TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-87/3+364-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DURABILITY OF CONCRETE CONTAINING FLY ASH		5. Report Date May 1986 6. Performing Organization Code
7. Author(s) P. J. Tikalsky and R. L. Carrasquillo		8. Performing Organization Report No. Research Report 364-3
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin Austin, Texas 78712-1075		10. Work Unit No. 11. Contract or Grant No. Research Study 3-9-84-364
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763		13. Type of Report and Period Covered Interim 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration

Research Study Title: "Production of Concrete Containing Fly Ash"

16. Abstract

The variability in the chemical composition and physical properties of fly ash from different sources affect both the fresh and hardened properties of concrete containing fly ash. Resident engineers and manufacturers that ignore these differences do not ensure proper quality or durable concrete.

This report summarizes the observations and conclusions from an experimental program investigating the durability of concrete containing fly ash. Tests were performed to determine the freeze-thaw resistance, strength, shrinkage, creep, abrasion resistance, and air entrainment characteristics of concrete containing fly ash. Types A and B fly ash were used in this study as a replacement for 0, 20, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type A fly ash was used.

The results from this study reveal that concrete containing fly ash can be designed to meet present Texas SDHPT specifications. In many cases concrete containing fly ash is shown to be more durable and economical than plain concrete containing no fly ash.

This report provides the resident engineer with recommendations to ensure the durability of concrete containing fly ash and points out concerns for future investigations.

17. Key Words concrete, fly ash, durability, freeze-thaw resistance, strength, shrinkage, creep, abrasive resistance, air entrainment	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	162	

Form DOT F 1700.7 (8-69)

DURABILITY OF CONCRETE CONTAINING FLY ASH

by

P. J. Tikalsky

and

R. L. Carrasquillo

Research Report Number 364-3

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 third report in a series of four reports which summarizes the effect of fly ash on the production of concrete containing fly ash in highway applications. 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 concrete pavements. 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 recommended mix proportioning procedure for concrete containing fly ash. It 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 SDHPT specifications for a given application.

The work reported herein 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 variability in the chemical composition and physical properties of fly ash from different sources affect both the fresh and hardened properties of concrete containing fly ash. Resident engineers and manufacturers that ignore these differences do not ensure proper quality or durable concrete.

This report summarizes the observations and conclusions from an experimental program investigating the durability of concrete containing fly ash. Tests were performed to determine the freeze-thaw resistance, strength, shrinkage, creep, abrasion resistance, and air entrainment characteristics of concrete containing fly ash. Types A and B fly ash were used in this study as a replacement for 0, 20 and 35% Type I portland cement by weight. In addition Type IP cement containing 20% Type A fly ash was used.

The results from this study reveal that concrete containing fly ash can be designed to meet present Texas SDHPT specifications. In many cases concrete containing fly ash is shown to be more durable and economical that plain concrete containing no fly ash.

This report provides the resident engineer with recommendations to ensure the durability of concrete containing fly ash and points out concerns for future investigations.

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 and durability of concrete with fly ash.

The study shows that current production procedures for concrete may not be adequate for the production of concrete containing fly ash. Modified mix design procedures and adequate quality control measures are necessary to take advantage of the economics and improved quality of concrete containing fly ash. Durable concrete must have a good air entrainment system regardless of whether fly ash is present or not. Lower water contents due to the use of fly ash may provide higher long-term strength, improved serviceability, and greater economic savings than plain concrete when used in Texas highways.

CONTENTS

Chapter Page

TABLES

FIGURES

CHAPTER 1

INTRODUCTION

1.1 General

The production of concrete containing fly ash for construction applications has risen steadily in the United States during the last decade. The increased use of fly ash has come about for two reasons: a) there is a growing need for more cost effective construction materials; and, b) materials with higher strengths and more desirable physical properties are in increasing demand by design engineers. Both of these objectives can be met through the proper use of fly ash in portland cement concrete.

The economic consideration for the use of fly ash in concrete is twofold. First, fly ash has been used satisfactorily as a direct replacement for portland cement, the most expensive component of concrete. Second, fly ash is an inexpensive material that is readily available nearly everywhere in the United States. In the United States, 51,332,889 tons of fly ash were produced in 1984, of which only 5,486,219 tons were used in concrete as shown in Fig. 1.1.

Today's need for the production of better and more durable materials at a reduced cost is the basis of the research program presented herein. In this chapter a brief overview of the research program is presented. A brief description of the basic parameters considered in the study as well as their importance in the production of concrete is presented.

1.2 Justification of Research

The Resource Conservation and Recovery Act (RCRA), passed by the United States Congress in 1976, includes provisions to encourage the utilization of by-product materials. These provisions are meant to protect the environment by conserving materials and energy to their fullest extent. Under the mandate from the RCRA, the Environmental Protection Agency (EPA) has issued guidelines through the Federal Highway Administration for the procurement of cement and concrete containing fly ash. These guidelines require that any agency purchasing concrete with federal funds allow bidders to submit bids on the basis of equivalent concrete containing fly ash, either as an admixture or in blended cement.

The purchase of concrete for highway construction projects, by the Texas State Department of Highways and Public Transportation (SDHPT), falls directly under these guidelines. As a result, specific guidelines for the use of fly ash are needed by Texas SDHPT field

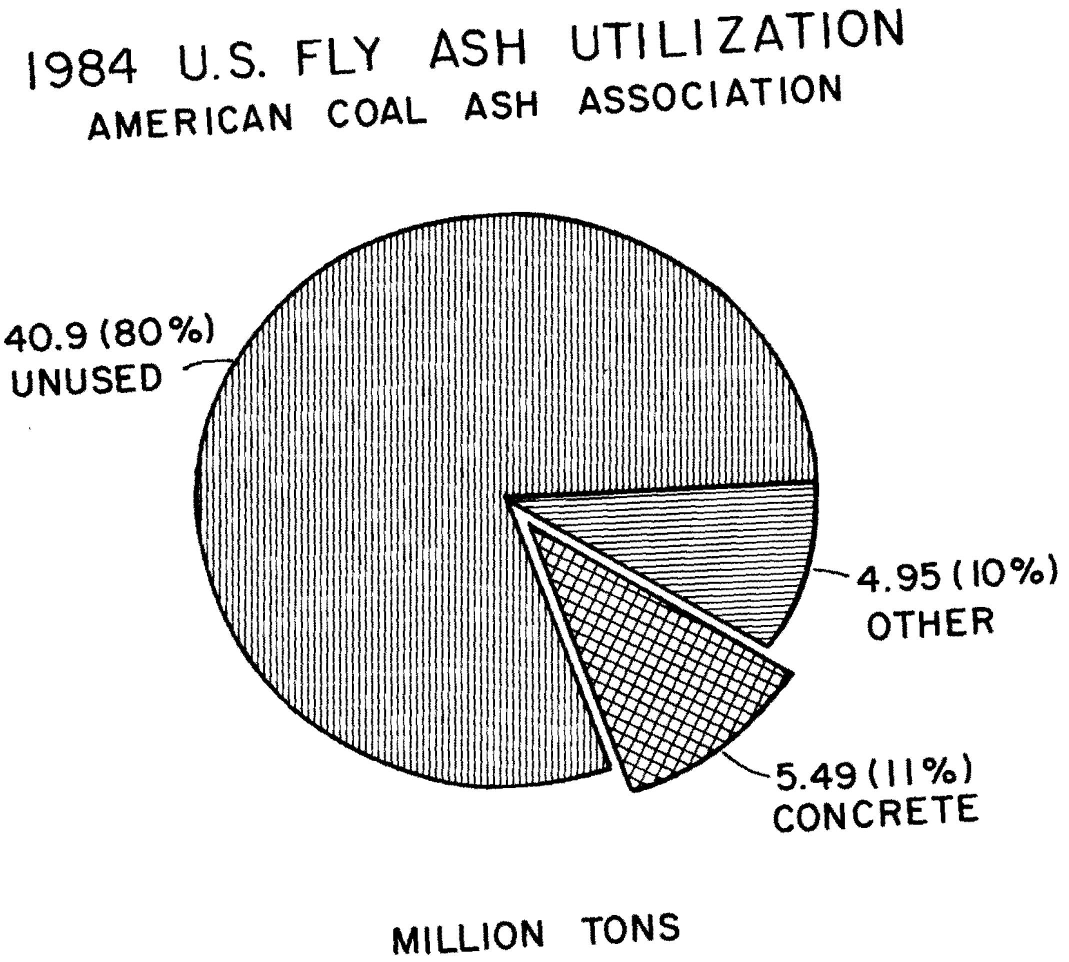


Fig. 1.1 1984 fly ash utilization in the United States as reported by the American Coal Ash Association [3].

personnel to ensure that concrete containing fly ash will perform equal to or better than concrete without fly ash. Questions regarding rheological characteristics, strength and durability of fly ash - portland cement concrete must be answered before it is accepted as a suitable construction material in highway applications.

1.3 Definition of Fly Ash

Fly ash is defined in ASTM C618-84 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete, as a "finely divided residue that results from the combustion of ground or powdered coal." Fly ash consists of very fine particulate matter which escapes the combustion chamber of a powdered coal-burning furnace. The fly ash is carried by the flue gases to precipitators, either mechanical or electrostatic, which extract the ash from the gases. The fly ash consists of tiny glassy spherical particles composed mainly of silica, alumina, calcium and iron oxides.

The spherical nature of the particles is a result of the coal burning at high temperatures, in excess of 2700°F, followed by rapid cooling. The impurities in the coal, namely clays, calcite and pyrite, are transformed during the molten state to complex aluminates, silicates, calcium oxide and iron oxide. The small molten droplets harden forming a heterogeneous mixture of unburned coal, and spherical glassy particles, commonly referred to as fly ash.

Fly ash is classified as a pozzolanic material; a siliceous or aluminous material in reactive form which, in a finely divided state, is capable of combining with lime in the presence of water to form stable calcium silicates having cementitious properties [29]. In addition to being a pozzolan, some types of fly ash contain significant amounts of calcium oxides and, as a result, display cementitious properties similar to those of portland cement.

Electrical power generation is the chief source of fly ash. As different power plants use different sources of coal, the physical composition of the coal and the subsequent fly ash also vary from source to source. The following section describes the major classifications of fly ash and the criteria for those classifications.

1.3.1 Fly Ash Classification. The chemical composition of fly ash is largely due to the type of coal burned. The most common types of coal used by electric utilities are bituminous, subbituminous and lignite.

Bituminous coal, referred to as eastern coal, is usually obtained from deep mining operations in the eastern and north central United States. Its energy potential is the highest of the three coal types, at over 11,000 Btu per pound [44]. The carbon content of bituminous coal is typically higher than that of the other types of coal. ASTM C618-84 states that fly ash produced from bituminous or anthracite coal is normally classified as ASTM Class F fly ash.

Fly ash produced from subbituminous or lignite coals are normally classified as ASTM Class C fly ash. These types of coal are considered 'dirtier' coals because they often possess high quantities of noncombustible minerals. The energy potential of these coals is less than that of bituminous coal. Subbituminous coal typically produces about 9000 Btu per pound and lignite coal produces less than 7000 Btu per pound. Both of these coals are normally extracted through strip mining processes in the western and southwestern United States.

Table 1.1 lists the chemical requirements for fly ash according to three different fly ash specifications: Federal SS-P-570b, Specifications for Pozzolans for the Use of Portland Cement Concrete, ASTM C618-84 and Texas SDHPT D-9-8900, Departmental Materials Specification for Fly Ash. From Table 1.1 it is seen that most ASTM Class C fly ash meets the specifications of Texas SDHPT Type B fly ash. Similarly fly ash meeting ASTM Class F fly ash requirements meet Texas SDHPT Type A fly ash requirements. The Federal specification is consistent with most foreign specifications, and does not differentiate between types of fly ash. Throughout this report the Texas SDHPT D-9-8900 designation will be used.

The primary difference between the Texas SDHPT Type A and B fly ashes is the minimum amount of silica, alumina and ferric oxides. The importance of the quantity of calcium oxide is that an ash with a low content will only possess pozzolanic properties, whereas an ash with a high content of calcium oxide will exhibit both pozzolanic and cementitious properties.

1.4 Problem Statement

The use of fly ash in the production of concrete in the United States has increased significantly in the last decade and is expected to continue to increase due to both economic and technical considerations and the increased supply of fly ash. Texas will produce over 6 million tons of fly ash in 1985 and the supply is rising steadily, as shown in Fig. 1.2. The effect of fly ash on the properties of concrete for highway applications is not fully understood. The variability in the chemical composition and physical properties of fly ash from different sources affect both the fresh and hardened properties of concrete. Concrete manufacturers that ignore these differences and use fly ash in their concrete without proper quality control procedures cannot ensure proper quality or durable concrete.

Table 1.1 Fly Ash Chemical Composition Requirements According to Different Specifications

Fly Ash Chemical Composition Requirements					
	ASTM 618-84		Federal SS-P-570b	Texas DSHPT D-9-8900	
	Class C	Class F		Type A	Type B
Si+Al+Fe oxides minimum %	50	70	70	65	50
Ca oxide maximum %	-	-	-	*	*
Mg oxide maximum %	-	-	5.0	5.0	5.0
Sulfate maximum %	5.0	5.0	4.0	5.0	5.0
Available Alkalies as Na oxide maximum %	1.5	1.5	1.5	1.5	1.5
Loss on Ignition maximum %	6.0	6.0	6.0	3.0	3.0
Moisture maximum %	3.0	3.0	3.0	2.0	2.0
Fineness #325 maximum retained	34	34	34	30	30
Pozzolanic Activity	75	75	75	75	75
Shrinkage maximum %	.03	.03	.03	.03	.03

* 4% maximum variation from previous ten samples

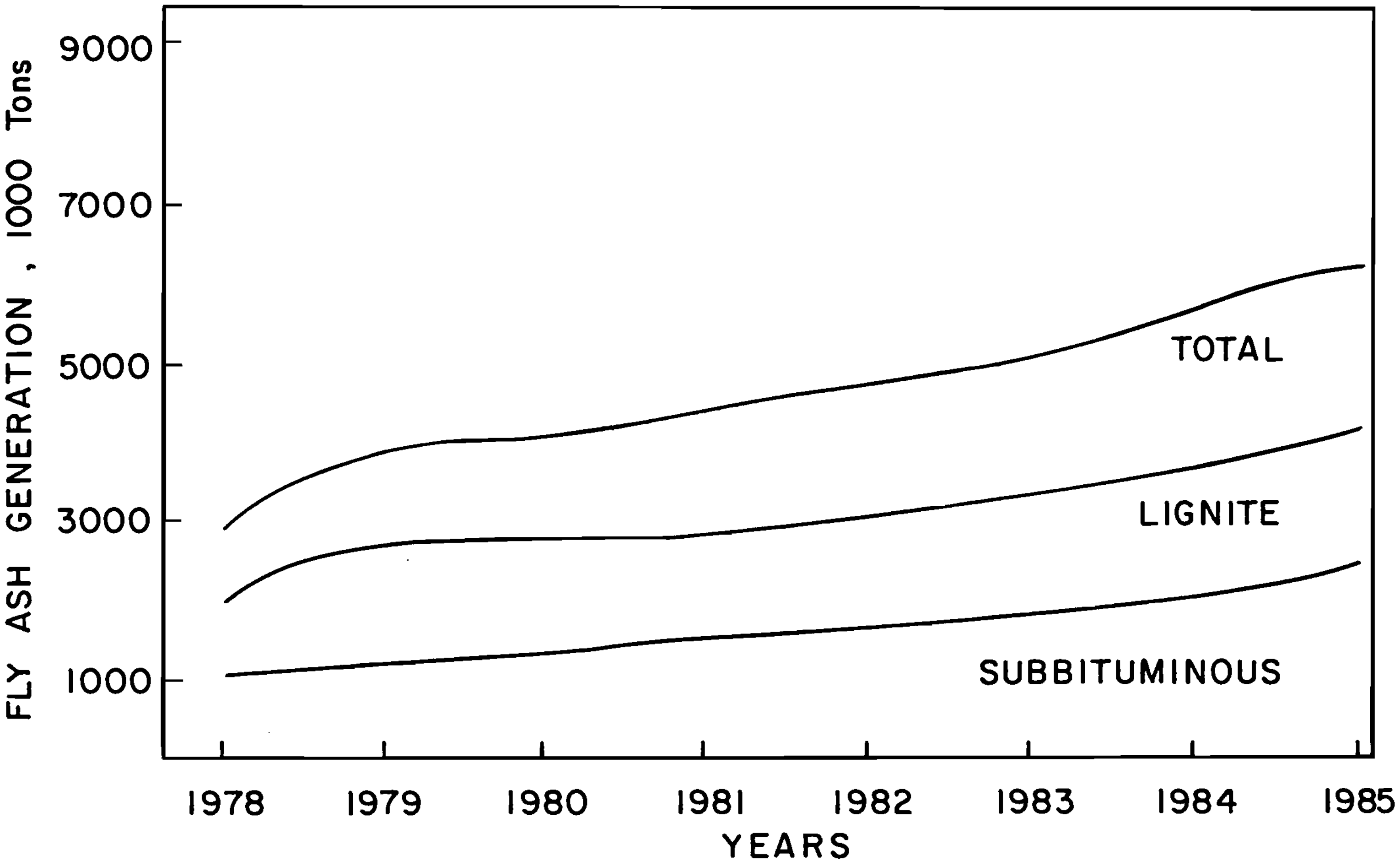


Fig. 1.2 Fly ash generation in Texas [4].

1.5 Research Objectives

The main objective of the work presented herein is to establish guidelines to be followed by the resident engineer in the form of material specifications and mix design procedures to ensure good quality and durable concrete containing fly ash for highway applications. The resulting guidelines are meant to supplement present material specifications and mix design procedures. Although the research presented addresses a limited number of physical properties, it is intended that the most relevant properties of fly ash affecting both fresh and hardened concrete will be identified and that information from this program can be used in conjunction with both past and future research.

1.6 Research Plan

The research plan reported herein concentrated on five separate testing programs of concrete containing fly ash:

(1) Effectiveness of air-entraining admixtures;

(2) Drying Shrinkage;

(3) Abrasion Resistance;

(4) Creep Behavior; and

(5) Compressive and Flexural Strength.

The study of the effectiveness of air-entraining admixtures was performed by varying the dosage of air entraining agent, the type of admixture and the amount of fly ash in the concrete. Specimens were tested according to ASTM C666-77, "Resistance of Concrete to Rapid Freezing and Thawing". The abrasion resistance of concrete was evaluated according to ASTM C944-80, "Abrasion Resistance of Concrete or Mortar by the Rotating-Cutter Method". Creep was determined in accordance with ASTM C512-76, "Creep of Concrete in Compression". Drying shrinkage was measured between gage points attached positively to specimens in a controlled environment. Strength testing included both compressive strength and modulus of rupture, as per ASTM C 39-79, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", and C 293-79, "Standard Test Method for Flexural Strength of Concrete", for concrete containing between 0 and 35% fly ash.

Throughout the entire research plan the water, slump and air content of the fresh concrete were closely monitored. In addition, all the testing programs included both Texas SDHPT Type A and Type B fly ash. Testing was done in cooperation with the Material and Test Division of Texas SDHPT.

1.7 Format

A brief explanation of the fundamentals of air entrainment, creep, and shrinkage, abrasion and sulfate attack as they affect concrete performance, is presented in Chapter 2. A review of the technical literature and previous research relevant to this study is presented in Chapter 3. A detailed description of test procedures, materials and test results is presented in Chapters 4 and 5. The results of the research program are discussed in Chapter 6, and Chapter 7 contains the conclusions and recommendations for future research based on the present research study.

The research program presented herein is the second part of a broad project on the "Production of Concrete Containing Fly Ash" conducted jointly between the Center for Transportation Research and the Phil M. Ferguson Structural Engineering Laboratory at the University of Texas at Austin under the sponsorship of the Texas SDHPT. Earlier research studies [9,53] concentrated on developing the mix proportioning procedure needed to design a concrete mix containing fly ash to meet current Texas SDHPT concrete specifications for different classes of concrete.

CHAPTER 2

FUNDAMENTAL MECHANISMS OF HARDENED CONCRETE

2.1 Introduction

This chapter will provide a brief explanation of the fundamentals of air entrainment, creep, shrinkage, sulfate attack and abrasion resistance of concrete and how these affect concrete performance.

2.2 Air Entrainment

Entrained air refers to tiny air bubbles incorporated into the concrete through the use of an admixture. These bubbles may range in size from 0.05 to 1.25 mm in diameter and are both disconnected and uniformly distributed throughout the mortar matrix. Entrained air alters the properties of fresh and hardened concrete. Air-entrained fresh concrete is more plastic and workable than non-air-entrained concrete, while air entrainment in hardened concrete provides the durability necessary to resist unfavorable environmental conditions.

2.2.1 Air Entrainment Mechanism. The stirring and kneading actions in mixing concrete introduce air in the mortar matrix. These air bubbles tend to collide and combine to form the smallest interfacial area in the mortar, subsequently the materials lowest free energy state. The principal purpose of an air entraining agent (AEA) is to reduce the coalescence of these air bubbles and provide the concrete with a uniformly distributed system of small air voids.

The AEA molecules have hydrophobic and hydrophilic portions as shown in Fig. 2.1(a). When added to the mixing water of concrete, the agent causes the water to foam. The hydrophobic portions of the molecules orient toward the air bubbles providing stable spherical voids illustrated in Fig. 2.1(b), which are locked into the paste as it hardens. While most of these bubbles are not visible with the naked eye, they are readily visible through a reflected light microscope. In most air-entrained concrete, the voids occupy between 1.5 and 9.0% of the total concrete volume. The actual amount of entrained air depends upon the amount and type of air entraining agent used, the composition of the paste, the physical properties of the cement, the type and duration of mixing, concrete consistency and temperature, other admixtures, and on the handling, placement and compaction of the fresh concrete mix.

2.2.2 Air Void System. Air-entrained concrete with an adequate air void system is the most effective and economical system for producing concrete with adequate resistance against potentially

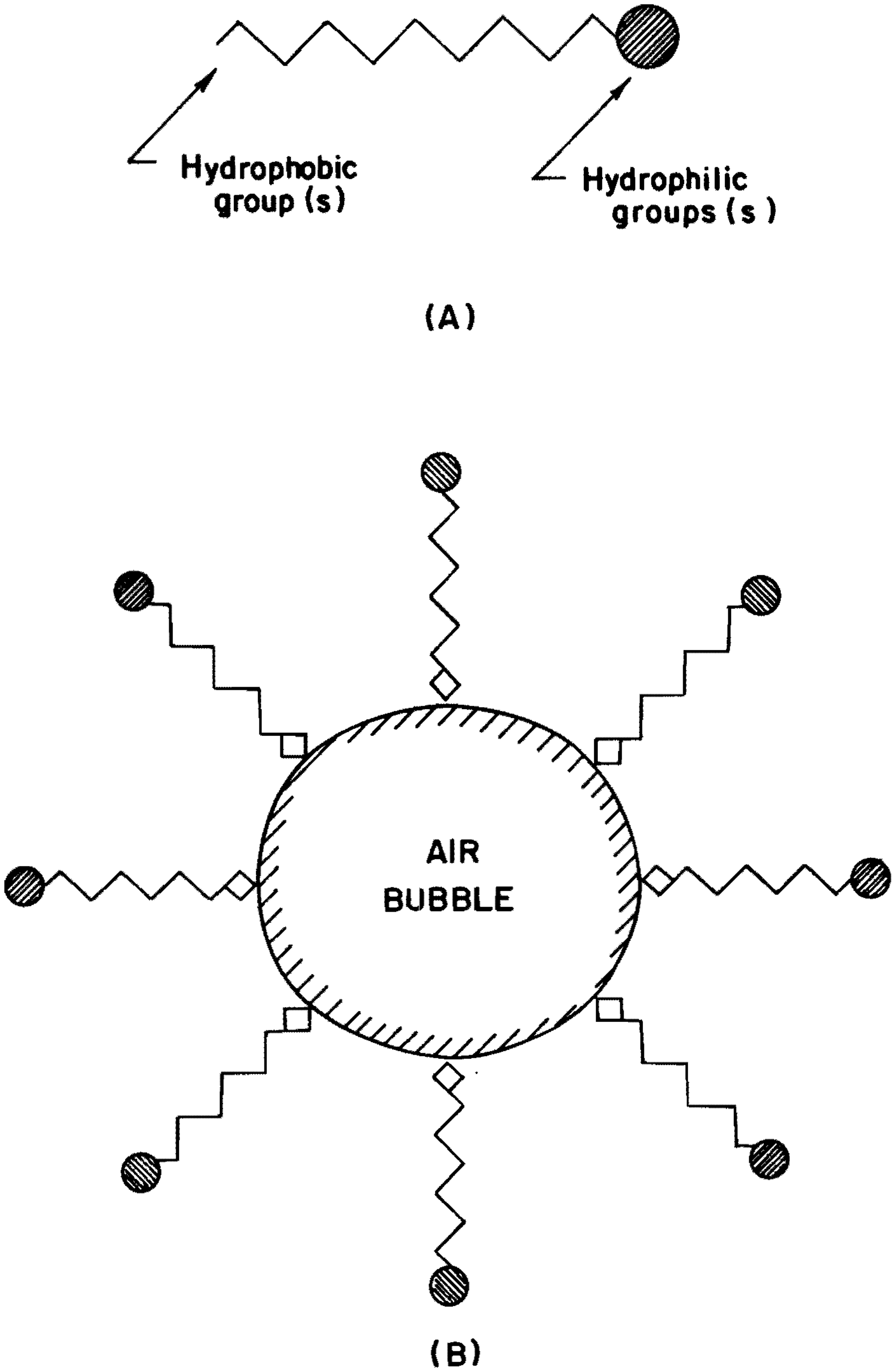


Fig. 2.1 The mechanism of air entraining agents. [49]

damaging environments especially freezing and thawing. The air void system is composed of three important factors:

(a) total volume of voids;

(b) size of voids; and

(c) distribution of voids.

The primary function of an air void system is to improve the durability of the concrete. The small, uniformly spaced air bubbles provide reservoirs to accomodate the expansion of water in the concrete during freeze-thaw cycles. The expansion of excess water could rupture the concrete if a means of pressure relief is not provided. The amount of pressure relief depends upon the distance the water molecules must travel to the nearest air void.

The volume of air necessary to provide adequate durability is dependent on the type of exposure the concrete must endure and the nominal size of the coarse aggregate [6,56]. The void spacing must be such that the expanding water does not induce internal pressures greater than the tensile strength of the concrete. For a constant volume of air, smaller voids result in a smaller spacing between bubbles, therefore better protection against freeze-thaw damage. Guidelines for the size and distribution of the air voids are given in ASTM C457, "Standard Recommended Practice for Microscopical Determination of the Air-Void System in Hardened Concrete." Although these parameters are seldom actually measured during the production of concrete, the average maximum distance between any point in the paste to the edge of the nearest air void should not exceed 0.20 mm and the specific surface of the air void volume should exceed $25 mm^2/mm^3$.

2.2.3 Effects of Entrained Air. Air-entrained concrete is recommended for use wherever concrete is exposed to freezing and thawing, deicing salts and whenever concrete is subjected to potentially damaging environmental conditions [6]. Air-entrained concrete provides several advantages over non-air-entrained concrete:

(a) improved workability and cohesiveness;

(b) decreased permeability;

(c) decreased segregation and bleeding;

(d) reduced water demand;

(e) improved durability;

(f) resistance to scaling; and

(g) improved sulfate resistance.

Along with these advantages, air-entrained concrete is accompanied by one notable disadvantage. A loss in strength of 10 to 20% can be anticipated in most concrete which contains three to five percent entrained air by volume as shown in Fig. 2.2.

There are between 2 and 4 million bubbles in a cubic inch of air entrained concrete. These uniformly distributed bubbles act as frictionless ball bearings to lubricate the fine aggregate in the mix. This additional lubrication provides better workability than that of a similar non-air-entrained mix while improving the cohesiveness of the fresh concrete. The matrix of disconnected air voids inhibits the formation of bleed water channels by increasing the homogeniety of the paste in the setting concrete. Therefore, air entrainment reduces both bleeding in the fresh concrete and permeability in the hardened concrete. In addition, air entrainment tends to decrease segregation in the fresh concrete. The reason for this is related to the increased cohesiveness of the paste [58]. In mixes having equal slump, air entrainment will reduce the mixing water demand over that of non-air-entrained concrete, partially compensating for the strength loss. The reduction in mixing water demand for a given slump is directly due to the ball bearing effect of the air voids resulting in better workability.

The freeze-thaw durability of air-entrained concrete is over ten times that of concrete without air entrainment as shown in Fig. 2.3. In the previous section, the function of the air void system with relation to the freeze-thaw mechanism was briefly explained. Scaling from deicing salts is also decreased when an entrained air void system is present. The increased uniformity of the paste prevents excessive bleeding, a major cause of scaling. Sulfate attack damage is also prevented through the use of air entrainment. The decreased permeability of air entrained concrete provides increased resistance against the absorption of sulfates and the subsequent physical deterioration caused by sulfate attack.

The loss of strength due to entrained air is acceptable in most concrete where durability is of importance. The increased durability attained from small quantities of entrained air outweighs the benefits of higher strengths in concrete exposed to potentially damaging environments.

2.3 Creep in Concrete

Concrete undergoes three basic types of deformation: elastic strain, shrinkage, and creep. Elastic strains are deformations that

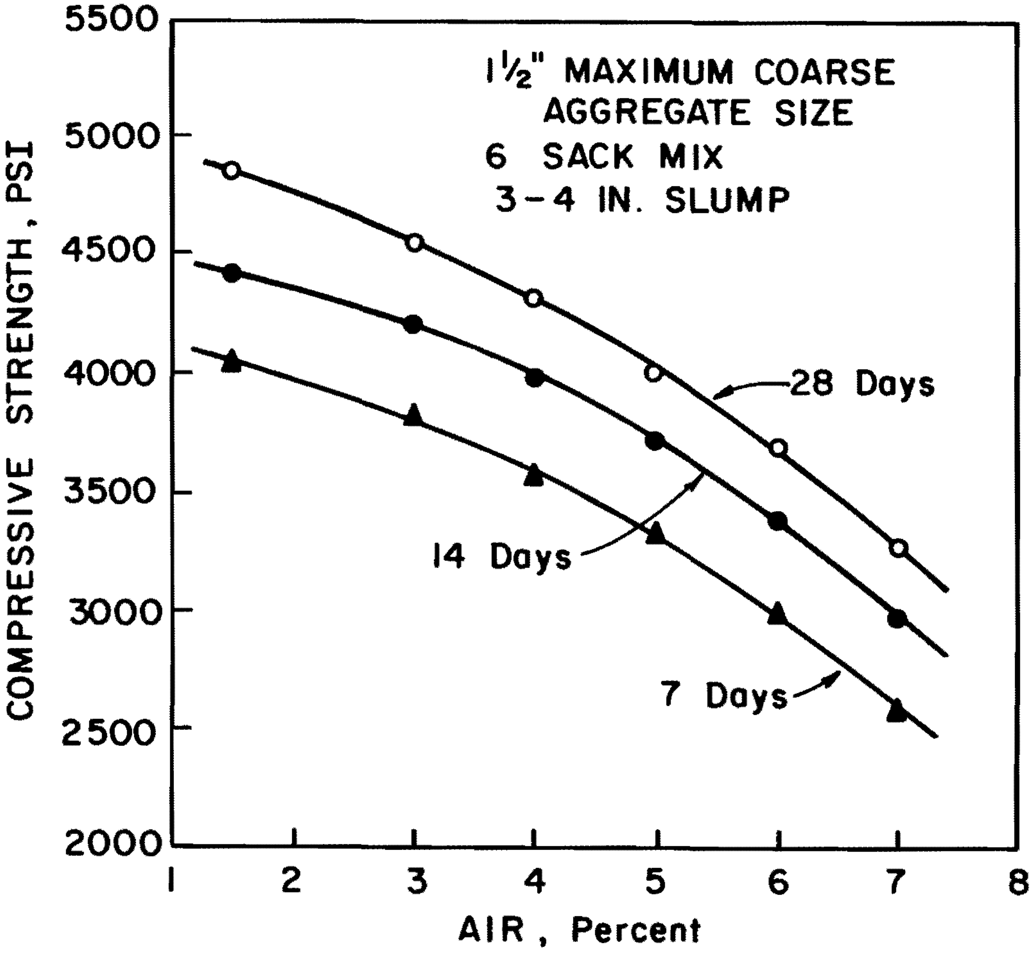
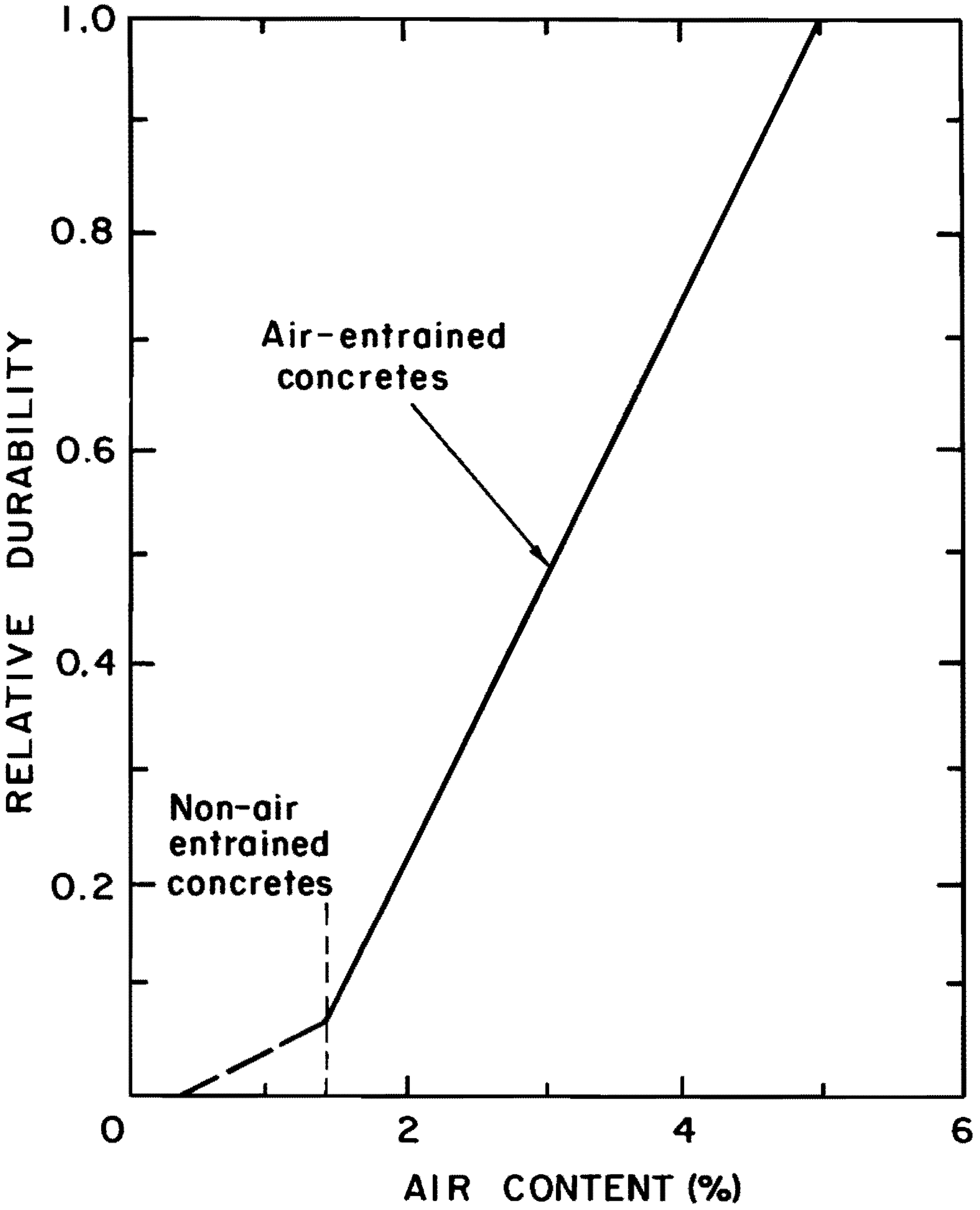


Fig. 2.2 The relationship between strength and air content [79].



2.3 Durability of air entrained concrete [49].

are proportional to the concrete's modulus of elasticity. These strains are wholly recoverable upon unloading at maximum stresses less than one half of the ultimate strength of concrete, 0.5 f'_c. Shrinkage refers to volumetric changes resulting from moisture loss in the concrete. Shrinkage will be addressed in more detail in the succeeding section. Creep refers to the inelastic time-dependent deformation of a material under a sustained loading. Although this inelastic strain does not generally affect the ultimate strength capacity of the concrete member, creep strain must be considered in deformation calculations in order to properly predict deflections of structural members.

The creep phenomenon in concrete has been the subject of many research studies. Many theories have been proposed to explain the mechanism of creep in concrete. The precise reason(s) for concrete creep remains open for discussion. The most widely accepted theories state that the primary mechanism of the inelastic creep strain is the plastic flow of the cement gel under load [4]. While the concrete is under sustained load, both the pore water and the water adsorbed to the cement gel particles are under pressure. The van der Waal bonds between the calcium silicate hydrate (C--S--H) crystals are weakened by this pressure and the crystals slip by one another. The result is the inelastic deformation referred to as creep. For this same reason, dry concrete does not creep. Creep occurs at a microscopic level as a means of pressure relief for stress concentrations in the cement paste. The flow of the gel results in a redistribution of the local internal stresses. The time-dependent deformations caused by creep in concrete decrease with time as shown in Fig. 2.4. Typically, 90% of all creep strain occurs within 200 days after loading [4]. Of this creep less than 20% is recoverable upon unloading [10]. The reason for creep recovery is not yet fully understood and is the topic of current research.

The customary measure of creep is referred to as the creep coefficient. This is the simple ratio of creep strain, E_{creep}, to initial elastic strain, $E_{elastic}$.

$$C_t = E_{creep}/E_{elastic}$$

Creep is affected by many factors:

(a) applied stress ;

(b) water/cement ratio;

(c) curing conditions;

(d) temperature;

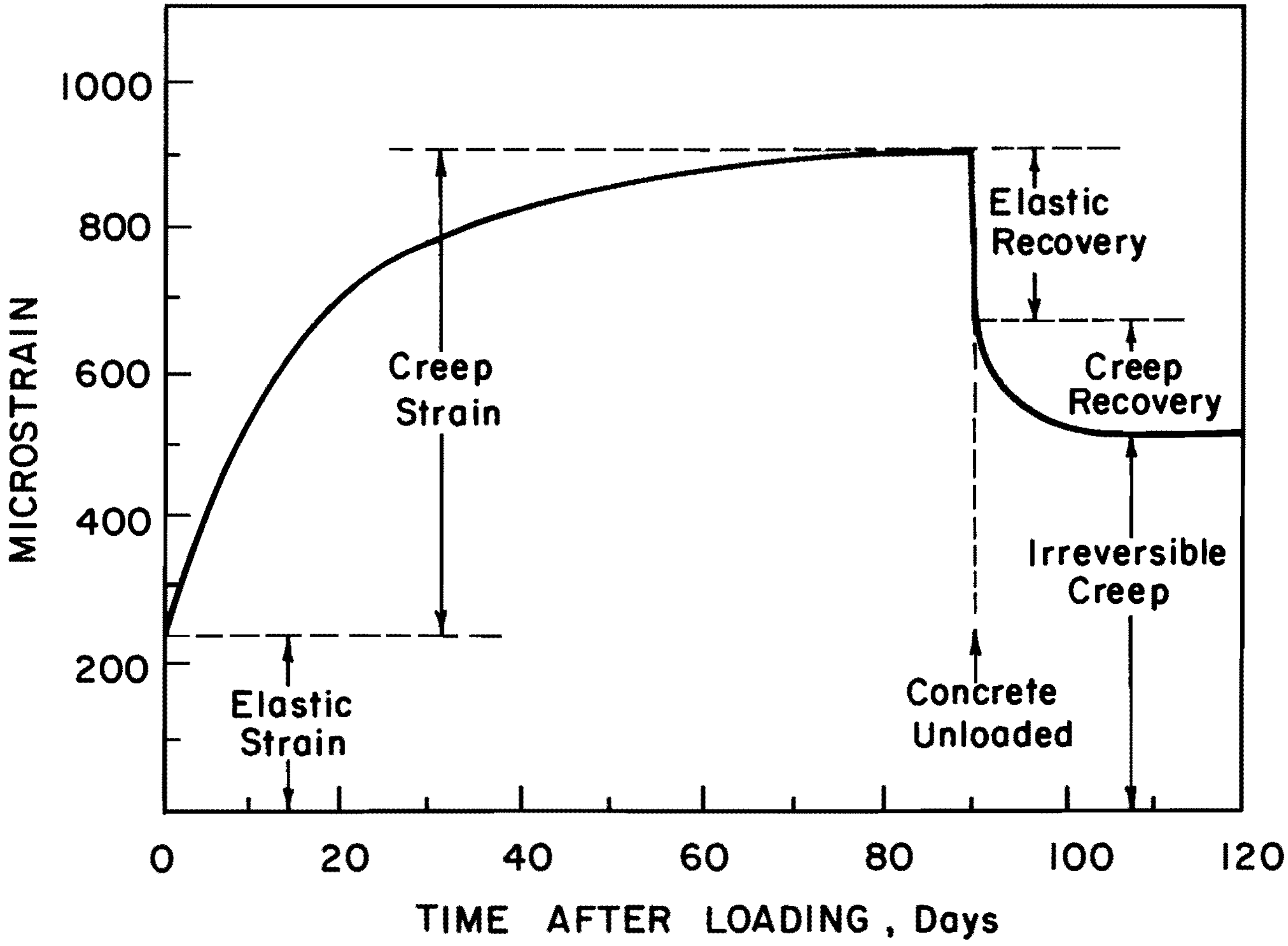


Fig. 2.4 Typical creep curve for plain concrete [79].

(e) slump;

(f) moisture condition;

(g) cement composition; and

(h) admixtures.

The first three of these are the most important factors. The creep strain increases nearly linearly with applied stresses in the range between 0.2 - 0.5 f_c' [4] as shown in Fig. 2.5. Higher applied stresses produce higher internal pore water pressure in the concrete which induces slippage between the C--S--H particles in the cement gel. Also, there is evidence that increased amounts of evaporable water increases creep strain [63]. Since the available water depends on the w/c ratio, there is a direct relationship between creep and the w/c ratio. In addition, creep is observed to be less in concrete with a high maturity. Well cured concrete exhibits more thorough hydration; and therefore will have reduced creep strain.

Although a basic explanation of creep in concrete has been presented here, a complete understanding of the creep phenomenon in concrete is not presently available. Many variables influence the cement paste behavior and those associated with creep have not yet been fully researched. While creep is not often the cause of concrete failure, it may produce undesirable deflections and non-structural damage.

2.4 Shrinkage

Limiting deflection is the main serviceability requirement in most structural design. It is the design engineer's responsibility to limit concrete deflections to an acceptable level. In order to control deformations, the engineer must be able to predict with reasonable certainty the short and long term deflections of all structural elements. The prediction of material deformations is a complex series of calculations involving many uncertain variables. Each of which may contribute significantly to the overall deformation of the concrete.

In addition to elastic and creep strains, shrinkage is a major contributor to concrete deformations. Shrinkage is a time-dependent reduction in volume, at a constant load level, due mainly to loss of moisture in the concrete. Shrinkage is a phenomenon involving the contraction of cement paste, while aggregates in concrete provide physical restraint to this contracting action.

2.4.1 Shrinkage Mechanism. The mechanisms involved in cement paste shrinkage will be briefly described in this section. Although

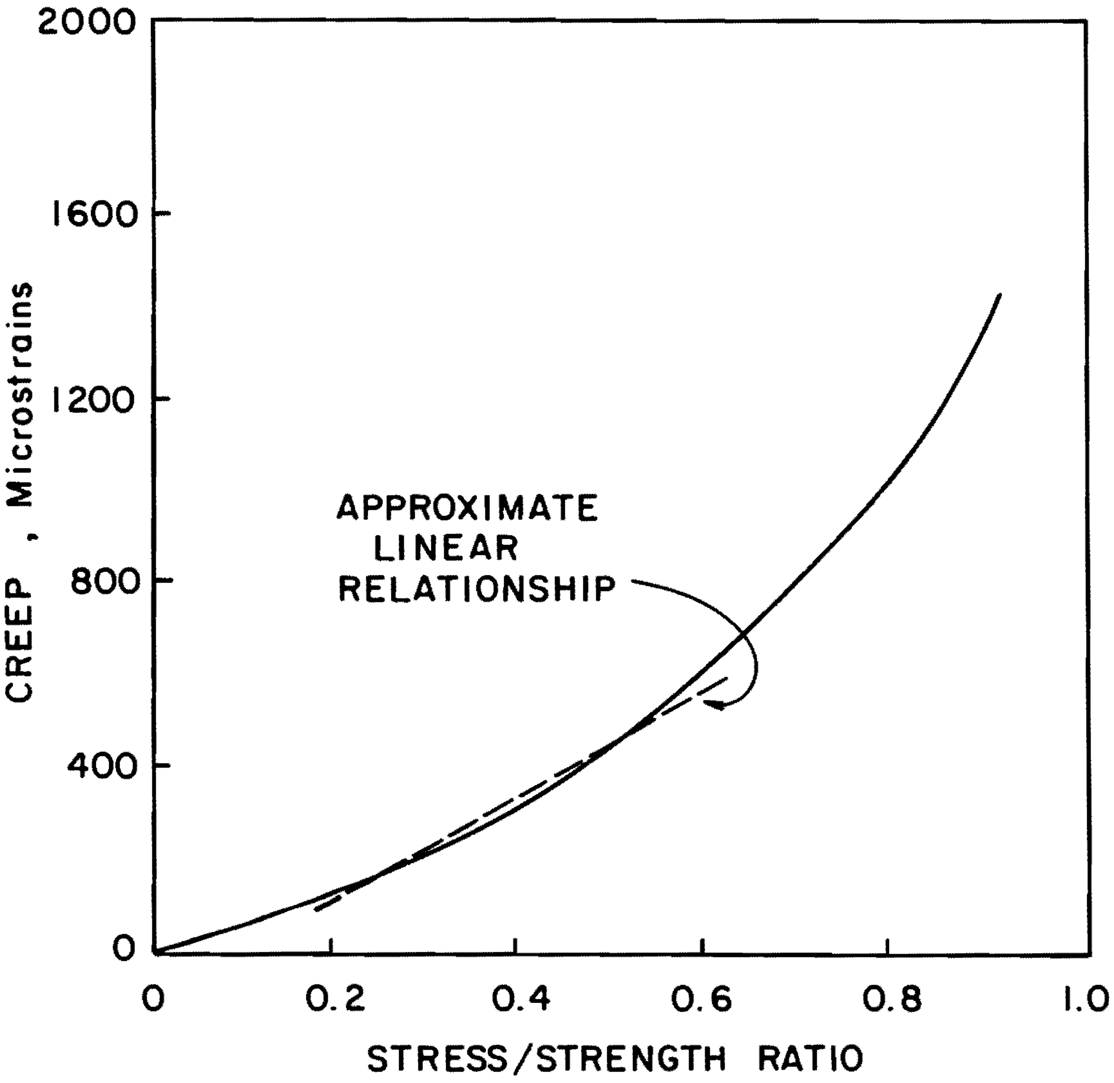


Fig. 2.5 Typical relationship between creep deformations and the applied stress [49].

several shrinkage theories exist, nearly all of them concede that moisture is the single most important variable governing the overall shrinkage of the concrete. Hardened concrete expands with an increase in moisture and contracts with a loss in moisture. The former process in referred to as swelling, while the latter is called shrinkage. Swelling of cement paste introduces compressive stresses which generally enhance the performance of the concrete. For this reason swelling is seldom considered a severe structural problem. Conversely, shrinkage generates tensile stresses which lead to cracking and warping in concrete.

Shrinkage can be classified as one of two types. First, plastic shrinkage is a volumetric reduction which occurs while the concrete is still fresh. If quality concrete is placed on a damp subgrade and is cured properly, this kind of shrinkage is not likely to occur. Therefore, the problem of plastic shrinkage will not be considered further in this study. The second type of shrinkage is known as drying shrinkage. Drying shrinkage, which occurs in nearly all classes of concrete, is a stress-independent volumetric reduction of hardened concrete due to the loss of moisture with time. The design engineer and contractor are expected to allow for shrinkage effects by providing control joints to minimize the damage of cracking and warping of concrete members, which accompany shrinkage strains.

Water is present in hardened concrete in three states:

(1) During the hydration process, water combines with portland cement to form calcium silicate hydrate (C--S--H). This water is chemically bound into the compound. The C--S--H particles are attracted to each other and form crystalline structures within the cement gel.

