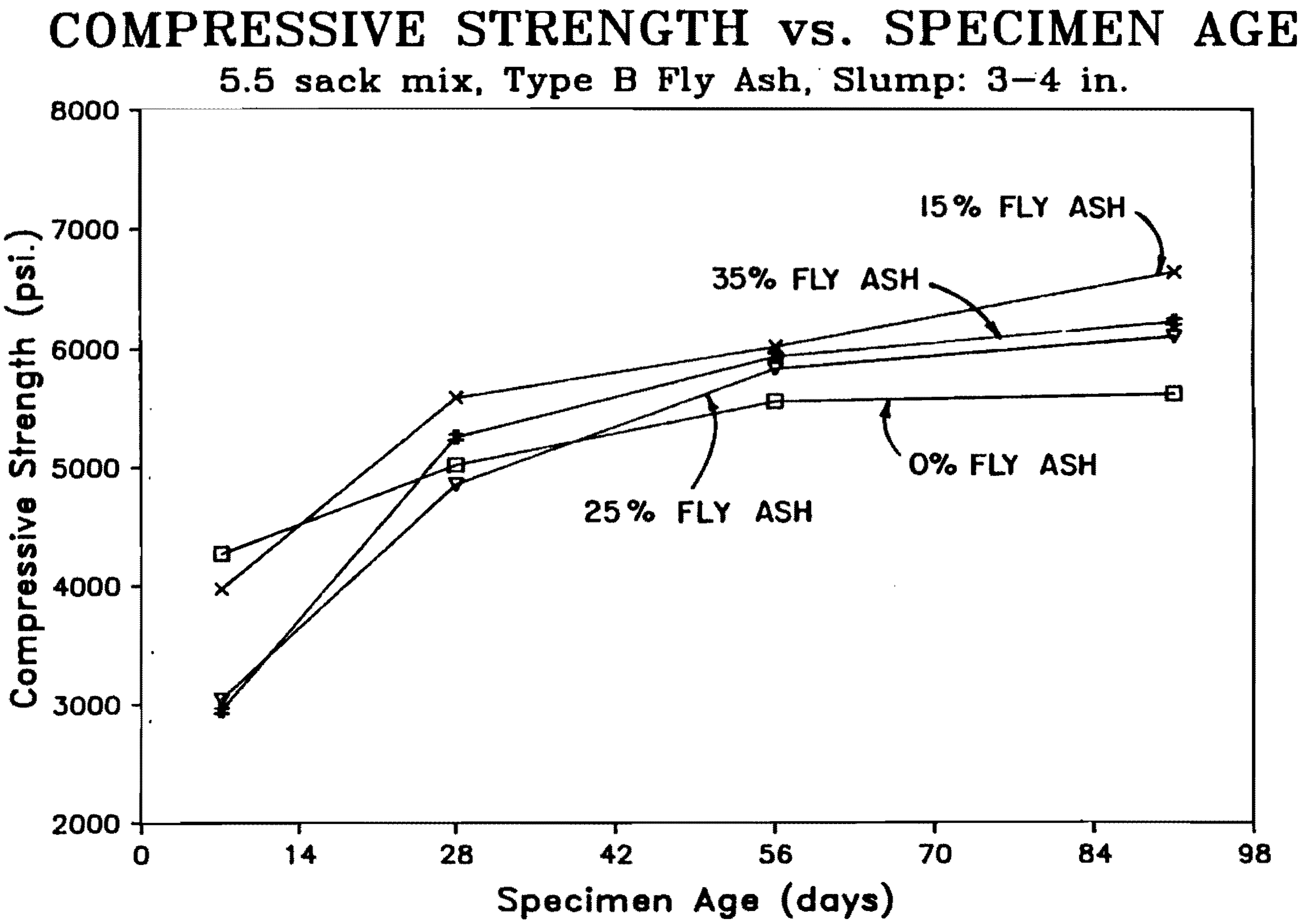


Fig. 8.16 Strength gain relationship for 5.5 sks concrete mixes containing Type B fly ash

