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16. Abstract

This report consists of results, observations, and conclusions from an experimental program investigating the effect of superplasticizers on fresh and hardened concrete properties. Tests for workability, air content, unit weight, setting times, strength, and durability were conducted for the mixes that made up this study. Variables for these mixes included initial slump, coarse aggregate type, cement content, retarder dosage, time of addition, and admixture combinations.

The results from this study show that superplasticizers can provide desirable characteristics for a concrete mix such as increased workability, increased compressive and flexural strengths, and increased resistance to abrasion. However, superplasticizers can also produce undesirable and deleterious characteristics for a concrete mix such as rapid slump loss, loss of air, and delayed finishing due to delayed setting times.

This report provides the resident engineer with recommendations for production of superplasticized flowing concrete and suggestions for further research.

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GUIDELINES FOR THE PROPER USE OF SUPERPLASTICIZERS IN CONCRETE

by

William C. Eckert
and
Ramon L. Carrasquillo

Research Report Number 1117-2F

Research Project 3-5-87-1117

Guidelines for Proper Use of Superplasticizers and the Effect of Retempering Practices on Performance and Durability of Concrete

Conducted for

Texas
State Department of Highways and Public Transportation

In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by

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

June 1988

PREFACE

This is the first report of two in a series of reports which will present proposed guidelines for the use of superplasticizers in ready mix concrete to ensure the production of good quality and durable concrete. In particular, this report addresses the use of superplasticizers in hot weather. The second report will address proper guidelines for the use of superplasticizers under cold weather concreting conditions.

The work reported herein is part of Research Project 3-5-87-1117, entitled, "Guidelines for the Proper Use of Superplasticizers and the Effect of Retempering Practices on Performance and Durability of Concrete." 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 overall study was directed and supervised by Dr. Ramon L. Carrasquillo.

SUMMARY

This report consists of results, observations, and conclusions from an experimental program investigating the effect of superplasticizers on fresh and hardened concrete properties. Tests for workability, air content, unit weight, setting times, strength, and durability were conducted for the mixes that made up this study. Variables for these mixes included initial slump, coarse aggregate type, cement content, retarder dosage, time of addition, and admixture combinations.

The results from this study show that superplasticizers can provide desirable characteristics for a concrete mix such as increased workability, increased compressive and flexural strengths, and increased resistance to abrasion. However, superplasticizers can also produce undesirable and deleterious characteristics for a concrete mix such as rapid slump loss, loss of air, and delayed finishing due to delayed setting times.

This report provides the resident engineer with recommendations for production of superplasticized flowing concrete and suggestions for further research.

IMPLEMENTATION

The results of this study indicate that certain precautions are necessary when the decision to use superplasticizers has been made. This decision should be based on considerations of each specific application. A superplasticizer can be an advantageous component for the concrete mix, but it may just as easily create more problems than the situations that led to the consideration for use of the admixture in the first place. In a consideration of the technical benefits or shortcomings, an economic analysis should not be ignored.

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CHAPTER 1
INTRODUCTION

1.1 General

A superplasticizer is an admixture that may be used in readymix concrete to achieve certain desired plastic or hardened concrete properties. Primarily, the desired properties are high strength concrete or a fresh concrete mix of very high workability. In addition, economic benefits may be possible through reduced cement contents and less labor intensive concrete placement in the field.

These admixtures were first developed concurrently in Japan and West Germany in 1964[22] and may also be commonly referred to as high-range water reducers. Their use later spread to North America. Superplasticizers may cost from $5.00 to $6.50 per gallon. Therefore, for a typical 5 sack mix, the total cost for the superplasticizer admixture may be as high as $4.00 per cubic yard of concrete. Thus their cost is not inconsequential.

The basis for this research program is to provide guidelines for the proper use of these admixtures. A brief overview and description of all the parameters investigated in this research program are presented in this chapter. The conclusions will be of particular interest to Texas State Department of Highways and Public Transportation (TSDHPT) field engineers and personnel.

1.2 Justification of Research

The increased use of superplasticizers has not been without problems. Of particular objection to field personnel has been the potential for superplasticized concrete to exhibit excessive bleeding or segregation, delayed or difficult finishing, rapid losses in workability, changes in the air content and air void system characteristics, and possibly, combinations of these items. Additional confusion can result with the use of superplasticizers due to the lack of knowledge about the proper dosage and time of addition, effect of temperature, and compatibility with the cements, pozzolans, or other admixtures used, such as air entraining agents, retarders, or accelerators.

Some state agencies, namely the Indiana Department of Highways and Virginia Department of Highways and Transportation, have limited the use of superplasticizers because of a lack of quality control. The superplasticized concrete in question did not exhibit adequate durability to freezing and thawing tests. In another instance, during the casting of precast box segments for a bridge in San Antonio, TSDHPT was delayed for several weeks because of inconsistencies in the characteristics of the superplasticized concrete.

1.3 Research Objectives

The main objectives of this research were to provide field personnel with guidelines for avoiding the potential problems that accompany the use of superplasticizers in readymix concrete and to ensure the production of good quality and durable concrete containing superplasticizers. The majority of previous research has focused on the use of small capacity laboratory concrete mixers. However, in order to duplicate existing field conditions as closely as possible to guarantee applicable test results, commercial readymix concrete facilities were used in this investigation. In particular, this report addresses the use of superplasticizers in hot weather. A later report will address recommendations for the use of superplasticizers under cold weather concreting conditions.

1.4 Research Plan

The research plan devised to meet the research objectives consisted of:

1. A laboratory study to permit investigation of the effects of multiple dosages of superplasticizer on concrete mixes where the variables studied included:

   a. two cement contents,

   b. two coarse aggregate types,

   c. three initial slumps,

   d. two set retarding admixture dosages, and

   e. two air entraining agents.

2. A field study to permit investigation of the effects of time of addition of a superplasticizer on concrete mixes where the variables studies included:

   a. two superplasticizing admixtures,

   b. two set retarding admixtures,

   c. three air entraining agents,

   d. four set retarding admixture dosages, and

e. two initial slumps.

