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16. Abstract

Structural applications of concrete containing fly ash have been limited mainly to high strength concrete in the past. This trend is primarily due to the lack of information available to the resident engineer concerning curing conditions, setting times, strength characteristics and durability of normal strength fly ash concrete. This study addresses some of the major concerns of resident highway engineers on concrete containing fly ash for structural concrete in highway applications. This report summarizes the experimental observations and conclusions from a research program investigating the properties of both fresh and hardened structural concrete containing fly ash. Tests were performed to establish guidelines for the selection of materials and trial mix design procedures for producing quality concrete containing fly ash. The study investigated freeze-thaw resistance, flexural and compressive strength characteristics, mixing conditions and procedures and curing conditions such as temperature, humidity, curing methods and rate of strength gain. Types A and B fly ashes were used in this study as a replacement for 0, 15, 25, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type A fly ash was used. The results of this study show that concrete containing fly ash can be designed and proportioned to meet present Texas SDHPT specifications for structural applications. In addition, this study reveals that an optimum mix design for concrete containing fly ash is both technically and economically advantageous to the Texas SDHPT. This report provides the resident engineer with recommendations to ensure the production of quality concrete containing fly ash for structural applications.

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PRODUCTION OF CONCRETE CONTAINING FLY ASH

FOR STRUCTURAL APPLICATIONS

by

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P. J. Tikalsky

and

R.L. Carrasquillo

Research Report Number 364-1

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
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by the

CENTER FOR TRANSPORTATION RESEARCH
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THE UNIVERSITY OF TEXAS AT AUSTIN

May 1986

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views of policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This is the first report in a series of four reports which summarizes the effect of fly ash on the production of concrete containing fly ash. The first report in the series summarizes the effect of fly ash on the production of structural concrete. The second report summarizes the effect of fly ash on concrete used for highway applications. The third report of the series summarizes the effects of fly ash on the durability of concrete containing fly ash. The fourth, and final, report of the series outlines a mix proportioning procedure for concrete containing fly ash. 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.

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

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

SUMMARY

Structural applications of concrete containing fly ash have been limited mainly to high strength concrete in the past. This trend is primarily due to the lack of information available to the resident engineer concerning curing conditions, setting times, strength characteristics and durability of normal strength fly ash concrete. This study addresses some of the major concerns of resident highway engineers on concrete containing fly ash for structural concrete in highway applications.

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

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

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

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

IMPLEMENTATION

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

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

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CHAPTER 1

INTRODUCTION

1.1 Need for Research

Civil engineers must constantly search for alternative sources of construction materials, for building more economical and durable structures.

In recent years special attention has been given to the use of industrial by-products, i.e. fly ash, silica fume, and blast furnace slag as alternative sources for building materials, especially for concrete construction. Fly ash, being readily available and of lower cost than portland cement has been increasingly used in the concrete construction industry. Besides the immediate savings provided by the reduced material cost, concrete containing fly ash has proven to be as durable or of improved durability than ordinary concrete [11,32,35].

Concrete containing fly ash has been used, in the United States, for the last 45 years,. Until the last ten years concrete containing fly ash was used exclusively for mass concrete construction with limited application in roadway and structural concrete construction. In the last ten years, use of concrete containing fly ash for structural concrete construction has risen with the increased use of high-strength concrete. However, little information has been developed concerning the identification of relevant parameters in the selection of materials and proportions for producing concrete containing fly ash. This is due mainly to the high variability of the chemical and physical properties of the fly ash obtained from different regions of the United States. Concrete manufacturers seem to ignore these differences, and use fly ash in their concrete without proper quality control procedures to ensure that high quality and durable concrete is produced.

As a result, what is needed most is a systematic, reproducible procedure for producing concrete containing fly ash with readily available materials using conventional ready-mix batching procedures.

This research program constitutes the much needed first step towards the development of the necessary information for the use of concrete containing fly ash in highway structures in the State of Texas.

1.2 Objectives

The overall objectives of the research program described herein are as follows:

1. Establish guidelines in a form useful to highway resident engineers in Texas, for the selection of materials and trial mix design procedures for producing quality concrete containing fly ash.

2. Identify the most relevant properties of fly ash affecting the properties of both fresh and hardened concrete.

3. Conduct laboratory tests to provide information on the freeze-thaw resistance of concrete containing fly ash.

4. Study the effects of different curing conditions, i.e. temperature, humidity, and curing methods, on the rate of strength gain of concrete containing fly ash.

1.3 Advantages of Concrete Containing Fly Ash

There are definite advantages, both technical and economical, in using concrete containing fly ash for structural applications. The use of fly ash benefits concrete in both its fresh and hardened state.

Due to the pozzolanic properties of fly ash, early uses were in mass concrete construction. Davis et al. [10] at the University of California were the first to conduct a thorough and comprehensive study on fly ash, its chemical and physical properties and the effect fly ash has on the properties of fresh and hardened concrete.

For a constant water-cementitious ratio (w/cm), concrete containing fly ash has increased workability compared to portland cement concrete. Bleeding of concrete containing fly ash is less than that of a comparable concrete mix containing no fly ash. Due to the pozzolanic nature of the fly ash, concrete containing fly ash, has a longer setting time than portland cement concrete. In addition hardened concrete containing fly ash has improved properties compared to portland cement concrete. Concrete containing fly ash has higher long term strength, improved sulfate resistance, lower alkali aggregate reactivity and lower permeability.

Concrete containing fly ash develops higher strength at later ages than portland cement concrete due to its pozzolanic properties. The increased impermeability, improved sulfate resistance and improved durability are influenced mainly by the particle size of fly ash. Alkali aggregate reactivity may be decreased due to the chemical composition of the fly ash.

1.4 Disadvantages of Concrete Containing Fly Ash

Most of the disadvantages of using concrete containing fly ash reported by engineers result from a lack of research and available information on the behavior of concrete containing fly ash under actual field conditions. The high variability in the chemical and physical properties of fly ash is the main drawback hindering the incorporation of fly ash in a larger percentage of the concrete produced today [5, 12,16].

Possible disadvantages resulting from the use of concrete containing fly ash include [32,35]:

1. Need for increased quality control.

2. Good quality fly ash may not be readily available in a given region.

3. An additional bin for the storage of fly ash may be required at the ready mix concrete plant.

4. Formwork removal time may increase due to the slower strength gain of concrete containing fly ash.

1.5 Scope of this Study

Approximately 1100 concrete specimens, representing 78 different batches of concrete were made and tested as part of this study. While mixing procedure and slump were kept constant, the variables studied included fly ash content, cementitious content, mixing temperature, the effect of mixing time, test age, and curing conditions.

In this study, the research approach followed was to investigate the basic interactions among concrete components in mix proportions which are suitable for producing concrete containing fly ash, i.e., fly ash content, and cementitious content. Only commercially available materials and conventional production techniques used by the Texas State Department of Highways and Public Transportation (TSDHPT) were utilized in this program. As a result of this study valuable guidelines have been established to be followed by practicing engineers in the development of trial mixes for producing concrete containing fly ash. Without question, a trial mix design procedure must be used for proportioning concrete containing fly ash in the field.

This report is divided into seven chapters. An introduction and background information on the properties of fly ash are presented in Chapters 1 and 2. A brief review of literature on the production of concrete containing fly ash is presented in Chapter 3. The experimental work is described in Chapter 4. Test results are presented, discussed and analyzed in Chapter 5. Recommendations for producing concrete containing fly ash and a cost comparison study are presented in Chapter 6. The conclusions obtained in this study are presented in Chapter 7.

1.6 Terminology

The terminology adopted in this report is defined as follows:

1. Cementitious Content--the total content of Portland cement plus fly ash, by weight.

2. Water-Cementitious Ratio (w/cm)--the ratio of water to the total content of portland cement plus fly ash, by weight.

3. Fly Ash Content--the weight of fly ash in a concrete mix expressed as a percentage of the total cementitious content.

4. Ordinary concrete -- concrete produced with Type I portland cement and without fly ash.

CHAPTER 2

FLY ASH: BACKGROUND

The following is a brief introduction concerning properties of fly ash and its effects on the properties of concrete, both in its fresh and hardened state.

2.1 Classification

Texas State Department of Highways and Public Transportation (TSDHPT) Departmental Material Specification D-9-8900, "Fly Ash," classifies fly ash into Type A and Type B. In this study, fly ash meeting ASTM C618-84 Standard Specification for "Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete" classifies fly ash into Type F and Type C. ASTM Standard Specification C618-84 Type F fly ash also met the requirements of TSDHPT Material Specification D-9-8900 Type A fly ash, and fly ash meeting ASTM Specification C618-84 Type C fly ash meets the requirements of TSDHPT Material Specification D-9-8900 Type B fly ash. Table 2.1 summarizes TSDHPT Material Specification D-9-8900 chemical requirements for fly ash. Table 2.2 summarizes the physical requirements for fly ash as required by TSDHPT Material Specification D-9-8900.

According to TSDHPT Material Specification D-9-8900 chemical requirements, the main difference between Type A and Type B fly ash is the minimum percent for the combination of silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3) required for each fly ash. Type B fly ash requires a minimum of 50%. Type A fly ash requires a minimum of 65%. The loss of ignition (LOI) for Type A and Type B fly ash is limited to 3%. The loss of ignition is defined as the percentage of residual organic matter contained in fly ash; the organic matter is composed mainly of unburned carbon. Throughout this report, fly ash will be classified and referred to according to TSDHPT Material Specification D-9-8900.

2.2 Source

Fly ash constitutes the fine particulate matter, obtained from the combustion of coal, that escapes the combustion chamber

TABLE 2.1 Texas State Department of Highways and Public Transportation Departmental Material Specification D-9-8900, Chemical Requirements

	Type A	Type B
Silicon dioxide (SiO_2) plus aluminum oxide (AL_2O_3) plus iron oxide (FeO_3), min, %	65.0	50.0
Sulfur trioxide (SO_3), max, %	5.0	5.0
Calcium oxide (CaO), variation in percentage points of CaO from the average of the last 10 samples (or less provided 10 have not been tested) shall not exceed plus or minus	4.0	4.0
Magnesium oxide (MgO), max, %	5.0*	5.0*
Available alkalies, as Na_2O, max, % (when used in conjunction with reactive or potentially reactive aggregates)	1.5	1.5
Moisture content, max, %	2.0	2.0
Loss on ignition, max, %	3.0	3.0

* When the autoclave expansion or contraction limit is not exceeded, an MgO content above 5.0% may be acceptable.

TABLE 2.2 Texas State Department of Highways and Public Transportation Departmental Material Specification D-9-8900, Physical Requirements

	Type A	Type B
Fineness--retained on 325 sieve (45 cm), max, %	30.0	30.0
Variation in percentage points retained on the 325 sieve from the average of the last 10 samples (or less provided 10 have not been tested) shall not exceed	5.0	5.0
Pozzolanic activity index with portland cement as a minimum percentage of the control at 28 days	75	75
Water requirement, maximum percentage of control	100	100
Soundness, autoclave expansion or contraction, max, %	0.8	0.8
Increase of drying shrinkage of mortar bars at 28 days, max, %	0.03	0.03
Reactivity with cement alkalies mortar expansion at 14 days, max, %	0.020	0.020
Specific gravity, maximum variation from average %	5.0	5.0

Drying shrinkage shall be tested in accordance with ASTM C157.

Alkali reactivity shall be tested in accordance with ASTM C441.

Specific gravity shall be tested in accordance with ASTM C188.

All other physical requirements shall be tested in accordance with ASTM C311.

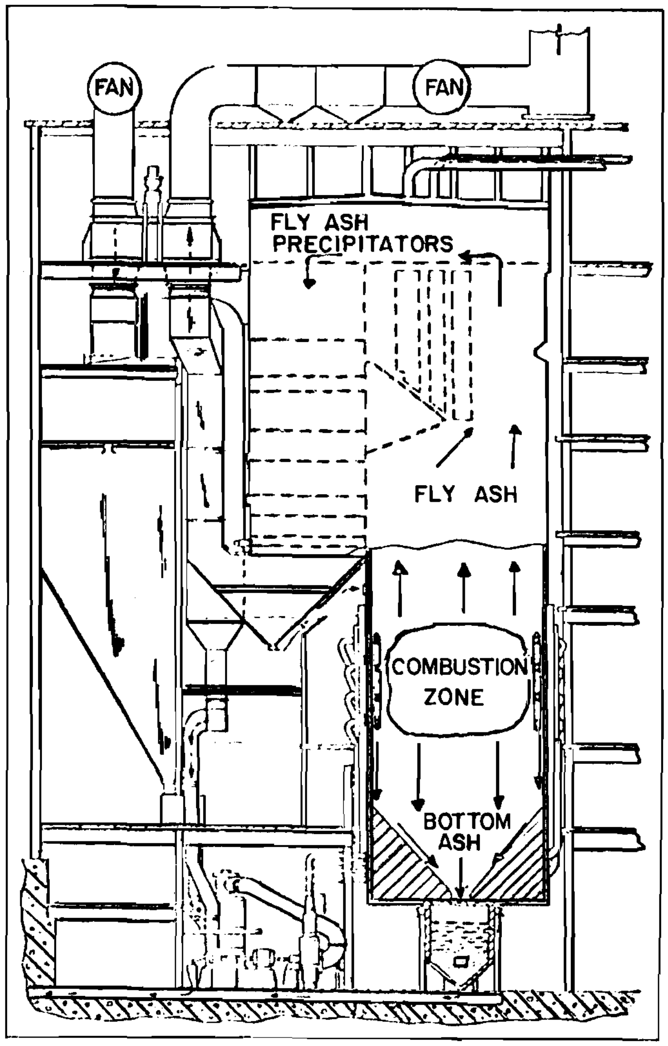

Fig. 2.1 Typical schematic of the coal burning process [8].

with the flue gases. Fly ash is then collected using mechanical or electrostatic precipitators. Figure 2.1 shows a typical schematic of the coal burning process. Bottom ash is obtained from larger particles, which are collected at the bottom of the combustion chamber. This study only concerns the use of fly ash.

Coal used for power generation is classified as either bituminous, sub-bituminous, or lignite. Bituminous coal, obtained primarily in the eastern United States, is of a high carbon content. Sub-bituminous and lignite coals are obtained in the western and the southwestern regions of the United States. These coals contain higher quantities of noncombustible materials and are therefore referred to as "dirtier" coals. Type A fly ash is obtained primarily from the combustion of bituminous coal. Sub-bituminous and lignite coals produce mostly Type B fly ash. Due to the comparatively lower calcium content obtained from bituminous coal ash, Type A fly ashes are commonly referred to as low-calcium ashes. Type A fly ashes possess pozzolanic properties only. Sub-bituminous and lignite ashes, having a higher calcium content, are generally referred to as high-calcium ashes. Type B fly ashes possess both cementitious and pozzolanic properties. The higher calcium content of Type B fly ashes provide the cementitious properties.

Noticeable variations in the chemical and physical properties of fly ashes obtained using the same coal source have been observed [10,32,35]. Besides the coal source, other factors affecting the variability of the fly ash properties are: degree of coal pulverization, firing unit design, loading and firing conditions, ash collection and processing methods, and fly ash storage methods [24]. Combustion of finer coal results in a finer fly ash having a lower loss on ignition (LOI). Firing units operating at a constant temperature provide ashes of more uniform consistency as compared to less efficient firing units. The collection systems used in power generating plants are either mechanical or electrostatic precipitators. Electrostatic precipitators are more efficient than mechanical precipitators, and are capable of collecting ashes with a greater percentage of fine particles. Mechanical precipitators, on the other hand, are limited to collecting coarser particles about the size of cement particles.

2.3 Chemical Properties

The chemical composition of fly ash affects the properties of concrete, mainly in its hardened state. Fly ash has a direct influence on the strength of the hardened concrete and its sulfate resistance. The chemical composition of fly ash, as outlined in Table 2.1, consists primarily of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3). TSDHPT Material Specification D-9-8900 also limits the amount of sulfur trioxide (SO_3) and the available alkalis (Na_2O) present in fly ashes.

In concrete containing fly ash, the silica from the fly ash combines with calcium hydroxide, formed during the hydration of portland cement, to produce additional calcium silicate hydrate. The additional calcium silicate hydrate produced by the incorporation of fly ash in a concrete mix contributes mostly to the long term compressive strength development of the concrete. The decreased amount of tricalcium silicate (C_3S) and slower rate of hydration in concrete mixes containing fly ash, results in a lower heat of hydration, making it suitable for mass concrete construction.

The magnesium oxide content in fly ash is limited to a maximum of 5% to prevent the expansion caused by the formation of magnesium hydroxide gel. Rossouw [34] has reported that a distinction should be made between magnesia (MgO) in the form of periclase and magnesia (MgO) in combination with glass. Only in the form of periclase, does magnesia (MgO) cause unsoundness of the concrete.

The limit on the maximum available alkali content in fly ash is expressed as the Na_2O content in TSDHPT Material Specification D-9-8900. Most fly ashes have been found to contain an available alkali content of less than 1.5% [32]. The limit placed on the maximum alkali content available, is to prevent expansions due to alkali-aggregate reactions.

To reduce the possibility of excessive delays in the setting time of concrete, the sulfur trioxide (SO_3) content in fly ash is limited to a maximum of 5%.

The loss of ignition (LOI) of fly ash has a direct influence on the durability of concrete, mainly its freeze-thaw resistance. LOI is also referred to as the carbon content of the fly ash. Fly ash with high carbon contents greater than 6% require higher dosages of air-entraining admixture to obtain the required air-void system for adequate freeze-thaw resistance. Carbon has an affinity for the air-entraining admixture available in the fresh concrete. Air entraining admixtures in the presence of carbon are adsorbed by the carbon particles, reducing the amount of available air-entraining admixture available to form an adequate air-void system. Type A fly ashes usually have higher carbon contents than Type B fly ashes since they are produced from coals containing a higher carbon content.

2.4 Physical Properties

The physical properties of fly ash affect concrete mainly in its fresh state. Workability and bleeding of concrete containing fly ash are dependent primarily on the shape and size of the fly ash particles.

Fly ash particles range in size from about 100 n to less than 1 n, with approximately 75% or more passing the 45 n (No. 325) sieve. The particle size of a fly ash depends primarily on the type of collection system used and the efficiency of the firing unit used. For equivalent weights, fly ash particles, being smaller than the cement particles, have a larger surface area. This has a direct effect in reducing the bleeding rate of a fresh concrete mix. Fly ash particles act as void fillers between the cement particles, closing pores available for water to escape through. Bleeding in concrete containing fly ash is also reduced due to the lower mixing water content required for a given workability as compared to a similar concrete mix containing no fly ash.

Fly ash particles are spherical in nature and can be either solid or hollow. Hollow particles are termed cenospheres. These are lightweight particles composed of silicate spheres filled with nitrogen and carbon dioxide. Fly ashes with large concentrations of cenospheres are not desirable since they are lighter than water and tend to float during the finishing process, producing streaks on the concrete surface [32]. On the other hand the spherical nature of the solid fly ash particles imparts improved workability on the concrete, allowing for reductions in the mixing water content as compared to ordinary concrete mixes.

In general, fly ash has a lower bulk specific gravity than Portland cement. If cement is replaced on an equal weight basis with fly ash, the fresh concrete will contain a larger volume of fine particle material as compared to ordinary concrete. This results in an increased volume of paste, improving the rheological properties of the mix.

CHAPTER 3

LITERATURE REVIEW: CONCRETE CONTAINING FLY ASH

The following is a survey of technical publications which deal with the production of concrete containing fly ash. Properties of concrete containing fly ash in its fresh and hardened state are discussed. Mix proportioning methods are also surveyed.

In the United States, Davis et al. [10], in 1937, were the first to publish test results concerning the incorporation of fly ash in concrete mixes. Until recent years, the use of concrete containing fly ash had been limited to mass concrete applications.

As its use expanded, more research has been conducted to study the properties of concrete containing fly ash. In recent years much of the pioneering work to expand the applications of concrete containing fly ash has been performed by Cook [7,8], Lane [19], Malhotra [27], Cannon [4], Lovewell and Washa [20].

3.1 Properties of Fresh Concrete Containing Fly Ash

In general, concrete containing fly ash exhibits improved performance in its fresh state compared to ordinary concrete. Studies have shown that the improved rheological behavior of concrete containing fly ash is due mainly to the physical properties of the fly ash [18,22,25]. The following discussion summarizes research conclusions concerning the effects of fly ash on fresh concrete.

3.1.1 Workability. Production of quality concrete requires fresh concrete exhibiting the following properties [45]:

1. Its flow properties should be such that it is capable of filling completely the forms for which it was designed.

2. It must be fully compacted without the need for excessive amounts of energy.

3. It must not segregate during placing and consolidation.

4. It must be capable of being finished properly.

Due to its smaller size and spherical particle shape, fly ash enhances the abovementioned properties of concrete as compared to ordinary concrete.

Use of fly ash as a partial replacement of cement will usually reduce the water requirement of the concrete for equal workability [32].

Lane and Best [18] have reported that workability is governed by such factors as the volume of paste, the water-cement (w/cm) ratio and proportion, grading, shape and porosity of the aggregates. Berry and Malhotra [2] state that the small size and essentially spherical shape of the particles comprising fly ash usually influence the rheological properties of cement pastes. This causes a reduction in the amount of water required for a given degree of workability from that required for an equivalent paste without fly ash. Pasko and Larson [46] examined the amount of water required to maintain a nominal 2.5-in. slump in concrete mixes with partial replacement of the cement with fly ash. They found that the water requirement was reduced 7.2% in a mix in which 30% fly ash by weight, replaced 20% cement by weight.

Fly ash has a lower bulk specific gravity than cement. For a one to one replacement, by weight, of cement with fly ash, concrete containing fly ash will have a greater volume of paste than ordinary concrete. Mehta [25] states that the cohesiveness of concrete mixes is controlled by the volume of paste in the concrete. Due to its increased cohesiveness, concrete containing fly ash has shown excellent pumpability qualities. Samarin et al. [35] noted that fly ash has been found to be highly consistent and cost effective in the production of flowing concrete.

3.1.2 Temperature and Setting Time. In general, fly ash, a pozzolan, reduces the hydration temperature of concrete. Sturrup et al. [38] noted that the pozzolanic reactions of the alumino-silicates in fly ash with the calcium hydroxide liberated by the tricalcium silicate (C_3S) and dicalcium silicate (C_2S) of portland cement take place more slowly than that of tricalcium silicate (C_3S) and approximate the reaction rate of dicalcium silicate (C_2S). This results in concrete having a reduced heat of hydration. An added advantage of the reduced heat of hydration in concrete containing fly ash is the longer setting time which helps avoid cold joints during construction. Manz

[23] reports that some fly ashes with high calcium contents, mainly Type B fly ash, produce rapid heat rises and false set in concrete mixes. Even though fly ash generally slows the setting of concrete, both initial and final setting times remain within specified ASTM Standard Specification C150-84, "Portland Cement," limits. Retardation of setting due to the addition of fly ash to concrete may be affected by the proportion, fineness, and chemical composition of the fly ash; although cement fineness, water content, and ambient temperature usually have a much greater effect on setting time than the addition of fly ash. The chemical composition of fly ash also has been observed to influence the setting time of mortars, particularly those with high carbon contents. Concrete containing fly ash with a LOI above 10%, increase the time of setting due to an increased water demand of the fresh concrete [32]. Berry and Malhotra [2] reported that the soluble portion of the tricalcium silicate (C_3S) content of fly ash must be limited to avoid excessive delays in setting. Figure 3.2 compares the effect of fly ash on the temperature rise in concrete as compared to ordinary concrete.

Materials in a non-crystalline form and of small size, hydrate at a slower rate than crystalline materials in the presence of water. As a result, composition and particle size provide better indicators of the reaction rate of fly ash than does its chemical composition. Type B fly ash has been found to have an increased reaction rate over that of Type A fly ash. Type B fly ashes have been found to contain increased amounts of tricalcium aluminate (C_3A) which tend to increase the reaction rate through the formation of calcium aluminate hydrates. This may cause the false setting of the concrete mix.

Samarin et al. [35] have noted that fly ash in itself does not have a significant effect on the setting time of concrete. They noted that the fly ash particles act as a nuclei for the formation of the hydration products of concrete thus actually accelerating the setting process of concrete. Setting time is affected mainly by temperature and water demand of the fresh concrete. Fly ash with a high LOI, in general, has a higher water demand, therefore causing an increase in the concrete set time. Shown in Fig. 3.3 is a plot of the required mixing water content of concrete for a given workability as a function of the loss on ignition (LOI) of the fly ash.

3.1.3 Bleeding and Segregation. Problems associated with excessive bleeding of concrete include segregation, poor finishability, lower abrasion resistance, high concrete

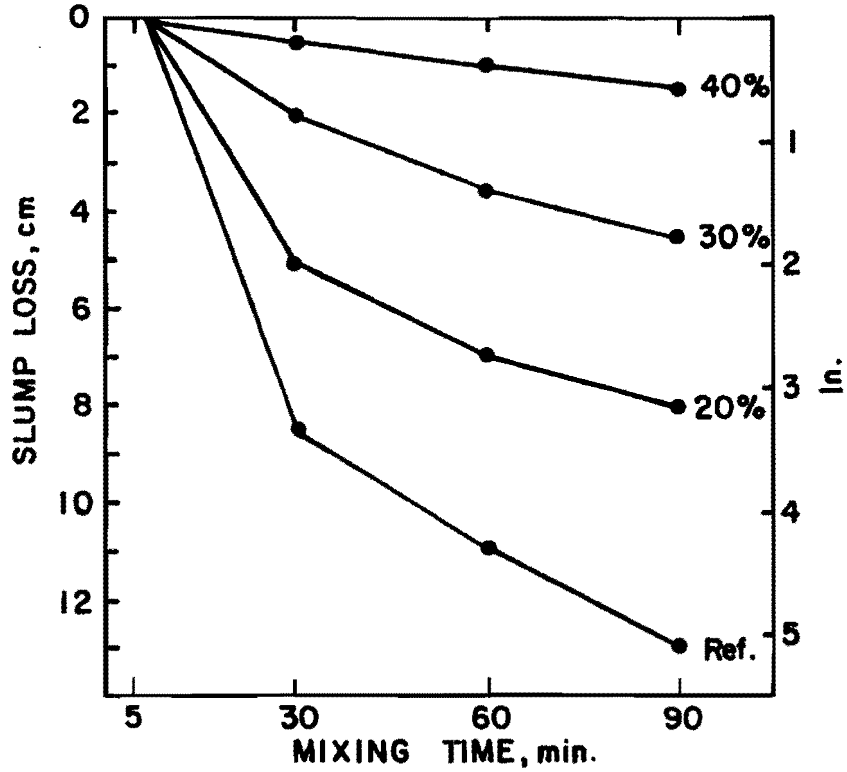

Fig. 3.1 Slump loss in concrete containing fly ash as a a replacement for 1.5 X cement weight [33].

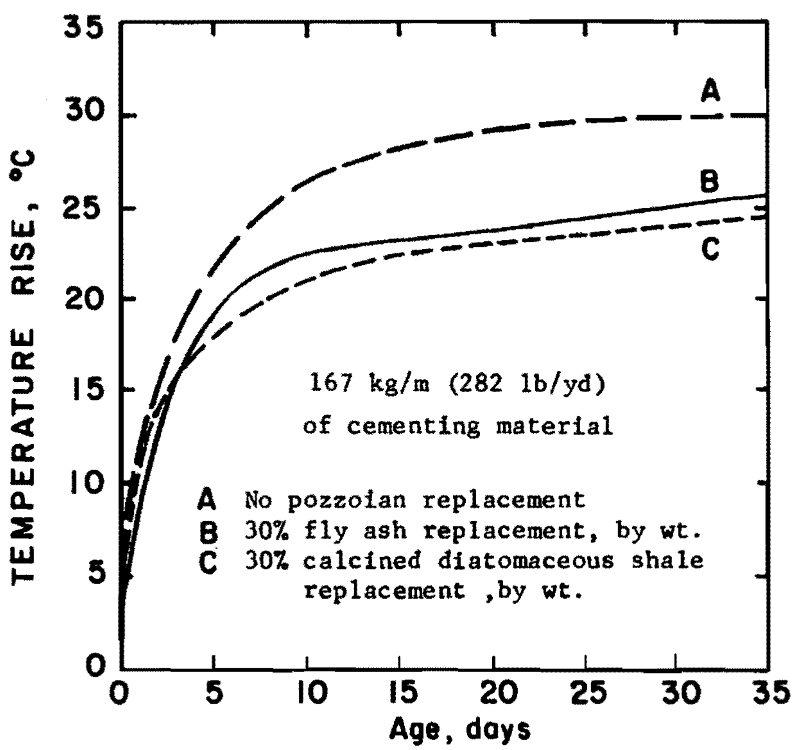

Fig. 3.2 Effect of pozzolan on temperature rise in concrete[2].

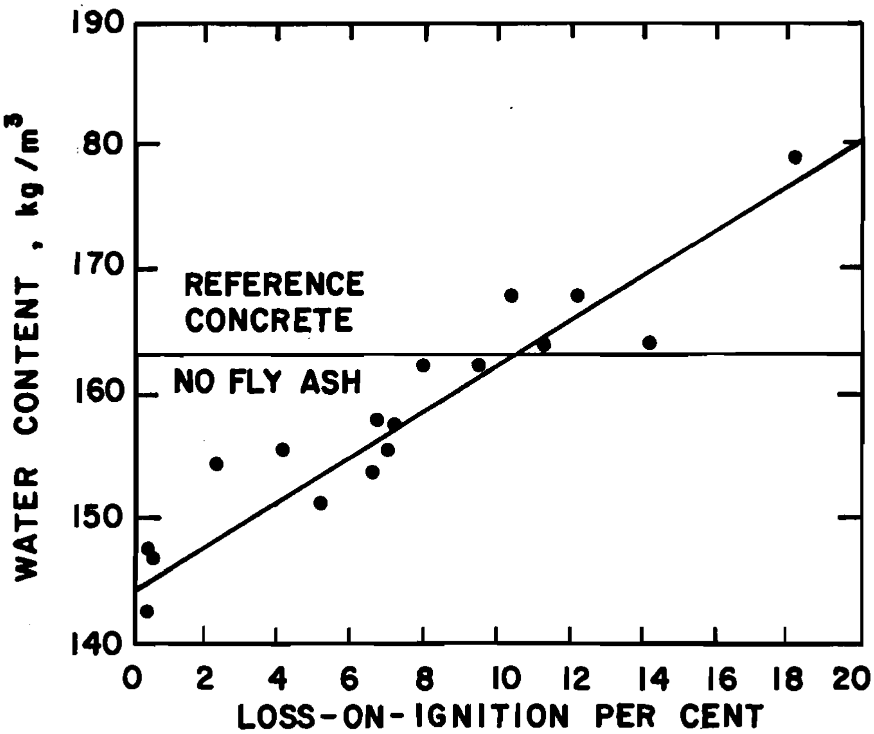

Fig. 3.3 Effect of LOI on water demand of fresh concrete [38].

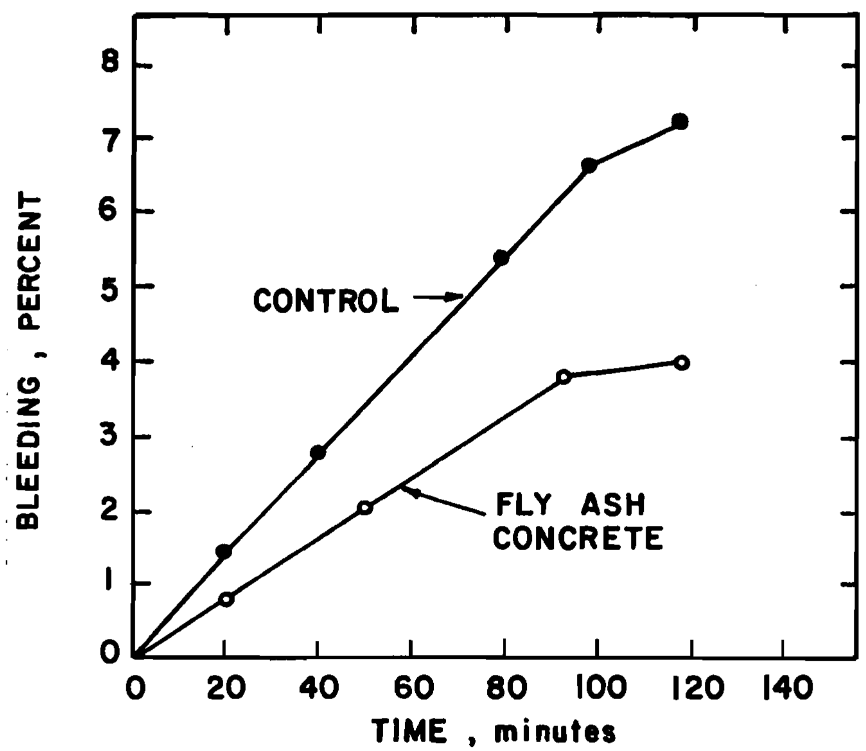

Fig. 3.4 Comparison of bleed between ordinary concrete and concrete containing fly ash[2].

permeability, and the lower strength of the hardened concrete. Throughout the years the use of air-entraining admixtures has proven to be adequate in most cases in reducing bleeding of concrete. The effectiveness of the air entraining admixtures in reducing bleeding of concrete results from the size and shape of the resulting entrained air. Entrained air chokes off the flow of water by entrenching itself between the cement particles and closing off the capillaries through which the water flows.

Due to its particle size and shape, fly ash has also been shown to reduce the bleeding rate in concrete. Reduced segregation and improved finishability characteristics are added benefits obtained because of the reduction in bleeding rates [25]. Samarin et al. [35] noted that an increase in the total particle surface area decreases the bleeding rate in concrete mixes.

Setting time has been reported to influence the overall bleeding capacity of a mix. The longer the bleeding duration, the higher the bleeding capacity. Extended setting time increases the bleeding duration time, increasing the bleeding capacity.

The use of chemical admixtures also influence bleeding rates. Admixtures in general act as flocculators or deflocculators. Flocculators such as air-entraining admixtures decrease the rate of bleeding by reducing the available void space in concrete mixes. Deflocculators, such as water reducers, when added to mixes of a given mixing water content increase the bleeding rates of that concrete due to an increase in the amount of free water. Retarders increase the setting time, and therefore increase the bleeding capacity of a concrete mix [35]. It should be noted that water reducers decrease the water requirements in concrete mixes, therefore reducing the free water available for bleeding.

The water-reducing properties imparted by fly ash on the concrete reduce the bleeding capacity. For lower water-cementitious (w/cm) ratios, the formation of gel proceeds at a faster rate reducing the amount of water available for bleeding [18]. The increased cohesiveness of concrete containing fly ash compared to ordinary concrete reduces the probability of segregation in the concrete mix.

3.2 Properties of Hardened Concrete Containing Fly Ash

Concrete containing fly ash has been noted for its lower strength at early age, high susceptibility to freeze-thaw damage, high sulfate resistance and its low alkali-aggregate reactivity. The following discussion summarizes recent literature related to the properties of hardened concrete containing fly ash.

3.2.1 Concrete Strength. Due to the pozzolanic properties of fly ash, concrete containing fly ash exhibits a slower compressive strength gain than ordinary concrete. At an age of 90 days, concrete containing fly ash exhibits compressive strengths equal to or greater than that of ordinary concrete. Variations in the rate of compressive strength gain depend on the type of fly ash used, amount of fly ash used, and the type of cement used.

Cannon [4] reported that concrete mixes proportioned using fly ash as a cement replacement on a one-to-one basis, either by weight or by volume, generally have lower strengths at 28 days than ordinary concrete mixes. At 90 days and beyond, concrete mixes containing fly ash have compressive strengths equal to or higher than those of ordinary concrete. To overcome this strength deficiency at early ages, Cannon [4] recommends using the approach developed by Lovewell and Washa [20] which is based on proportioning concrete mixes having a fly ash content which exceeds that of the cement replaced. Samarin et al. [35] indicated that besides the quality of the fly ash and the cement used, the method of mix proportioning is the single most important factor affecting the properties of the hardened concrete. The following three mix proportioning method have been proposed:

1. Partial replacement of cement.

2. Addition of fly ash as fine aggregate.

3. Partial replacement of both cement and fine aggregate.

In general, the optimum fly ash content in a concrete mix varies from 20 to 35% by weight of cement replaced. Cement type, type of fly ash, coarse and fine aggregate gradation, and the use of admixtures are all factors which influence what the optimum fly ash content will be.

TSDHPT Departmental Material Specification D-9-8900 classifies fly ash as either Type A, low calcium fly ash and Type

B, high calcium fly ash. Noticeable differences have been observed between the strength development of concrete containing Type A fly ash and concrete containing Type B fly ash. Observations indicate that a high calcium fly ash may start its cementitious and pozzolanic activity as early as 3 days after the hydration of the cement begins whereas a low calcium fly ash does not show enough pozzolanic activity to affect the strength of concrete until about two weeks after cement hydration has begun [25]. The availability of calcium released by the hydration of Type B fly ash, acts as a catalyst for the continued formation of hydration products, mainly calcium silicate hydrate (C-S-H).

Early strength in concrete is provided by the hydration of tricalcium silicate (C_3S), which is a highly reactive compound. The dicalcium silicate (C_2S) component of cement provides low initial strength with an eventual increase of strength over that provided by the tricalcium silicate (C_3S) compound at later ages. Concrete containing Type A fly ash has a slower reaction rate than ordinary concrete due to the pozzolanic effect of the fly ash. The reactions of the alumino silicates in fly ash with the calcium hydroxide liberated by the tricalcium silicate (C_3S) and dicalcium silicate (C_2S) compounds of portland cement occur at a slower rate than the tricalcium silicate (C_3S) reaction and approximate the reaction rate of dicalcium silicate (C_2S). The reduction in the amount of available tricalcium silicate (C_3S) is due to the partial replacement of the cement with fly ash. Yuan and Cook [42] have reported results of compressive, flexural and durability tests on concrete containing Type B fly ash. It was reported that in general the compressive strengths of concrete containing 30% Type B fly ash, by weight, were higher than those of the ordinary concrete control mix.

Fly ash has also been blended with cement at cement mills to produce Type IP and Type I-PM cements. Type IP cement is similar in properties to a Type IV cement and Type I-PM cement is similar to a Type II cement. Fly ash contents in Type IP cement vary from 15 to 40% by weight of cement. Fly ash contents in Type I-PM cement vary from 5 to 15% by weight of cement.

3.2.2 Freeze-Thaw Resistance. Provided equal dosages of air-entraining admixture are used, concrete containing fly ash is more susceptible to freeze-thaw damage than ordinary concrete [2,19]. Concrete containing fly ash will have adequate freeze-thaw resistance provided the proper amount of air is entrained in the mix. The ability of concrete containing fly ash to develop an adequate air-void system depends on the chemical composition of the fly ash, the type of fly ash used, and the amount of fly ash in the mix.

The loss on ignition (LOI) or carbon content of the fly ash is the single most important factor affecting the ability to adequately entrain air in concrete containing fly ash [38]. Due to the incomplete combustion of carbon in the firing units, all fly ashes contain residual carbon particles. Due to the large surface area of the carbon particles and the chemical composition of the air-entraining admixtures, the air-entraining admixture in concrete containing fly ash is adsorbed by the carbon particles. This results in a smaller amount of available air-entraining admixture to form an adequate air-void system in the concrete for proper freeze-thaw protection. Gebler and Klieger [12] noted that as the total alkali content in the fly ash increases, the air-entraining admixture required to provide an adequate air void system in the concrete decreases. In addition, as the specific gravity of fly ash increases the retention of air in concrete increases. This is due to the lower organic matter content of fly ashes having a higher specific gravity. They also noted that the retention of air in the concrete increased as the sulfur trioxide (SO_3) content of the fly ash increased.

Freeze-thaw resistance of concrete containing fly ash depends on the type of fly ash used as well. Type A fly ash has, in general, a higher residual carbon content. The carbon content for Type A fly ash has been reported to be in the range of 1 to 19% by weight while the carbon content for Type B fly ash ranges between 1 to 12% by weight [24].