(2) These crystals adsorb water from the free water in the mortar matrix, physically binding water to the surfaces of the calcium silicate hydrate crystals; and

(3) The remaining water is contained in the capillary pores of the mortar as shown in Fig. 2.6.

As concrete dries, water evaporates first from large pores in the mortar matrix. This has very little effect on the volume stability of the concrete. Water then evaporates from smaller capillary pores. As the water content decreases, menisci form in the pores inducing internal tensile stresses in the concrete. The increased pore water pressure induces a strain sometimes referred to as capillary shrinkage. This shrinkage is only partially reversible upon rewetting of the concrete. As the drying continues, the pore and capillary water will be evaporated out of the concrete.

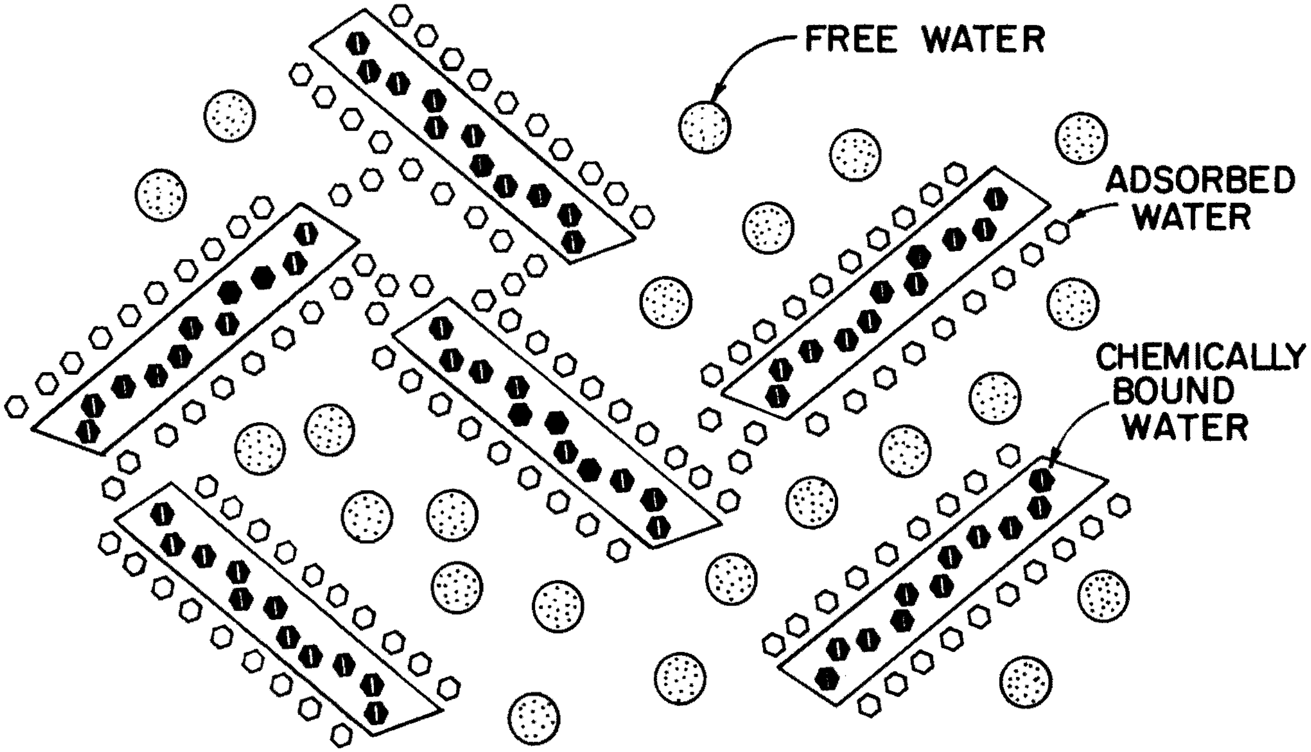


Fig. 2.6 Schematic representation of the three forms of water in the cement gel.

Water adsorbed to the surfaces of the C--S--H crystals will begin to evaporate at a relative humidity below 50%. As the water film around the crystals decreases in thickness, van der Waal bonds between hydrate particles draw the crystals together providing an effective shrinkage. This time-dependent volume change is fully reversible upon rewetting at a relative humidity above 50%.

The remaining water in concrete after the adsorbed water is drained out is incorporated in the calcium silicate hydrate structure. Further drying will result in a breakdown of the structural bonds between the C—S—H crystals and eventually the hydrate particles. One possible mechanism for the breakdown of the hydrate particles may be related to the lattice spacing of C—S—H particles. Calcium silicate hydrate experiences a change in lattice spacing upon drying, dropping from 14 to 9 angstroms [13]. However research has not yet determined whether the moisture movement associated with the shrinkage at the particle level is inter- or intracrystalline. The main cause of this type of shrinkage is believed to be related to the physical structure of the cement gel rather than its chemical or mineralogical characteristics. Shrinkage at this level is more difficult to attain, as the diffusion of water through concrete is reduced as the moisture content of the concrete decreases. This type of shrinkage is also fully reversible upon rewetting.

Another source of shrinkage in concrete is atmospheric carbon dioxide. Carbon dioxide will react over a long period of time with hardened cement paste, inducing shrinkage in aged concrete. The carbon dioxide reacts with the calcium hydroxide in the paste to produce calcium carbonate and water. This water is then available for evaporation. Carbonation shrinkage is normally limited to the exposed surfaces of the concrete, thereby adding to the problem of differential shrinkage, where differential shrinkage refers to the uneven shrinkage across a concrete member. Since water must diffuse through the concrete before evaporating, drying shrinkage occurs more readily at the surface. The combination of the increased drying shrinkage and carbonation shrinkage at the surface causes greater tensile stresses at the surface of a member than at mid-depth. Differential shrinkage is prevalent in massive members and members with opposite faces subjected to different environmental conditions.

2.4.2 Factors Influencing Shrinkage. The three most important factors influencing shrinkage in concrete are:

(1) water/cement ratio;

(2) relative humidity; and

(3) coarse aggregate content.

The water/cement ratio and the relative humidity both directly affect the moisture content of the hardened concrete. Fig. 2.7 shows that an increase in the w/c ratio increases shrinkage. The additional water occupies a position in the mortar matrix and is available for adsorption or to fill pores in the concrete. Figure 2.7 also shows the effect of coarse aggregate content on shrinkage. Higher coarse aggregate content reduces the cement paste volume and thereby decreases shrinkage. Lower relative humidity drives off moisture in the paste, increasing shrinkage as shown in Fig. 2.8. In addition to aggregate content, the physical properties of the aggregate also influence shrinkage. Aggregate which has a higher modulus of elasticity will restrain shrinkage more effectively than a lower stiffness aggregate.

Any practice that increases the water content of the cement paste will increase the shrinkage in the concrete. Accelerators and other admixtures which increase the water demand of a mix can be expected to result in higher drying shrinkage of concrete. An increase in the fine aggregate content will also result in added shrinkage.

To minimize shrinkage in concrete the following guidelines should be observed:

(1) Keep slump as low as possible without causing placement problems;

(2) Use strong sound aggregate;

(3) Keep the coarse aggregate content high;

(4) Avoid admixtures which increase the water demand; and

(5) Provide adequate shrinkage reinforcement.

Shrinkage reinforcement is specified by the American Concrete Institute (ACI 318-83) for all slabs and large structural members. While steel reinforcement does not prevent drying shrinkage it restrains it in a direction parallel to the direction of the bars, therefore reducing cracking and warping.

2.5 Sulfate Attack

Concrete which is exposed to environments containing sulfates will deteriorate unless adequate precautions are taken to resist the chemical attack of sulfates on the cement paste. Sulfates permeate into the concrete from sources such as: groundwater, seawater and industrial wastes and leachates. The sulfates react with monosulfoaluminates in the cement paste to form ettringite. The

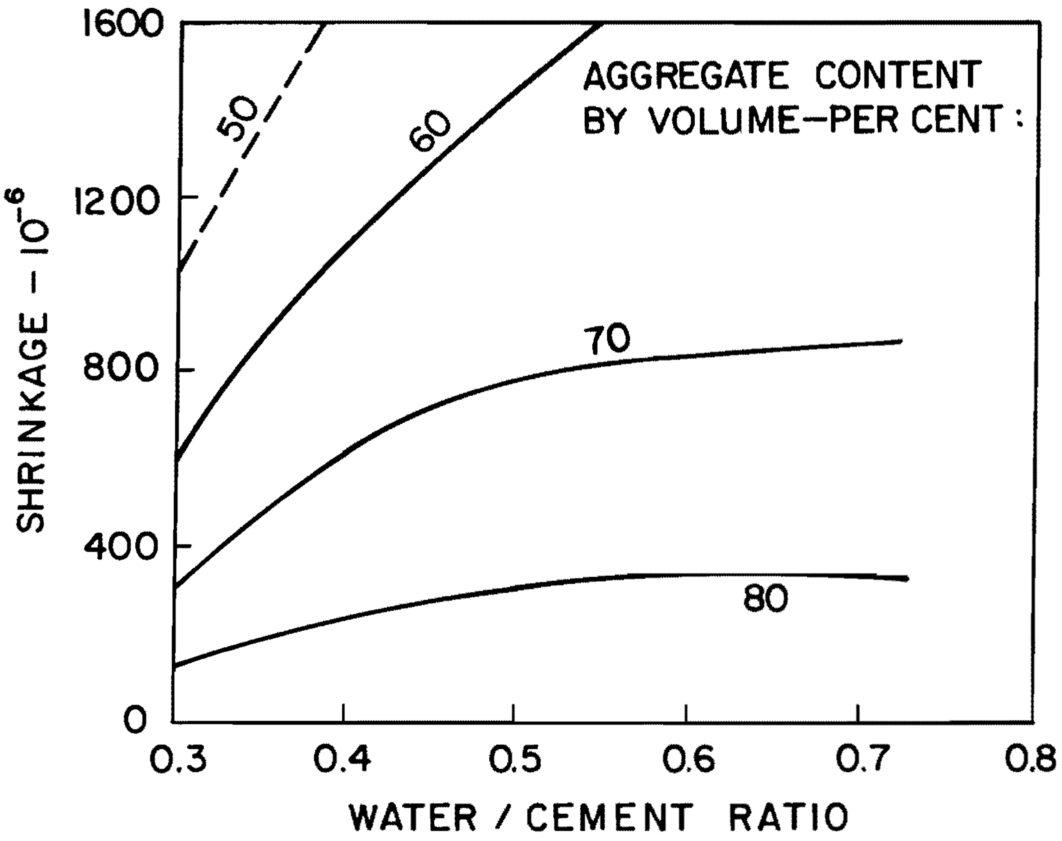


Fig. 2.7 Influence of coarse aggregate content and w/c ratio on shrinkage in concrete [12].

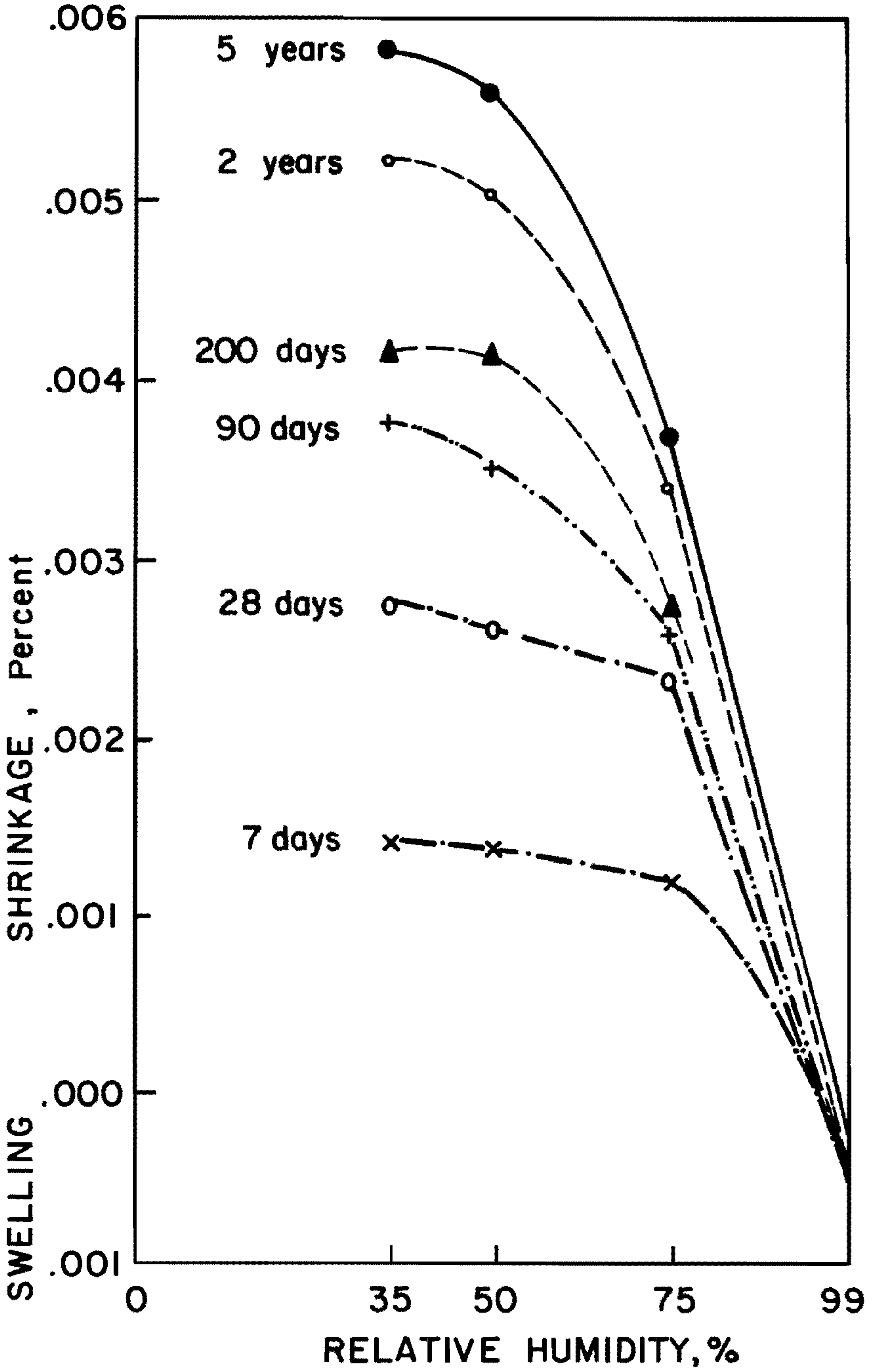


Fig. 2.8 The effect of relative humidity on the shrinkage of concrete.

formation of ettringite is accompanied by a large volume expansion, as shown in Fig. 2.9. The paste expansion induces internal stresses and leads to cracking in the concrete. The cracked concrete is then more permeable and allows for deterioration to continue until the concrete is no longer able to function as originally intended.

Sulfates also react with gypsum and magnesium in the concrete. These reactions are expansive, but the expansions are smaller as compared to that of the formation of ettringite.

The most important factors influencing sulfate attack are the tricalciumaluminate, C_3A, content and the permeability of the concrete. Since sulfates react with C_3A hydrate, cements with lower C_3A contents, ASTM Types II and V, are more resistant to sulfate attack. Similarly concrete which exhibits low permeability is also more resistant to sulfate attack and the accompanying physical deterioration.

2.6 Abrasion

Traffic on pavements and industrial floors can result in severe wearing of concrete surfaces. Abrasion of concrete refers to wearing of these concrete surfaces by repeated rubbing or frictional processes [49].

The abrasion resistance of concrete is related to the hardness of the aggregate and the water/cement ratio of the concrete mix. Since the cement paste does not have good wearing characteristics by itself, hard, sound aggregate is essential for durable concrete surfaces. Aggregates such as pure limestone and chert provide very poor abrasion resistance, while traprock and granite provide excellent abrasion resistance. It is common practice to mix several different types of aggregates in concrete for wearing surfaces. The different aggregates wear at different rates, providing nonuniform surface wear and better abrasion resistance. In addition to the wearing characteristics of an aggregate, aggregates which fracture are often more advantageous than those that polish to a smooth finish.

Lower w/c ratios provide dense, strong concrete which will have improved wearing characteristics as shown in Fig. 2.10, when the wearing surface is properly finished with uniform steel troweling.

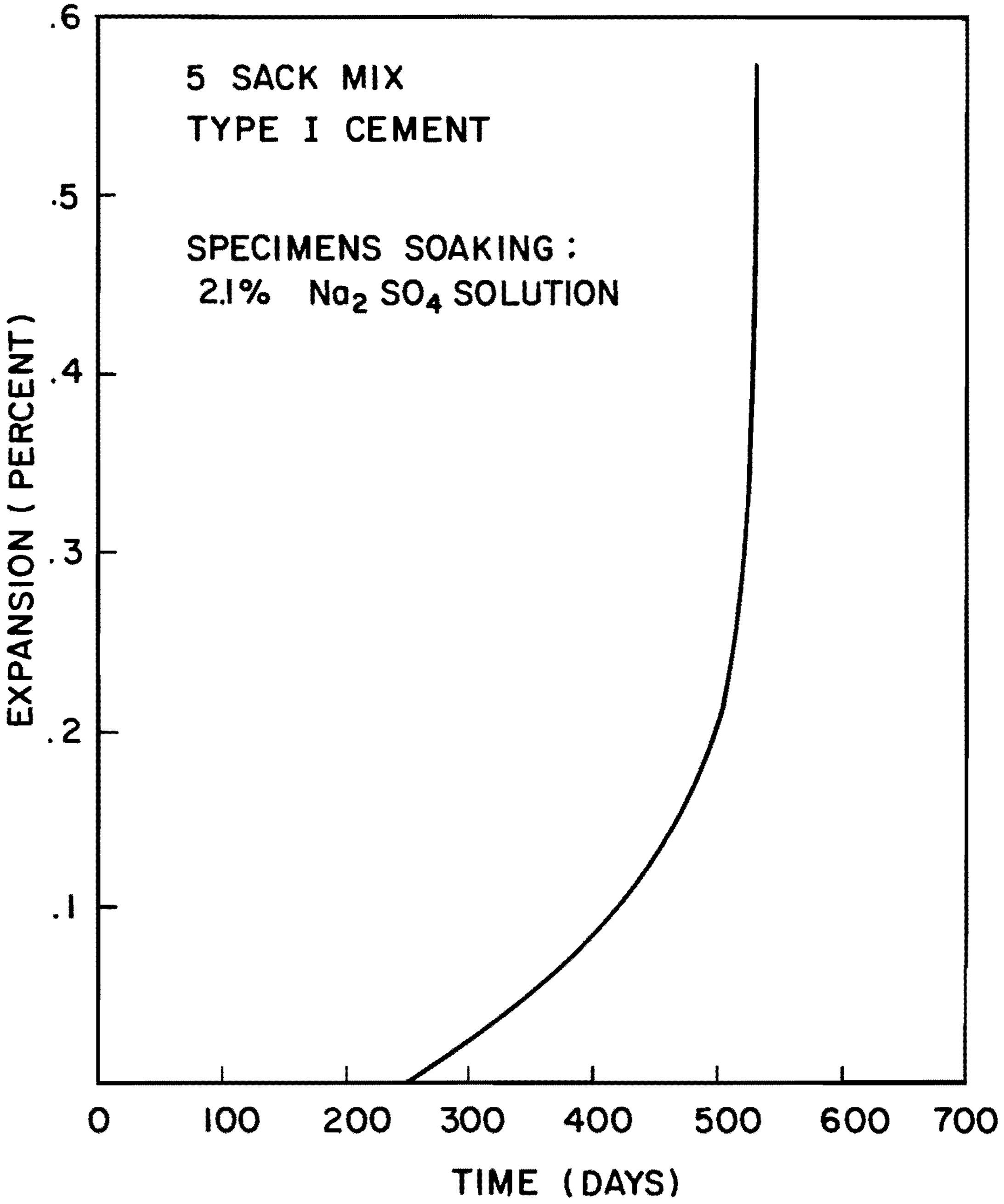


Fig. 2.9 Effect of sulfate on concrete [24].

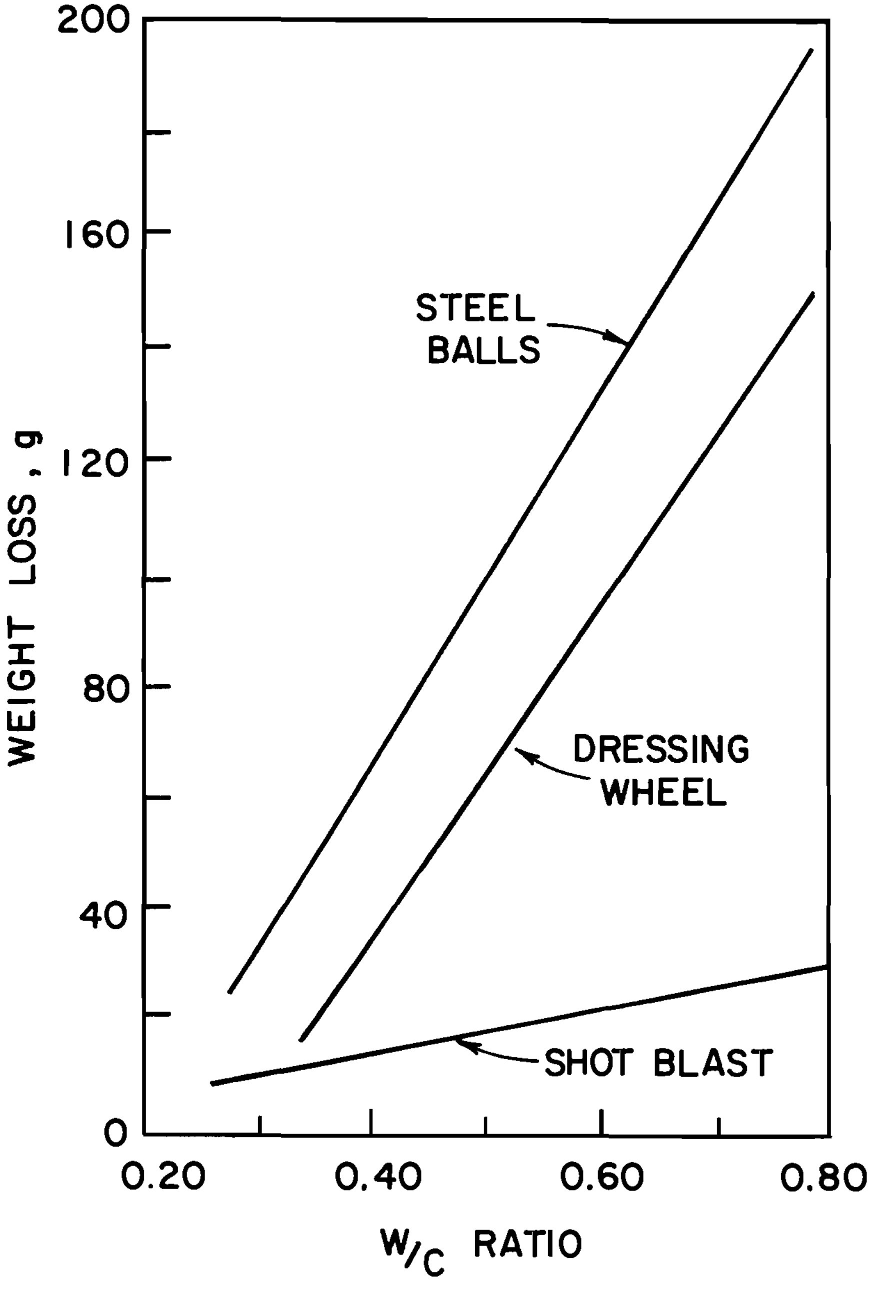


Fig. 2.10 Influence of w/c ratio on the abrasion resistance of concrete [65].

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

A review of literature pertaining to the effects of fly ash, used as a partial replacement for portland cement, on the properties of concrete is presented in this chapter. The review contained herein is restricted to literature related to the particular topics of this study. These topics include the effects of fly ash on air entrainment, freeze-thaw resistance, shrinkage, creep, abrasion resistance, sulfate resistance, and the strength of concrete. The results of previous studies have been incorporated wherever appropriate to substantiate facts and conclusions made throughout this study. Many of the studies cited in this chapter have been repeated by separate investigators using different fly ash and cement sources; as redundant as this may seem, the repetition is necessary in confirming the effects on concrete of a by-product material such as fly ash.

3.2 Effects of Fly Ash on Air Entrainment

The beneficial effect of air entrainment on concrete durability was clearly determined by the early 1930's. Several years later an interest arose in using fly ash as a component in concrete. The pioneer investigations into air-entrained concrete containing fly ash indicated that fly ash decreased the air content of concrete for a constant dosage of air entraining agent [14,22,23,42,50,70,79].

Each of the early studies provided a better understanding of the air content loss problem in concrete. Davis et al. [23] were the first to discover that fly ash affected the entrainment of air in cement mortars. In 1947, Taylor [70] recognized a rapid loss in air content when carbon black was used to darken concrete for pavements and established a distinct relationship between carbon content and air content. This study also confirmed the corresponding loss of durability with lower air contents. Mardulier [42] reported in 1948 that the particle size of carbon black is a predominant factor related to air loss in darkened concrete. Coarsely ground carbon black was shown to alleviate the problem of low air content in darkened concrete, indicating that the air content is related to the surface area as well as the amount of carbon in the concrete.

Although the relationship between carbon and air content was clearly established, it was not until 1952 that comprehensive investigations on the freeze-thaw resistance of concrete containing fly ash were completed [77,79]. Washa and Withey [79] investigated the effects of fly ash as a mineral admixture, studying strength and durability characteristics on concrete containing fly ash. This study determined that by increasing the air entraining agent dosage a specified air content can be obtained as shown in Fig. 3.1. Bloem [14] confirmed the results of Washa and Withey and noted that increasing amounts of air entraining agent are required for mixes with higher fly ash contents and that different ashes require different dosages of AEA. The significance of these early investigations is that the phenomena of air content loss in concrete containing fly ash was reduced to a problem of relating air entraining agent demand to the properties of the fly ash.

In 1954, Minnick [50] suggested that carbon adsorbs organic compounds, of which most AEAs are composed, and further postulated that once the carbon particles are saturated, the standard dosage of agent could be used to entrain the needed air. Data from later experimental programs [18,19,55] have agreed with most of Minnick's findings.

The results of Clendenning and Durie [18] showed a strong correlation between the AEA demand of the concrete, and both the carbon content and loss on ignition (LOI) of the fly ash. Since the LOI and the carbon content are inherently related to one another, the LOI has been adapted as a measure of the carbon content of fly ash. The primary reason for this is that the LOI can be easily determined by a laboratory test.

In addition to the LOI, the fineness of the fly ash plays an important role in the AEA demand of concrete containing fly ash. Clendenning [18] and others in more recent years [60,71] have found that as the fineness of the fly ash increases, the air content of the mortar and the concrete decreases, therefore adding to the air entraining agent demand.

The development of specifications for fly ash has resulted in different allowable limits on the LOI of a fly ash for use in concrete. ASTM C 618-84 has established a limit of 6% and Texas SDHPT a limit of 3% as the LOI of acceptable fly ash. While older studies concentrated on fly ashes with LOIs between 3 and 30%, more recent studies [54,60,71] have emphasized ashes within the specification limits, of 0 to 6% LOI. Rose and Floyd [60] showed that fly ashes with different finenesses and LOIs within the ASTM C618-84 specification vary greatly in the amount of AEA demand for a given air content. However they reported that LOI was the predominant factor affecting AEA demand. According to their study, concrete produced with 20% fly ash by weight having greater than 6% LOI did not generally reach 5% air content with dosages of up to 2.2 times the standard dose of AEA to achieve 5% air content in non-fly ash concrete. Burns et al. [15] investigated the possibility of neutralizing the demand of

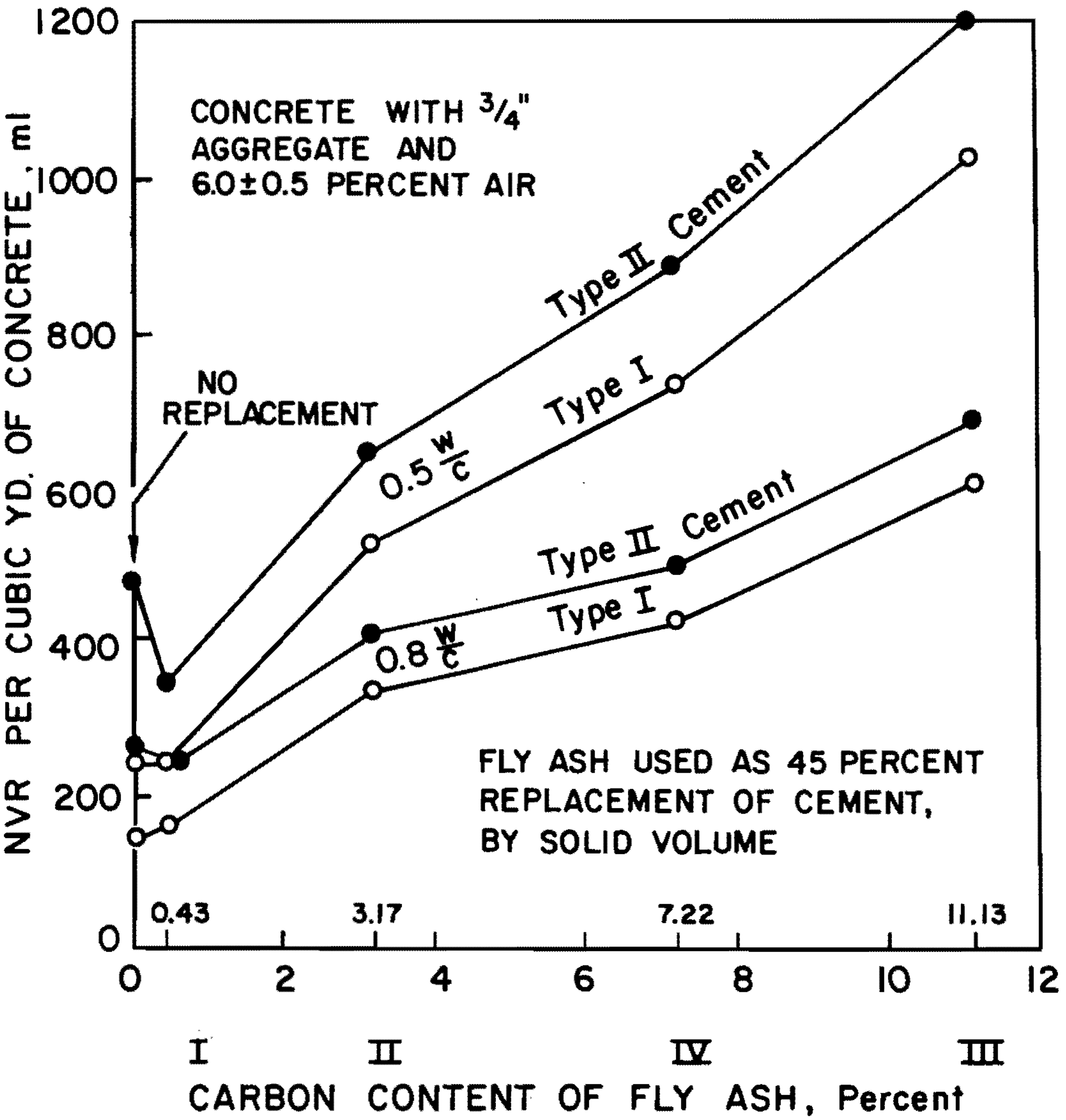


Fig. 3.1 Influence of carbon content of fly ash on the air entraining agent dosage for constant air content [50].

the carbon by using organic compounds which would be adsorbed preferentially by the carbon over most air entraining agents. Their findings indicated that chlorine gas and hypochlorines can be added safely to fly ash to effectively reduce the AEA dosage requirements in concrete for the most commonly used air entraining agents.

The control of entrained air in concrete containing fly ash is still not as predictable as in portland cement concrete. This is principally due to the variable sources of fly ash. However trial batching and the use of fly ashes with low carbon contents provide reliable AEA dosage information for the production of good quality and durable concrete.

3.3 Freeze-Thaw Resistance

There has been some concern as to the effect of fly ash on the freeze-thaw durability of concrete. Early research indicated that fly ash may have a detrimental effect on the resistance of concrete to freeze-thaw cycles [33,74,77]. These studies revealed that the freeze-thaw durability of concrete containing fly ash was reduced below acceptable levels on specimens containing equal volumes of air that were subjected to short curing times of about 7 to 14 days, followed by drying at relative humidities below 50% until testing. Short curing times in concrete containing fly ash result in lower early strength concrete while the drying induces shrinkage cracks. The combination of these two factors increase the permeability of the concrete, allowing water to enter into the matrix of the concrete. The expansion and contraction of the water during the freezing and thawing cycles progressively damages the concrete specimen until the integrity of the concrete is destroyed.

There is also evidence that fly ash can be used to improve the freeze-thaw resistance of concrete where calcium chloride accelerators are used [1]. The mechanism which enhances the durability is related to the reduction of free lime deposits and the deleterious effects accompanying them.

As shown in Fig. 3.2, more recent studies [18,19,32,34,54,64] have found that concrete specimens which have equal air contents and equal strengths will generally exhibit the same resistance to freeze-thaw action, regardless of whether the concrete contains fly ash or not. However, concrete containing fly ash has a substantially lower resistance to freeze-thaw damage at early ages, due to its slower strength gain characteristics. Larson [34] states that the primary effect of fly ash, related to freeze-thaw durability, is on the air entraining agent demand and not upon the characteristics of the air void system. If the air entrainment demand of fly ash is met and an adequate air content is obtained, then the concrete will exhibit adequate resistance to freezing and thawing cycles.

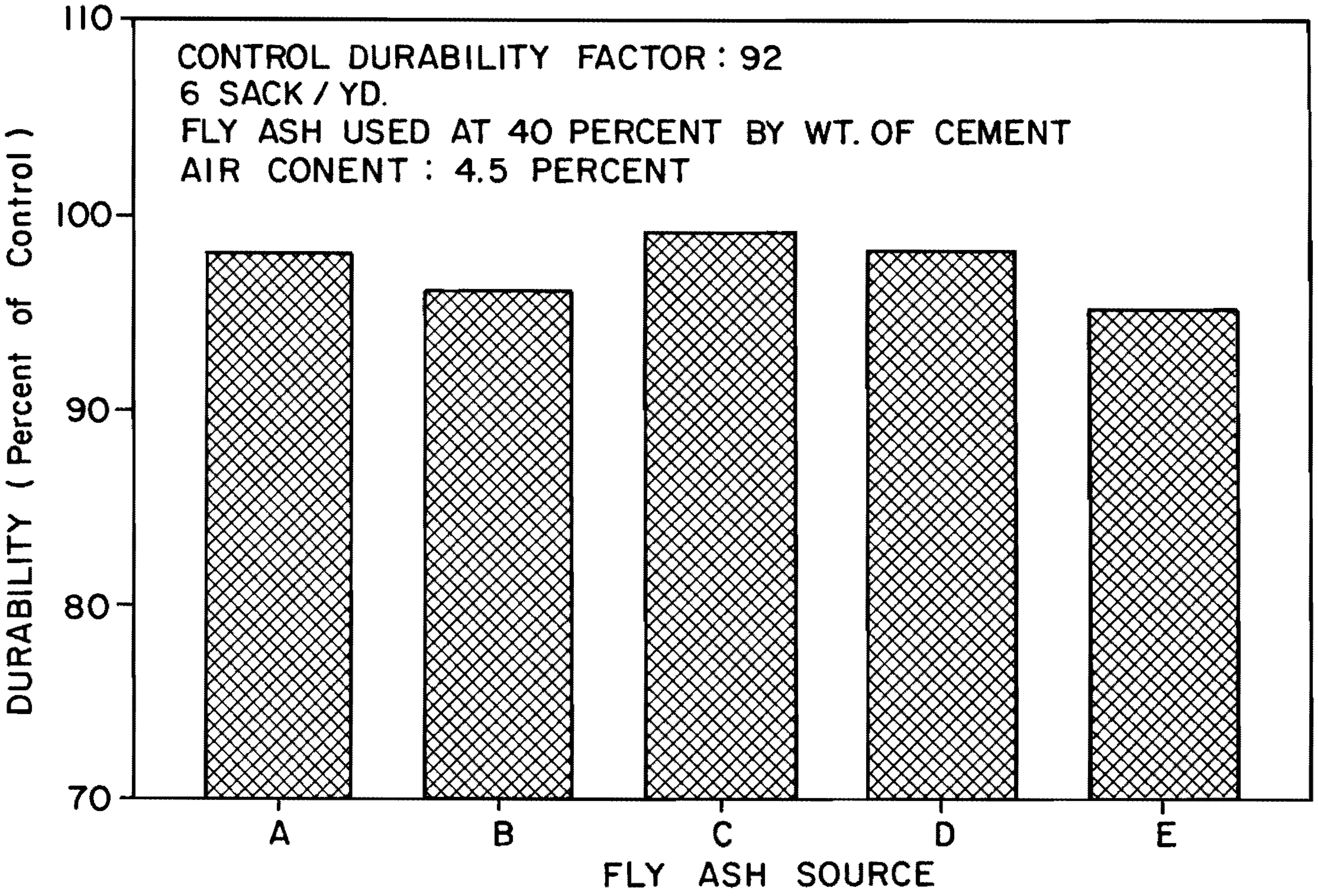


Fig. 3.2 Freeze-thaw durability of concrete containing fly ash [19].

Many other research studies have substantiated the above results. However the majority of the research has been done on Texas SDHPT Type A fly ash. Enough data is not presently available to make generalizations on the behavior of Texas SDHPT Type B fly ash.

3.4 Shrinkage

Numerous studies have indicated that drying shrinkage in concrete containing fly ash is the same as or less than that of portland cement concrete of equal workability [1,22,23,28,32,71,74]. Figure 3.3 shows that while drying shrinkage occurs at a slower rate in concrete containing fly ash at early ages, it approaches the same volumetric reduction over long periods of time.

Drying shrinkage is primarily a function of the volume of paste in the mix, and the water-cement ratio. The lower specific gravity of fly ash provides an increase in the volume of paste, for equal weight replacement proportioning, which tends to increase drying shrinkage. However the use of fly ash provides additional workability and allows a reduction in the water content for equal slump concretes, which in turn decreases the drying shrinkage. The combination of these two effects balance and produce no significant difference in drying shrinkage between concrete containing fly ash and plain portland cement concrete having the same workability.

3.5 Creep

The experimental results on the effect of fly ash on creep varies from concrete containing fly ash having a lower creep by up to 35% to an increase in creep of up to 15%. Creep is highly dependent upon the compressive strength and the modulus of elasticity of the concrete. Since concrete containing fly ash has a slower strength gain, tests on concrete containing fly ash loaded at early ages showed higher creep strains than those measured in plain concrete [22]. However, greater creep at early ages can be used to decrease the incidence of cracking in the concrete where low early strengths are acceptable such as in mass concrete [32,71]. More recent studies have shown that concrete containing fly ash exhibits up to 35% reduction in creep strains when compared to portland cement concrete containing no fly ash having the same strength and loaded at equal ages [71] as shown in Fig. 3.4.

In other programs, creep in fly ash - portland cement concrete showed no significant difference from plain concrete when a 25% replacement by weight was used and specimens were loaded between 28 and 100 days. Specimens containing fly ash loaded after 100 days produced progressively less creep [28,71]. The decreasing creep strains may be attributed to the continuing strength gain of fly ash-

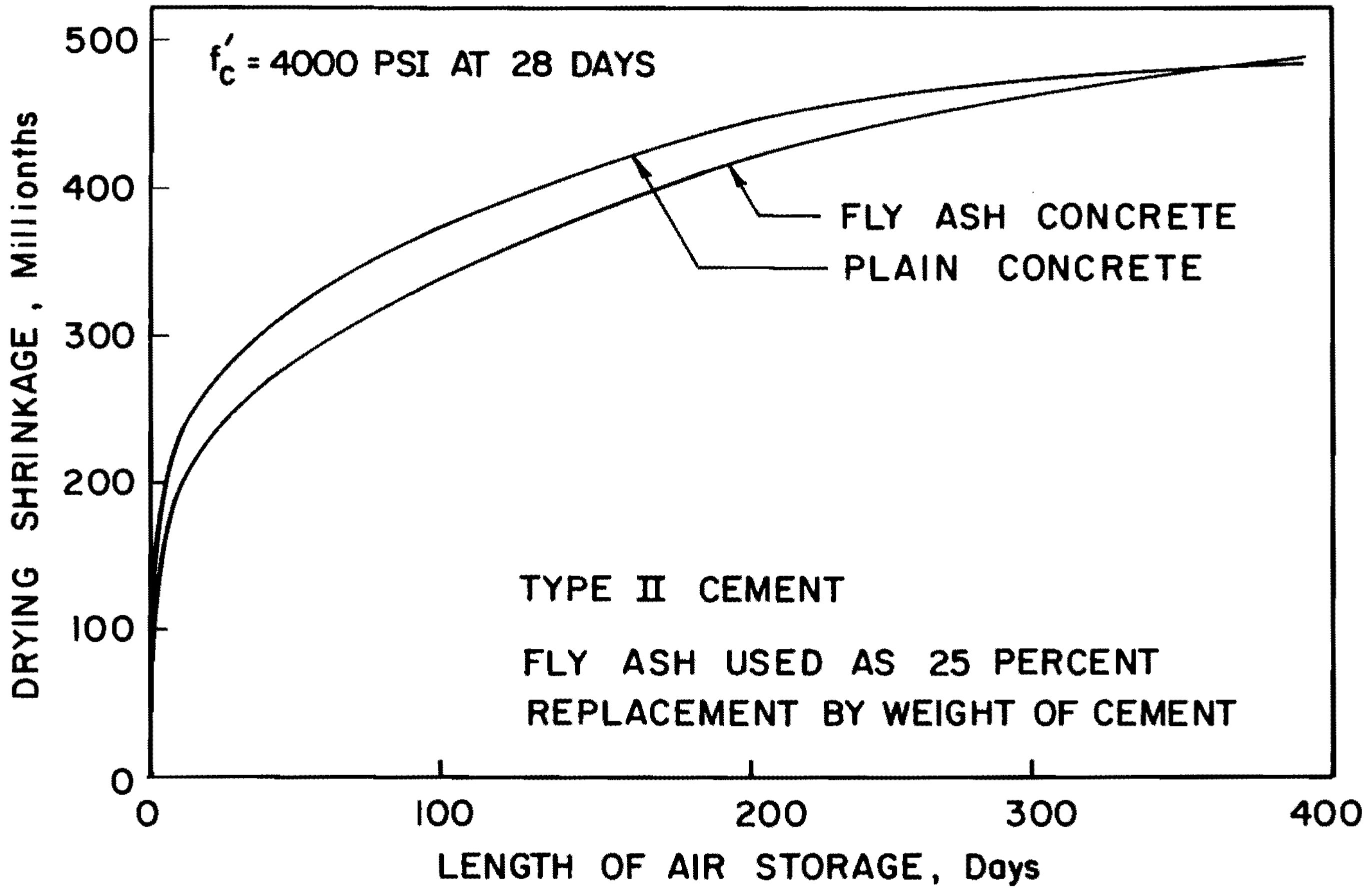


Fig. 3.3 Comparison of drying shrinkage in concrete [71].

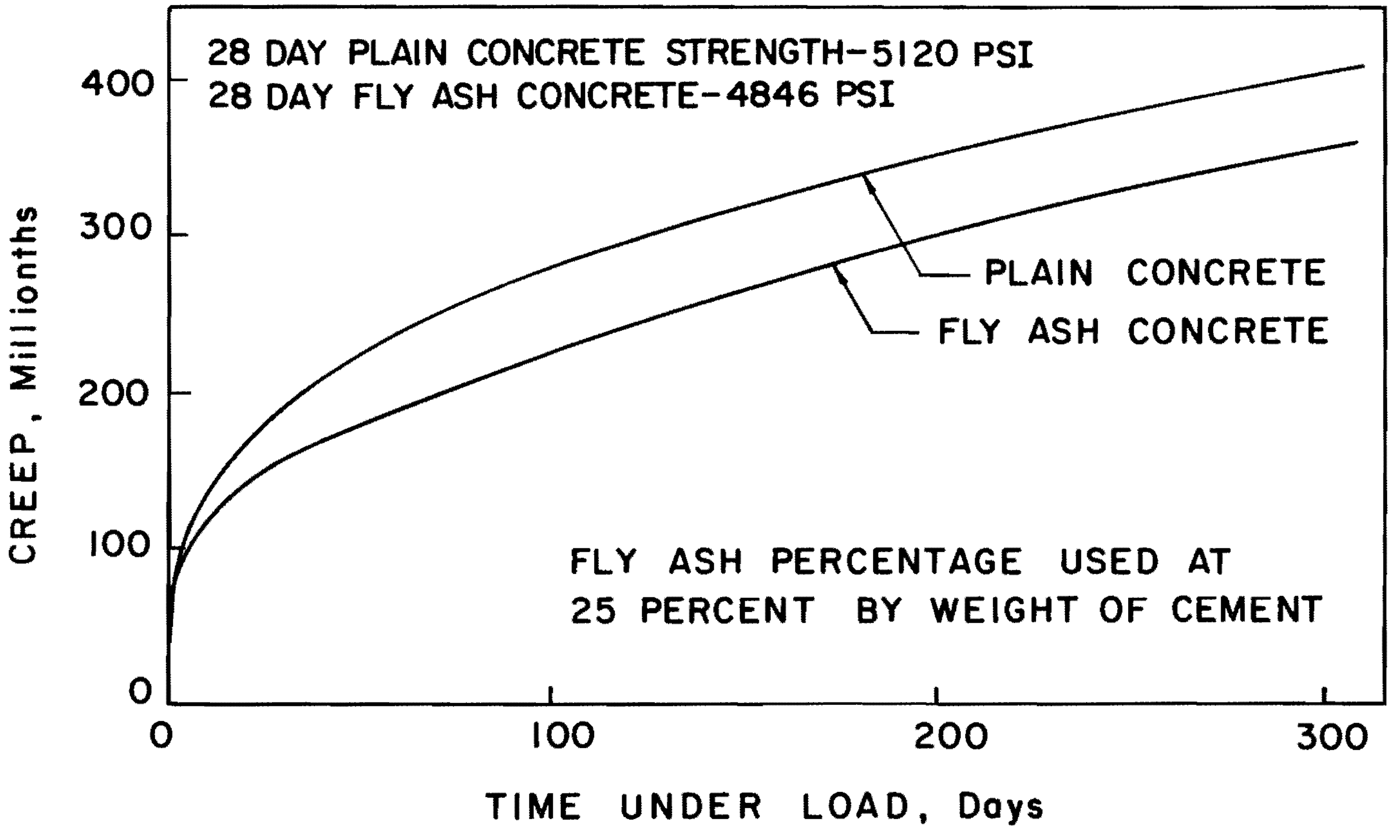


Fig. 3.4 Comparison of creep in plain concrete and concrete containing fly ash [71].

portland cement concrete after the time of loading, whereas the portland cement concrete strength gain at later ages is minimal.

3.6 Abrasion

Early studies performed by the United States Bureau of Reclamation [76,77] on concrete containing fly ash indicated a decrease in the abrasion resistance in lean mixes typical of those used in mass concrete. However very little experimental data is available to substantiate this trend for richer mixes such as those used in pavement concrete. Since the abrasion resistance of concrete is controlled by the compressive strength, curing and finishing properties of the concrete, it is believed that the effect of fly ash on these properties will control the wear resistance of concrete containing fly ash.

In a Federal Highway Administration study completed in 1981, the wear resistance of concrete containing fly ash was found to be related to the compressive strength of the concrete at the time of testing [64]. When concretes are compared at equal strengths or later ages, the abrasion resistance of concrete containing fly ash is superior to that of plain portland cement concrete as shown in Fig. 3.5. This may be due to the improved surface hardness from reduced bleeding and higher compressive strengths of concrete containing fly ash over the lifetime of the concrete.

3.7 Sulfate Resistance

The beneficial effect of pozzolans on the sulfate resistance of concrete was first recognized by Jewett and published in the "Engineering Record" in 1908. Since that time, studies have shown that most concrete containing fly ash consistently improved the sulfate resistance of concrete over similar concrete produced without fly ash [24,25]. This is not true of all pozzolans. Blast furnace slags and even some isolated sources of fly ash have been shown to cause a significant decrease in the sulfate resistance of concrete [25]. For this reason, it is extremely important to evaluate the chemical composition of the fly ash before using it as a component in concrete. Dikeou [24] and Dunstan [25] report that the calcium and iron contents of the fly ash are the important factors related to the sulfate resistance of concrete containing fly ash. As the calcium content of the fly ash increases, the sulfate resistance of concrete decreases, and as the iron content of the fly ash increases, the sulfate resistance of concrete increases.