For the laboratory study, the following tests were conducted on fresh and hardened concrete specimens before the addition of superplasticizer and after the first and second dosages of the superplasticizer:

1. slump,
2. air content,
3. concrete temperature,
4. unit weight,
5. setting times,
6. compressive strength,
7. flexural strength,
8. abrasion resistance,
9. freeze-thaw resistance, and
10. deicing-scaling resistance.

For the field study, the following tests were conducted on fresh and hardened concrete specimens before and after the addition of superplasticizer:

1. slump,
2. air content,
3. concrete temperature, and
4. compressive strength.

All tests were done in accordance with the latest American Society for Testing and Materials (ASTM) specifications and the Texas State Department of Highways and Public Transportation (TSDPHT) specifications where applicable.

1.5 Format

A review of technical literature pertinent to this research topic is presented in Chapter 2. A description of all materials used and the laboratory and field experimental programs are presented in Chapter 3. Chapter 4 includes all results for the laboratory and field experimental programs. Discussion and analysis of the laboratory and field experimental programs are presented in Chapter 5. The existing federal workplan for the use of superplasticizers and subsequent submittal of a method by the Texas SDHPT to meet these federal requirements are discussed in Chapter 6. Chapter 7 includes a summary, conclusions, proposed guidelines for establishing a workplan when superplasticizers are to be used, and recommendations for further research.

This study is part of a continuing research project investigating proposed guidelines for the use of superplasticizers in concrete. All research was conducted at the Phil M. Ferguson Structural Engineering Laboratory at the Balcones Research Center of The University of Texas at Austin and at the Capitol Aggregates readymix plant in Austin under the sponsorship of The Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

A review of the literature relevant to the topic under investigation is presented here. This includes descriptions of basic concrete materials and admixtures. Specifically, applications, composition, mode of action, and effects on fresh and hardened concrete of such admixtures as superplasticizers, retarders, and air-entraining agents are detailed.

2.2 Concrete Materials

The following discussion considers how certain variations in the amount, type, or gradation of the various constituents of concrete may affect the characteristics and properties of concrete.

2.2.1 Cement. Cement content affects concrete primarily through its effect on the water-cement ratio and amount of fines in the concrete. As the cement content is increased, it is likely that the water-cement ratio decreases for a given slump. This will result in greater compressive and flexural strengths. In addition, the more efficient cement hydration process for lower water-cement ratios results in a decrease in porosity of the paste and, therefore, lower permeability of the concrete. This will provide increased durability and resistance to physical and chemical attack such as abrasion, freeze-thaw cycling, and deicing chemical exposure.

Several sources[32,36,38,41,59] have investigated the effects on concrete when the cement content varies. Most researchers[32,36,41,59] have shown that mixes with low cement contents show a more rapid rate of slump loss. However, Perenchio, et al.[38], found that slump loss is more pronounced in higher cement content mixes. All conclusions were based on concrete mixes without retarding admixtures. Mailvaganam[32] and Mukherjee and Chojnacki[36] conducted their tests at ambient temperatures of approximately 73°F; however, the remaining investigators did not mention the ambient temperature at which the tests were conducted.

It is well known, however, that an increase in cement content, and thus fines, will decrease the potential for excess bleeding and segregation. Higher fines content increases the cohesiveness of the fresh concrete and can result in a sticky concrete mix difficult to finish and place by pumping.

2.2.2 Coarse Aggregate. The type and gradation of the coarse aggregate chosen for the concrete mix can affect the fresh and hardened concrete properties. River gravel aggregates are relatively smooth, whereas crushed stone aggregates are more angular and rough. For the same size aggregate, crushed stone will require more paste than river gravel to lubricate the surface area of the aggregate to achieve a similar concrete workability. In addition, there is greater interparticle friction among crushed stone aggregate particles. Each of these factors may lead to decreased workability for concretes with crushed stone aggregates.

Crushed stone aggregates do have one advantage over gravel aggregates. The rough surface and texture produce a greater mechanical bond between the paste and aggregate. This can increase the flexural strength of concrete made with this type of aggregate.

In addition, the abrasion resistance of concrete is increased as aggregate hardness is increased.[34,4,10]

2.2.3 Fine Aggregate. The physical characteristics of a fine aggregate or sand will also influence the properties of fresh concrete. As with cement, an increase in fine aggregate content will result in higher fines content and will help to decrease the potential for excessive bleeding and segregation. The fineness modulus (FM) is typically used as an indicator of the gradation of the fine aggregate. Typical FM values for sands used in concrete production range from 2.3 to 3.1.[34] Smaller values indicate a fine sand whereas larger numbers indicate coarser sands.

2.3 Superplasticizers

Superplasticizers are a relatively new family of admixtures available for use in concrete. These admixtures are also referred to as high-range water reducers, super water reducers, or superfluidizers. Their use has been gaining increased acceptance since their development in 1964 by Kenichi Hattori.[22] Concurrent to these Japanese developments, the West Germans introduced a similar product. These first superplasticizers have since been joined in the commercial market by additional products from other companies.

2.3.1 Applications. Superplasticizers are capable of reducing the water content of a concrete mix by 15 to 30% without reducing the slump of the fresh concrete.[34] A superplasticizing admixture is a key component of concrete when trying to produce high strength concrete of normal workability. High strength concrete requires good materials and a low water cement ratio. The addition of a superplasticizer can provide the necessary workability for the mix at the low water-cement ratio needed for high strength concrete.

High strength concrete is especially useful in the precast concrete industry. The higher strength mixes allow a shorter curing period and earlier release. As a result, the industry can increase production which defrays the additional cost of the admixture. In addition, designers are beginning to specify higher strength concrete for structural applications, mainly high rise buildings. Currently, a building is under construction in Seattle where a compressive strength of 19,000 psi has been specified for the columns.[15]

Another application of superplasticizers involves normal strength concrete of increased workability. This so called flowing concrete is achieved not by increasing the water content, but by using the superplasticizer as a workability agent. As a result, cohesive concrete mixes with slumps greater than 8 inches can be produced. Other sources may refer to flowing concrete as self-compacting concrete, flocrete, soupcrete, or collapsed slump concrete.[19]

Flowing concrete is a must when placing concrete in complex shapes or heavily reinforced formwork when thorough consolidation by vibration may be difficult to accomplish in the field. Furthermore, flowing concrete is used for simple shapes such as large slabs or mat foundations. The self-leveling characteristics of the mix may require fewer workers to place the concrete. Extremely large concreting operations may extend beyond normal working hours thus requiring overtime pay.[19] Flowing concrete can speed up the casting and finishing operations saving the contractor time and money.