Gebler and Klieger [12] noted that test results have shown that concretes containing Type B fly ash have a more stable air-void system than concretes containing Type A fly ash. They added that the higher the organic content of a fly ash, the higher the air-entraining admixture requirements. In addition higher air-entraining admixture requirements result in a greater loss of entrained air on extended mixing. Yuan and Cook [42] have noted that air-entrained concrete containing Type B fly ash had an improved freeze-thaw resistance over that of the control mix. In their tests, specimens were subjected to 1200 freeze-thaw cycles, with the specimens of concrete containing Type B fly ash having a reduction of the dynamic modulus at 1200 cycles of approximately 30% from the initial dynamic modulus. They also observed that concrete mixes containing a Type B fly ash replacement of 50% were found to satisfy ASTM Standard Specification C666-80, "Resistance of Concrete to Rapid Freezing and Thawing," requirements.

3.2.3 Drying Shrinkage and Creep. Data on shrinkage and creep of concrete containing fly ash is limited. Drying shrinkage refers to the volume change in concrete due to the loss of moisture in the hardened concrete. Creep refers to the long term deformation of concrete due to applied loads.

Fly ash added to concrete has a two fold effect on the drying shrinkage of concrete. Due to a lower specific gravity, fly ash replacement of cement on a equal weight basis results in an increase in the paste volume of the fresh concrete mix. If the water demand of the concrete containing fly ash increases over that of the control mix, the drying shrinkage of the concrete containing fly ash may increase compared to that of the control mix. However, the fly ash generally reduces the water demand of a mix, therefore reducing the water loss due to shrinkage. This results in a negligible increase in shrinkage due to the use of fly ash in concrete [18]. Studies by the Tennessee Valley Authority (TVA) [32] indicate negligible differences between the drying shrinkage of ordinary concrete and that of concrete containing fly ash. Tests by Hague et al. [15] indicate that the drying shrinkage of concrete decreases with an increase in the fly ash content.

Results of shrinkage measurements done on concrete containing fly ash, and ordinary concrete indicate a reduction in shrinkage for the concrete containing fly ash [13]. In this study, the 28-day compressive strength of the concrete containing fly ash was equivalent to that of the control mix. The main difference in the concrete mixes was a lower water-cementitious (w/cm) ratio for the concrete containing fly ash as compared to the ordinary concrete.

Much confusion still exists among researchers concerning the effect of fly ash on the creep characteristics of concrete. Samarin, et al. [35] noted that concrete containing fly ash exhibited lower creep as compared to ordinary concrete. Lane and Best [18] reported that concrete containing fly ash may exhibit higher creep strain than ordinary concrete due to the lower early strength of concrete containing fly ash as compared to that of ordinary concrete. As a result of this, creep specimens made of concrete containing fly ash loaded at 28 days will show increased creep strains as compared to creep specimens made of ordinary concrete. They further added that specimens of concrete containing fly ash of comparable compressive strength to ordinary concrete showed no increases in creep strains as compared to the ordinary concrete.

Factors affecting the creep process in concrete include the water-cementitious ratio (w/cm), cement composition, and permeability of the concrete. In general concrete containing fly ash has a reduced water-cementitious ratio (w/cm), decreasing the amount of water available for creep. Due to the particle size and shape of the fly ash, concrete containing fly ash is more impermeable than ordinary concrete. The use of fly ash in concrete reduces the voids available for the movement of water. The chemical composition of the cement has some effect on creep behavior of concrete as well [45]. It has been noted that lower tricalcium silicate (C_3S) contents in the cement increase creep. Concrete containing fly ash has a reduced amount of available tricalcium silicate (C_3S) due to the partial replacement of the portland cement. Exactly how the tricalcium silicate (C_3S) content of the cement influences the creep behaviour of concrete is not yet fully understood.

3.2.4 <u>Sulfate Resistance</u>. The use of fly ash in concrete has been shown to improve the resistance of the concrete to sulfate attack. Fly ash in concrete has a twofold effect in increasing the resistance to sulfate attack of the concrete. This is accomplished by reducing the permeability of the concrete and reducing the amount of tricalcium aluminate (C_3A). An extensive research program was undertaken by the U.S. Bureau of Reclamation [11] to investigate the resistance of concrete containing fly ash to sulfate attack. This research indicates that the use of fly ash greatly improves the resistance of concrete to sulfate attack. The following list summarizes the sulfate resistance of concrete, from the highest resistance to the least resistance:

Type V cement and fly ash (highest resistance)

Type II cement and fly ash

Type V cement

Type II cement

Type I cement and fly ash

Type I cement (least resistance)

The reaction of silica in fly ash with free calcium forms additional calcium silicate hydrate (C-S-H) which reduces the permeability of the concrete. Due to its reduced permeability, concrete containing fly ash is more resistant to the influx of chemicals in the environment. Sulfate attack results from the combination of aluminates and sulfates producing calcium sulfoaluminates (ettringite). This causes a volume expansion within the paste which generates large internal stresses resulting in the formation of cracks in the concrete and its ultimate deterioration. Provided the sulfate content in the concrete is kept to a minimum the formation of damage causing ettringite will be kept to a minimum.

Reductions in the amount of aluminate in the concrete are of beneficial effect in its sulfate attack resisting capacity. The use of less portland cement in concrete containing fly ash reduces the amount of aluminates available for reaction with sulfates for the formation of ettringite.

3.2.5 Alkali-Aggregate Reactivity. Alkali-aggregate reaction failures in concrete are due to expansions caused by a chemical reaction between the alkalis contained in the cement paste and certain reactive forms of silica within the aggregate. The use of fly ash in concrete has been shown to reduce the probability of alkali-aggregate reactions [2].

The mechanisms by which fly ash reduces alkali-aggregate reactivity are not fully understood. Replacement of portland cement with fly ash reduces the available alkali content in the concrete . Further reductions in alkalinity may be obtained as the pozzolanic reaction progresses [25]. Type B fly ashes may contain a large amount of soluble alkali sulfates which may increase rather than decrease the alkali-aggregate reactivity. It must be noted that it is the soluble alkali and not the total alkali present in the fly ash which affects the alkali-aggregate reactivity [25]. The standard test for measuring the effectiveness of a fly ash in reducing alkali reactivity is ASTM Standard Specification C441, "Control of Alkali-Aggregate Reaction Using Mineral Admixtures." Sturrup et al. [38] indicated that the alkalis in the cement combine with the reactive silica of the fly ash to reduce expansions caused by alkali aggregate reactions. Due to the rapid reaction of the cement alkali and fly ash silica, expansion caused by the attraction of water by the alkali-silicate gel, is reduced [45].

3.3 Mix Proportioning Procedures

Mix proportioning of concrete containing fly ash vary from that used for ordinary concrete. In the United States, various researchers and organizations have proposed mix proportioning techniques for the incorporation of fly ash in concrete. In general these techniques fall into one of the three following procedures:

1. Direct replacement of cement with fly ash by weight.

2. Replacement of fine aggregate with fly ash.

3. Replacement of cement and fine aggregate with fly ash.

Fly ash, used as recommended by Method 2 would be considered an admixture rather than a cementitious material. Method 1 has been used extensively in the production of mass concrete.

ACI Standard 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete," recognizes the cementitious properties provided by the fly ash and recommends the use of the water-cementitious (w/cm) ratio referring to the water/cement plus fly ash ratios by weight.

Tests by Lovewell and Washa [20] indicate the need to use Method 3 if comparable early strengths are to be obtained. Again the use of the water-cementitious (w/cm) ratio is recognized for use in making workability and strength comparisons. Listed in Table 3.1 are sample mix designs for concrete containing fly ash [8].

TABLE 3.1 Sample Mix Designs for Concrete Containing Fly Ash

Cementitious content (lbs/yd^3)	586	532
Compressive strength @ 28 days (psi)	6419	6658
Cement (Type I) (lbs/yd^3)	467	381
Type of Fly Ash	B	B
Fly Ash (lbs/yd^3)	119	151
Fine Aggregate (lbs/yd^3)	1238	1329
Coarse Aggregate (lbs/yd^3)	1928	1803
Water (lbs/yd^3)	250	272
WR--Admixture (3 oz/cwt)	18 oz.	----
Air	----	2.5
Slump	4	4.5
Water-cementitious ratio	0.42	0.51
Unit wt (lbs/ft^3)	148.5	----

CHAPTER 4

MATERIALS AND TEST PROCEDURES

4.1 Introduction

Throughout this investigation, only commercially available materials currently approved by the Texas State Department of Highways and Public Transportation (TSDHPT) were used. Workability as measured by the slump test was the controlling factor for all mixes. All the concrete mixes had slumps of at least 3-1/2 in. ± 1/2 in. Production, curing, and testing of concrete specimens in this study were conducted according to applicable procedures described in the TSDHPT Manual of Testing Procedures Physical Section 400-A Series. The American Society for Testing and Materials' 1984 Annual Book of ASTM Standards, Part 14, "Concrete and Mineral Aggregates," and the TSDHPT 1982 Standard Specifications for Construction of Highways, Streets and Bridges.

In this chapter, a description of the materials, mix proportioning, and mixing procedures used in this study are presented.

4.2 Material Properties

The materials used in this study include two sources of portland cement, one type of coarse aggregate, one type of fine aggregate, one water-reducing and retarding ASTM C494 type D admixture, one air-entraining ASTM C260 admixture, two types of fly ash, and local tap water. Composition and physical properties of the cements and fly ashes used are presented in Appendix A.

4.2.1 Portland Cement. Two types of Portland cement, ASTM C150 types I and IP were included in this study. Each of the two cements were produced in Texas at two different plants. For mix design purposes, the specific gravity of the Type I cement was assumed to be 3.15.

The type IP cement used was a blended cement consisting of 20% by weight, Type A fly ash and 80% Type I cement. This cement was manufactured using Type A fly ash obtained from the Monticello plant near Mt. Pleasant, Texas. The specific gravity of the Type IP cement was 3.01. Table A.1 summarizes the chemical and physical properties of these cements. Table A.3 summarizes the chemical and physical properties of the Type A fly ash used in the production of the Type IP cement.

4.2.2 Coarse Aggregate. The coarse aggregate used in this study was a siliceous rounded river gravel obtained from a commercial supplier in Texas. The maximum size of the aggregate was 1 in. Table 4.1 summarizes the properties of this aggregate.

4.2.3 Fine Aggregate. Natural sand was used in this study. This aggregate was provided by a commercial supplier in Texas. Table 4.2 summarizes the properties of this aggregate.

4.2.4 Fly Ash. A Type A and a Type B fly ash, satisfying the requirements of TSDHPT Material Specification D-9-8900, was used in this study. These were obtained from commercial suppliers in the State of Texas. The fly ash was used as a partial replacement of cement in concrete mixes using the following quantities: 15, 25 and 35 percent by weight of the total cementitious content. The fly ash and portland cement were batched simultaneously. Table A.2 summarizes the chemical and physical properties of the fly ash used.

4.2.5 Chemical Admixtures. A water reducer-retarder, ASTM C494 Type D admixture was used. The air-entraining admixture used was a neutralized vinsol resin. In calculating the water-cementitious (w/cm) ratio of all mixes, the quantity of admixture added was included as part of the mixing water.

4.2.6 Water. Tap water was used in all mixes. The unit weight of water was taken to be 62.4 lbs/cu.ft. The water temperature was $75^{\circ}F \pm 5^{\circ}F$ during this study.

4.3 Mixing and Testing

All mix designs were based on the saturated surface dry condition of the aggregate. The main variables considered in mix proportioning were: the water-cementitious (w/cm) ratio required to produce concrete of a given slump, the cementitious content and the fly ash content.

Slump was maintained at 3-1/2 in. ± 1/2 in. in all batches. Two cementitious contents, 6.0, and 7.0 sacks/cu. yd. (564, and 658 lbs/cu.yd.) were considered. All mixes were proportioned for an approximate air content of 3%.

TABLE 4.1 Summary of Coarse Aggregate Properties

Nominal size (in.)	1.0
Texas Grade	4
Type and description	siliceous rounded river gravel
Bulk specific gravity, SSD	2.52
Absorption, %	0.68
Dry rodded unit weight (lb/ft^3), SSD	98

TABLE 4.2 Summary of Fine Aggregate Properties

Fineness modulus	2.73
Bulk specific gravity, SSD	2.61
Absorption, %	0.04
Unit weight, SSD	97.1 lb/ft^3
Description	Siliceous sand

The concrete was mixed in 4-1/2 cu.ft. batches. For most concrete batches, the following specimens were cast: twelve 6 x 12-in. cylinders cast in steel molds, and three 6 x 6 x 21-in. flexure test beams cast in steel molds. Three 6 x 12-in. cylinders from each batch were tested for compressive strength at 7, 28, 56, and 91 days for strength gain comparisons. The three flexure beams were tested at 7 days. Tests to study the effects of different curing conditions and the curing time required the casting of nine additional flexure test beams. For these tests twelve 6 x 12-in. cylinders and twelve 6 x 6 x 21-in. flexure beams were tested at 28 days. The variable in these tests was the difference in time the specimens were moist cured. The moist curing time varied from 1, 3, 7 or 28 days. In addition two 3 x 4 x 16-in. specimens were cast for freeze-thaw tests for the first 16 batches. Additional batches were used to study other variables such as: effect of high temperature during mixing; the influence of mixing time on the concrete strength; and the effect of using a membrane curing compound on the strength development of the concrete. The concrete mixing room including the concrete mixer used in this study are shown in Fig. 4.1.

4.3.1 Mixing Procedures. The mixing procedure for all concrete mixes consisted of first batching the aggregate, cement and fly ash together, and mixing the dry material for two minutes before adding the water. The air-entrainning admixture was added with the first 30% of the water. The batch was mixed for five minutes afterward. Then the water-reducing admixture was diluted with an additional 30% of the mixing water and added to the batch. The remainder of the water was added as required to reach the desired slump.

For the study of the effect of high temperature on the properties of fresh concrete, similar batching procedures as described earlier were followed except that the materials were preheated overnight to a temperature of 100^{o}F and hot tap water at a temperature of about 105^{o}F was used for mixing water. During mixing, the mixer was kept hot by continuously running hot tap water over the drum. A plastic cover fitted over the mouth of the mixer prevented cooling of the fresh concrete during the duration of the mixing. One 6 x 12-in. cylinder and one 6 x 6-in. x 21-in. flexure beam were cast immediately after the desired slump was obtained.

After mixing for 60 minutes, the slump was adjusted to the original slump, by adding water, and two 6 x 12-in. cylinders and two 6 x 6 x 21-in. flexure beams were cast. After mixing for 90 minutes the slump was again adjusted by adding water and two more

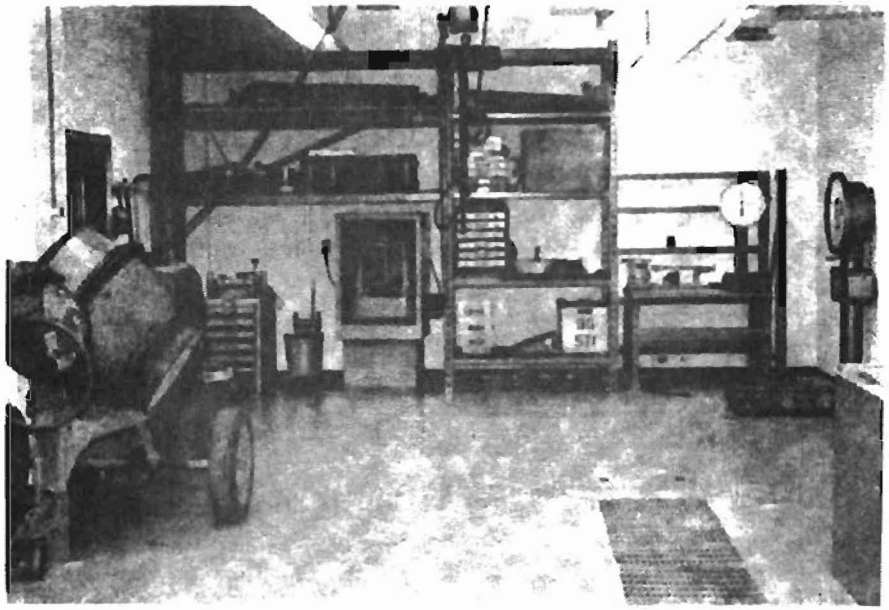

Fig. 4.1 Concrete batching laboratory showing the concrete mixer at left.

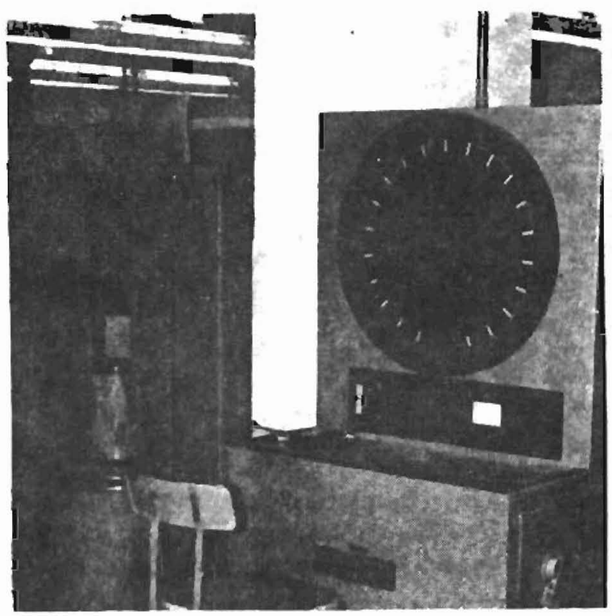

Fig. 4.2 The 400-kip compressive testing machine.

6 x 12-in. cylinders and two 6 x 6 x 21-in. flexure beams were cast. The remainder of the mix was discarded. All other mixes required approximately 15 minutes mixing time before casting.

Mixes performed to study the strength development characteristics of membrane cured concrete containing fly ash were done using the above mentioned procedure. The effect of curing temperature was also studied with these mixes. Only concrete containing Type A fly ash was studied in this investigation. A TSDHPT Item 526, "Membrane Curing," Type 2 curing compound was applied to one set of specimens at the time of demolding and allowed to sit at room temperature and 72% relative humidity until time of testing. The same curing compound was applied to the second set of specimens; however, these were placed in a room at 100°F, and 33% relative humidity until time of testing.

4.3.2 Tests on Fresh Concrete. The mixer was a 6 cu.ft. maximum capacity Essex drum mixer with a mixing speed of 30 rev/min. Concrete was made and molded according to ASTM Standard Specification C192-81, "Making and Curing Concrete Test Specimens in the Laboratory", and Tex-418-A, "Compressive Strength of Molded Concrete Cylinders," except for the following exceptions from some of the specified procedures:

1. A primary goal of this research was to show whether or not concrete containing fly ash could be produced using materials and handling procedures similar to those used at batching plants. Therefore, coarse and fine aggregates were stored as received, in bins, at a constant moisture content rather than in separate size fractions or under water.

2. The mixer was moistened thoroughly, but was not buttered before each mix.

3. Except for "hot weather" mixes, every batch was steadily mixed for about ten to fifteen minutes, with stops as necessary to check and adjust the slump until the desired slump was reached.

4. Flexural test specimens were moist cured under the same conditions at 98% relative humidity and at a temperature of 73°F $\pm$ 3°F, as were the compressive strength cylinders.

Slump tests were conducted according to ASTM Standard

Specification C143-78 for "Slump of Portland Cement Concrete", and Tex-415-A, Testing Procedure "Slump of Portland Cement Concrete". The fresh unit weight of every mix was measured according to ASTM Standard Specification C138-81, "Unit Weight, Yield, and Air Content (Gravimetric) of Concrete", using a 0.25 cu.ft. container. Yield was calculated on the basis of batch weights and specific gravities. The temperature of each mix was also recorded.

Specimens were cured in a curing room meeting ASTM Standard Specification C511-80, "Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes".

4.3.3 Test Procedures. The following specifications were followed for compressive, and flexural strength testing: ASTM Standard Specification C39-81, "Compressive Strength of Cylindrical Concrete Specimens"; Tex-418-A, "Compressive Strength of Molded Concrete Cylinders"; ASTM Standard Specification C239-79, "Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)"; Tex-420-A, "Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)"; ASTM Standard Specification C666-80, "Resistance of Concrete to Rapid Freezing and Thawing".

Compressive strength tests were performed using a 400-kip compression testing machine, shown in Fig. 4.2. Flexure testing was carried out on a hydraulic, hand-operated, single-point loading beam tester having a 12,000 lb capacity. All compressive strength test specimens were capped using a high strength capping compound.

CHAPTER 5

PRESENTATION AND DISCUSSION OF TEST RESULTS

5.1 Introduction

The experimental test results are presented and discussed in this chapter. The effect of the use of fly ash as it relates to the production of Texas State Department of Highways and Public Transportation (TSDHPT) Standard Specification Item 421, "Concrete for Structures," Class C concrete is discussed. Recommendations for the incorporation of concrete containing fly ash into the above mentioned specification are provided. Comparisons are also made, for mixes having a constant cementitious content, on the performance of concrete containing fly ash with respect to ordinary concrete. Specifications for TSDHPT Item 421, Class C concrete are summarized in Table 5.1.

This chapter is divided into the following four sections: strength characteristics of concrete containing fly ash, durability of concrete containing fly ash subjected to freeze-thaw cycles, the influence of moist curing time (78°F, 98% RH) and subsequent curing conditions (100F°F, 33% RH or 40°F, 55% RH) on the strength of concrete containing fly ash, and the effect mixing time, mixing temperature and retempering have on the strength of concrete containing fly ash. The results for the tests performed are presented and discussed in each section, with recommendations for the specification of materials, batching procedures and performance requirements given, wherever possible, for the use of concrete containing fly ash in structural applications.

The test results presented in this chapter are based on 16 basic trial mixes. Table 5.2 summarizes the differences between the 16 mixes considered in this study. For mixes having an equal cementitious content the amount of fine aggregate, amount of coarse aggregate, and admixture dosage used remained constant. These trial mixes are based on an Item 421, Class C concrete mix design provided by the TSDHPT. This mix design is shown in Table 5.3. For purposes of our study, the fine and coarse aggregate quantities used were adjusted to reflect the physical properties of the aggregates used. The mix proportions of the concrete tested in this study are presented in Appendix B. The slump of the fresh concrete was used as an indicator of uniformity between

TABLE 5.1 TSDHPT Specifications for Item 421 Class C Concrete

Minimum cement content	564 lbs/yd^3
Minimum compressive strength (f'_c @ 28 days)	3600 psi
Minimum beam strength @ 7 days	600 psi
Maximum water-cementitious ratio	0.53
Coarse aggregate no.	1-2-3-4-5-8*
Usage	Drilled shafts, bridge railing and substructure, culverts, wingwalls

NOTE: When Type II cement is used with Class C concrete, the seven-day beam strength required will be 550 psi minimum.

* Grade 8 aggregate for use in machine laid curb.

TABLE 5.2 Concrete Mixes Considered in This Study

Mix I.D.	Cementitious Content (lbs/cu.yd.)	Type of Fly Ash Used	Fly Ash Content (% by wt)	Type of Cement Used
6I	564	-	0	I
6IP		A	20	IP[a]
6A15			15	I
6A25			25	
6A35			35	
6B15		B	15	
6B25			25	
6B35			35	
7I	658	-	0	I
7IP		A	20	IP[a]
7A15			15	
7A25			25	
7A35			35	
7B15		B	15	
7B25			25	
7B35			35	

[a] This cement is produced by blending 80% (by weight) Type I cement and 20% (by weight) Type A fly ash.

TABLE 5.3 Mix Design Originally Submitted by TSDHPT for Use in This Study

Aggregate Characteristics

Material	Specific Gravity	Dry Rodded SSD Unit Wt. (lbs/cu.ft.)	Percent Solids
Fine Aggregate	2.61	97.1	59.5
Coarse Aggregate	2.55	96.4	60.5

Mix Proportions

Material	Quantity (lbs/cu.yd.)
Cement	564
Fine Aggregate, SSD	1050
Coarse Aggregate, SSD	2082
Water	234
Admixture	**Dosage**
Air-Entraining	1/2 oz/sack
Reducer-Retarder	33 oz/cu.yd.

batches. The allowable slump range for all mixes was 3-1/2 $\pm$ 1/2 in.

5.2 Strength Characteristics of Concrete Containing Fly Ash

The effect of the use of fly ash in concrete mixes, as a partial replacement of cement, on its flexural and compressive strength performance are discussed in this section. A total of 16 batches were mixed to study the effect the variation of fly ash content and fly ash class have on the strength of concrete. In this set of tests, the cementitious content was also varied to obtain a comparison of its effect on the strength of concrete. For each batch twelve 6 x 12 in. compressive strength cylinders, three 6 x 6 x 21 in. flexural strength beams and two 3 x 4 x 16 in. freeze-thaw beams were poured. All the specimens were moist cured (78^{o}F, 98% RH) until time of testing. The three flexural strength beams were tested at 7 days while the three compressive strength cylinders were tested at 7, 28, 56, and 91 days, respectively. The values shown in the plots represent the average of 3 specimens tested.

5.2.1 Flexural Strength of Concrete Containing Fly Ash. Results for the 7-day flexural strength of concrete containing fly ash are shown in Figs. 5.1 through 5.4. Provided the water-cementitious (w/cm) ratio was lower than that obtained for ordinary concrete, concrete containing fly ash had a 7-day flexural strength equal to or greater than the flexural strength of ordinary concrete. No noticeable differences were noted in the flexural strength performance of concrete containing Type A fly ash and concrete containing Type B fly ash. The variation in the water-cementitious (w/cm) ratio of concrete containing Type A fly ash and concrete concrete containing Type B fly ash averaged 9% for the 6-sack mixes and 3% for the 7-sack mixes. The higher variation in the water-cementitious (w/cm) ratio of the 6-sack mixes is probably due to their higher water-cementitious (w/cm) ratios as compared to the 7-sack mixes. Compared to ordinary concrete, the water-cementitious (w/cm) ratio of concrete containing fly ash was approximately 5% lower for the 6-sack mixes and approximately 3% lower for the 7-sack mixes. The lower difference in water-cementitious (w/cm) ratios of 7-sack mixes containing fly ash compared to the control mix is also due to the high cementitious content of these mixes.

All the mixes containing fly ash had 7-day flexural strengths higher than the minimum specified for TSDHPT Item 421 Class C concrete. The only mix containing fly ash failing to

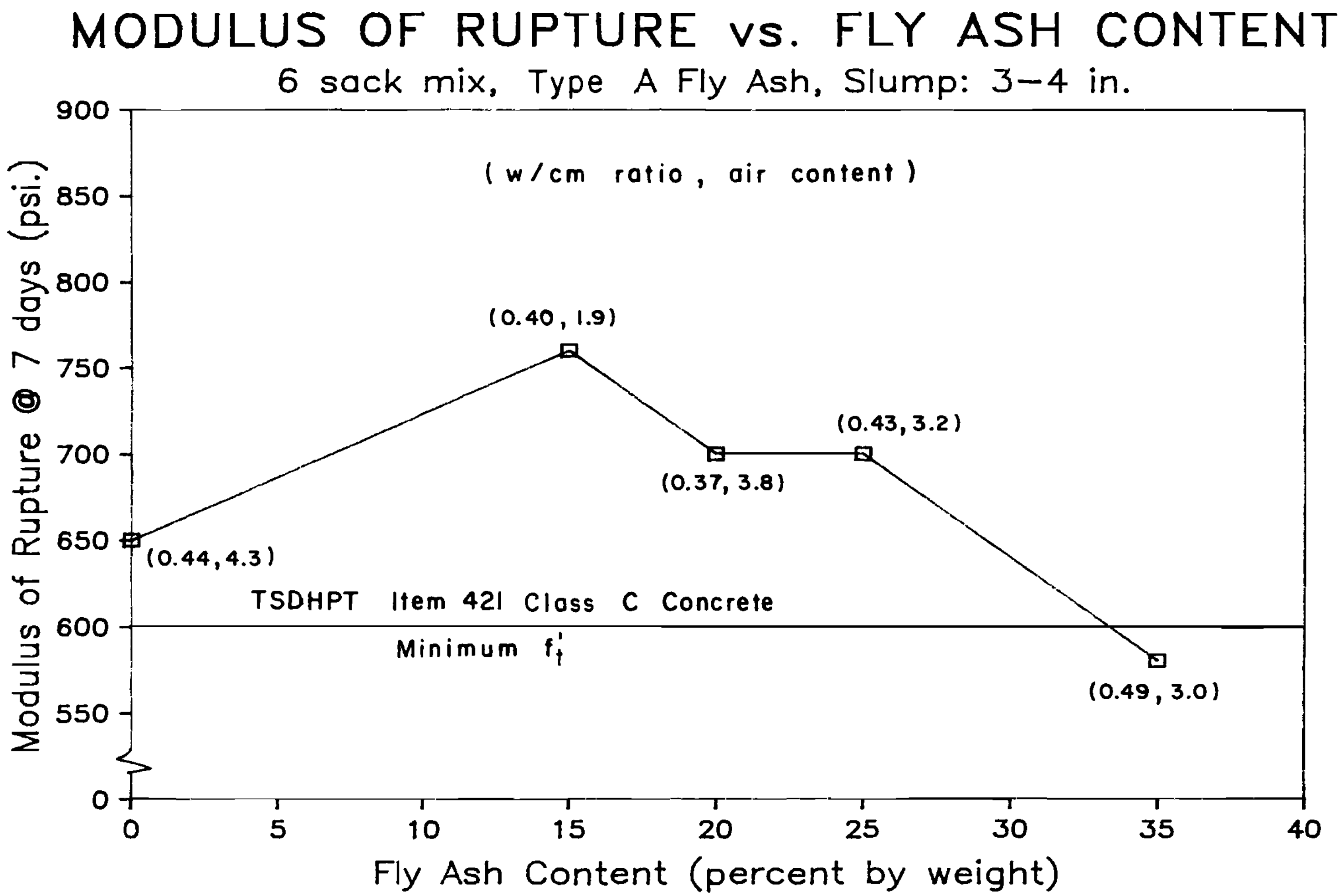

Fig. 5.1 Modulus of rupture versus the Type A fly ash content of six sack mixes.

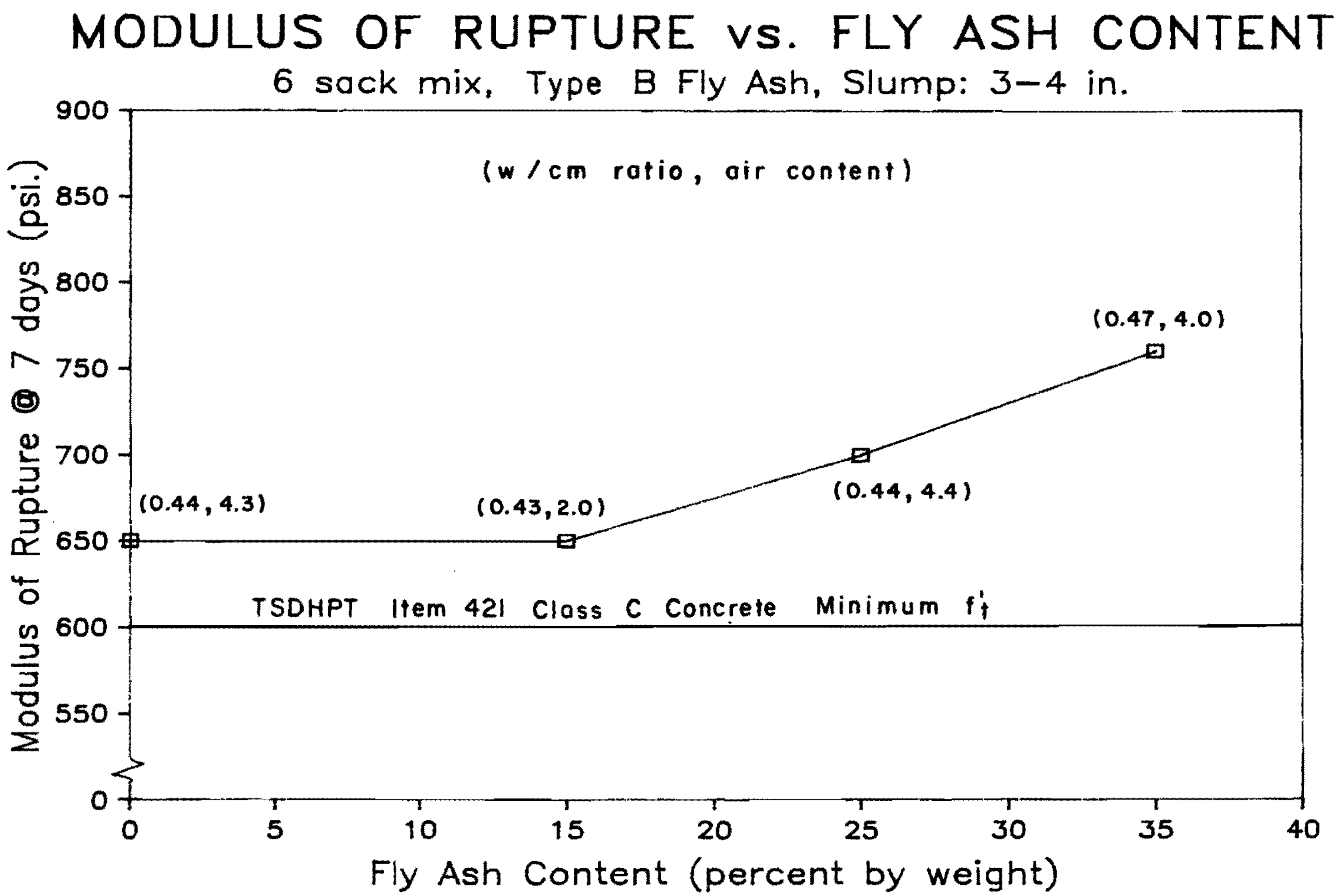

Fig. 5.2 Modulus of rupture versus the Type B fly ash content of six sack mixes.

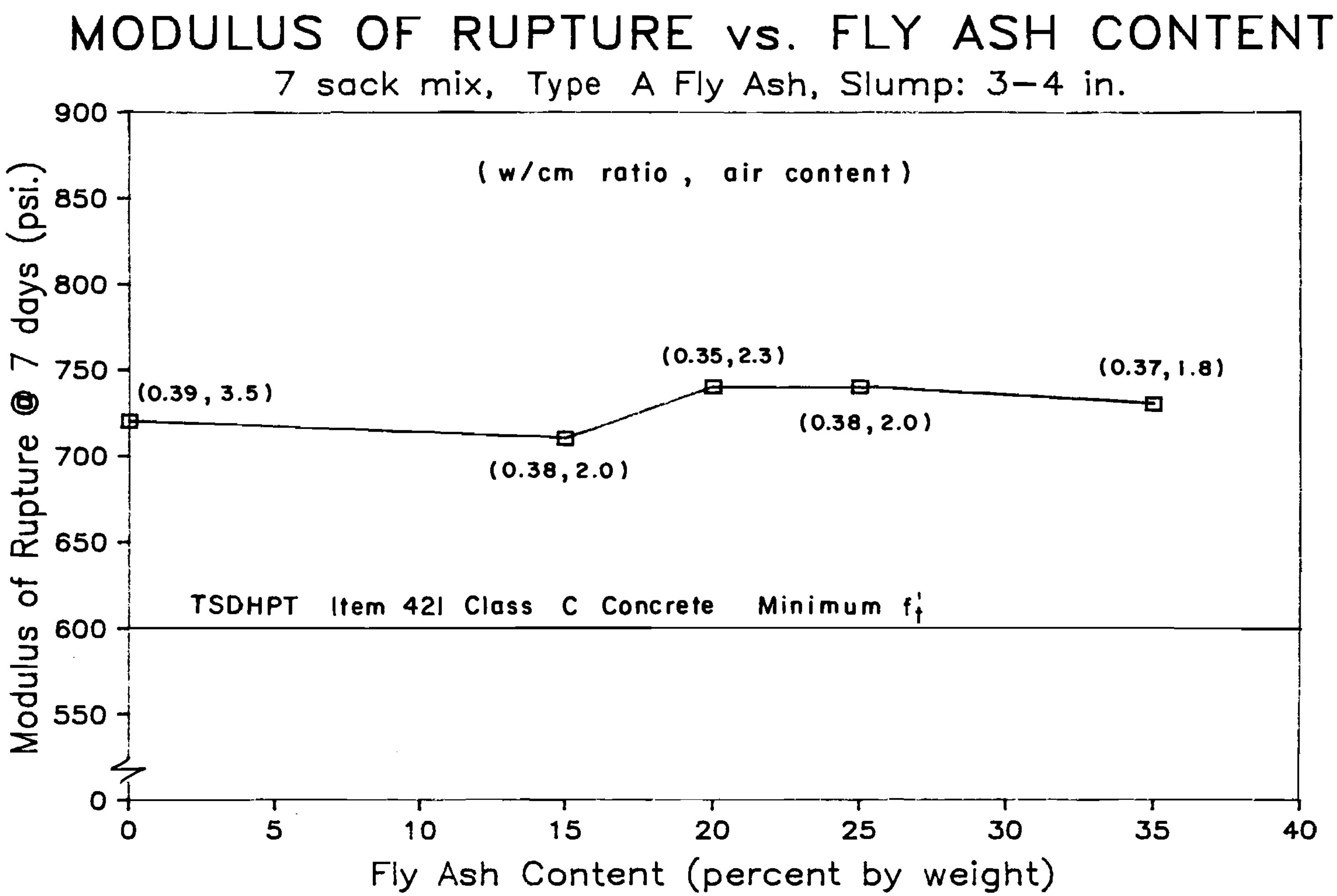

Fig. 5.3 **Modulus of rupture versus the Type A fly ash content of seven sack mixes.**

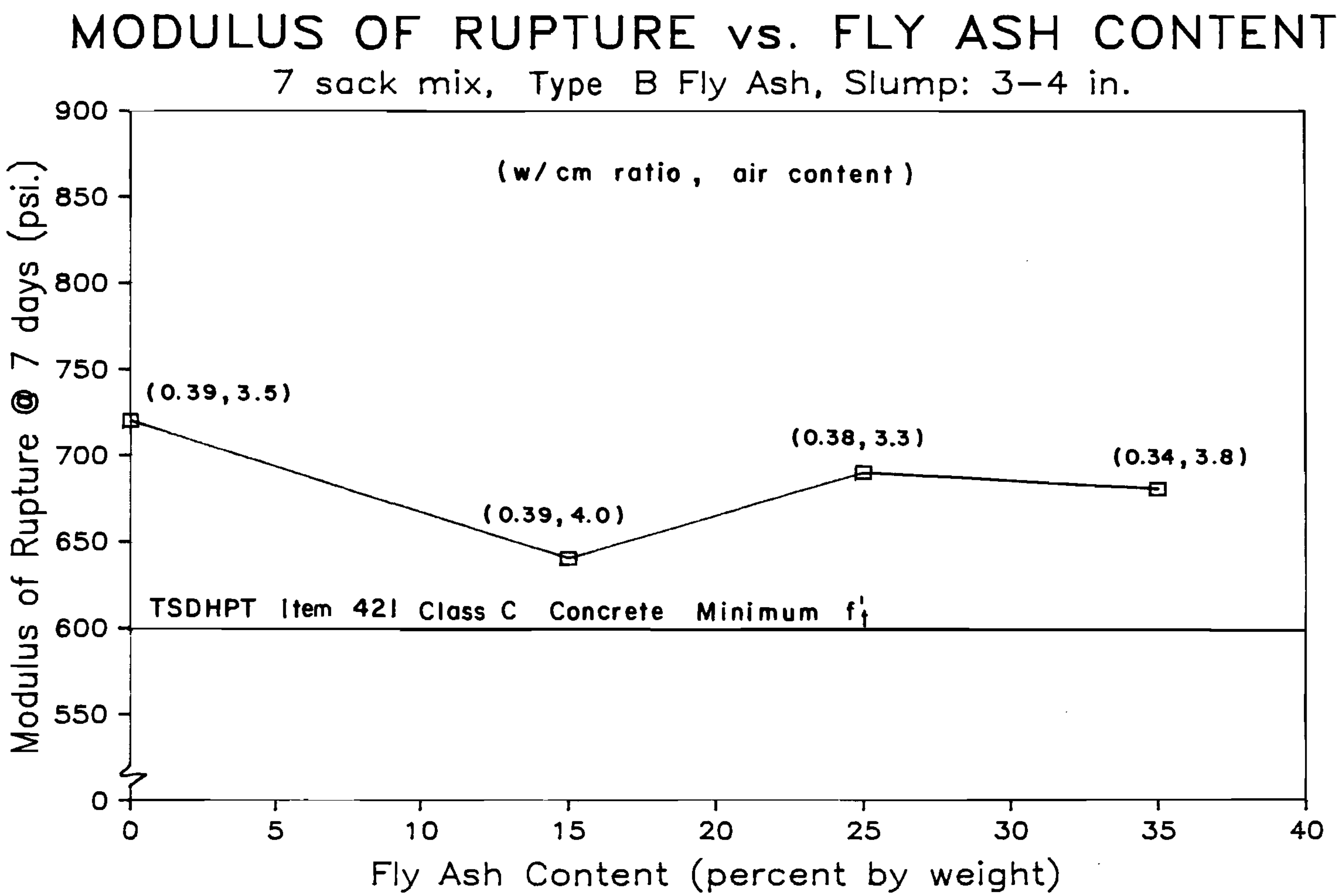

Fig. 5.4 Modulus of rupture versus the Type B fly ash content of seven sack mixes.

meet this requirement was the 6-sack mix containing 35% Type A fly ash. This mix had an unusually high water-cementitious (w/cm) ratio, 11% higher than that of the control mix, which is the cause of its poor performance. The 7-day flexural strength of concrete containing fly ash varied from 650 to 760 psi for concrete having both cementitious contents.