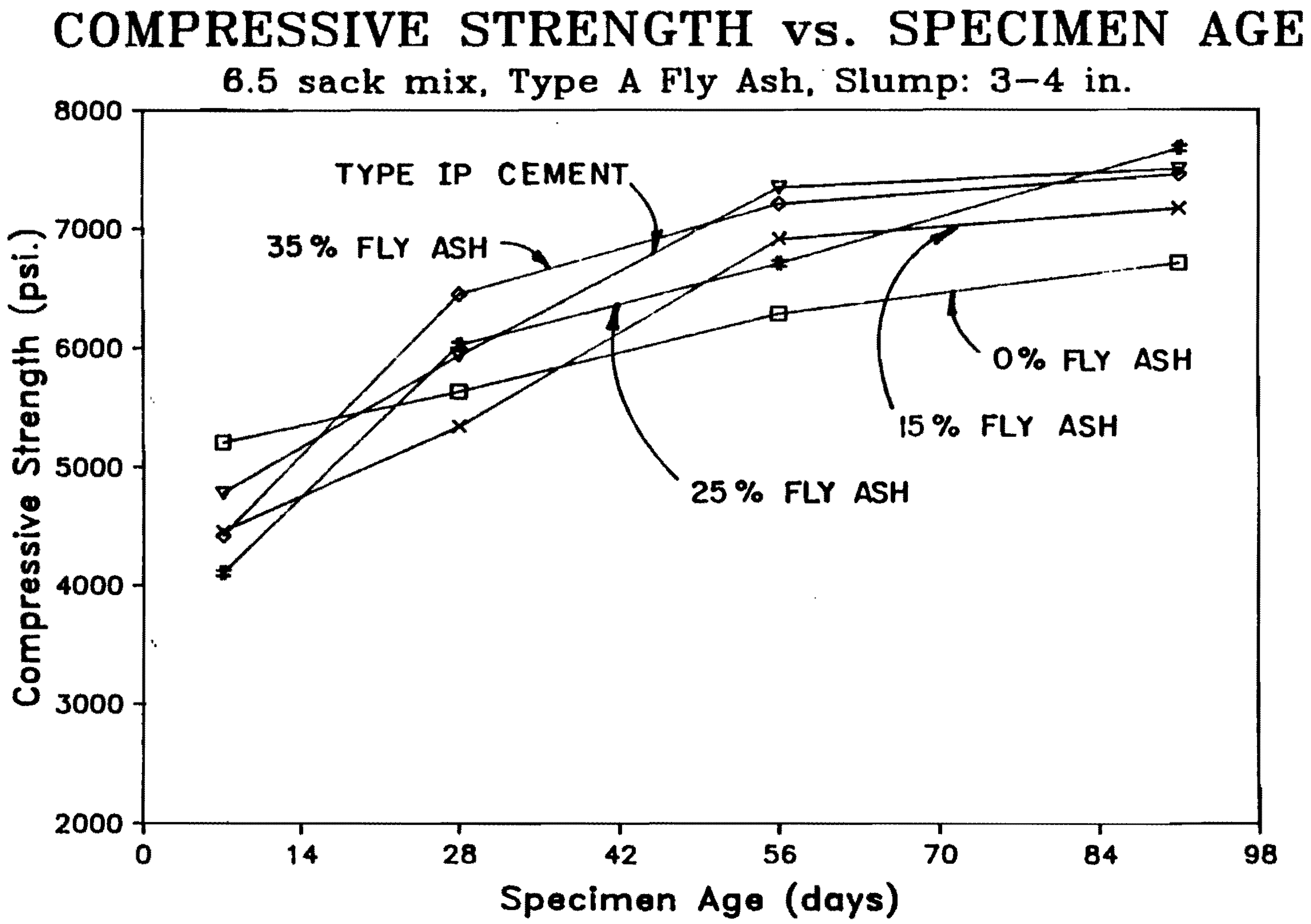


Fig. 8.17 Strength gain relationship for 6.5 sks concrete mixes containing Type A fly ash

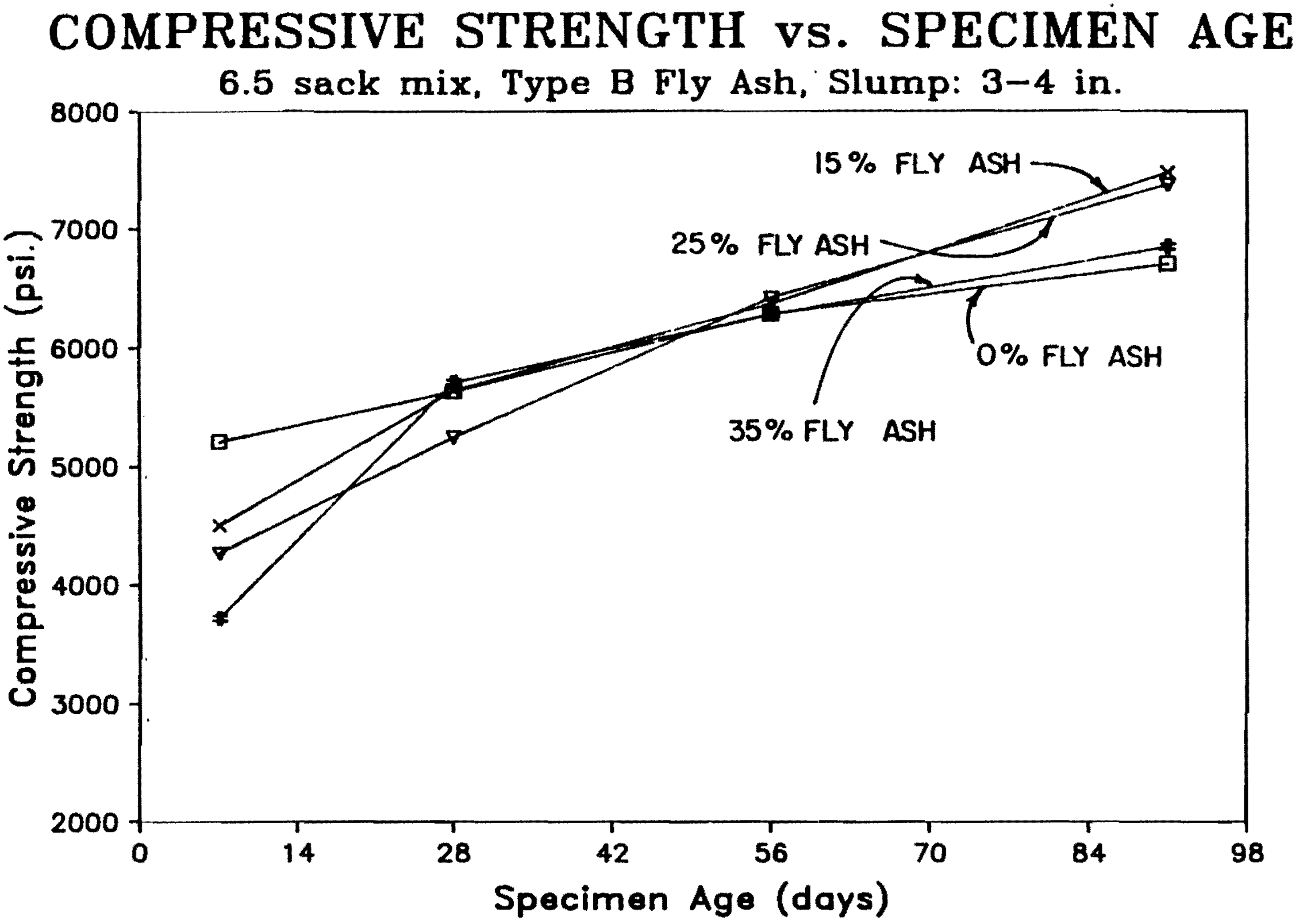


Fig. 8.18 Strength gain relationship for 6.5 sks concrete mixes containing Type B fly ash