A third application involves decreasing the cement content of the concrete mix. Superplasticizers can increase the workability of fresh concrete. However, when it is desirable to maintain a given workability, the mixing water content must be reduced. Correspondingly, the cement content could be decreased to maintain the original water-cement ratio. As a result, a decrease in the total cost of materials could result from the reduction in the amount of cement which is the most expensive ingredient in concrete.

Other authors[19,41] list additional uses for superplasticizers. Placement of concrete underwater using a tremie pipe and pumping efficiency are significantly improved with superplasticized concrete. Also, the use of superplasticizers improves the appearance of pigmented concrete through a more uniform distribution of color.

2.3.2 Composition. Superplasticizers are manufactured primarily from one of three materials. These materials are:

1. sulfonated naphthalene formaldehyde condensates,
2. sulfonated melamine formaldehyde condensates, and
3. modified lignosulfonates.

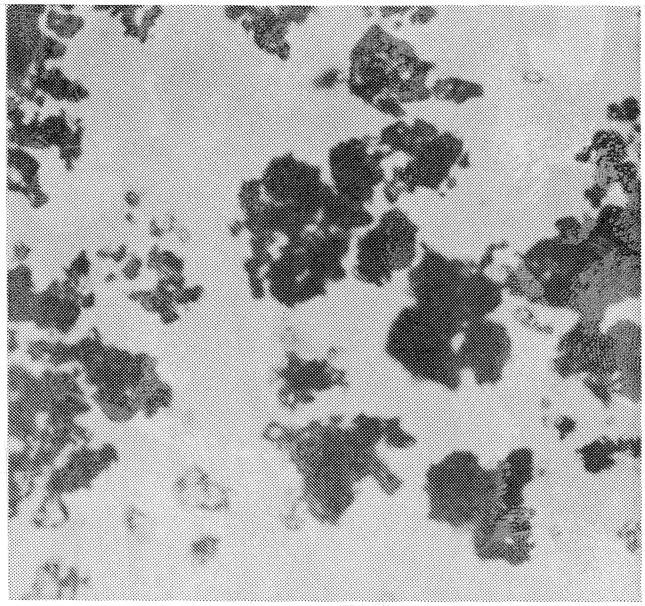
Each of these substances is a "linear polymer containing sulfonic acid groups attached to the polymer backbone at regular intervals."[34]

2.3.3 Mode of Action. The increase in workability due to the use of superplasticizers is achieved through dispersion of the individual cement particles in the mix. Cement particles tend to cluster together in concrete mixes containing no superplasticizer. Some researchers[31,34,35] believe that each type of superplasticizer is capable of imparting negative charges to each cement particle and, therefore, the cement particles repel each other. This creates a lubricating film at the surface of the cement particle and the entire mix flows easier. Another source[20] describes different mechanisms of action for each of the three types of superplasticizer. Nevertheless, cement particles are dispersed as shown in Fig. 2.1 when the admixture is used.

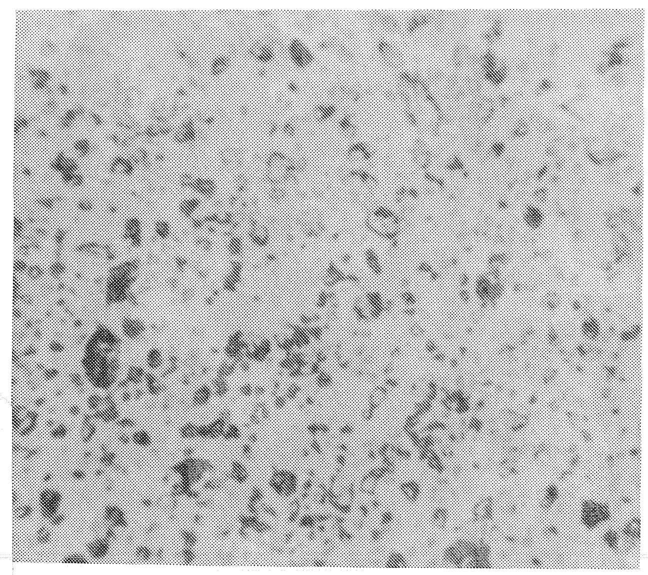
The effectiveness of superplasticizers on fresh concrete properties varies with the admixture type and concentration, material types and proportions, temperature of the concrete, method of mixing, and time of addition.[9]

Several sources[11,25,33,41] have investigated the interaction between cement constituents and superplasticizers; no retarding admixtures were present. The literature includes information on the reactions of tricalcium aluminate (C_3A) with and without gypsum, and tricalcium silicate (C_3S) in the presence of a superplasticizer. Tricalcium aluminate is the fastest reacting component in portland cement. Accordingly, the majority of research has focused on the reaction of this component when in the presence of superplasticizers. Researchers have not yet fully agreed on the effects of superplasticizers on the C_3A reaction. Results seem dependent on the water-to-solids ratio, dosage and molecular weight of the superplasticizer, ratio of C_3A to gypsum, and temperature of the mix.

Ramachandran[41] states that most agree with his statement that naphthalene and melamine based superplasticizers retard the hydration of C_3A. He has shown using conduction calorimetric curves that during the initial 30 minutes after water-cement contact, the total amount of heat generated and the accompanying peak for the rate of heat development are lower for the C_3A reaction when melamine superplasticizers are present.