Although several theories exist as to why the presence of fly ash improves the resistance of concrete to sulfate attack, there is no single accepted theory as of this writing. Several characteristics of

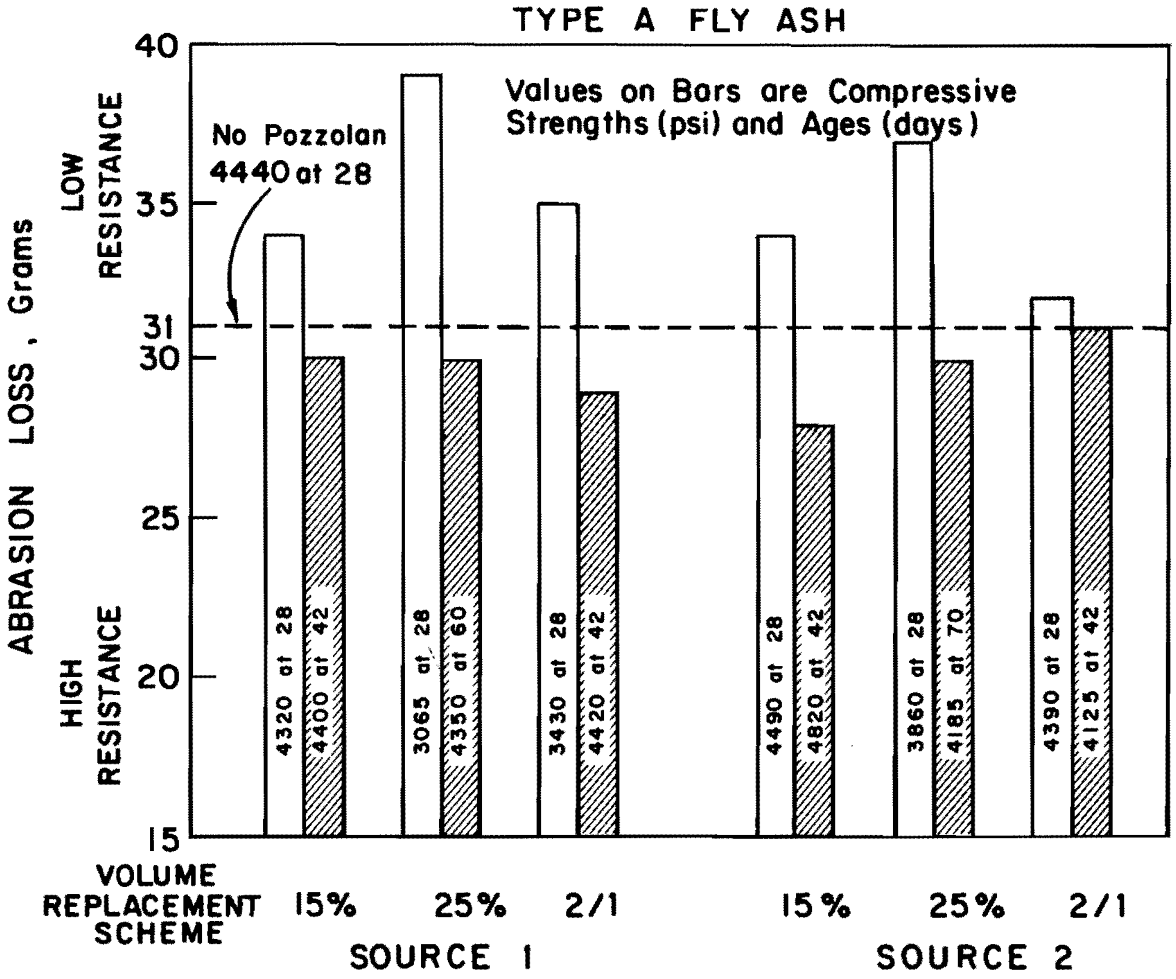


Fig. 3.5 Abrasion loss in concrete containing fly ash [64].

concrete containing fly ash lead to increased impermeability in concrete. The pozzolanic reaction of fly ash and free lime in the paste prevents the free lime from leaching out of the concrete by forming a stable calcium silicate hydrate, thereby decreasing the porosity of the concrete over similar concrete without fly ash. Furthermore when fly ash is used as a replacement for portland cement, the total amount of C_3A in the paste is decreased. This decreases the available alumina which could combine with the sulfates and calcium hydroxide to form ettringite. Ettringite is the expansive compound which forms during sulfate attack. The expansive action of the ettringite introduces internal tensile stresses in the concrete and eventually degrades the concrete paste.

Texas SDHPT Types A and B fly ash can be satisfactorily used to combat sulfate attack if proper guidelines existed. However, Type B fly ash usually contains substantial amounts of calcium and alumina oxides and should only be considered after careful investigation. When Type B fly ash is used in small amounts, the sulfate resistance of the concrete may be substantially diminished, as shown in Fig. 3.6.

Fly ash has been used throughout the United States in concrete exposed to sulfate attack. Most notably by the U.S. Bureau of Reclamation in structures exposed to sea water and by the concrete pipe industry for pipes which are exposed to sulfate rich soils on the exterior or are used to transport concentrated sulfate solutions.

3.8 Strength

The number of published studies relating concrete strength of fly ash concrete are too many to quote. These studies have used different ashes, specimens, proportioning techniques, fly ash contents, replacement schemes, water contents, testing methods, mixing procedures, curing conditions and admixtures. The variability of each of these studies make it extremely difficult to compare their results. However there are specific correlations between the conclusions of these studies which provide definite trends relating strength to the properties of concrete containing fly ash.

It is generally acknowledged that the early rate of strength gain of concrete containing fly ash for any fly ash content is equal to or lower than that of concrete containing an equal weight or volume of portland cement as shown in Fig. 3.7. The fundamental reason for the lower strength gain of fly ash concrete is that fly ash contributes to the strength of the concrete mainly through a pozzolanic reaction, which requires the presence of free lime (CaO). Free lime is a byproduct of the cementitious reaction of portland cement and water. Therefore, the cementitious reaction must occur first in order for the fly ash to react and provide strength to the concrete. Although the strength gain is slower in concrete containing

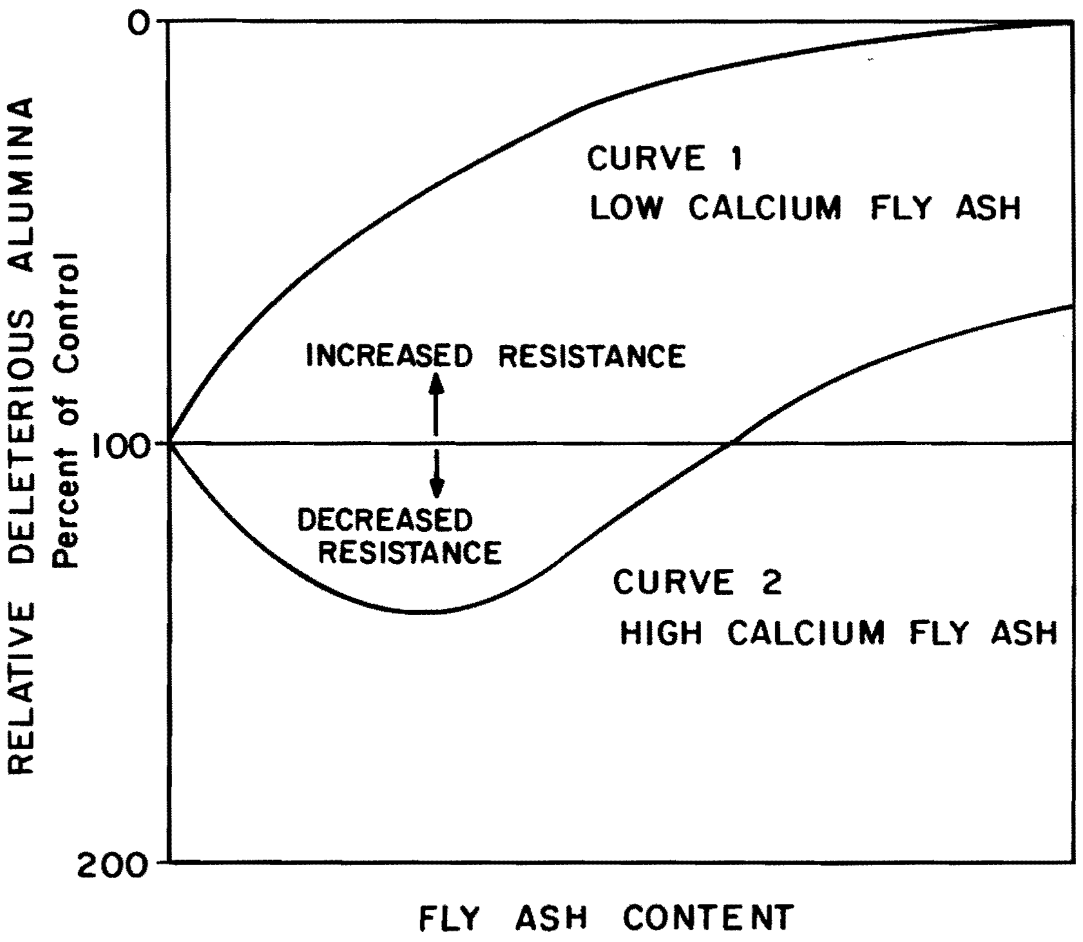


Fig. 3.6 Effect of fly ash content on sulfate resistance of concrete [25].

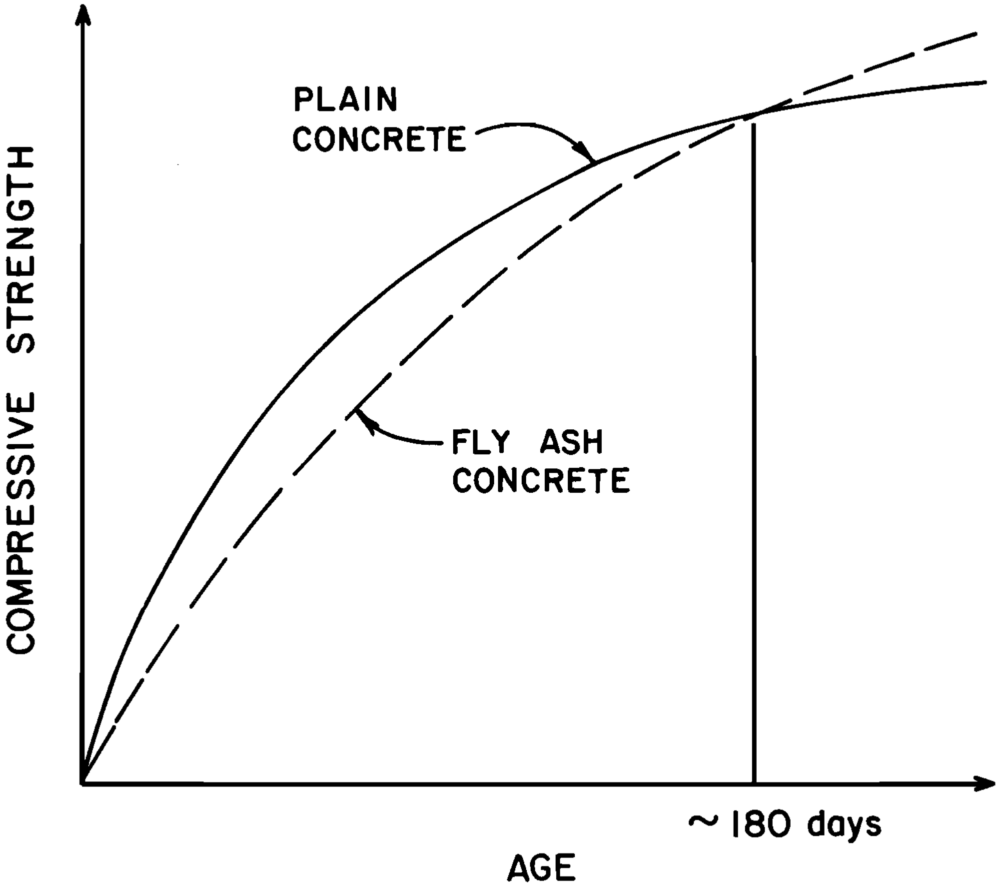


Fig. 3.7 Strength development of concrete with and without fly ash [39].

fly ash it continues for much longer than the reaction of portland cement. This results in lower early age strengths and higher ultimate strengths for concrete containing fly ash [2,9,14,16,18,22,23,32,33,50,53,71,74,77,79].

The use of different types of fly ash is also a primary factor in determining the strength behavior of fly ash concrete. Fly ash blended into portland cement and fly ash containing large quantities of free lime provide higher strength gain characteristics, as do finer fly ashes as is shown in Fig. 3.8.

Different proportioning techniques, replacement schemes and fly ash contents affect the ultimate strength of concrete [16]. Direct weight replacement of portland cement holds the cementitious content constant, whereas direct volume replacement decreases the cementitious content of the mix. The cementitious content is the amount of portland cement plus fly ash by weight. In general, for below 40% replacement, the direct weight replacement method provides higher ultimate strengths than the equal volume replacement method for a given fly ash. Figure 3.9 shows that the use of fly ash is effective in increasing the strength in both lean and rich concrete mixes for either of these replacement schemes [1]. Replacement schemes which include replacing a percentage of the fine aggregate increase the cementitious content and the strength but make it difficult to generalize about strength behavior as compared to equivalent portland cement concrete mixes [32,39,71].

Since fly ash makes concrete more workable for a given w/c ratio and has lower early strength, both water content and curing conditions affect the ultimate strength of concrete containing fly ash [77,79]. Reduction of the water content to a level of a minimum acceptable workability will provide higher ultimate strengths as will slightly longer curing conditions.

In conclusion, the ultimate strength of concrete containing fly ash may be equal to or better than that of portland cement concrete on an equal weight or volume replacement percentage. The rate of strength gain may be slower but the strength will generally be greater after 100 days.

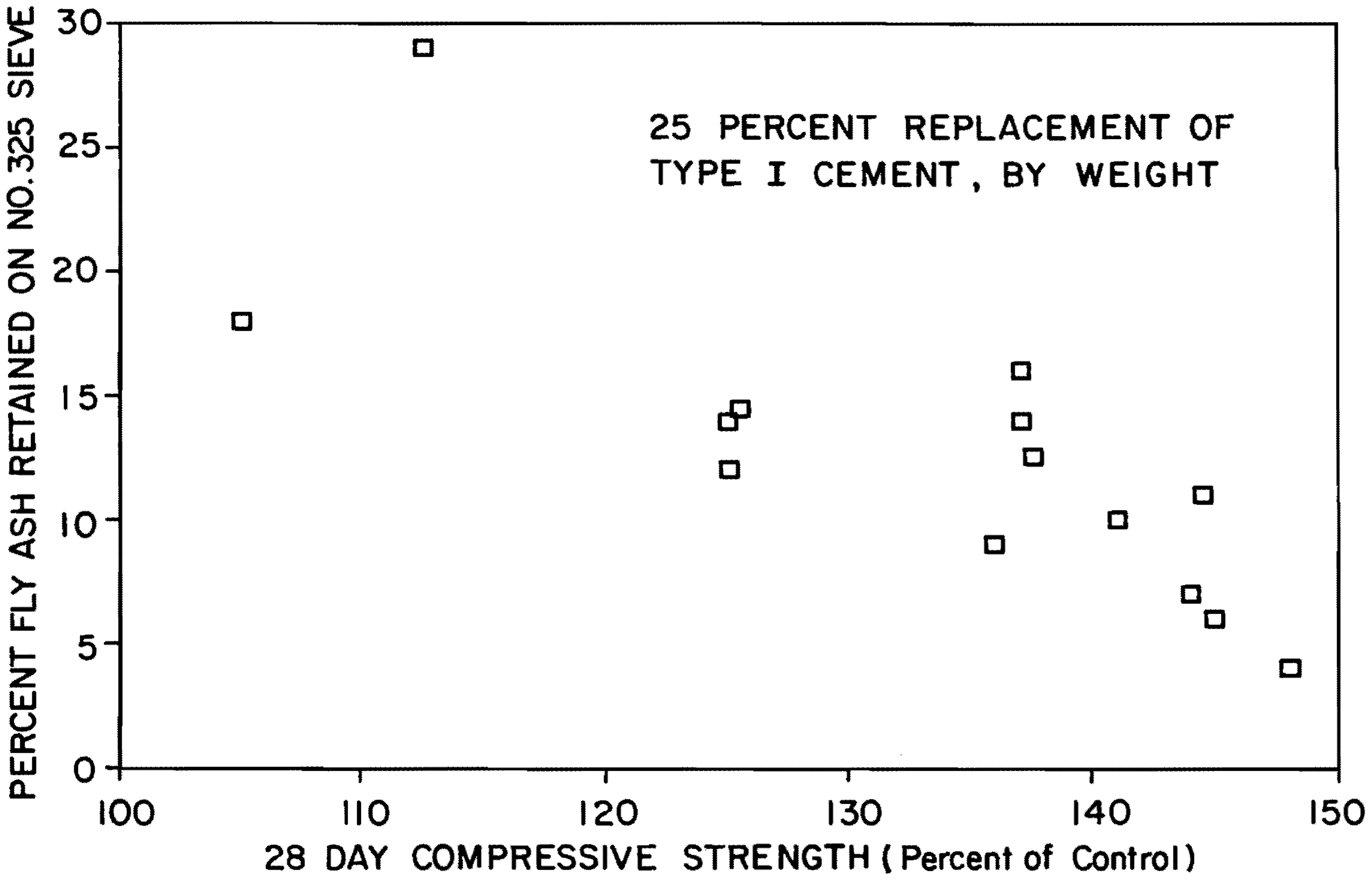


Fig. 3.8 Effect of fly ash fineness on concrete strength [19].

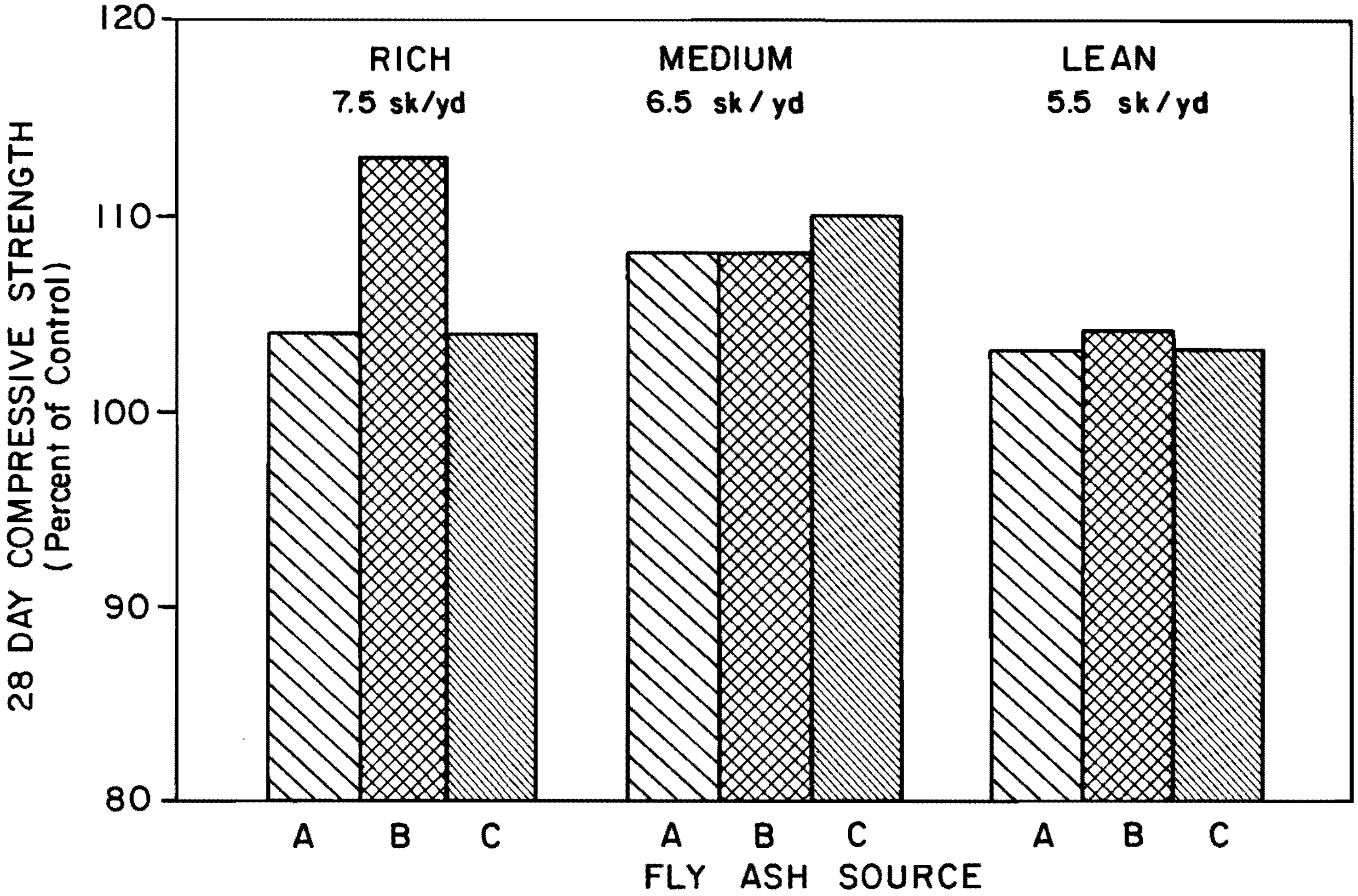


Fig. 3.9 Strength of concrete containing fly ash with varying cementitious content for mixes having 25% fly ash replacement by volume of cement [19].

CHAPTER 4

MATERIALS AND EXPERIMENTAL PROGRAM

4.1 Introduction

The testing procedures and materials described herein are currently approved procedures and materials by the Texas SDHPT. Furthermore, all the materials used in this experimental program are commercially available throughout Texas.

The testing procedures and material standards comply with those described in the Texas SDHPT Manual of Testing Procedures Physical Section 400-A Series, the American Society for Testing and Materials' 1984 Annual Book of ASTM Standards, Part 13, "Cement; Lime; Gypsum," and Part 14, "Concrete and Mineral Aggregates," and the Texas SDHPT 1982 Standard Specifications for Construction of Highways, Streets and Bridges.

4.2 Materials

The materials used in this experimental program are those typically used in the production of concrete: portland cement, coarse aggregate, fine aggregate, water reducing-retarding and air entraining admixtures, and water. In addition to these materials, two types of fly ash were included, Texas SDHPT D-9-8900 Type A and Type B.

4.2.1 Portland Cement. Two types of portland cement are considered in this study: Type I and Type IP. The Type I portland cement was commercially produced by General Portland, Inc., at the Trinity South Division Plant near New Braunfelds, Texas. The Type I cement was produced in accordance with ANSI/ASTM C 150-80, "Standard Specification for Portland Cement". The Type IP portland cement was commercially produced by Texas Industries, Inc., at the Cement Division Plant located in Midlothian, Texas. The Type IP cement was produced in accordance to ANSI/ASTM C595-79, "Standard Specification for Blended Hydraulic Cement," and contains approximately 20% Texas SDHPT Type A fly ash by weight. The chemical and physical properties of the Type I and Type IP portland cements are presented in Table 4.1 and Table 4.2, respectively.

For initial mix design purposes the specific gravity of both types of portland cement was assumed to be 3.10 as recommended by the Texas SDHPT mix design procedure [72]. Mix proportions were adjusted for the appropriate specific gravity of the cement used as shown in section 4.3, "Mix Proportioning". The fly ash used in the Type IP blended cement will be addressed later in this chapter under Sec. 4.2.6, "Fly Ash".

Table 4.1 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^2/gm	
Wagner	1880 cm^2/gm	
Compressive Strength		
1-day	2020 psi	
3-day	3800 psi	
7-day	4760 psi	

Table 4.2 Chemical and Physical Properties of Type IP Portland Cement

Chemical Composition		Percent
Silicon Dioxide (SiO)		28.9
Aluminum Dioxide ($A1_2O_3$)		7.9
Ferric Oxide (Fe_2O_3)		3.8
Calcium Oxide (CaO)		53.1
Magnesium Oxide (MgO)		.1
Sodium Oxide (NaO)		.2
Potassium 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^2/gm	
Wagner	1355 cm^2/gm	
Compressive Strength		
1-day	1922 psi	
3-day	3513 psi	
7-day	4545 psi	
28-day	6093 psi	

4.2.2 Coarse Aggregate. The coarse aggregate used in this study consisted of two sizes of round siliceous river gravel. A 1-in. nominal maximum size, THD Grade No. 4 coarse aggregate, was used in all specimens except those specimens in the abrasion testing procedures, where 1 1/2-in. nominal maximum size aggregate was used to represent the standard aggregate in pavement concrete. For this aggregate, the bulk specific gravity at SSD was 2.52, the absorption capacity was 4.0% and the dry rodded unit weight was 98 pounds per cubic foot.

4.2.3 Fine Aggregate. The fine aggregate used in this experimental program was a natural siliceous sand having a bulk specific gravity at SSD of 2.61. The absorption capacity of the fine aggregate was 2.6% and it had a fineness modulus of 2.73.

4.2.4 Admixtures. Four liquid admixtures were used in this study: a water reducer-retarder, Pozzolith 300R, a vinsol resin air entraining agent, MB-VR, a non-vinsol resin air entraining agent, MB-AE-10 and an organic resin air entraining agent, Micro Air. The admixtures were used in compliance with Texas SDHPT Standard Specification Item 437 and with the exception of micro air, are approved admixtures by the Texas SDHPT Material and Test Division. The water reducer-retarder meets the requirements of ASTM C 494, while the air entraining agents meet the requirements of ASTM C 260.

4.2.5 Water. The mixing water utilized throughout this program was potable tap water approved by the Texas State Health Department in compliance with Texas SDHPT Standard Specification Item 421.2.

4.2.6 Fly Ash. Fly ashes satisfying Texas SDHPT Departmental Material Specification D-9-8900 and ASTM 618-80 were used in this study for mixes containing fly ash. Low calcium fly ash, Texas SDHPT Type A, was obtained from the Big Brown Plant near Fairfield, Texas and high calcium fly ash, Texas SDHPT Type B, was obtained from the Welch Plant near Cason, Texas. The fly ash used in the blended Type IP cement was from the Monticello Plant in Mt. Pleasant, Texas and is classified as Texas SDHPT Type A fly ash. A summary of the physical and chemical test results for these three fly ashes is presented in Table 4.3 along with the Texas SDHPT material specification D-9-8900 requirements.

The fly ashes used as a mineral admixture throughout this study had a loss of ignition below 0.45% and a fineness of less than 13% retained on the no. 325 sieve. These fly ashes were used as a partial replacement by weight of the portland cement at the rate of 20 and 35% in the concrete mixes.

Table 4.3 Fly Ash Chemical Composition

	Experimental Program			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

These fly ashes are typical of those produced throughout Texas and are commercially available as Texas SDHPT approved sources in Texas.

4.3 Mix Proportioning

The fundamental concrete mix proportions used in this study were designed according to the Texas SDHPT 1982 Standard Specification for Construction of Highways, Streets and Bridges, Item 421, Class S. All the concrete mixes in this experimental program were based on the design factors and basic proportions presented in Table 4.4 with the exception of the series of specimens used in the abrasion tests. The series of specimens used in the abrasion resistance testing were mixed according to Texas SDHPT Standard Specification Item 360 with a cement factor of 5.5 sacks/yd^3 of concrete and a coarse aggregate factor of 0.77. The actual mix proportions differ slightly from the design mix proportions because the mixing water was adjusted in each mix to obtain equal workability and a slump between 3 and 4 inches.

Fly ash was used as a direct weight replacement of portland cement in the quantities of 20 and 35% in the mixes of concrete containing fly ash. The volume of the fresh concrete was increased due to the difference in specific gravity of fly ash and portland cement. Therefore the mix proportions were adjusted to compensate for the increased yield by reducing the fine aggregate content appropriately.

4.4 Mixing Procedures

The concrete mixing was done under laboratory conditions in a 6 cu.ft. electric revolving drum tilting mixer according to ASTM C192-76, "Standard Method of Making and Curing Concrete Test Specimens in the Laboratory." All batches were larger than 1/2 the capacity of the mixer and were made at an ambient laboratory temperature of 73 ± 3°F.

All the concrete materials were stored indoors at room temperatures prior to mixing. The aggregates were kept in separate 2-cu.yd. bins, and the cement and fly ash were stored in metal moistureproof containers. Chemical admixtures were stored at room temperature in sealed 3 gallon containers. Mixing was accomplished in two intervals: 3 minutes of initial mixing, followed by a 3 minute rest and 2 minutes of final mixing. The quantity of mixing water was determined based on a slump requirement of 3 to 4 in.

The concrete was placed in lightly oiled metal forms. The concrete specimens were covered with wet burlap for the first 24 hours, and then demolded and placed in a laboratory curing room. The curing room was kept at 73 ± 3°F and 100% relative humidity, according

Table 4.4 Concrete Mix Proportion Design

Design Factors	
Cement Factor (CF)	6.0 sacks per cu.yd.
Coarse Aggregate Factor (CAF)	0.77
Water Factor (WF)	5.0 gal per sack
Air Factor (AF)	5.0%
Batch Factor	6.0 batches per cu.yd.
Admixtures	
Pozzolith 300R	33 oz per cu.yd.
MB-VR	1/2 oz per sack
or	
MB-AE-10	3/8 oz per sack
or	
Micro Air	1 oz per sack
Design Mix Proportions	lb/cu.yd
Cement	564
Coarse Aggregate	2005
Fine Aggregate	1002
Water	250

to ASTM C511-80, "Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes". All prismatic specimens made with 35% fly ash content using Texas SDHPT Type A fly ash were demolded at 36 hours to prevent damage during the demolding procedures. These specimens were typically fragile after the first 24 hours.

4.5 Fresh Concrete Testing

The fresh concrete of each mix was tested for slump, air content and unit weight. The concrete slump was measured according to ASTM C143-78, "Standard Test Method for Slump of Portland Cement Concrete" and Texas SDHPT procedure TEX 415-A, "Slump of Portland Cement Concrete". The air content of the fresh concrete was determined according to ASTM C231-78, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method", with a Type B meter. The unit weight of the concrete was measured using a metal 0.25 cu.ft. bowl in compliance with ASTM C 138-77, "Standard Test Method for Unit Weight, Yield and Air Content of Concrete". All three test procedures were performed immediately after final mixing and before placing the concrete in the molds.

4.6 Hardened Concrete Testing

A hardened concrete testing program was established in this study to compare both the strength and durability characteristics of concrete containing fly ash to those of portland cement concrete. All the concrete was designed and mixed according to Texas SDHPT Specifications. The following six tests were performed on various size concrete specimens:

a) Compressive Strength;

b) Flexural Strength;

c) Freeze-Thaw Durability;

d) Shrinkage;

e) Creep; and

f) Abrasion Resistance.

Each of these tests was performed under controlled laboratory conditions on specimens of equal age, geometry and cement plus fly ash content.

4.6.1 Compressive Strength. The compressive strength of concrete was measured on 6 x 12 in. cylindrical specimens cast in reusable steel molds and capped with Forney's High Strength Sulfur Capping Compound according to ASTM C 617-76, "Standard Method of Capping Cylindrical Concrete Specimens". The compressive strength of the concrete was determined according to ASTM C 39-79, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" and Texas SDHPT procedure TEX 418-A, "Compressive Strength of Molded Concrete Cylinders". A SATEC 400 kip compression testing machine calibrated in accordance with ASTM E 4-79, "Standard Methods of Load Verification of Test Machines", on 8/12/83 was used for all compression testing.

4.6.2 Flexural Strength. Flexural strength testing was performed on 6 x 6 x 20 in. prismatic beams according to ASTM C 293-79 "Standard Test Method for Flexural Strength of Concrete" and Texas SDHPT procedure TEX-420-A, "Flexural Strength of Concrete". The test used a center point loading set up having a simply supported 18-in. span. The flexural test was performed on a Rainhart Series 416 Beam Tester with a manual hydraulic load application device.

4.6.3 Freeze-Thaw Resistance. The durability of concrete subjected to repeated freezing and thawing cycles was tested in accordance to ASTM C 666-80, "Standard Test Method for Resistance of Concrete to rapid Freezing and Thawing". Procedure B was followed using 3 x 4 x 16 in. prismatic specimens, which determines the resistance of concrete specimens by rapid freezing in air and thawing in water. The specimens were moist cured for 14 days and then frozen at 0°F until testing could begin. All specimens completed 300 freeze-thaw cycles and were monitored twice weekly by weighing the specimen and measuring the fundamental transverse frequency of the beam according to ASTM C 215-76, "Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens".

4.6.4 Shrinkage. Shrinkage was measured in two parallel series of tests; one series consisted of specimens moist cured for 3 days and the other series of specimens moist cured for 7 days before shrinkage testing began. The shrinkage testing was performed in a controlled environmental chamber at a temperature of 100 ± 1°F and a relative humidity of 32 ± 2%. The temperature was controlled by an automated thermostat and the relative humidity was controlled through the use of solid magnesium chloride. Two sets of gage points were placed longitudinally on each 3 x 4 x 16 in. specimen. The points were positively affixed with an epoxy resin adhesive at 8-in. gage lengths. The shrinkage strains were measured using a portable DeMec Mechanical Strain Gage.

4.6.5 Creep. Creep in concrete was measured according to ASTM C 512-76, "Standard Test method for Creep of Concrete in

Compression". Two 6 x 12 in. cylindrical specimens were placed in series in each frame and loaded approximately to 0.40 f'_c. The load was maintained by monitoring low stiffness springs at the frame base. Two unloaded specimens were kept in the same environment as those being tested as a control to indicate deformations due to reasons other than load such as shrinkage and temperature. Each specimen had three sets of gage points equally spaced about the circumference of the cylinder. The positively attached gage points were placed at 8-in. gage lengths and length measurements were made using a DeMec Mechanical Strain Gage.

4.6.6 Abrasion Resistance. The abrasion resistance of concrete was determined in accordance with ASTM C 944-80, "Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating Cutter Method". Specimens 4 1/4 x 6 x 12 1/2 in. were tested after being moist cured for 28 days and air dried at 50% relative humidity for 7 days. A Soiltest drill press was used with the dressing wheel rotating at 200 rpm and a downward force of 10 kilograms. Each specimen was subjected to four 2-minute abrasion periods. After each period, the mass of the specimen was measured to the 0.5 gram and the depth of wear at predetermined locations was measured with a micrometer mounted on an InVar reference frame.

CHAPTER 5

TEST RESULTS: EFFECT OF FLY ASH ON CONCRETE

5.1 Introduction

Concrete containing fly ash was studied in this experimental program to compare the characteristics of concrete containing fly ash to those of plain concrete. The experimental results of this study are presented in this chapter and will be discussed thoroughly in the succeeding chapter. The data presented herein was compiled from tests performed on over 400 specimens between November, 1984 and December, 1985.

The test data is presented both in graphical and tabular form to facilitate interpretation. Appendix A contains the proportions used in this study. The nomenclature used throughout the testing program to identify specimens is presented in Table 5.1. Specimen designations consist of four parts: 1) a number designating the amount of fly ash used in the mix as a percentage of the total cementitious content by weight; 2) two upper case letters indicating the type of air entraining agent used; 3) one upper case letter indicating the type of fly ash used; and 4) one upper case suffix denoting whether a standard dose (D) of air entraining agent was used or the dosage was adjusted to obtain a 5% air content in the concrete (A).

5.2 Mix Proportions

The mix design proportions were presented in the preceding chapter. Table 5.2 lists the specification requirements for Texas SDHPT Specification Item 421, Class S Concrete. Fly Ash was used as a direct replacement for portland cement by weight. This replacement scheme is recognized by American Concrete Institute Standard 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete." Where fly ash was used as a replacement for portland cement in concrete, the water/"cement + fly ash" ratio (w/c+p) is used in place of the water/cement ratio (w/c). The "cement + fly ash" content is defined hereafter as the combined weight of cement plus fly ash per cu.yd. of concrete, and a "sack" will refer to 94 lb of cementitious material, either fly ash, portland cement, or a combination of cement plus fly ash.

5.3 Data Acquisition and Reduction

All the data points in this chapter are presented as the average of at least three separate tests performed on identical

Table 5.1 Mix Design Nomenclature

Mix Designation	Fly Ash % by wt	Fly Ash type	Air Entraining Agent	Dosage
OVRN-D	0	N/A	MB-VR	STANDARD
OAEN-D	0	N/A	MB-AE-10	STANDARD
20VRA-D	20	A	MB-VR	STANDARD
20AEA-D	20	A	MB-AE-10	STANDARD
20VRA-A	20	A	MB-VR	ADJUSTED
20AEA-A	20	A	MB-AE-10	ADJUSTED
20VRB-D	20	B	MB-VR	STANDARD
20AEB-D	20	B	MB-AE-10	STANDARD
20VRB-A	20	B	MB-VR	ADJUSTED
20AEB-A	20	B	MB-AE-10	ADJUSTED
35VRA-D	35	A	MB-VR	STANDARD
35AEA-D	35	A	MB-AE-10	STANDARD
35VRA-A	35	A	MB-VR	ADJUSTED
35AEA-A	35	A	MB-AE-10	ADJUSTED
35VRB-D	35	B	MB-VR	STANDARD
35AEB-D	35	B	MB-AE-10	STANDARD
35VRB-A	35	B	MB-VR	ADJUSTED
35AEB-A	35	B	MB-AE-10	ADJUSTED
IPVRA-D	TYPE IP CEMENT		MB-VR	STANDARD
IPAEA-D	TYPE IP CEMENT		MB-AE-10	STANDARD

Table 5.2 Texas SDHPT Specifications for Item 421 Class S Concrete

Minimum Cement Content	564 lb/cu.yd
Minimum 28-day Compressive Strength	3600 psi
Minimum 7-day Beam Strength for Type I Cement	600 psi
Minimum 7-day Beam Strength for Type II Cement	550 psi
Maximum Water/Cement Ratio by Weight	.44
Coarse Aggregate Number	2,3,4,5
Usage	bridge slab, top slab of direct traffic culverts

specimens. Identical specimens were made from the same concrete batch, cast in molds of the same dimensions and cured under identical conditions.

The acquisition of data for most tests was done according to the appropriate ASTM standards. In tests not specified by ASTM, the data was acquired as described in this chapter. Wherever a mechanical strain gage was used between two positively affixed gage points, three strain readings were taken in succession and averaged for each test value. The same procedure was used when measuring depth of wear with a micrometer.

5.4 Fresh Concrete Testing

The fresh concrete in this study was tested for slump, air content and unit weight. The slump of all the concrete mixes was between 3 and 4 in. The air content varied between 1.0 and 8.5%. The unit weight of fresh concrete ranged from 136.8 to 151.2 lb/per cu.ft. These three fresh concrete test values are documented for all mixes in appendix A.

5.5 Effect of Fly Ash on Concrete Strength

The effect of fly ash on the strength of concrete was studied by comparing both the 28-day compressive strength and the 7-day flexural strength of concrete containing fly ash to that of plain concrete having the same workability and "cement plus fly ash" content. Fly ash was used as a direct weight replacement for portland cement at levels of 20 and 35%. Concrete mixes were made using Type I cement in combination with Texas SDHPT Types A and B fly ash. A parallel series of tests was performed on concrete using Type IP cement. Two different air entraining agents were used: MB-VR and MB-AE-10.

5.5.1 Compressive Strength. The results of the compressive strength tests are plotted in Figs. 5.1 through 5.6. Compressive strength is plotted vs fly ash content as a percentage of the "cement + fly ash" content. The test results are presented in two sets: Figs. 5.1, 5.2 and 5.3 contain the data for concrete with an air content between 4.5 and 5.5%, while Figs. 5.4, 5.5 and 5.6 contain the data for concrete which had a standard dosage of air entraining agent. A standard dosage is defined as the amount of AEA required to produce 5% air in plain concrete mix containing no fly ash.

The average compressive strength of concrete containing fly ash was higher than the average compressive strength of the plain concrete with 5% air, regardless of the air content of the concrete containing fly ash. The 28-day design compressive strength was 3600

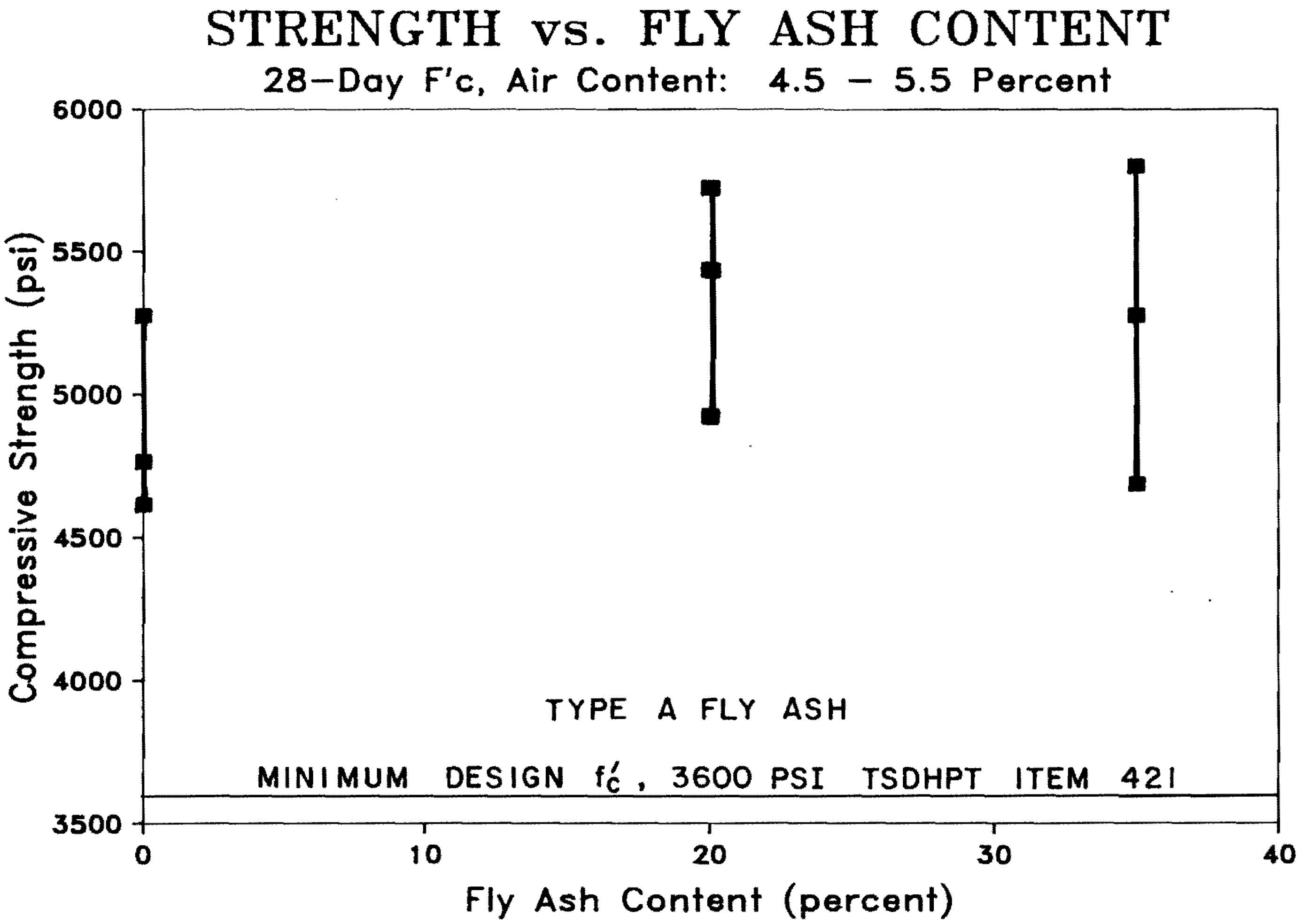


Fig. 5.1 Compressive strength of concrete containing Type A fly ash with constant air content.

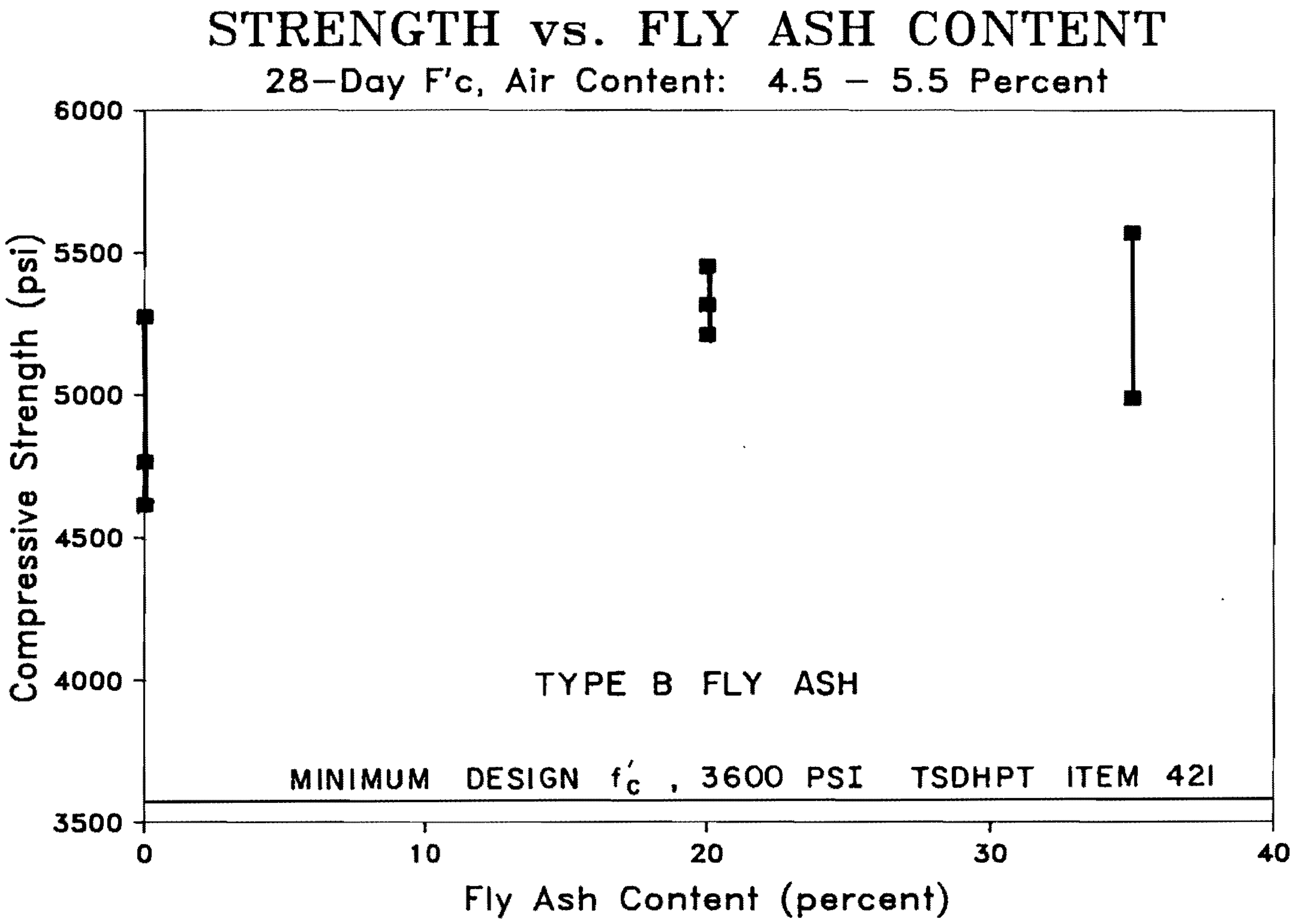


Fig. 5.2 Compressive strength of concrete containing Type B fly ash with constant air content.