5.2.2 Compressive Strength of Concrete Containing Fly Ash. The results of the compressive strength with age for concrete containing fly ash are presented in Figs. 5.5 through 5.8. As can be noted from Figs. 5.5 and 5.7, concrete containing Type A fly ash had compressive strengths that were approximately equal to or higher than the compressive strength of the control mix at 56 days and beyond. At 28 days the compressive strength of concrete having a Type A fly ash content of 25% or higher was approximately 10% below that of the control mix. Concrete containing Type B fly ash, in general, had compressive strengths lower than the control mix even after 91 days. The most noticeable difference in the compressive strength of concrete containing Type B fly ash and ordinary concrete can be noted from Fig. 5.6, which shows the compressive strength of 6-sack mixes containing Type B fly ash. The decreased compressive strength of the concrete mixes shown in this figure compared to those shown in Fig. 5.8 can be attributed mainly to the variation in the water-cementitious (w/cm) ratio. The 7-sack mixes had water-cementitious (w/cm) ratios equal to or less than that of the control mix. For the 6-sack mixes shown in Fig. 5.6 the water-cementitious (w/cm) ratio was higher for mixes containing fly ash than that of the control mix.

The improved performance of concrete containing Type A fly ash over that of concrete containing Type B fly ash can be attributed mainly to the lower air contents of concrete containing Type A fly ash. The air content of concrete containing Type A fly ash ranged from 1.8 to 4.3%, the average being 3.0%, and for concrete containing Type B fly ash the range was from from 2.0 to 4.4%, the average being 3.7%. Increasing the air content of a concrete mix results in a decrease in the compressive strength; therefore, higher compressive strengths were obtained by concrete containing Type A fly ash. Another factor affecting the performance of the concrete was the water-cementitious (w/cm) ratio. Concrete containing Type A fly ash, in general, had lower water-cementitious (w/cm) ratios than concrete containing Type B fly ash.

5.2.3 Discussion of Test Results. The use of fly ash for the production of TSDHPT Item 421 Class C concrete produced

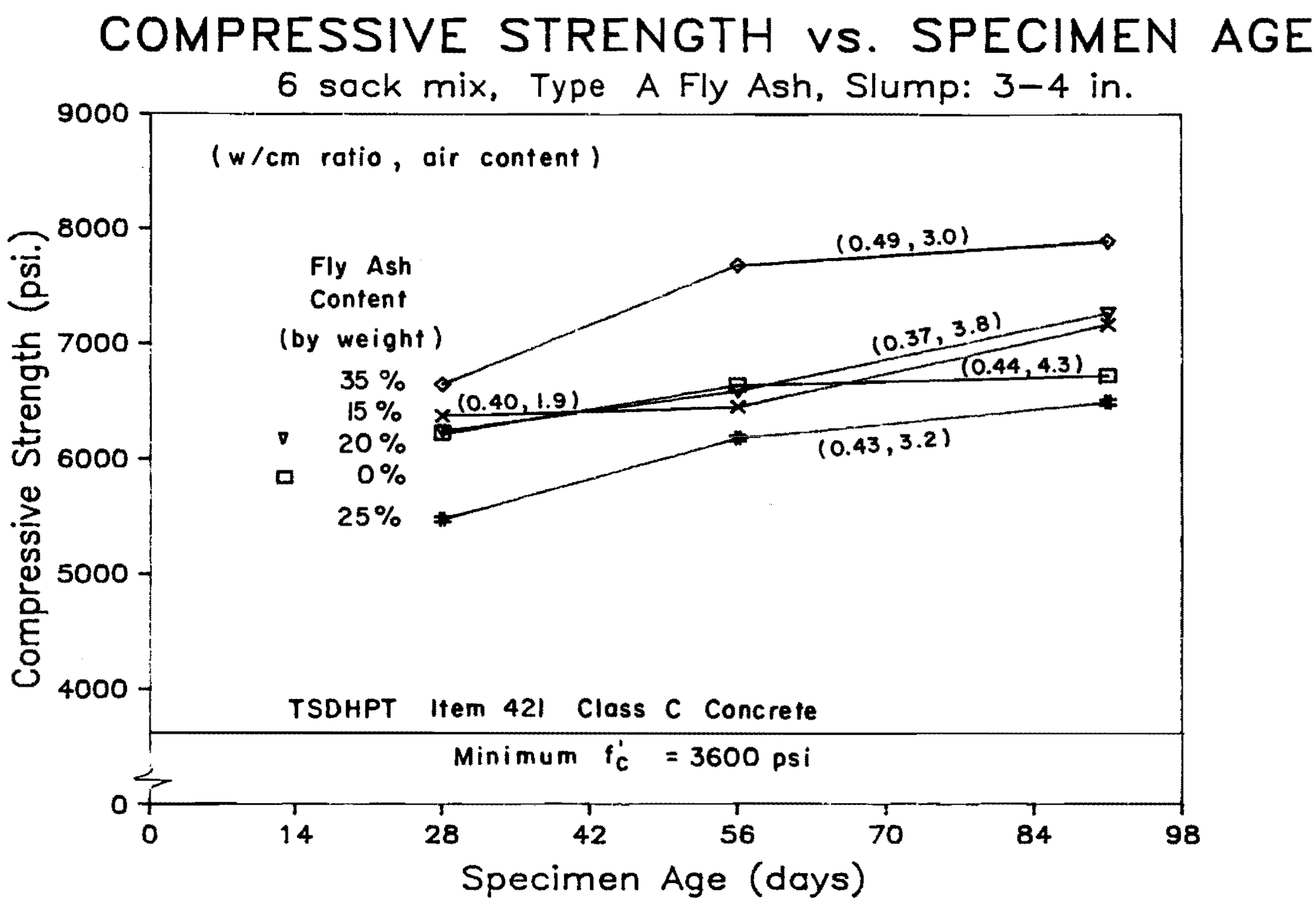

Fig. 5.5 Compressive strength versus age, six sack mixes, Type A fly ash.

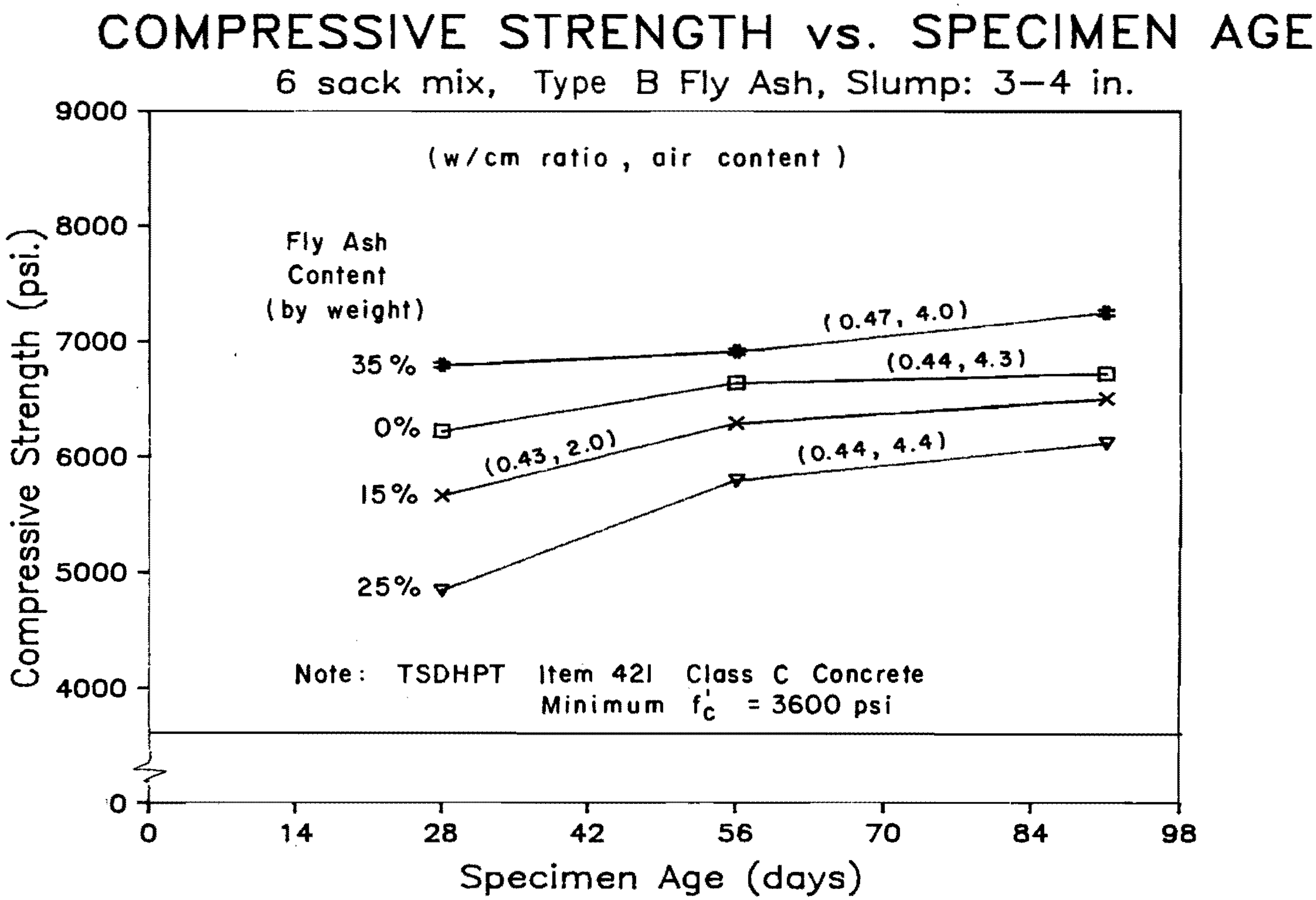

Fig. 5.6 Compressive strength versus age, six sack mixes, Type B fly ash.

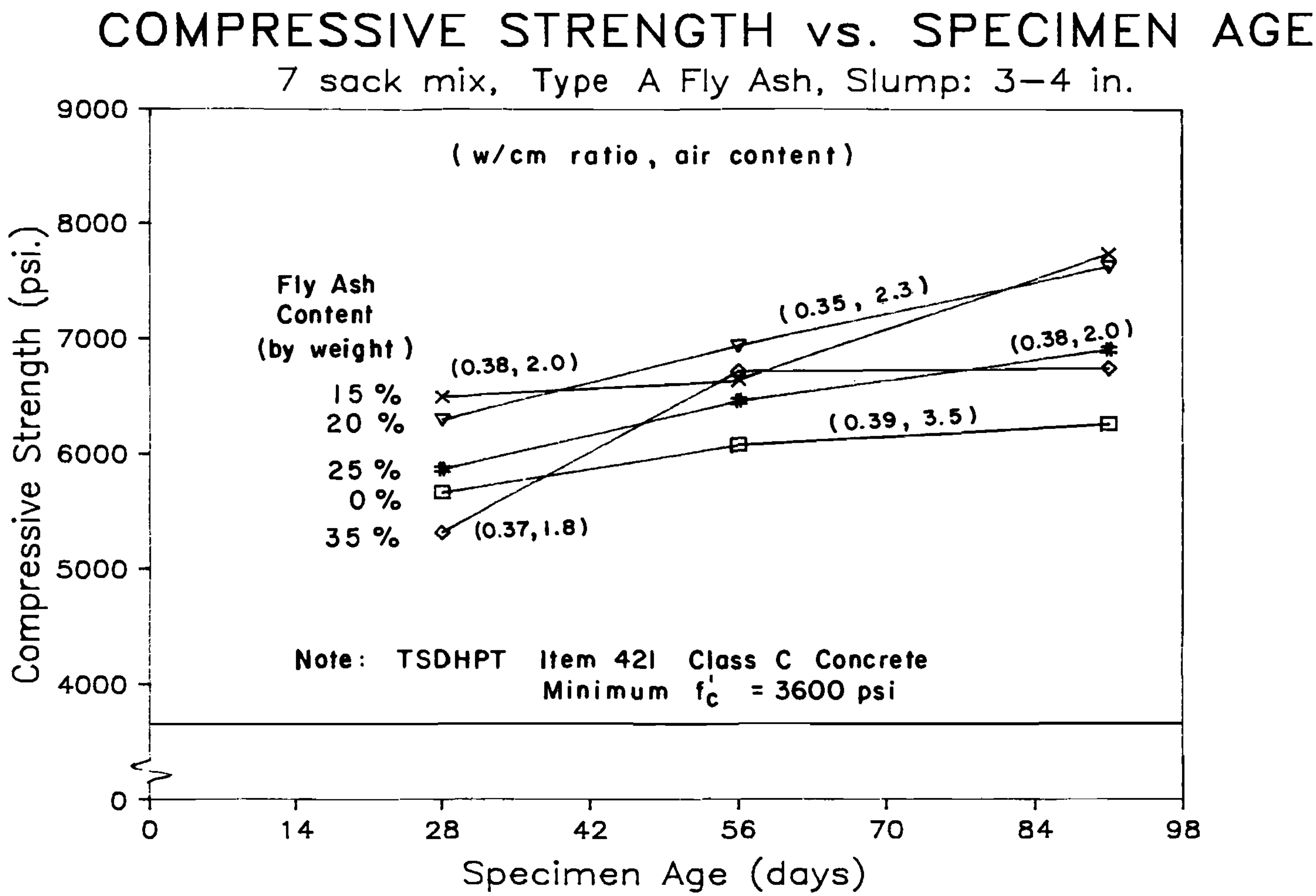

Fig. 5.7 Compressive strength versus age, seven sack mixes, Type A fly ash.

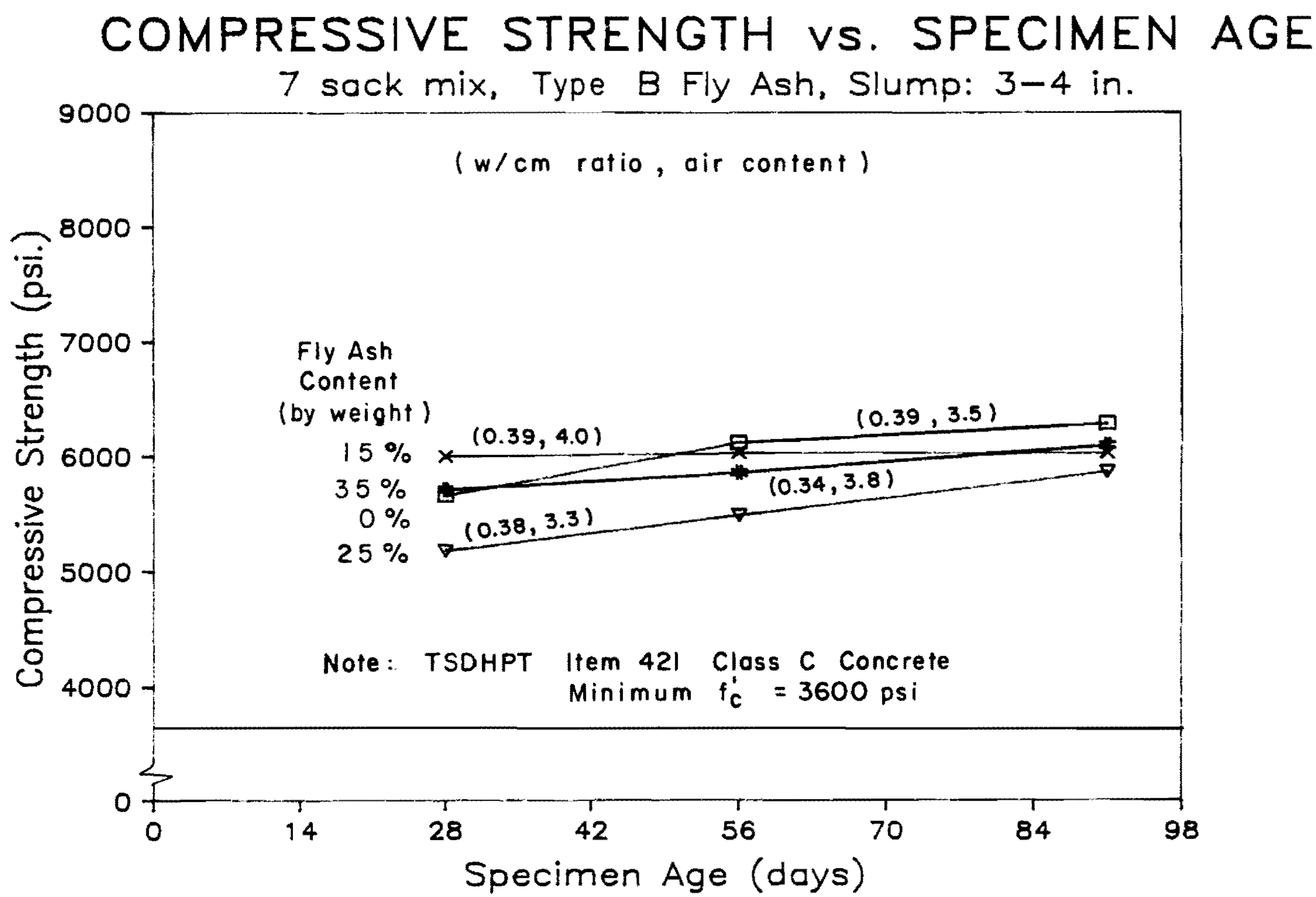

Fig. 5.8 Compressive strength versus age, seven sack mixes, Type B fly ash.

concrete satisfying the minimum requirements specified for the above mentioned concrete specification. Both types of fly ash used in this study satisfied the requirements of the TSDHPT Departmental Materials Specification D-9-8900, "Fly Ash". The fly ash content of concrete mixes made in this study ranged from 15% to 35% by weight of portland cement. Concrete produced using a Type IP blended cement containing 20% Type A fly ash by weight was also studied for comparison with ordinary concrete. For trial mix design programs in the State of Texas, the replacement of cement with fly ash should range from 20% to 35% by weight. If a Type IP cement containing fly ash as a partial replacement of cement is readily available and of delivered cost less than or equal to the delivered cost of the Type I cement it should also be included in the trial mix design program to ensure the most economical and durable concrete is obtained. If possible, both Type A and Type B fly ash should be evaluated in the trial mix design program.

For both cementitious contents studied the 7-day flexural strength of concrete containing Type A fly ash ranged from 0 to 11% higher than the 7-day flexural strength of concrete containing Type B fly ash. This was due in general to the lower water-cementitious (w/cm) ratio of concrete containing Type A fly ash as compared to concrete containing Type B fly ash. The decrease in the water-cementitious (w/cm) ratio of concrete containing Type A fly ash ranged from 0 to 7% below that of concrete containing Type B fly ash. The difference in the water-cementitious (w/cm) ratio of concrete containing Type A fly ash and concrete containing Type B fly ash is due to differences in their chemical composition. Type B fly ash is of a higher calcium content than Type A fly ash. The Type B fly ash used in this study had a calcium oxide content of 38% and the Type A fly ash used in this study had a calcium oxide content of 10%. The higher calcium content of Type B fly ash allows for a more rapid cementitious reaction to occur due to the liberation of calcium hydroxide during its hydration. This results in a higher content of hydration products in concrete containing Type B fly ash than in concrete containing Type A fly ash. Therefore, to obtain equal workability, concrete containing Type B fly ash requires higher amounts of water than concrete containing Type A fly ash. This is also due to the immediate hydration of Type B fly ash in concrete compared to Type A fly ash.

The 6-sack mixes containing fly ash had 7-day flexural strengths equal to or greater than that obtained for the 6-sack control mix, except for the mix having a Type A fly ash content of 35%. The highest 7-day flexural strength of a 6-sack mix containing fly ash was 18% greater than the 7-day flexural strength of the 6-sack control mix. The lower water-cementitious (w/cm) ratios obtained for concrete containing fly ash as compared to the control mix is due to the physical properties of the fly ash. The spherical shape of the fly ash particles and the lower specific gravity of fly ash combine to improve the workability of concrete containing fly ash over that of ordinary concrete. Replacement of cement with fly ash on an equal weight basis, as done in this study, results in concrete having an increase in the paste volume, due to the lower specific gravity of fly ash. The specific gravity of the fly ash used in this study ranged from 2.46 for Type A fly ash to 2.72 for Type B fly ash, compared to the specific gravity of cement, 3.15. The increased paste volume of concrete containing fly ash over the paste volume of ordinary concrete results in improved workability, which allows for reductions in the water-cementitious (w/cm) ratio of concrete containing fly ash compared to ordinary concrete.

For both cementitious contents studied, concrete containing Type A fly ash had 28-day compressive strengths 9 to 13% higher than the 28-day compressive strength of concrete containing Type B fly ash. The 7-sack mix containing Type B fly ash had higher 28-day compressive strengths compared to the 6-sack mixes containing Type B fly ash except for the 6- and 7-sack mixes containing 35% Type B fly ash. The lower 7-day flexural strength of the 7-sack mixes containing Type B fly ash compared to 6-sack mixes containing Type B fly ash was due to the use of the ASTM C494 Type D water reducing-retarder admixture used in the 7-sack mixes. The dosage rate specified in the trial mix design specified by the TSDHPT for use in this study was 33 oz/cu.yd. The decrease in the water requirement of the 7-sack mixes compared to the 6-sack mixes allowed for a higher concentration of the water reducing-retarder admixture in the concrete. This caused delayed setting of 7-sack mixes containing Type B fly ash.

In some instances the specimens of 7-sack mixes containing fly ash had to have an additional 24 hours curing time before being demolded. This problem was overcome by mixing all the materials until the desired amount of workability was obtained in our case a a slump in the range of 3 to 4 in. Once the required slump was obtained the mix was allowed to sit for 5 minutes. After waiting 5 minutes the batch was mixed for 2 additional minutes at which time the slump was checked again to ensure the mix had the proper degree of workability. At this point the water content of the mixes had to be increased by approximately 1% to restore the workability to the desired range.

Compressive strength development characteristics of concrete containing fly ash were comparable to those of ordinary concrete. Concrete containing fly ash averaged a compressive strength increase of 10% compared to an average compressive strength increase of 8% for the control mixes from 28 to 56 days. From 56 to 91 days the average compressive strength increase of concrete containing fly ash was 6% compared to a 2% increase in the compressive strength of the control mixes.

For trial mix design purposes it is recommended that the 7-day modulus of rupture be used as the acceptance criteria of the concrete strength. A comparison of Figs. 6.1 and 6.5 shows that the 7-day flexural strength of concrete containing fly ash is more critical than the 28-day compressive strength of the same concrete in meeting the TSDHPT Item 421 Class C concrete specifications.

5.3 Durability of Concrete Containing Fly Ash Subjected to Freeze-Thaw Cycles

The results of the freeze-thaw durability test performed on concrete containing fly ash are presented and discussed in this section. Along with the 3 flexure beams and 12 cylinders used to perform the tests discussed in the previous section, two 3 x 4 x 16 in. freeze-thaw beam specimens were cast for the 16 mixes studied. These were used to perform the freeze-thaw durability test according to TSDHPT Testing Procedure Tex. 423-A, "Resistance of Concrete to Rapid Freezing and Thawing." For concrete freeze-thaw durability comparisons all the mixes done in this study had an equal dose of air-entraining admixture. The type and brand of the air-entraining admixture used was the same throughout this study. This study was done to investigate the effect the use of fly ash had on the freeze-thaw durability of concrete. In this section the variability of the air content with fly ash content is discussed as is the durability of concrete containing fly ash.

5.3.1 Air Content of Concrete Containing Fly Ash. The air contents of all the mixes studied in this project are plotted versus concrete fly ash content on Figs. 5.9 through 5.12. For a constant fly ash content, concrete containing Type A fly ash had a lower air content than concrete containing Type B fly ash. The air content of concrete containing Type A fly ash ranged from 1.2

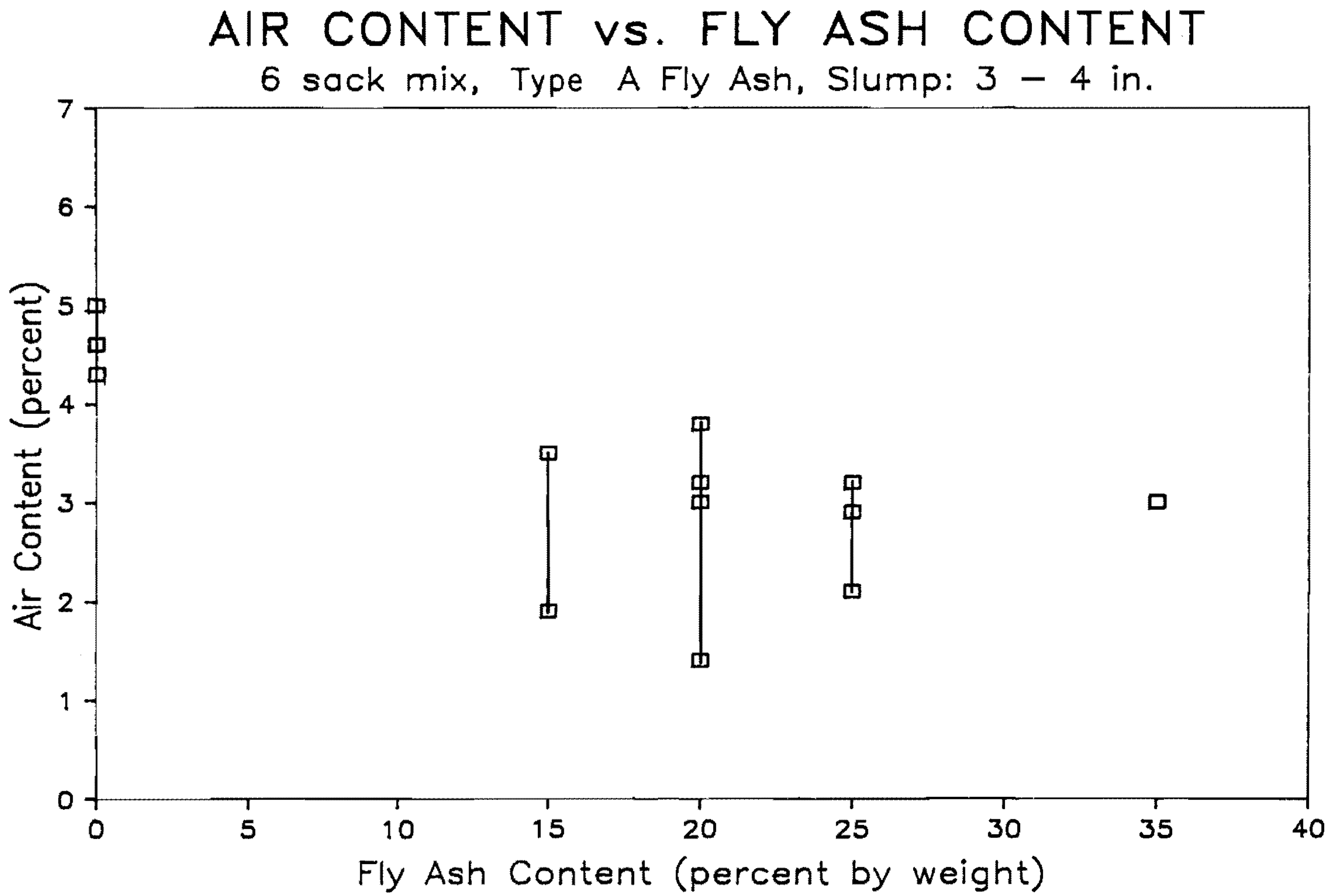

Fig. 5.9 Air content versus Type A fly ash content, six sack mixes.

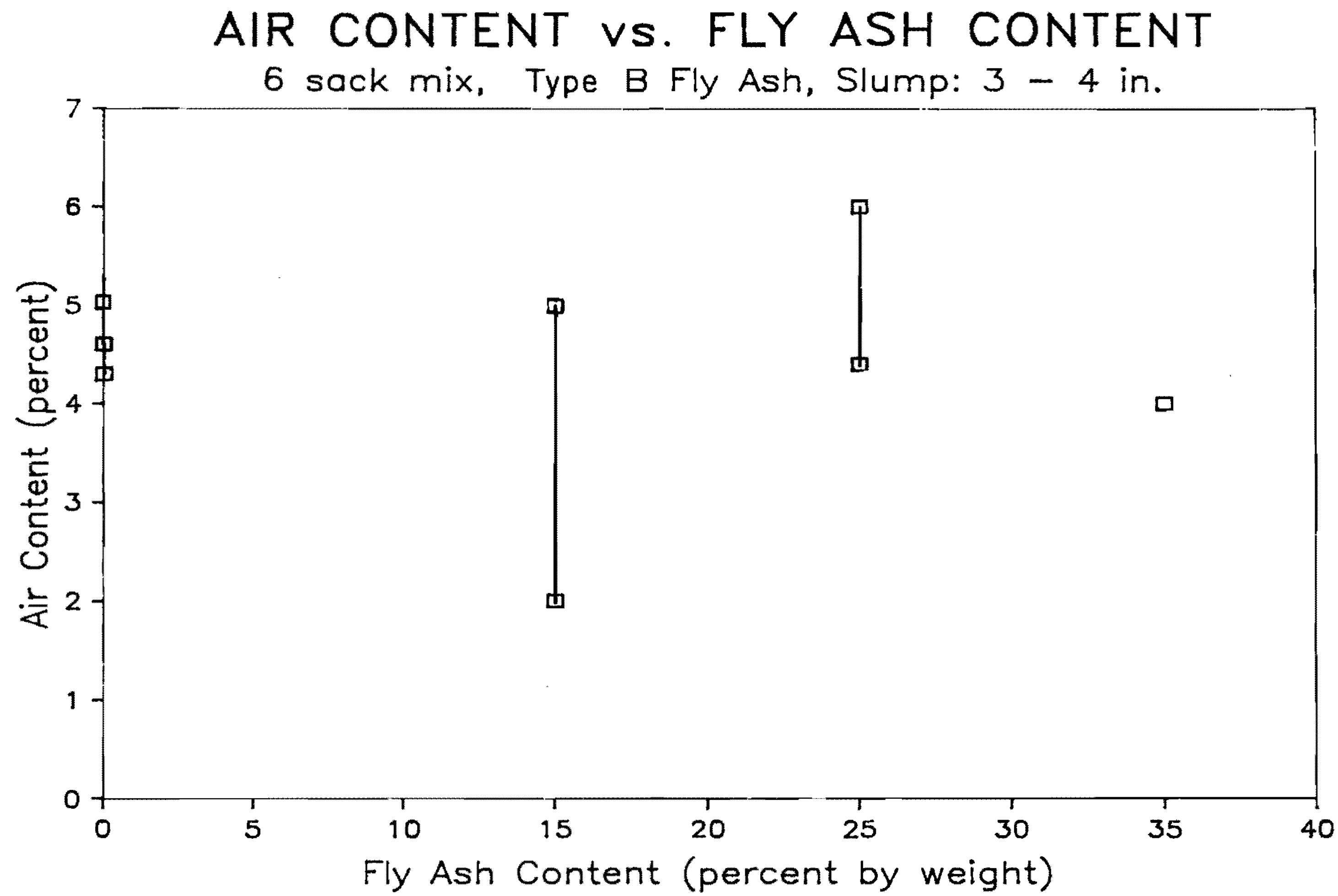

Fig. 5.10 Air content versus Type B fly ash content, six sack mixes.

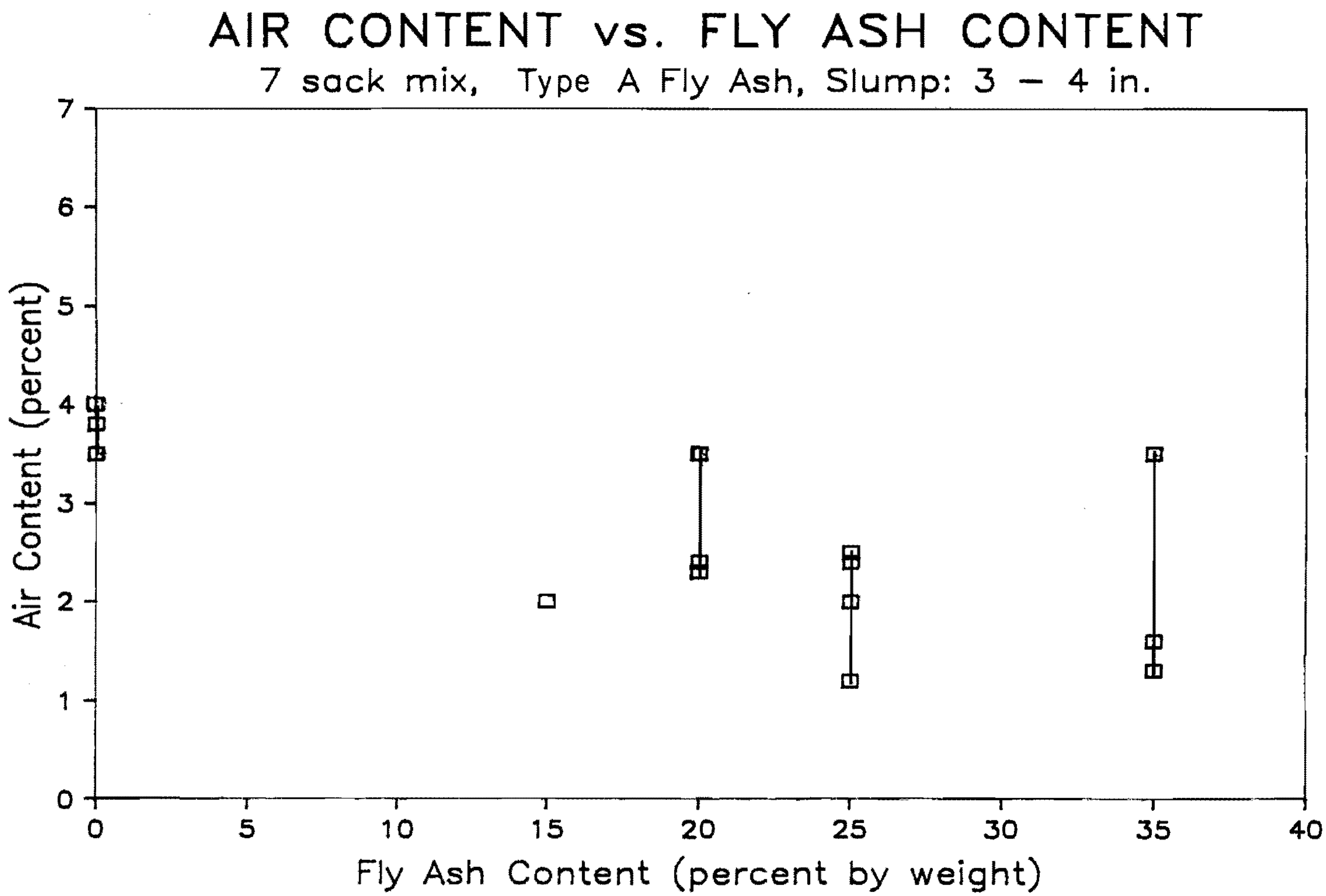

Fig. 5.11 Air content versus Type A fly ash content, seven sack mixes.

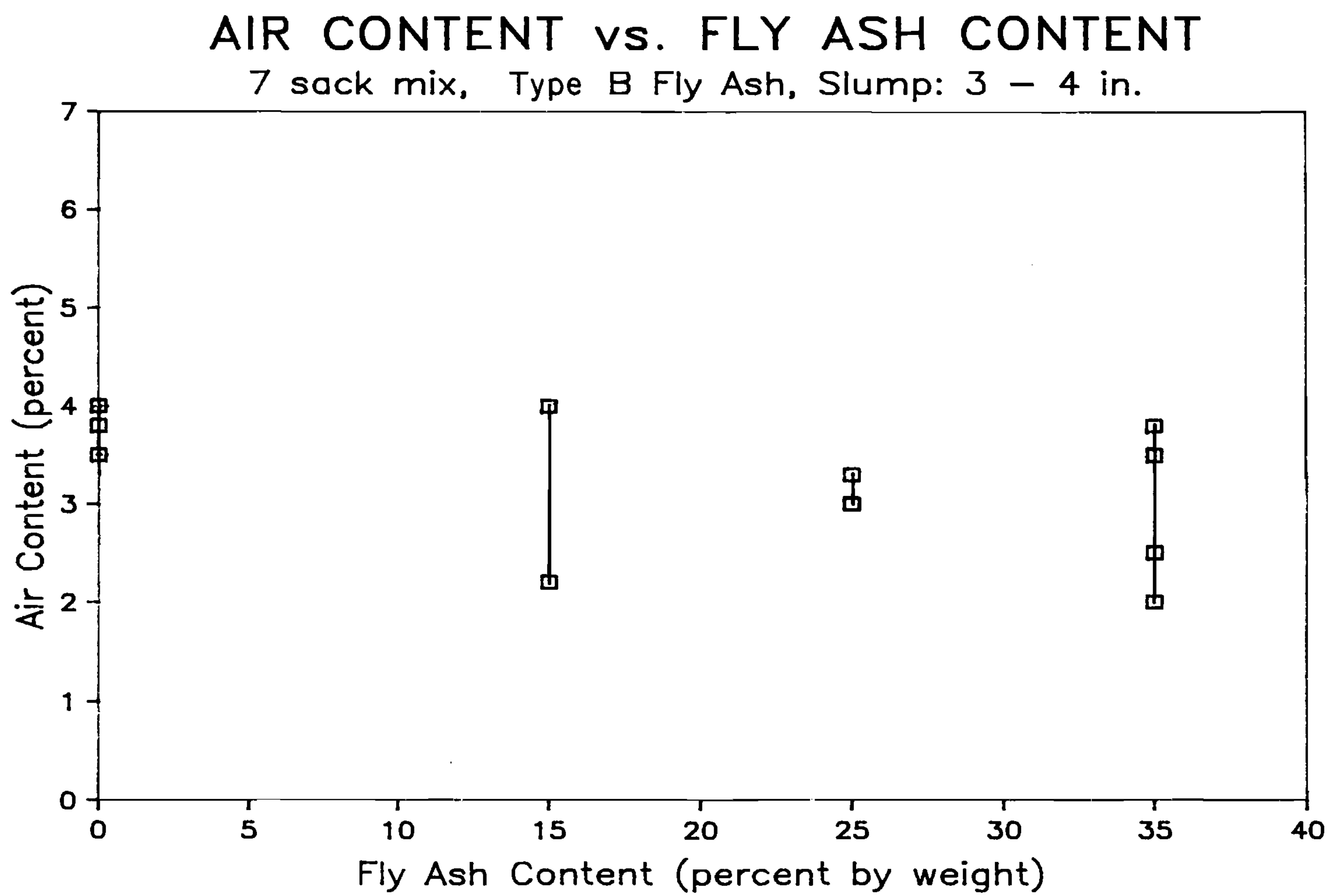

Fig. 5.12 Air content versus Type B fly ash content, seven sack mixes.

to 4% compared to a range of 2 to 6% for concrete containing Type B fly ash. Concrete containing Class A showed a trend toward a decreased air content with an increase in the fly ash content. This was not obvious in concrete containing Type B fly ash.