(A)



(B)

Fig. 2.1 Photomicrographs showing the dispersing effect of superplasticizers on cement: A) Cement alone (400X); B) Cement plus a naphthalene base superplasticizer (400X)[11]

When the hydration of tricalcium aluminate is studied in conjunction with gypsum and superplasticizers, opinions diverge. It seems that researchers have found retardation, acceleration, and no change to occur in the hydration of C_3A in the presence of superplasticizers. During hydration, sulfate ions from the gypsum combine with C_3A to form a compound commonly called ettringite. This compound is stable only while the supply of sulfate is plentiful. When the amount of sulfate available becomes lower than that needed to continue this reaction, the ettringite is converted to monosulfoaluminate. This compound contains less sulfate and allows the remainder of the C_3A to react. In most cements, this conversion to monosulfoaluminate occurs within 12 to 36 hours after water-cement contact.[34]

Ramachandran[41] has shown that superplasticizers retard the conversion of ettringite to monosulfoaluminate. His investigations included melamine superplasticizer dosages of 1, 2, and 4% of the total cement weight. In each case, the conduction calorimetric curves showed a delayed peak of activity. The increase in dosage to 2% delayed the peak of heat development further from that of the 1% dosage. An additional increase in dosage to 4% still retards the reaction, but it proceeds more quickly than the other two cases.

The effects of superplasticizers on the reaction of tricalcium silicate seem more clear. Ramachandran[41] has shown that as more superplasticizer is added, the time to peak heat generation increases in each case. Thus, the hydration of C_3S is retarded by the action of superplasticizers.

Ramachandran[41] has noted that the C_3A phase adsorbs a percentage of the superplasticizer. Depending on the amount of alkali sulfates in the cement, the resulting formation of ettringite may be accelerated or retarded. This leaves less admixture in solution to delay the silicate reactions.

Dezhen, et al.[11], have found that the rate of early hydration of cement is accelerated when a naphthalene superplasticizer is used. This is due primarily to the enhanced dispersion which increases the surface area available for chemical activity. In later stages, the diffusion rate of water molecules penetrating the layer of hydrated product stabilizes, but it remains slightly slower for superplasticized mixes than for mixes with no superplasticizer.

Khalil and Ward[25] concluded that there is a slight delay in all hydration reactions. They found enhanced reactivity between the C_3A and gypsum due to dispersion, but no acceleration of the reaction. Their conduction calorimeter curves show a delayed, but sustained peak rate of heat hydration.

Microscopic analysis of hydrated cement is another method for determining changes due to the presence of superplasticizers. Investigators have noted that the morphology of ettringite changes as early as 30 to 60 minutes after water-cement contact. Without superplasticizers, large fibrous bundles result whereas needle-like hydration products are formed when the admixture is included. Analysis at six months shows tricalcium silicate to have hydrated into a tighter and more complete structure when superplasticizers are present.

2.4 Retarders

These particular admixtures have been in use much longer than superplasticizers since the advantages derived from their use were discovered during the 1930's.

2.4.1 Applications. Retarders are admixtures primarily used in concrete to prolong the dormant phase of the cement hydration. This increases the time that the fresh concrete mix remains in the plastic state. This is particularly advantageous when placing concrete in hot weather.

Additional uses may involve operations where placement is significantly delayed from the time of batching. Furthermore, set retarders can aid in preventing cold joints in large casting operations. Finally, retarders can help eliminate form- deflection cracks in unshored construction.[34,39]

2.4.2 Composition. The composition of retarders is based primarily on the following materials:

1. lignosulfonates,
2. hydroxycarboxylic acids,
3. carbohydrates, and
4. various other compounds such as inorganic materials, amines, and certain polymeric compounds.

Retarders are very closely related to the family of admixtures referred to as water reducers. In essence, a water reducer is a retarder to which an accelerator such as calcium chloride or triethanolamine[41] has been added to negate the retardation. The water reducer then functions only to reduce the water demand of the mix anywhere from 5 to 10%. However, retarders are not required to provide any water reduction.

2.4.3 Mode of Action. The chemical composition of the particular portland cement used will influence the effectiveness of a retarder in concrete. Ramachandran[41] identifies these compounds as C_3A, alkali, and sulfate contents.

During very early hydration, the C_3A reaction tends to adsorb the retarding admixture. This accelerates the hydration of the aluminate, and in fact, cements with a large ratio of C_3A to C_3S may experience an accelerated initial set in conjunction with the use of a retarder. Accordingly, extremely large doses of the retarding admixture may cause quick set. Mindess and Young[34] recommend postponing the addition of the retarder to the mix for a few minutes. This allows the initial C_3A:gypsum reaction to proceed without removing a percentage of the retarder from the system.

Regardless of the effect on early hydration, the retarding admixture will delay final setting. Because the previously produced ettringite adsorbed the retarder, the breakdown into monosulfoaluminate is delayed. In addition, the concentration of retarder in solution is enough to retard the onset of the hydration of C_3S.

Cements with low sulfate (gypsum) contents may experience extreme retardation when retarders are used. The lack of gypsum changes the C_4AF reaction. Ramachandran[41] describes a process whereby ferric oxide gel is deposited on the C_3S and C_2S. Strength gain is, therefore, significantly affected since the silicates are prevented from hydrating. The solutions, however, are relatively simple if this is discovered during trial batching. Extreme retardation may be counteracted by increasing the gypsum content or decreasing the retarder dosage. The same problem may occur with low alkali cements, but this mechanism is less understood.

As hydration continues to the age of approximately 24 hours, other changes become apparent. The concentration of the admixture in solution is quickly reduced as the second hydration of C_3A begins. The formation of more ettringite adsorbs large amounts of the remaining retarder. This frees the C_3S enabling the silicate hydration to proceed. These changes depend upon the fineness and composition of the cement and on the type and dosage of retarder. Coarse cements and large amounts of retarding admixtures tend to show the changes at later periods in the hydration cycle. Low C_3A contents also delay the silicate reaction because the admixture is taken out of solution more slowly.

2.4.4 Effects of Retarders on Concrete. The primary advantages of retarders are increased working time and greater ultimate strength. The delay in hydration could result in lower concrete strengths for specimens tested at 1 to 3 days; however, retarders can provide greater compressive and flexural strengths at later ages. This is due to the cement dispersion capabilities of the admixture and improved hydration product.

2.5 Air Entrainment

Air-entraining admixtures are commonly used in readymix concrete. They are relatively inexpensive and can impart desired qualities to both fresh and hardened concrete.