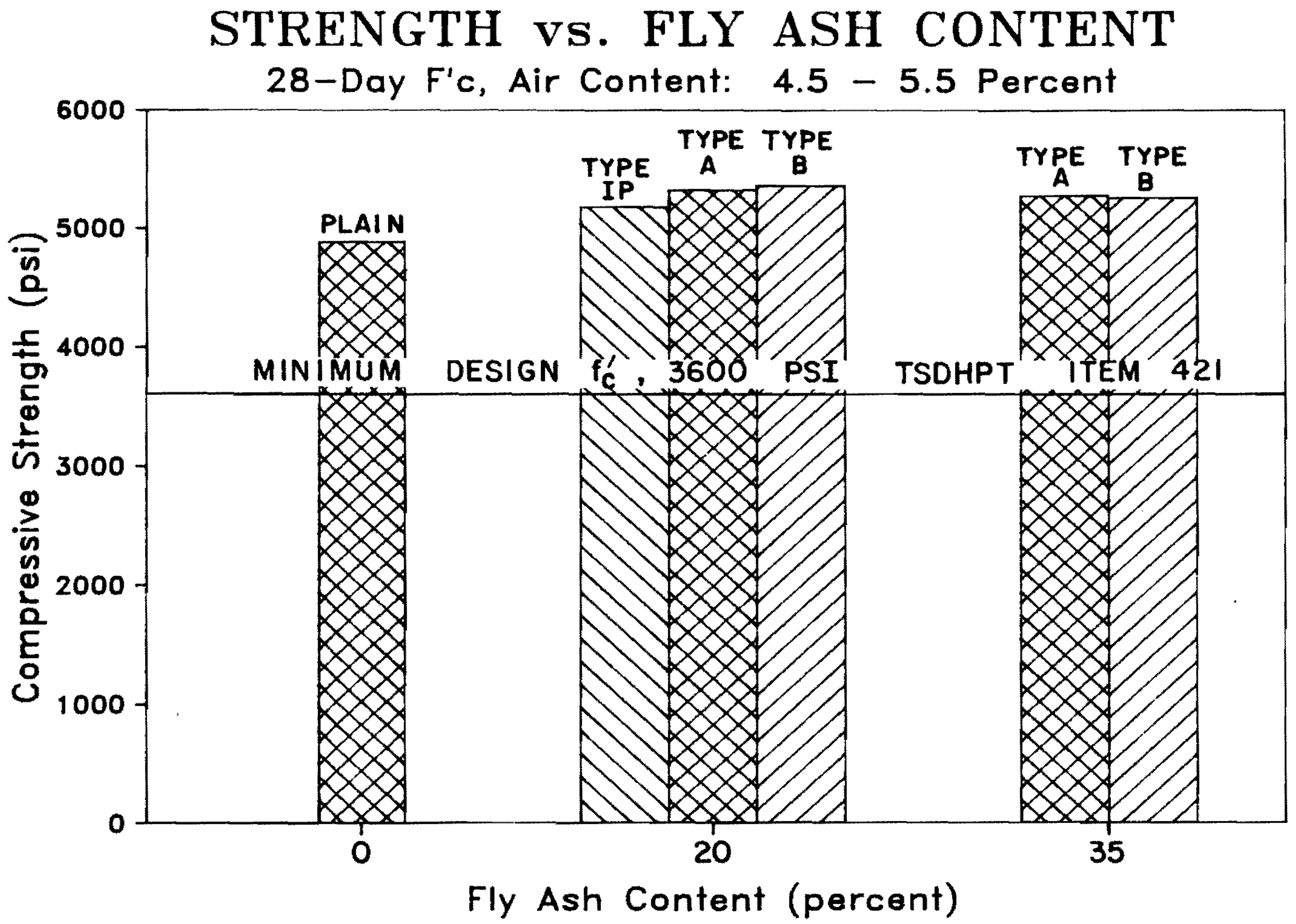


Fig. 5.3 Summary of compressive strength of concrete containing fly ash with constant air content.

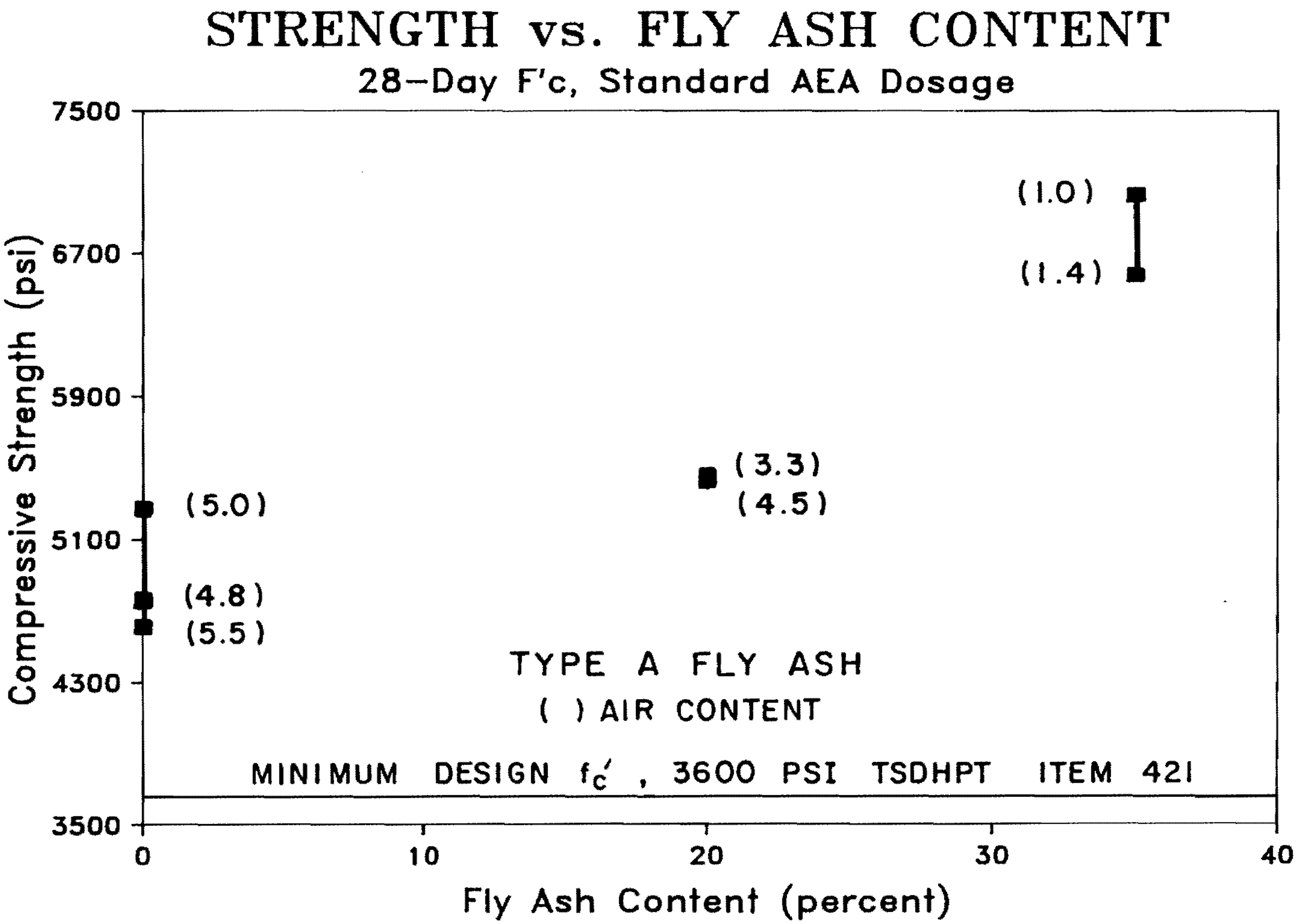


Fig. 5.4 Compressive strength of concrete containing Type A fly ash with constant AEA dosage.

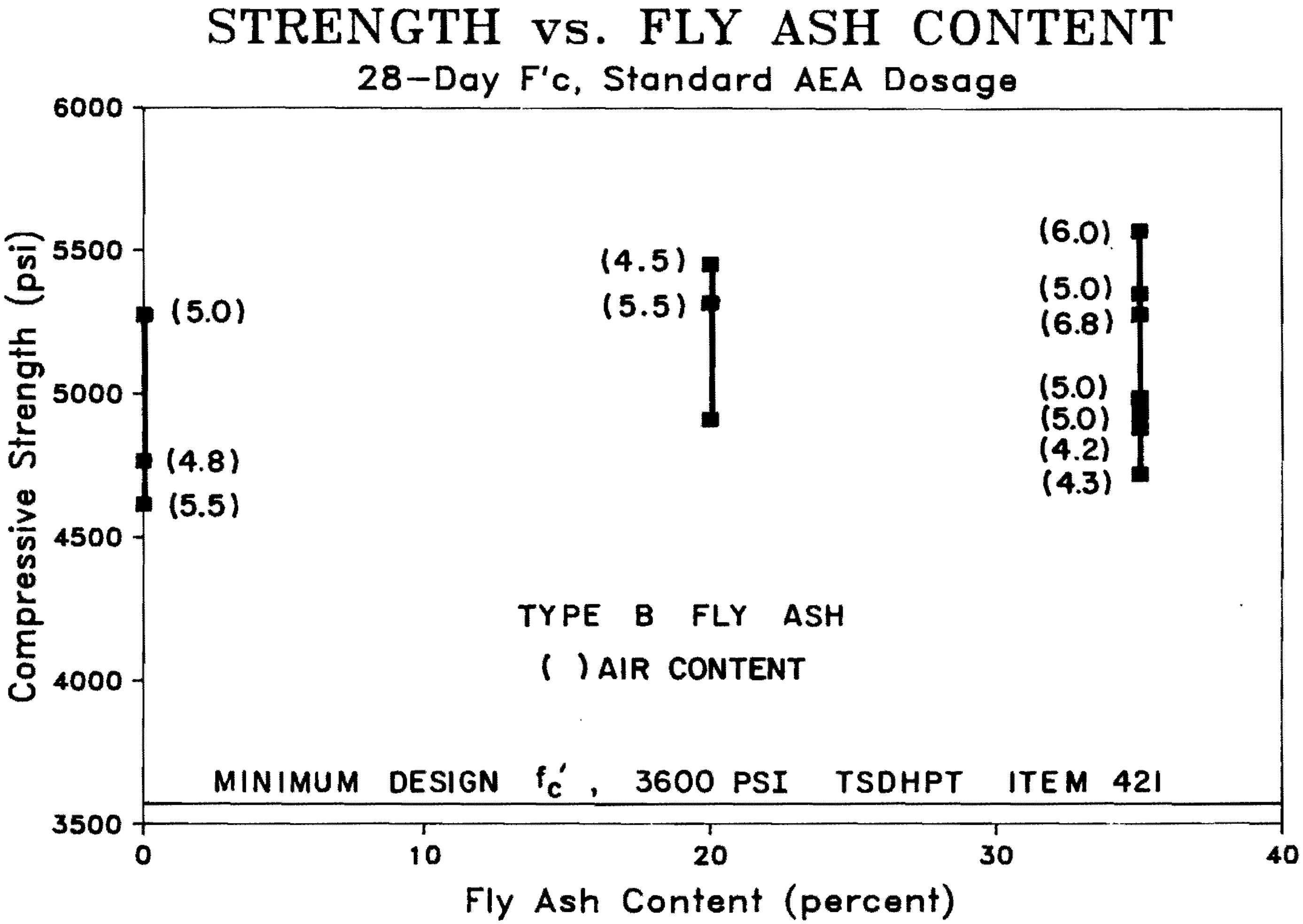
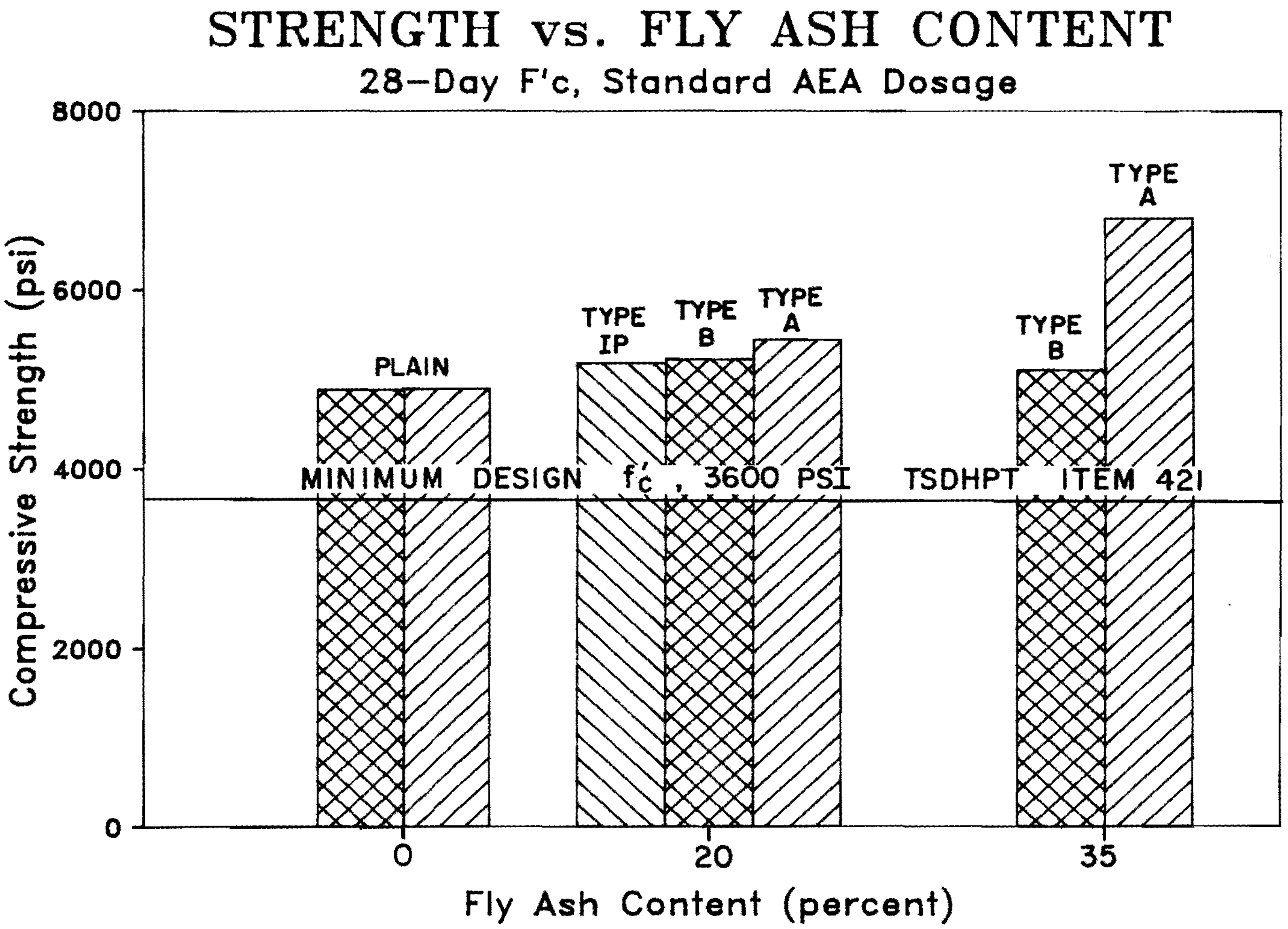


Fig. 5.5 Compressive strength of concrete containing Type B fly ash with constant AEA dosage.



5.6 Summary of compressive strengths of concrete containing fly ash with constant AEA dosage.

psi. All concretes tested in this program exceeded this specified minimum value and no individual specimen tested below this limit.

5.5.2 Flexural Strength. The 7-day flexural strength test results are presented in Figs. 5.7 through 5.12. The modulus of rupture is plotted vs fly ash content. The first three figures are plots of concrete with air contents between 4.5 and 5.5% and the second three figures are plots of concrete with a standard dosage of air entraining agent. The average flexural strength of concrete containing fly ash with 5% air was in all cases lower than the average flexural strength of plain concrete. The 7-day specified design flexural strength was 600 psi. Of all specimens tested, one concrete mix failed to meet this minimum requirement and three individual test specimens failed to meet the design flexural strength.

5.6 Effects of Fly Ash on Air Entrained Concrete

The effects of fly ash on air entrained concrete were also studied in this experimental program. Included in this part of the program was the AEA demand of concrete containing fly ash and Type IP cement to produce 5% air content, freeze-thaw durability and the effect of fly ash content on the air content of concrete. Both Texas SDHPT Types A and B fly ashes were investigated using three different air entraining agents. "Micro Air" AEA was used only in two batches of concrete: one control mix and one mix containing 35% Type A fly ash. Typically this AEA would only be used in concrete where other AEA's had difficulties entraining and maintaining proper air contents, therefore it was only used in this study to investigate the worst conditions.

5.6.1 Air Entraining Agent Dosage. The amount of air entraining agent required to yield an air content between 4.5 and 5.5% in concrete containing fly ash and Type IP cement was studied and is presented graphically in Figs. 5.13 through 5.16. The data is shown in two formats for ease of interpretation. Figures 5.13 and 5.14 show the dosage of a given air entraining agent required to obtain a 5% air content for different fly ash contents including both Types A and B fly ash. Figures 5.15 and 5.16 illustrate the required dosage of different air entraining agents to obtain 5% air for a particular type of fly ash. The air entraining agents used were Master Builders products: MB-VR, MB-AE-10 and Micro Air. The plots indicate that concrete containing Type A fly ash requires more AEA than concrete made with Type B fly ash. The figures also show that MB-AE-10 is more sensitive to different fly ash contents than MB-VR.

5.6.2 Fly Ash Content. Figures 5.17 through 5.20 relate the air content of concrete to the amount of fly ash in the mix for a standard dosage of air entraining agent. The first two figures plot the effect of different air entraining agents on air content in

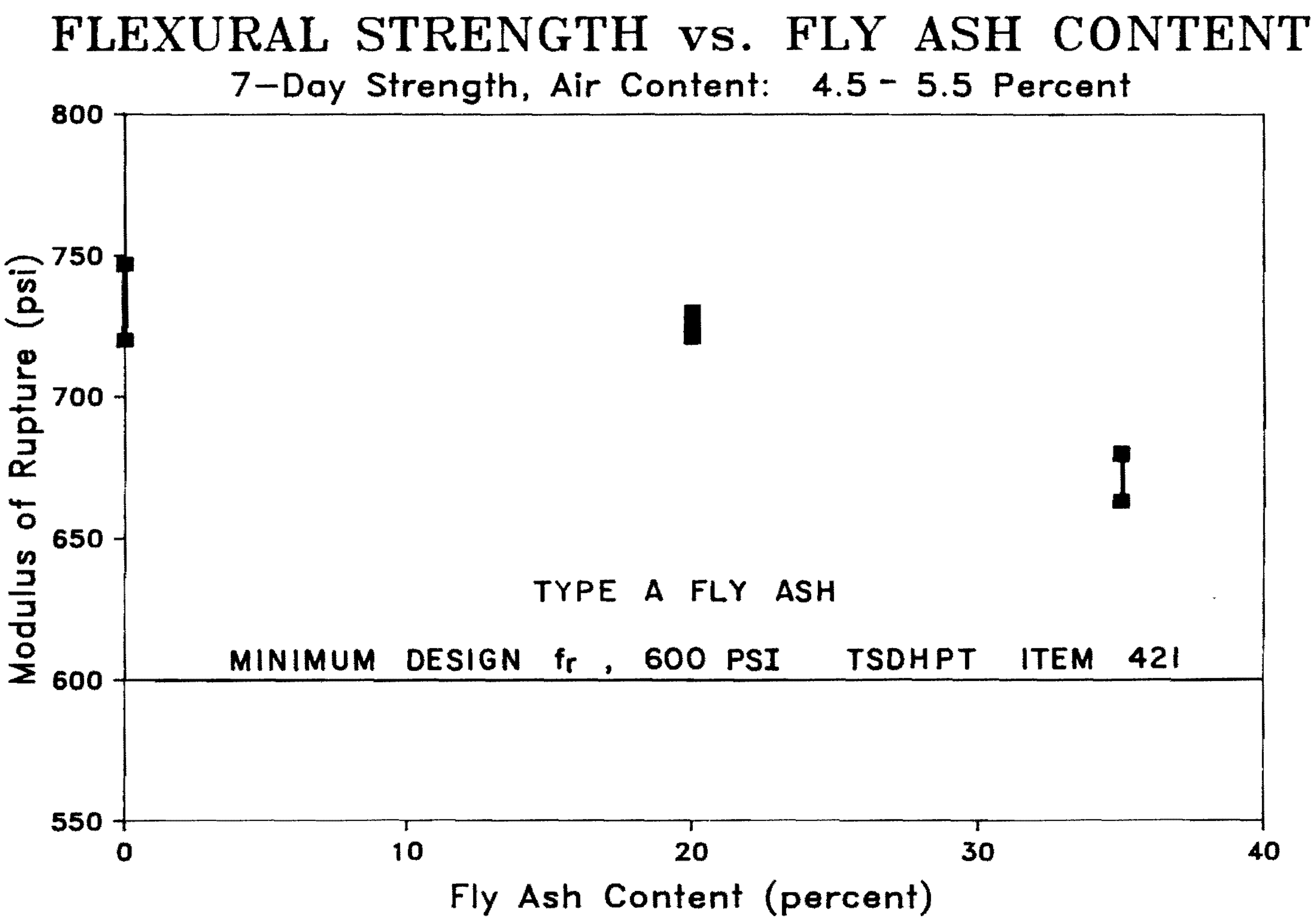


Fig. 5.7 Flexural strength of concrete containing Type A fly ash with constant air content.

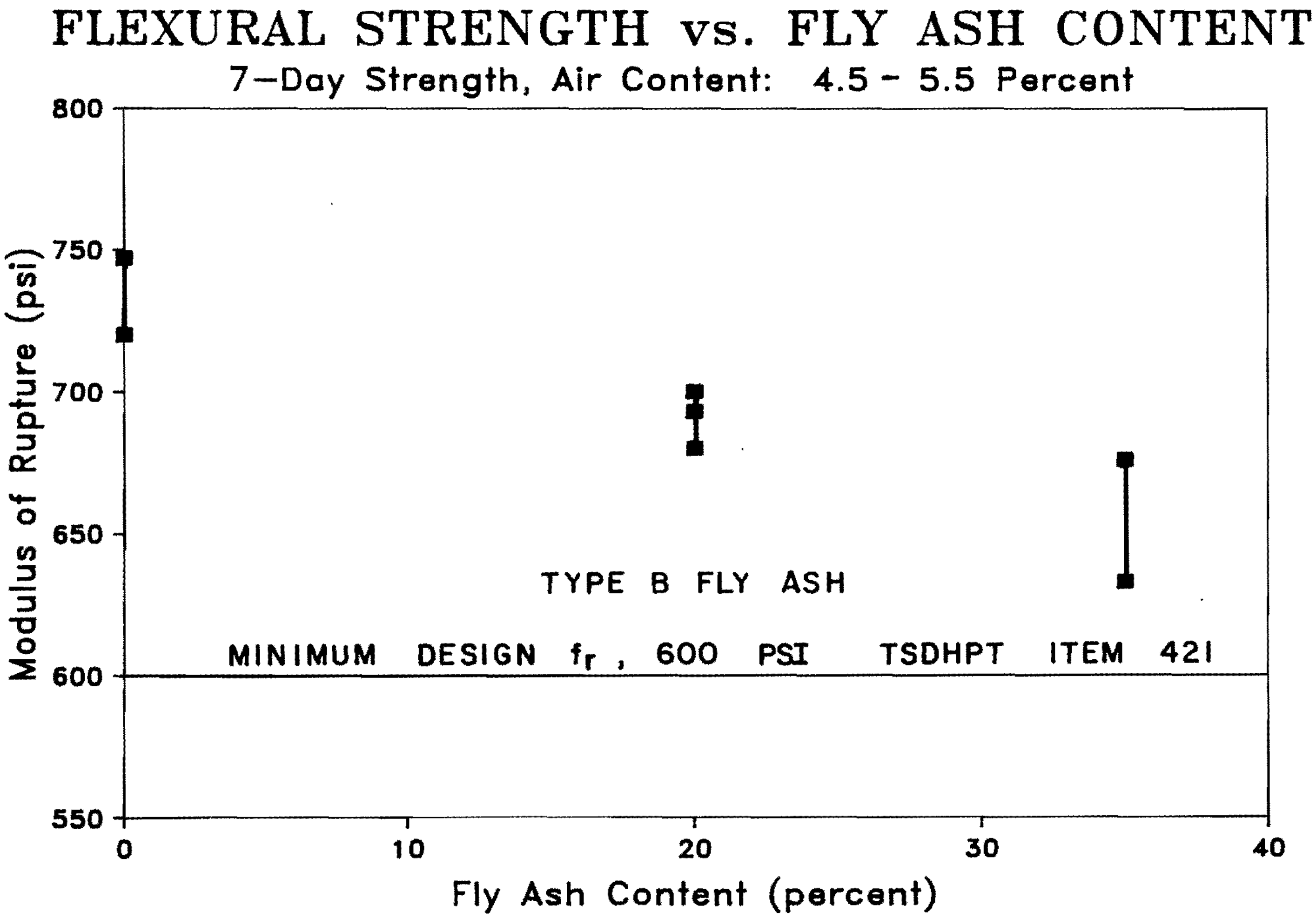


Fig. 5.8 Flexural strength of concrete containing Type B fly ash with constant air content.

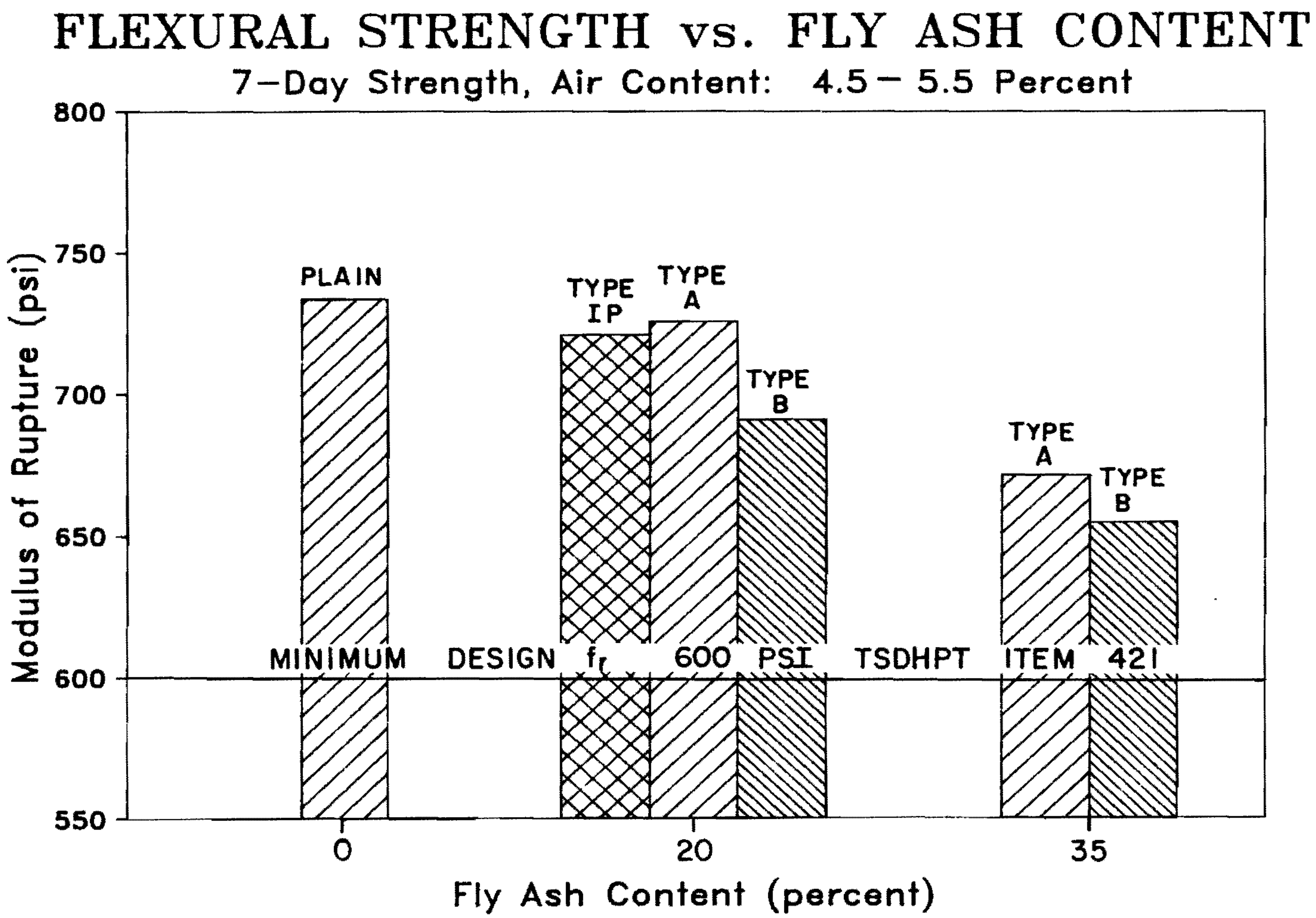


Fig. 5.9 Summary of flexural strength of concrete containing fly ash with constant air content.

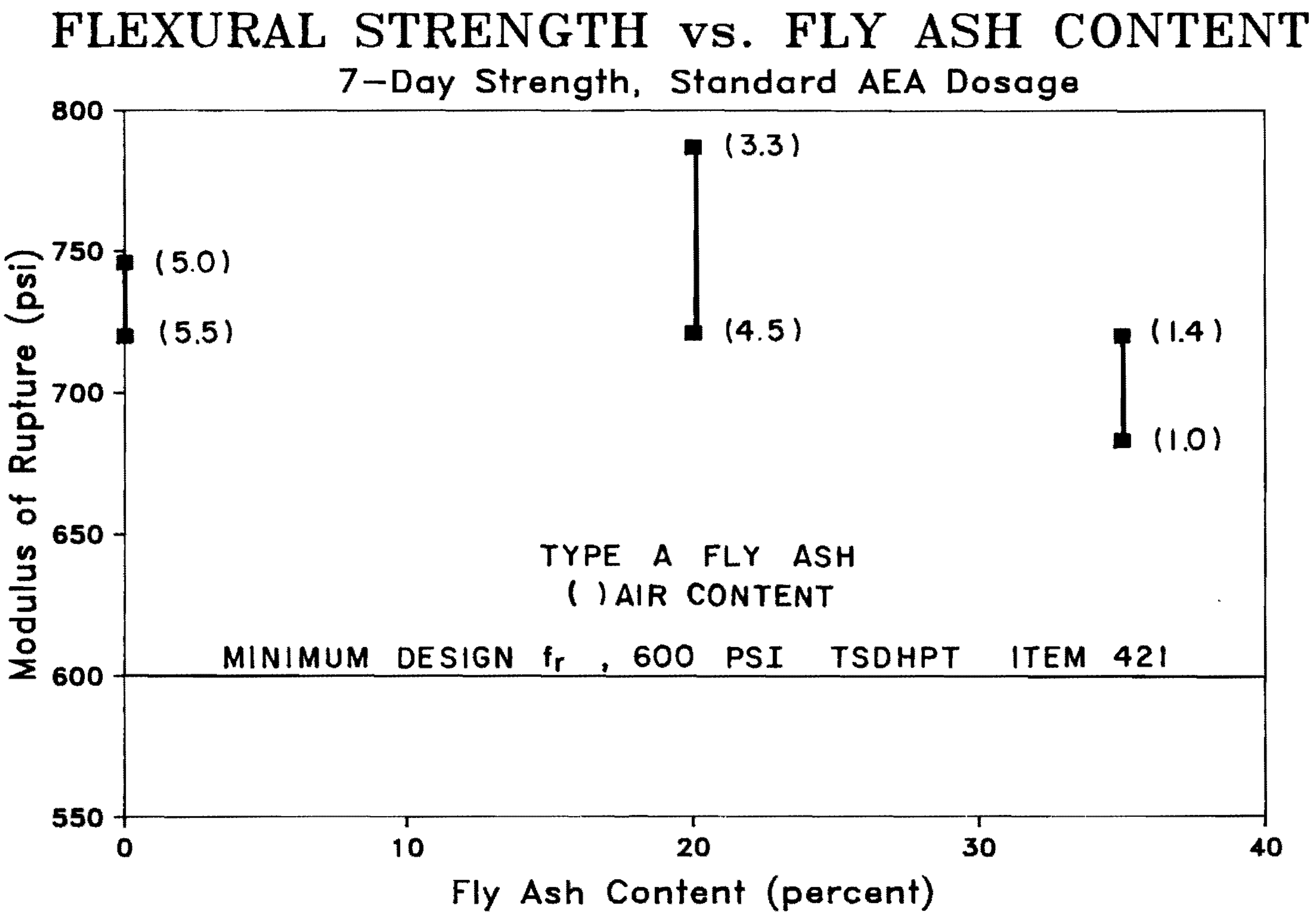


Fig. 5.10 Flexural strength of concrete containing Type A fly ash with constant AEA dosage.

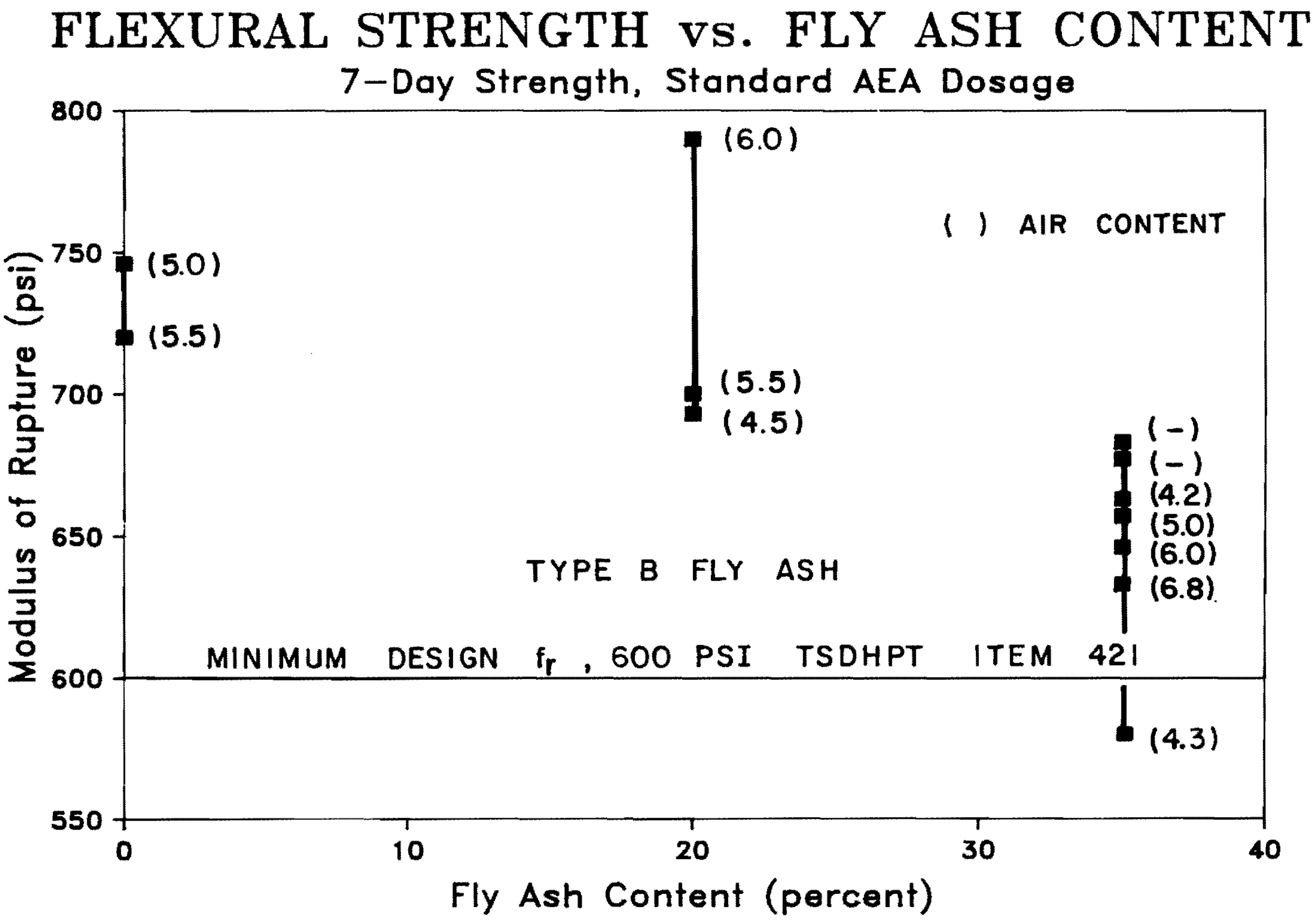


Fig. 5.11 Flexural strength of concrete containing Type B fly ash with constant AEA dosage.

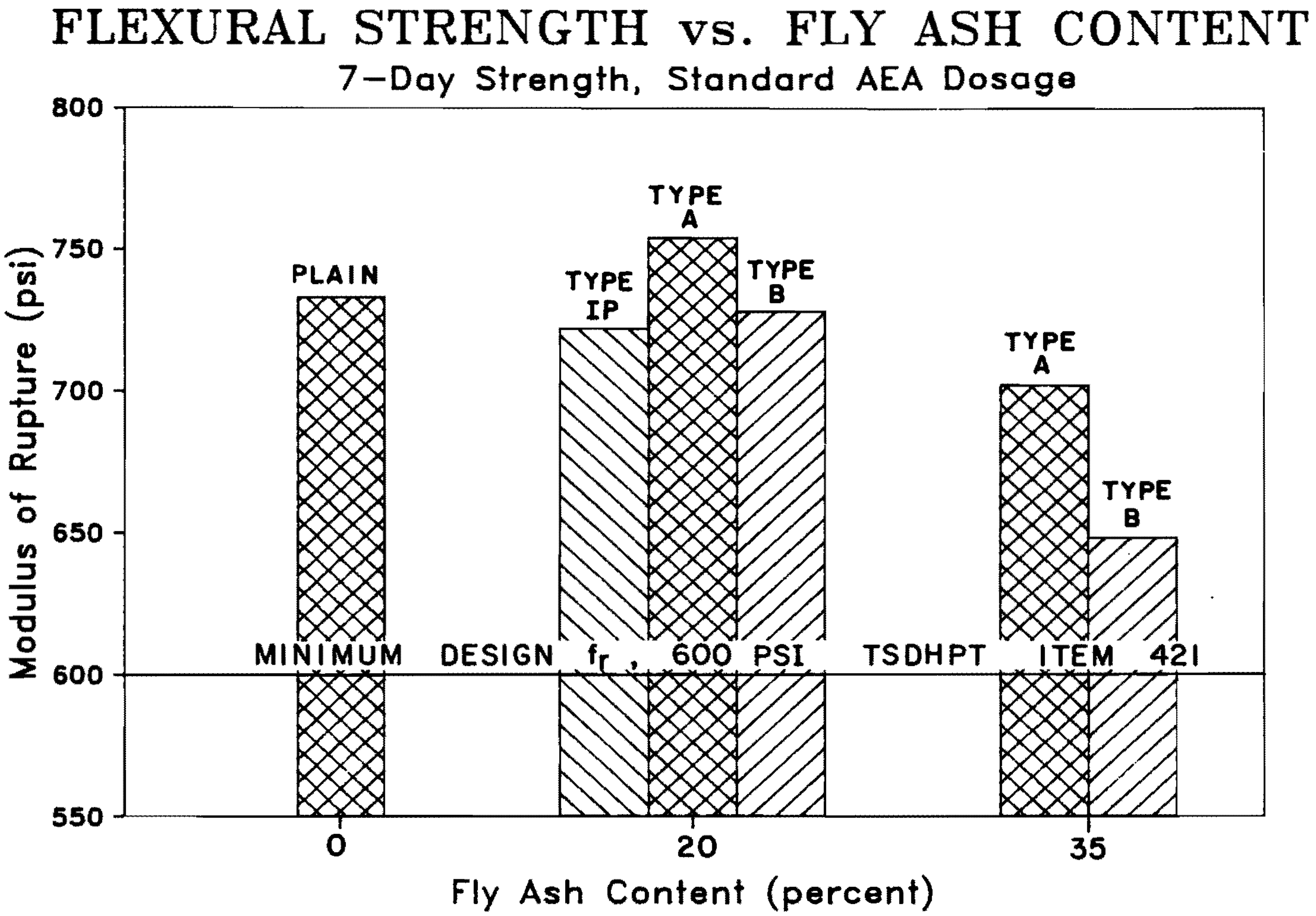


Fig. 5.12 Summary of flexural strength of concrete containing fly ash with constant AEA dosage.

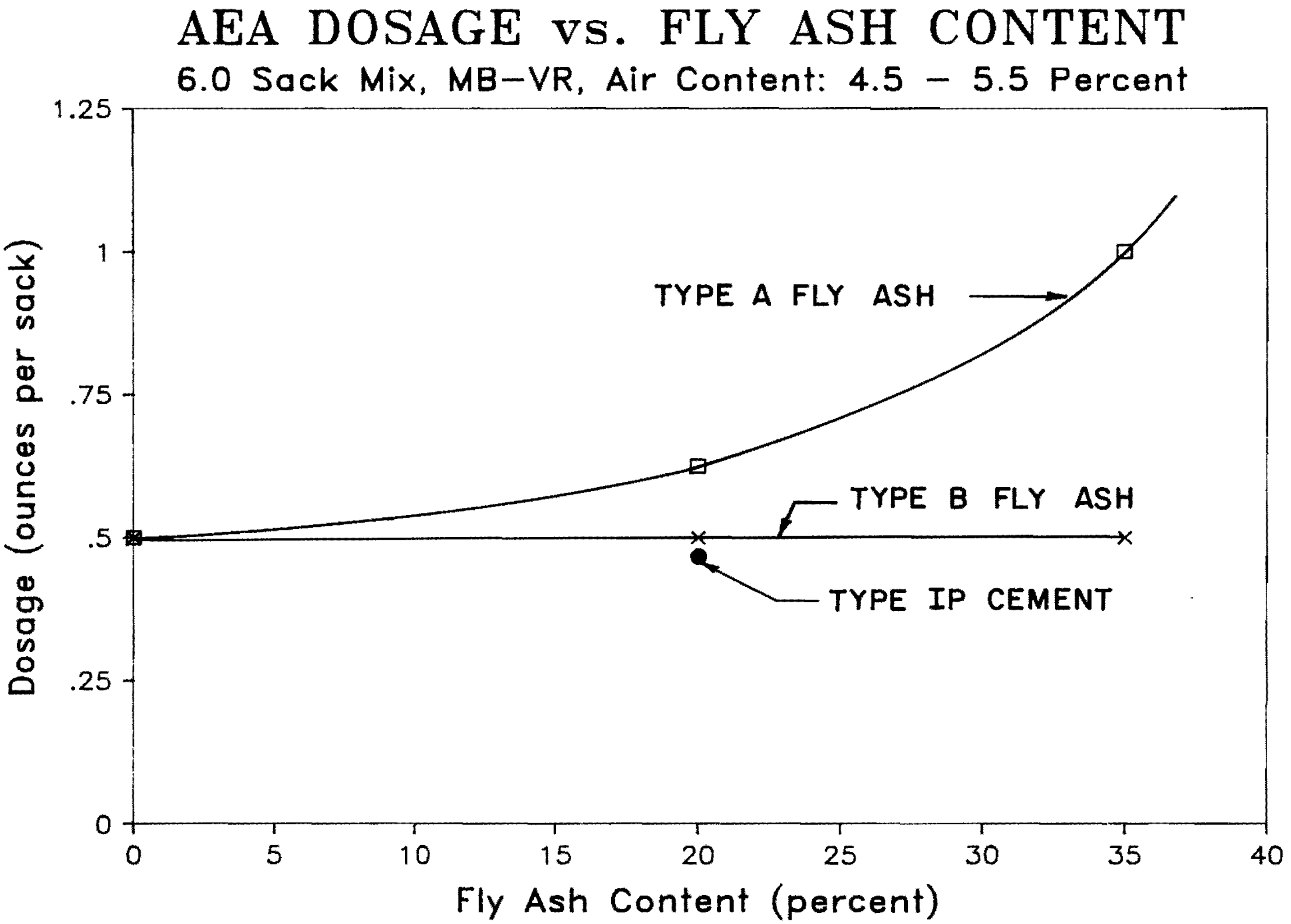


Fig. 5.13 Effect of fly ash content on dosage of MB-VR for constant air content.

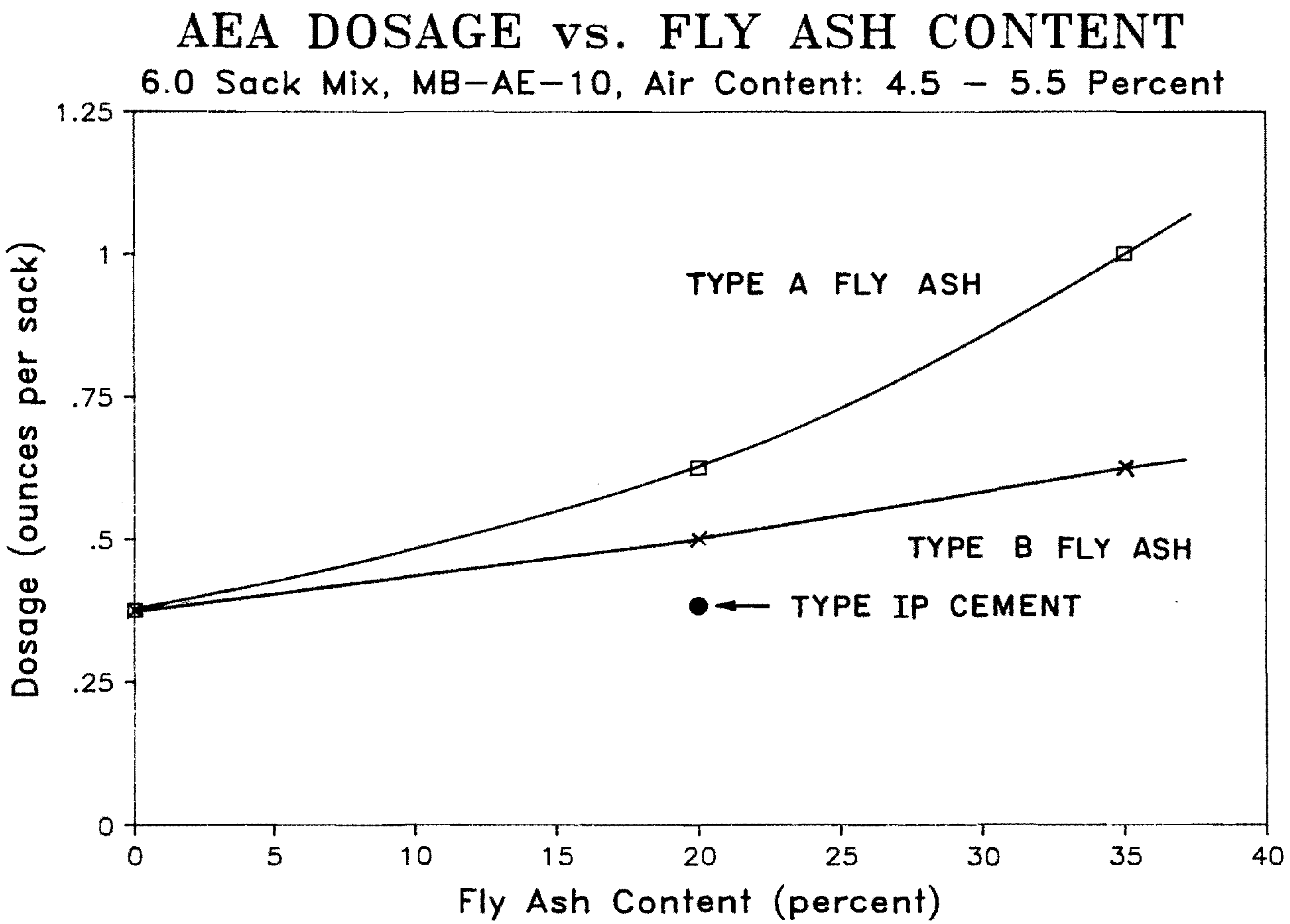


Fig. 5.14 Effect of fly ash content on dosage of MB-AE-10 for constant air content.