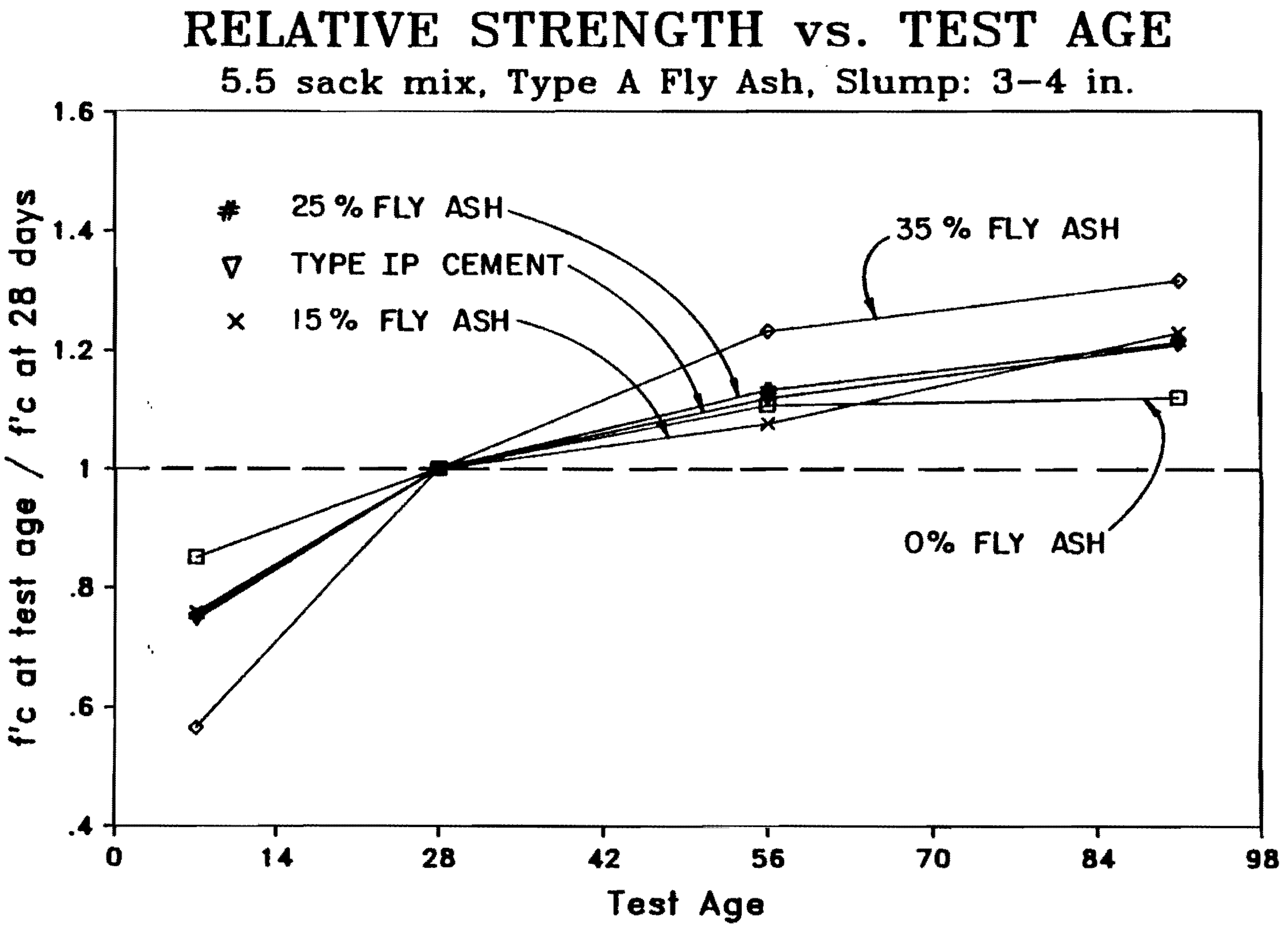


Fig. 8.19 Relative compressive strength in 5.5 sks concrete mixes containing Type A fly ash