2.5.1 Applications. The advantage of air-entrained concrete is perhaps most often described as increased durability, namely, resistance to freezing and thawing. Any concrete that is to be exposed to shifts in temperature above and below freezing should be air-entrained. Bridges, foundations, retaining walls, parking garages, dams, pavements, and exterior columns are a few examples. Bridge decks, in particular, need to be air-entrained since they are also likely to be exposed to deicing chemicals in conjunction with freezing and thawing weather.

The American Concrete Institute (ACI) standard practice for mix proportioning[2] stipulates the necessary air contents for producing concrete of adequate durability. The amount of air, stated as a percentage of the total volume of concrete, may vary from 3 to 8%. The required amount depends on a classification of the concrete's exposure as mild, moderate, or severe, and on the nominal maximum aggregate size.

2.5.2 Composition. Probably the most commonly used air entraining admixture is neutralized vinsol resin. It is, in fact, the basis of comparison for all other air-entraining agents in the ASTM specifications. Other admixtures may be made from organic acid salts, sulfonated hydrocarbon derivatives, mixtures of fatty acids, salts of sulfonic acids and stabilizing agents, and water-soluble hydrocarbon derivatives.[1]

These admixtures are available for use in concrete production as a liquid admixture added to the water and batched with all the other materials or as a powder admixture added to the cement during the grinding process to produce air-entrained cement. Such cements are denoted with an "A" following the type, such as Type IA portland cement.

2.5.3 Mode of Action. Air-entraining agents are characterized as surface-active agents. They congregate at the air- bubble interface and lower the surface tension. Each molecule of the admixture contains a hydrophobic and hydrophilic end. The hydrophobic end is non-polar and is thus repelled by the polar water molecule. The hydrophilic end is a permanent dipole and is thus attracted to the water molecule.[53] This encourages the formation of bubbles. This idealization is shown in Fig. 2.2.

The entrained air bubbles are relatively stable and are then uniformly distributed in the fresh concrete by the mechanical mixing action. Because each bubble is buoyant, it tends to rise. Most aggregates, however, have multi-polar surfaces due to their ionic crystal composition. If the attraction is strong enough, the bubble then adheres to the aggregate. Larger bubbles, whose buoyant forces overcome this attraction, then rise to the surface. This process is desirable because larger air bubbles are ineffective in aiding concrete durability and only decrease strength.

2.5.4 Effects of Air Entrainment on Concrete. Air entrainment affects the properties of fresh and hardened concrete. While concrete is in the plastic state, the use of an air-entraining admixture will improve the workability of the mix. The network of spherical shapes facilitates interparticle flow. The mix will seem more cohesive and finish easier. Bleeding and segregation may also be reduced when these admixtures are used.[3]

An adequate air-void system will also provide increased resistance to internal stresses from freezing. The voids allow room for the expansion of water or a deicing chemical solution upon freezing. However, because of the voids, compressive and flexural strengths will be lower than that of concrete having similar proportions and containing no entrained air. Air entrainment has little, if any, effect on the abrasion resistance of hardened concrete.[10]

2.6 Effect of Superplasticizers on Fresh Concrete

Superplasticizers can have a significant effect on the properties of concrete in the plastic state including workability, air content, segregation and bleeding, finishing characteristics, setting times, and unit weight. Other factors affecting the use of superplasticizers in concrete include the ambient temperature, repeated dosage and time of addition of the superplasticizer, and water content of the mix.

2.6.1 Workability. The concept of workability is usually defined by the slump test. However, the use of the slump test is questionable when used to measure the workability of flowing concrete. Several sources[6,12,21,33,42,47,49,57] have investigated other measures of workability. These include the two- point test, flow table spread, minislump technique, vebe time, yield value and plastic viscosity test, and compacting factor test.

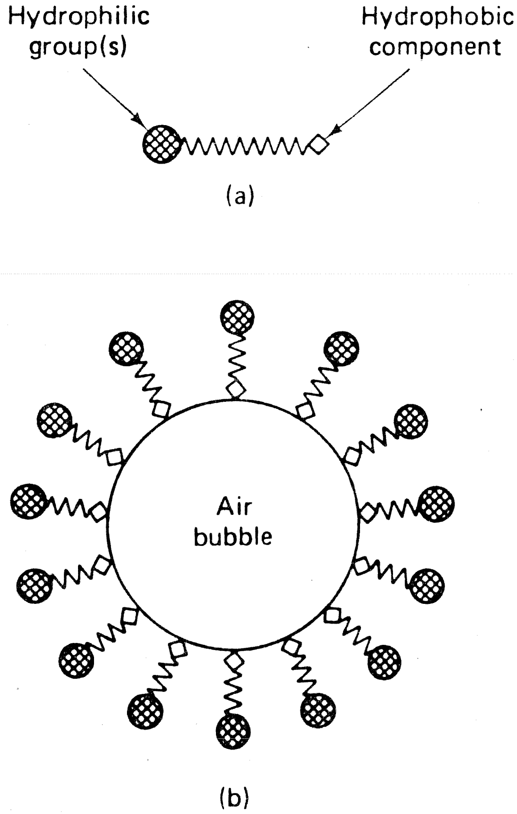


Fig. 2.2 Schematic representation of air entrainment by surface-active molecules: A) surface- active molecule; B) stabilized air bubble[34]

Regardless of the method, these tests will show that the use of superplasticizers can result in large increases in the workability of the fresh concrete. A superplasticizer can change a one-inch slump mix into an eight-inch slump mix when added in dosages within the manufacturer's recommendations.

A major problem when using superplasticizers is that the increase in workability is often unpredictable and of short duration. The term "slump loss" is used to describe the rapid decrease in slump with time exhibited by concrete containing a superplasticizer. Other terms used include slump window which refers to the length of time it takes for a three-inch slump to decay to a one-inch slump. The total working time is the length of time it takes for a mix to go from flowing concrete to a one inch slump.

There is no lack of references for slump loss studies in superplasticized concrete. Generally, researchers have found that the high workability is maintained for 30 to 60 minutes.[41] Ravindrarajah[45] has demonstrated this phenomenon as shown in Fig. 2.3. The length of time for which high slumps are maintained has been shown to depend on the type, dosage, and time of addition of the superplasticizer, ambient and concrete temperature, cement content, and initial slump.