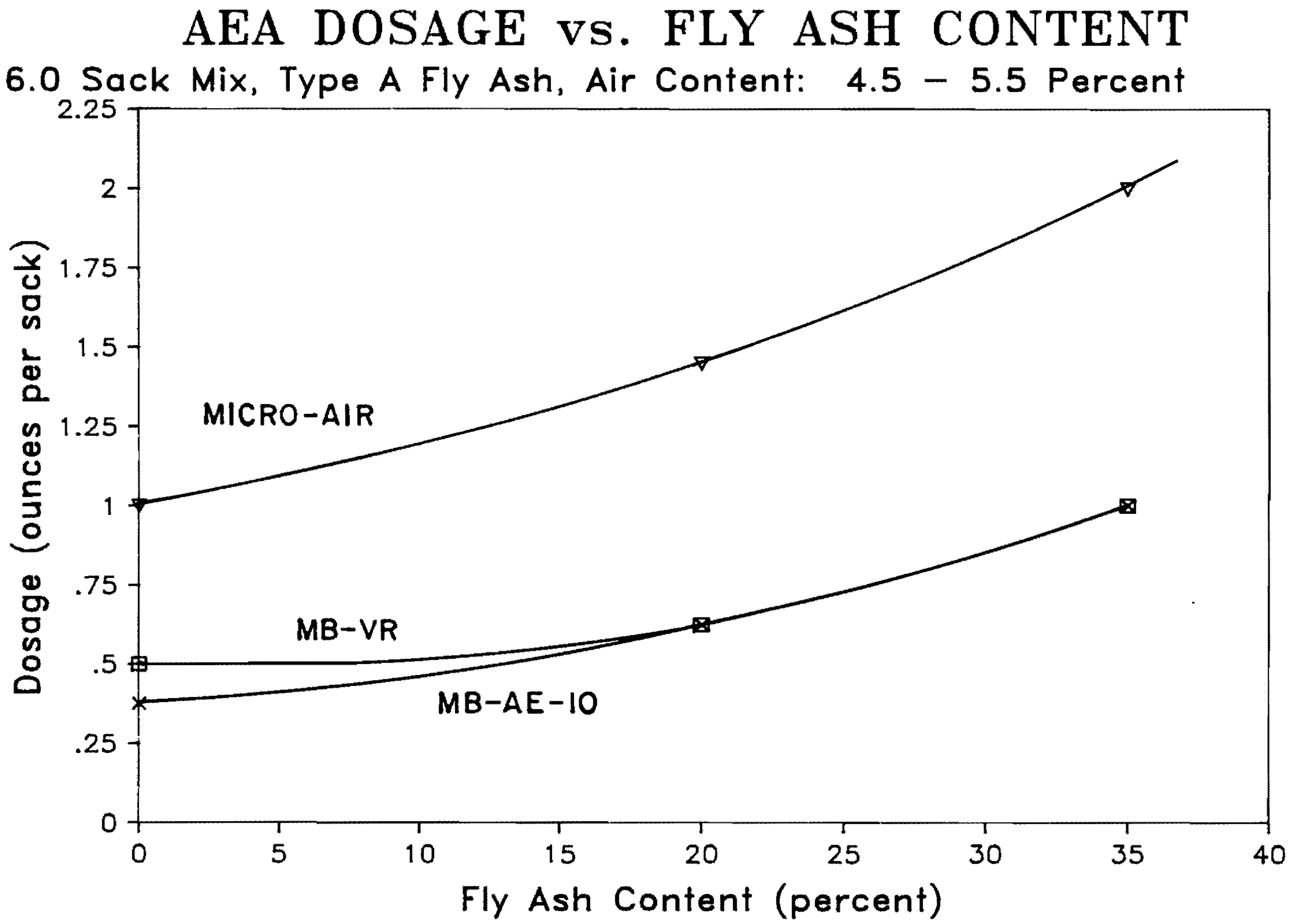


Fig. 5.15 Effect of Type A fly ash on dosage of AEA for constant air content.

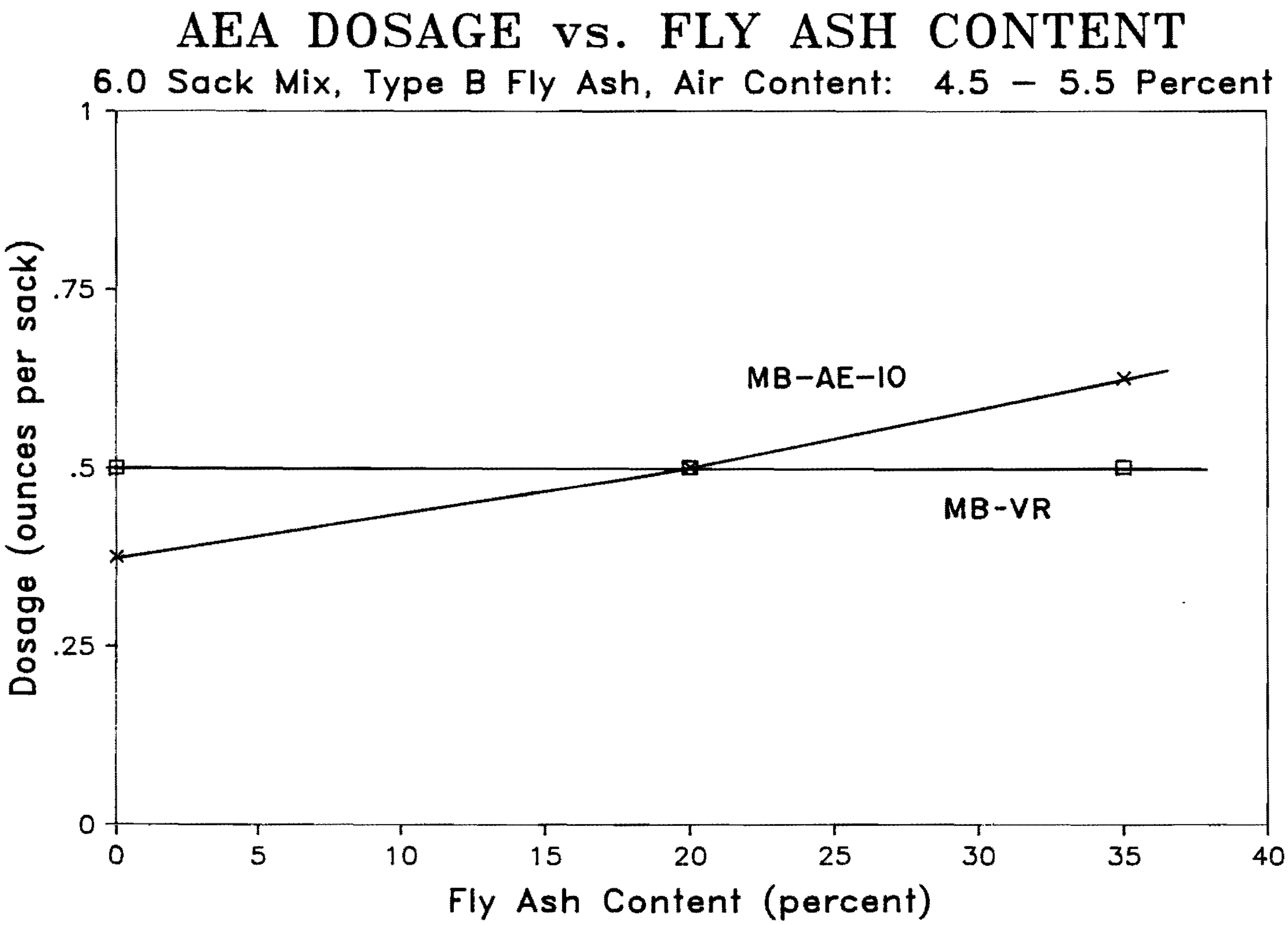


Fig. 5.16 Effect of Type B fly ash on dosage of AEA for constant air content.

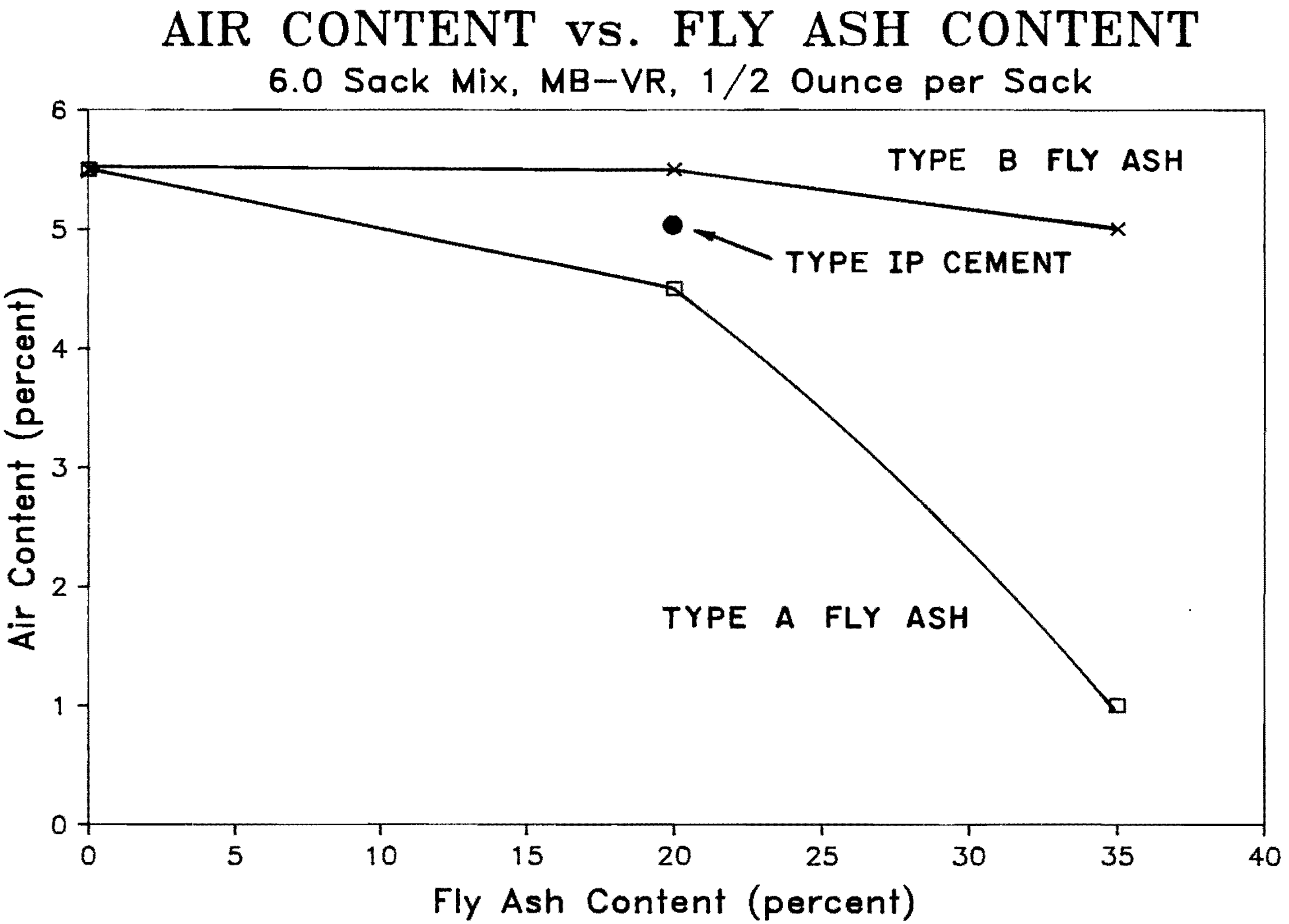


Fig. 5.17 Air content of concrete containing 1/2 ounce per sack of MB-VR.

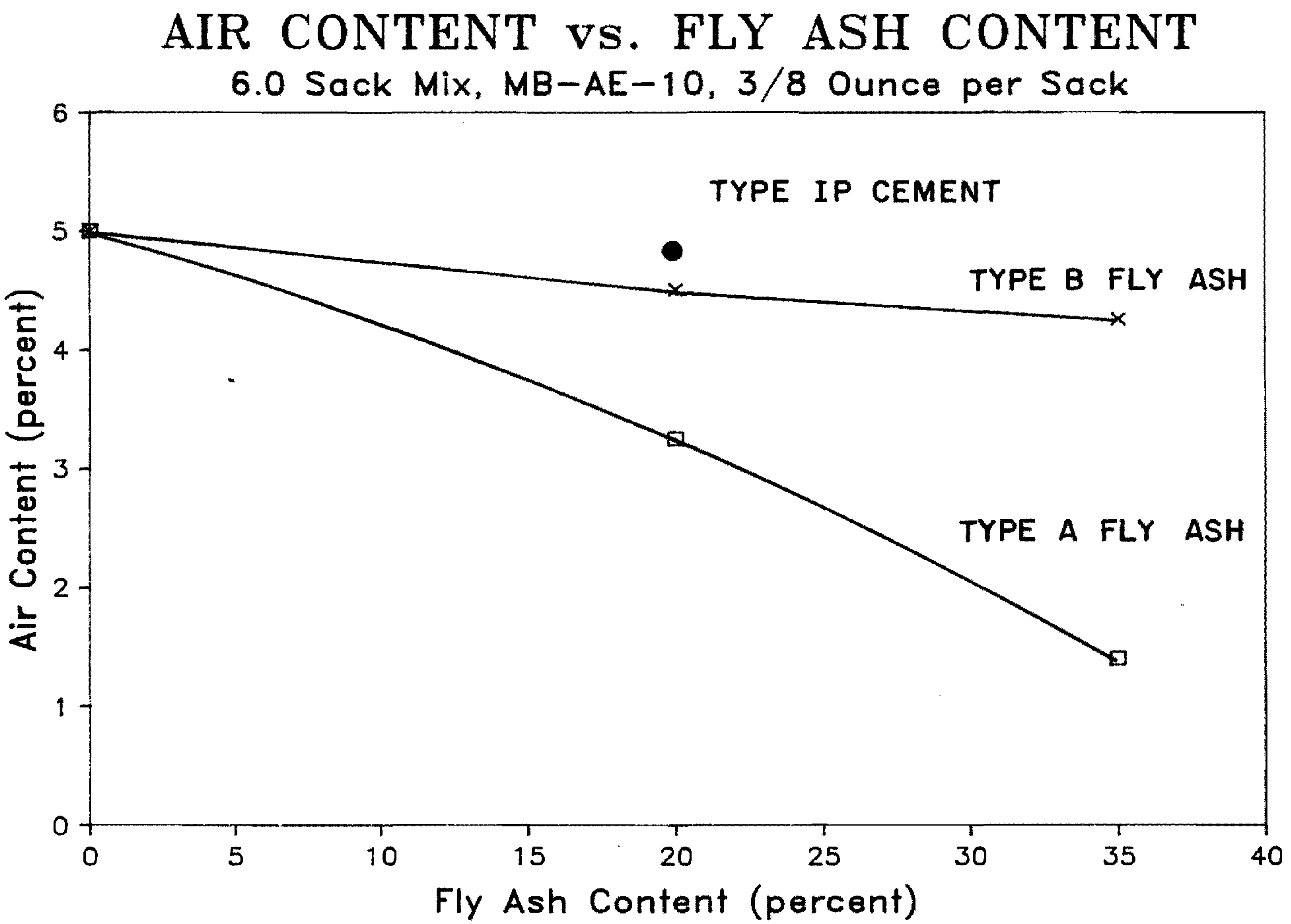


Fig. 5.18 Air content of concrete containing 3/8 ounce per sack of MB-AE-10.

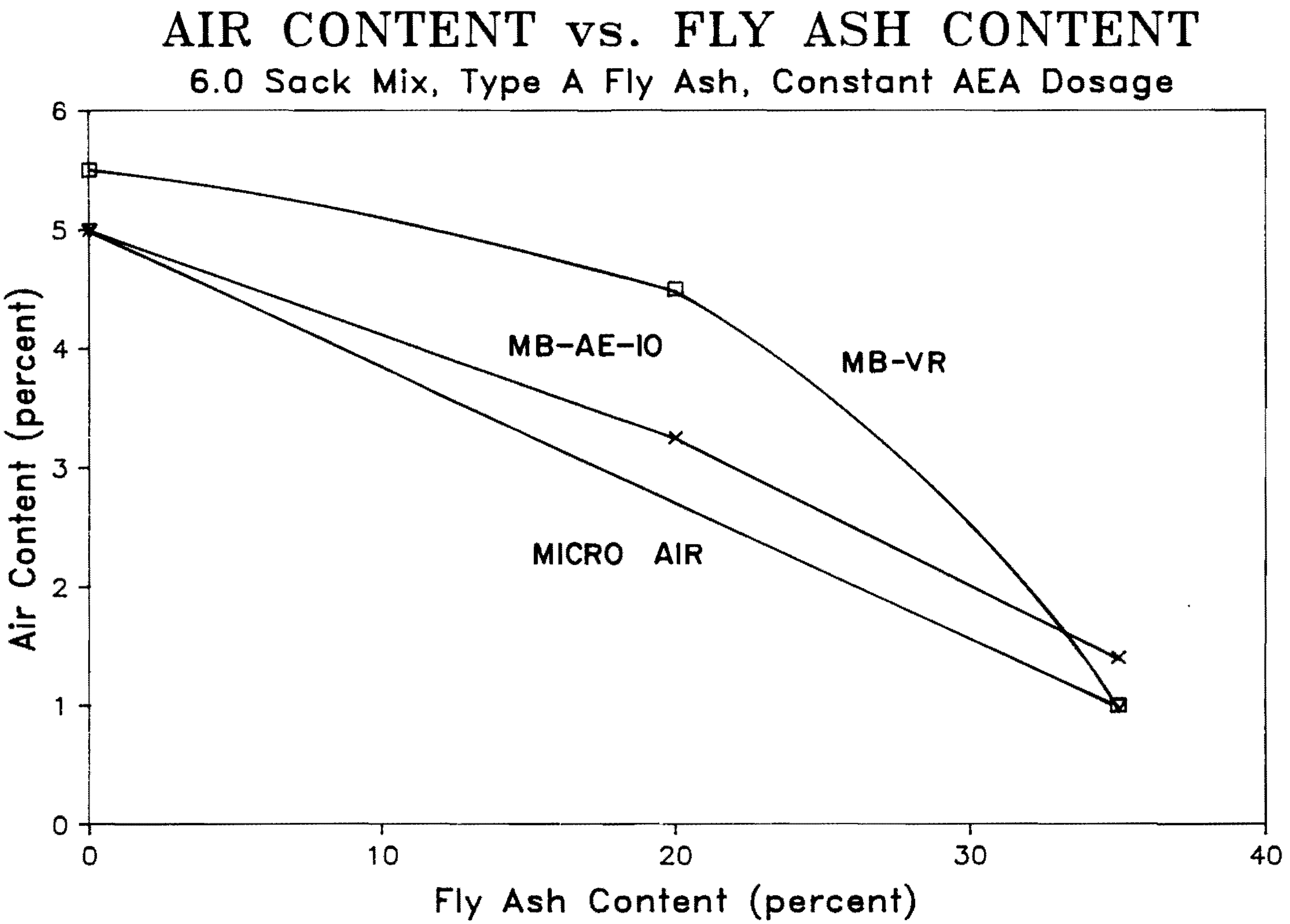


Fig. 5.19 Effect of Type A fly ash on air content.

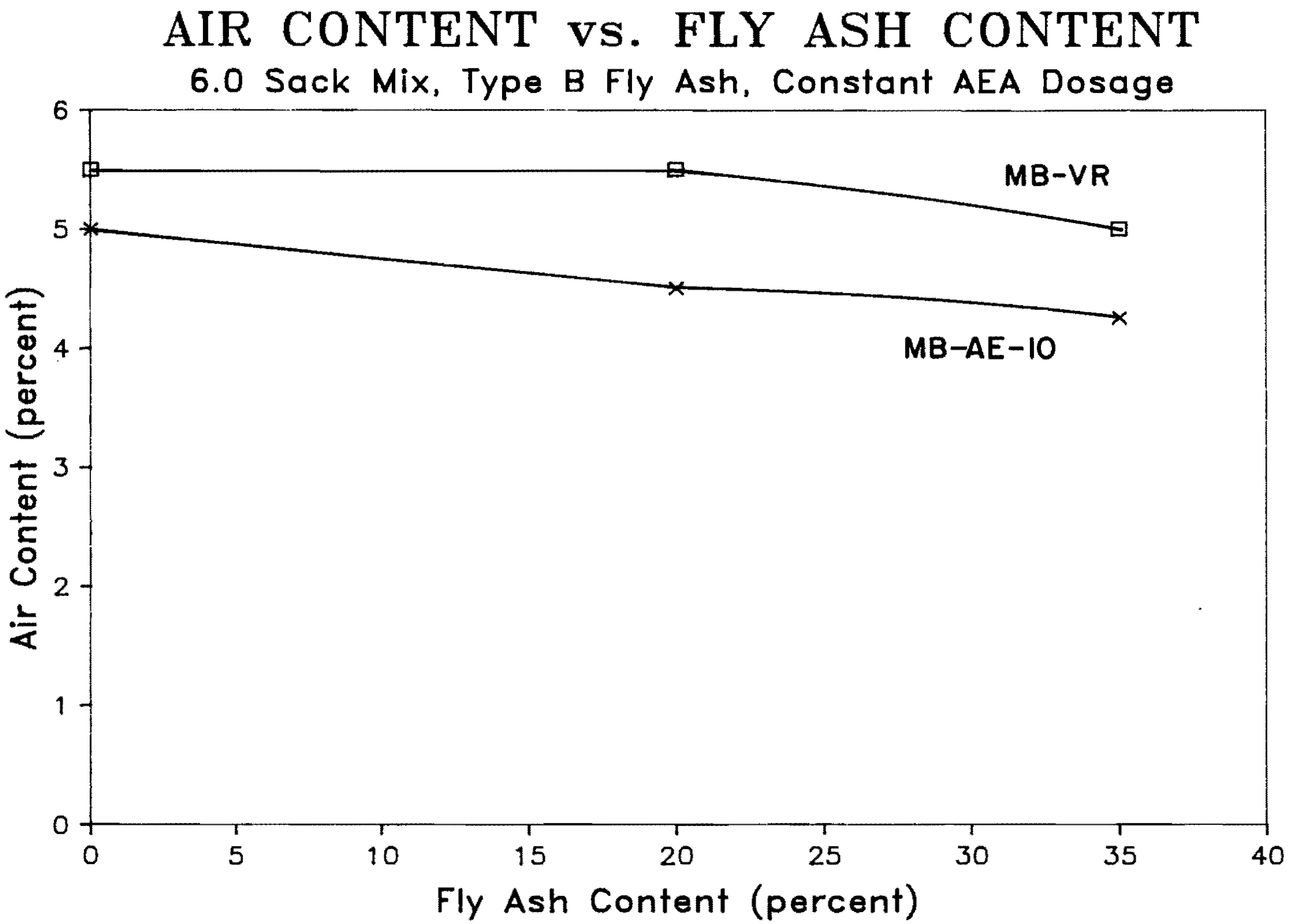


Fig. 5.20 Effect of Type B fly ash on air content.

concrete containing Types A and B fly ash. Figures 5.19 and 5.20 illustrate the differences in air content due to the type of fly ash while holding the dosage and brand of air entraining agent constant. The more significant effect of fly ash on air content occurs when using Type A fly ash. Regardless of the air-entraining agent used, the air content was substantially decreased with the addition of Type A fly ash as compared to Type B fly ash.

5.7 Freeze-Thaw Durability

The freeze-thaw durability of concrete containing fly ash was tested according to ASTM C666-80 and compared to that of control specimens of plain concrete tested in the same manner. In this test the fundamental transverse frequency, FTF, of the specimen is monitored over 300 freeze-thaw cycles. As the specimen degrades internally from freeze-thaw damage, the FTF decreases, indicating deterioration in the internal structure of the concrete specimen.

Two properties of concrete were computed and plotted in this section: Dynamic Modulus of Elasticity (DE), and the Durability Factor (DF). The dynamic modulus of elasticity is calculated using the formula below:

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

where,

C = geometric constant equal to 0.114 for 3 x 4 x 16 in. beams

W = weight of the specimen in pounds

n = fundamental transverse frequency of the specimen in cycles per second

Since the weight of the specimens in this study never varied more than 1% over the 300 cycle test, the average weight of the specimen was used to compute DE. The durability factor is defined as the ratio of the square of the FTF after c cycles to that of the specimen before the first cycle:

$$DF = (n_c^2 \ / \ n_o^2) \quad \times 100, \text{ percent}$$

The tests were done in two series. The first series used a standard dosage of AEA for all concretes, where the standard is defined as the amount required to produce 5% air in the control plain concrete mix. The second series contained an adjusted dosage of air entraining agent so as to produce 5% air in all specimens. The results of the first series are plotted in Figs. 5.21 through 5.24,

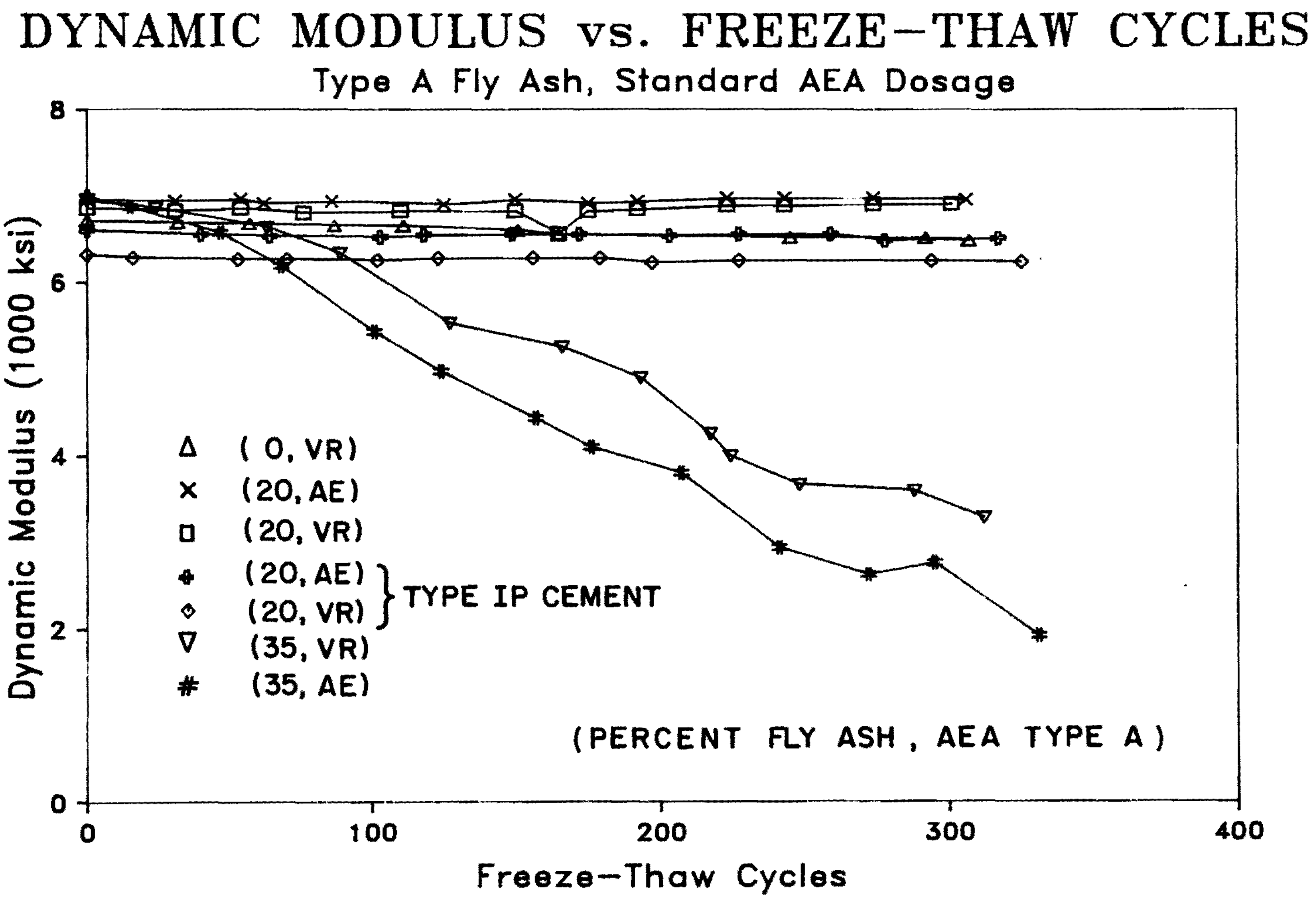


Fig. 5.21 Dynamic modulus of concrete containing Type A fly ash with constant AEA dosage.

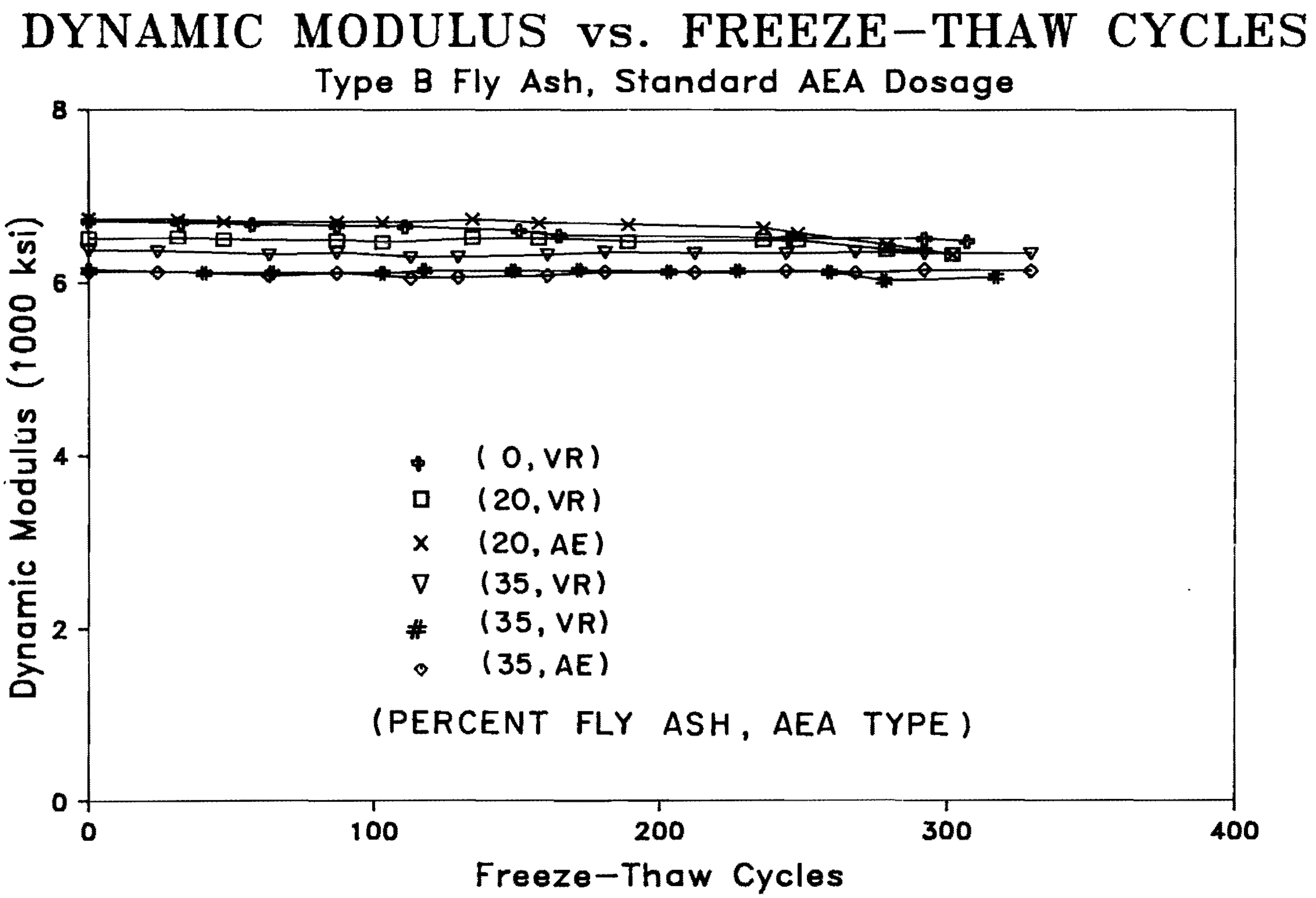


Fig. 5.22 Dynamic modulus of concrete containing Type B fly ash with constant AEA dosage.

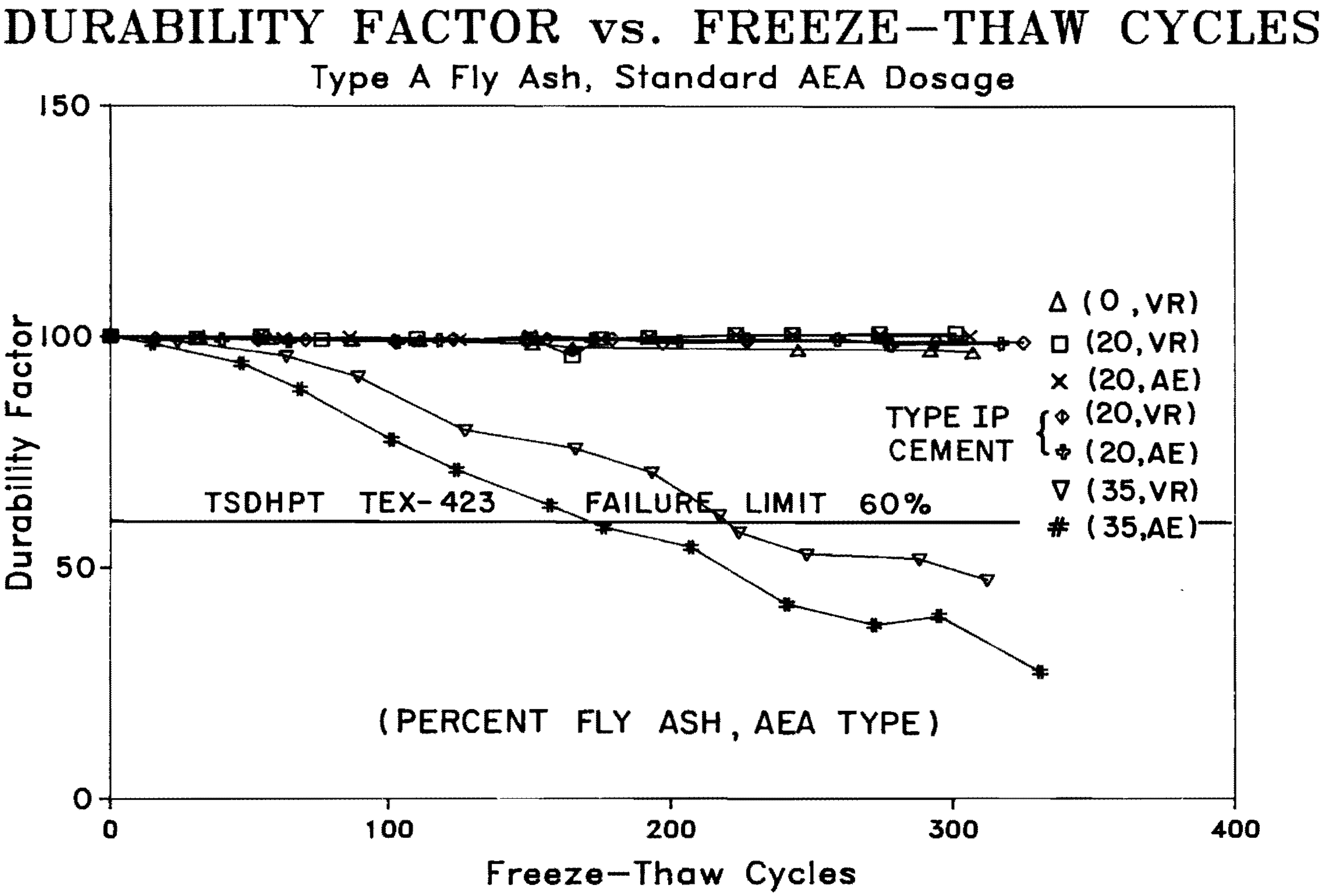


Fig. 5.23 Durability factor of concrete containing Type A fly ash with constant AEA dosage.

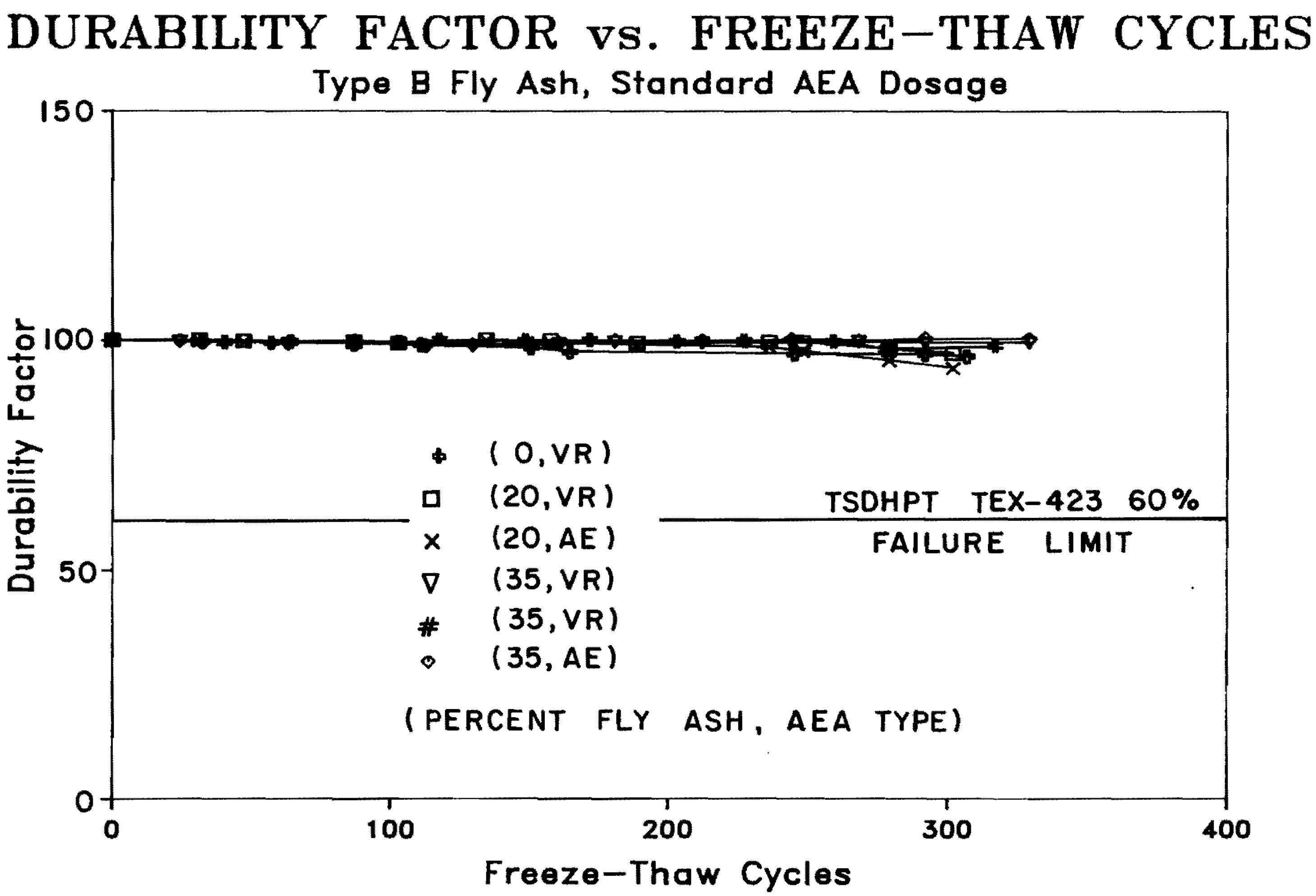


Fig. 5.24 Durability factor of concrete containing Type B fly ash with constant AEA dosage.

and the second series is plotted in Figs. 5.25 through 5.28. The dynamic modulus is presented in the first two figures of each set, while the durability factor is plotted in the last two figures of each set. From the graphs presented, it is seen that only concrete containing 35% Type A fly ash with low air content was adversely affected by freezing and thawing. All concrete containing more than 3% air performed adequately throughout the 300 cycle tests. According to Texas SDHPT specifications, satisfactory freeze-thaw resistance of concrete is defined as concrete having a DF of 60% or higher after 300 freeze-thaw cycles. The initial and final fundamental transverse frequencies for all tests are tabulated in appendix A.

5.8 Shrinkage of Concrete Containing Fly Ash

The effect of fly ash on volumetric changes in concrete is presented in this section. Thirty concrete beams were placed in a controlled environment at 100°F and a relative humidity of 32% for over 100 days. Shrinkage was monitored periodically using a mechanical strain gage; where shrinkage is the average strain reading over six sets of DeMec points positively affixed to 3 identical beams. One half of the specimens tested were moist cured for 3 days, while the other 15 specimens were moist cured for 7 days.

5.8.1 Effect of Fly Ash Content. Shrinkage of concrete containing fly ash is compared to that of plain concrete in Figs. 5.29 through 5.38. Variables considered included both the type and the amount of fly ash in the concrete. The first five figures refer to specimens that were moist cured for 3 days and the second five figures to specimens that were moist cured for 7 days. Each group compares the results of concrete containing fly ash to those of plain concrete in the first four figures and summarizes the results in the fifth figure.

While the rate of shrinkage of concrete containing fly ash was similar to that of plain concrete, the total shrinkage of concrete containing 35% Type A fly ash was equal to or less than the total shrinkage of plain concrete.

5.8.2 Effect of Moist Curing Time. The figures presented in this section compare the shrinkage of concrete moist cured for 3 days to that of concrete moist cured for 7 days. Figures 5.39, 5.40, and 5.41 illustrate the differences in shrinkage of concrete containing the same proportions of fly ash, while Fig. 5.42 summarizes the data in a bar graph format.

Except for the case of concrete containing 35% Type B fly ash, fly ash concrete displayed greater shrinkage when moist cured 7 days. This is contrary to the behavior of the control specimens of

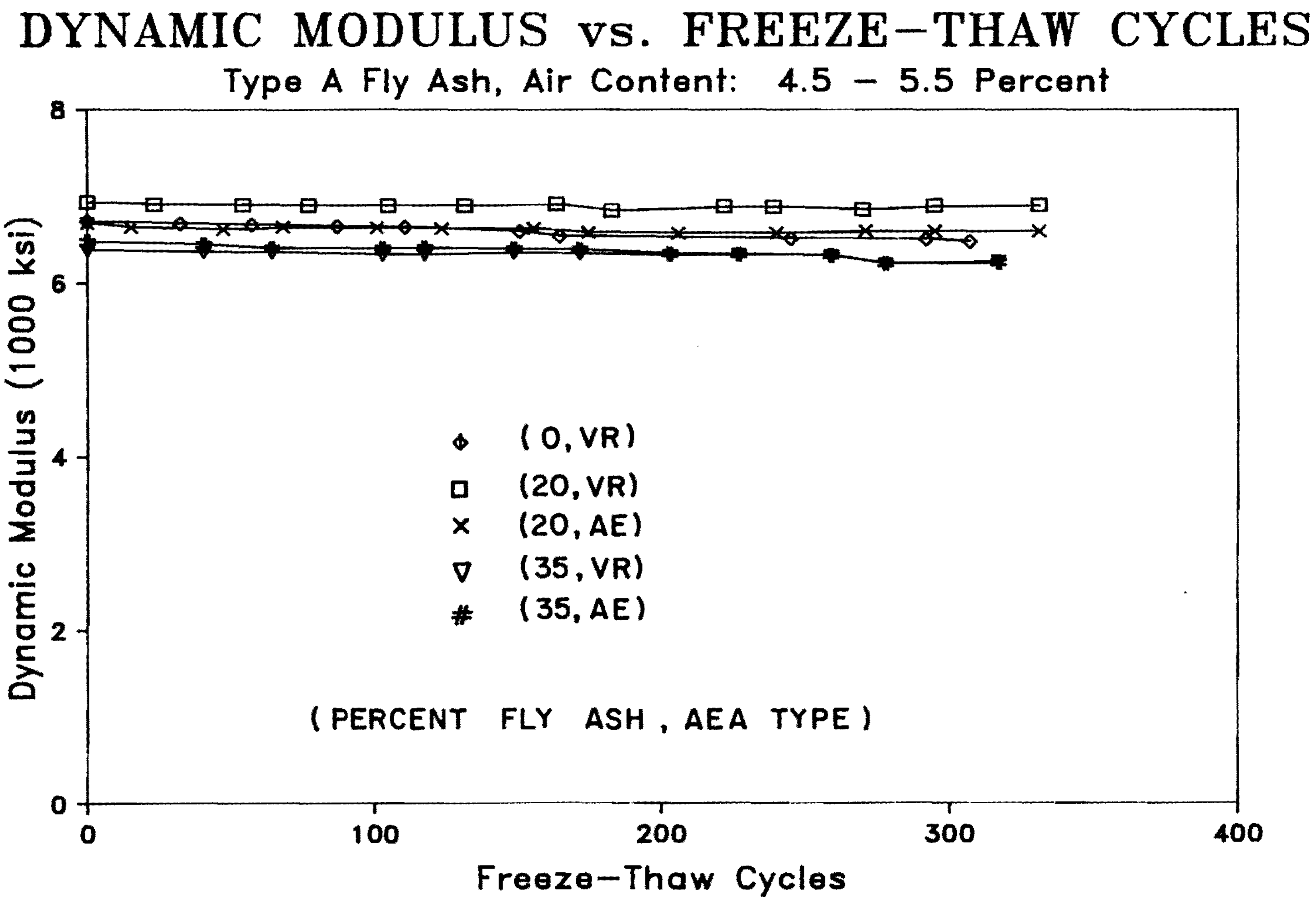


Fig. 5.25 Dynamic modulus of concrete containing Type A fly ash with constant air content.

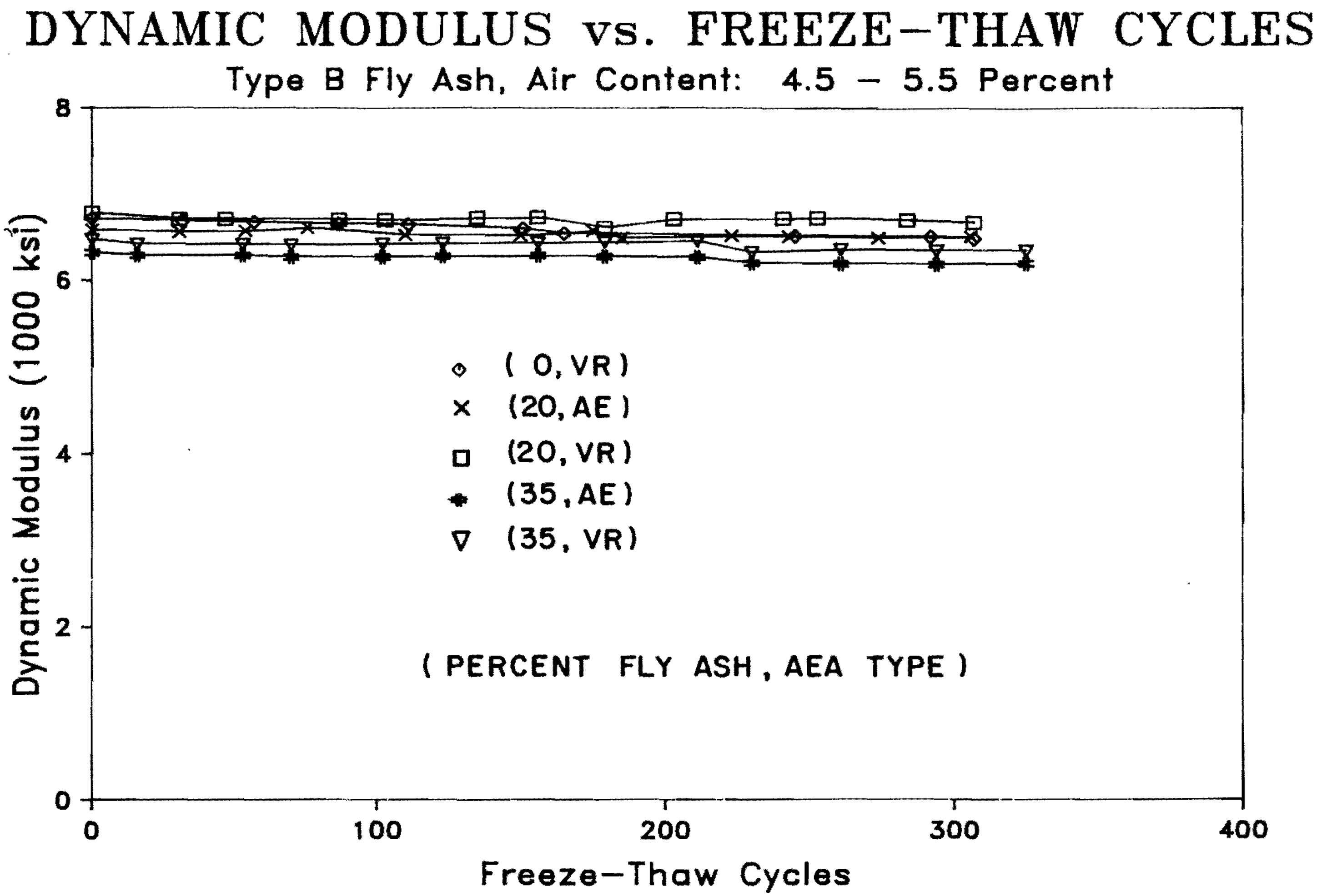


Fig. 5.26 Dynamic modulus of concrete containing Type B fly ash with constant air content.