Compared to the control mixes, concrete containing fly ash had lower air contents. Concrete containing Type A fly ash averaged air contents 34% lower than the control mix, while concrete containing Type B fly ash averaged air contents 14% lower than the control mix.

5.3.2 Deterioration Rate of Concrete Containing Fly Ash Subjected to Freeze-Thaw Cycles. To obtain an indication of the deterioration rate of concrete containing fly ash subjected to freeze-thaw cycles, the variation of the dynamic modulus with an increase in the number of freeze-thaw cycles is plotted in Figs. 5.13 through 5.16. It is obvious from these figures the improved resistance of concrete containing Type B fly ash, compared to concrete containing Type A fly ash, to freeze-thaw cycles. The dynamic modulus of concrete containing fly ash was generally less than that of the control mix after an equal number of cycles, but for concrete containing Type B fly ash this difference was generally not higher than 10%. For concrete containing Type A fly ash differences as high as 45% were obtained. From these figures it can be noted that concrete mixes containing fly ash having a variation in the dynamic modulus not higher than 10% of the control mix generally had air contents of 3% or higher.

5.3.3 Durability. Texas State Department of Highways and Public Transportation Testing Procedure Tex. 423-A, "Resistance of Concrete to Rapid Freezing and Thawing," states that "the point of failure of concrete specimens subjected to this test shall be P_c of 60% or 300 cycles, whichever is least". P_c is the relative dynamic modulus of elasticity after c cycles of freezing and thawing, calculated using the following equation:

$$P_c = n_c^2/n^2 \times 100\% \tag{5.1}$$

where:

n_c = Fundamental transverse frequency of resonance after c cycles of freezing and thawing.

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

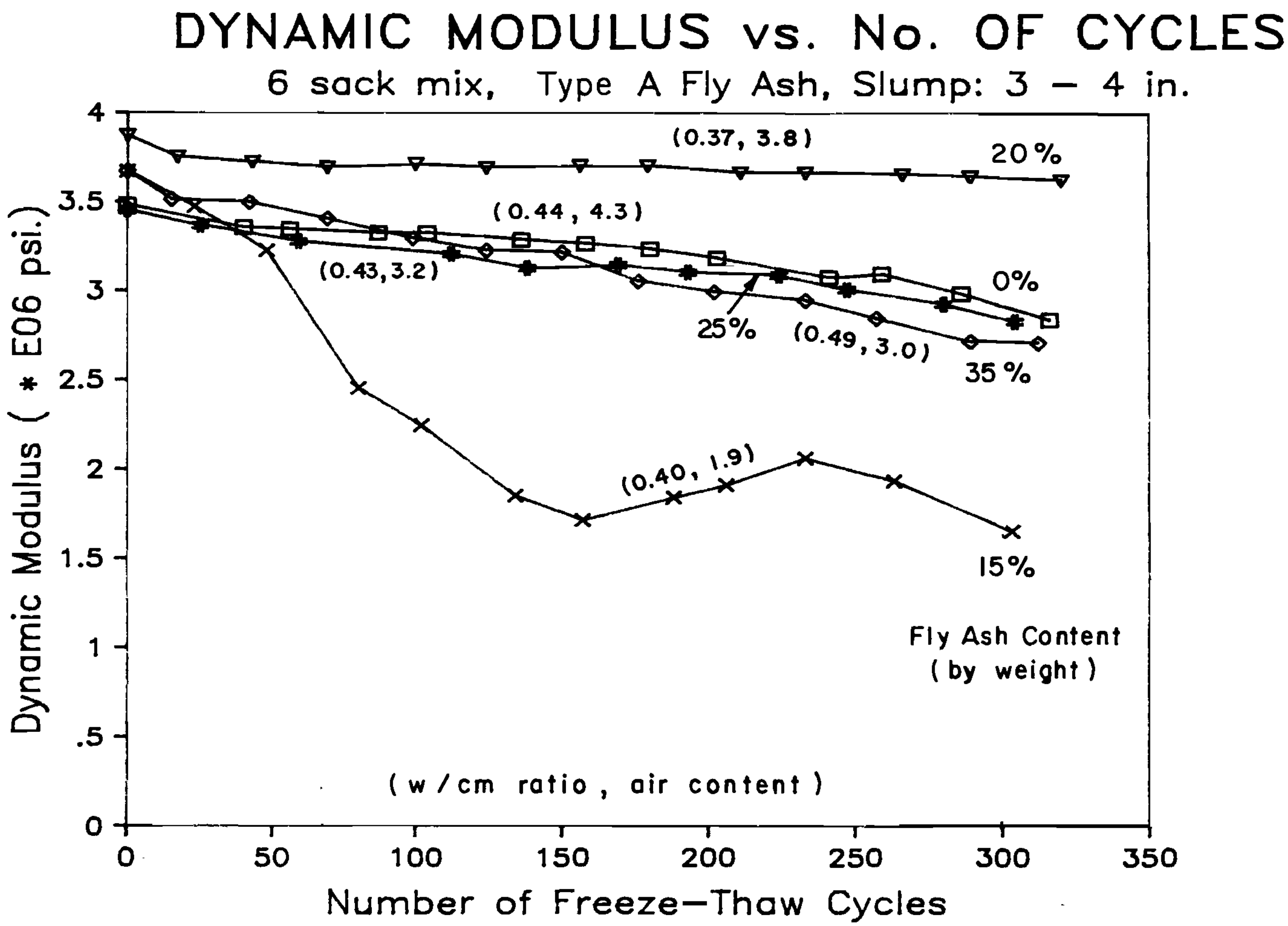

Fig. 5.13 Dynamic modulus versus number of freeze-thaw cycles, six sack mixes, Type A fly ash.

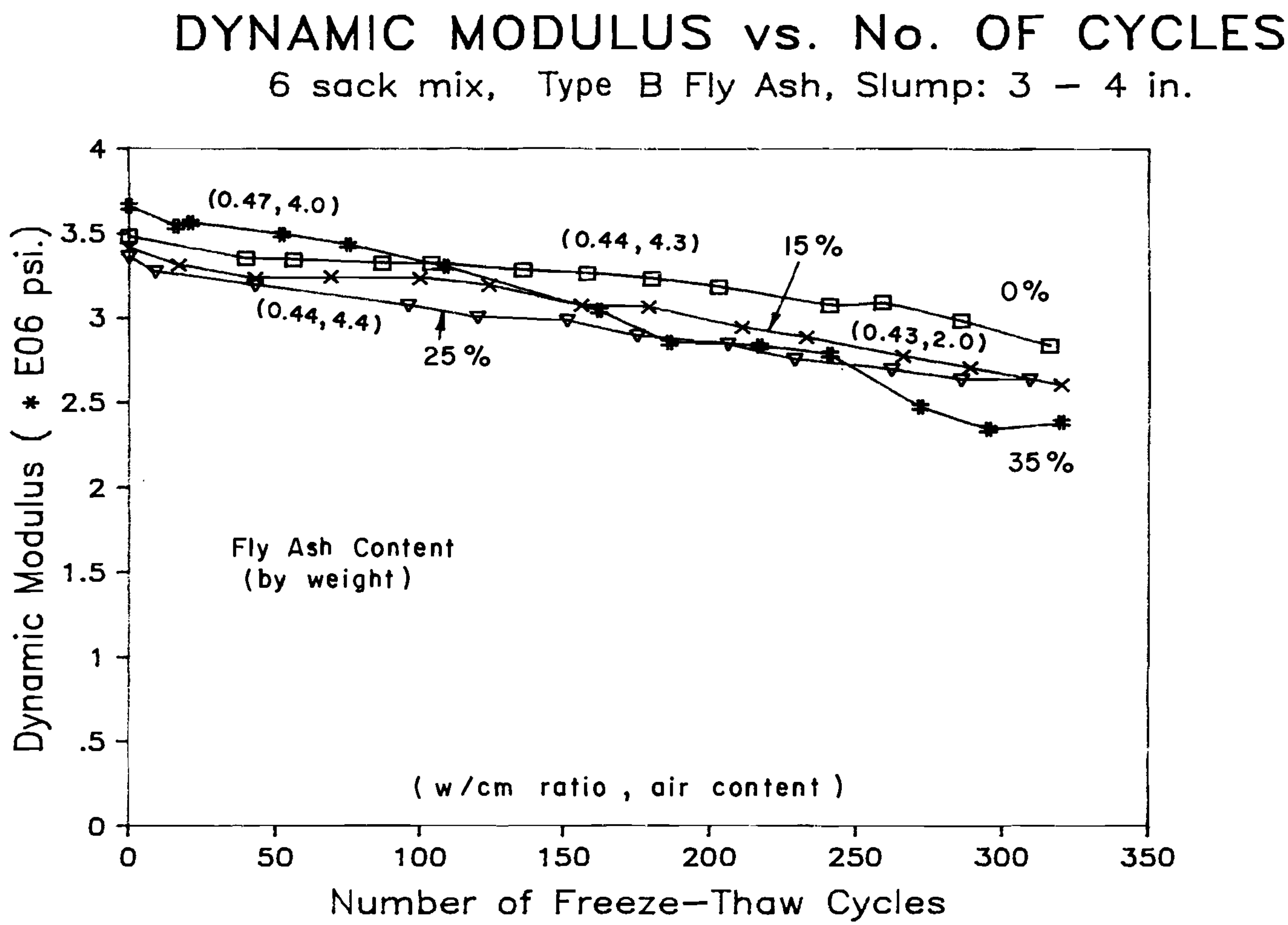

Fig. 5.14 Dynamic modulus versus number of freeze-thaw cycles, six sack mixes, Type B fly ash.

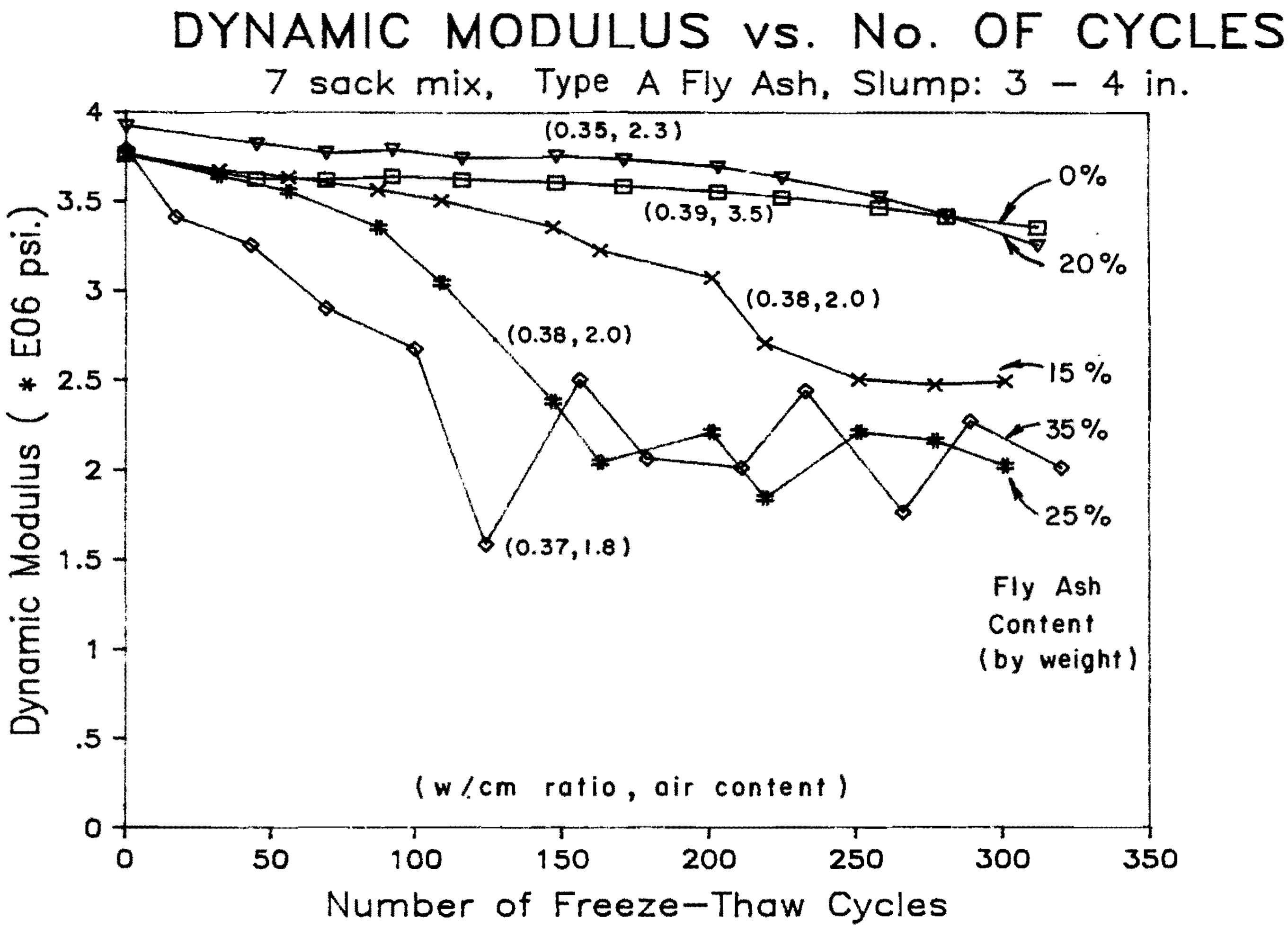

Fig. 5.15 **Dynamic modulus versus number of freeze-thaw cycles, seven sack mixes, Type A fly ash.**

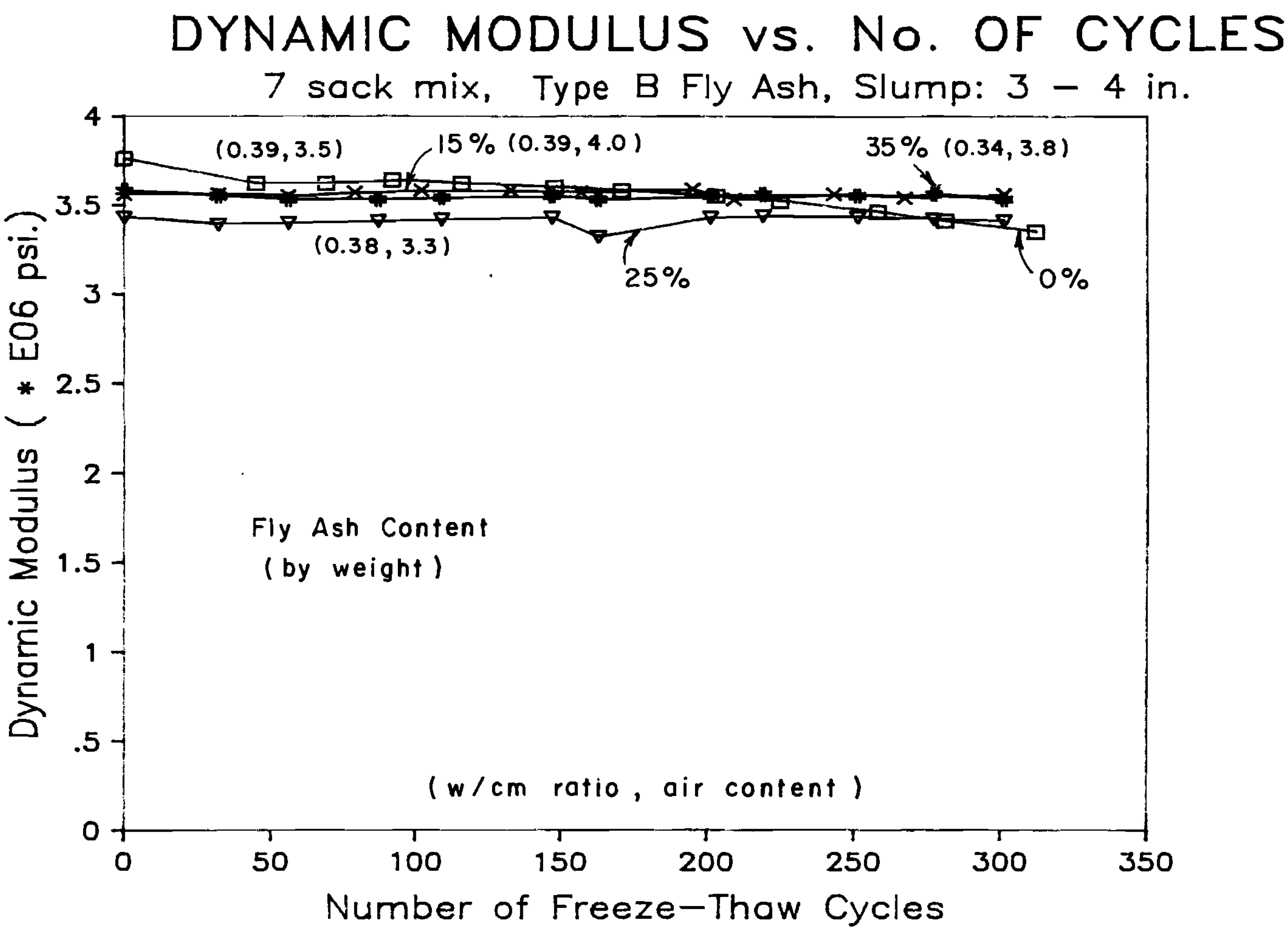

Fig. 5.16 **Dynamic modulus versus number of freeze-thaw cycles, seven sack mixes,** Type **B fly ash.**

Concrete specimens are considered to have adequate freeze-thaw resistance if the Durability Factor (DF) of the test specimen is 60% or greater where DF is calculated using the following equation:

$$DF = NP_c/M \tag{5.2}$$

where:

P_c = as calculated using Eq. 5.1

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

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

Figures 5.17 through 5.20 contain plots of the Durability Factor (DF) versus Fly Ash content for the mixes performed in this study. From these figures it can be noted that an increase in the Type A fly ash content of concrete results in a decrease in the air content. Also, for concrete containing Type A fly ash an increase in the cementitious content from 564 lbs/cu.yd. to 658 lbs/cu.yd. resulted in a decrease in the durability factor (DF). In this study the only mixes to fail Tex. 423-A were those containing Type A fly ash with air contents less than 3%. There was one case shown in Fig. 5.18 and two cases shown in Fig. 5.19 in which the concrete tested had air contents less than 3% but still had a durability factor higher than 60%. If Figs. 5.14 and 5.15 are compared it will be noted that these mixes had water-cementitious (w/cm) ratios as much as 10% below that of the control mix. The increased strength of these mixes compared to the other mixes probably resulted in the good performance observed. Concrete containing Type B fly ash performed satisfactorily regardless of the fly ash content used.

Pictures taken of the various specimens, after the freeze-thaw tests were completed, are shown in Figs. 5.21 through 5.28. The first number in the identification card indicates the cementitious content. The letter represents the class of fly ash used in the mix. F-Type A, C-Type B. The last two numbers specify the fly ash content in percent. Concrete containing Type

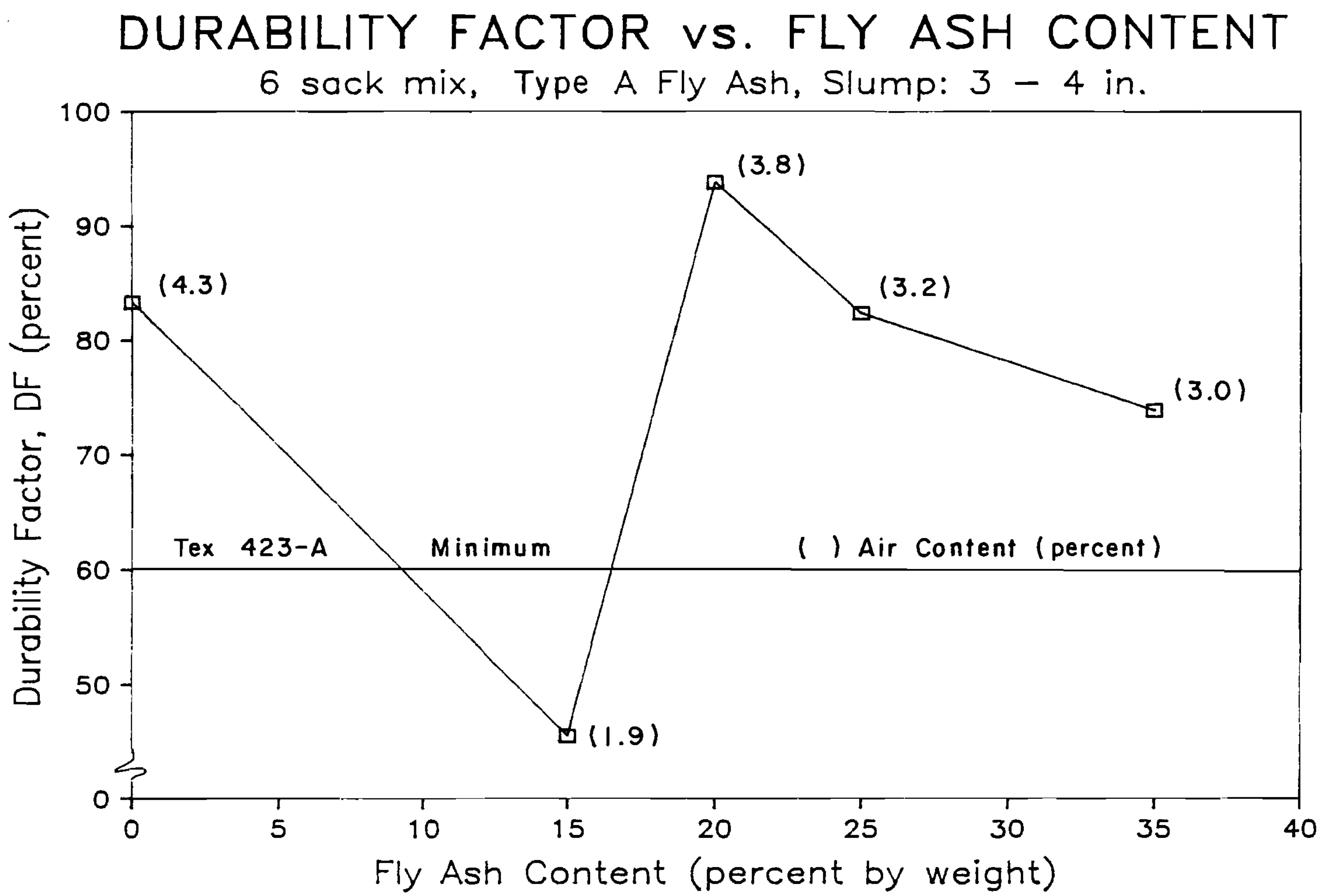

Fig. 5.17 Durability factor (DF) versus Type A fly ash content, six sack mixes.

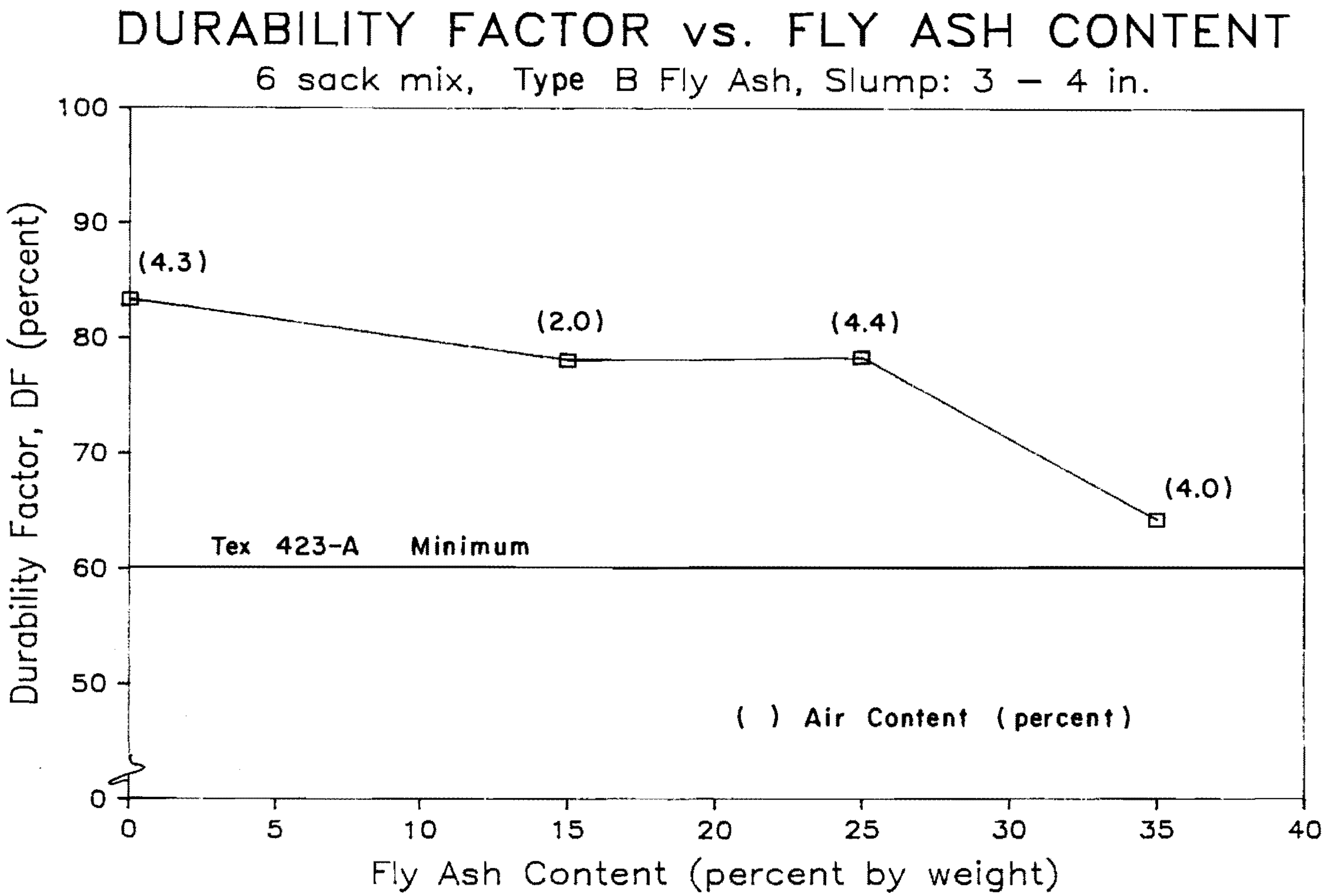

Fig. 5.18 Durability factor (DF) versus Type B fly ash content, six sack mixes.

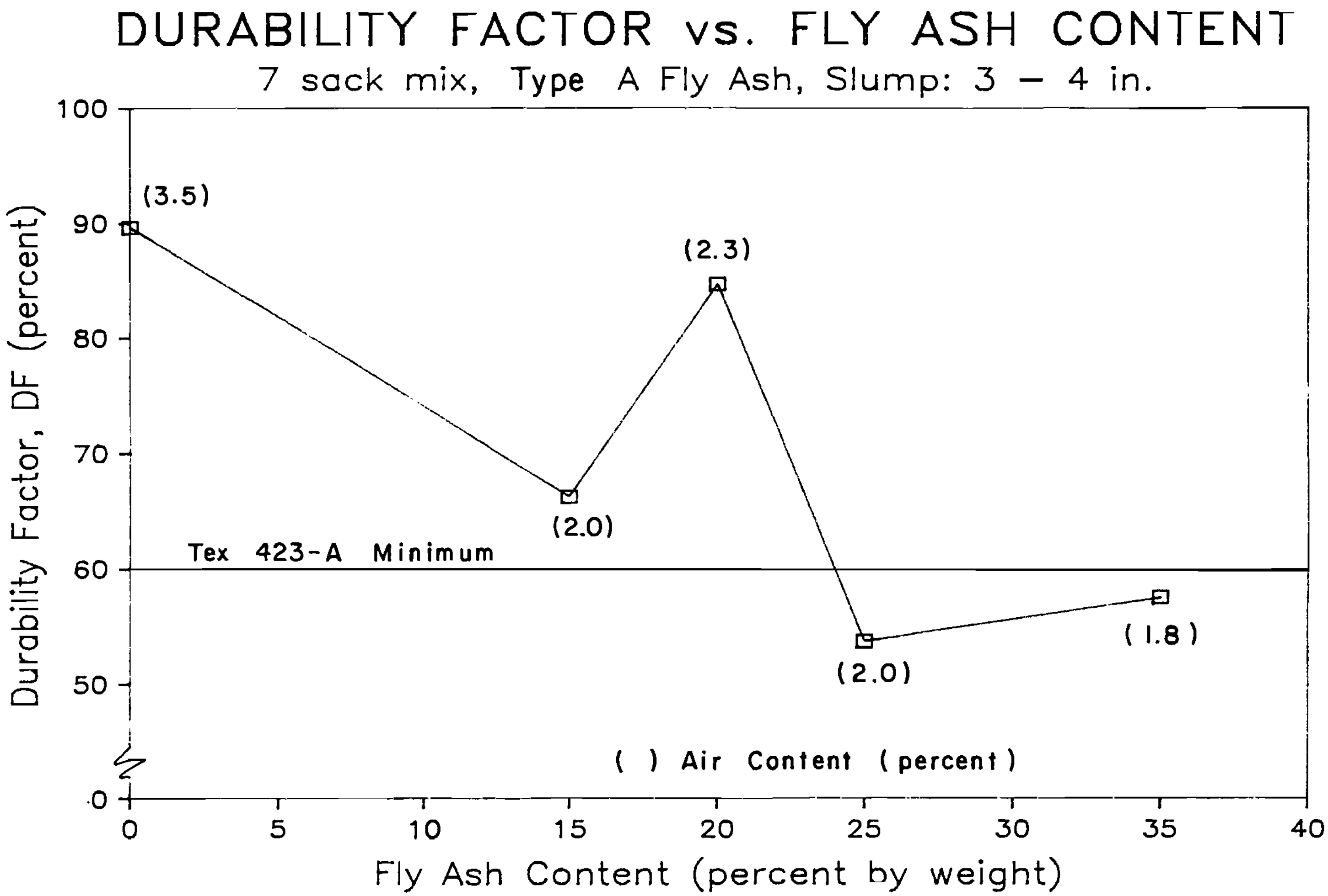

Fig. 5.19 Durability factor (DF) versus Type A fly ash content, seven sack mixes.

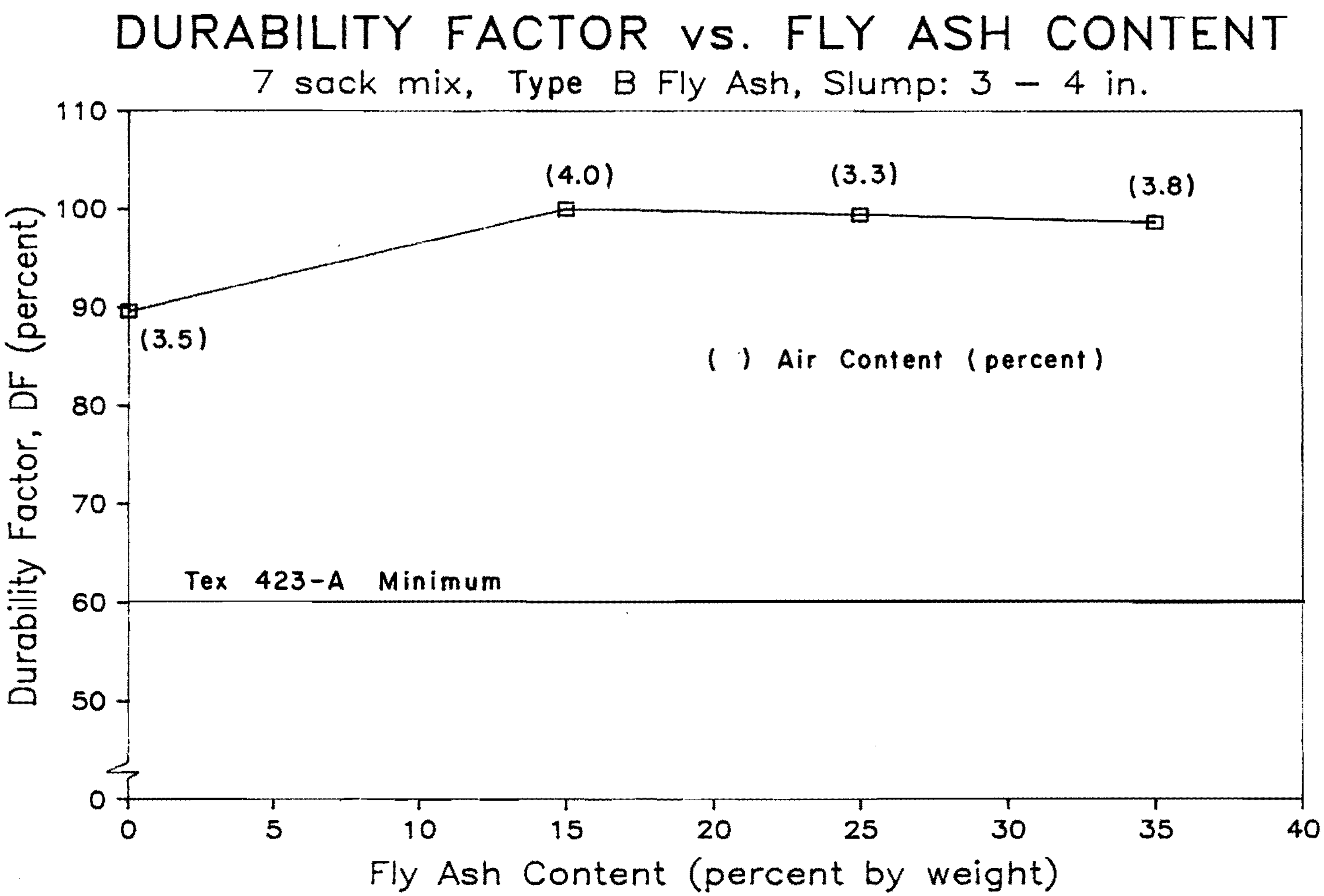

Fig. 5.20 Durability factor (DF) versus Type B fly ash content, seven sack mixes.

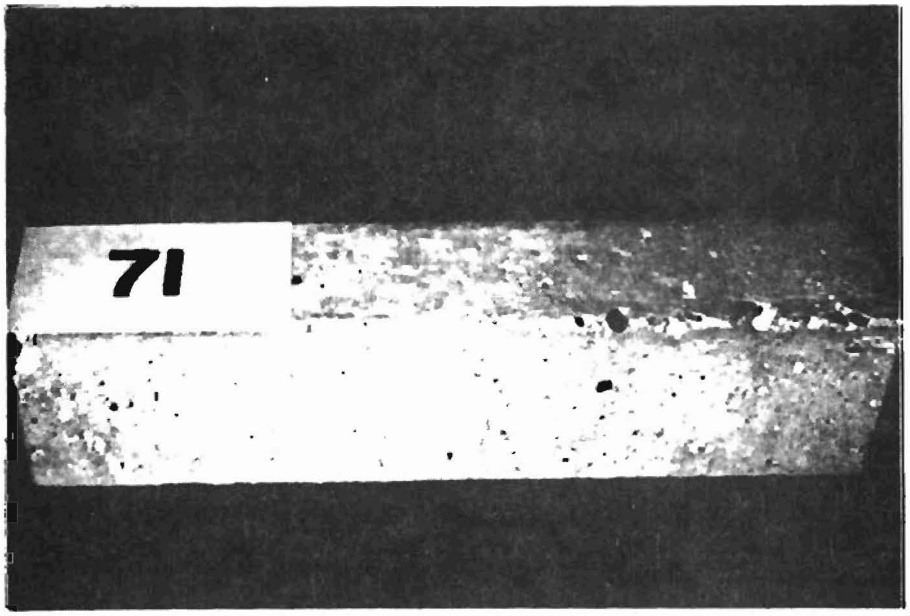

Fig. 5.21 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing no fly ash.

Fig. 5.22 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 15% Type B fly ash.

Fig. 5.23 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 25% Type B fly ash.

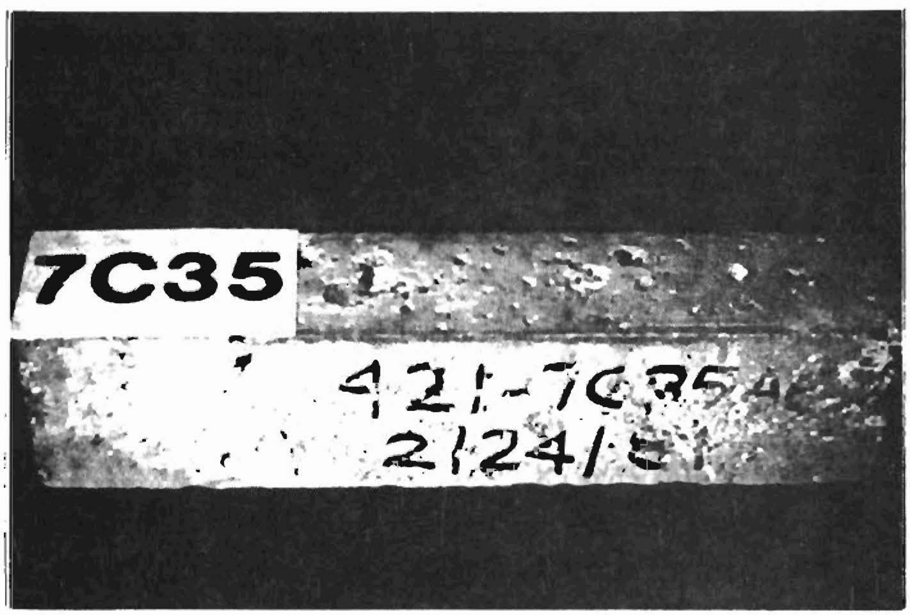

Fig. 5.24 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 35% Type B fly ash.

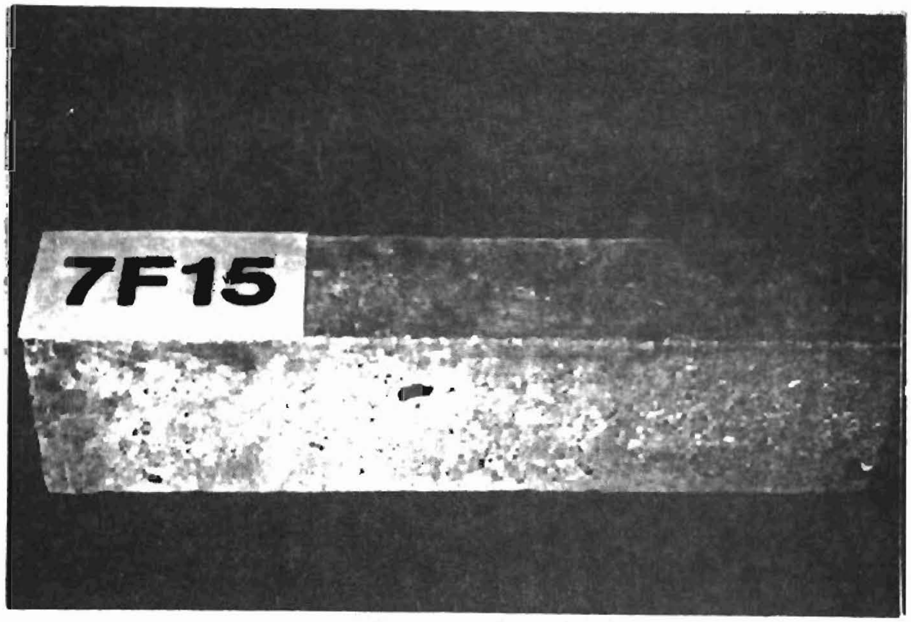

Fig. 5.25 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 15% Type A fly ash.