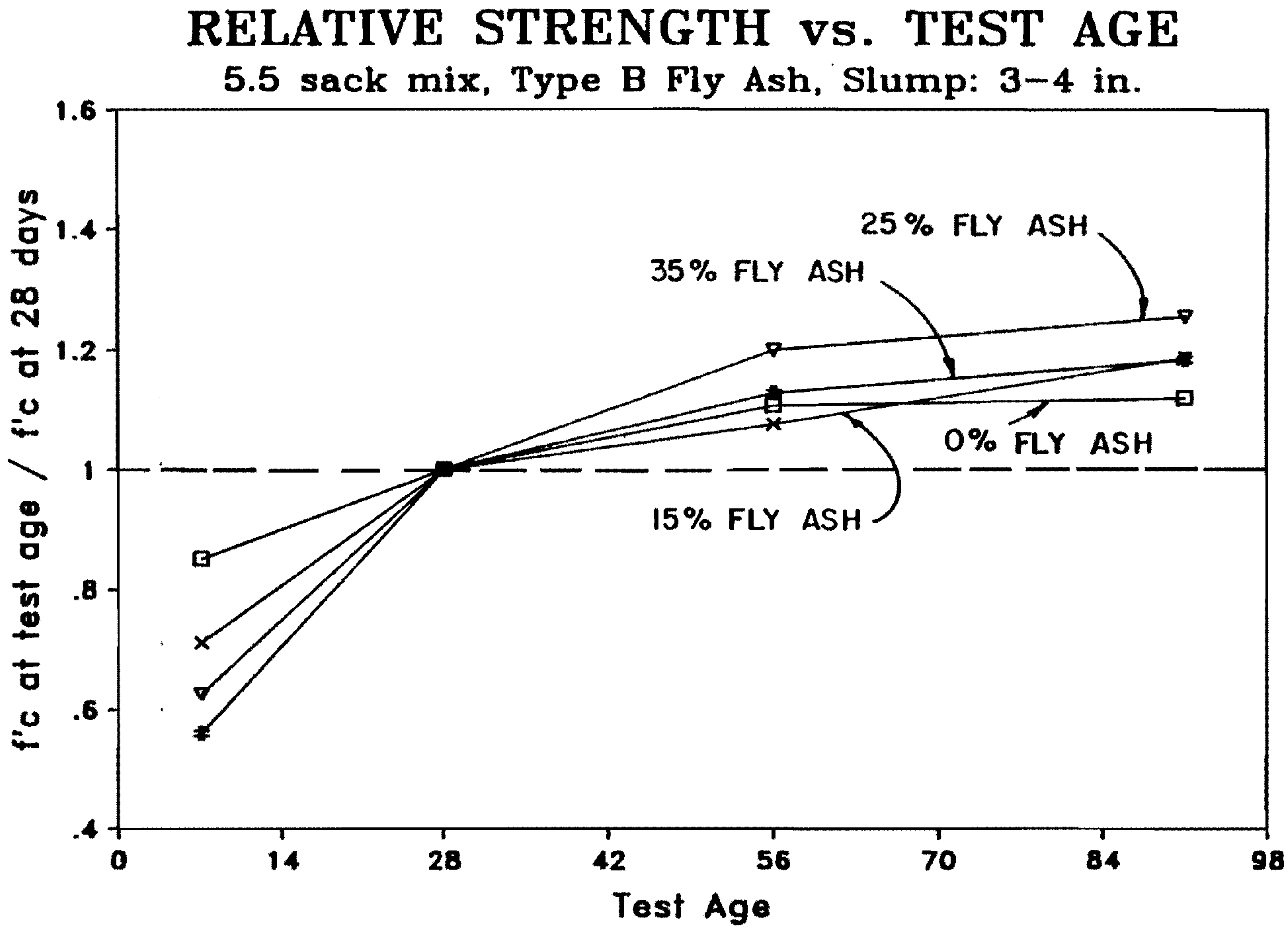


Fig. 8.20 Relative compressive strength in 5.5 sks concrete mixes containing Type B fly ash

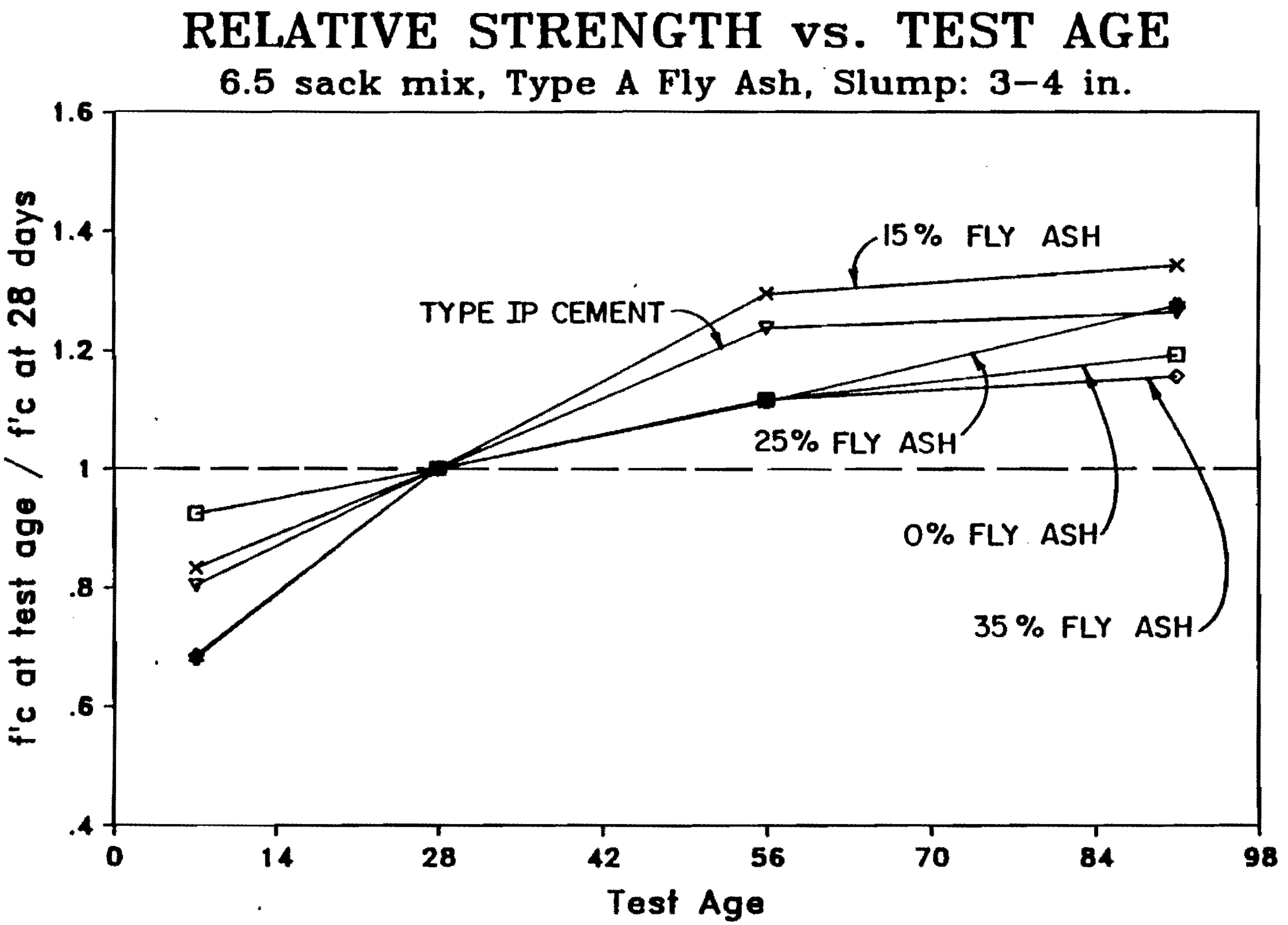


Fig. 8.21 Relative compressive strength in 6.5 sks concrete mixes containing Type A fly ash