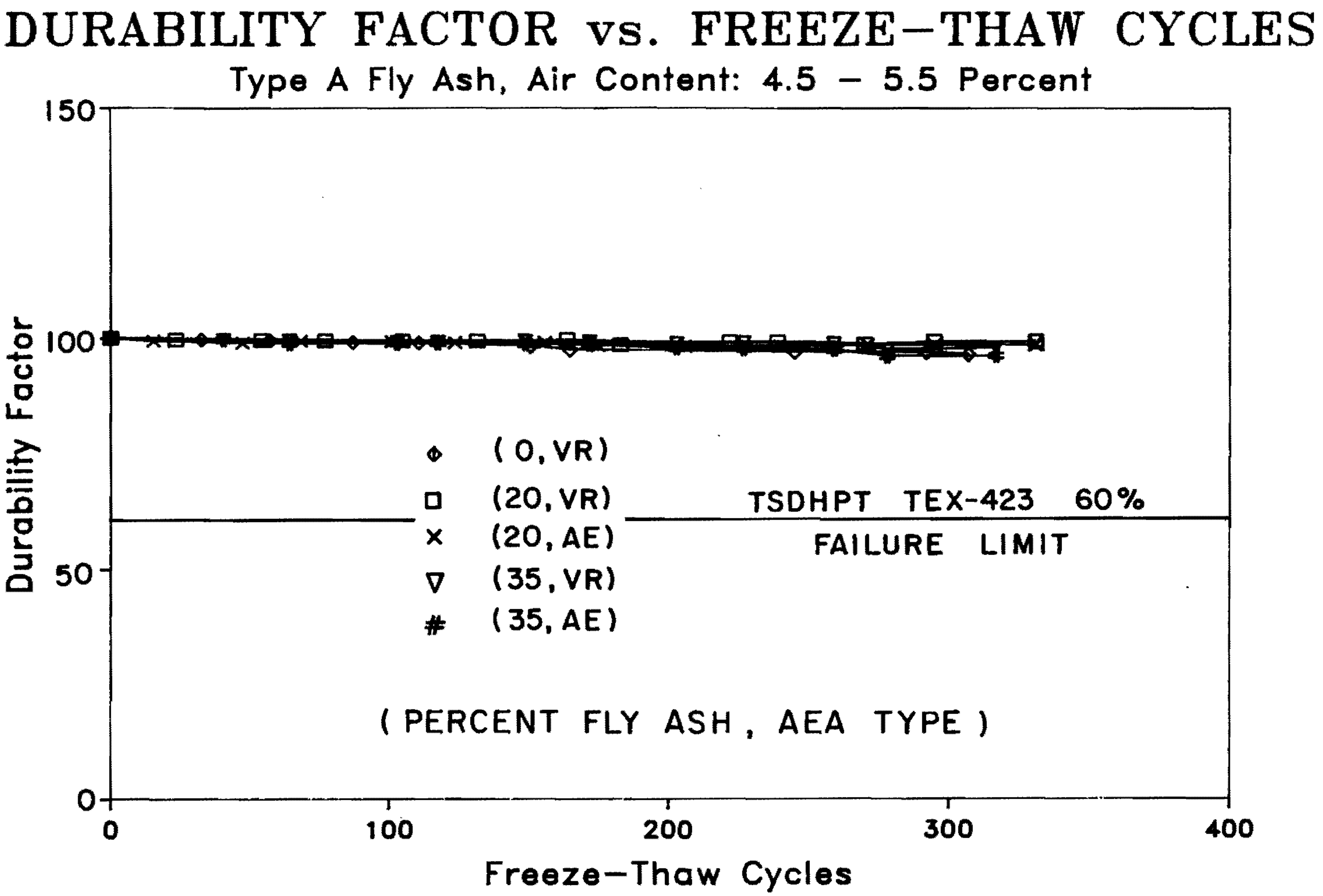


Fig. 5.27 Durability factor of concrete containing Type A fly ash with constant air content.

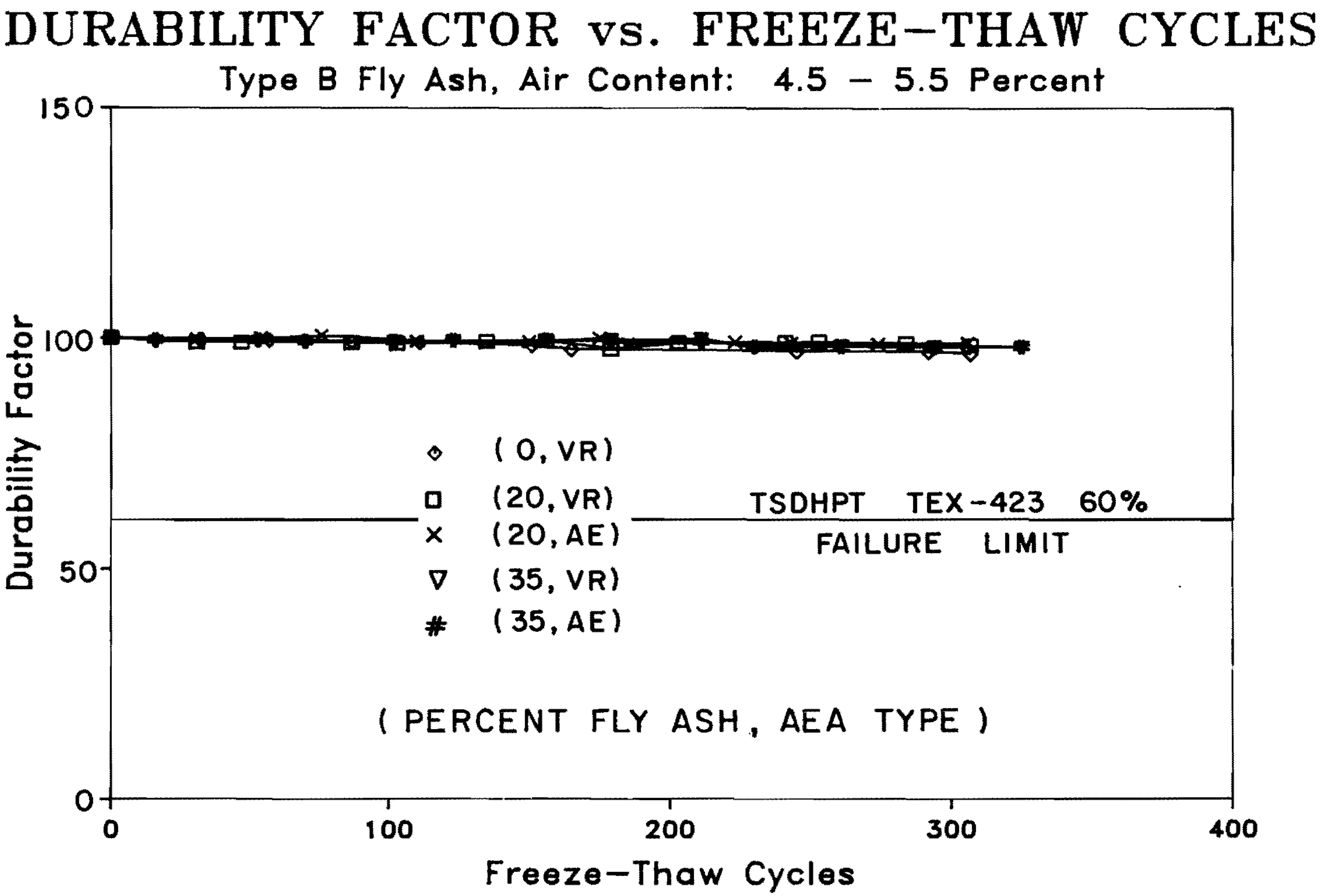


Fig. 5.28 Durability factor of concrete containing Type B fly ash with constant air content.

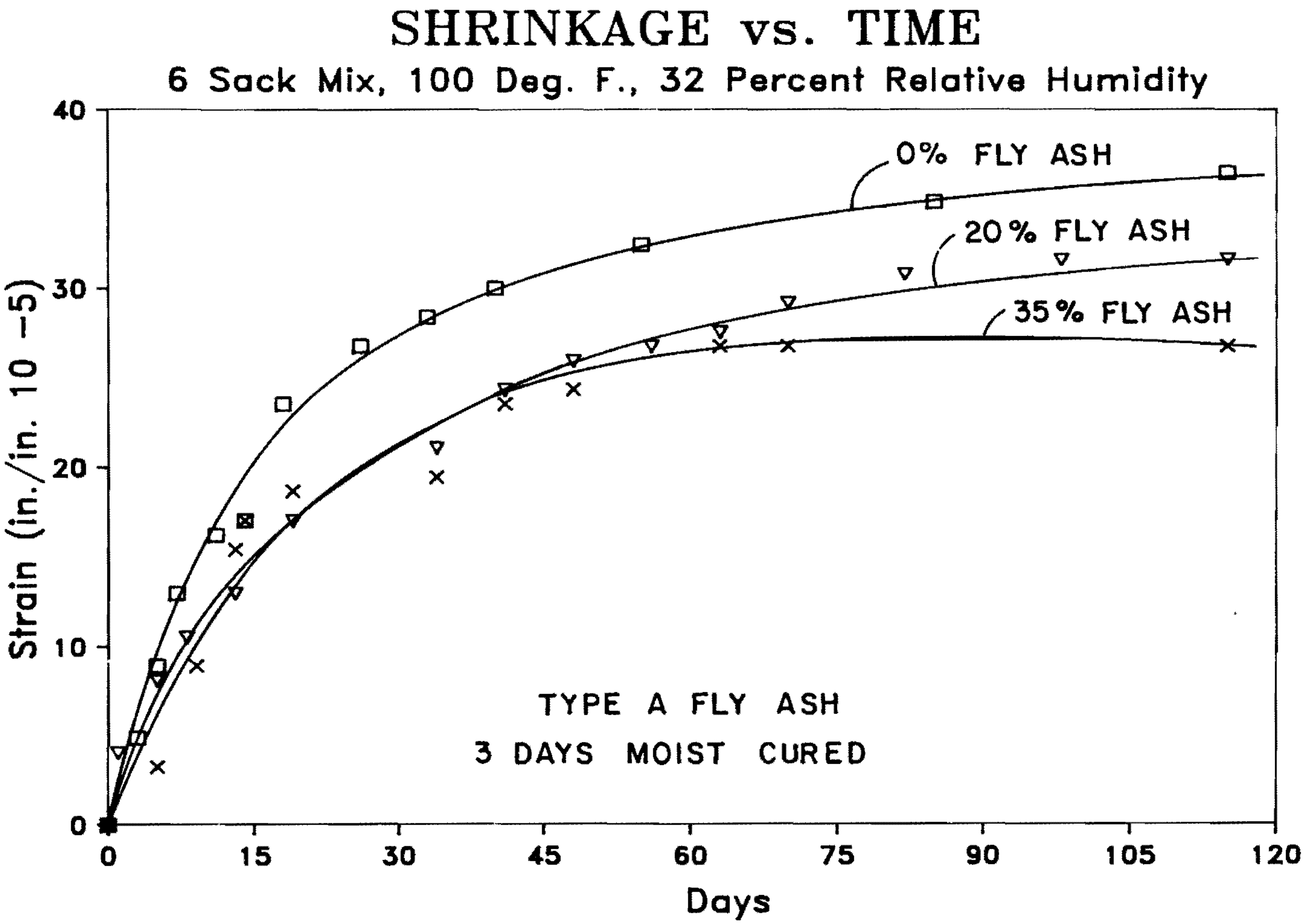


Fig. 5.29 Shrinkage of concrete containing Type A fly ash under hot-dry conditions, moist cured for 3 days.

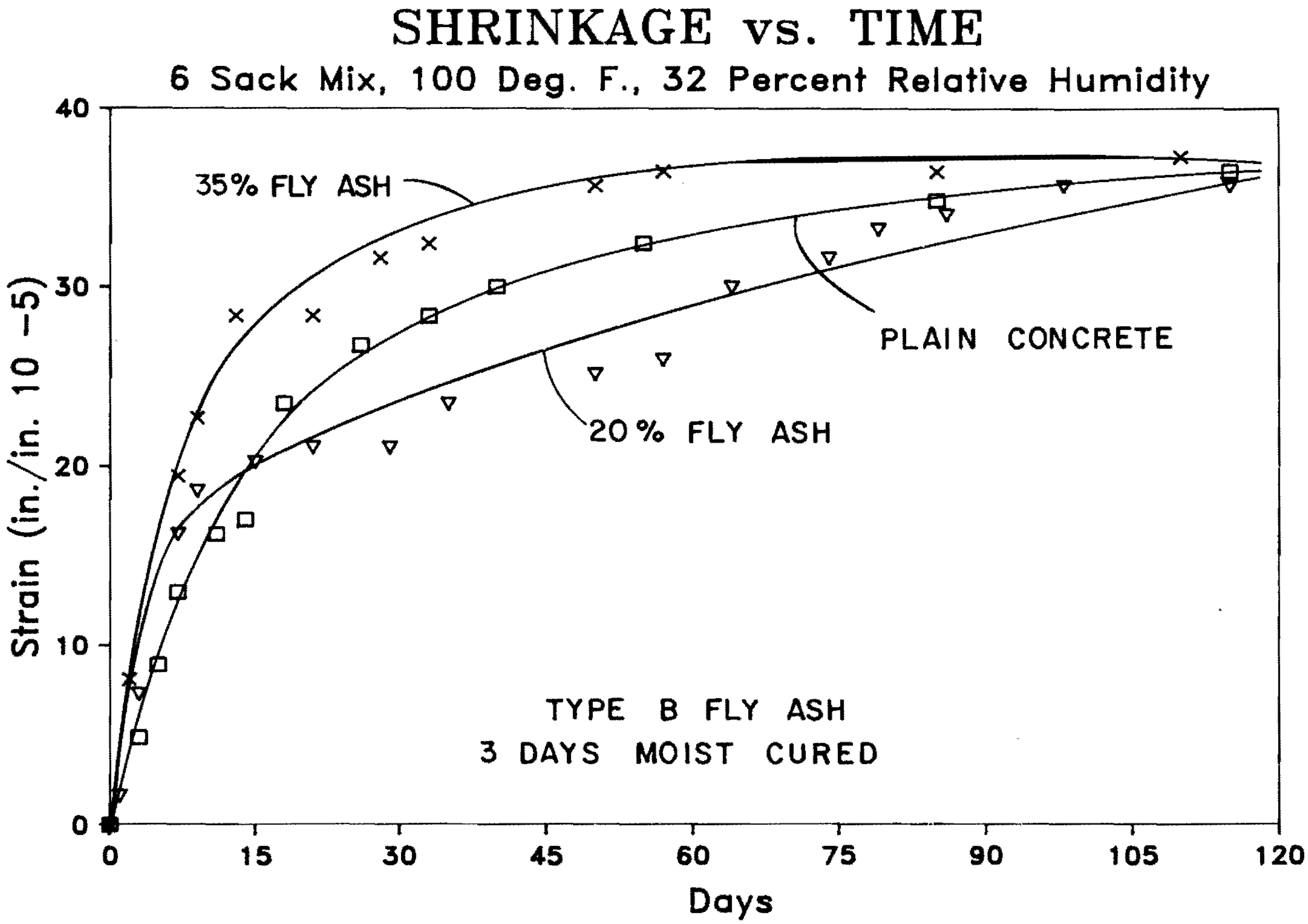


Fig. 5.30 Shrinkage of concrete containing Type B fly ash under hot-dry conditions, moist cured for 3 days.

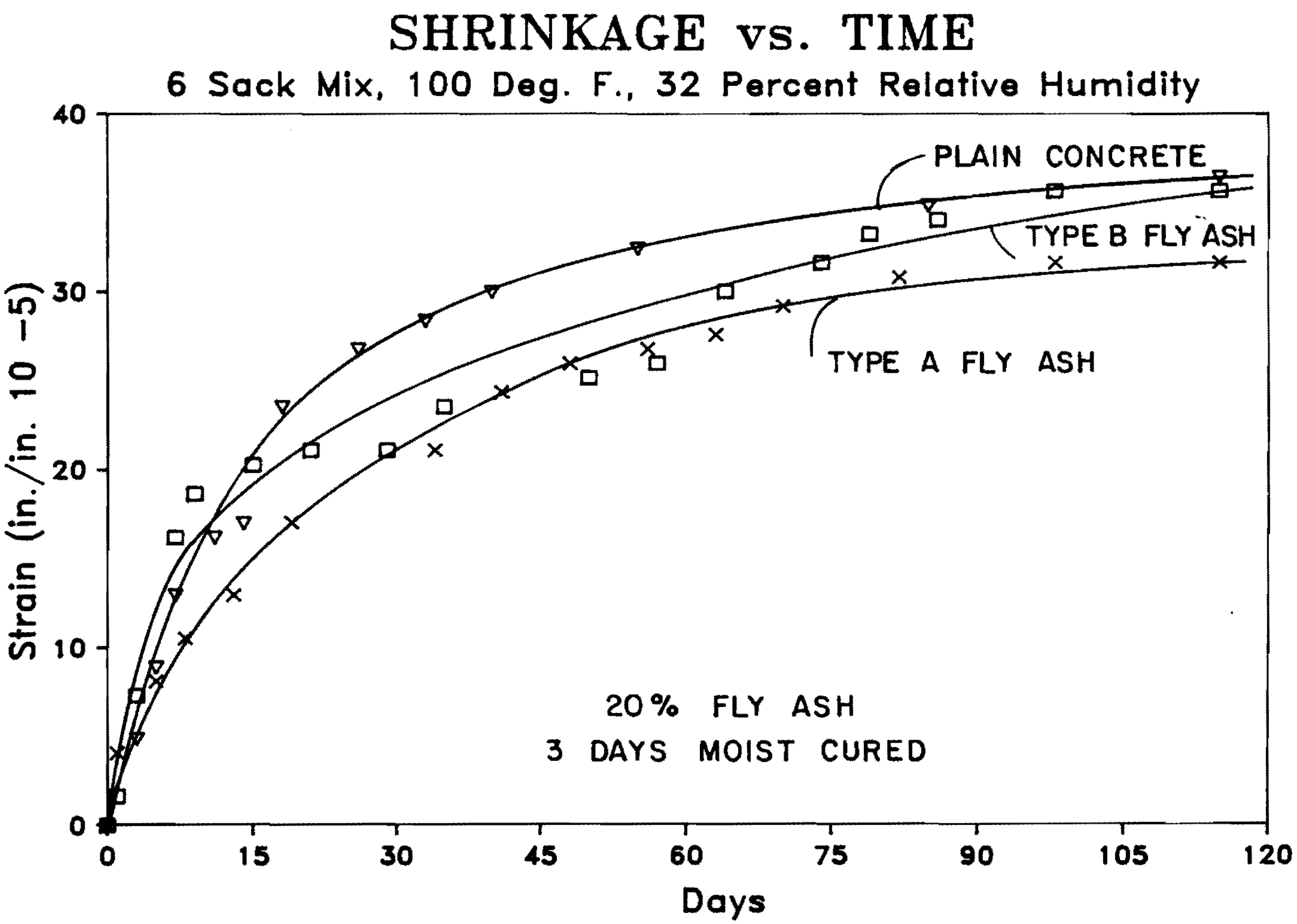


Fig. 5.31 Shrinkage of concrete containing 20% fly ash under hot-dry conditions, moist cured for 3 days.

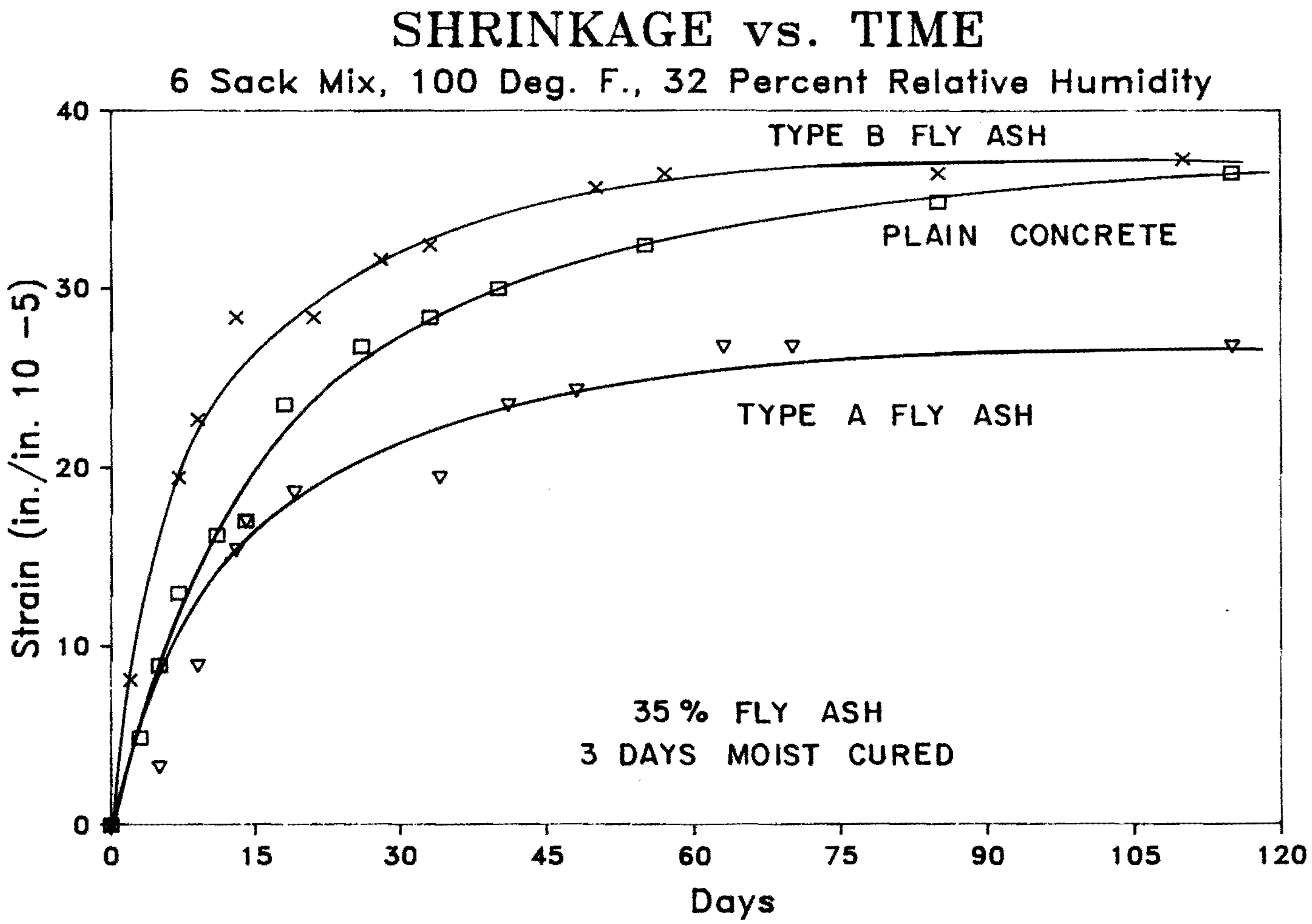


Fig. 5.32 Shrinkage of concrete containing 35% fly ash under hot-dry conditions, moist cured for 3 days.

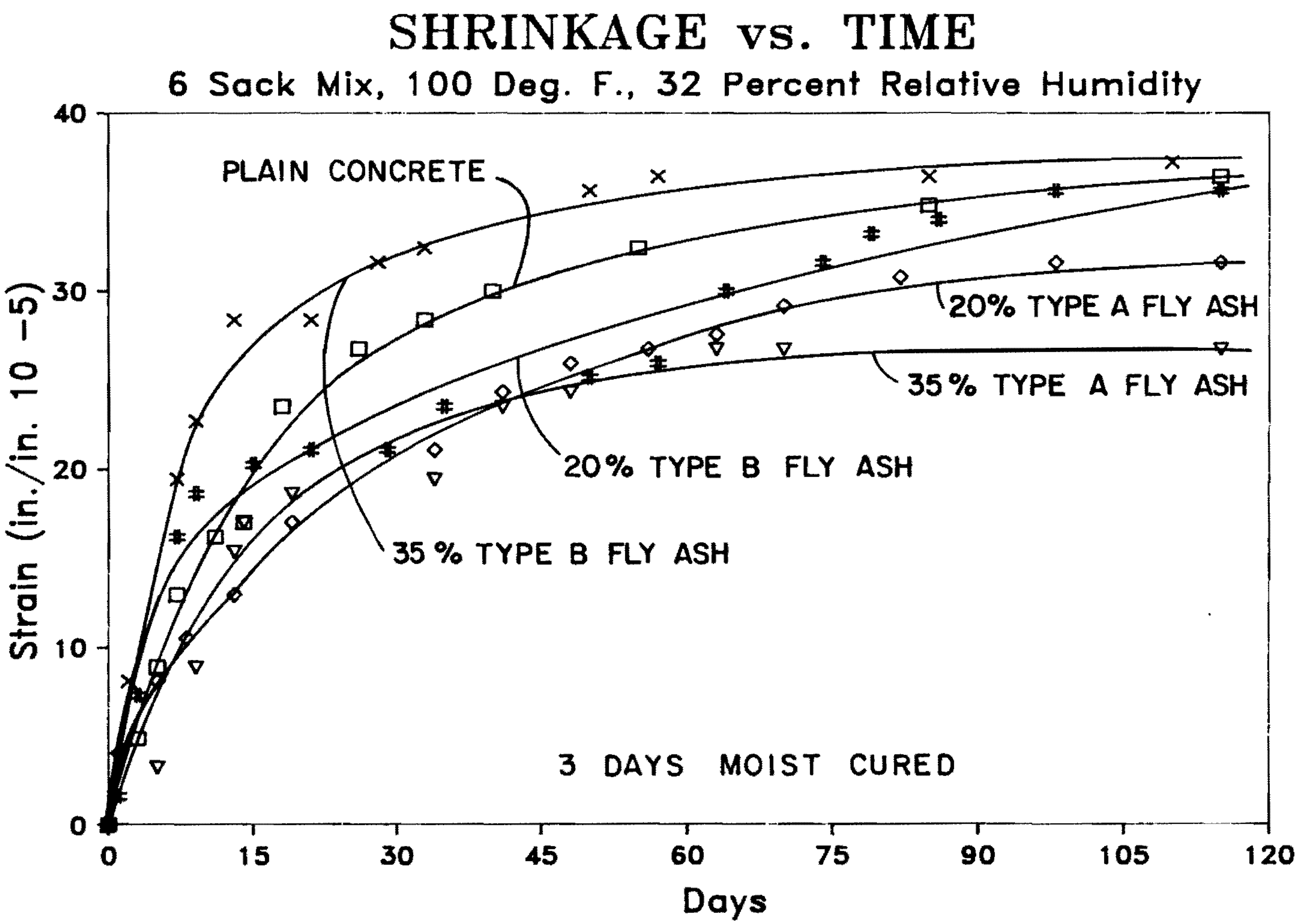


Fig. 5.33 Summary of shrinkage under hot-dry conditions, moist cured for 3 days.

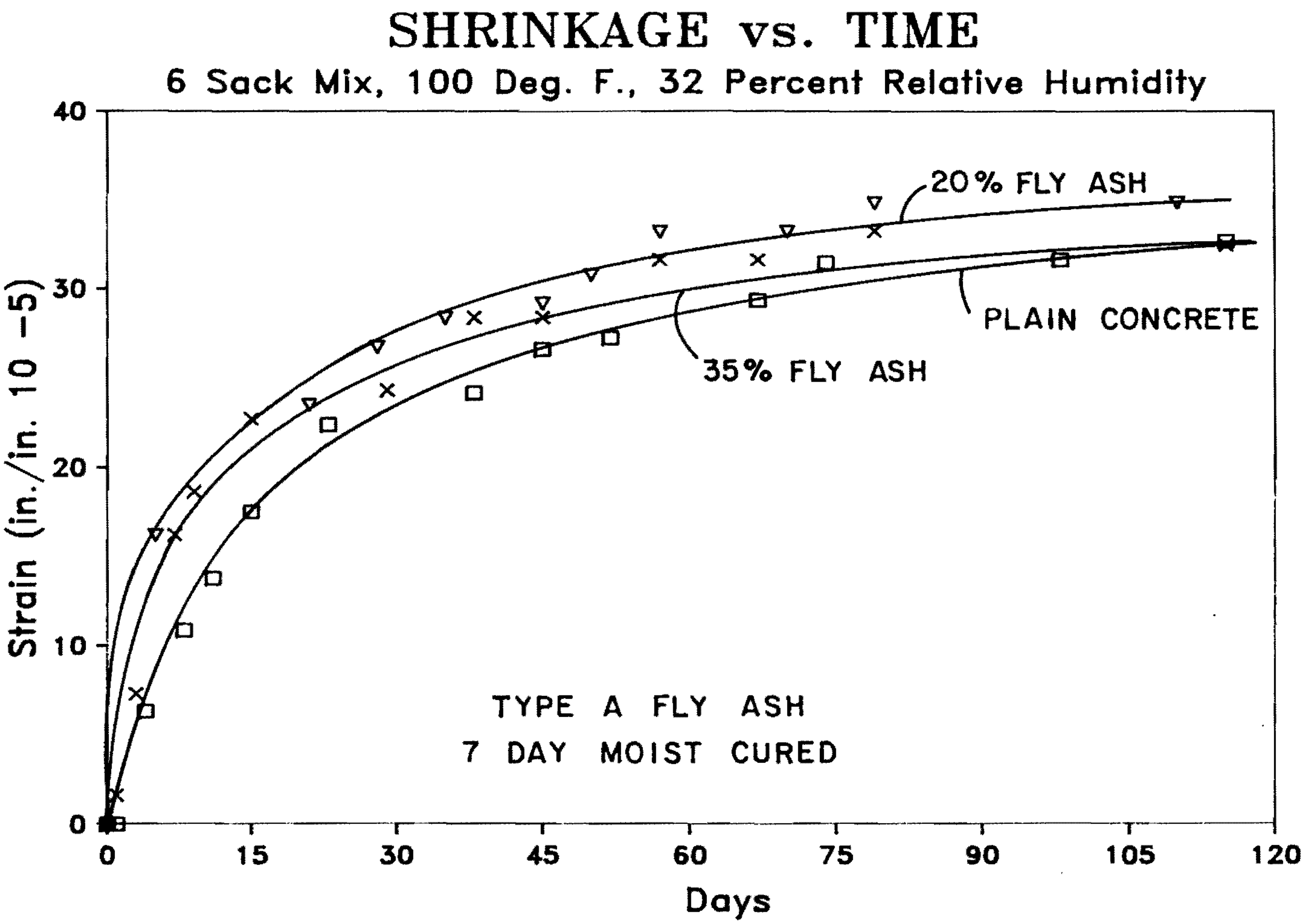


Fig. 5.34 Shrinkage of concrete containing Type A fly ash under hot-dry conditions, moist cured for 7 days.

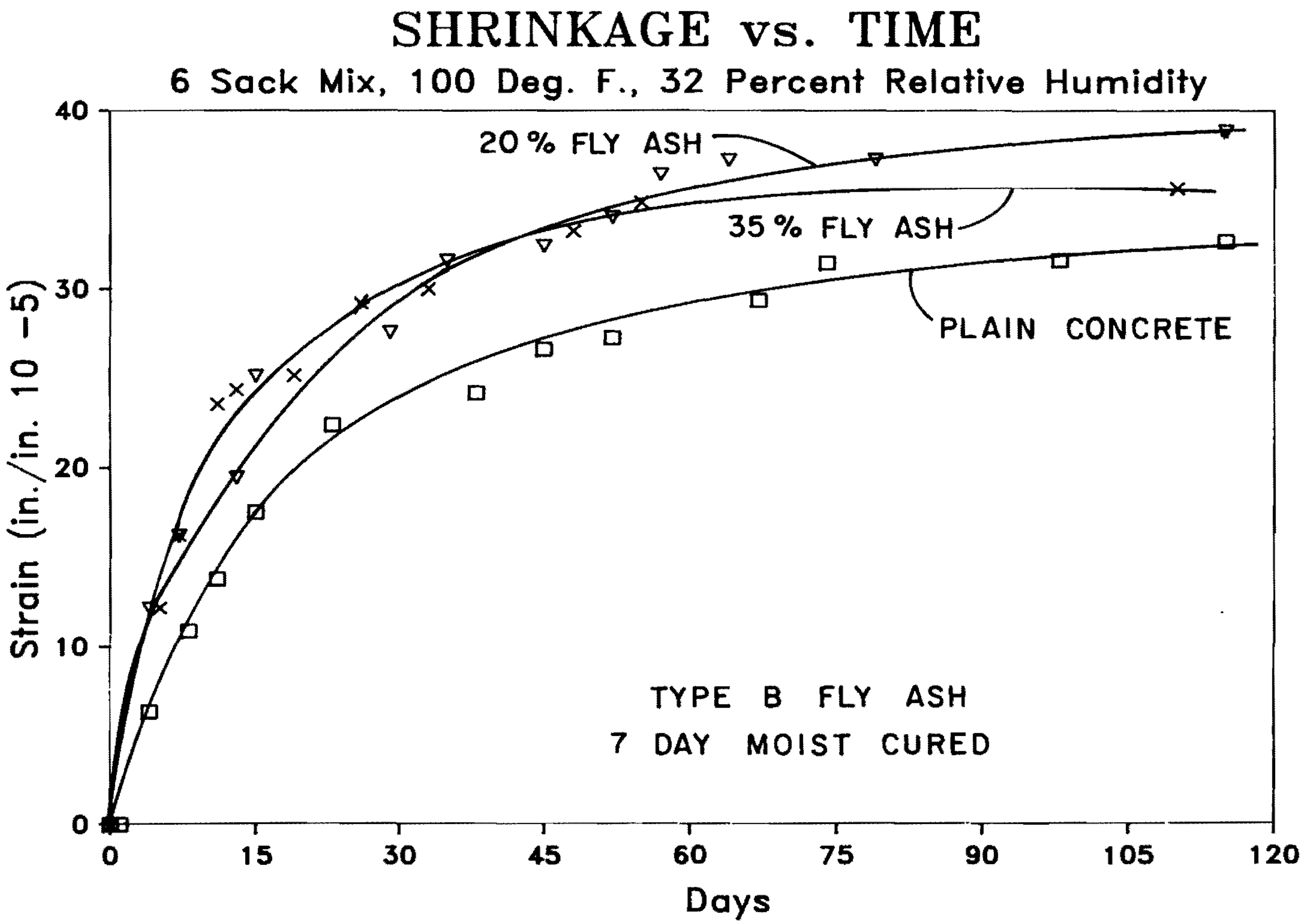


Fig. 5.35 Shrinkage of concrete containing Type B fly ash under hot-dry conditions, moist cured for 7 days.

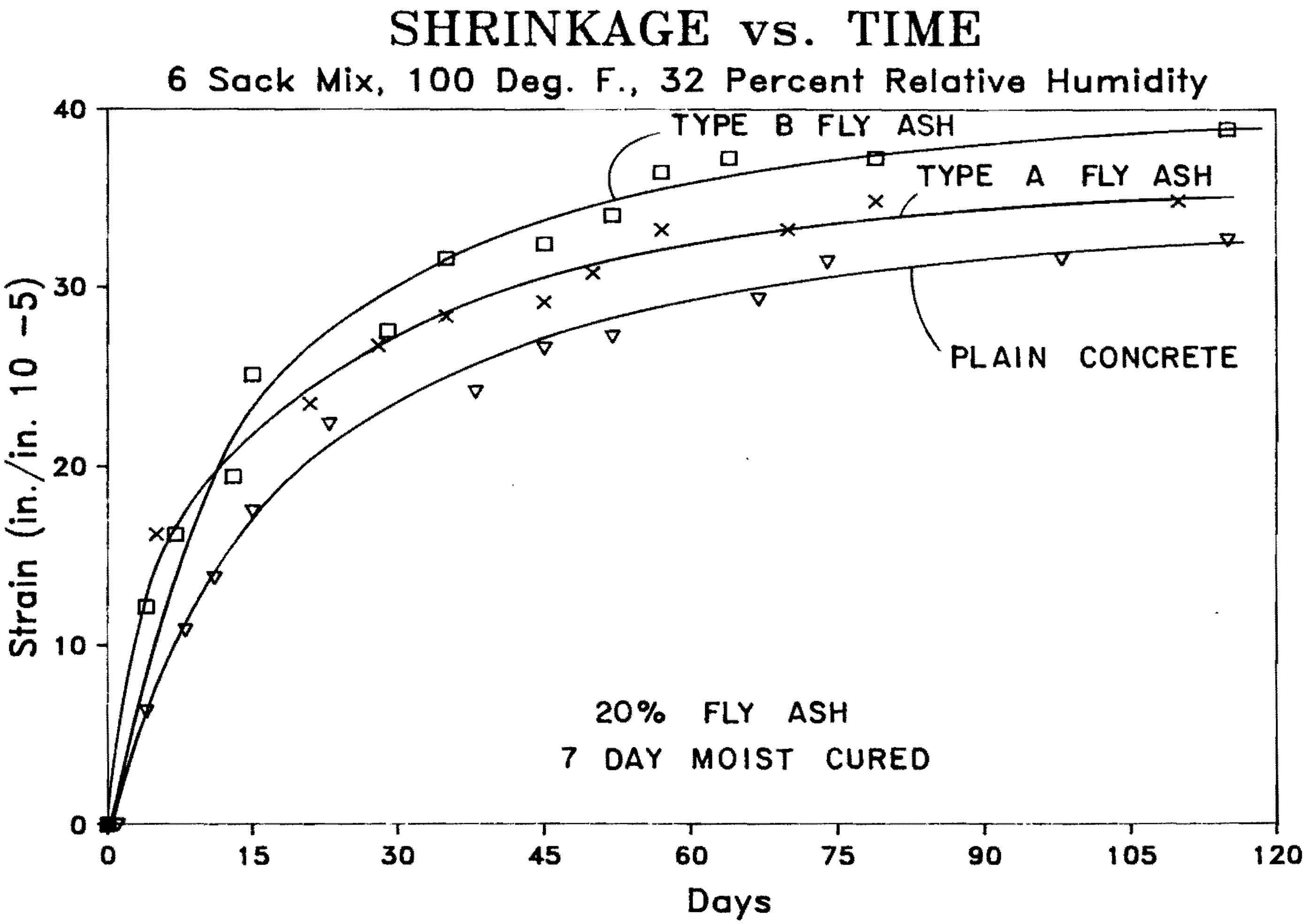


Fig. 5.36 Shrinkage of concrete containing 20% fly ash under hot-dry conditions, moist cured for 7 days.

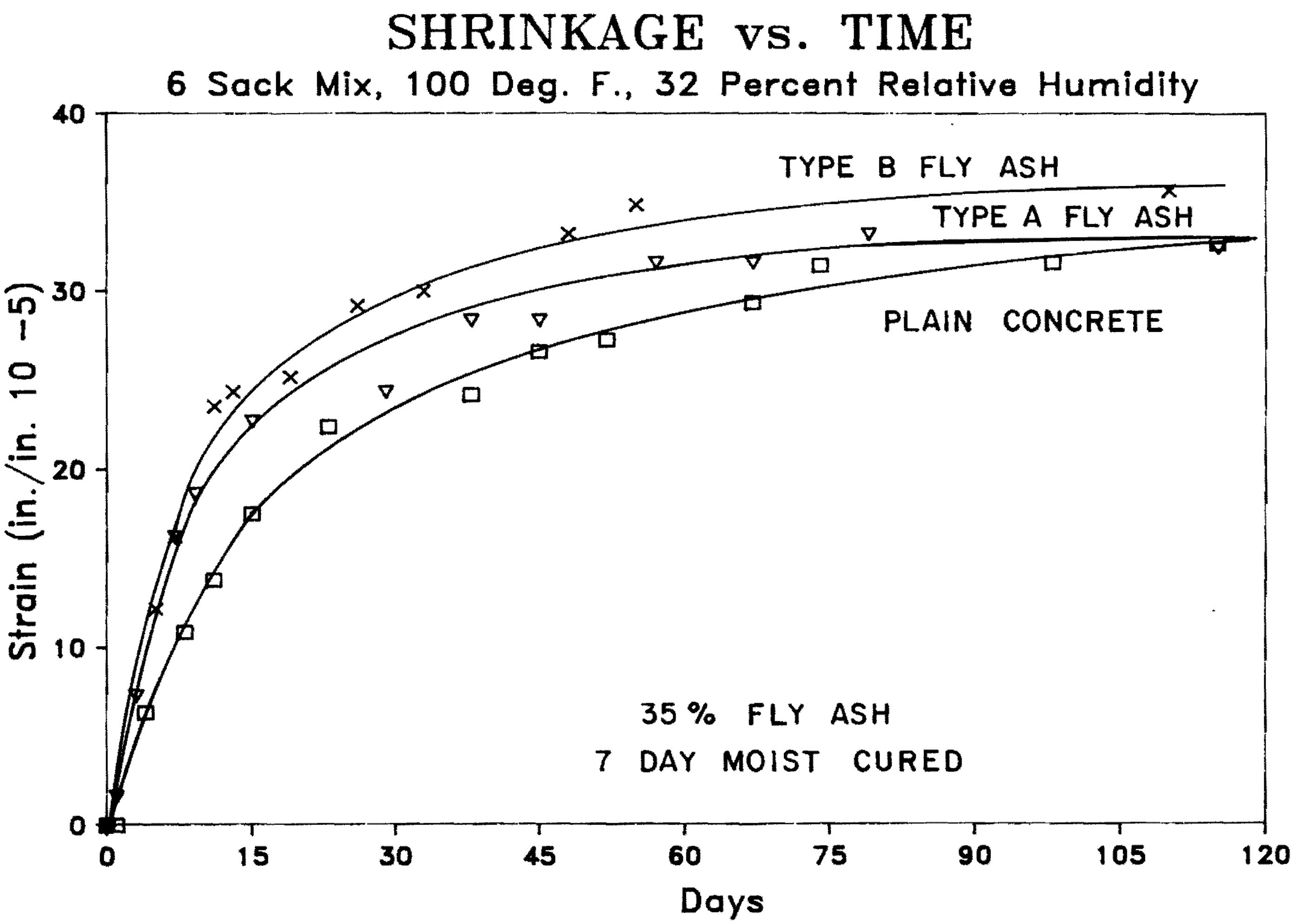


Fig. 5.37 Shrinkage of concrete containing 35% fly ash under hot-dry conditions, moist cured for 7 days.

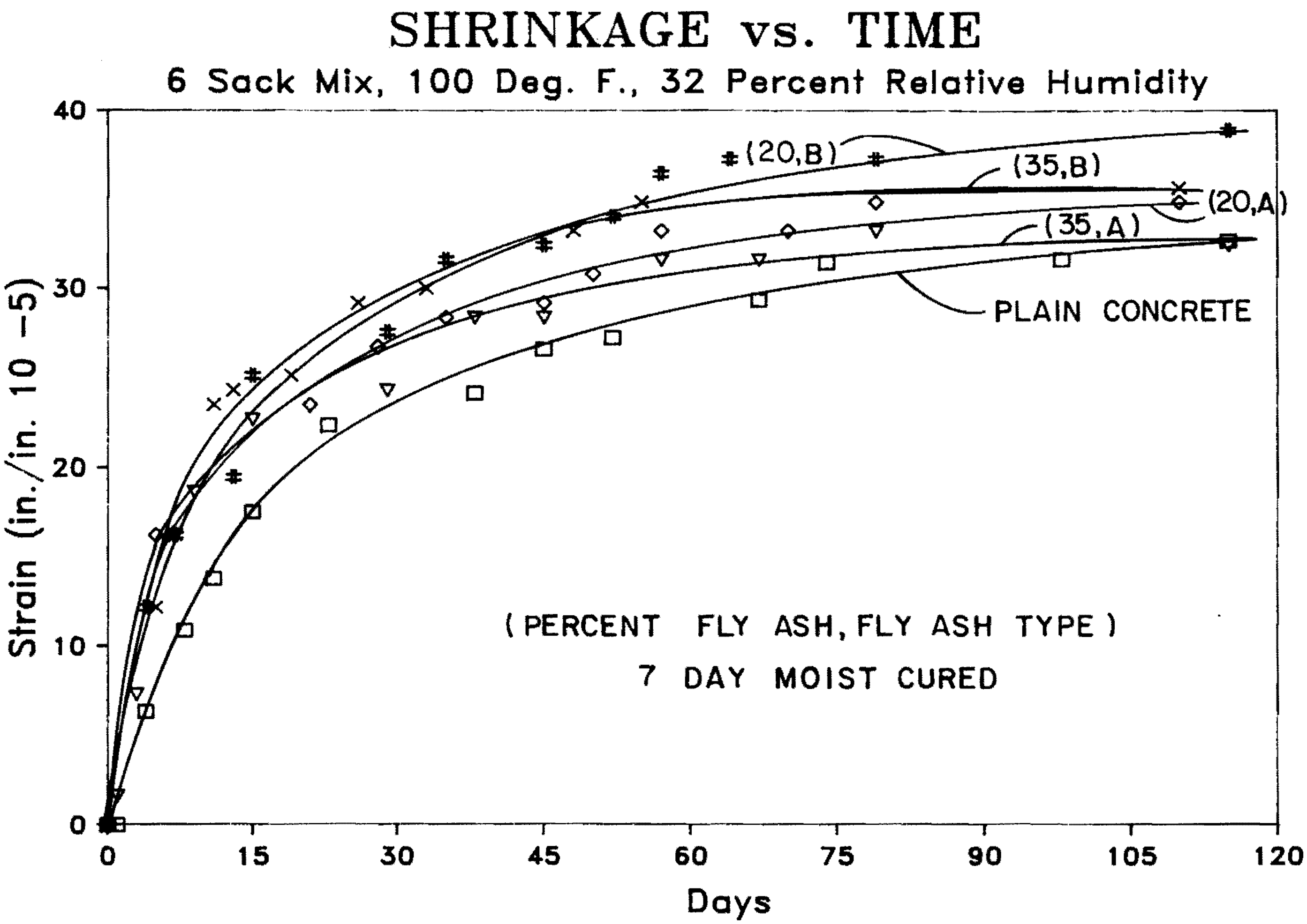


Fig. 5.38 Summary of shrinkage of concrete under hot-dry conditions, moist cured for 7 days.

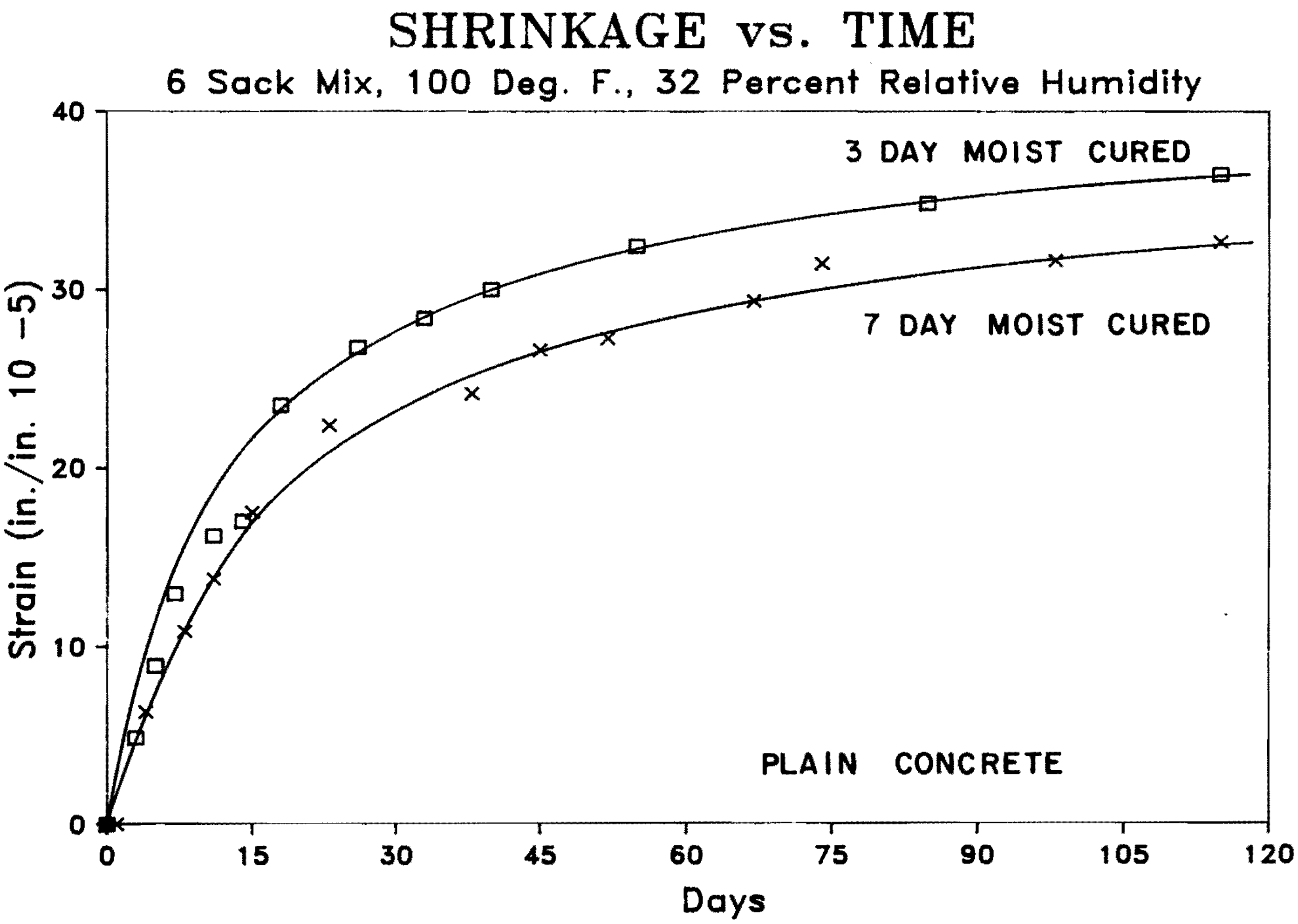


Fig. 5.39 Shrinkage of plain concrete under hot-dry conditions.