Malhotra and Malanka[31] investigated the effects of different types of superplasticizers on slump loss. Their results are shown in Fig. 2.4. Using the manufacturer's maximum recommended dosage rates on 6.8 sack mixes at approximately 70°F, a slump of 10 inches was reached for each mix. At the end of the monitoring period of 2 hours, the lignosulfonate shows the least slump loss. While the naphthalene performed better than the melamine, neither one did as well as the lignosulfonate. The results from other investigators[23,35,47] agree with these findings.

Researchers[31,37,38,44,49] agree that as the dosage amount of any type of superplasticizer is increased, the corresponding gain of slump is increased and the rate of slump loss is reduced as shown by Ravina and Mor[44] in Fig. 2.5. In this particular case, the data include slump measurements at approximately 30 minute intervals for 0, 1, 2, and 3% superplasticizer dosages by weight of cement.

Due to the time duration limitations for a flowing consistency, superplasticizers are usually added to the concrete mix at the job site. In an effort to optimize the potential benefits, several researchers[32,38,44] have investigated the effects of the time of addition ranging from 20 to 90 minutes after batching on slump loss in fresh concrete. Ravina and Mor[44] have shown that flowing concrete could be achieved up to 90 minutes after batching

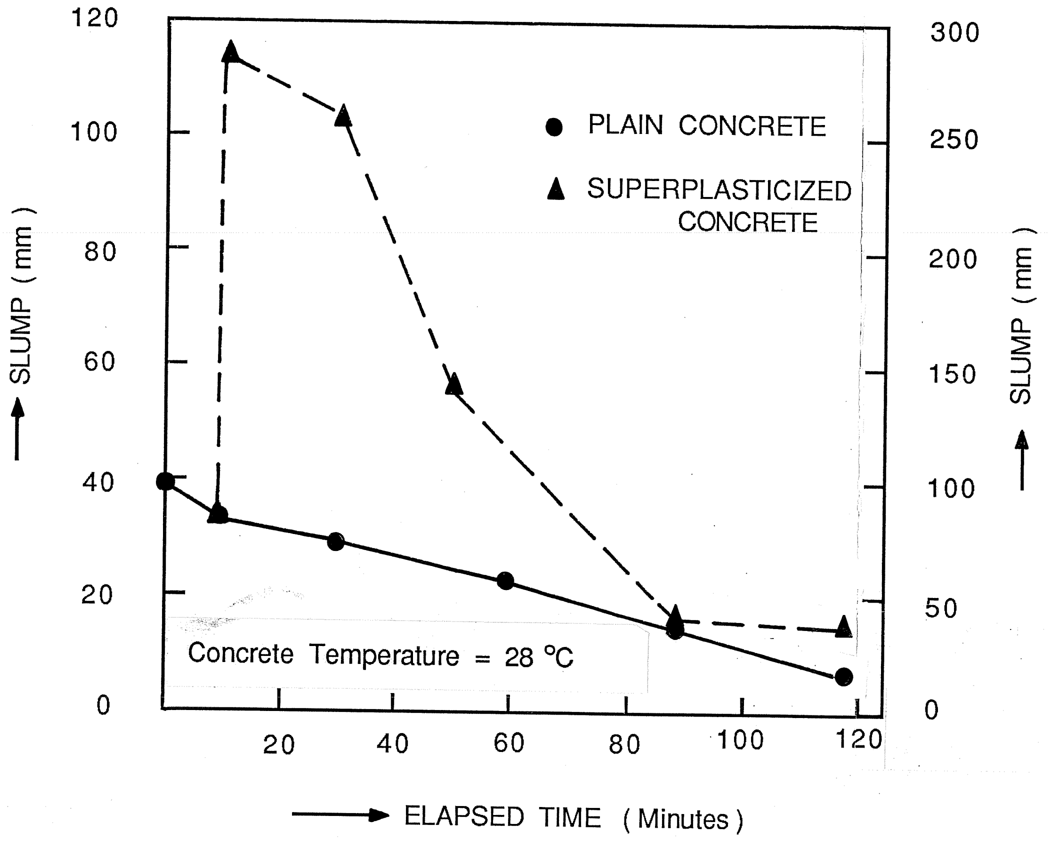


Fig. 2.3 Change in slump with elapsed time of plain and superplasticized concrete[45]