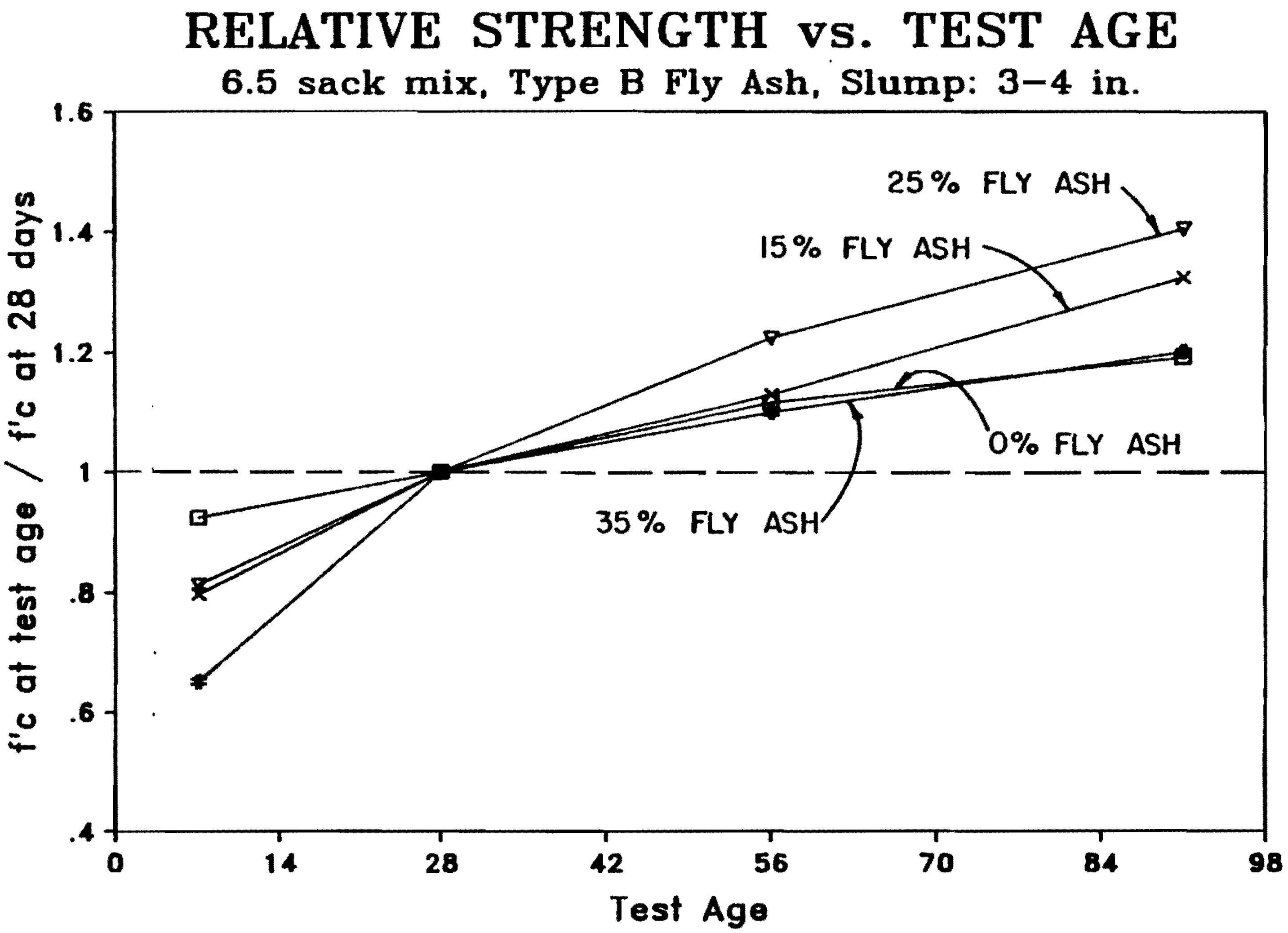


Fig. 8.22 Relative compressive strength of 6.5 sks concrete mixes containing Type B fly ash

For all cases when the extended mixing time is necessary, it is suggested that several trial mixes be made so that the required degree of workability can be determined.

8.5 Effect of Curing Compound

The curing compound used in this study had no effect on the flexural strength and a nominal effect on the compressive strength under hot dry conditions, as shown in Figs. 7.41 and 7.42. The use of the spray curing compound shows a detrimental effect to fly ash concretes cured at 75°F. Figure 7.42 shows that plain concrete cured at 72°F and 100% relative humidity had nearly the same compressive strength as plain concrete cured at 75°F, 55% relative humidity and with a curing compound; whereas fly ash mixes under the same curing conditions showed drastically lower strengths were the curing compound was used.

Fly ash realizes much greater strength gains when a moist condition is maintained in the concrete. The pozzolanic reaction of fly ash requires both calcium hydroxide, a product of cement hydration, and water to provide additional binding agents to the concrete. The spray curing compound does not provide an adequate moisture barrier in fly ash concrete.

8.6 Effect of Curing Conditions

The compressive and flexural strength test results for concrete subjected to different curing conditions are presented in Sec. 7.6. Figures 7.43 through 7.50 show the effects of curing concrete containing fly ash at cold, but not freezing, temperatures. In general, the flexural and compressive strength developments in fly ash concretes is similar to that of concretes without fly ash. Type IP cement performed well under these cold conditions, especially in the 5.5 sks mix. Concrete containing Type IP at 5.5 sks/cu.yd. had both higher flexural and compressive strengths than either 0 or 25% Type A fly ash replacement mixes. Compressive strengths in cold cured mixes with a CF of 6.5 was greater in nearly all fly ash mixes than in concrete without fly ash. In general, cold curing did not substantially affect the strength of concrete containing fly ash in this study.

The effects of hot curing conditions are presetned in Figs. 7.51 through 7.58. Specimens were moist cured for different times to distinguish the optimal moist curing time of concrete containing fly ash from that of portland cement concrete mixes under high temperatures and low humidity. Again, the flexural strength developments of all the mixes were similar, and Type IP cement produced higher strengths regardless of the moist curing time when compared to concrete without fly ash.

From Figs. 7.55 and 7.56 it is seen that for mixes with a CF of 5.5, a 3-day moist curing period followed by 25 days of hot dry conditions produced the highest compressive strengths. The results were the same for fly ash concretes and concrete without fly ash. In mixes with a CF of 6.5 the optimum compressive strength varied between 3 and 7 days for different fly ash contents and types. Mixes containing 35% Type A fly ash reached the highest strengths when moist cured 3 days and stored at hot dry conditions for 25 days. However, concrete containing 0, 25 and 35% Type B fly ash or 20 and 25% Type A fly ash reached optimal strength after 7 days of moist curing and 21 days of hot dry conditions. The strength gain of these fly ash mixes were typically much greater between 3 and 7 days when compared to plain concrete without fly ash.

In summary, optimal moist curing time depends on the cement plus fly ash content, as well as, the percent replacement of cement with fly ash and environmental conditions after moist curing is discontinued. However, fly ash mixes benefit more than mixes without fly ash from slightly extended moist curing times.