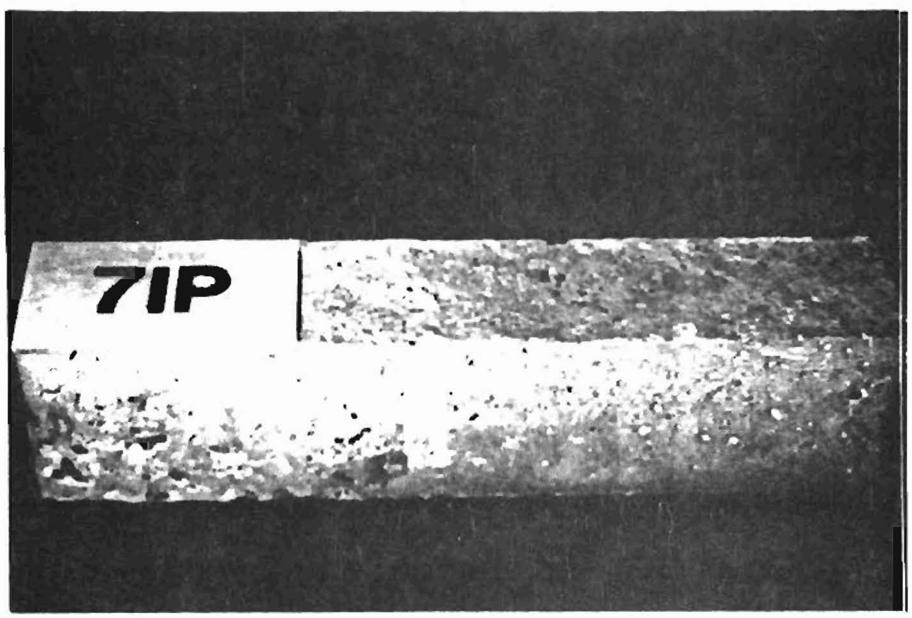

Fig. 5.26 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 20% Type A fly ash.

Fig. 5.27 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 25% Type A fly ash.

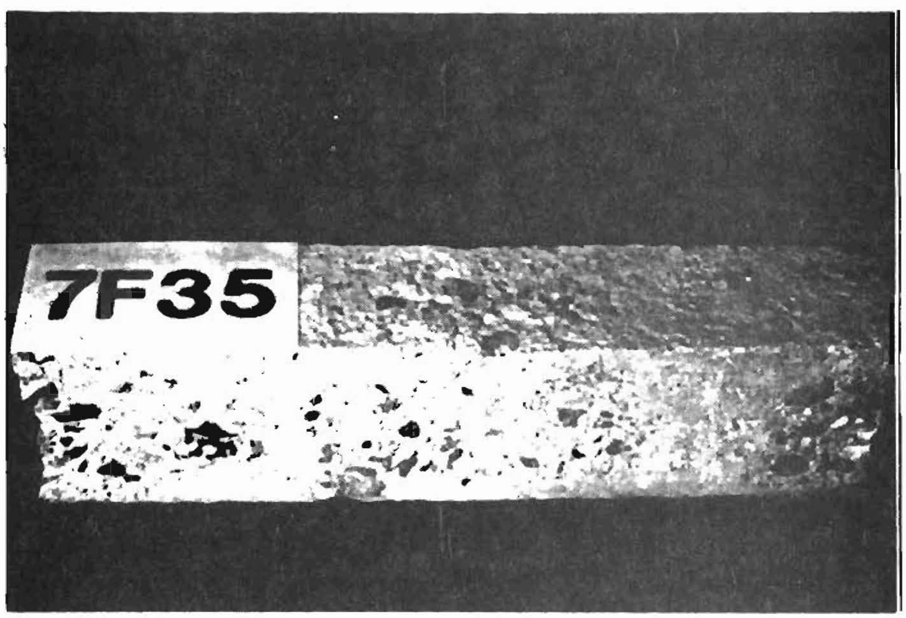

Fig. 5.28 Seven sack mix specimen subjected to 300 freeze-thaw cycles containing 35% Type A fly ash.

I or IP cement only are identified by the letters I or IP. Figures 5.22 through 5.24 show the concrete specimens containing Type B fly ash. Comparing these specimens to the control specimen shown on Fig. 5.21 indicates that these specimens had approximately equal degree of concrete deterioration. Concrete specimens containing Type A fly ash subjected to the freeze-thaw testing are shown in Figs. 5.25 through 5.28. Figures 5.27 and 5.28 clearly show the highly deteriorated state of the concrete containing 25 and 35% Type A fly ash. This is in agreement with the results shown in Fig. 5.19 which indicated that these two specimens failed according to TSDHPT Testing Procedure Tex. 423-A.

5.3.4 Discussion of Test Results. Concrete containing fly ash is more susceptible to freeze-thaw damage than ordinary concrete. The most important factor affecting the susceptibility of concrete containing fly ash to freeze-thaw damage is the loss on ignition (LOI) or carbon content of the fly ash used. In this study the Type A fly ash used had a LOI of 0.43% and the Type B fly ash used had a LOI of 0.26%. The LOI of the Type A fly ash was 65% higher than that of the Type B fly ash. The LOI of the Type A fly ash used in the manufacture of the Type IP blended cement was 0.24%.

The poor performance of concrete containing Type A fly ash compared to concrete containing Type B fly ash was due mainly to its lower air content. Six-sack mixes containing Type A fly ash averaged air contents 27% lower than the air content of the 6-sack mixes containing Type B fly ash. Seven-sack mixes containing Type A fly ash averaged air contents 44% lower than the 7-sack mixes containing Type B fly ash. The reduction in the air content of concrete containing Type A fly ash is due to the higher carbon content, reflected in the LOI, of these fly ashes. The residual carbon contained in fly ash has a high affinity for the air-entraining admixture, absorbing it and reducing the amount of air-entraining admixture available to form an adequate stable air-void system. The type of air-entraining admixture used in this study was limited to a neutralized vinsol resin based solution satisfying the requirements of ASTM C260-77, "Air-Entraining Admixtures for Concrete"; therefore, the effect of other types of air-entraining admixtures on the performance of concrete containing fly ash will not be discussed.

The dosage of air-entraining admixture was kept constant for all mixes throughout this study; therefore, no comparisons were made into what effect the air-entraining admixture dosage had on the air-void system of concrete containing fly ash.

As was noted earlier the LOI of the Type A fly ash used in this study was 0.43% while the LOI of the Type A fly ash used in the blended cement, Type IP, was 0.24%, even though both of these fly ashes were obtained from the same source. From Fig. 6.4 it can be observed that the mix containing the blended cement, 20% fly ash by weight, averaged a durability factor 3% above that of the control mixes. Even though TSDHPT Departmental Material Specification D-9-8900, "Fly Ash", allows for a maximum LOI of 3% for both Type A and Type B fly ash it is recommended that for the production of concrete containing fly ash subjected to freeze-thaw cycles the LOI of the fly ash used be limited to 0.26%. If the LOI of the fly ash used exceeds this limit, it is necessary to ensure the concrete has the proper amount of entrained air. This is obtained by increasing the air-entraining admixture dosage until a proper air-void system is obtained. The LOI of the Type B fly ash used in this study was 0.26. Its performance to freeze-thaw cycles was adequate; therefore, this limit should ensure that durable concrete containing fly ash subjected to freeze-thaw cycles is produced.

5.4 Effect of Curing Conditions on the Strength of Concrete Containing Fly Ash

To study the effect curing conditions had on the strength of concrete containing fly ash a series of tests were performed. Two environmental conditions, a summer condition with a temperature of 100°F and a relative humidity of 33% and a winter condition with a temperature of 40°F and a relative humidity of 55%, were considered. These were thought to be the temperature extremes in which concrete would be batched and cast in the State of Texas. This set of tests consisted of pouring twelve 6 x 12 in. cylinders and twelve 6 x 6 x 21 beams, moist curing (78°F, 98% RH) sets of 3 specimens for 1, 3, 7, or 28 days and removing them from the moist curing room after a specified moist curing time, be it 1, 3, or 7 days, and placing the specimens in an environment room with the temperature and relative humidity set to simulate the desired environmental condition. Once inside the environmental room the concrete specimens were not moist cured at any time. A set of control specimens to be used for comparison purposes were left in the moist curing room (78°F, 98% RH) until the time of testing. The flexural beams moist cured (78°F, 98%

RH) for 1, 3, and 7 days were tested at 7 days. For comparison purposes a set of flexure beams were moist cured (78°F, 98% RH) for 28 days and tested at 28 days. This was done to obtain an indication of the flexural strength gain obtained between 7 and 28 days. All the compressive strength specimens were tested at 28 days. From these results, the moist curing time required for an adequate strength to develop in concrete can be obtained. Table 5.4 summarizes the mixes done in this study. These mixes were done twice, once for each environmental condition investigated. For these mixes, the slump was maintained between 3 to 4 in. to obtain concrete having approximately equal consistency.

To investigate the effect the use of a membrane curing compound had on the strength of concrete containing fly ash, tests using only 6-sack mixes containing Type A fly ash were performed. For this set of tests, the curing compound was applied immediately after demolding the specimen. The specimens were then subjected to either a temperature of 78°F or 100°F. Specimens were left in the same curing condition until time of testing, either at 7 or 28 days.

5.4.1 Concrete Cured at High Temperatures. The results on the study of the effect of moist curing time and curing temperature on the flexural and compressive strength of concrete are presented in this section.

All flexural test specimens poured were tested at 7 days except for 3 which were moist cured until the time of testing at 28 days. Flexural strength specimens moist cured for 1 and 3 days and compressive strength test specimens moist cured for 1, 3, and 7 days were placed in an environmental chamber set at 100°F and 33% relative humidity after being moist cured for the specified amount of time.

Specimens were moist cured according to ASTM Standard Specification C192, "Making and Curing Concrete Test Specimens in the Laboratory". The control concrete mix having a cementitious content of 564 lb/cu.yd. did not have any flexural strength specimens tested at 28 days; therefore, the graph for this mix terminates at 7 days as shown in Fig. 5.20.

5.4.1.1 Flexural Strength. The results of the flexural strength obtained for the mixes investigated are shown on Figs. 5.29 through 5.32.

TABLE 5.4 Mixes Performed to Study the Effect of Curing Condition on Concrete Strength

Mix I.D.	Cementitious Content (lbs/cu.yd.)	Type of Fly Ash Used	Fly Ash Content (% by wt)
6I	564	-	0
6IP		A	20
6A25		A	25
6B25		B	25
7I	658	-	0
7IP		A	20
7A25			25
7A35			35
7B25		B	25
7B35		B	35

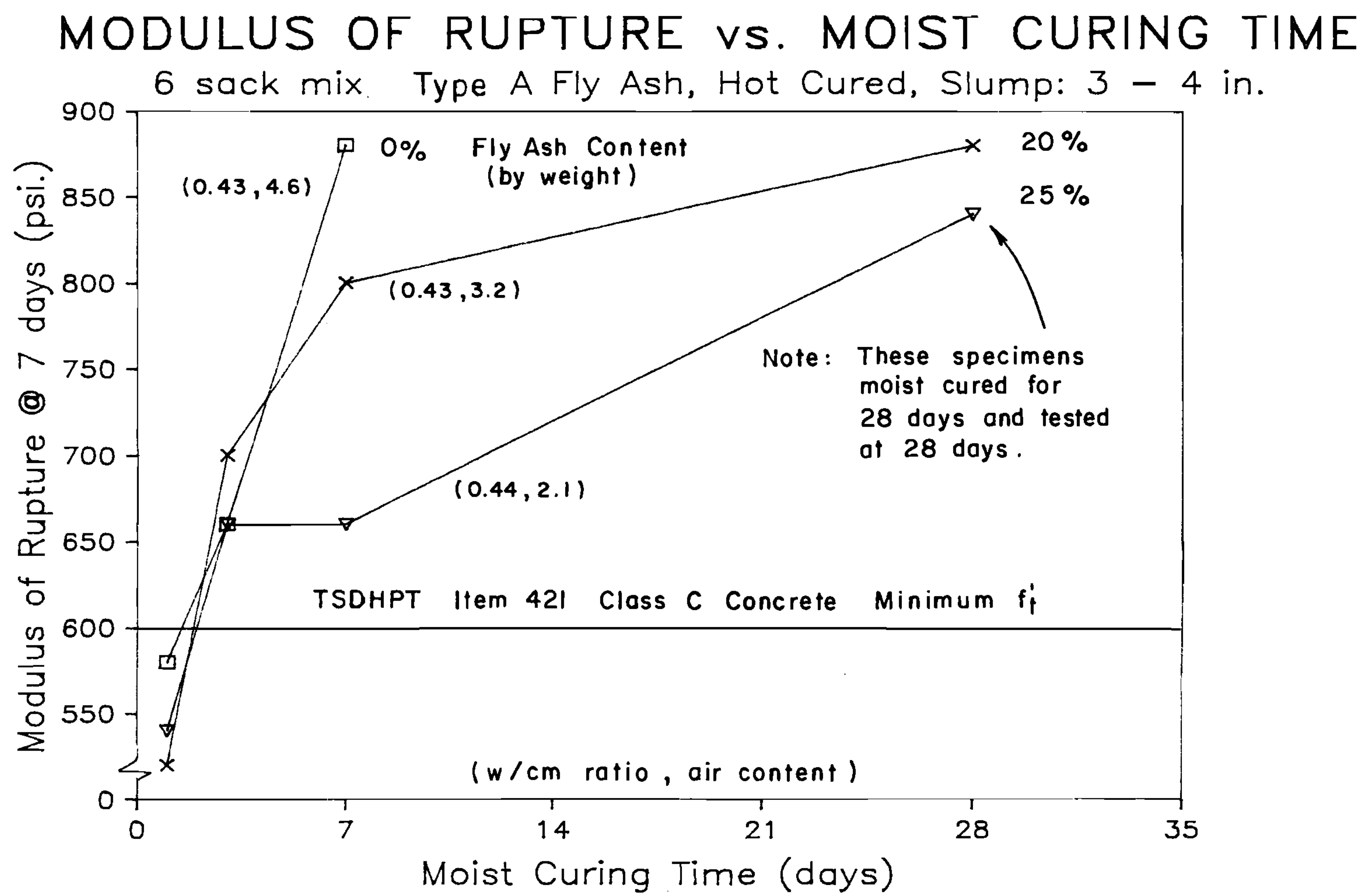

Fig. 5.29 Modulus of rupture versus moist curing time, six sack mixes, Type A fly ash, cured at 100°F.

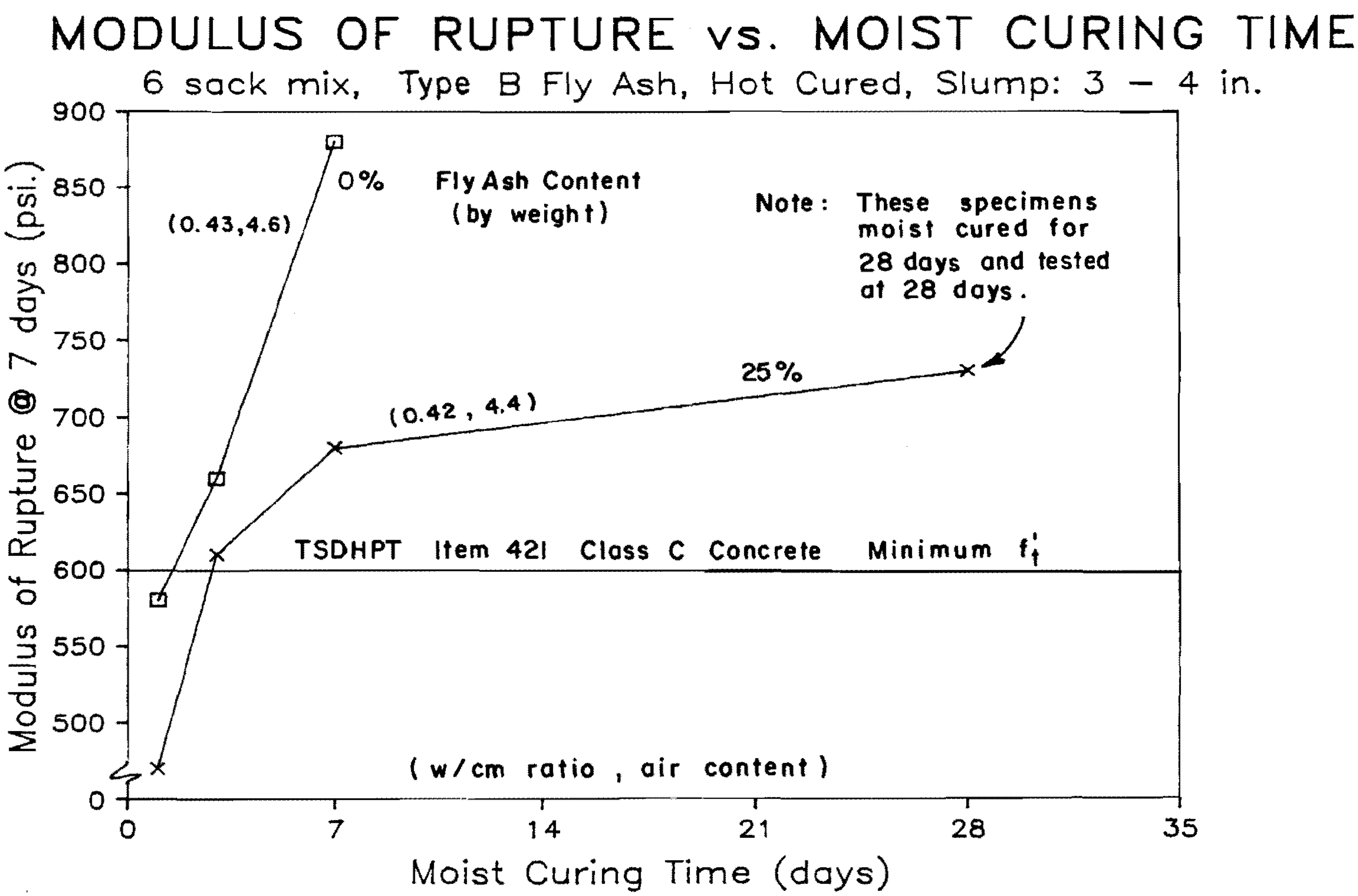

Fig. 5.30 Modulus of rupture versus moist curing time, six sack mixes, Type B fly ash, cured at 100°F.

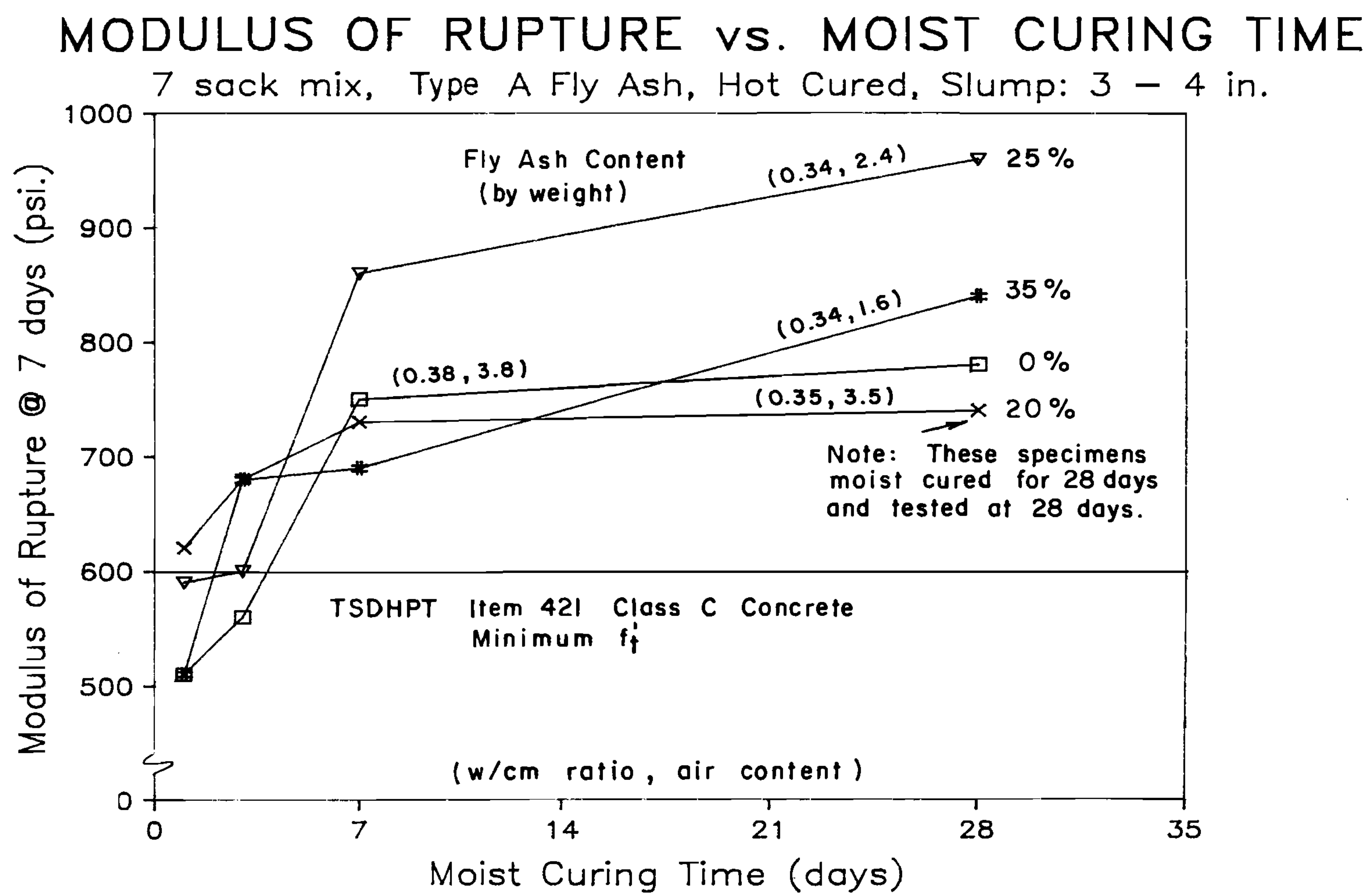

Fig. 5.31 Modulus of rupture versus moist curing time, seven sack mixes, Type A fly ash, cured at 100^{o}F.

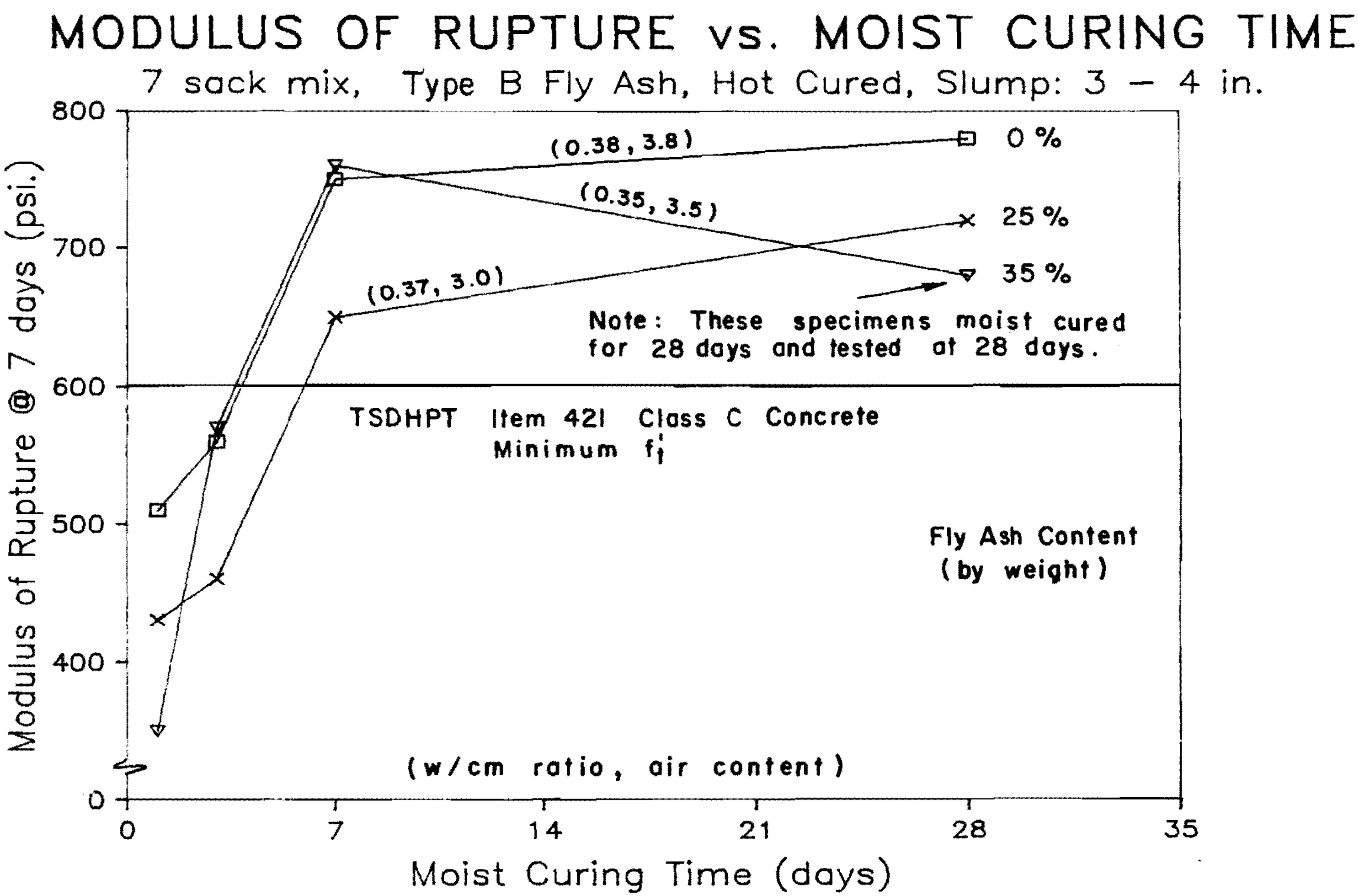

Fig. 5.32 Modulus of rupture versus moist curing time, seven sack mixes, Type B fly ash, cured at 100°F.

A moist curing length of only one day was not adequate enough for any of the concrete specimens to develop the minimum 7-day flexural strength required for TSDHPT Item 421 Class C concrete, except for the mix having a Type IP cementitious content of 658 lbs/cu.yd. Extending the moist curing length to 3 days improved the performance of most mixes. Moist curing for 7 days resulted in all specimens having strengths greater than the minimum 7-day flexural strength required for TSDHPT Item 421 Class C concrete. No distinct pattern of behaviour was observed for mixes containing the same type and amount of fly ash but having different cementitious content. The pattern of flexural strength gain with increased moist curing time was not uniform with increased time.

5.4.1.2 Compressive Strength. Results of the average 28-day compressive strength of 3 concrete specimens containing fly ash moist cured for 1, 3, or 7 days and placed in a controlled environment of 100°F and 33% relative humidity until the time of testing at 28 days are shown in Figs. 5.33 through 5.36. Unlike the results obtained for the 7-day flexural strength, all the specimens tested had 28-day compressive strengths equal to or greater than the minimum 28-day compressive strength required by the TSDHPT for Item 421 Class C concrete.

The decrease in compressive strength gain for moist curing from 7 to 28 days for concretes containing Type A fly ash and having a cementitious content of 658 lbs/cu.yd. was due mainly to the sharp decrease in the 28-day compressive strength obtained for the mix having a Type A fly ash content of 35% and moist cured for 28 days.

5.4.2 Concrete Cured at Low Temperature. The results of tests performed to investigate the effect of curing time at low temperatures on the flexural and compressive strength of concrete containing fly ash are presented in this section. The test procedures followed were the same as those presented in Section 5.4.1 of this chapter except specimens were placed in a controlled environment at 40°F and 55% relative humidity instead of a controlled environment at 100°F and 33% relative humidity as specified in the previous section.

The same concrete mixes performed in Section 5.4.1 of this chapter were performed for this set of test. As stated in Section 5.4.1 specimens were moist cured for a specified amount of time 1, 3, 7 or 28 days, then placed in the controlled environment room until time of testing. Once placed in the

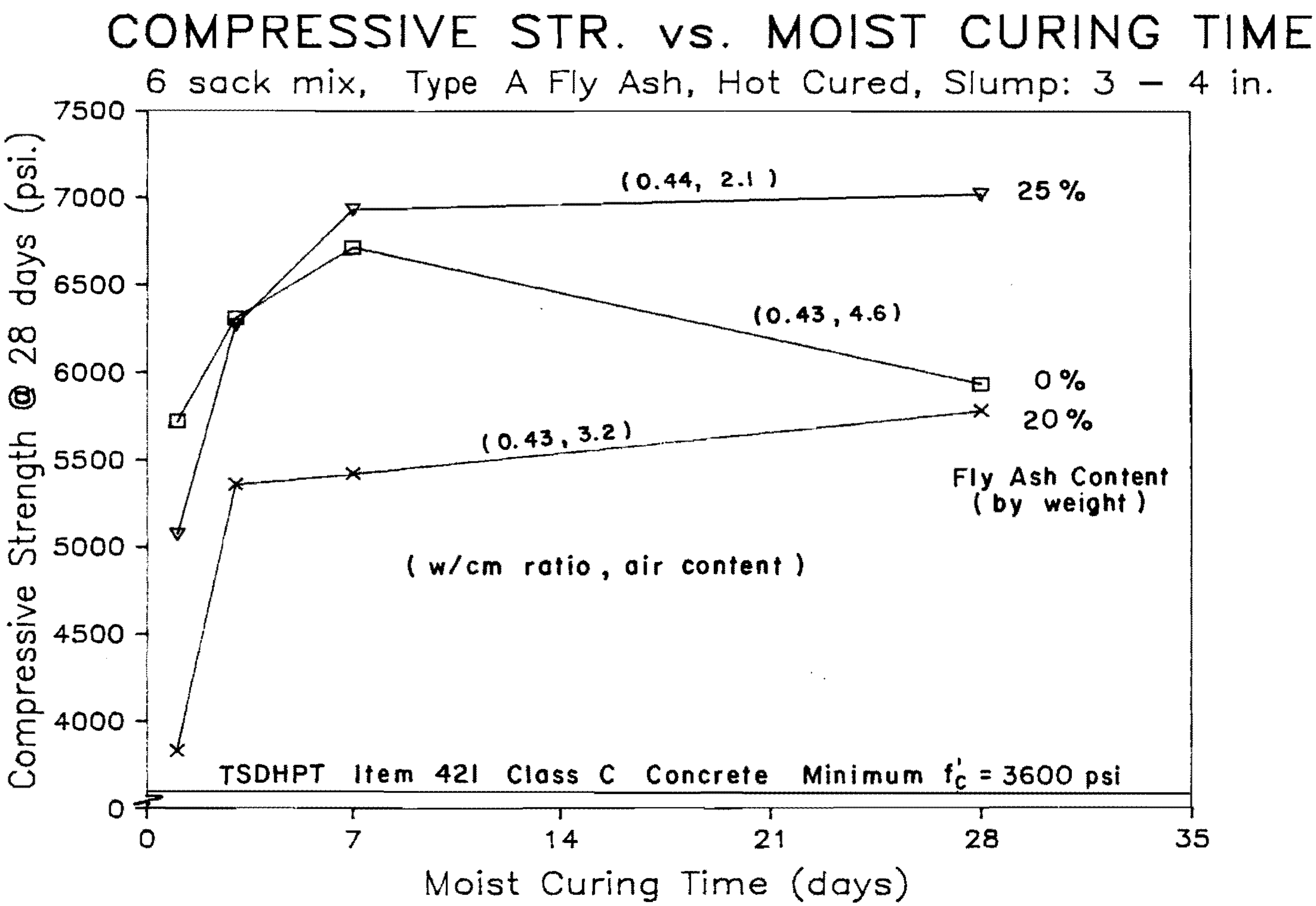

Fig. 5.33 Compressive strength versus moist curing time, six sack mixes, Type A fly ash, cured at 100°F.

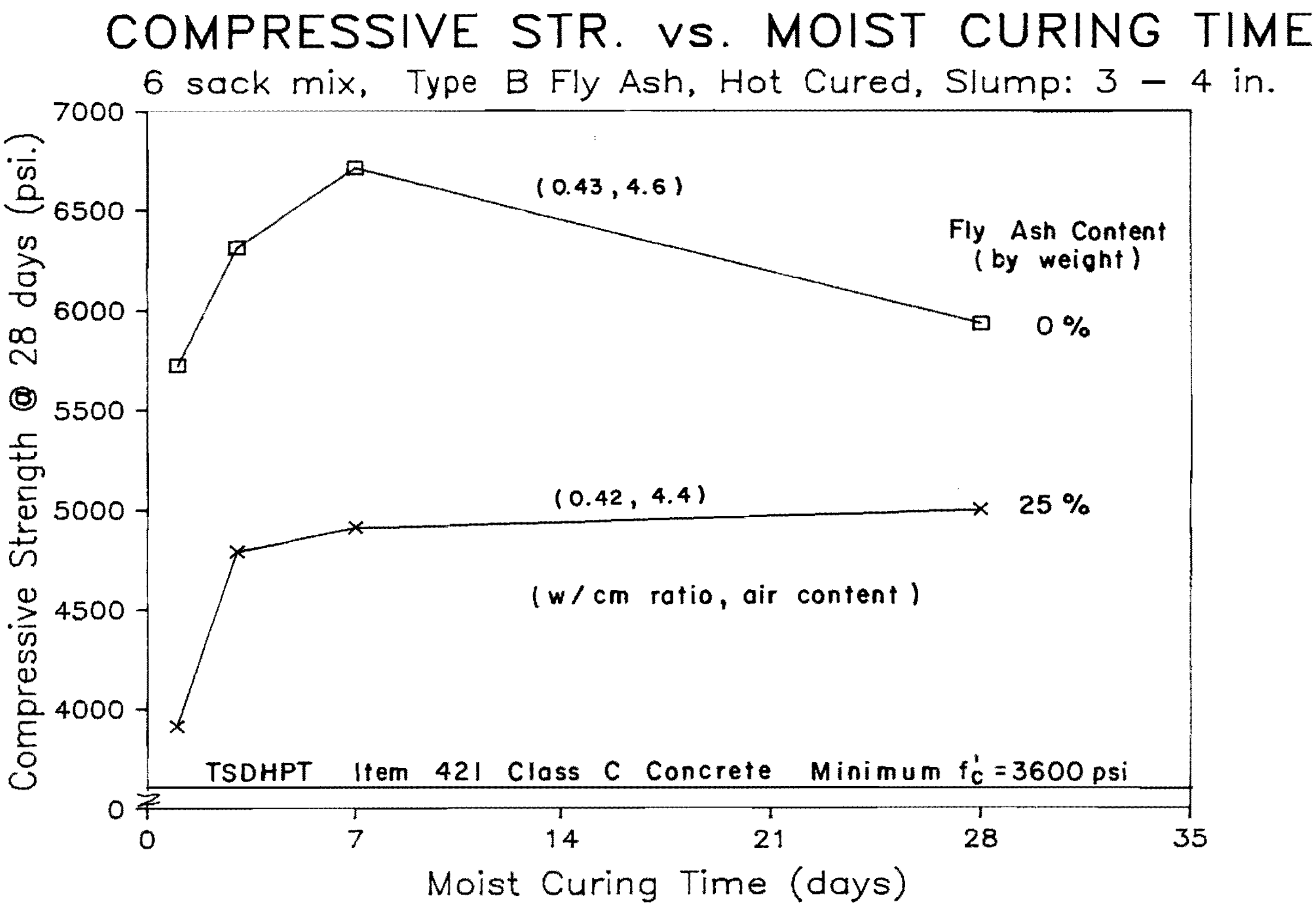

Fig. 5.34 Compressive strength versus moist curing time, six sack mixes, Type B fly ash, cured at 100°F.

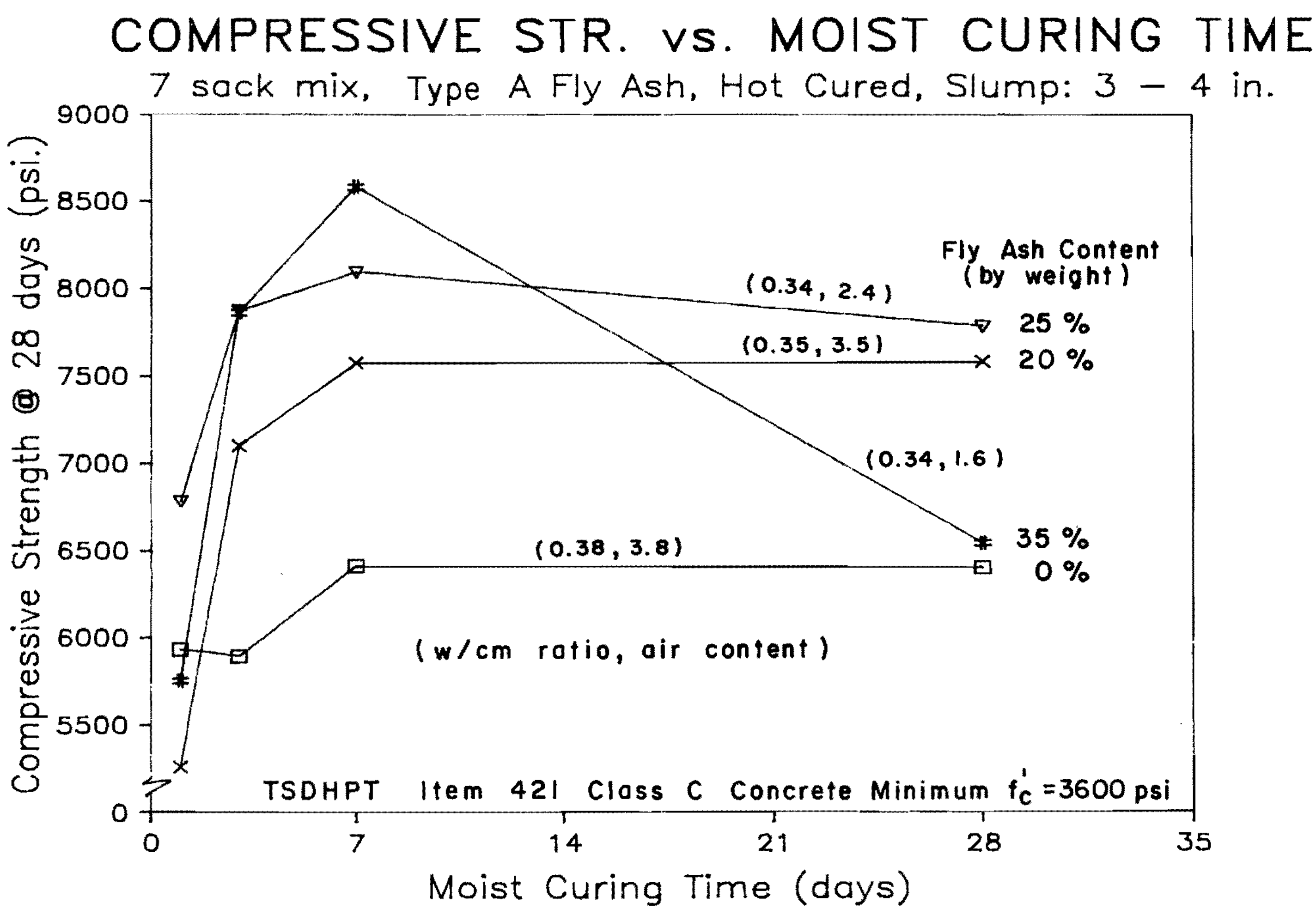

Fig. 5.35 Compressive strength versus moist curing time, seven sack mixes, Type A fly ash, cured at 100°F.