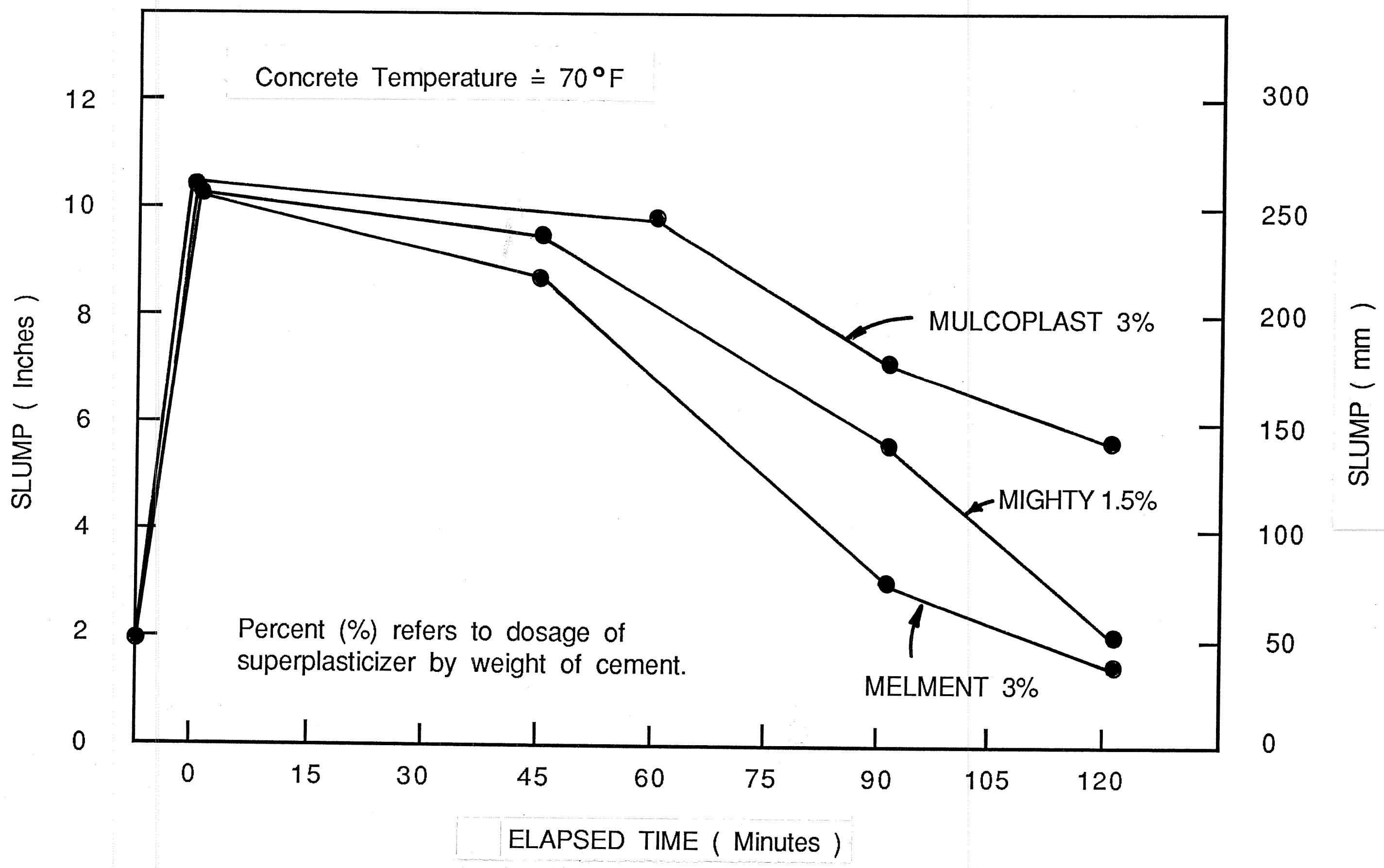


Fig. 2.4 Change in slump with elapsed time for maximum recommended dosages of three superplasticizer types Lignosulfonate: Mulcoplast, and Naphthalene: Mighty, and Melamine: Melment[31]

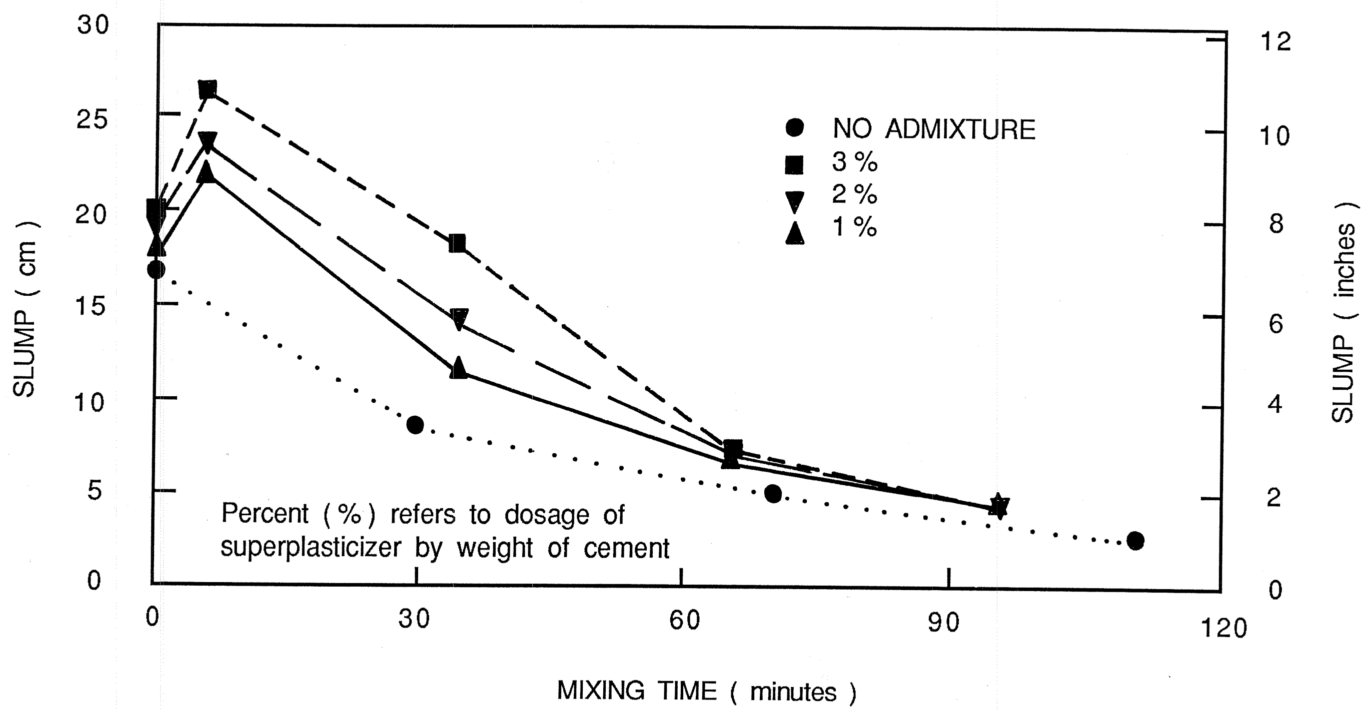


Fig. 2.5 Change in slump with elapsed time for fresh concrete mixes with no superplasticizer and increasing dosages of the same superplasticizer[44]

when using maximum dosages. Minimum dosages may become ineffective in producing flowing concretes as early as 30 minutes after batching. However, Mailvaganam[32] found "no clear trend" and Perenchio, et al.[38], found "insufficient improvements of any practical significance" in similar investigations.

The use of superplasticizers in hot weather concreting becomes more critical than at other times. The rate of slump loss is increased significantly[16,32,42,51,62] at higher temperatures, as shown by Mailvaganam[32] in Fig. 2.6. In addition, Yamamoto and Kobayashi[62] and Whiting[59] state that correspondingly smaller dosages of a superplasticizer are needed as the ambient temperature increases to achieve the same increase in slump.