8.7 Freezing and Thawing

From the results of freeze-thaw tests presented in Chapter 8, the following generalizations can be made:

1. The 6.5 sks concrete mixes with or without fly ash performed excellently in the test from the standpoint of reduction in dynamic modulus and physical appearance. The type and the amount of fly ash were not significant factors;

2. The freeze-thaw resistance of 5.5 sks mixes was influenced by the type and the amount of fly ash. Concrete containing higher contents of Type A fly ash experienced greater freeze-thaw damage than concrete containing Type B fly ash;

3. The amount of entrained air in the 6.5 sks concrete series was not as important in providing better freeze-thaw resistance of the concrete as in the 5.5 sks concrete series. The study demonstrated that use of a low calcium, higher LOI Type A, fly ash affects the amount of air entrainment of concrete; and

4. It may be concluded from the above findings, that the use of fly ash with a relatively rich concrete mix has a negligible effect on the freezing and thawing durability of that concrete. In lean mixes, however, the amount of air should be carefully controlled in order to assure that the durability of fly ash concrete is comparable with the durability of a concrete without fly ash.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The decision to use or not to use fly ash should be based on such factors as the quality of the material available, the effect of the fly ash on the properties of fresh and hardened concrete, and cost effectiveness. The test results presented in this report refer mainly to the second factor mentioned above - properties of concrete containing fly ash.

The detailed comments on the results of physical tests performed on fly ash concretes are presented in Chapter 8. Based on those results, more general conclusions are presented in this chapter, which should serve as guidelines for the selection of materials and trial mix design procedure for proportioning concrete containing fly ash.

While using these guidelines the resident engineer should remember that the test results are based upon and reflect a given set of cements and fly ashes. The authors cannot overemphasize the necessity of testing the particular materials being considered and not assuming that the results will be similar to a "like" set of materials being used elsewhere. Brands of cement and sources of fly ash vary too much to assume specific behaviors. One can only say that the trends observed should be similar to those presented here.

The data presented demonstrates clearly that concrete mixes with different cement factors containing up to 35% by weight of fly ash can be designed to have adequate workability, strength, and durability for highway pavement applications. The following conclusions have been made regarding the selection of materials, strength and durability properties as well as mix design procedure:

1. During the mixing operations, it is recommended that a constant slump and constant air content be used as the criterion for establishing the water requirement, since fly ash is a workability agent. The use of fly ash as a partial cement replacement will usually reduce the water content of concrete at equal consistency. The reduction of water will depend on the mix proportioning as well as type and properties of fly ash;

2. Since the air content appears to be related to the type of fly ash used, in cases when air-entrained concrete is specified several trial mixes should be made so that the required dosage of air-entraining agent can be determined;

3. Although in general the setting time of fly ash concrete was comparable with the setting time of plain concrete, some retardation of setting due to the use of fly ash may occur depending on the proportions of concrete mix and chemical composition of the ash;

4. In these tests, the effect on the strength of both the type and amount of fly ash is quite distinct. Fly ash concrete showed lower flexural strength (especially at 7 days) when compared to the corresponding control concretes with no fly ash. The reduction in flexural strength tends to be greater for higher fly ash contents. The compressive strength of fly ash concrete was at 28, 56, and 90-day values exceeded that of the non-fly ash concretes;

5. Mixes containing fly ash have been found to be more influenced by prolonged mixing time than plain concrete mixes. For cases where the extended mixing time might be necessary it is suggested that several trial mixes be made under the expected job conditions; and

6. Fly ash concretes tend to be more sensitive to curing temperature, humidity, and air entrainment than plain concretes.

9.2 Mix Design Recommendations

Mix design procedures for conventional portland cement concrete 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. The extent of physical tests necessary for confidence 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 design of concretes containing fly ash, as well, because in general the fly ash mix design procedure has as its objective a particular concrete strength at a desired consistency.

The mix design may be in terms of weights or volumes, but must ultimately yield one cubic yard for the specified c+p content, coarse aggregate factor, air content, and water factor. The procedure proposed in Report 364-4 is primarily concerned with the problem of rationally proportioning the constituents in concrete containing fly ash to produce good quality concrete that meets all applicable specifications. The procedure also must provide a means of optimizing the fly ash content through a range of cement factors, so as to realize both the technical and economic advantages of concrete containing fly ash.

It is the recommendation of this report that trial batches of varying cement factors and fly ash contents, by weight or volume, be performed and tested to obtain an economically efficient mix design which meets all necessary specifications.

The recommended trial batching and mix proportioning procedure are presented in detail in Research Report 364-4.

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APPENDIX A

MATERIAL PROPERTIES

This section contains the physical and chemical properties of the cements, fly ashes and aggregates used in this study.

Table A.1 Chemical and Physical Properties of Type I Portland Cement

Chemical Composition	Percent
Silicon Dioxide (SiO)	22.0
Aluminum Dioxide (Al_2O_3)	4.1
Ferric Oxide (Fe_2O_3)	3.1
Calcium Oxide (CaO)	65.8
Magnesium Oxide (MgO)	.9
Sulfur Trioxide (SO_3)	2.7
Loss on Ignition	.9
Insoluble Residue	.5
Free Lime (CaO)	1.0
Tricalcium Silicate (C_3S)	59.0
Tricalcium Aluminate (C_3A)	6.0

Physical Properties	Gilmore		Vicat
Time of Setting:			
Initial	91 min		86 min
Final	172 min		167 min
Specific Surface:			
Blaine		3310 cm/gm	
Wagner		1880 cm/gm	
Compressive Strength:			
1-day		2020 psi	
3-day		3800 psi	
7-day		4760 psi	

Table A.2 Chemical and Physical Properties of Type IP Portland Cement

Chemical Composition			Percent
Silicon Dioxide (SiO)			28.9
Aluminum Dioxide (Al_2O_3)			7.9
Ferric Oxide (Fe_2O_3)			3.8
Calcium Oxide (CaO)			53.1
Magnesium Oxide (MgO)			.1
Sodium Oxide (NaO)			.2
Postassium Oxide (KO)			.4
Insoluble Residue			14.7
Free Lime (CaO)			.7
Physical Properties	Gilmore		Vicat
Time of Setting:			
Initial	165 min		106 min
Final	280 min		226 min
Specific Surface:			
Blaine		3026 cm/gm	
Wagner		1355 cm/gm	
Compressive Strength:			
1-day		1922 psi	
3-day		3513 psi	
7-day		4545 psi	
28-day		6093 psi	