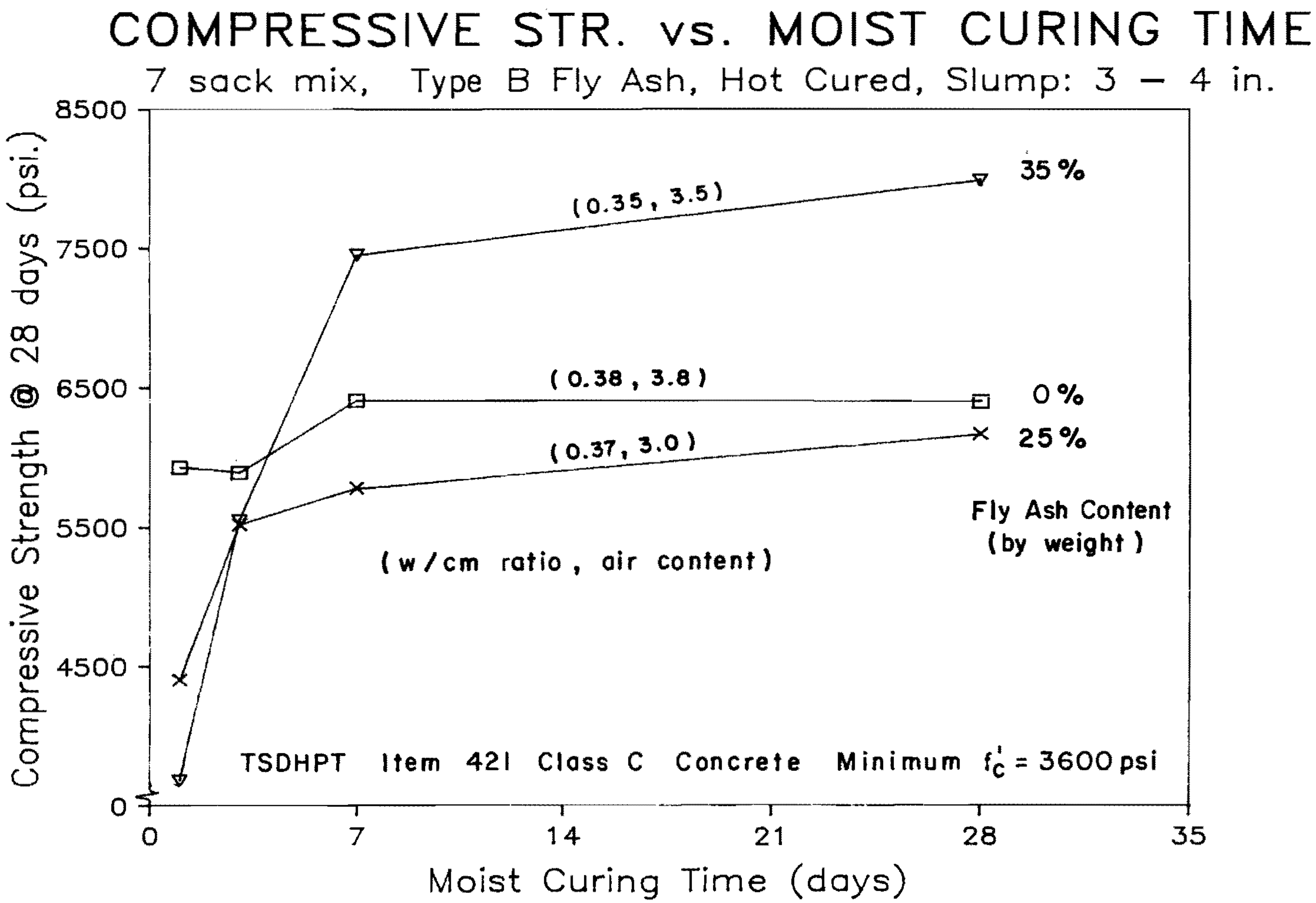

Fig. 5.36 Compressive strength versus moist curing time, seven sack mixes, Type B fly ash, cured at 100°F.

controlled environment room, moist curing of the test specimens was terminated.

5.4.2.1 Flexural Strength. Results of the 7-day flexural strength tests performed are shown in Figs. 5.37 through 5.40. Half of the specimens moist cured for one day had 7-day flexural strength lower than the minimum 7-day flexural strength required for TSDHPT Item 421 Class C concrete. All specimens moist cured for 3 days, except the mix having a cementitious content of 564 lb/cu.yd. and containing 25% Type B fly ash, had 7-day flexural strengths equal to or greater than the minimum allowed for the above mentioned TSDHPT class of concrete. All the specimens moist cured for 7 days except the above mentioned mix had 7-day flexural strengths equal to or greater than the minimum 7-day flexural strength required for TSDHPT Item 421 Class C concrete. No particular behaviour pattern was observed for mixes having the same class of fly ash and fly ash content but different cementitious content.

5.4.2.2 Compressive Strength. Results of the average 28-day compressive strength of 3 concrete specimens containing fly ash moist cured for 1, 3, or 7 days and placed in a controlled environment of 40°F and 55% relative humidity until time of testing at 28 days are shown in Figs. 5.41 through 5.44. None of the mixes tested failed to meet the minimum 28-day compressive strength required for TSDHPT Item 421 Class C concrete.

A decrease in the 28-day compressive strength of concrete with an increase in the moist curing time was obtained for the control mix having a cementitious content of 564 lbs/cu.yd. with an increase in the moist curing time from 1 to 3 days. The control mix having a cementitious content of 658 lbs/cu.yd., with an increase in the moist curing time from 3 to 7 days, also had a decrease in the 28-day compressive strength. The 28-day compressive strength of the control mix was higher for specimens moist cured for 3 days than for specimens moist cured 28-days.

5.4.3 Use of Membrane Curing Compounds. A limited number of mixes were batched to study the effect of curing the specimens using a membrane curing compound. This study was limited to mixes having a cementitious content of 564 lbs/cu.yd. and containing Type A fly ash only. Instead of moist curing the specimens, a membrane curing compound was applied on the specimens immediately after casting. The effect of the environmental condition during the time of curing on the strength development of the concrete was studied by placing one set of

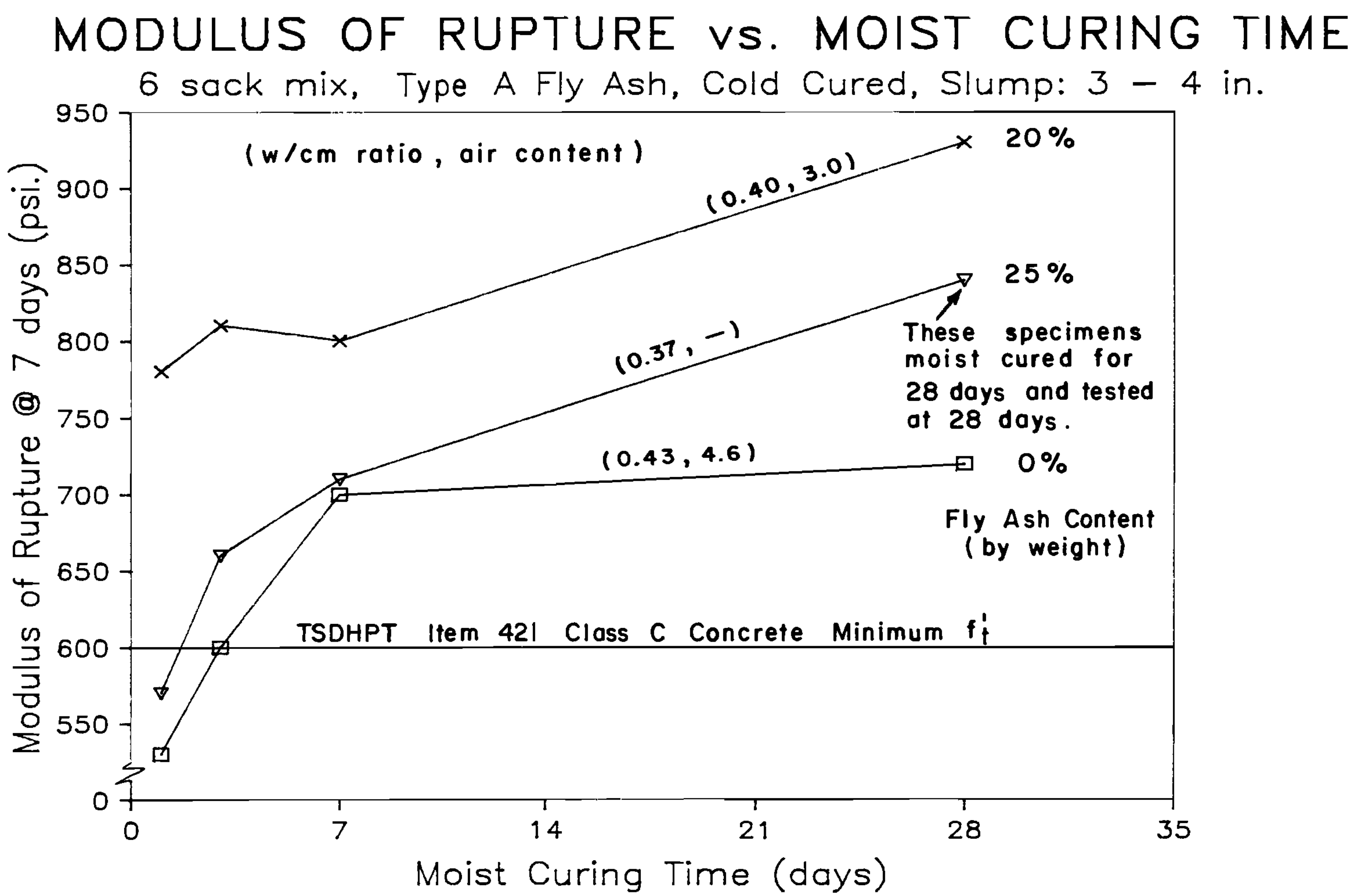

Fig. 5.37 Modulus of rupture versus moist curing time, six sack mixes, Type A fly ash, cured at 40°F.

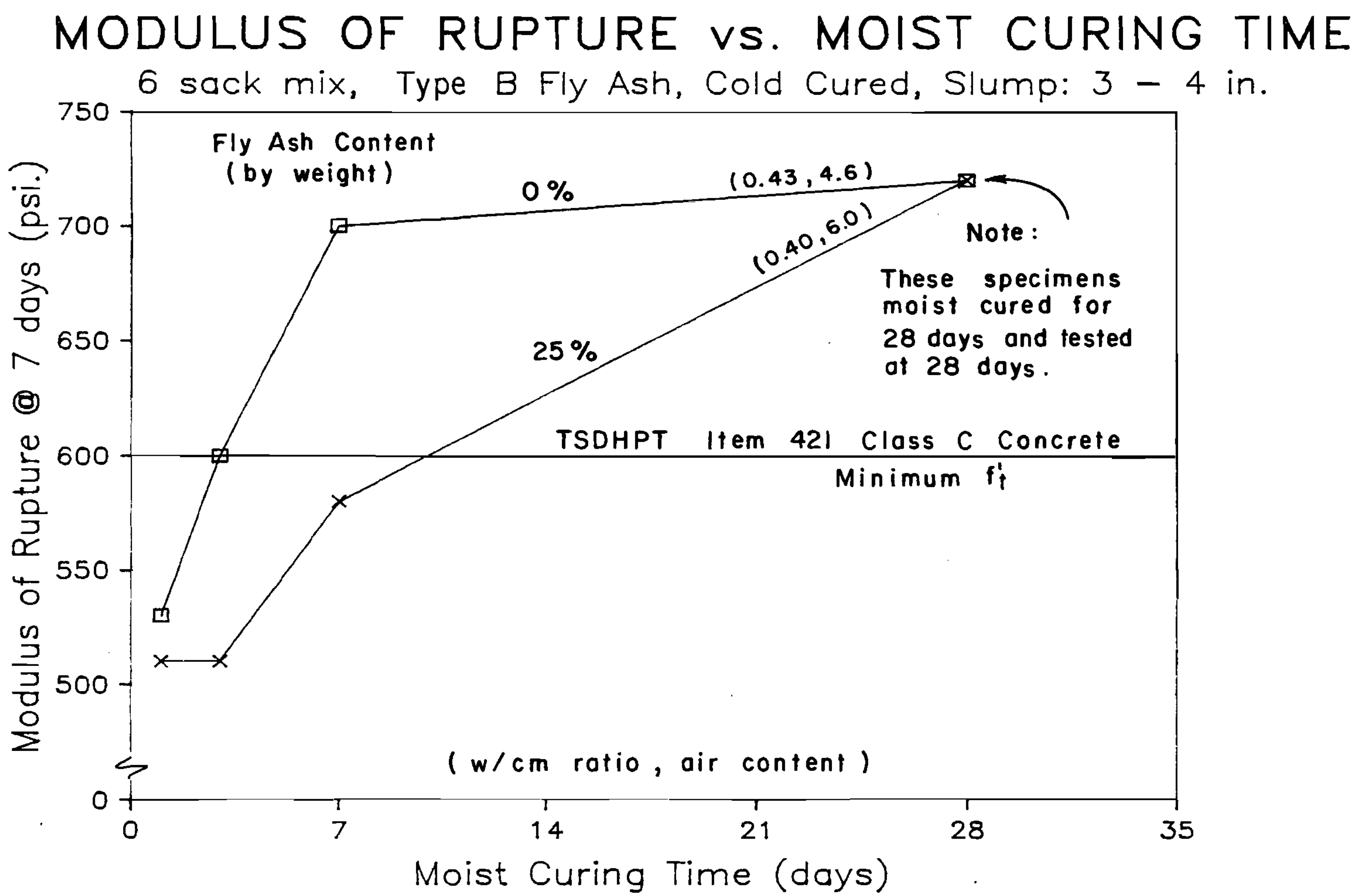

Fig. 5.38 Modulus of rupture versus moist curing time, six sack mixes, Type B fly ash, cured at 40°F.

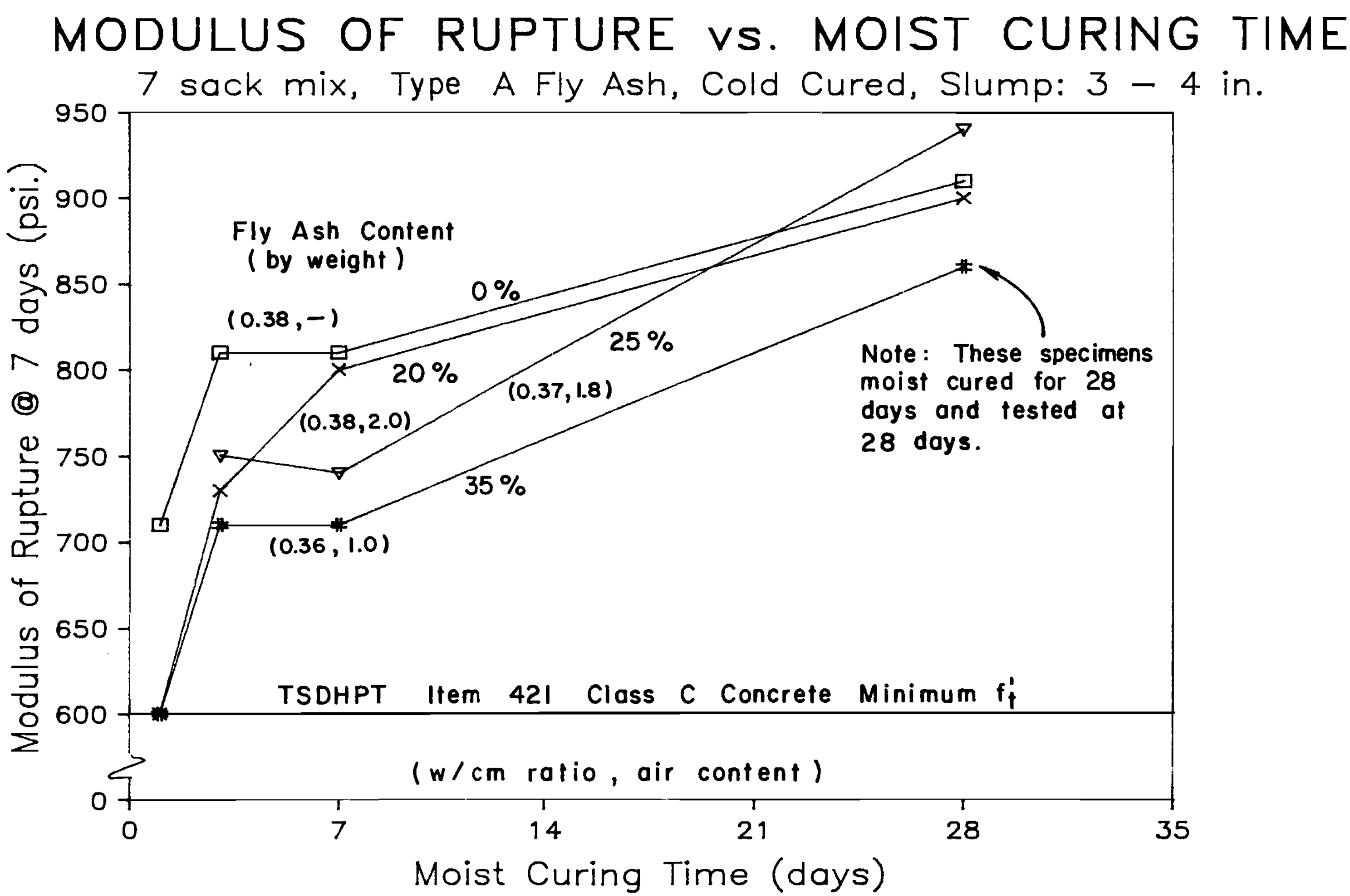

Fig. 5.39 Modulus of rupture versus moist curing time, seven sack mixes, Type A fly ash, cured at 40°F.

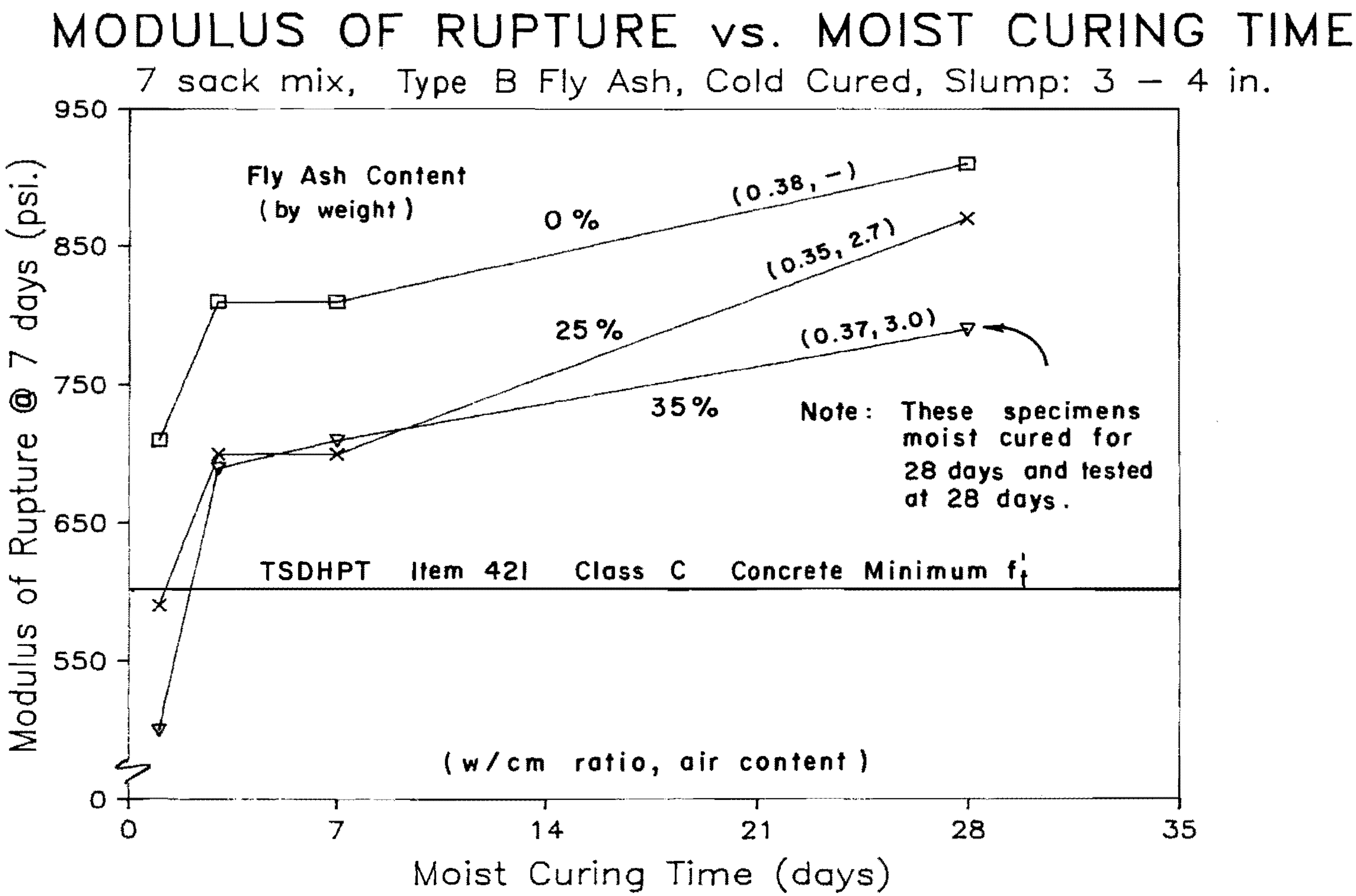

Fig. 5.40 Modulus of rupture versus moist curing time, seven sack mixes, Type B fly ash, cured at 40°F.

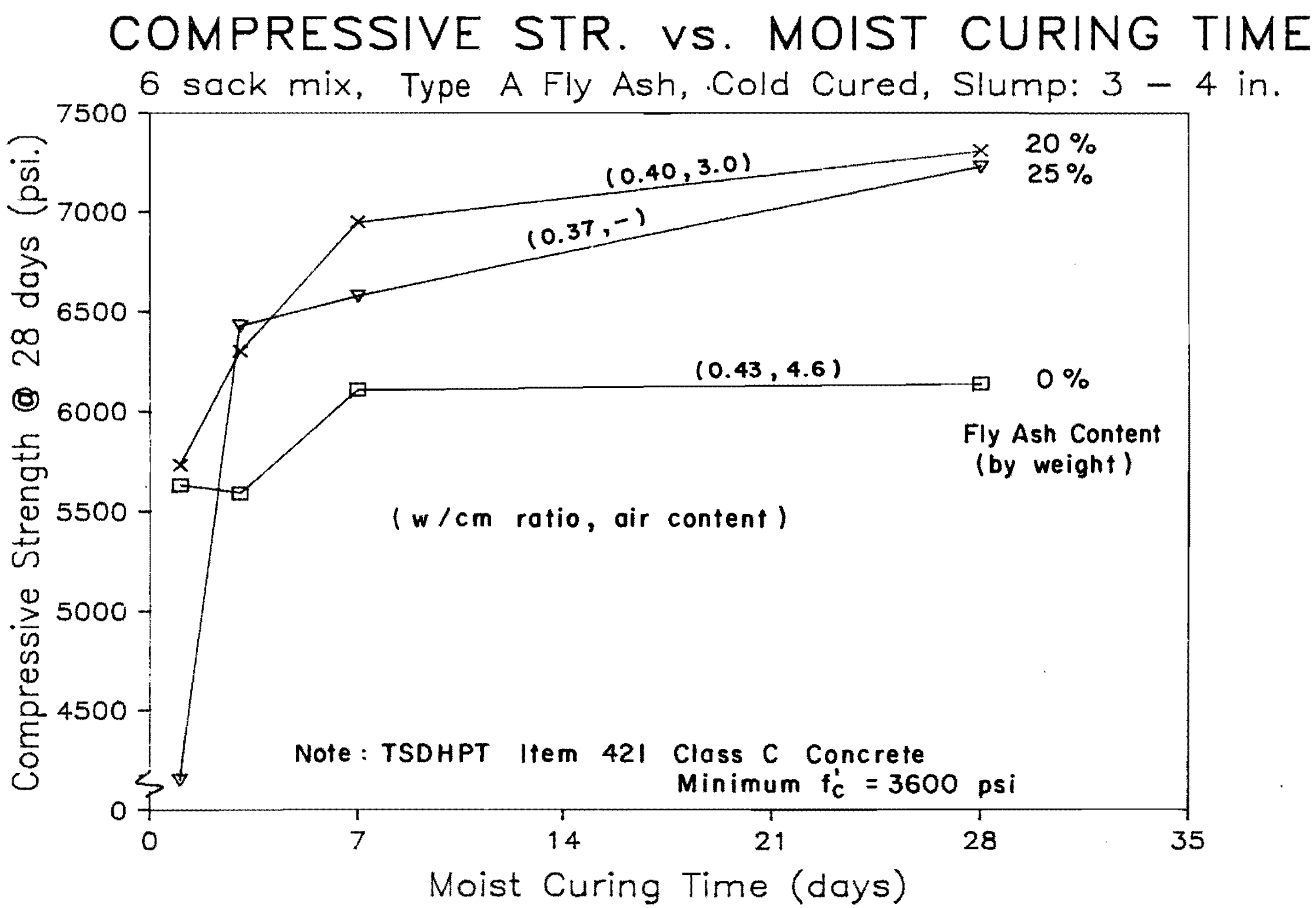

Fig. 5.41 **Compressive strength versus moist curing time, six sack mixes, Type A fly ash, cured at 40°F.**

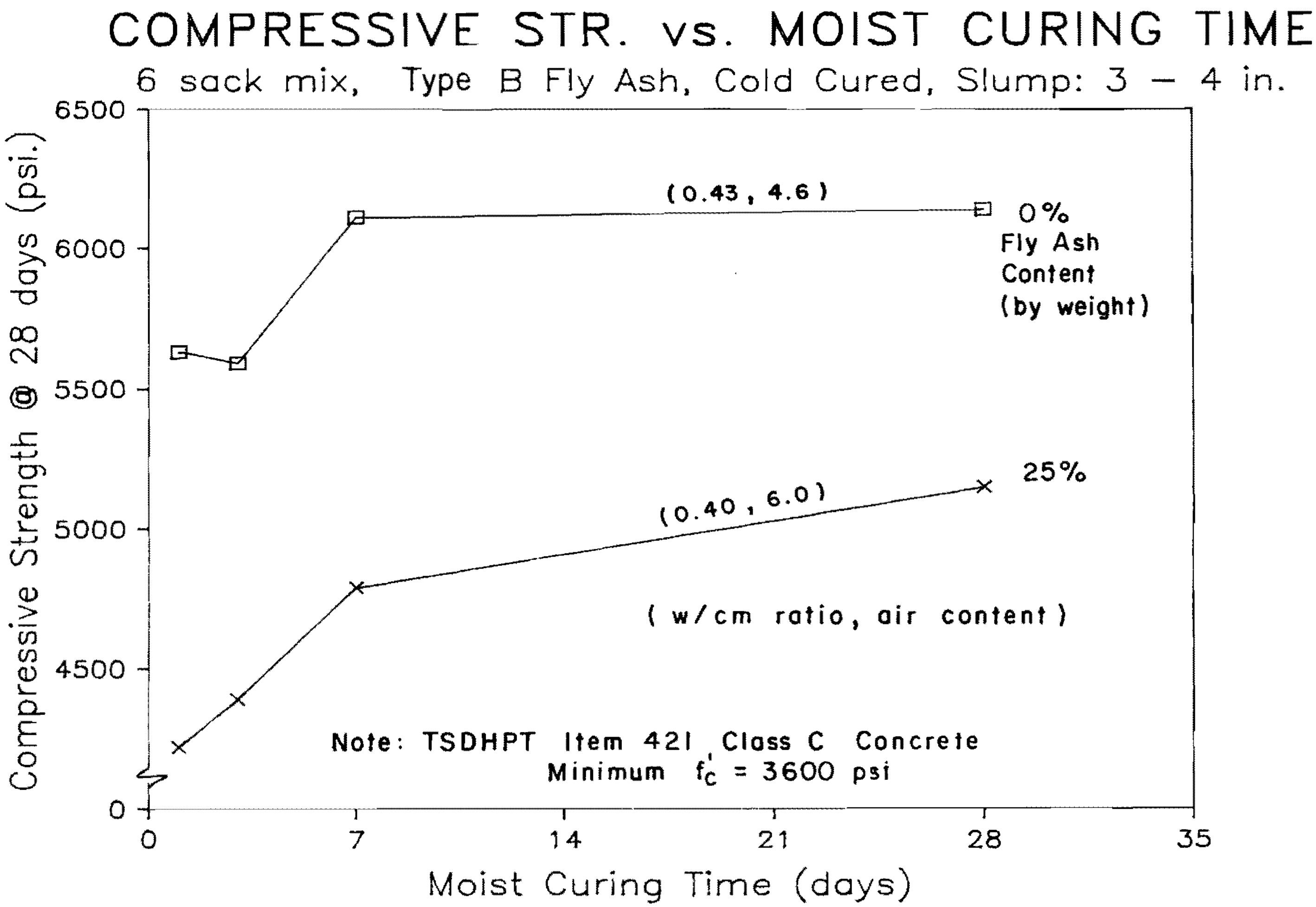

Fig. 5.42 **Compressive strength versus moist curing time, six sack mixes, Type B fly ash, cured at 40^{o}F.**

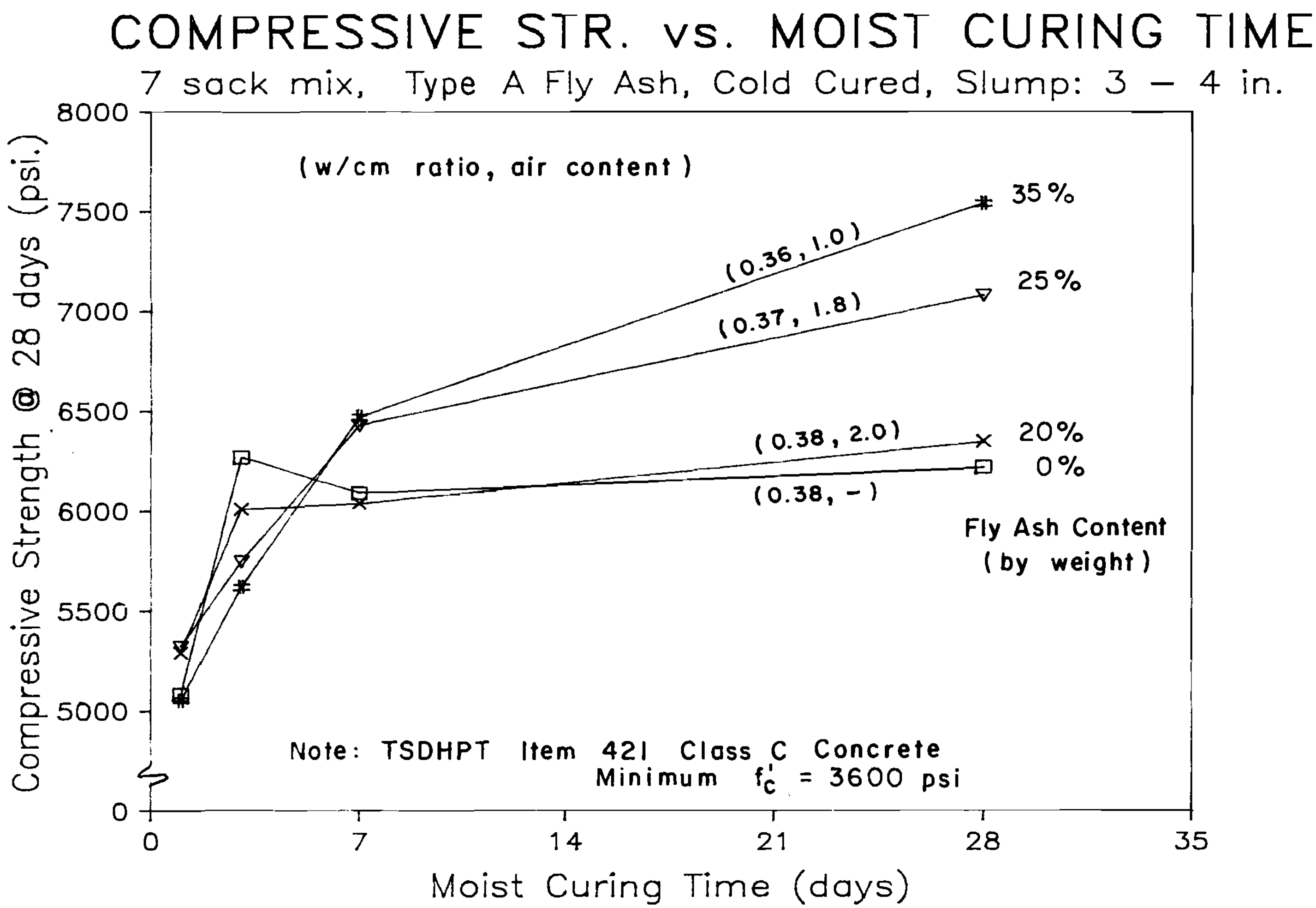

Fig. 5.43 Compressive strength versus moist curing time, seven sack mixes, Type A fly ash, cured at 40°F.

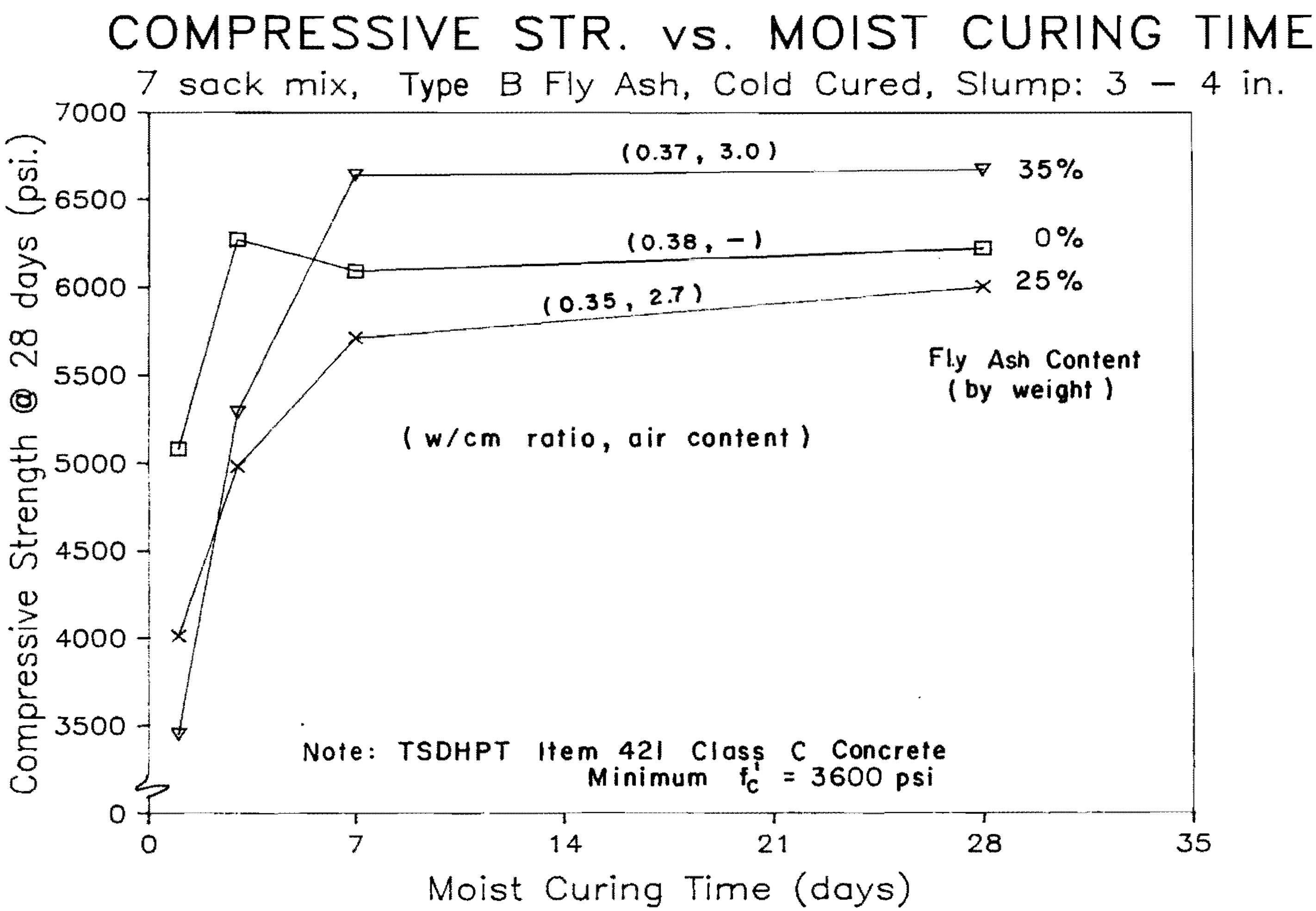

Fig. 5.44 Compressive strength versus moist curing time, seven sack mixes, Type B fly ash, cured at 40^{o}F.

specimens at an ambient room temperature of 78^oF, and one set of specimens in a environmental controlled chamber at 100^oF and 33% relative humidity. The membrane curing compound used was a TSDHPT Standard Specification Item 526 "Membrane Curing", Type 2 membrane curing compound. The membrane curing compound used satisfied the requirements of TSDHPT Test Procedure Tex-219-F "Testing of Concrete Curing Materials".

5.4.3.1 Flexural Strength. Results of the 7-day flexural strength tests for specimens cured using a membrane curing compound are shown in Fig. 5.45. The 7-day flexural strength of concrete containing Type A fly ash exposed to a temperature of 78^oF ranged from 10% below to 12% above that of the control mix. The average 7-day flexural strength of concrete containing Type A fly ash was 2% lower than that of the control mix. The concrete mixes containing 25 and 35% Type A fly ash failed to satisfy the minimum 7-day flexural strength requirement for TSDHPT Item 421 Class C concrete. The 7-day flexural stength of concrete containing Type A fly ash exposed to a temperature of 100^oF ranged from 4% to 29% higher than the 7-day flexural strength of the control mix. The average 7-day flexural strength of concrete containing Type A was 20% higher than that of the control mix. The control mix and the mix having a fly ash content of 25% by weight failed to meet the minimum 7-day flexural strength for TSDHPT Item 421 Class C concrete.

The flexural strength of the concrete specimens exposed to a temperature of 100^oF was less than the flexural strength of concrete specimens exposed to a temperature of 78^oF except for concrete containing 35% fly ash. The 7-day flexural strength of concrete containing fly ash cured using a membrane placed in an environmental chamber at 100^oF were comparable to the 7-day flexural strength for specimens moist cured one day and then placed in an environmental chamber set at 100^oF.