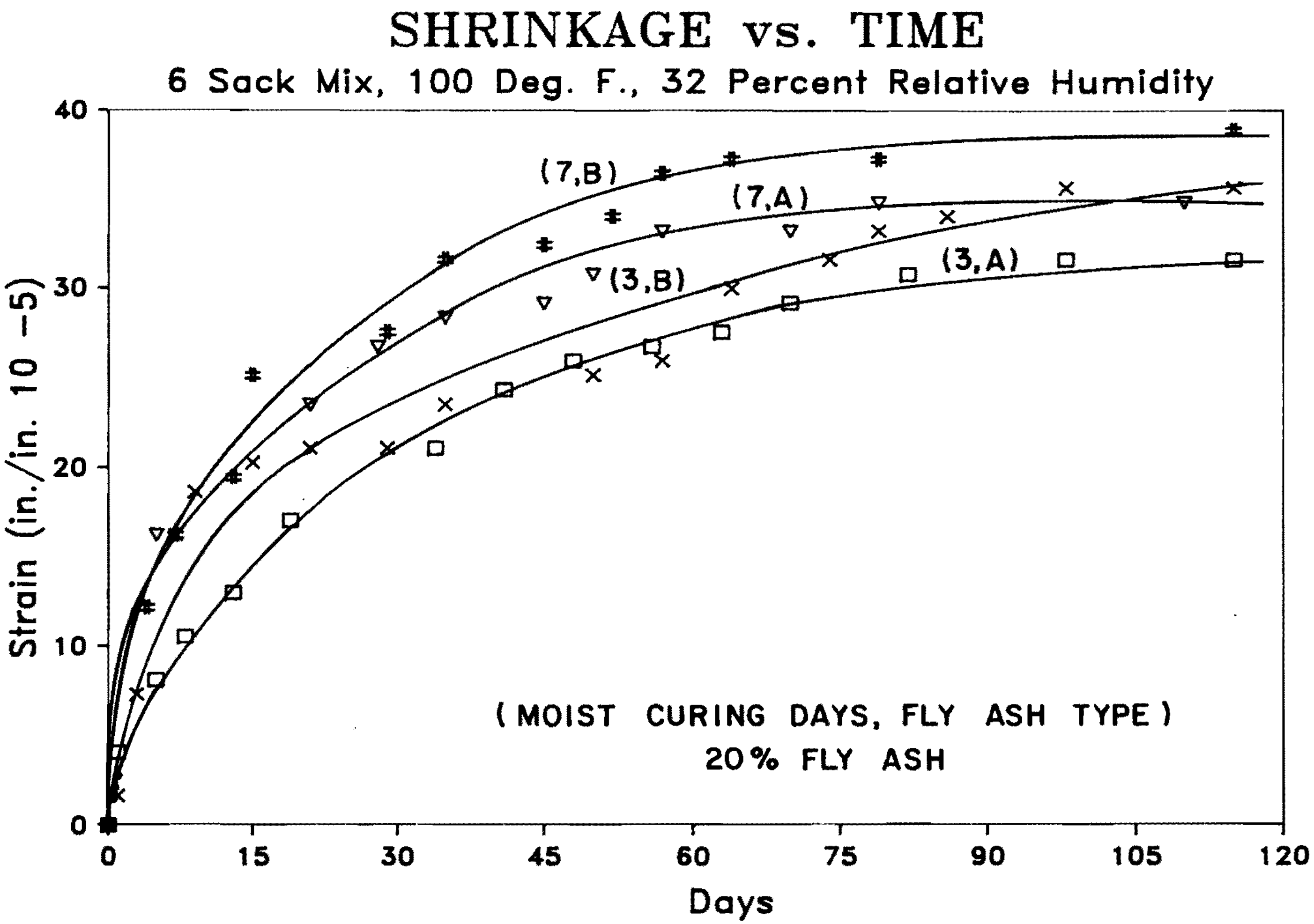


Fig. 5.40 Shrinkage of concrete containing 20% fly ash under hot-dry conditions.

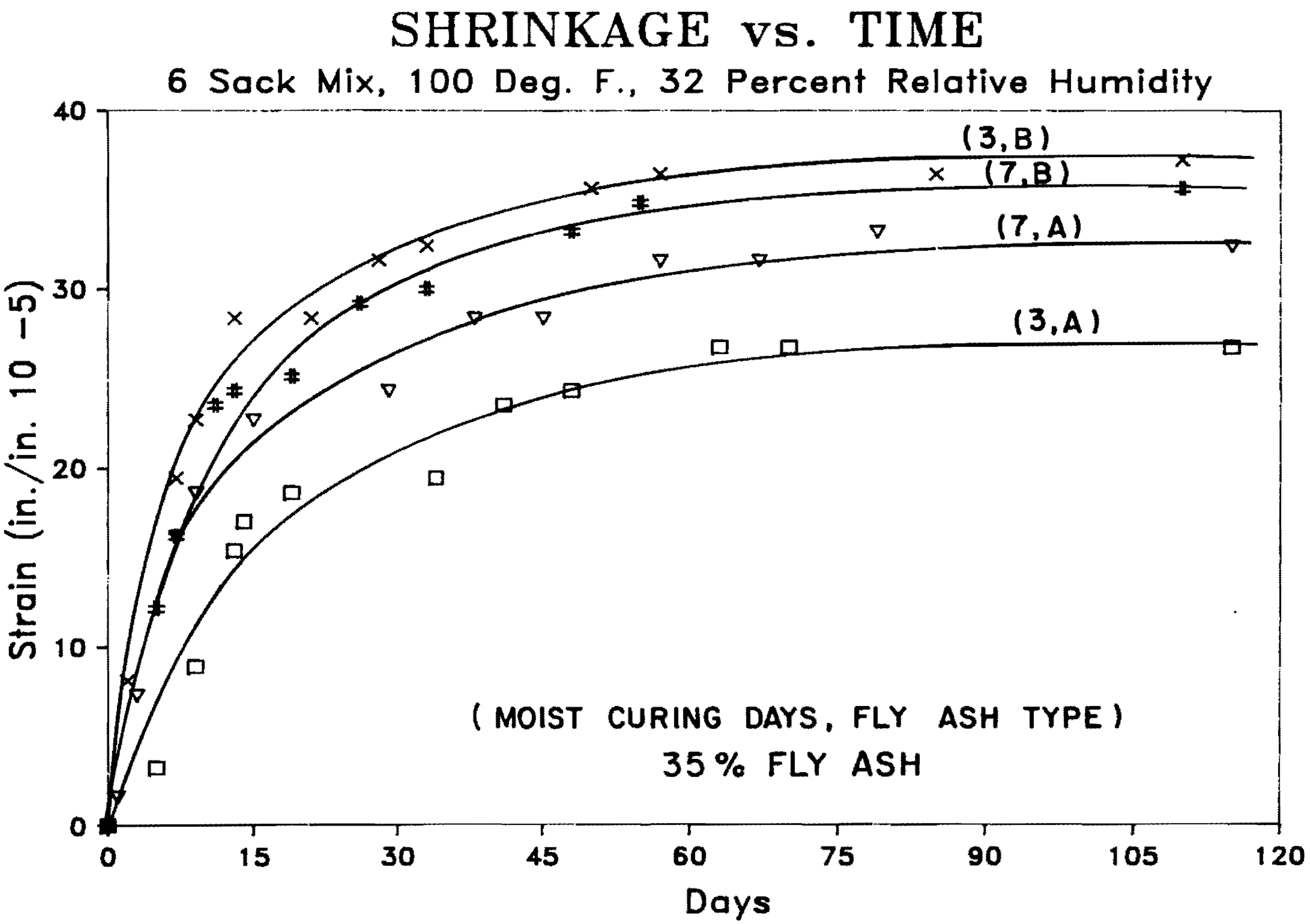


Fig. 5.41 Shrinkage of concrete containing 35% fly ash under hot-dry conditions.

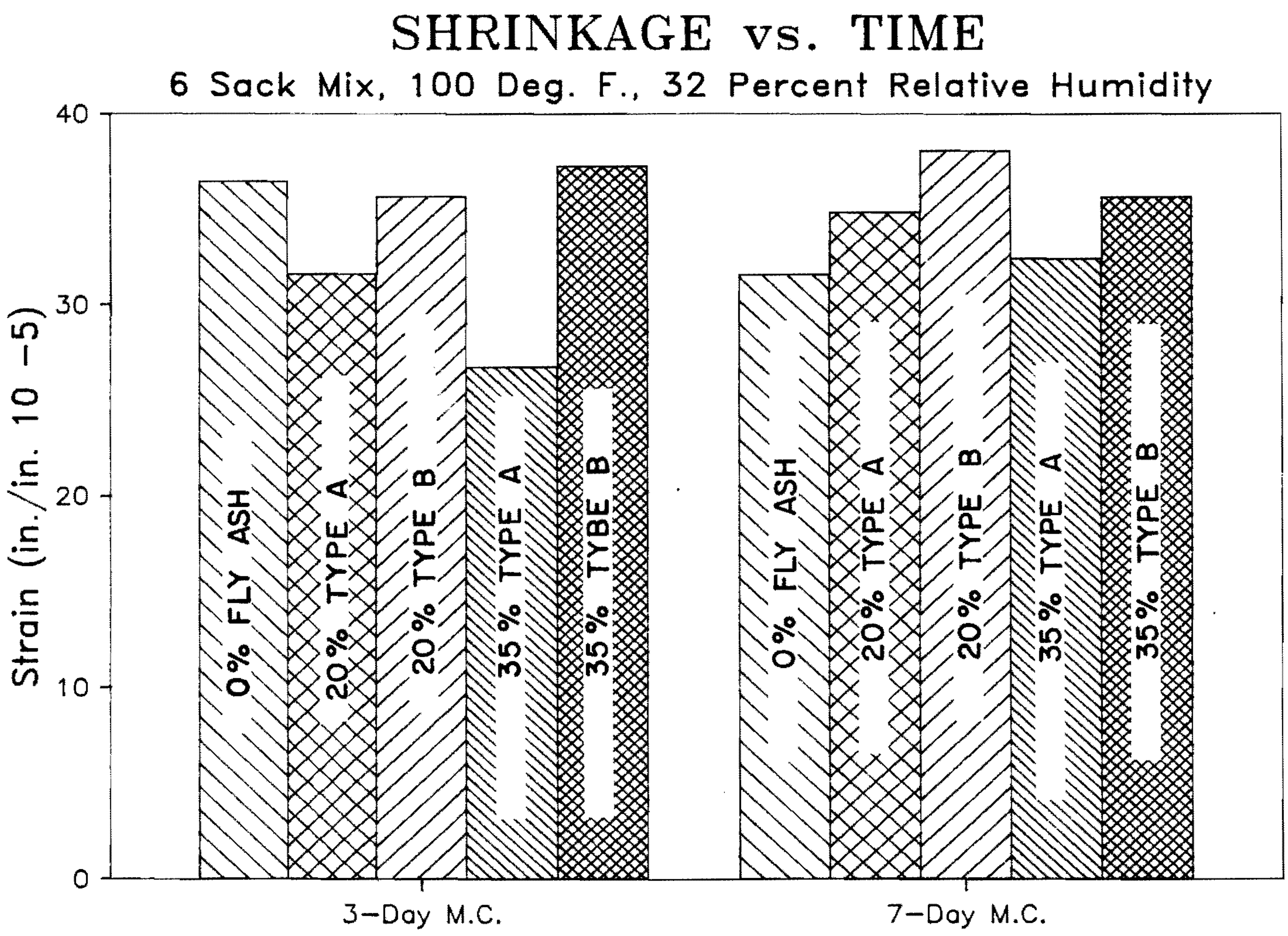


Fig. 5.42 Summary of concrete shrinkage under hot-dry conditions.

plain concrete which showed a decrease in shrinkage in the 7 day moist cured specimens as compared to the 3-day moist cured specimens.

5.9 Creep of Concrete Containing Fly Ash

Creep in concrete was determined in this experimental program to observe the effect of sustained load on fly ash concrete. Three separate tests were conducted: one on plain concrete, one on concrete containing 35% Type A fly ash and one test on concrete containing 35% Type B fly ash. The specimens were moist cured for 14 days before beginning the tests and were subjected to a 50,000 lb sustained load. The load was maintained for 250 days and deformations were periodically recorded. Figures 5.43 through 5.45 show total strains, creep strains and strains in the control specimens. The control strains are strains in identical but unloaded specimens and consist of the effects of shrinkage, temperature and relative humidity on concrete. The creep strains were calculated by subtracting the control strains from the total strains of the loaded specimens. Figure 5.46 compares the creep in concrete containing fly ash to that of plain concrete containing no fly ash.

Concrete containing fly ash displayed less creep than plain concrete. In addition, concrete containing Type B fly ash showed more creep deformation than concrete containing Type A fly ash.

5.10 Effect of Fly Ash on the Abrasion Resistance of Concrete.

The abrasion resistance of concrete containing fly ash is compared to that of plain concrete in Fig. 5.47. Depth of wear is used to indicate abrasion instead of weight loss as suggested in ASTM C944-80. None of the concrete specimens showed any substantial loss of weight during these tests. However, when depth of wear was measured against the time under testing, concrete containing Type B fly ash exhibited better abrasion resistance than either plain concrete or concrete containing Type A fly ash.

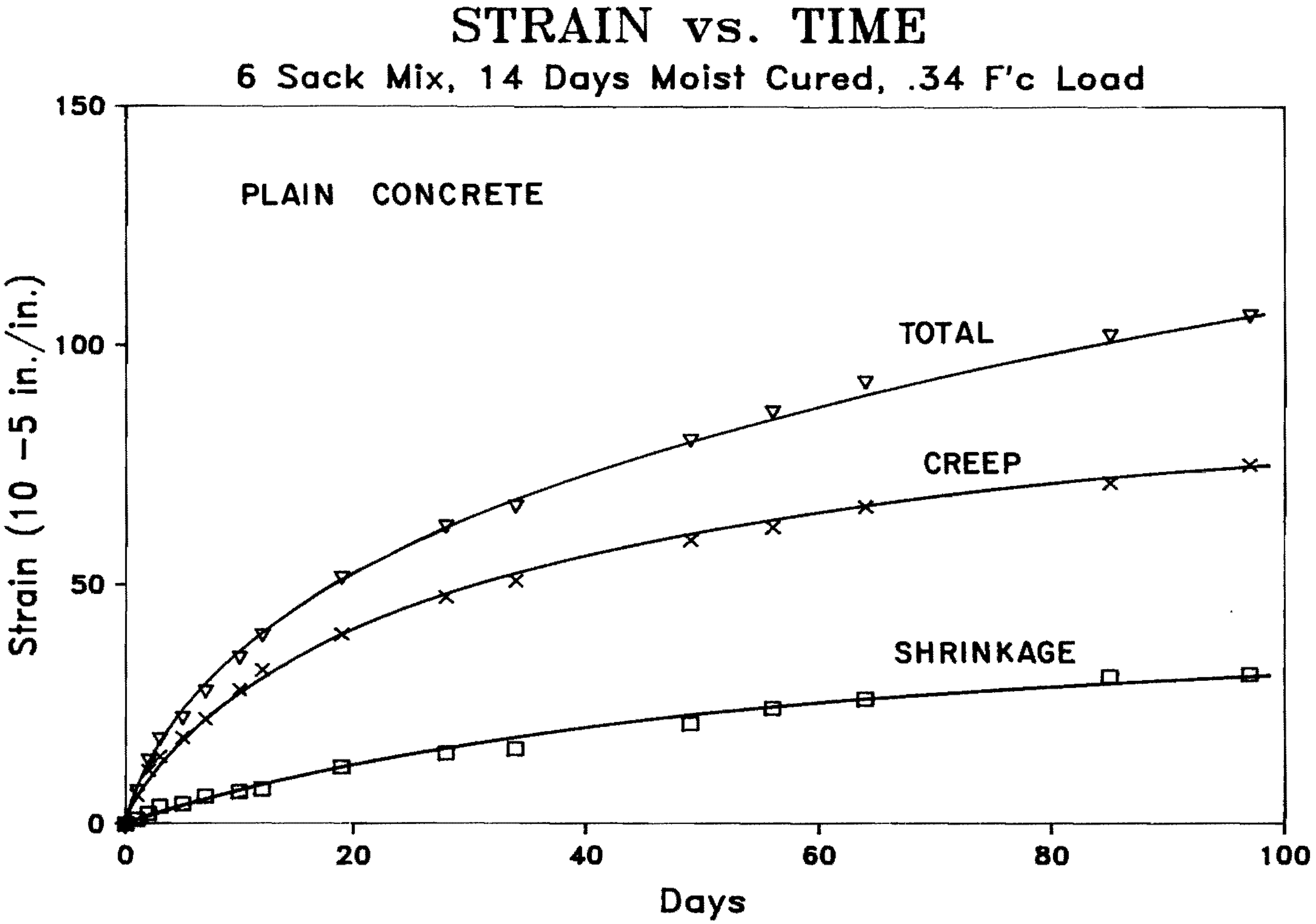


Fig. 5.43 Creep deformation of plain concrete.

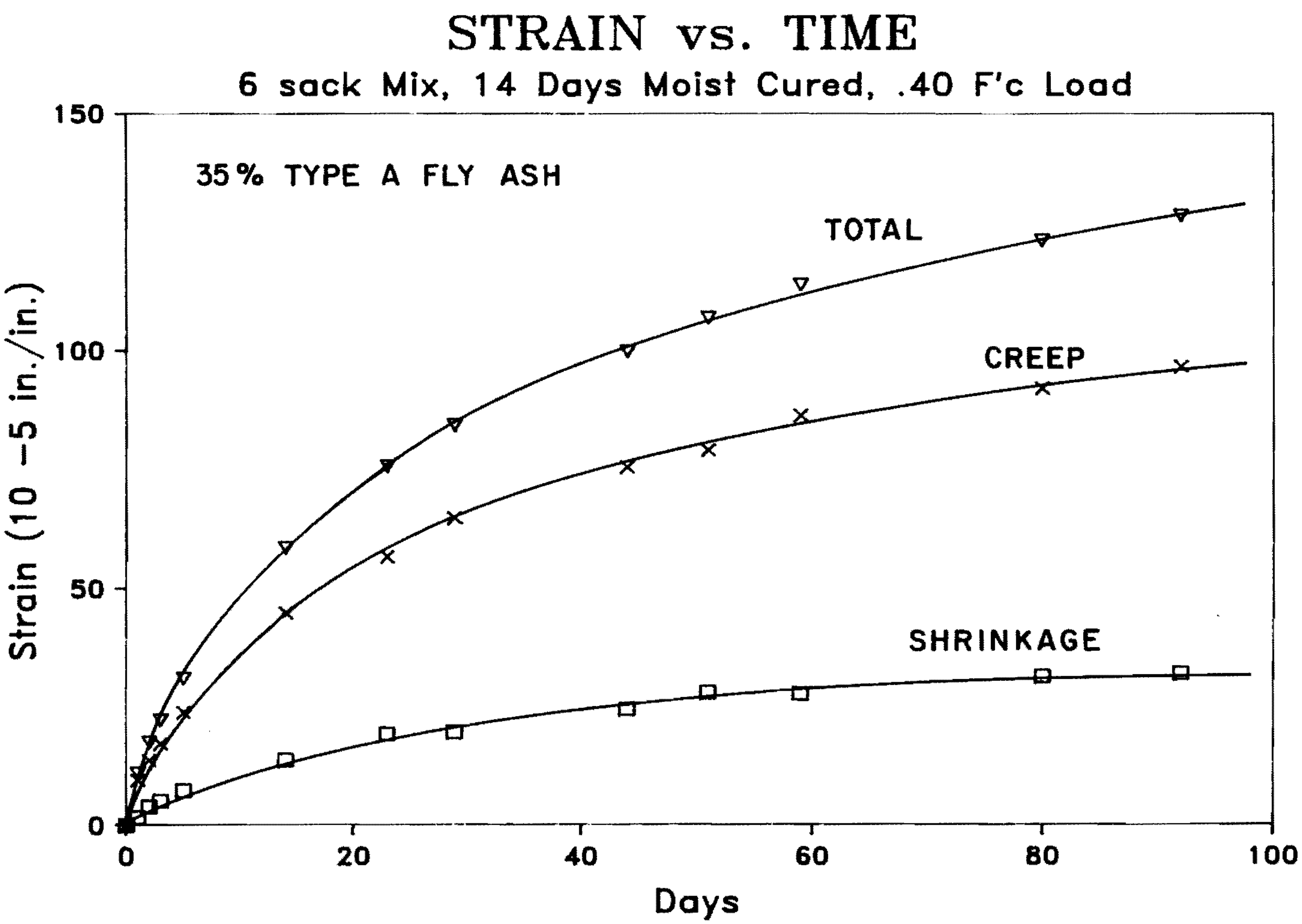


Fig. 5.44 Creep deformation of concrete containing 35% Type A fly ash.

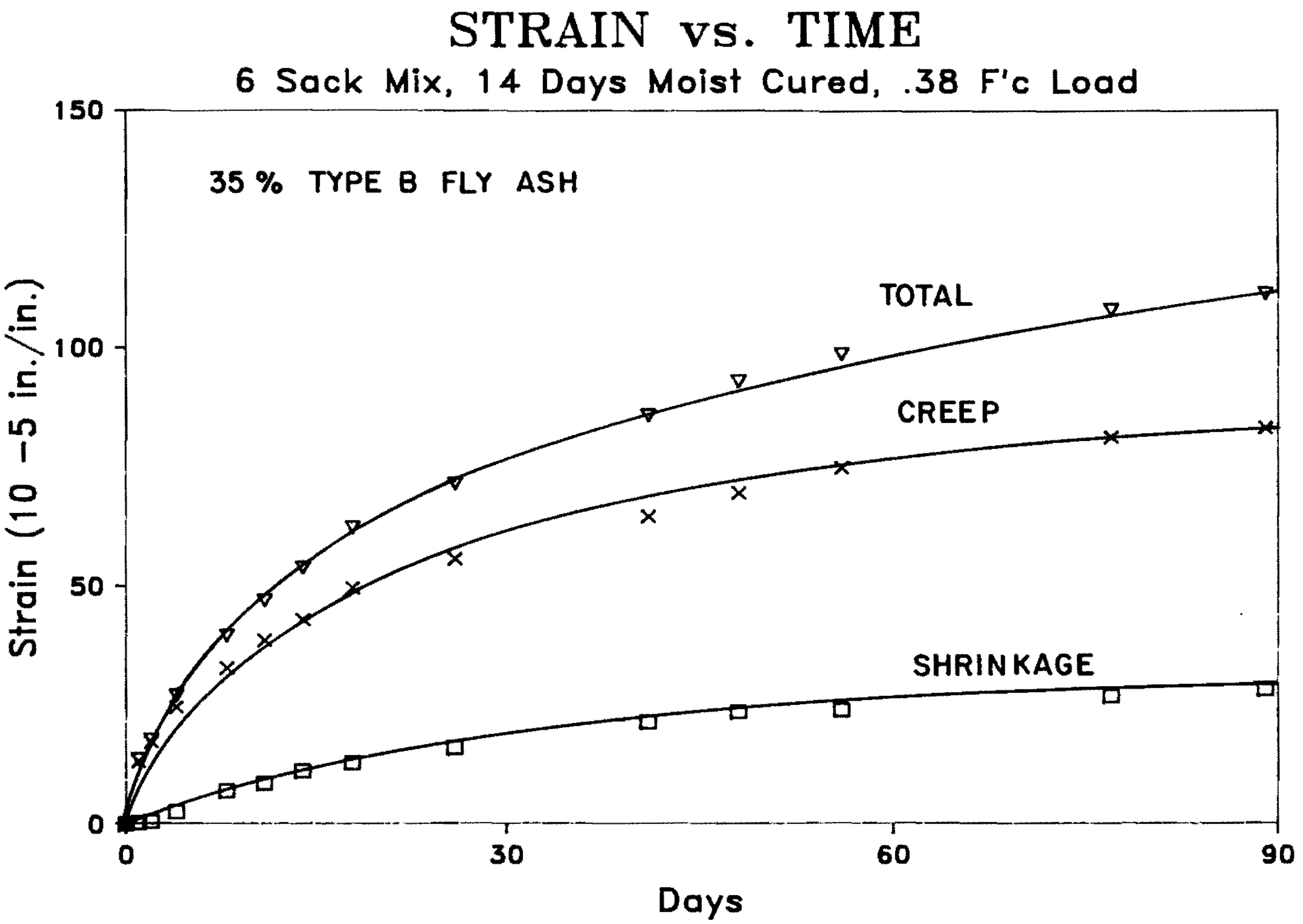


Fig. 5.45 Creep deformation of concrete containing 35% Type B fly ash.

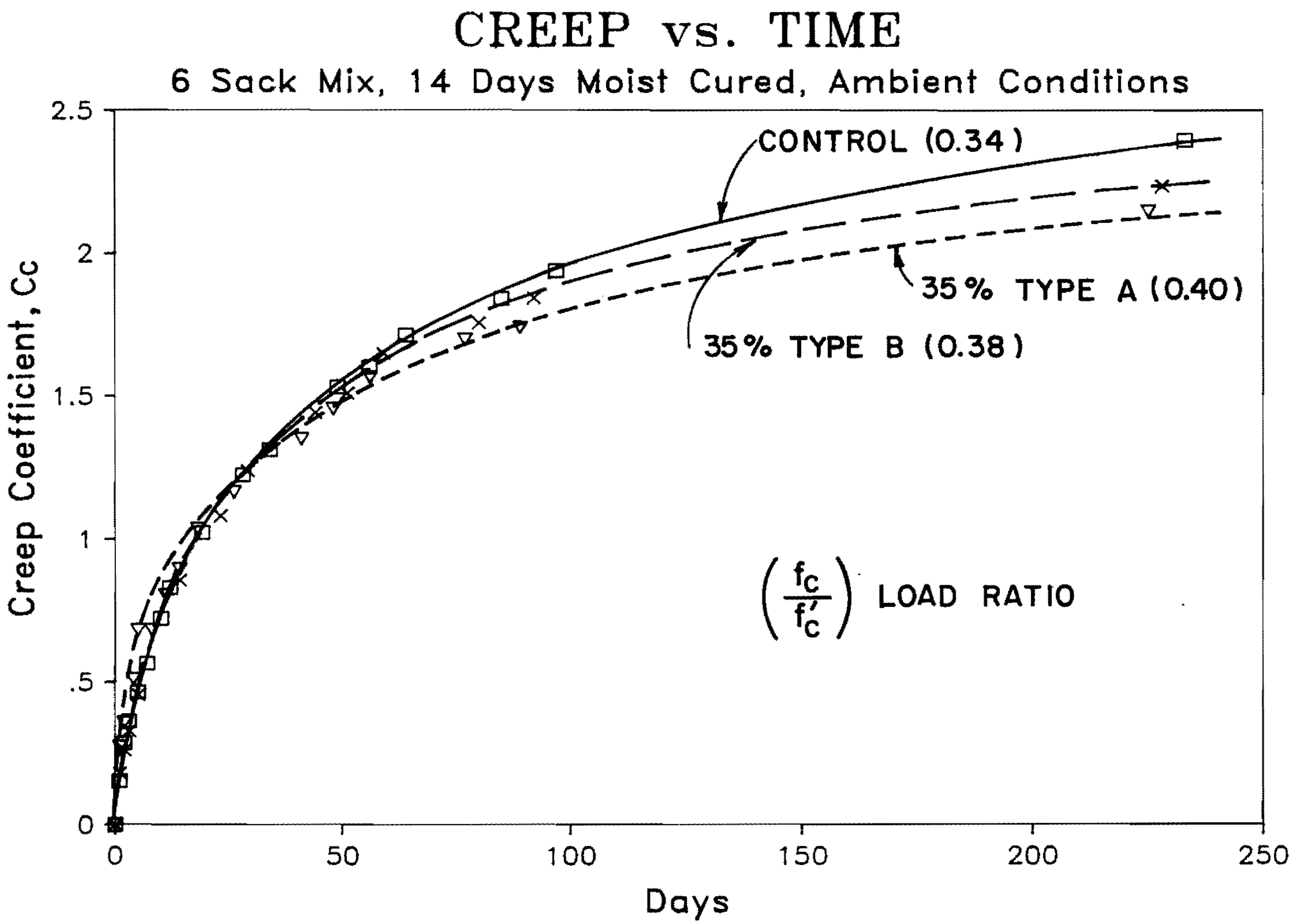


Fig. 5.46 Summary of creep deformation in concrete.

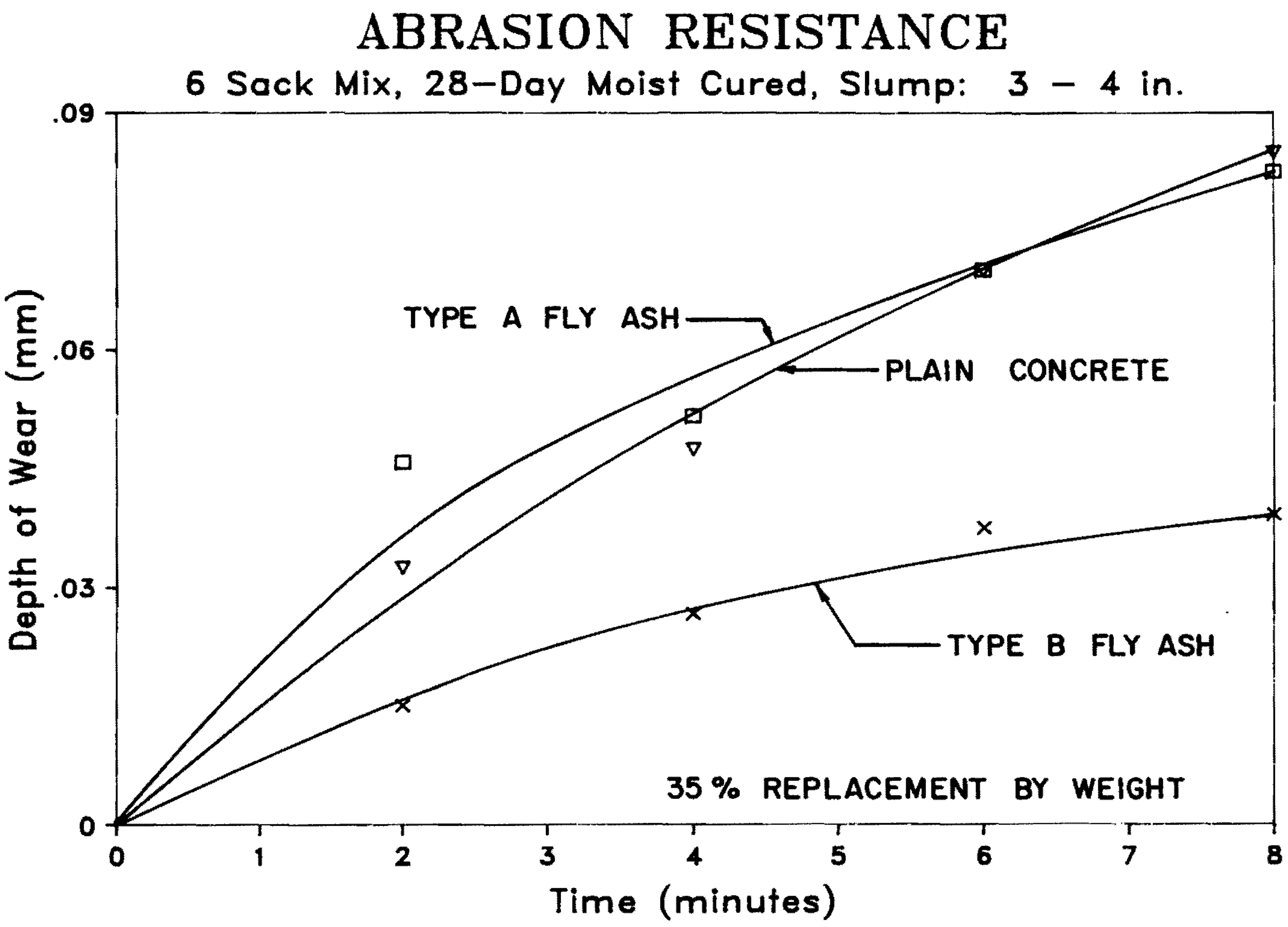


Fig. 5.47 Depth of wear in concrete.

CHAPTER 6

DISCUSSION OF TEST RESULTS

6.1 General

The test results presented in the previous chapter are discussed in this chapter. The results will be summarized and the dominant trends in the data will be discussed. Wherever practical, the test results are correlated with the compressive strength or the air content of the concrete, since these quantities can be measured in production concrete and are often related to the durability properties of hardened concrete. In addition, the results of this experimental program are compared to the results of previous studies. The differences in the results with those of the investigators are explained where appropriate.

The fly ash used in this study is representative of fly ash found throughout Texas, but does not encompass the entire range of chemical compositions encountered in Texas fly ashes. Therefore the results discussed herein are restricted to the fly ashes used in this study.

6.2 Testing Program

This test program was designed to observe the performance of concrete containing fly ash and compare the results to those of plain concrete. The mixes are of two basic types:

(1) Mixes containing a standard dosage of air entraining agent.

(2) Mixes containing an adjusted dosage of air entraining agent to produce a 5% air content in the concrete.

This scheme was used in order to observe the effects on the durability of concrete of not adjusting the AEA dosage when using fly ash in concrete. This is an anticipated problem in the production of concrete containing fly ash or Type IP cement. When directly comparing the performance of hardened concrete containing fly ash against that of plain concrete in this study, equivalent concrete mixes refer to mixes having the same air content and "cement plus fly ash" content by weight.

The dosage of the water-reducing admixture was held constant in all mixes, because it was not a studied parameter in this investigation. This does not imply that the water-reducing admixture did not affect the results. As stated in chapter 4 the demolding procedure was delayed on concrete containing 35% Type A fly ash. This was due to over retardation of the mix. No excessive retardation was observed in the concrete mixes containing 35% fly ash Type B. Since Type A fly ash has very little cementitious properties, retarding the fly ash portion of the "cement plus fly ash" content is not necessary. As a result, the cement is actually exposed to much more admixture than would normally be prescribed for a similar mix containing no fly ash.

Nearly all previous experimental studies concentrated on the effects of Type A fly ash. However the increased use of subbituminous and lignite coals has made Type B fly ash readily available throughout the state of Texas and is the likely economic choice for concrete production. For this reason, both Types A and B fly ash were investigated in this study and are compared in the succeeding sections along with equivalent plain concrete.

6.3 Effect of Fly Ash on Concrete Strength

6.3.1 Compressive Strength.

Figures 6.1 and 6.2 summarize the 28-day compressive strength results of this study. The results show that in concrete with equal air contents, the compressive strength of concrete containing fly ash and Type IP cement is equal to or higher than that of the equivalent plain concrete. Note that when the use of fly ash in a concrete mix containing a constant dosage of AEA results in a lower air content, the increase in strength of the concrete containing fly ash is higher than when the AEA dosage is adjusted to produce a constant air content. The 28-day compressive strengths of concrete containing fly ash with 5% air in this study are over 40% higher than the required design strength. In all cases, concrete containing fly ash with 5% air and a 6-sack "cement plus fly ash" content tested higher in compressive strength than an equivalent plain concrete mix; this includes concrete produced with Type IP cement containing 20% Type A fly ash.

These results are in agreement with previous studies [47,64,71,79]. Lane reports for the Tennessee Valley Authority that when fly ash is used as an equal weight replacement or as a 2 to 1 volume replacement for portland cement, 28-day compressive strengths are higher than in similar plain concrete. However, Simmons and Pasko [64], and Rosner [62] showed that 28-day compressive strengths of concrete containing fly ash mixed using equal volume replacement schemes are not in general higher than those of similar plain concrete mixes. The use of fly ash in concrete on an equal weight replacement basis could benefit the compressive strength of concrete in three

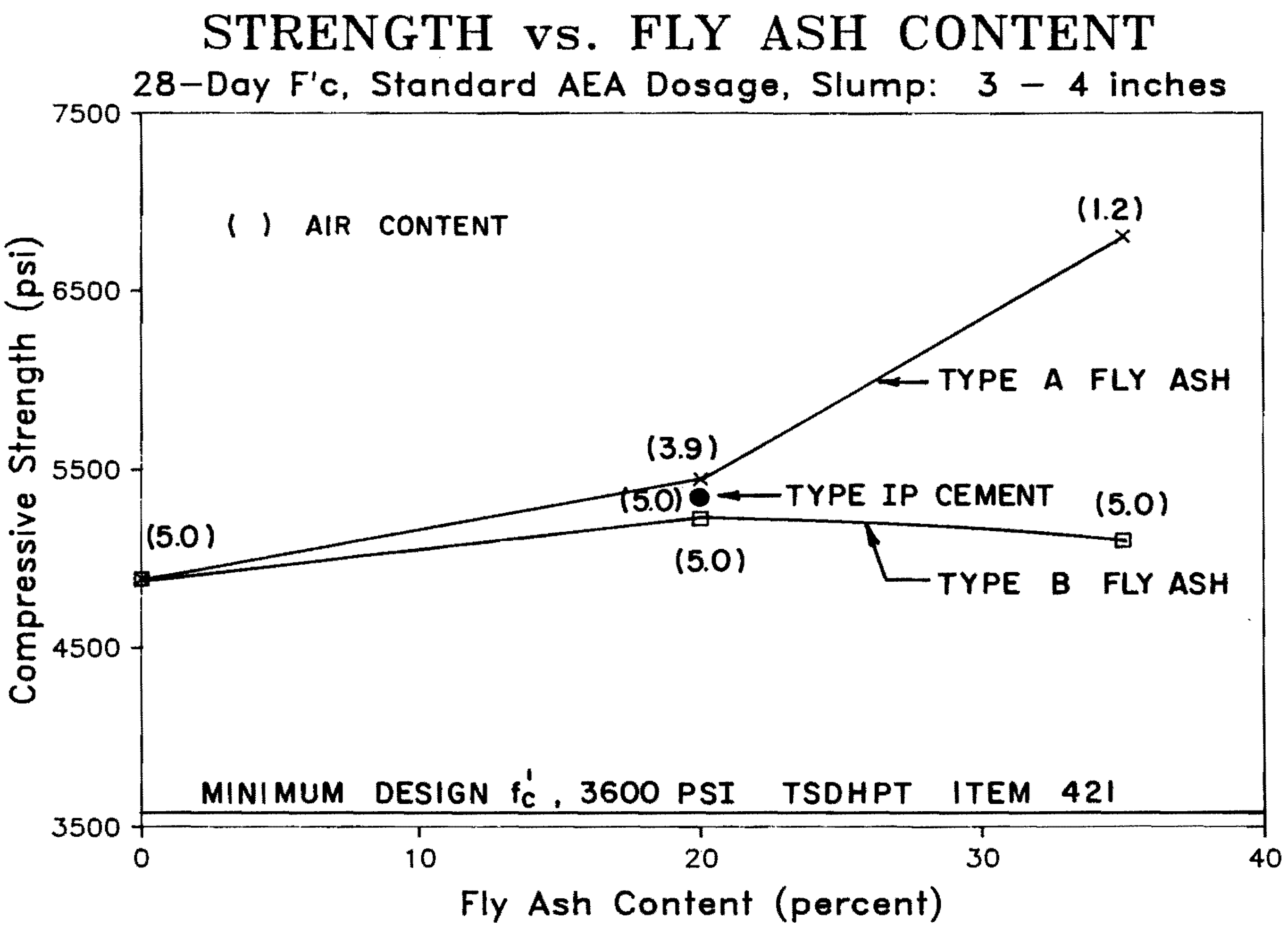


Fig. 6.1 Compressive strength of concrete containing fly ash with a constant dosage of AEA.

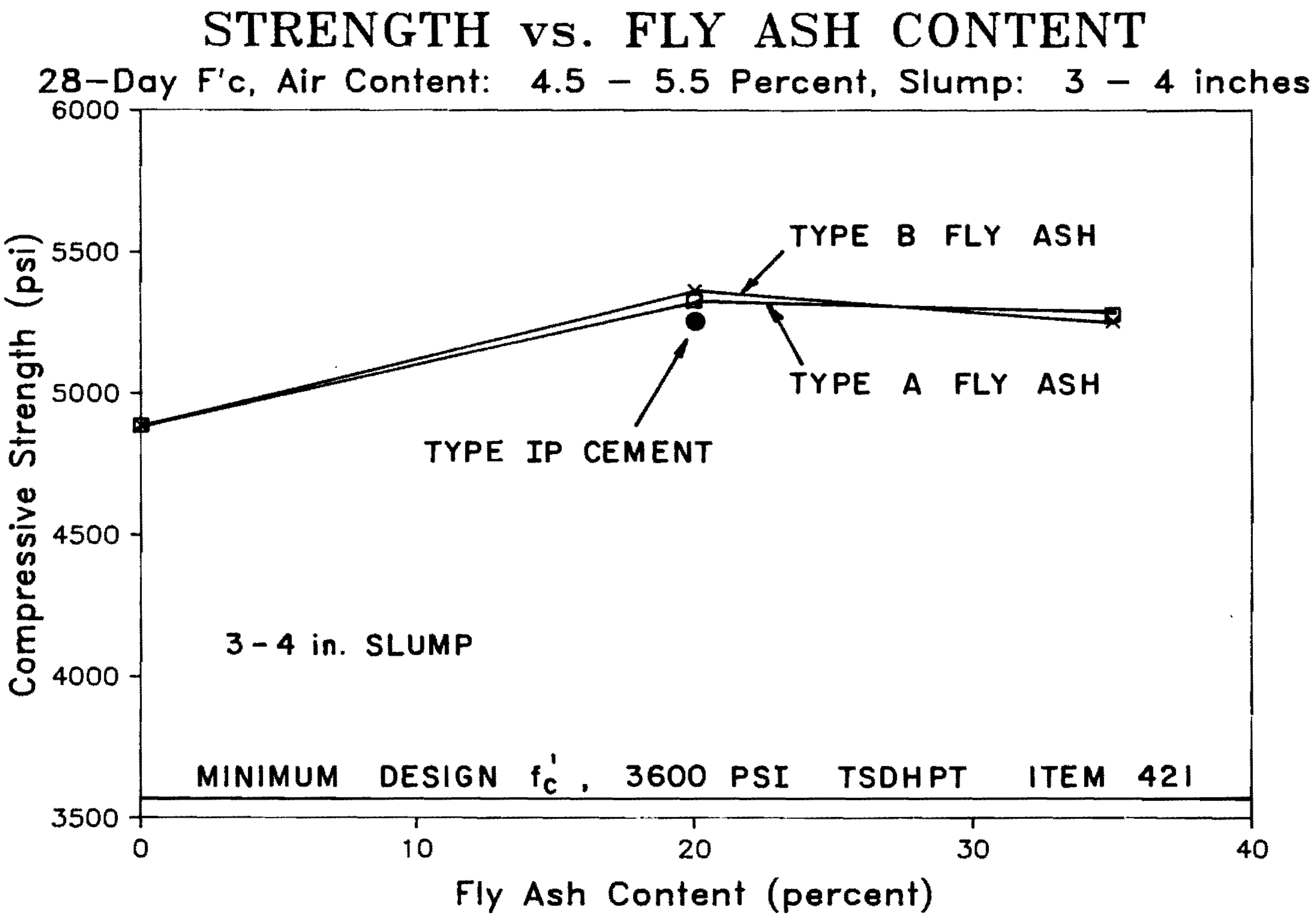


Fig. 6.2 Compressive strength of concrete containing fly ash with constant air content.

ways:

(1) reduces the water requirement of concrete for a given workability;

(2) increases the volume of "cement plus fly ash" material; and

(3) provides a long term strength gain at later ages.

Later age compressive strengths of concretes containing fly ash have been documented by the TVA at over 50% of the 28-day compressive strength. However, it should be noted that when producing concrete containing fly ash to meet a given specified strength, cement replacement with fly ash on an equal weight basis could result in unnecessarily higher strength and higher "cement plus fly ash" contents. This higher "cement plus fly ash" content may lead to less than optimum performance of the concrete mix especially during hot weather conditions.

6.3.2 Flexural Strength. The flexural strength test results of concrete containing fly ash are summarized in Figs. 6.3 and 6.4. From these figures, it could be observed that for the materials used in this study, that the 7-day flexural strength of concrete containing fly ash is in general lower than the 7-day flexural strength of plain concrete, and that the 7-day flexural strength decreases as the fly ash content increases.

Despite these deficiencies, all concrete containing fly ash tested above the Texas SDHPT Specification, Item 421, minimum design flexural strength of 600 psi. The 7-day flexural strengths of both Types A and B fly ash were higher when a standard dosage of AEA was used as compared to when the dosage was adjusted to obtain a 5% air content. Concrete produced with Type IP cement and concrete containing 20% Type A fly ash showed flexural strengths within 3% of the control plain concrete.

The primary reason the 7-day flexural strength of portland cement-fly ash concrete tested lower than plain concrete is that the test is performed at early ages, before the pozzolanic reaction of fly ash has a chance to contribute substantially to the strength. Concrete made with Type B fly ash had a lower flexural strength than that of concrete made with Type A fly ash. This is contrary to what was expected, since Type B fly ash contains a relatively large amount of free lime (CaO), and it would be expected to contribute to the early strength of concrete through cementitious reaction. Earlier studies by Olek [53] and Archuletta [9] show the same phenomena for mixes with a "cement plus fly ash" content of 6.5 sacks per cu. yd., as shown in Fig. 6.5.

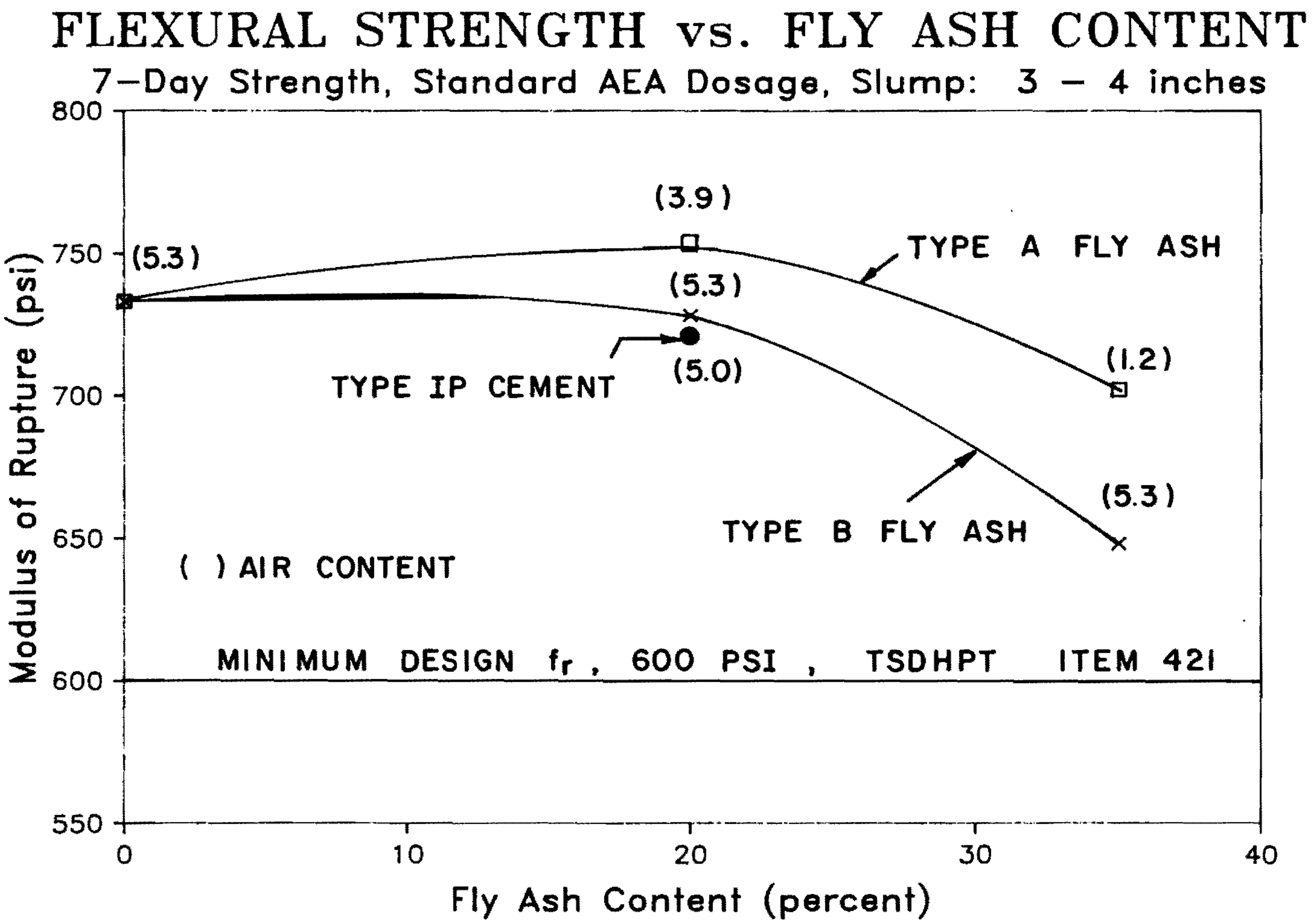


Fig. 6.3 Effect of fly ash content on flexural strength of concrete with constant AEA dosage.