Table A.3 Fly Ash Chemical Composition Requirements

	Experimental Program			Specifications Texas SDHPT	
	Big Brown	Monticello	Welch	Type A	Type B
Si+Al+Fe oxides minimum %	78.47	85.47	57.05	65	50
Ca oxide maximum %	10.22	9.22	38.09	*	*
Mg oxide maximum %	1.73	1.88	6.80	5.0	5.0
Sulfate maximum %	0.94	0.25	4.24	5.0	5.0
Available Alkalies as Na oxide maximum %	-	0.17	-	1.5	1.5
Loss on Ignition maximum %	0.43	0.24	0.26	3.0	3.0
Moisture maximum %	0.10	-	0.15	2.0	2.0
Fineness #325 maximum retained	12.80	35.70	12.80	30	30
Pozzolanic Activity	96.95	989 psi	106.05	75	75
Shrinkage maximum %	0.011	-	0.008	.03	.03

* 4% maximum variation from previous ten samples

Table A.4 Coarse Aggregate

Material: Partially crushed river gravel

Maximum size: 1.0 in.

Bulk specific gravity, SSD: 2.55 lb/cu.ft. (ASTM C127)
(Tex 403A)

Unit weight, SSD: 96.4 lb/cu.ft. (ASTM C29)
(Tex 404A)

% of solids: 60.5% (Tex 405A)

Absorption: 0.77% (ASTM C127)
(Tex 403A)

Seive Size	% Passing	ASTM C33 Size 57	Texas Item 421 Grade 4
1-1/2 in	100	100	Same as ASTM
1 in.	98.9	95-100	
1/2 in.	34.8	25-60	
#4	1.2	0-10	
#8	0.3	0-5	
Pan	0	-	

Table A.5 Fine Aggregate

Material: natural sand

Fineness modulus: 2.73

Bulk specific gravity, SSD: 2.61 lb/cu.ft. (ASTM C128)

Unit weight, SSD: 97.1 lb/cu.ft. (ASTM C29)

% of solids: 59.5%

Absorption: 0.4%

Seive Size	% Passing	ASTM C33	Texas Item 421 Grade 1
3/8 in.	100	100	100
#4	99.2	95-100	95-100
#8	93.3	80-100	80-100
#16	73.2	50-85	50-85
#30	46.6	25-60	25-65
#50	13.6	10-30	10-35
#100	1.1	2-10	0-10
#200	-	-	0-3
Pan	0	0	0

APPENDIX B

MIX DESIGN

This section contains the "original" mix proportions as supplied by the Texas State Department of Highways and Public Transportation as well as the "re-designed" mix proportions for mixes with a CF of 5.5 and 6.5 sks/cu.yd., respectively.

Table B.1 5.5-Sack Mix Proportions (per cubic yard)

Mix Description	Cement (lb)	Fly Ash (lb)	Sand (lb)	CA (lb)	Water (lb)	Pozzolith (oz) MBVR (oz)	Slump (in.)	Air Content (%)	Unit wt (lb/ft^3)
A No Fly Ash	498	-	1254	1924	218	33/2.75	3.0	6.5	144
B 15% Type B	423	75	1209	1884	218	33/2.75	3.0	6.5	140
C 25% Type B	382	127	1183	1973	224	33/2.75	3.7	4.5	144
D 35% Type B	330	177	1177	1965	218	33/2.75	3.0	4.6	143
E 35% Type A	331	178	1182	1973	224	33/275	4.0	3.5	144
F 25% Type A	383	127	1186	1980	211	33/275	3/5	3.5	144
G 15% Type A	426	75	1237	1909	228	33/275	3.0	4.0	142
H 20% Type A IP Cement	511	-	1186	1980	224	33/2.75	3.8	4.1	144.5

Table B.2 6.5-Sack Mix Proportions (per cubic yard)

Mix Description	Cement (lb)	Fly Ash (lb)	Sand (lb)	CA (lb)	Water (lb)	Pozzolith (oz) MBVR (oz)	Slump (in.)	Air Content (%)	Unit wt (lb/ft^3)
J No Fly Ash	596	-	1017	1960	246	33/3.25	4.0	6.0	141.0
K 15% Type B	526	93	1097	1968	246	33/3.25	3.3	5.0	145.0
L 25% Type B	447	150	1018	1962	245	33/3.25	3.5	6.0	142.0
M 35% Type B	400	215	1040	2022	239	33/3.25	3.5	4.7	145.0
N 15% Type A	512	90	999	1973	258	33/3.25	3.5	4.3	142.0
O 25% Type A	462	153	1031	2014	228	33/3.25	3.75	3.8	144.0
P 35% Type A	396	212	1075	2005	226	33/3.25	3.5	2.5	145.0
I 20% Type A IP Cement	602	-	1000	1975	265	33/3.25	3.0	4.0	142.0

APPENDIX C

FREEZE-THAW TEST DATA

This section contains the freeze-thaw test data for concrete mixes investigated in this study. The tests have been conducted by personnel from the Materials and Test Division of the Texas State Department of Highways and Public Transportation.

Results of Laboratory Freezing-Thawing Tests*
(5.5 sk mixes)

Mix Designation	AN	BN	CN	DN	EN	FN	GN	HN
Type of Fly Ash		B	B	B	A	A	A	A (Type IP Cement)
Percent Replacement by wt	0	15	25	35	35	25	15	20
No. of Cycles	Frequency (hz)							
0	1803	1886	1798	1813	1818	1849	1754	1809
30	1781	1857	1783	1789	1625	1756	1719	1738
60	1771	1848	1776	1784	1501	1635	1706	1704
90	1771	1849	1781	1760	1479	1481	1699	1708
120	1777	1843	1787	1725	1419	1403	1685	1688
150	1753	1837	1785	1684	1411	1240	1679	1686
180	1744	1823	1781	1644	1452	1321	1639	1697
210	1726	1806	1775	1617	1436	1388	1624	1690
240	1707	1783	1773	1572	1253	1439	1598	1769
270	1702	1757	1776	1543	1464	1433	1566	1675
300	1704	1739	1768	1465	1391	1362	1514	1656

* Each value is the average of at least two tests.