5.4.3.2 Compressive Strength. Results of the 28-day compressive strength test for specimens cured using a membrane curing compound are shown in Fig. 5.46. The 28-day compressive strength of concrete containing Type A fly ash exposed to a temperature of 78^oF ranged from 1% below to 8% above that of the control mix. Concrete containing fly ash averaged a 28-day compressive strength 3% higher than that of the control mix. The 28-day compressive strength of concrete containing Type A fly ash exposed to a temperature of 100^oF ranged from 1% lower to 16% higher than the 28-day compressive strength of the control mix. Concrete containing fly ash averaged a 28-day compressive strength 6% higher than the 28-day compressive strength of the

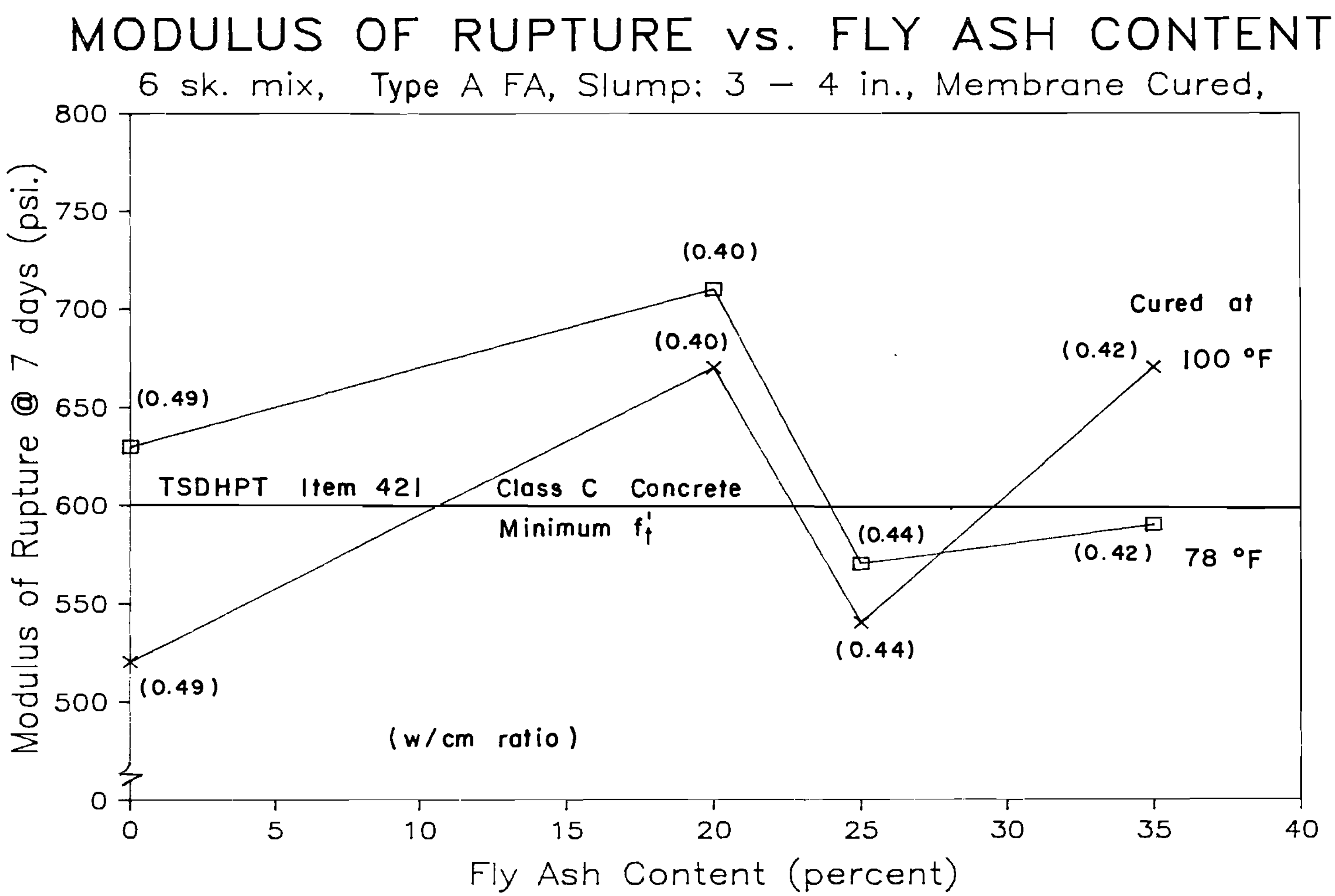

Fig. 5.45 Modulus of rupture of six sack mixes containing Type A fly ash, subjected to membrane curing.

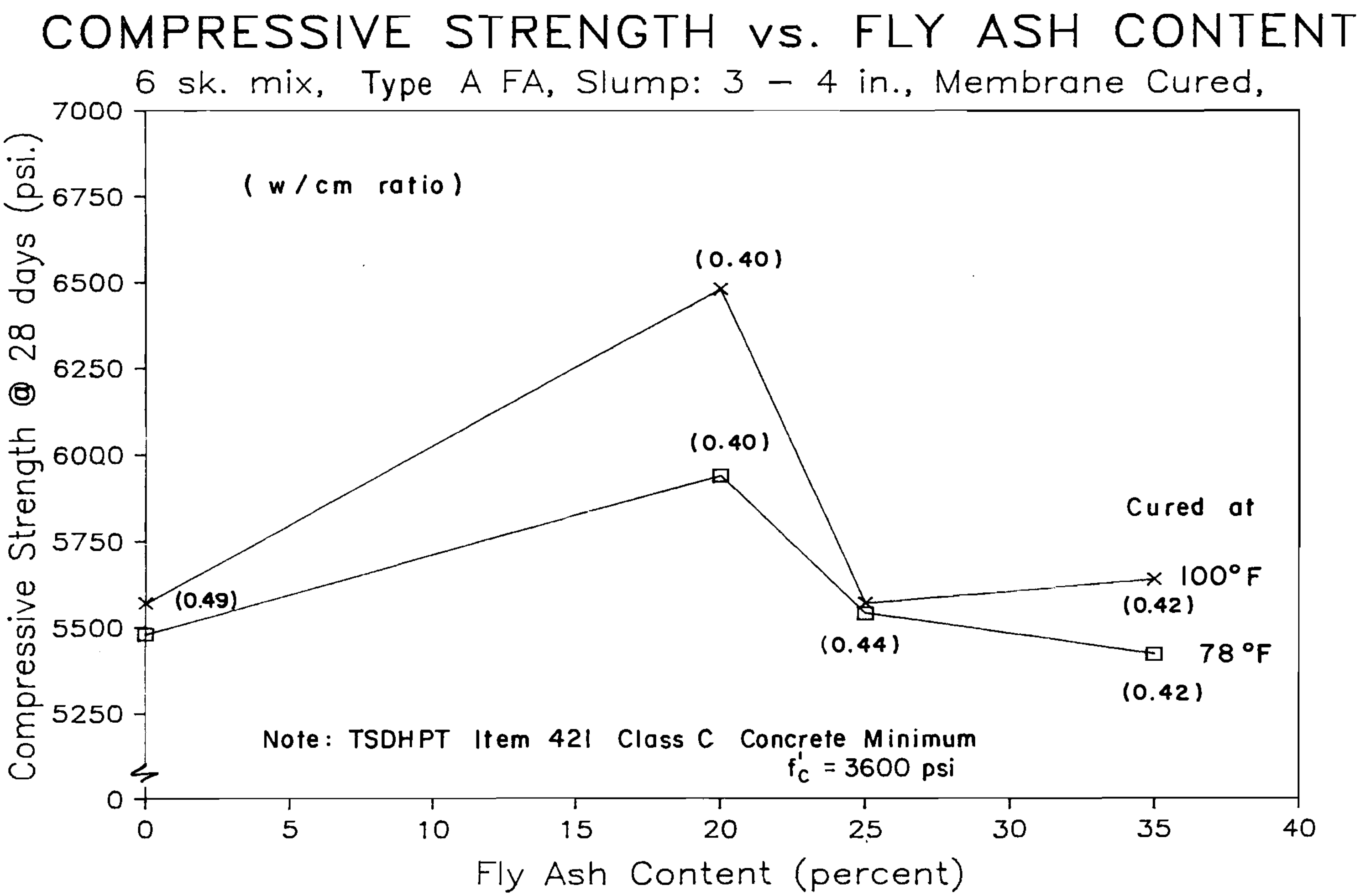

Fig. 5.46 Compressive strength of six sack mixes containing Type A fly ash, subjected to membrane curing.

control mix. The compressive strength of concrete specimens exposed to a temperature of 100°F was higher than the compressive strength of concrete specimens exposed to a temperature of 78°F.

5.4.4 Discussion of Test Results. It is recommended that concrete containing fly ash designed to meet the requirements of TSDHPT Item 421 Class C concrete cast in temperatures not exceeding 100°F be moist cured for at least 7-days. For concrete containing fly ash cast in the winter time in temperatures as low as 40°F it is recommended that it be moist cured at least 3-days to ensure strength properties satisfying the requirements of the above mentioned TSDHPT class of concrete. Concrete containing Type A fly ash having a cementitious content of 564 lbs/cu.yd. should have a maximum water-cementitious (w/cm) ratio of 0.40 if it is to be membrane cured. This includes concrete containing fly ash cast in temperatures of approximately 100°F.

The 7-sack mixes cured at 100°F, 33% RH after being initially moist cured (78° F, 98% RH) for a period of 1, 3 or 7 days required 7 days of moist curing compared to at least 3 days of moist curing required for the 6-sack mixes to obtain 7-day flexural strengths equal to or greater than that specified for TSDHPT Item 421 Class C concrete. This probably resulted due to the lower water-cementitious (w/cm) ratio of the 7-sack mixes compared to that of the 6-sack mixes.

It is theorized that placement of 7-sack concrete mixes in the environmental chamber set at 100°F, moist cured less than 7 days, resulted in excessive loss of water due to evaporation, therefore reducing the hydration rate of the concrete and its 7-day flexural strength. This is not reflected in the 28-day compressive strength of the 7-sack mixes, since hydration of the concrete has continued up to the time of testing, at 28 days, resulting in higher strengths. The opposite effect was observed for concrete containing fly ash moist cured for either 1, 3 or 7 days and placed in an environmental chamber set at 40°F. The lower water-cementitious ratio of the 7-sack mixes compared to the 6-sack mixes resulted in concrete having a higher 7-day flexural strength. Six-sack mixes averaged water-cemetitious ratios 20% higher than the 7-sack mixes. The 7-day flexural strength of the 7-sack mixes averaged a 10% increase over that of the 6-sack mixes. As shown in Fig. 6.9, the 28-day compressive strength of the 7-sack mix containing Type B fly ash had strength development properties equal to those obtained for the 7-sack mix cured at 100°F.

The increased 28-day compressive strength of concrete cured using a membrane compound at 100°F is probably due to a steam curing effect obtained by the use of the membrane and the hot enviromental surrounding. Moisture in the concrete was probably trapped by the curing membrane resulting in a steam curing effect. This caused accelerated curing of the concrete which resulted in concrete of higher strengths. This increase in the 28-day compressive strength averaged 3%.

5.5 Effects of Mixing Time and Temperature

A limited study to investigate the effect of mixing time and temperature on the slump, water-cementitious (w/cm) ratio, 7-day flexural strength, and 28-day compressive strength of concrete containing Type A fly ash was conducted. Mixes were batched at room temperature, 78°F, and at 100°F as outlined in Chapter 4, Section 4.3.1. Concretes containing Type A fly ash contents of 25 and 35% by weight were studied. A concrete mix using Type IP cement was also done at a mixing temperature of 100°F. All mixes studied had a cementitious content of 564 lbs/cu.yd. Tests on the fresh concrete were performed at 30-minute intervals from the time of initial mixing up to a mixing time of 90 minutes. Two 6 x 6 x 21-in. flexural strength beam specimens and two 6 x 12 in. compressive strength cylinders were cast at 60 and 90 minutes after initial mixing. The reference point taken as the 0 minute mark corresponded to the time at which the mix had reached the desired slump, in the range of 3 to 4 in.

5.5.1 Slump. Results of the slump measured at 30-minute intervals during the 90 minutes of mixing for concrete containing Type A fly ash are presented in Figs. 5.47 and 5.48 for the two mixing temperatures considered.

After 60 and 90 minutes of mixing, water was added to the batch to increase the concrete slump. Once this was accomplished, specimens were cast to be tested at a later age.

The results obtained indicate that increases in the Type A fly ash content of concrete results in a higher slump loss with mixing time.

The slump loss of concrete containing Type A fly ash mixed at 78°F ranged from 54 to 67% for the first 30 minutes of mixing, 33 to 45% for the second 30 minutes of mixing, and 29 to 43% for the last 30 minutes of mixing after the batch had been retempered

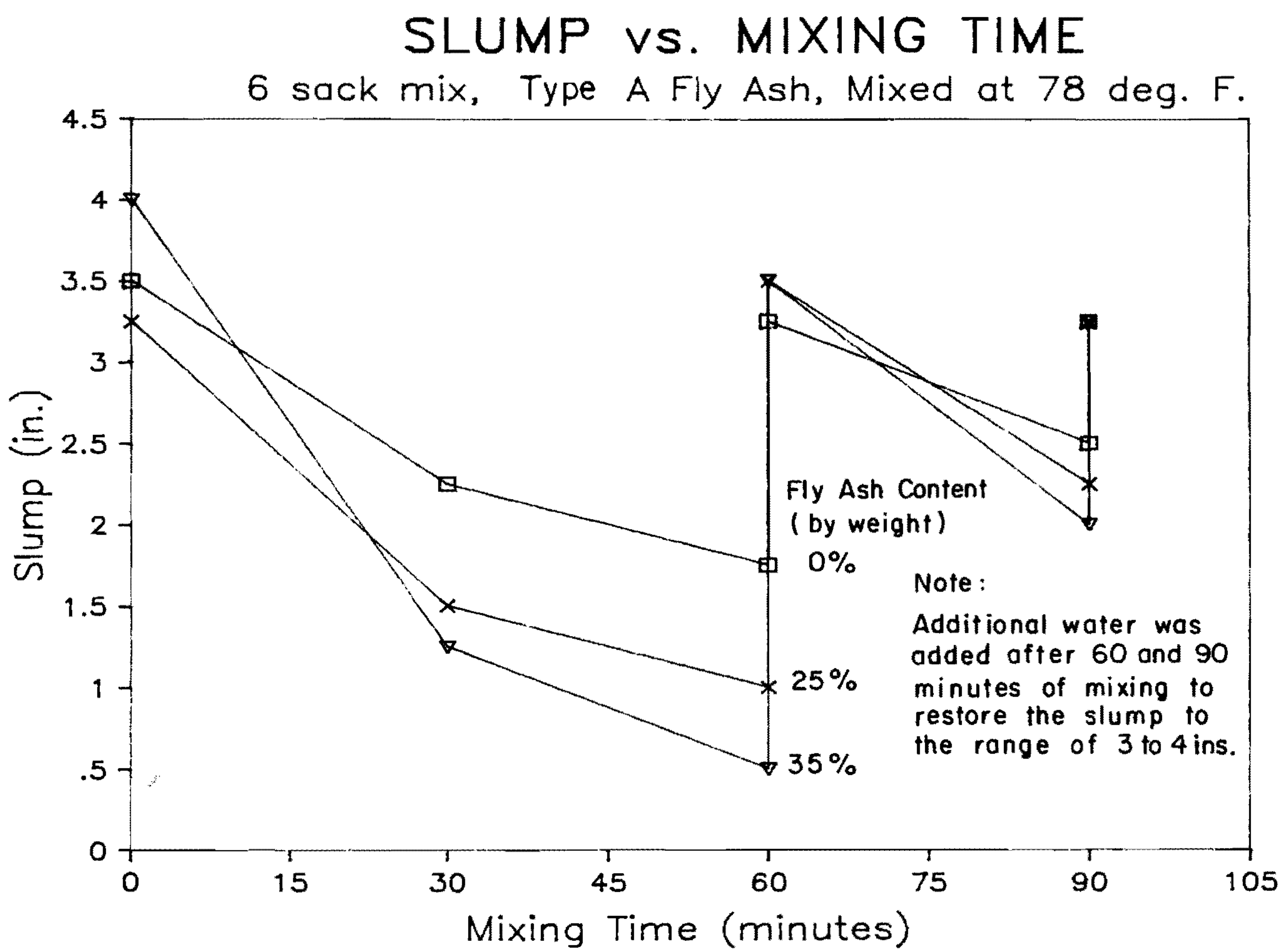

Fig. 5.47 Slump versus mixing time, six sack mixes, Type A fly ash, mixed at 78°F.

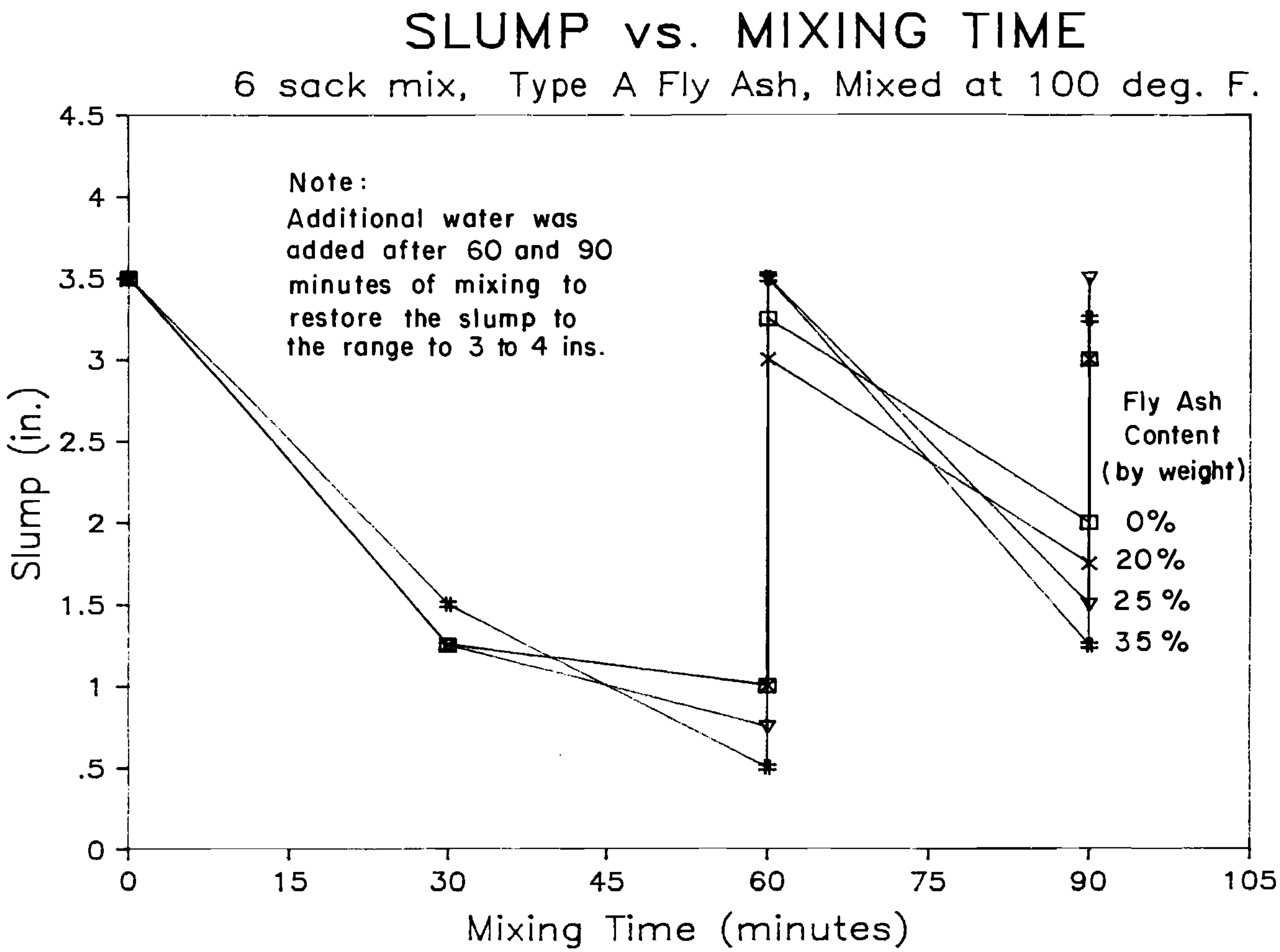

Fig. 5.48 Slump versus mixing time, six sack mixes, Type A fly ash, mixed at 100°F.

with water. The slump loss for the control mix was 36% for the first 30 minutes of mixing, 20% for the second 30 minutes of mixing, and 23% for the last 30 minutes of mixing after retempering to restore the slump.

The slump loss of concrete containing Type A fly ash mixed at 100°F ranged from 57 to 64% for the first 30 minutes of mixing, 20 to 67% for the second 30 minutes of mixing, and 42 to 63% for the last 30 minutes of mixing after the batch had been retempered with water. The slump loss for the control mix at 100°F was 64% for the first 30 minutes of mixing, 20% for the second 30 minutes of mixing and 38% for the last 30 minutes of mixing after retempering the batch.

5.5.2 Water-Cementitious Ratio. Figures 5.49 and 5.50 show the increase in the measured water-cementitious (w/cm) ratio with increased mixing time for concrete containing fly ash. At the time interval of 60 and 90 minutes the water-cementitious (w/cm) ratio was that measured after retempering water was added to the batch to restore the slump to the range of 3 to 4 in.

For concrete containing Type A fly ash mixed at 78°F, the increase in the water-cementitious (w/cm) ratio due to the added water demand after 60 minutes of mixing ranged from 8 to 12%, and from 4 to 5% over the water-cementitious (w/cm) after the concrete was retempered at a mixing time of 90 minutes. Concrete containing Type A fly ash mixed at 100°F had a water-cementitious (w/cm) ratio increase due to the added water after 60 minutes of mixing in the range of 8 to 21% and from 7 to 11% over the water-cementitious (w/cm) ratio obtained at 60 minutes after the concrete was retempered at a mixing time of 90 minutes. The increase in the water-cementitious (w/cm) ratio of the control batch mixed at 78°F due to the added water demand after a mixing time of 60 minutes was 4%. Retempering the control concrete batch at a mixing time of 90 minutes resulted in an increase of the water-cementitious ratio over that obtained at a mixing time of 60 minutes of 4%.

5.5.3 Flexural Strength. Results of the 7-day flexural strength test on concrete containing Type A fly ash cast after 0, 60 and 90 minutes of mixing are presented in Figs. 5.51 and 5.52. Compared to ordinary concrete, concrete containing fly ash had a higher loss in flexural strength after 60 minutes of mixing time. Provided the flexural strength of the mix containing fly ash was greater than that of the control mix at time t = 0 min., the flexural strength of concrete containing fly ash was still higher than that of the control mix after 60 minutes of mixing time. If

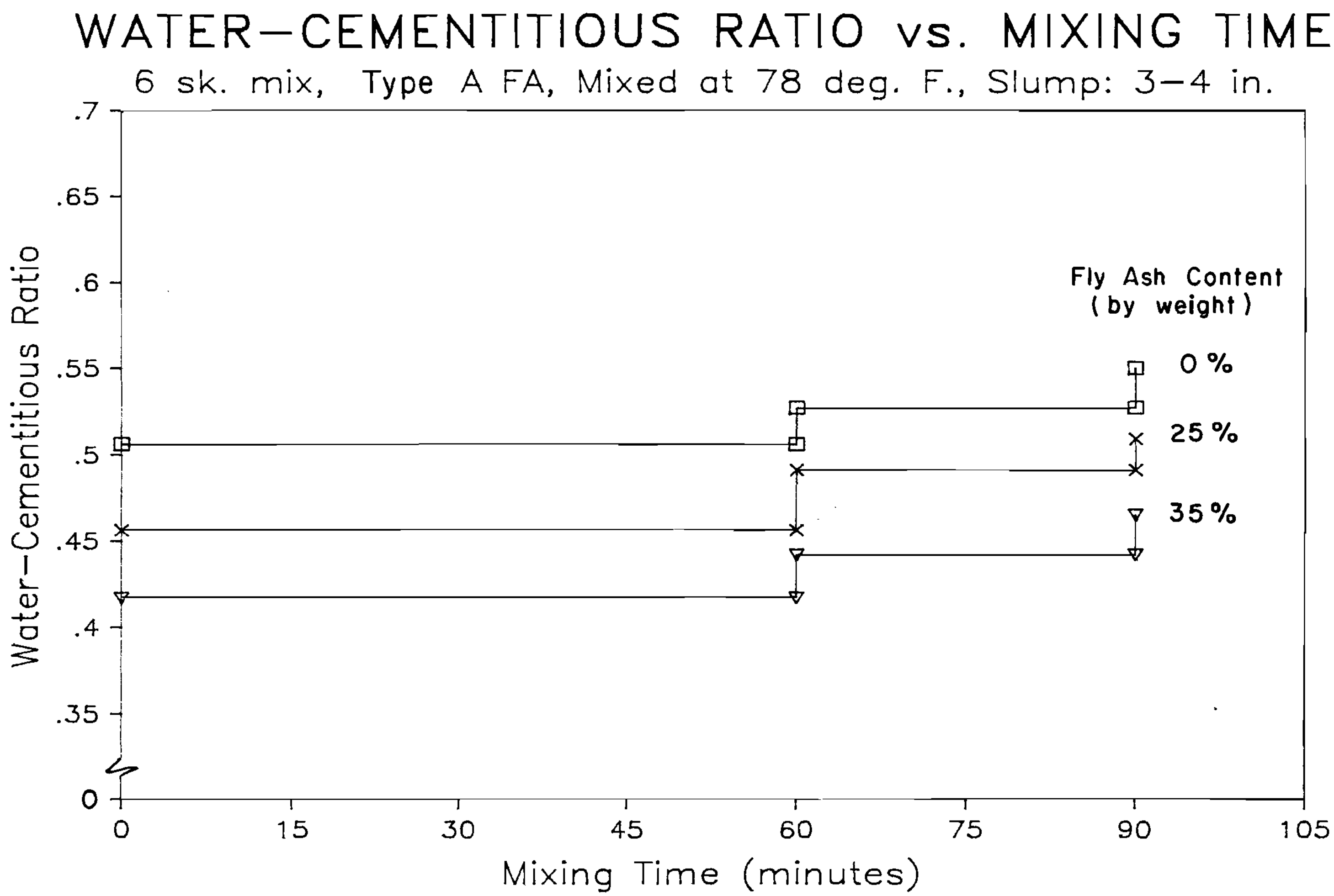

Fig. 5.49 Water-cementitious ratio versus mixing time, six sack mixes, Type A fly ash, mixed at 78°F.

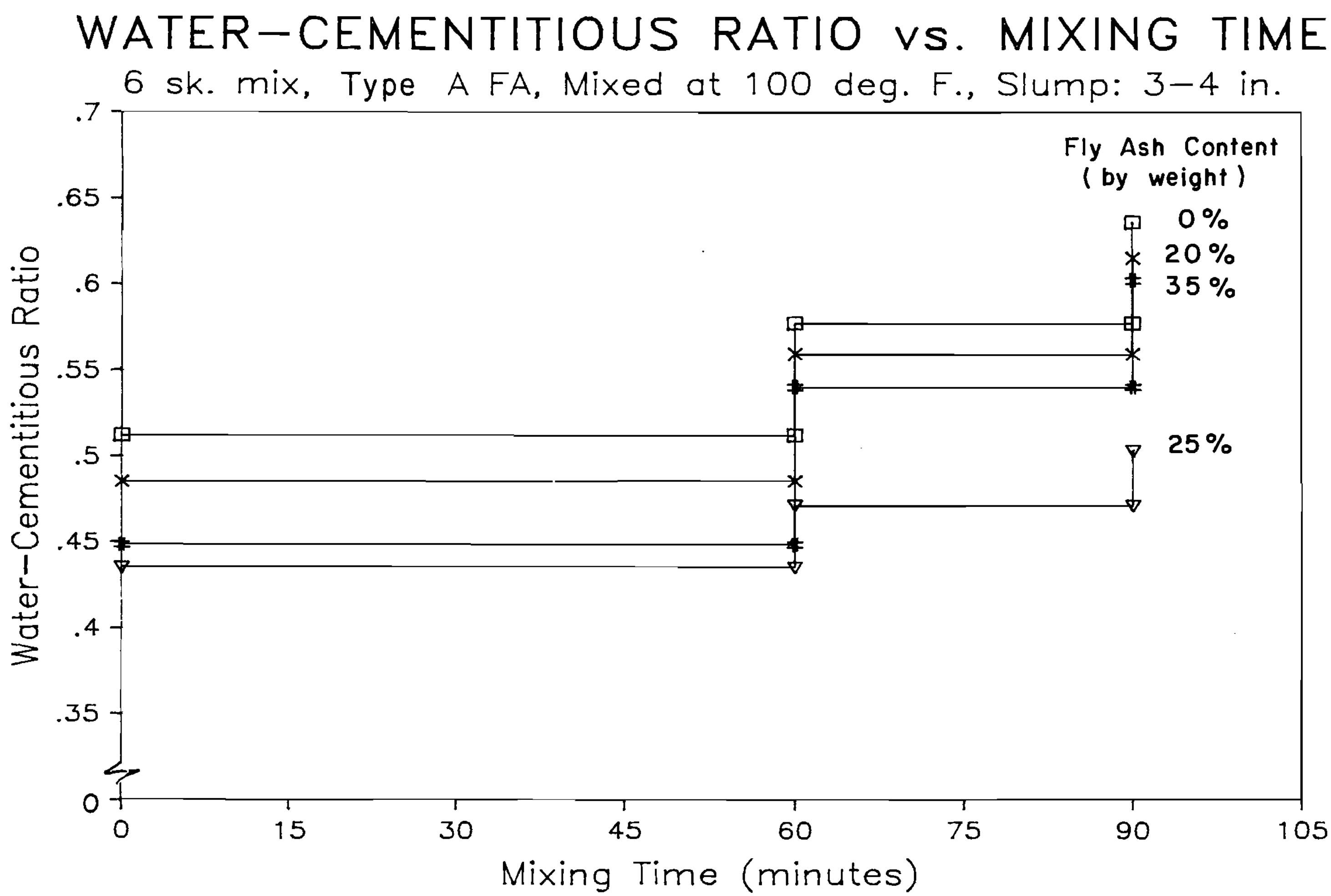

Fig. 5.50 Water-cementitious ratio versus mixing time, six sack mixes, Type A fly ash, mixed at 100°F.

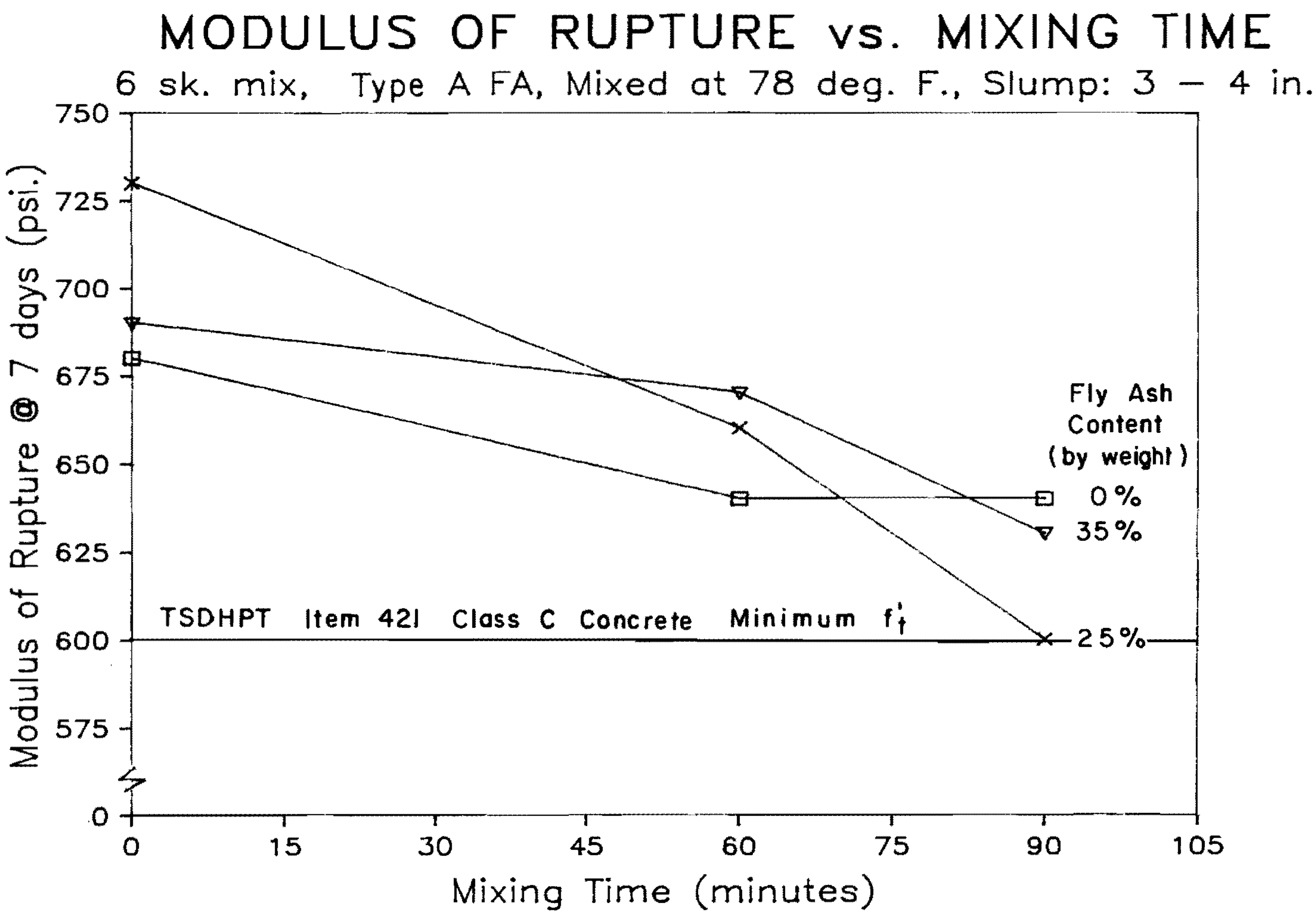

Fig. 5.51 Modulus of rupture versus mixing time, six sack mixes, Type A fly ash, mixed at 78°F.

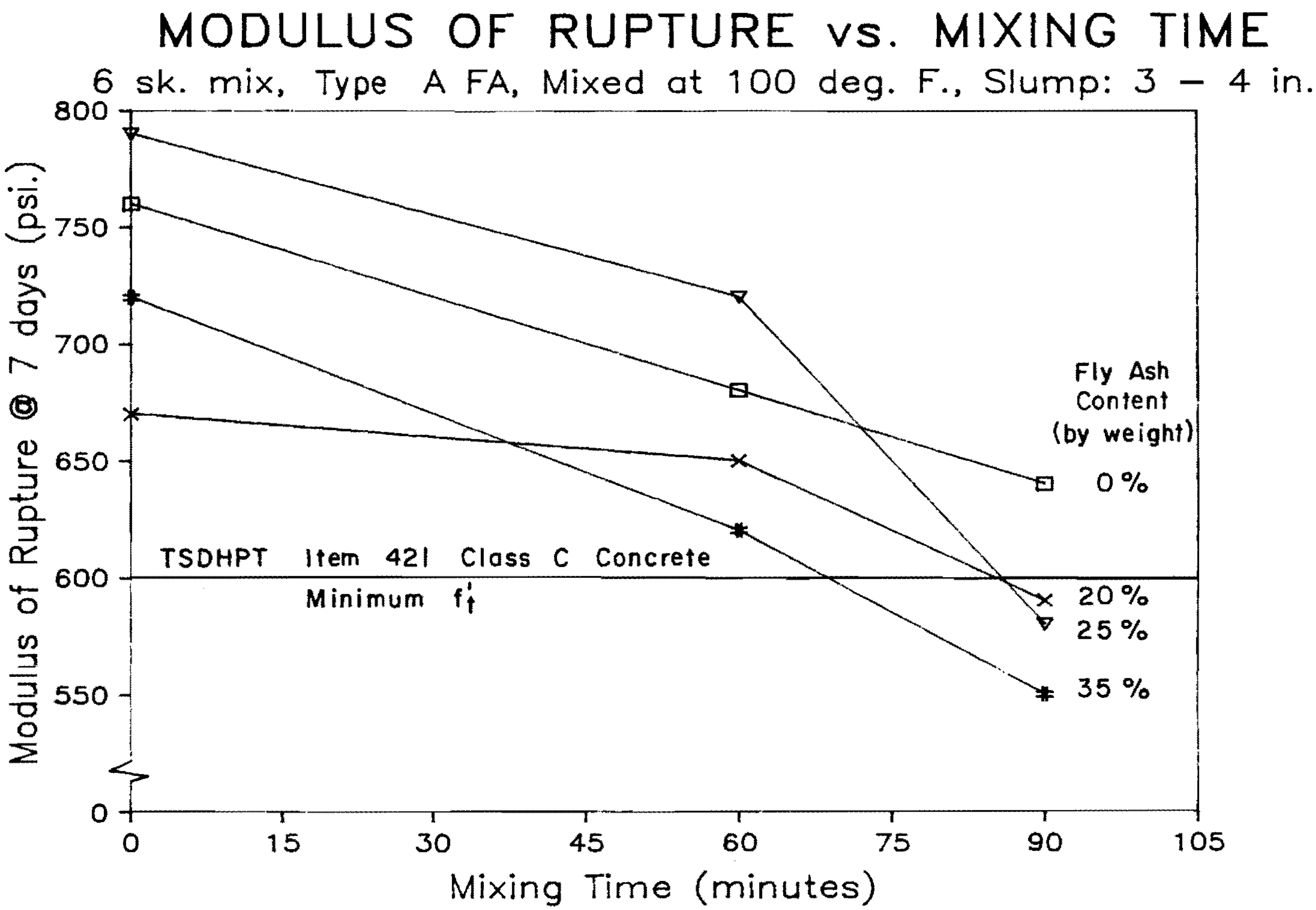

Fig. 5.52 Modulus of rupture versus mixing time, six sack mixes, Type A fly ash, mixed at 100°F.

the mixing time was extended to 90 minutes the flexural strength of concrete containing fly ash was lower than that of the control mix. Some of the concrete containing fly ash mixed at 100°F and cast at 90 minutes had flexural strength lower than the minimum required for TSDHPT Item 421 Class C concrete.

5.5.4 Compressive Strength. Results of the 28-day compressive strength test on concrete containing Type A fly ash cast after 0, 60 and 90 minutes of mixing are presented in Figs. 5.53 and 5.54. The general trend observed for the 28-day compressive strength of concrete containing fly ash was a decrease in compressive strength with an increase in the fly ash content. This loss in 28-day compressive strength was higher for mixes batched at 100°F. Mixes containing Type A fly ash in the range of 25 to 35% by weight had a decrease in the compressive strength in the range of 18% with an increase in the mixing time to 60 minutes. After the mixes were retempered at 60 minutes the 28-day compressive strength loss due to an additional 30 minutes of mixing was in the range of 3%.

The mixes containing Type A fly ash batched at 78°F had a decrease in the 28-day compressive strength in the range of 8% after the mixes were retempered at 60 minutes and mixed an additional 30 minutes. The differences observed here are due to the high temperature of the mixes batched at 100°F and the extended mixing time, 60 minutes, before the mixes were retempered. After 60 minutes of mixing, the water demand of the mixes containing Type A fly ash batched at 100°F was higher than that of mixes containing Type A fly ash batched at 78°F. This can be noted by comparing Figs. 5.49 and 5.50. This was due mainly to the evaporation of water in the concrete mix due to the high temperature. Concrete batched at 78°F was not susceptible to the loss of water by evaporation; therefore, the slump loss after 60 minutes of mixing was less than the slump loss obtained for the same mixing time for concrete batched at 100°F.