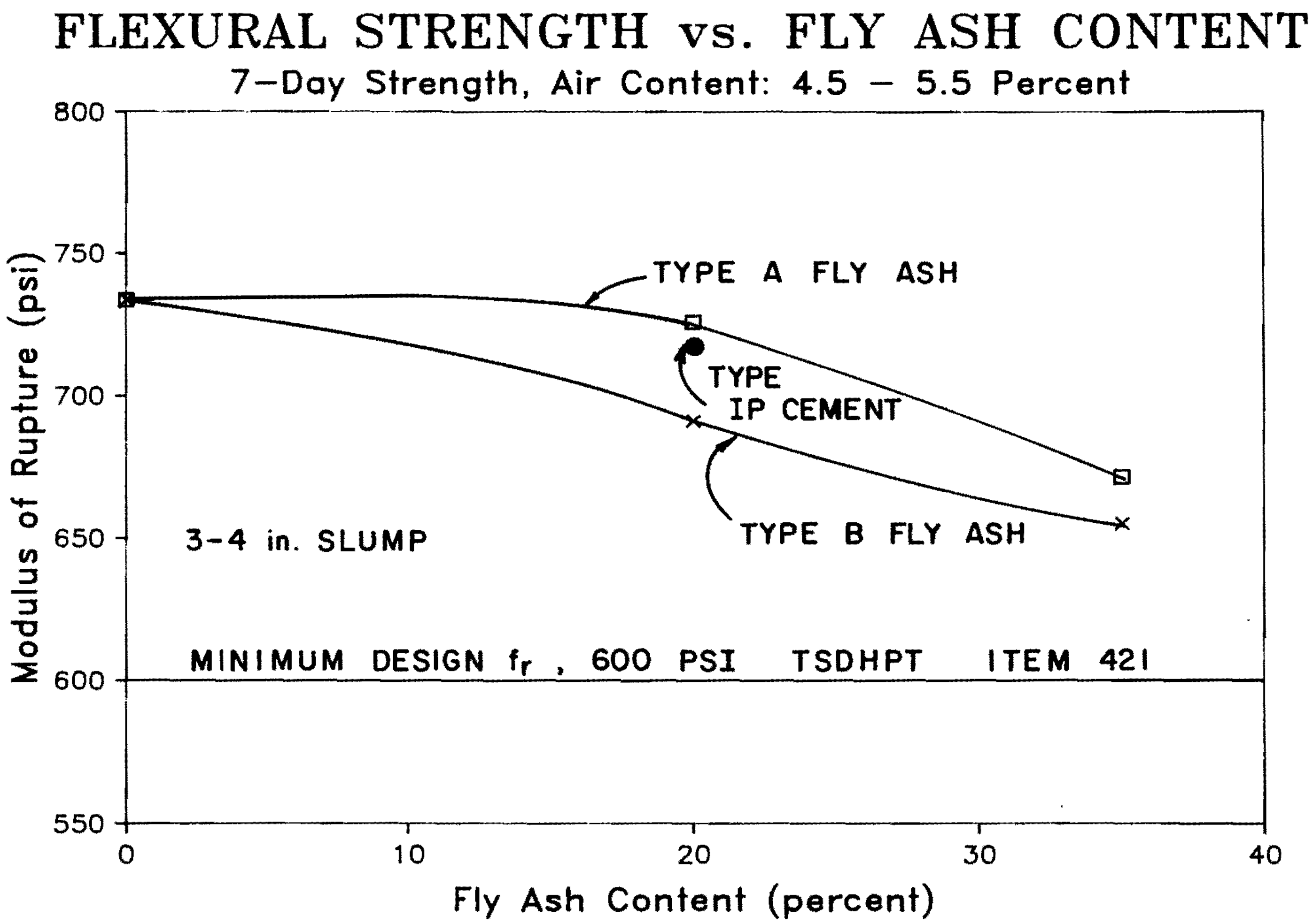


Fig. 6.4 Effect of fly ash content on flexural strength of concrete with constant air content.

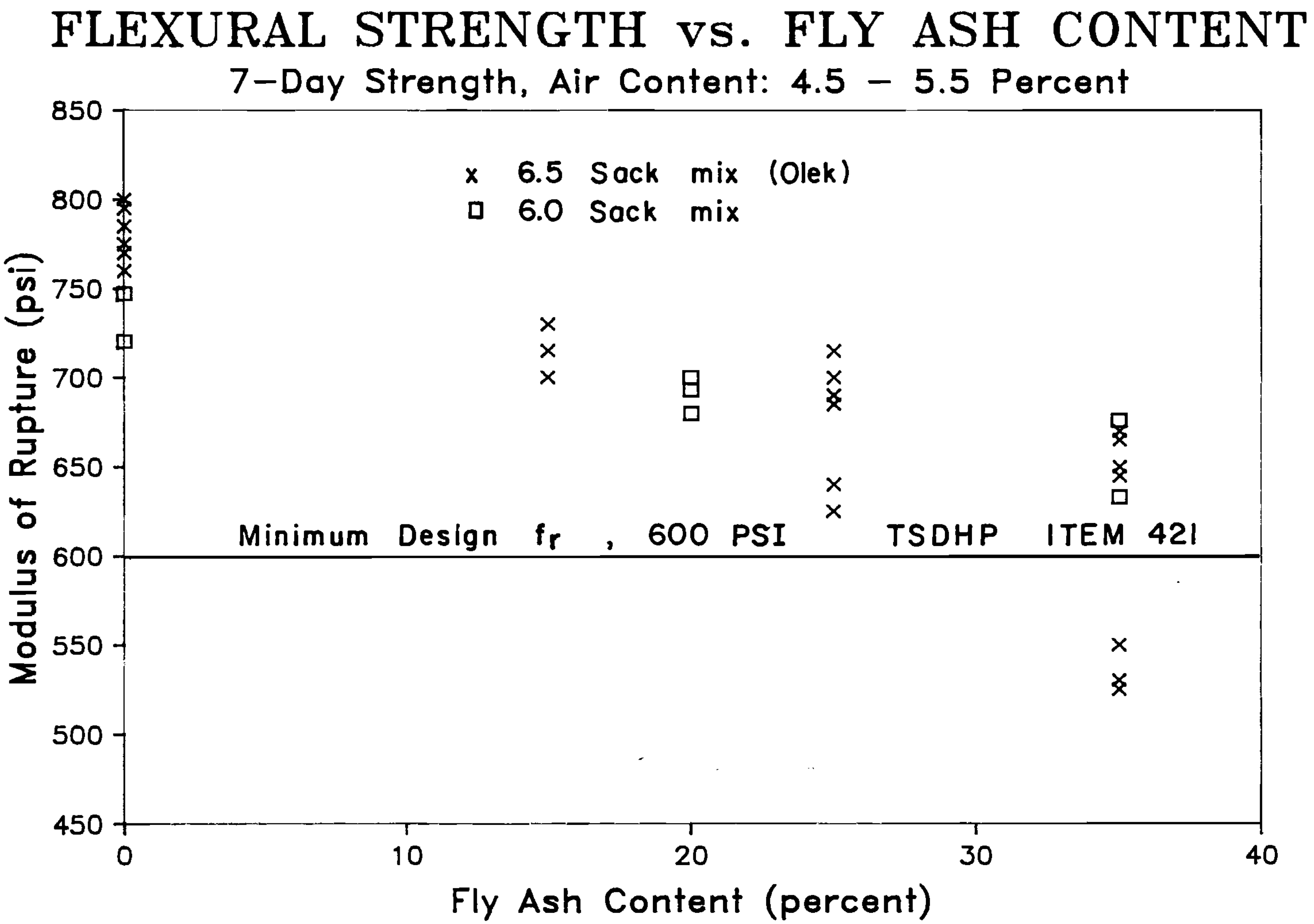


Fig. 6.5 Summary of flexural strength of concrete containing Type B fly ash with constant air content.

Flexural strength also decreases as fly ash content is increased. The reason for this is again the pozzolanic nature of the fly ash. There is less hydration in concrete with larger quantities of fly ash and this leads to slower strength development in the concrete.

6.4 Effects of Fly Ash on Air Entrained Concrete

The air content of plain concrete affects both the compressive and the flexural strengths of concrete containing no fly ash. The same is true of concrete containing fly ash. However, concrete containing fly ash may be more sensitive to the entrainment of air using organic air entraining agents than concrete containing no fly ash. Based on the test results from this study, the rate of compressive strength loss is about 520 psi per % air content. This rate is similar to that of concrete containing no fly ash, which is usually stated as 500 psi per % air content.

The modulus of rupture of concrete containing fly ash was also affected by variation in air content. However, not enough data is available to establish a trend.

6.4.1 Effect of Fly Ash on Air Entraining Agent Dosage. The dosage of an air entraining agent required to produce an air content between 4.5 and 5.5% in concrete containing fly ash or Type IP cement was determined in this experimental study. The amount of AEA required is an important consideration in the production and performance of concrete. In the production of concrete, the cost of additional air entraining admixture may outweigh the cost benefits of the use of mineral admixtures such as fly ash. Long term concrete performance and durability is also dependent upon adequate entrainment of air in concrete.

There are two predominant effects shown in Sec. 5.6.2:

(1) The Texas SDHPT Type A fly ash induced a higher air loss in concrete than Texas SDHPT Type B fly ash or Type IP cement, and

(2) MB-AE-10 air entraining admixture is more sensitive to fly ash content than MB-VR.

Figure 5.13 shows that concrete containing 35% Type A fly ash required twice the dosage of MB-VR used in plain concrete to entrain the same amount of air, while concrete made with 35% Type B fly ash or Type IP cement required no additional dosage to entrain the prescribed air. A similar trend is shown in Fig. 5.14, where MB-AE-10 was used. A dosage of MB-AE-10 2.67 times that needed in plain concrete was required in concrete containing 35% Type A fly ash to entrain 5% air, whereas concrete made with Type B fly ash required only 1.67 times the standard dosage.

It has long been recognized that fly ash concrete requires more AEA than plain concrete. The reason for this is that the carbon in fly ash has an affinity for organic compounds such as air entraining agents. The carbon in fly ash is believed to be in a form similar to that of activated carbon; the form of carbon used to filter organic impurities from water. The Type A fly ash used in this study had an LOI nearly twice that of the Type B fly ash. The fineness of the fly ash is also a consideration when evaluating the effect of ly ash on the AEA dosage. With equal carbon contents, a finer fly ash will adsorb more AEA. In this study both ashes had a fineness of 12.80% retained on the #325 sieve. Comparing the carbon contents and the fineness of the two ashes used in this study, the Type A fly ash should be expected to require more AEA than concrete made with Type B fly ash.

The Type IP cement used in this program also used Type A fly ash; however, the LOI of this fly ash is .26, similar to that of the Type B fly ash used in the study. Consequently, it exhibited similar behavior to that of concrete containing Type B fly ash. Concrete made with Type IP cement required no additional AEA over that used in plain concrete or to obtain the prescribed 5% air content. In addition, upon closer examination of the composition of the fly ash used in the Type IP cement, it is seen that the fly ash is much coarser, 38% retained on the #325 sieve, than either of the other two fly ashes. This measurement of fineness may be misleading in this case, because the fly ash is ground into the clinker at the cement plant, which results in a finer ash.

While MB-AE-10 required a relatively larger dosage than did MB-VR, both indicated the same trends and neither was immune to the effects of fly ash. Micro air was used with concrete containing Type A fly ash because it contains a stabilizing agent to entrain air in concrete which is resistant to other AEAs. In other words, micro air is recommended for use in hard to entrain air concrete mixes. The effect of carbon on air entraining agents is not one of a stabilizing nature, therefore, the increased trend in dosage observed is the same as when using either MB-VR or MB-AE-10. All three air entraining agents are organic compounds in nature and are consequently preferentially adsorbed by the carbon in fly ash. The adsorption of AEA would not be anticipated when using non-organic compounds. These types of AEA are more expensive and not as widely available.

6.4.2 Effect of Fly Ash on Air Content. Section 5.6.2 presents a series of figures which illustrate the effect of fly ash content on the amount of air entrained in concrete. The graphs illustrate the same results as were obtained in earlier studies of air entrained fly ash concrete [1,60]. That is, that concrete containing Type A fly ash exhibits a rapid loss of air as fly ash content is increased. Figure 5.20 shows that when Type B fly ash or Type IP cement is used in concrete, air content drops only slightly; air loss was less than 1/2% for concrete containing up to 35% Type B fly ash. Comparing air content behavior of concrete containing Type A and Type B fly ash several observations can be made:

(1) Since both types of fly ash have the same fineness, the air content loss is primarily related to the carbon content of the fly ash;

(2) Type B fly ash has a LOI 1/2 of that of the Type A fly ash and both carbon contents are below 0.5%, however, the air loss is only minimal in concrete mixed with Type B fly ash and is significantly higher in concrete mixed with 35% Type A fly ash; and

(3) The air loss behavior of concrete containing fly ash or Type IP cement was independent of the air entraining agent used.

Clendenning and Durie [18] and Minnick [46] stated that the carbon will adsorb AEA until it is saturated and then the concrete will require the standard dosage of AEA to entrain the prescribed air. In this experimental program the carbon in Type A fly ash adsorbed all of the AEA and left only entrapped air in the concrete, while the carbon in Type B fly ash and the Type IP cement adsorbed little, if any, AEA and entrained the prescribed air without increasing the required AEA dosage over that used in plain concrete containing no fly ash.

A possible explanation for this difference in behavior of carbon from different sources is that the carbon in the Type A fly ash closely resembles activated carbon, whereas carbon found in Type B fly ash may be encased in silica glass beads [42, 70]. Activated carbon is a form of carbon with a high surface area and an affinity for organic compounds and is commonly used to filter organics from water. There is evidence that some types of burning processes cause the carbon in fly ash to be encased in droplets of silica during the rapid cooling period in which fly ash is collected [33]. Furnace temperature, the means of collection and the properties of the silica all contribute to this phase of fly ash. Although this phenomena has only been observed in some Type A fly ashes with carbon content at or above 6%, Type B fly ashes have not yet been investigated.

6.5 Freeze-Thaw Durability

The results of the freeze-thaw testing of concrete containing fly ash and Type IP cement were presented in Sec. 5.7. The durability factors of the different concretes are the best indicators of the concrete's ability to resist freeze-thaw damage. The rate of change of the dynamic modulus of elasticity is reflected by the durability factor.

Of the 66 specimens tested in this study, only six showed excessive damage due to repeated freezing and thawing cycles. The damaged specimens contained 35% Type A fly ash and had air contents below 1.5%. The undamaged specimens ranged in air contents from 3 to 6% and contained 0, 20 and 35% Types A and B fly ash and Type IP cement. The deterioration of the damaged specimens was not restricted to internal degradation of the mortar matrix, but also included spalling at the surface of the specimens. Some surface degradation was visible on several of the undamaged specimens; however, this degradation did not affect the performance of the concrete over the 300-cycle test.

It has long been known that an adequate entrained air structure is necessary to prevent freeze-thaw damage. In concrete containing 35% Type A fly ash, the standard dosage of AEA was fully adsorbed by the carbon in the fly ash and provided no entrained air and subsequently lead to substantial deterioration of the concrete. When concrete containing 35% Type A fly ash had 5% air content, the concrete sustained no physical damage.

These tests illustrate that fly ash does not affect the freeze-thaw resistance of concrete when an adequate structure of entrained air is present.

6.6 Shrinkage of Concrete Containing Fly Ash

6.6.1 Effect of Fly Ash Content on Shrinkage. The results of the shrinkage tests presented in Sec. 5.8.1 illustrate that under hot-dry environmental conditions, concrete containing fly ash exhibits volumetric changes that differ from those of plain concrete. Fly ash content is a factor which must be considered in shrinkage calculations when concrete is subjected to these environmental conditions.

Under hot-dry conditions, the shrinkage of concrete mixed with portland cement and Type A fly ash differed from that of concrete made with portland cement and Type B fly ash. As the fly ash content in mixes containing Type A fly ash increased from 0 to 35%, shrinkage decreased by an average of 15%. Shrinkage decreased an average of 10% for mixes with Type A fly ash contents varying from 20 to 35%. However, in mixes containing Type B fly ash, the difference in shrinkage between fly ash contents of 0 and 35% was a 5% increase.

This shrinkage behavior under hot-dry conditions is similar to that displayed in concrete containing 35% fly ash when stored at room temperature and 50% relative humidy, as shown in Fig. 6.6.

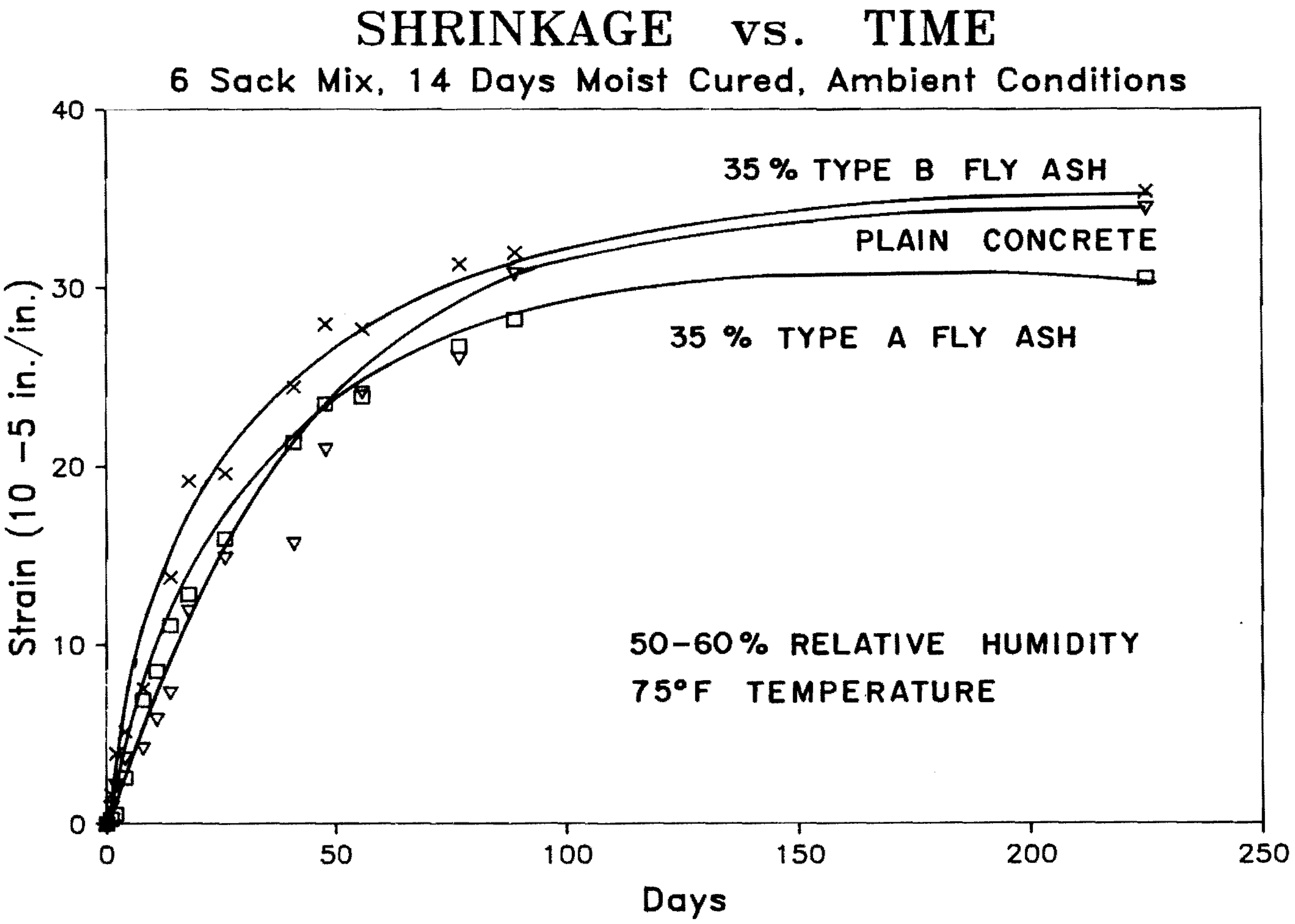


Fig. 6.6 Shrinkage of concrete under ambient conditions.

Previous studies have investigated the shrinkage of concrete containing Type A fly ash [1]. The results of these studies have indicated that the concrete containing fly ash in equal weight replacement of portland cement has less shrinkage than that of similar plain concrete. This study indicates the same result for Type A fly ash but in general this result cannot be extended to concrete containing Type B fly ash. The two primary reasons that Type A fly ash reduces shrinkage is that it reduces the water demand and increases the ultimate strength of concrete. While the Type B fly ash used in this study also reduced the water demand, it yielded ultimate strengths nearly equal to those of plain concrete.

6.6.2 Environmental Effects on Shrinkage of Fly Ash Concrete. The environment to which plain concrete is subjected is the most important consideration with respect to computing volumetric changes in concrete. This is also true of concrete containing fly ash. The effects of shortened moist curing times coupled with a hot-dry environment were investigated in this study. Shrinkage of concrete containing fly ash and plain concrete specimens cured for 3 days before being placed in the hot-dry environmental chamber are compared to that of concrete moist-cured 7 days before being placed in the chamber. The results are presented in Sec. 5.8.2.

The results show that plain concrete and concrete containing 35% Type B fly ash display less shrinkage when moist cured longer. This behavior is the same as that shown in other studies on plain concrete [32,49]. Unexpectedly, concrete containing Type A fly ash displayed the opposite behavior; these concrete specimens showed between 5 and 10% increase in shrinkage when cured an additional 4 days.

The concrete made with 20% Type B fly ash had a w/(c+p) ratio of 0.44; much higher than that of the other shrinkage mixes which had w/(c+p) ratios between 0.35 and 0.38. As a result, the additional water in this mix caused additional shrinkage which is not directly related to the parameters being observed such as type of fly ash.

Comparing the shrinkage of plain concrete and concrete containing 35% fly ash in a hot-dry environment to the shrinkage of concrete in room temperature (75^{o}) and 50 to 60% relative humidity, properly moist cured for 14 days, the following can be observed:

(1) The initial rate of shrinkage of specimens in hot-dry conditions is much greater than the rate of shrinkage of concrete kept in a laboratory environment; and

(2) The overall shrinkage of plain concrete and concrete containing fly ash is increased when subjected to hot-dry environments.

In general, it was noted that regardless of the temperature and relative humidity, the shape of the shrinkage vs time curve for plain concrete was similar to that of concrete containing fly ash.

6.7 Creep in Concrete

Creep in concrete containing 35% fly ash was studied in this experimental program. The results of the test are shown in section 5.9. The results indicate that the creep in concrete containing fly ash is lower than or equal to the creep in plain concrete containing no fly ash. Upon further investigation into the conditions of the test, four observations should be noted:

(1) The test was started after 14 days of moist curing;

(2) The ratio of sustained load to 28-day compressive strength was higher in the fly ash concrete creep tests than in the plain concrete test;

(3) The rate of creep deformation in concrete containing fly ash during the first 20 days of the test was higher than the rate of creep in plain concrete; and

(4) The creep in concrete containing Type B fly ash was greater than that of concrete with Type A fly ash.

The third observation can be explained by the fact that the creep strain is load and time related. The early strength of concrete containing fly ash is lower than that of plain concrete. As a result, the relatively higher applied stresses at early ages in the concrete containing fly ash caused creep nearly equal to that in plain concrete. The rate of creep at later ages is also nearly the same in both plain concrete and concrete containing fly ash. These results can be interpreted as correlating well with previous studies [28] which state that concrete containing fly ash exhibits creep strains equal to or less than those of plain concrete loaded at equal strengths and ages.

6.8 Abrasion Resistance

The abrasion resistance of concrete was tested according to ASTM C944-80 and the results were measured in terms of depth of wear. Concrete containing fly ash performed as well or better than plain concrete in the dressing wheel abrasion test. Concrete containing Type A fly ash showed a similar resistance to wear as that of plain concrete. Concrete containing Type B fly ash showed superior resistance to wear in this test.

The concretes used in this test had equal strengths, air contents and "cement plus fly ash" contents. Abrasion resistance is related to the volume of paste and the strength of the concrete. The Type B fly ash concrete had a w/(c+p) ratio of 0.38 while both the Type A fly ash and plain concrete had w/(c+p) ratios of 0.43. Since the concretes had the same compressive strengths at the time of testing, the volume of paste can be considered the primary parameter affecting abrasion resistance. Concrete containing Type A fly ash had a greater paste volume than the mix made with Type B fly ash and subsequently provided less abrasion resistance.

These results agree with the work done by the Federal Highway Administration [64]. The abrasion resistance of concrete containing fly ash can be expected to increase over the life of a pavement or bridge deck because of the long term strength gain characteristics of fly ash. Further studies are needed to ensure adequate abrasion resistance of concrete containing fly ash at early ages.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The use of fly ash in concrete for Texas highway applications will increase in the future because of both economic and technical reasons. This report addresses the immediate concerns of the Texas Highway Department resident engineer in regards to the durability of concrete containing fly ash. The results of the study presented herein demonstrate that concrete containing a replacement between 0 and 35% Type A or B fly ash by weight of portland cement and concrete made with Type IP cement can be proportioned and placed to meet all Texas SDHPT durability specifications. In addition, this study shows that concrete containing fly ash or Type IP cement can be designed to perform equal to or better than plain portland cement concrete.

This study investigated only two sources of fly ash and one of Type IP cement. While the source of Type IP cement is presently the only one in Texas, many sources of fly ash are available in this state. Each source of fly ash has a unique chemical composition and should therefore be investigated thoroughly before being used in concrete for highway applications.

7.2 Conclusions

The purpose of the work presented herein is to provide the resident engineer with an understanding of the effects of fly ash on concrete durability and on the time dependent properties of concrete, i.e. shrinkage and creep. Although many of the basic properties and functions of hardened concrete are not changed by the addition of fly ash to concrete, there are several fundamental differences which the engineer must be aware of:

(1) The rate of strength gain of concrete containing fly ash is different from that of plain concrete. While the rate of strength gain is slower during the first few days, concrete containing fly ash will continue to gain strength for a much longer period of time. This long term strength gain provides an additional factor of safety over plain concrete;

(2) The flexural strength of concrete at 7 days may be reduced by the use of fly ash;

(3) Fly ash provides additional workability to concrete. The water required for a given workability should be

reduced or the dosage of water-reducer/retarder should be decreased or both when using fly ash in concrete;

(4) The dosage of air entraining agent needed to entrain the required air must be determined by trial batching. The engineer cannot rely on "standard dosages" of AEA to entrain the prescribed amount of air into concrete containing fly ash;

(5) Concrete containing fly ash is as resistant to freeze-thaw damage as plain concrete if the air contents are the same. Fly ash in concrete does not allow the engineer to reduce the air content in concrete for the same freeze-thaw durability;

(6) The shrinkage of concrete containing fly ash is less than or equal to that of plain concrete under normal environmental conditions. However, temperature and humidity affect concrete containing fly ash at early ages much differently than plain concrete. When adverse environmental conditions are anticipated at early ages, precautions should be taken to protect the concrete from drying out until adequate curing is complete; and

(7) Creep in concrete is the same or lower when fly ash is used. However, creep from early loading should be accounted for by using a strength gain curve for concrete containing fly ash and not portland cement concrete.

7.3 Recommendations for Future Research

The effects of fly ash on the properties of concrete are not yet fully understood. Although this study has addressed some of the more urgent questions facing the concrete industry and the resident engineer, many questions still remain and several more have been posed by this experimental program.

Future research should be concentrated to investigate the following topics:

(1) The effect of fly ash on the sulfate resistance of concrete. Very little information is available in this area, and the information that is, indicates that fly ash may substantially increase the resistance of concrete to sulfate attack;

(2) The effect of environmental conditions on the shrinkage of concrete containing fly ash. An analytic method to

predict the effects of fly ash on the shrinkage of concrete is needed as the use of fly ash increases in structural concrete;

(3) The effect of non-organic air entraining agents on fly ash concrete. This may be especially valuable when high carbon fly ash is the only type available;

(4) Fly ash from other sources and of different compositions need to be studied before future sources are certified to furnish fly ash to concrete producers. Very little data is available on sources of Type B fly ash in Texas;

(5) The effect of fly ash on lean concrete mixes is still a point of controversy. This is especially true when Type B fly ash is used;

(6) Lightweight and specialty concretes containing fly ash should also be investigated in the future. Since fly ash increases the paste volume and has a lower specific gravity than portland cement, there is a potential to develop stronger lighter concrete for architectural and structural purposes; and

(7) The effect of different curing conditions should be further investigated. Environmental conditions affect the strength gain characteristics of concrete containing fly ash differently than those of plain concrete containing no fly ash. As a result, the abrasion resistance and freeze-thaw durability of the concrete may be adversely affected.

(8) The effect of different cement sources on concrete containing fly ash.

APPENDIX A

Table A.1 Concrete Batch Information and Fresh Concrete Data

Mix	Cement*	Coarse*	Fine*	Fly Ash*	Water*	W. Reducer^{+}	MB-VR^{+}	MB-AE-10^{+}	Slump (in.)	Air %	Weight (lb/ft^{3})	W/(C+P)
OVRN-D1	67.7	256.2	99.0	0.0	28.5	117.0	21.2	N/A	3.5	8.5	139	.42
OVRN-D2	67.7	256.2	99.0	0.0	28.3	117.0	16.0	N/A	3.2	7.0	141	.42
OVRN-D3	67.7	240.6	120.3	0.0	29.5	117.0	10.6	N/A	3.0	5.5	144	.44
OVRN-D4	33.8	120.3	60.2	0.0	15.1	58.5	5.3	N/A	3.0	4.7	142	.45
OAEN-D2	67.7	240.6	120.3	0.0	28.8	117.0	N/A	7.9	3.0	5.0	144	.43
20VRB-D	54.2	240.6	118.6	13.5	25.5	117.0	10.6	N/A	3.5	5.5	144	.38
20AEB-D	54.2	240.6	118.6	13.5	26.2	117.0	N/A	7.9	3.0	4.5	146	.39
20VRB-A1	54.2	240.6	118.6	13.5	26.5	117.0	10.6	N/A	3.7	6.0	144	.39
20AEB-A1	54.2	240.6	118.6	13.5	24.4	117.0	N/A	10.6	3.0	5.5	143	.36
20VRA-D	54.2	240.6	117.3	13.5	25.8	117.0	10.6	N/A	3.75	4.5	144	.38
20AEA-D	54.2	240.6	117.3	13.5	24.6	117.0	N/A	7.9	3.75	3.2	147	.36
20AEA-A	54.2	240.6	117.3	13.5	29.7	117.0	13.2	N/A	3.0	4.7	145	.44
20AEA-A	54.2	240.6	117.3	13.5	28.1	117.0	N/H	13.2	3.25	5.0	144	.42
35VRB-D1	48.4	264.6	129.1	26.0	-	117.0	10.6	N/A	3.75	5.0	142	-
35AEB-D1	44.0	240.6	117.4	23.7	-	117.0	N/A	7.9	3.0	-	143	-
35VRB-D2	44.0	240.6	117.4	23.7	-	117.0	10.6	N/A	3.5	-	136	-
35VRB-D3	44.0	240.6	117.4	23.7	25.2	117.0	10.6	N/A	4.0	6.8	140	.37
35AEB-D2	44.0	240.6	117.4	23.7	31.4	117.0	N/A	7.9	3.0	4.2	143	.46
35VRB-A	44.0	240.6	117.4	23.7	27.2	117.0	10.6	N/A	4.0	6.0	142	.40
35AEB-A	44.0	240.6	117.4	23.7	27.9	117.0	N/A	7.9	3.0	4.2	144	.41
35VRA-D	44.0	240.6	115.0	23.7	30.7	117.0	10.6	N/A	3.0	1.0	151	.45
35AEA-D	44.0	240.6	115.0	23.7	30.2	117.0	N/A	7.9	3.2	1.4	147	.45
35VRA-A1	44.0	240.6	115.0	23.7	28.9	117.0	16.0	N/A	3.5	4.0	144	.43
35AEA-A1	44.0	240.6	115.0	23.7	29.2	117.0	N/A	16.0	3.5	3.6	144	.43
35VRA-A2	44.0	240.6	115.0	23.7	30.7	117.0	21.0	N/A	3.5	4.5	144	.45
35AEA-A2	44.0	240.6	115.0	23.7	29.6	117.0	N/A	21.0	3.7	5.2	142	.44
35VRA-A3	22.0	120.3	57.5	12.7	15.8	58.5	10.6	N/A	4.0	5.0	137	.47
35AEA-A3	22.0	120.3	56.5	11.8	15.9	58.5	N/A	10.6	3.2	5.5	140	.47
IPVRA-D	67.7	240.6	120.3	-	-	117.0	10.6	N/A	3.2	5.0	141	
IPAEA-D	67.7	240.6	120.3	-	-	117.0	N/A	7.9	3.2	4.7	143	-
SH-1-N	50.7	201.0	99.5	0.0	19.4	87.7	8.0	N/A	3.0	4.0	140	.38
SH-2-B	33.0	180.4	88.0	17.7	17.7	87.7	8.0	N/A	3.0	4.0	N/A	.35
SH-3-A	33.0	180.4	88.0	17.7	17.9	87.7	15.0	N/A	4.0	5.0	N/A	.35
SH-4-B	40.6	180.4	87.9	10.1	16.7	87.7	8.0	N/A	4.0	5.0	N/A	.44
SH-5-A	40.6	180.4	87.9	10.1	17.5	87.7	10.0	N/A	3.2	5.0	N/A	.34
							Micro Air					
OMAN-D1	33.9	120.3	60.2	0.0	15.1	58.5	5.3		3.0	3.5	144	.44
OMAN-D2	33.9	120.3	60.2	0.0	15.2	58.5	10.6		3.5	5.0	142	.45
35MAF-D	22.0	120.3	57.5	11.8	14.44	58.5	21.2		3.2	4.8	141	.43

Table A.2

		Fundamental Transverse Frequency		
Mix	Air Content %	Zero Cycles	300 Cycles	Durability Factor
0VRN-D3	5.5	1890	1858	96
0AEN-D1	-	1862	1849	98
0AEN-D2	5	1919	1917	99
20VRA-D	4.5	1907	1914	100
20AEA-D	3.25	1908	1908	100
20VRA-A	4.7	1923	1917	99
20AEA-A	5	1901	1887	98
20VRB-D	5.5	1861	1834	97
20AEB-D	4.5	1883	1826	93
20VRB-A	6	1896	1881	98
20AEB-A	5.5	1872	1861	98
IPVRA-D	5	1848	1837	98
IPAEA-D	4.7	1883	1867	98
35VRA-D	1	1907	1342	47
35AEA-D	1.4	1906	1170	27
35VRA-A	4.5	1850	1830	98
35AEA-A	5.25	1877	1840	96
35VRB-D1	5	1852	1847	99
35VRB-D3	6.8	1833	1819	98
35AEB-D2	4.25	1815	1818	100
35VRB-A	6	1855	1837	-
35AEB-A	4.2	1841	1821	97

Table A.3 Mix Design Proportions

Mix	Control	Type A Fly Ash		Type B Fly Ash		Type IP
		20%	35%	20%	35%	Cement
Cement	564	452	367	450	372	561
Fly Ash	0	113	197	114	201	0
Air, %	5	5	5	5	5	5
Water	250	250	250	230	230	250
Sand	1003	980	958	1009	997	998
Gravel	2009	2012	2005	2049	2040	1999
Unit Wt (lb/ft^3)	142	141	140	143	142	141
W/(c+p)	0.44	0.44	0.44	0.40	0.40	0.44
<u>Volume (cu.ft./per cu.yd. of concrete)</u>						
Cement + Fly Ash	2.87	3.03	3.14	3.01	3.07	2.98
Paste	8.25	8.37	8.55	7.96	8.09	8.34
Mortar	14.40	14.38	14.42	14.15	14.20	14.46

REFERENCES

1. Abdun-Nur, Edward A.; Fly Ash Concrete - An Evaluation, Highway Research Board Bulletin No. 284, National Academy of Sciences - National Research Council Publication 854, 1961.

2. Albinger, John M.; "Fly Ash for Strength and Economy," Concrete International/April 1984.

3. American Concrete Institute; Guide for Use of Admixtures in Concrete, ACI Publication 212.2R-81.

4. American Concrete Institute Committee 209; "Effects of Concrete Constituents, Environment and Stress on Creep and Shrinkage of Concrete," ACI SP-27-1.

5. American Concrete Institute; Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Special Publication SP-79.

6. American Concrete Institute; Proportioning Concrete Mixes, Special Publication SP-46.

7. American Concrete Institute Committee 211; " Standard Practice for Proportioning Normal, Heavyweight and Mass Concrete," ACI 211.1-81.

8. American Society of Testing and Materials; 1984 Annual Book of ASTM Standards, ASTM 1984.

9. Archuleta, Louis G. Jr.; Production of Concrete Containing Fly Ash for Structural Applications, University of Texas at Austin, Thesis, August 1985.

10. Avram, Constantin, et al.; Concrete Strength and Strains, Elsevier Publishing Company, 1981.

11. Bannister, Billy N.; "Ash as a Replacement for Cement in Concrete Pavement," Texas State Department of Highways and Public Transportation.

12. Bazant, Z.P. and Wittmann, F.H.; Creep and Shrinkage in Concrete Structures, John Wiley & Sons, 1982.

13. Bernal, J.D.; "The Structure of Cement Hydration Compounds," Proc. 3rd Syposium on the Chemistry of Cement, London, 1952.

14. Bloem, D.L.; "Effects of Fly Ash on Concrete," Publication No. 48, National Ready Mix Concrete Association, Jan. 1954.

15. Burns, J.S., Guarnaschelli, C. and McAskill, N.; "Controlling the Effects of Carbons in Fly Ash on Air Entrainment," Proceedings, Sixth International Ash Utilization Symposium, U.S. Department of Energy, Reno, Nevada, 1982.

16. Cannon, R.W.; "Proportioning Fly Ash Concrete Mixes for Strength and Economy," ACI Journal/November 1968.

17. Chopra, S.K., Rehsi, S.S. and Garg, S.K.; " Use of Water and Set-Reducing Admixture in Fly Ash Concrete," International Symposium on Admixtures for Mortar and Concrete, Brussels, August 30th - September 1st, 1967.

18. Clendenning, T.G. and Durie, N.D.; "Properties and Use of Fly Ash from a Steam Plant Operating Under Variable Load," Proceedings, ASTM, Vol. 62, pp. 1019-1040, 1962.

19. Committee III-h, "Cooperative Test of Fly Ash as an Admixture in Portland Cement Concrete," Proceedings, ASTM, Vol. 62, pp. 314-348, 1962.

20. Cook, James E.; "Research and Application of High-Strength Concrete Using Class C Fly Ash," Concrete International/July 1982.

21. Cook, James E.; "Fly Ash in Concrete -- Technical Considerations," Concrete International/September 1983.

22. Davis, Raymond E.; "Use of Pozzolans," Proceedings, American Concrete Institute, Vol. 46, January 1950.

23. Davis, R.E., Carlson, R.W., Kelly, J.W. and Davis, H.E.; "Properties of Cements and Concretes Containing Fly Ash," Proceedings, American Concrete Institute, Vol. 33, pp. 577-612, May-June 1937.

24. Dikeou, J. T.; "Fly Ash Increases Resistance of Concrete to Sulfate Attack," Research Report No. 23, Water Resources Technical Publication, United States Department of the Interior Bureau of Reclamation.

25. Resistant Concrete for the 80's," United States Department of the Interior Bureau of Reclamation, Engineering Research Center, Denver, Colorado, March 7, 1980.

26. Federal Register, "Guidelines for Federal Procurement of Cement and Concrete Containing Fly Ash," U.S. Federal Register, Vol. 48 N. 20, pp. 4230-4253, Friday, January 28, 1983.

27. General Services Administration; "Specification for Pozzolans for the Use of Portland Cement Concrete," Federal Specification SS-P-570b, G.S.A., Washington, D.C.

28. Ghosh, Ram S. and Timusk, John; "Creep of Fly Ash Concrete," ACI Journal/September-October 1981.

29. Halstead, Woodrow J.; "Quality Control of Highway Concrete Containing Fly Ash," NRMCA Publication No. 164.

30. Haque, M.N., Langan, B.W. and Ward, M.A.; "High Fly Ash Concretes," ACI Journal/January-February 1984.

31. Lane, R.O.; "Effects of Fly Ash on Freshly Mixed Concrete," Concrete International/October 1983.

32. Lane, R.O. and Best, J.F.; "Properties and Use of Fly Ash in Portland Cement Concrete," Concrete International/July 1982.

33. Larson, Guy H.; "Field Substitution of Flyash for a Portion of Cement in Air-Entrained Concrete," Proceedings of the Highway Research Board, Vol. 29, 1949 and Vol. 33, 1953.

34. Larson, T.D.; "Air Entrainment and Durability Aspects of Fly Ash Concrete," Proceedings, American Concrete Institute, Vol. 64, pp. 866-886, 1964.

35. Litvan, G.G. and Sereda, P.J.; "Particulate Admixture for Enhanced Freeze-Thaw Resistance of Concrete," Cement and Concrete Research, Vol. 8, 1978.

36. Lopez-Flores, F.; *Fly Ash and Effects of Partial Cement Replacement by Flyash*, Purdue University, Report Number JHRP-82-11, 1982.

37. Lovewell, C.E., Washa, G.W.; "Proportioning Concrete Mixtures Using Fly Ash," Journal of the American Concrete Institute, Vol. 29, No. 12, June 1958.

38. Lydon, F.D.; *Concrete Mix Design*, Applied Science Publishers, New York.

39. Malhotra, V.M. and Berry, E.E.; "Fly Ash for Use in Concrete -- A Critical Review," ACI Journal/March-April 1980.

40. Malhotra, V.M.; "Use of Admixtures for Specialized Concretes," Concrete International/April 1984.

41. Manz, O.E.; "Review of American and Foreign Specifications for Use of Fly Ash in Portland Cement Concrete," Proceedings, Sixth International Ash Utilization Symposium, U.S. Department of Energy, 1982.

42. Mardulier, F.J.; "Particle Size of Dispersed Carbon Black Affects Entrainment of Air in Concrete," Civil Engineering, Vol. 18, p. 165, 1948.

43. Mather, Katherine; "Factors Affecting Sulfate Resistance of Mortars," U.S. Army Engineer Waterways Experiment Station - Vicksburg, Miscellaneous Paper SL-80-17, October, 1980.

44. McKerall, W. C., Ledbetter, W. B. and Teague, David J.; "Analysis of Fly Ash Produced in Texas," Texas Department of Highways and Public Transportation, Research Study 2-9-79-240.

45. Meininger, Richard C.; "Historical Perspective on Proportioning Concrete," Concrete International/August 1982.

46. Meininger, Richard C.; "Use of Fly Ash in Air-Entrained Concrete -- Report of Recent NSGA-NRMCA Research Laboratory Studies," National Ready Mix Concrete Association Technical Information Letter No. 381, April 3, 1981.

47. Meyers, James F., Pichumani, Ramon and Kappies, Bernadette S.; Fly Ash: A Highway Construction Material, U.S. Department of Transportation Publication FHWA-IP-76-16.

48. Mielenz, Richard C.; "Specifications and Methods of Using Fly Ash in Portland Cement Concrete," U.S. Bureau of Mines Inf. Circ. 8640, pp. 61-74, 1974.

49. Mindess, Sidney and Young, J. Francis; Concrete, Prentice-Hall, Inc.

50. Minnick, J.L.; "Investigations Relating to the Use of Fly Ash as a Pozzolanic Material and as an Admixture in Portland Cement Concrete", Proceedings, ASTM, Vol. 54, p. 2219, 1954.

51. Minnick, J.L., Webster, W.C. and Purdy, Edmund J.Jr.; "Predictions of the Effect of Fly Ash in Portland Cement Mortar and Concrete," Journal of Materials, JMLSA, Vol. 6, No. 1, March 1971, pp. 163-187.

52. Nevile, A.M.; Properties of Concrete, third edition, Pitman Publishing, 1981.

53. Olek, Jan; Fly Ash Concretes for Highway Pavements, University of Texas at Austin, Thesis, August 1985.

54. Pais-Cuddou, I.C.; Utilisation of Flyash in Cement Mortar and Concrete, Ministry of Irrigation and Power, Central Water and Power Commission - New Delhi, India.

55. Pasko, T.J. and Larson, T.D.; "Some Statistical Analyses of the Strength and Durability of Fly Ash Concrete," Proceedings, ASTM, Vol. 62, pp. 1064-1067, 1962.

56. Portland Cement Association; Design and Control of Concrete Mixtures, Twelfth Edition, PCA Publication.

57. Popovics, Sandor; "Strength Relationships for Fly Ash Concrete," ACI Journal/January-February 1982.

58. Popovics, Sandor; Fundamentals of Portland Cement Concrete: A Quantitative Approach, John Wiley & Sons, 1982.

59. Ravina, Dan; "Slump Loss of Fly Ash Concrete," Concrete International/April 1984.

60. Rose, Jerry G. and Floyd, R. Kevin; Fly Ash as a Component in Concrete, Institute for Mining and Minerals Research, Kentucky Center for Energy Research Laboratory, University of Kentucky.

61. Ross, A.D.; "Creep of Concrete Under Variable Stress," ACI Journal/March 1958.

62. Rosner, John C.; "Local Fly Ash Usage in Portland Cement Concrete," report reviewed by the Federal Highway Administration and the Arizona Department of Transportation.

63. Rusch, H., Jungwirth, D. and Hilsdorf, H.K.; Creep and Shrinkage, Springer-Verlag Publishing, 1983.

64. Simmons, D.D., Pasko, T.J. and Jones, W.R.; "Properties of Portland Cement Concrete Containing Pozzolanic Admixtures," FHWA Report No. FHWA/RD-80/184.

65. Smith, F.L.; "Papers on Cement and Concrete," ASTM STP 205, pp. 91-105, 1958.

66. Smith, I.A.; "Design of Fly-Ash Concretes," Paper No. 6982 Proceedings, Institution of Civil Engineers, April, 1964.

67. Sokal, Y.J.; An Overview of the Effects of Creep in Concrete Stuctures, University of Queensland, Dept. of Civil Engineering Research Report Number CE 46.

68. Stodola, Paul R.; "Performance of Fly Ash in Hardened Concrete," Concrete International/December 1983.

69. Swamy, R.N., Sami A.R. and Theodorakopoulos, D.D.; "Early Strength Fly Ash Concrete for Structural Applications," ACI Journal/ September-October 1982.

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

71. Tennessee Valley Authority; Properties and Use of Fly Ash in Portland Cement Concrete, TVA Technical Report CR-81-1.

72. Texas State Department of Highways and Public Transportation; Construction Bulletin C-11, TSDHPT, 1984.

73. Texas State Department of Highways and Public Transportation; 1982 Standard Specifications, TSDHPT, 1982.

74. Timms, Albert G. and Grieb, William E.; "Use of Fly Ash in Concrete," Proceedings, ASTM Vol. 56, p 1139, 1956.

75. Tripodi, Raymond A.;Coal Ash Disposal, Technomic Publishing Company, Inc. 1980.

76. United States Bureau of Reclamations; "Durability of Concrete Containing Canyon Ferry Aggregates and Pozzolans," USBR Concrete Laboratory Report No. C-609, Jan. 1952.

77. United States Bureau of Reclamations; "Laboratory and Field Investigation-Hungry Horse Dam," USBR Concrete Laboratory Report No. C-699, 1953.

78. Wang, C.K. and Salmon, C.G.; Reinforced Concrete Design, Fourth Edision, Harper & Row Publishing Company, 1985.

79. Washa, G.W. and Withey, N.H.; "Strength and Durability of Concrete Containing Fly Ash," Proceedings, American Concrete Institute, Vol. 49, 1953.

80. American Coal Ash Association; ACAA letter of information 8-1-85, Washington, DC.

81. Dunstan, Edwin R., Jr.; "A Spec Odyssey - Sulfate Resistant Concrete for the 80's," U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, 1980.

82. Texas State Department of Highways and Public Transportation; "Departmental Materials Specification for Fly Ash," Specification D-9-8900.

83. United States Government; "Federal Guidelines for Procurement of Cement and Concrete," Federal Register, Vol. 48, No. 20, pp. 4230-4253, Friday, January 28, 1983.