Results of Laboratory Freezing-Thawing Tests*
(6.5 sk mixes)

Mix Designation	IN	JN	KN	LN	MN	NN	ON	PN
Type of Fly Ash	A (Type IP Cement)		B	B	B	A	A	F
Percent Replacement by wt	20	0	15	25	35	15	25	35
No. of Cycles	Frequency (hz)							
0	1868	1928	1883	1883	1854	1896	1900	1944
30	1860	1904	1861	1876	1838	1894	1880	1930
60	1854	1892	1862	1876	1846	1893	1873	1931
90	1854	1892	1860	1876	1850	1895	1860	1930
120	1854	1887	1860	1873	1850	1888	1852	1932
150	1854	1889	1858	1877	1852	1891	1849	1932
180	1859	1874	1853	1874	1851	1887	1843	1934
210	1857	1869	1853	1871	1850	1881	1830	1933
240	1856	1868	1841	1868	1852	1881	1816	1933
270	1851	1859	1831	1870	1856	1870	1768	1929
300	1855	1847	1830	1868	1850	1868	1700	1929

* Each value is the average of at least two tests.

Results of Laboratory Freezing-Thawing Tests*
(5.5 sk mixes)

Mix Designation	AN	BN	CN	DN	EN	FN	GN	HN
Type of Fly Ash		B	B	B	A	A	A	A (Type IP Cement)
Percent Replacement by wt	0	15	25	35	35	25	15	20
No. of Cycles	Relative Dynamic Modulus (E x 10^6 psi)							
0	3.25	3.56	3.23	3.29	3.31	3.42	3.08	3.27
30	3.17	3.46	3.17	3.20	2.65	3.08	2.95	3.02
60	3.13	3.41	3.15	3.18	2.25	2.67	2.91	2.30
90	3.14	3.42	3.17	3.10	2.19	2.20	2.89	2.92
120	3.16	3.39	3.19	2.98	2.01	1.97	2.84	2.85
150	3.07	3.37	3.19	2.89	1.99	1.55	2.82	2.85
180	3.04	3.32	3.17	2.70	2.11	1.76	2.69	2.88
210	2.98	3.26	3.15	2.62	2.06	1.94	2.63	2.86
240	2.92	3.18	3.14	2.47	1.57	2.07	2.55	3.12
270	2.89	3.08	3.15	2.37	2.14	2.05	2.46	2.80
300	2.90	3.02	3.13	2.15	1.93	1.86	2.29	2.74

* Each value is the average of at least two tests.

Results of Laboratory Freezing-Thawing Tests*
(5.5 sk mixes)

Mix Designation	AN	BN	CN	DN	EN	FN	GN	HN
Type of Fly Ash		B	B	B	A	A	A	A (Type IP Cement)
Percent Replacement by wt	0	15	25	35	35	25	15	20
No. of Cycles	Durability Factor							
0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
30	97.6	96.9	98.3	97.3	76.3	90.1	95.9	92.3
60	96.5	95.9	97.6	96.7	68.1	78.4	94.6	88.7
90	96.5	96.1	98.2	94.1	66.1	64.2	93.7	89.1
120	97.1	95.4	98.8	90.5	60.8	57.6	92.2	87.1
150	94.5	94.8	98.8	86.3	60.2	45.3	91.7	87.1
180	93.5	93.3	98.3	82.2	63.8	51.4	87.2	88.1
210	91.8	91.6	97.4	79.5	62.3	56.8	85.5	87.5
240	89.8	89.3	97.3	75.1	47.4	60.5	82.8	95.7
270	89.0	86.6	97.5	74.4	64.8	60.0	79.7	85.8
300	89.2	84.8	96.9	65.3	58.3	54.4	74.4	83.8

* Each value is the average of at least two tests.

Results of Laboratory Freezing-Thawing Tests*
(6.5 sk mixes)

Mix Designation	IN	JN	KN	LN	MN	NN	ON	PN
Type of Fly Ash	A (Type IP Cement)		B	B	B	A	A	A
Percent Replacement by wt	20	0	15	25	35	15	25	35
No. of Cycles	Relative Dynamic Modulus (E x 10^6 psi)							
0	3.49	3.72	3.55	3.55	3.44	3.59	3.61	3.78
30	3.46	3.63	3.46	3.52	3.38	3.59	3.53	3.72
60	3.44	3.58	3.46	3.52	3.40	3.58	3.51	3.73
90	3.44	3.58	3.46	3.52	3.42	3.59	3.46	3.72
120	3.44	3.56	3.46	3.51	3.42	3.57	3.43	3.73
150	3.44	3.57	3.45	3.53	3.43	3.58	3.42	3.73
180	3.45	3.51	3.44	3.51	3.42	3.56	3.40	3.74
210	3.45	3.49	3.44	3.50	3.42	3.54	3.35	3.73
240	3.44	3.49	3.39	3.49	3.43	3.54	3.30	3.74
270	3.42	3.45	3.35	3.50	3.48	3.50	3.13	3.72
300	3.44	3.41	3.35	3.49	3.42	3.49	2.89	3.72

* Each value is the average of at least two tests.

Results of Laboratory Freezing-Thawing Tests*
(6.5 sk mixes)

Mix Designation	IN	JN	KN	LN	MN	NN	ON	PN
Type of Fly Ash	A (Type IP Cement)		B	B	B	A	A	A
Percent Replacement by wt	20	0	15	25	35	15	25	35
No. of Cycles	Durability factor							
0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
30	99.2	97.5	97.5	99.1	98.3	100.0	97.8	98.4
60	98.6	96.2	97.6	99.1	98.9	99.8	97.1	98.6
90	98.6	96.2	97.6	99.1	99.4	100.0	95.8	98.4
120	98.6	95.7	97.5	98.9	99.3	99.4	95.0	98.7
150	98.6	95.9	97.2	99.3	99.7	99.6	94.7	98.8
180	98.9	94.4	96.8	99.0	99.5	99.1	94.1	98.9
210	98.9	93.9	96.8	98.5	99.4	98.5	92.7	98.7
240	98.6	93.7	95.6	98.3	99.6	98.5	91.3	98.8
270	98.0	92.9	94.3	98.5	101.2	97.5	86.6	98.5
300	98.6	91.7	94.3	98.3	99.4	97.2	80.1	98.4

* Each value is the average of at least two tests.