5.5.5 Discussion of Test Results. Concrete containing Type A fly ash has a greater slump loss with increased mixing time compared to ordinary concrete. For mixes done at room temperature concrete containing fly ash averaged a slump loss 80% greater than that of the control mix after 30 minutes of mixing. After 60 minutes of mixing the slump loss of concrete containing fly ash was 75% greater than that of the control mix. The slump loss obtained for concrete containing Type A fly ash mixed at high temperatures 100°F, was approximately equal to that of the control mix after 30 minutes of mixing. After 60 minutes of

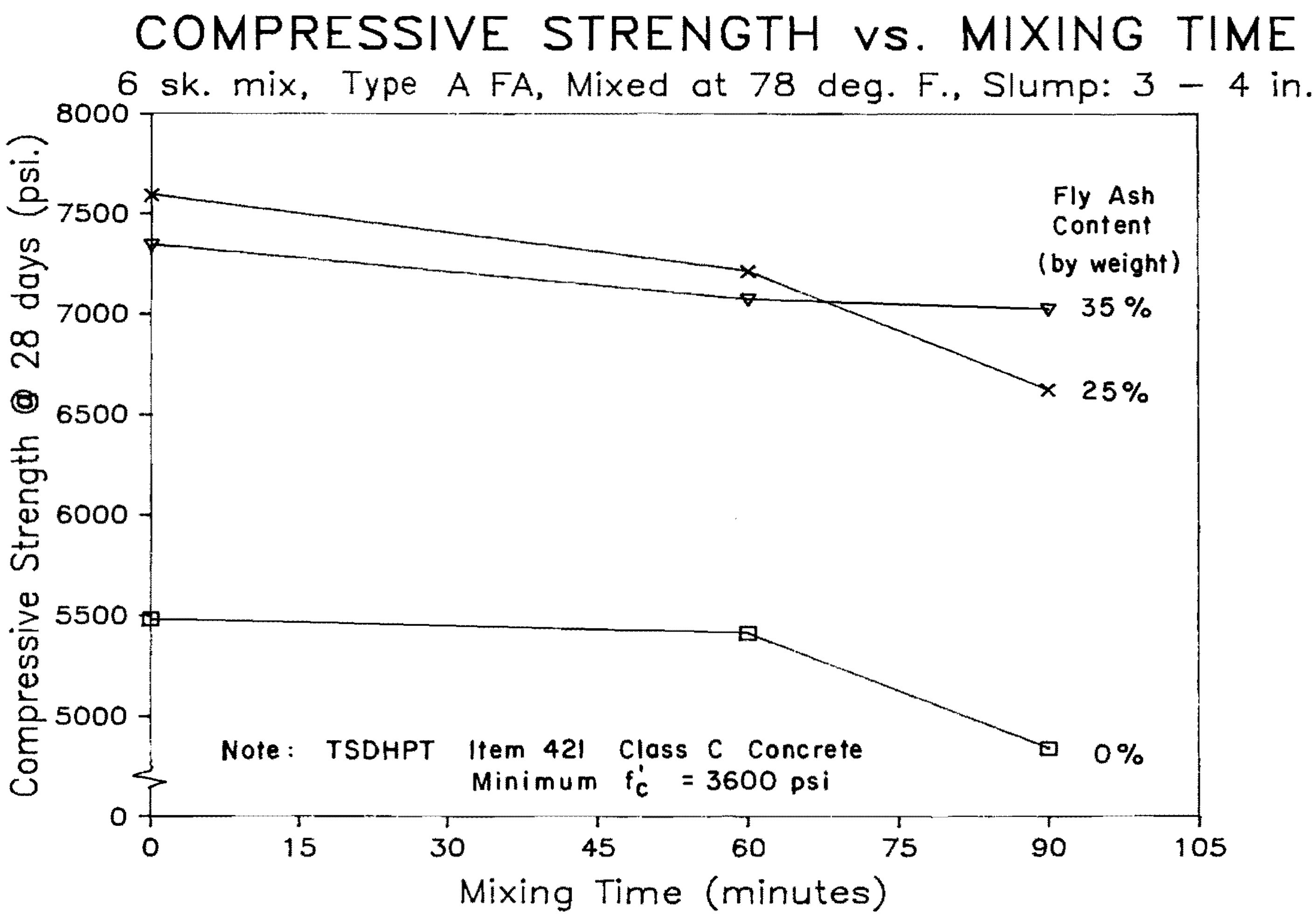

Fig. 5.53 Compressive strength versus mixing time, six sack mixes, Type A fly ash, mixed at 78°F.

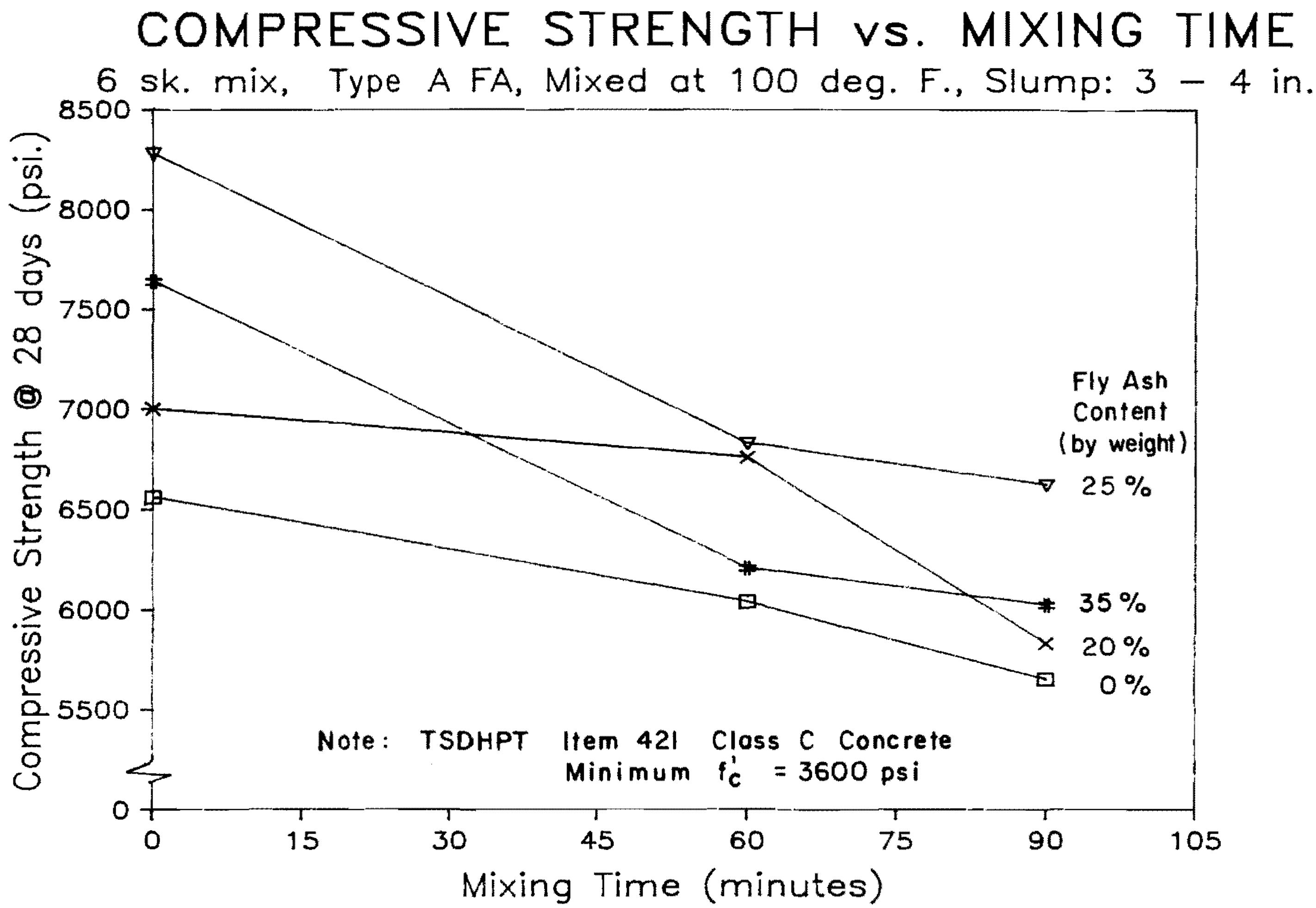

Fig. 5.54 Compressive strength versus mixing time, six sack mixes, Type A fly ash, mixed at 100°F.

mixing, concrete containing fly ash averaged a slump loss 10% greater than that obtained for the control mix.

Typically, concrete containing fly ash required a higher water content for retempering at 60 and 90 minutes compared to ordinary concrete. The increased water demand after 60 and 90 minutes of mixing required to obtain concrete with a slump in the range of 3 to 4 in. resulted in increases in the water-cementitious (w/cm) ratio of concrete poured at these times as compared to concrete poured at time, t = 0 minutes. However, concrete containing fly ash had water-cementitious (w/cm) ratios lower than that of the control mix for all mixing times including after the concrete was retempered. Concrete mixes containing fly ash done at a temperature of 78°F averaged water-cementitious (w/cm) ratios 14% lower than that of the control mix after initial mixing, 11% lower after 90 minutes of mixing. For mixes done at 100°F concrete containing fly ash averaged the following reductions in the water-cementitious ratios as compared to the control mix, 11% after initial mixing, 9% after 60 minutes of mixing, and 10% after 90 minutes of mixing. Mixes done at 100°F averaged water-cementitious ratios 2%, 10%, and 16% higher than mixes done at 78°F after 0, 60, and 90 minutes of mixing respectively.

Concrete containing fly ash mixed for more than 60 minutes did not satisfy TSDHPT Item 421 Class C concrete requirements. All mixes containing fly ash had 7-day flexural strength less than 600 psi if the specimen was poured after 90 minutes of mixing. The same results were obtained for concrete mixed at 78°F. Concrete containing fly ash mixed at 78°F averaged 7-day flexural strengths 4% higher than the control mix for the first 60 minutes of mixing. After 90 minutes of mixing the 7-day flexural strength of concrete containing fly ash was 4% lower than that of the control mix.

At a mixing temperature of 100°F concrete containing fly ash averaged a 7-day flexural strength 4% lower than the control mix for the first 60 minutes of mixing and 11% lower after 90 minutes of mixing. From these observations it is recommended that concrete containing fly ash have a mixing time limit of 60 minutes, if it is to be retempered at 60 minutes.

CHAPTER 6

MIX DESIGN RECOMMENDATIONS AND ECONOMICAL CONSIDERATIONS

6.1 Mix Design Recommendations

The governing specification used by the Texas State Department of Highways and Public Transportation (TSDHPT) for the production of structural concrete is the TSDHPT 1982 Standard Specification for the Construction of Highways, Streets and Bridges Item 421, "Concrete for Structures". This specification governs the mix design requirements for a total of ten classes of regular and special concrete. This study was concerned with the production of Item 421 Class C concrete. This class of concrete is generally used for drilled shaft, bridge railings and substructure, culvert, wingwall, concrete approach slab, concrete barrier railing and machine laid curb construction. The following recommendations concern the production of TSDHPT Item 421 Class C concrete.

Using a format similar to that used by the TSDHPT, Table 6.1 entitled "Mix Design Guidelines for the Production of Structural Concrete Containing Fly Ash" is presented here. The information in Table 6.1 is a result of over 40 trial batches of concrete made using materials commercially available to ready-mix plants in the State of Texas and mixed using conventional mixing techniques. The recommendations are based on a study of the interaction among components of concrete containing fly ash and its mix proportions, and of their contribution to the strength of the concrete produced. It is expected that the recommendations presented in Table 6.1 will serve as a guideline to resident engineers in the selection of materials and their proportions for producing concrete containing fly ash. Table 6.1 is intended to be used as a guideling only and it should not replace the making of trial mixes. As new information becomes available, the recommendations in Table 6.1 should be modified to incorporate field experience in using concrete containing fly ash. Substantial improvements in strength and workability may be achieved simply by experimenting with different brands of cement, fly ash, and chemical admixtures. Concrete producers are also encouraged to try fly ash contents greater than the maximums specified in Table 6.1. An increase in the amount of water used above that recommended may result in a drastic loss of strength. Admixture dosages can be expected to vary with brand of admixture and source of fly ash. In securing a source of fly ash to be

TABLE 6.1 Mix Design Guidelines for the Production of Structural Concrete Containing Fly Ash

Class of concrete	C
Sacks of cement per cu.yd. (min.)	6
Minimum compressive strength (f'_c) 28 day, psi	3600[a]
Minimum beam strength (f'_t) 7 day, psi	600[b]
Maximum water-cementitious ratio (gal/sack)	5.1[c]
Maximum water-cementitious ratio (gal/100 lbs)	5.4[d]
Maximum fly ash, LOI, %	0.26[e]
Fly ash content, % by wt	25-35

[a] Based on tests performed on a 6 x 12 in. cylinder of concrete cast in a rigid steel mold.

[b] Based on tests performed on a 6 x 6 x 18 in. simply supported beam tested at the centerpoint.

[c] Mixes containing no fly ash have a maximum water-cementitious ratio of 6 gal/sack.

[d] Mixes containing no fly ash have a maximum water-cementitious ratio of 6.4 gal/100 lbs.

[e] The use of fly ash having a LOI greater than 0.26 is permitted provided the proper amount of air is entrained in the concrete mix. This will require an increase in the dosage of the air-entraining admixture used. Air contents greater than 3% are recommended for for proper protection of concrete subjected to freeze-thaw cycles.

used it is important that the chemical and physical composition of the fly ash be maintained constant throughout the production of concrete. See the footnotes following Table 6.1 for additional important refinements to the guidelines.

For trial mix design purposes a total of at least three small trial mixes shall be made for any cementitious content selected. Trial mixing shall consist of one trial mix containing no fly ash and of two other trial mixes having two different fly ash contents. Fly ash contents by weight of total cementitious material in the range from 20 to 35% for both Type A and Type B fly ash are suggested. At least five flexural strength beam specimens for strength testing should be made. The beam specimens should be cured and tested at seven days in accordance with TSDHPT testing procedures. Plot the test results as shown in Fig. 6.1, "Trial mix design curves". The optimum mix proportion for use in the Field Trial Batch should be selected from the trial mix design curves (Fig. 6.1) based on the desired strength and cost effectiveness. Unless based on prior experience, the small trial mix design selected for field testing should have a flexural strength at least 1.10 times the minimum required flexural strength in the specification. The trial mix design procedure should be repeated as needed increasing the cementitious content until a mix satisfying all design and specification requirements is obtained.

6.2 Economic Considerations

The use of fly ash in concrete construction has been shown to result in more economical structures. Use of high strength concrete containing fly ash may result in a delivered cost saving of 5% per 1000 psi for a concrete compressive strengths in the range of 9000 to 12000 psi [29]. Use of fly ash in mass concrete has resulted in a delivered cost saving of $1.75/cu.yd. and a delivered cost saving of $1.50/cu.yd. for structural concrete [32].

Table 6.2 summarizes the costs of the materials used in the production of ordinary concrete and concrete containing fly ash. This program of study did not investigate variations in the admixture dosage requirements of concrete containing fly ash; therefore, the costs of the admixture required are not included. Concrete containing Type A fly ash which has a high carbon content may require excessive amounts of air-entraining admixture to develop a proper air-void system. High air-entraining admixture dosage requirements may reduce the cost savings achieved with the use of fly ash.

Cost comparisons of some of the concrete mixes studied in this report are presented in Table 6.3.

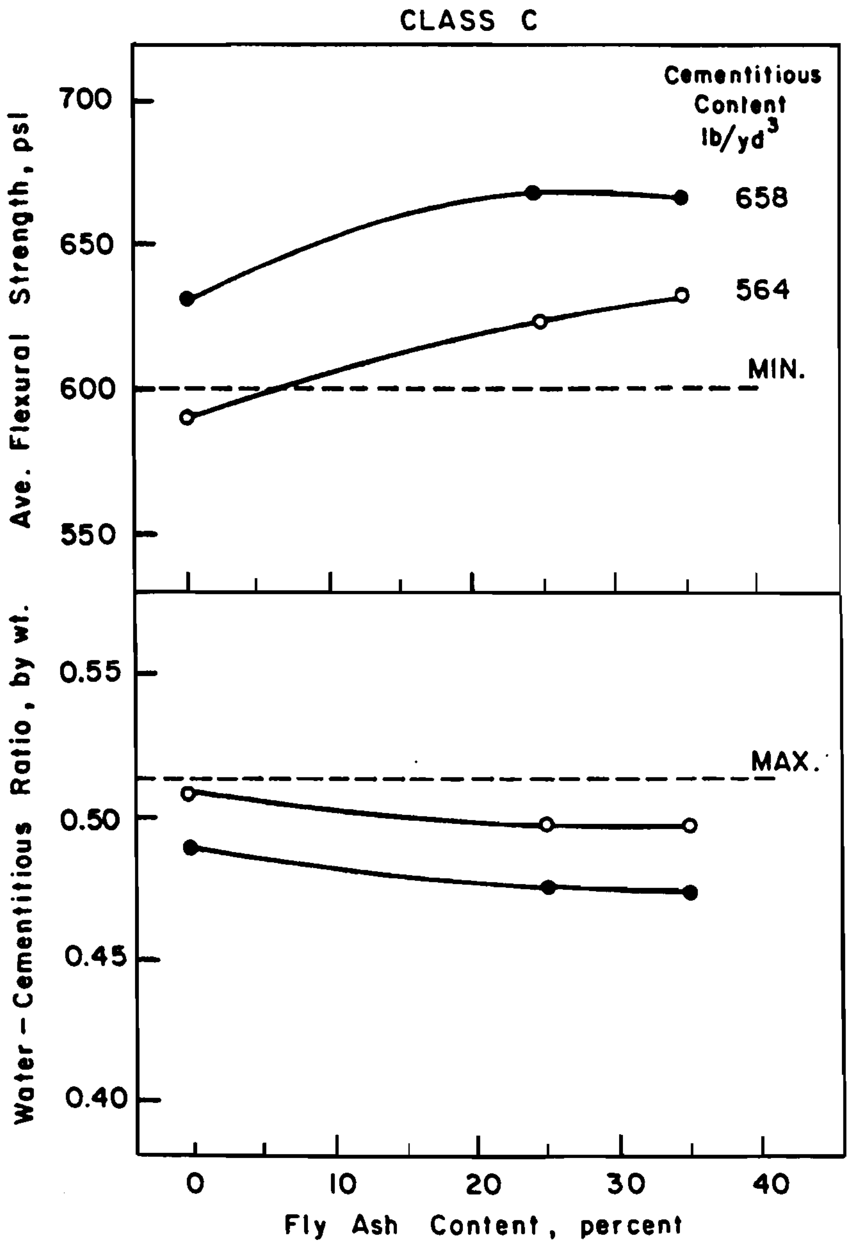

Fig. 6.1 Small trial mix design curves.

TABLE 6.2 Assumed Material Costs (based on February 1985 delivered price to Austin, Texas)

Type I cement	\$ 63.00/ton
Type IP cement	\$ 63.00/ton
Type A fly ash	\$ 24.08/ton
Type B fly ash	\$ 36.60/ton
Coarse aggregate	\$ 5.30/ton
Fine aggregate	\$ 3.50/ton

TABLE 6.3 Comparison of Material Costs for Concrete Containing Fly Ash (Fine and Coarse Aggregate Quantities Constant)

Concrete Description	Approximate Mix Design	Total Cost Material $/cu.yd.	Conc. Cost per cu.yd. %/ cu.yd.	Total Cost $/ 1000 psi	Relative Cost
7 sack, 5600 psi, no fly ash	Cement 658 lb Fly Ash ---	$20.73 ---- $20.73	100%	$3.66	1.00
7 sack, 5820 psi, Type IP cement	Cement 658 lb Fly Ash ---	20.73 ---- $20.73	100%	$3.56	0.97
7 sack, 6000 psi 15% Type B fly ash	Cement 559 lb Fly Ash 99 lb	$17.61 1.81 $19.42	91% 9	$3.24	0.89
7 sack, 6520 psi 15% Type A fly ash	Cement 559 lb Fly Ash 99 lb	$17.61 1.19 $18.80	94% 6	$2.88	0.79
7 sack, 5710 psi 35%, Type B fly ash	Cement 428 lb Fly Ash 230 lb	$13.48 4.21 $17.69	76% 24	$3.10	0.85
7 sack, 6940 psi 35% Type A fly ash	Cement 428 lb Fly Ash 230 lb	$13.48 2.77 $16.25	83% 17	$2.34	0.64

CHAPTER 7

CONCLUSIONS

The results of this study demonstrate that structural concrete containing fly ash can be produced in the State of Texas with readily available materials using conventional batching procedures. The following conclusions have been made regarding the selection of materials, mix design, and production of concrete containing fly ash satisfying the requirements of TSDHPT Standard Specification Item 421, "Concrete for Structrures," Class C concrete.

1. Concrete containing a maximum fly ash content of 35% by weight and having the minimum cementitious content specified for TSDHPT 421 Class C concrete (6 sacks/cu.yd.) satisfies the minimum flexural and compressive strength requirements for the above-mentioned class of concrete. It is therefore recommended that concrete containing fly ash have a minimum cementitious content of 564 lbs/cu.yd. (6 sacks/cu.yd.).

2. The water-cementitious ratio (w/cm) is the most important factor affecting the compressive strength of concrete. In general, to produce concrete containing fly ash having a 28-day compressive strength of at least 3600 psi, the water-cementitious ratio (w/cm) must be less than 0.45.

3. Replacement of cement with fly ash on an equal weight basis results in concrete of a lower 28-day compressive strength than ordinary concrete. At an age of approximately 91 days the compressive strength of concrete containing fly ash will be equal to that of ordinary concrete.

4. The most influential factor affecting the freeze-thaw resistance of concrete containing fly ash is the loss on ignition (LOI). To produce concrete containing fly ash having adequate freeze-thaw resistance the LOI of the fly ash used should be limited to 0.26%. Use of fly ash having a LOI greater than 0.26 is permitted provided the proper amount of air is entrained in the concrete mix. This will require an increase in the

dosage of the air-entraining admixture used. Air contents greater than 3% are recommended for the proper protection of concrete subjected to freeze-thaw cycles.

5. Fly ash is a highly variable material which is influenced by such factors as type of coal used, operating efficiency of the firing unit, type of collection equipment used, and storage conditions. Strict quality control must be enforced to ensure the fly ash used is of uniform consistency both chemically and physically.

6. For trial mix design purposes the seven-day modulus of rupture obtained using a simple beam with center point loading should be used as the acceptance criteria.

7. It has been shown that concrete containing fly ash is more economical than ordinary concrete. Concrete containing fly ash, delivered to the construction site, can be from 10 to 35% more economical than ordinary concrete. The main factor affecting the reduction in cost is the fly ash content of the mix. The user should be aware of concrete containing fly ash requiring a high dosage of air-entraining admixture for the development of a proper air-void system. In many cases, the increase in cost due to the admixture requirements may eliminate any savings in cost obtained by the use of fly ash.

8. The 28-day compressive strength of concrete containing fly ash which has been moist cured according to ASTM C192 (78°F, 98% RH) for seven days after casting is not seriously affected by curing in hot (100°F) and dry (33% RH) conditions from 7 to 28 days after casting.

9. The 28-day compressive strength of concrete containing fly ash which has been moist cured according to ASTM C192 (78°F, 98% RH) for three days after casting is not seriously affected by curing in cold weather (45°F, 55% RH) from 3 to 28 days after casting.

10. Concrete containing fly ash having a slump in the range of 3 to 4 in. can be produced even when mixing temperatures are of the order of 100°F and the total period of mixing does not exceed 60 minutes.

11. It is recommended that concrete mixes containing Type A or Type B fly ash requiring a water reducing-retarding admixture should be mixed to the desired workability, then allowed to stand for 5 to 10 minutes, and finally remixed, adding water if necessary, until the desired degree of workability is obtained. This should be done to ensure retardation of setting in the concrete does not occur.

APPENDIX A

MATERIAL PROPERTIES

The physical and chemical properties of the portland cement and fly ash used in this study are included in this section.

TABLE A.1 Chemical and Physical Properties of Cements Used in This Study

Cement Type	I	IP
Chemical Data		
SiO_2 (%)	22.0-22.4	28.94
Al_2O_3 (%)	4.1- 4.6	7.91
Fe_2O_3 (%)	3.1- 3.3	3.84
CaO (%)	64.3-65.5	53.05
MgO (%)	0.8- 0.9	0.96
SO_3 (%)	2.5- 2.7	2.70
Loss on Ignition (%)	0.7- 0.9	--
Insoluble Residue	0.3- 0.5	14.70
Free Lime	0.6- 0.9	0.74
Tricalcium Silicate (C_3S)	49.9-56.2	--
Tricalcium Aluminate (C_3A)	6.0- 7.0	--
Physical Data		
Specific Surface, sq. cm./gm.		
Blaine	3230-3340	3734
Wagner	1840-1900	----
Compressive Strength (psi)		
ASTM C109 Mortar Cubes		
1 day	1590-1910	1922
3 days	3320-3520	3513
7 days	4450-4700	4545
28 days	---	6093
Time of Setting (min.)		
Vicat		
Initial	88- 98	106
Final	205- 215	226
Gilmore		
Initial	126-135	165
Final	234-256	280
Air Entrainment (%)	9.1-10.8	6.7
Soundness (%)		
Autoclave Expansion	0.01-0.02	-0.021

TABLE A.2 Chemical and Physical Properties of Fly Ashes Used in This Study

	TDSHPT Type A	TDSHPT Type B
I. Chemical Analysis (% wt)		
A. Metal Oxides		
1. Sum of Fe_2O_3, SiO_2, and Al_2O_3	78.47	57.05
2. CaO	10.22	38.09
3. SO_3	0.94	4.24
4. MgO	1.73	6.80
B. Moisture Content	0.10	0.15
C. Loss on Ignition	0.43	0.26
D. Alkali Oxides		
1. Na_2O	-----	-----
2. K_2O	-----	-----
3. Total Alkalies	-----	-----
II. Physical Analysis		
A. Pozzolanic Activity Index (% of control)	96.95	106.04
B. Water Requirement (% of control)	91.67	91.67
C. Fineness (% retained on No. 325 sieve)	12.8	12.8
D. Soundness (% of control)	-0.016	0.106
E. Specific Gravity	2.46	2.72
F. Drying Shrinkage of Mortar Bar @ 28 Days (% of control)	-0.011	0.008

TABLE A.3 Chemical and Physical Properties of the Type A Fly Ash Used in the Type IP Cement

	TDSHPT Type A
I. Chemical Analysis (% wt)	
A. Metal Oxides	
1. Sum of Fe_2O_3, SiO_2, and Al_2O_3	85.47
2. CaO	9.22
3. SO_3	0.22
4. MgO	1.88
B. Moisture Content	----
C. Loss on Ignition	0.25
D. Alkali Oxides	
1. Na_2O	0.17
2. K_2O	0.22
3. Total Alkalies	0.31
II. Physical Analysis	
A. Pozzolanic Activity Index (% of control)	-----
B. Water Requirement (% of control)	-----
C. Fineness (% passing a No. 325 sieve)	64.3
D. Soundness (% of control)	-----
E. Specific Gravity	-----
F. Drying Shrinkage of Mortar Bar @ 28 Days (% of control)	-----

APPENDIX B

MIX PROPORTIONS

In the following pages, mix proportions used for the concrete mixes made during the experimental phase of this study are presented. The mixes are identified using the convention shown below:

Type of Fly Ash

6 B 15

Cementitious Content (sacks/cu.yd.)

Fly Ash Content (% by wt)

Concrete containing no fly ash is identified as follows:

6 IP

Cementitious Content (sacks/cu.yd.)

Type of Cement Used

MIX PROPORTIONS

Batch	6I	6B15	6B25	6B35	6A15	6IP	6A25	6A35
Batch wt (lbs):								
Cement	113.0	72.0	78.0	70.0	72.0	98.75	78.0	67.5
Fine Agg.	209.0	157.5	193.0	198.25	157.5	183.75	193.0	193.0
Coarse Agg.	401.0	312.25	370.5	380.5	312.25	364.25	370.5	370.5
Water	49.0	36.0	45.0	50.0	33.5	36.0	44.5	51.0
Fly Ash:								
Type		B	B	B	A	A	A	A
Wt (lbs)		12.75	26.0	37.5	12.75		26.0	36.75
% Replace.		15	25	35	15	20	25	35
Adm. (cc):								
Retarder	190	147	180	180	147		180	171
Air Entr.	18	13	16	16	13		16	15
w/cm Ratio	0.437	.428	0.435	0.466	0.396	0.367	0.432	0.494
Slump (in.)	3.5	3.0	3.5	5.0	3.5	3.0	4.5	3.5
% Air	4.3	2.0	4.4	4.0	1.9	3.8	3.2	3.0
Temp. °F	74	83	75	75	78	78	75	75
Unit Wt. (lb/ft^3)	144.0	146.0	144.0	144.0	146.0	142.0	143.0	146.0
f'_t @ 7 d (psi)	645	650	700	760	760	695	700	575
f'_c @ 28 d (psi)	6220	5660	4840	6790	6370	6240	5470	6640

Comments: Mixes for strength and durability comparisons.

MIX PROPORTIONS

Batch	7I	7B15	7B25	7B35	7A15	7IP	7A25	7A35
Batch wt (lbs):								
Cement	121.75	103.5	91.25	79.0	103.5	121.75	93.75	60.0
Fine Agg.	159.25	159.25	159.25	159.25	159.25	159.25	163.5	121.75
Coarse Agg.	370.25	370.25	370.25	370.25	370.25	370.25	380.25	291.5
Water	47.0	47.0	46.5	41.5	46.5	42.5	47.0	33.5
Fly Ash:								
Type	-	B	B	B	A	A	A	A
Wt (lbs)	-	18.25	30.5	42.5	18.25	-	31.25	32.25
% Replace.	-	15	25	35	15	20	25	35
Adm. (cc):								
Retarder	180	180	180	180	180	180	180	137
Air Entr.	19	19	19	19	19	19	19	14.5
w/cm Ratio	0.390	0.386	0.382	0.344	0.382	0.353	0.377	0.367
Slump (in.)	3.0	3.5	3.0	3.5	4.5	4.5	4.0	3.0
% Air	3.5	4.0	3.3	3.8	2.0	2.3	2.0	1.8
Temp. ^{o}F	75	74	76	75	74	75	74	73
Unit Wt. (lb/ft^3)	145.0	142.0	144.0	143.0	146.0	146.0	145	146.0
f'_t @ 7 d (psi)	715	615	700	670	710	740	740	700
f'_c @ 28 d (psi)	5660	6000	5200	4960	6520	5820	5850	6940

Comments: Mixes for strength and durability comparisons.

MIX PROPORTIONS

Batch	6I	6B15	6B25	6B35	6A15	6IP	6A25	6A35
Batch wt (lbs):								
Cement	203.5		148.5			193.25	150.0	
Fine Agg.	378.0		368.5			360.0	372.75	
Coarse Agg.	750.0		730.5			714.0	739.0	
Water	87.0		85.0			83.0	90.0	
Fly Ash:								
Type	-		C			F	F	
Wt (lbs)	-		53.5			-	54.25	
% Replace.	-		25			20	25	
Adm. (cc):								
Retarder	345		342			333	342	
Air Entr.	32		32			29	32	
w/cm Ratio	0.428		0.421			0.431	0.443	
Slump (in.)	4.0		4.0			3.75	3.75	
% Air	4.6		4.4			3.2	2.1	
Temp. ^{o}F	75		75			75	74	
Unit Wt. (lb/ft^3)	144.0		143.0			146.0	146	
f'_t @ 7 d (psi)	880		680			800	655	
f'_c @ 28 d (psi)	5930		5000			5780	7020	

Comments: Mixes for hot curing conditions (6 sacks).

MIX PROPORTIONS

Batch	7I	7B15	7B25	7B35	7A15	7IP	7A25	7A35
Batch wt (lbs):								
Cement	233.75		175.5	149.5		230.5	173.0	149.5
Fine Agg.	308.75		309.0	304.5		304.5	304.5	304.5
Coarse Agg.	739.5		739.5	729.0		729.0	729.0	729.0
Water	89.0		87.0	79.0		80.0	77.0	77.0
Fly Ash:								
Type	-		C	C		F	F	F
Wt (lbs)	-		58.25	80.5		-	57.5	80.5
% Replace.	-		25	35		20	25	35
Adm. (cc):								
Retarder	342		342	342		342	342	342
Air Entr.	36		36	36		36	36	36
w/cm Ratio	0.383		0.373	0.345		0.348	0.335	0.335
Slump (in.)	4.0		3.25	3.0		3.25	4.0	4.0
% Air	3.8		3.0	3.5		3.5	2.4	1.6
Temp. ^{o}F	75		75	77		75	75	75
Unit Wt. (lb/ft^3)	145.0		145.0	145.0		143.0	146.0	146.0
f'_t @ 7 d (psi)	750		650	755		725	855	685
f'_c @ 28 d (psi)	6400		6170	7990		7580	7780	6540

Comments: Mixes for hot curing conditions (7 sacks).

MIX PROPORTIONS

Batch	6I	6B15	6B25	6B35	6A15	6IP	6A25	6A35
Batch wt (lbs):								
Cement	197.5		148.0			197.5	148.0	
Fine Agg.	367.5		367.5			367.5	367.5	
Coarse Agg.	728.5		728.5			728.5	728.5	
Water	84.0		78.5			78.0	72.0	
Fly Ash:								
Type	-		C			F	F	
Wt (lbs)	-		49.5			-	49.5	
% Replace.	-		25			20	25	
Adm. (cc):								
Retarder	342		342			286.0	342	
Air Entr.	32		32			32	32	
w/cm Ratio	0.427		0.399			0.397	0.367	
Slump (in.)	3.5		5.0			3.0	3.0	
% Air	4.6		6.0			3.0	3.0	
Temp. ^{o}F	76		77			77	76	
Unit Wt. (lb/ft^3)	142.0		139.0			145.0	144.0	
f'_t @ 7 d (psi)	700		575			795	710	
f'_c @ 28 d (psi)	6140		5150			7310	7230	

Comments: Mixes for cold curing conditions (6 sacks).

MIX PROPORTIONS

Batch	7I	7B15	7B25	7B35	7A15	7IP	7A25	7A35
Batch wt (lbs):								
Cement	230.5		173.0	149.5		230.5	173.0	149.5
Fine Agg.	304.5		304.5	304.5		304.5	304.5	304.5
Coarse Agg.	729.0		729.0	729.0		729.0	729.0	729.0
Water	86.5		80.5	85.5		88.0	84.5	83.5
Fly Ash:								
Type	-		C	C		F	F	F
Wt (lbs)	-		57.5	80.5		-	57.5	80.5
% Replace.	-		25	35		20	25	35
Adm. (cc):								
Retarder	342		342	342		342	342	342
Air Entr.	36		36	36		36	36	36
w/cm Ratio	0.376		0.350	0.373		0.383	0.368	0.364
Slump (in.)	4.0		3.0	2.5		3.5	2.5	3.5
% Air	-		2.7	3.0		2.0	1.8	1.0
Temp. °F	78		77	84		80	78	83
Unit Wt. (lb/ft^3)	-		144.0	143.0		144.0	145.0	146.0
f'_t @ 7 d (psi)	805		695	705		800	740	750
f'_c @ 28 d (psi)	6220		6000	6670		6350	7080	7540

Comments: Mixes for cold curing conditions (7 sacks).

MIX PROPORTIONS

Batch	6I							
Mixing Time (min)	0	30 min.	60 min.	90 min.				
Batch wt (lbs):								
Cement	84.5							
Fine Agg.	157.5							
Coarse Agg.	312.25							
Water	42.5		+1.75	+2.0				
Fly Ash:								
Type	-							
Wt (lbs)	-							
% Replace.	-							
Adm. (cc):								
Retarder	145							
Air Entr	13							
w/cm Ratio	0.506		0.527	0.550				
Slump (in.)	3.5	2.25	3.25	3.25				
% Air	5.0		5.0	4.9				
Temp. °F	68		68	66				
Unit Wt. (lb/ft^3)	139.0		139.0	140				
f'_t @ 7 d (psi)	680		640	635				
f'_c @ 28 d (psi)	5480		5410	4840				

Comments: Mixes were done at room temperature.

MIX PROPORTIONS

Batch	6A25				6A35			
Mixing Time (min)	0	30 min.	60 min.	90 min.	0	30 min.	60 min.	90 min.
Batch wt (lbs):								
Cement	63.5				57.0			
Fine Agg.	157.5				162.75			
Coarse Agg.	312.25				322.75			
Water	38.5		+3.0	+1.5	36.0		+2.25	+2.0
Fly Ash:								
Type	F				F			
Wt (lbs)	21.0				30.5			
% Replace.	25				35			
Adm. (cc):								
Retarder	145				150			
Air Entr	13				14			
w/cm Ratio	0.456		0.491	0.509	0.417		0.442	0.465
Slump (in.)	3.25	1.5	3.5	3.25	4.0	1.25	3.5	3.25
% Air	2.9		1.4	1.2	3.0		1.5	1.1
Temp. °F	65		66	65	65		65	66
Unit Wt. (lb/ft^3)	144.0		147.0	146.0	145.0		147.0	147.0
f'_t @ 7 d (psi)	730		660	595	690		670	625
f'_c @ 28 d (psi)	7590		7210	6620	7340		7070	7020

Comments: Mixes were done at room temperature.

MIX PROPORTIONS

Batch	**6I**				6IP			
Mixing Time (min)	___	30 min.	60 min.	90 min.	___	30 min.	60 min.	90 min.
Batch wt (lbs):								
Cement	84.5	___	___	___	84.5	___	___	___
Fine Agg.	157.5	___	___	___	157.5	___	___	___
Coarse Agg.	312.25	___	___	___	312.25	___	___	___
Water	43.0	___	+5.5	+5.0	40.5	___	+6.25	+4.75
Fly Ash:								
Type	-	___	___	___	F	___	___	___
Wt (lbs)	-	___	___	___	-	___	___	___
% Replace.	-	___	___	___	20	___	___	___
Adm. (cc):								
Retarder	145	___	___	___	145	___	___	___
Air Entr	13	___	___	___	13	___	___	___
w/cm Ratio	0.512	___	0.577	0.636	0.485	___	0.559	0.615
Slump (in.)	3.25	1.5	3.0	3.0	3.5	1.25	3.25	3.0
% Air	2.9	___	2.3	1.9	2.3	___	1.8	1.4
Temp. °F	98	___	105	100	85	___	99	100
Unit Wt. (lb/ft^3)	143.0	___	147.0	148.0	145	___	145.0	144.0
f'_t @ 7 d (psi)	755	___	680	640	670	___	650	590
f'_c @ 28 d (psi)	6560	___	6040	5640	7000	___	6760	5830

Comments: Mixes were done at high temperature.

MIX PROPORTIONS

Batch	6A25				6A35			
Mixing Time (min)	0	30 min.	60 min.	90 min.	0	30 min.	60 min.	90 min.
Batch wt (lbs):								
Cement	63.5				57.0			
Fine Agg.	157.5				162.75			
Coarse Agg.	312.25				322.75			
Water	36.5		+3.0	+2.75	39.0		+8.0	+5.5
Fly Ash:								
Type	F				F			
Wt (lbs)	21.0				30.5			
% Replace.	25				35			
Adm. (cc):								
Retarder	145				150			
Air Entr	13				14			
w/cm Ratio	0.435		0.471	0.503	0.448		0.540	0.602
Slump (in.)	3.5	1.25	3.5	3.5	3.5	1.5	3.5	3.25
% Air	2.7		1.0	0.8	1.0		0.9	0.9
Temp. °F	90		101	102	102		104	102
Unit Wt. (lb/ft^3)	146.0		147.0	148.0	148		147.0	146.0
f'_t @ 7 d (psi)	790		715	575	720		620	5.50
f'_c @ 28 d (psi)	8280		6830	6620	7640		6210	6020

Comments: Mixes were done at high temperature.

MIX PROPORTIONS

Batch	6I	6B15	6B25	6B35	6A15	6IP	6A25	6A35
Batch wt (lbs):								
Cement	84.5					87.25	63.5	57.0
Fine Agg.	157.5					162.75	157.5	162.75
Coarse Agg.	312.25					322.75	312.25	322.75
Water	40.5					34.5	37.0	36.5
Fly Ash:								
Type	-					F	F	F
Wt (lbs)	-					-	21.0	30.5
% Replace.	-					20	25	35
Adm. (cc):								
Retarder	145					145	145	150
Air Entr.	13					13	13	14
w/cm Ratio	0.485					0.398	0.441	0.422
Slump (in.)	4.2					4.0	3.75	3.25
% Air	4.1					3.1	2.3	1.7
Temp. °F	63					65	63	65
Unit Wt. (lb/ft^3)	145					145	144.0	147.0
f'_t @ 7 d (psi)	-					-	-	-
f'_c @ 28 d (psi)	-					-	-	-

Comments: Samples were tested for curing compound effects.

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