There are conflicting conclusions about the effect of the initial slump on slump loss characteristics. Initial slump in this report refers to the slump of the concrete achieved with no superplasticizing admixtures. Ramakrishnan and Perumalswamy[42] concluded that the rate of slump loss is higher for higher initial slump mixes. On the other hand, Yamamoto and Takeuchi[61] reported that higher initial slumps decreased the rate of slump loss when newer slump-retentive superplasticizers were used.

The explanation for the phenomenon of slump loss is based mainly on the reaction between the tricalcium aluminate and the gypsum. Khalil and Ward[25] concluded that even though a superplasticizer retards the time of setting, the enhanced activity of the C_3A-gypsum reaction causes higher heat evolution. Furthermore, the product of the C_3A-gypsum reaction, ettringite, requires a large amount of the free water to form. Ravina and Mor[44] added that the continuous mixing of the concrete mechanically peels off the newly formed hydration products. This exposes additional unhydrated surfaces increasing the rate of hydration and, thus, water demand. Efforts are underway to solve the problem of slump loss. Proposals include optimizing the sulfate content, using retarders in conjunction with superplasticizers, and developing new slump-retentive admixtures. Slump loss is often manipulated by dosing the concrete mix a second or third time with the superplasticizer.

Khalil and Ward[25] investigated the effects on workability of varying the sulfate content of the cement. They were able to demonstrate that an optimum sulfate content could improve workability retention and prevent significant slump loss. For cement pastes cured at 25°C (77°F) and 40°C (104°F), they found the optimum sulfate content to be 3.15% and 5.65 %, respectively.

Several investigators[13,17,32,40,62] have studied the merits of including a retarder in the mix to help offset slump loss. Yamamoto and Kobayashi,[62] Mailvaganam,[32] and

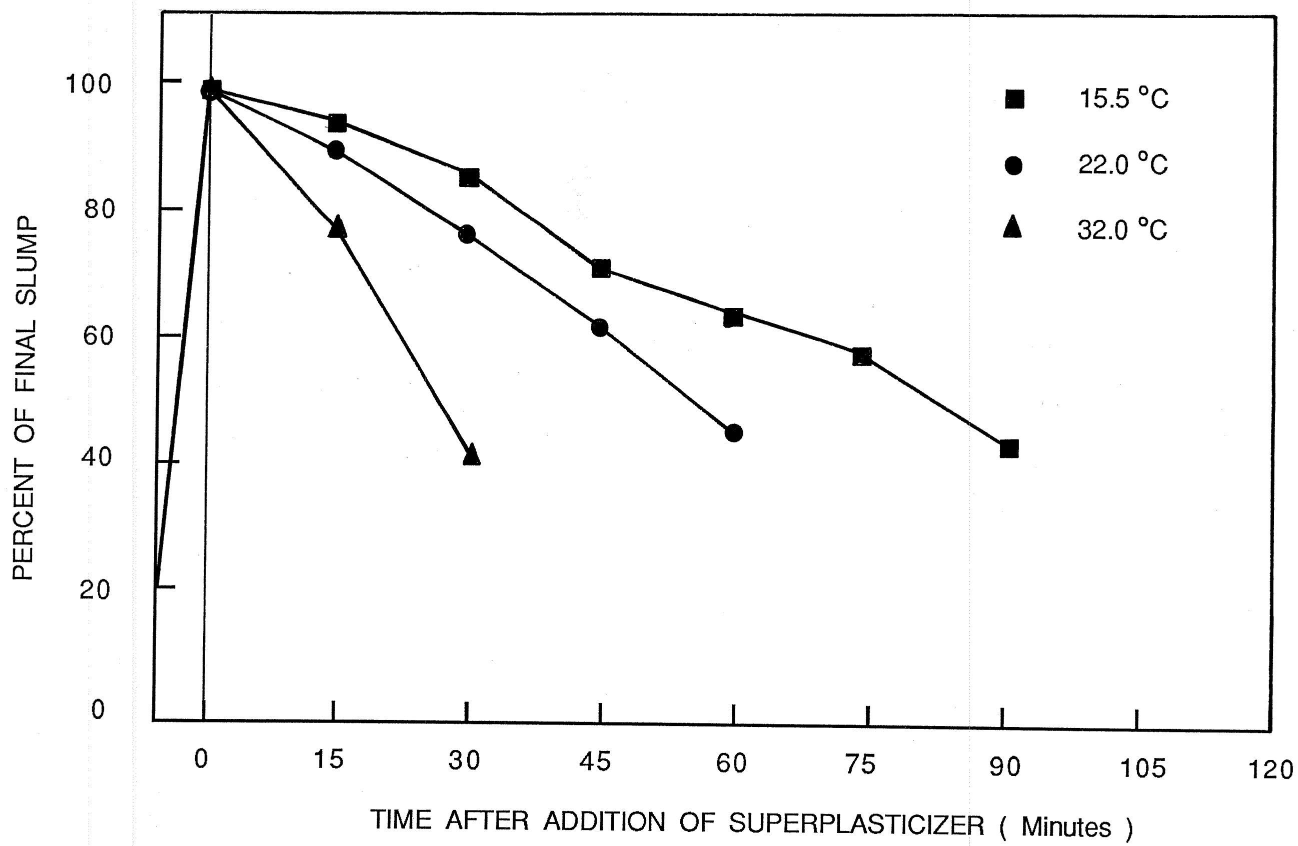


Fig. 2.6 Change in slump with elapsed time for similar initial slump mixes at three different temperatures. (All mixes included the same superplasticizer)[32]

Hampton[17] found no significant advantages for this practice at cooler temperatures around 20 to 22°C (68 to 72°F). However, for higher temperatures around 32 to 35°C (90 to 95°F), two of the investigators,[17,62] found a significant improvement in delaying slump loss. The results of the work of Hampton[17] are presented in Fig. 2.7. Ramachandran[40] studied the effects on slump loss of different types of retarders in conjunction with a melamine superplasticizer. He did not indicate the ambient temperature, but the results showed a sodium-gluconate retarder to work best. Edmeades and Hewlett[13] found that a 3:1 blend of superplasticizer and retarder gave significant improvements in workability retention.

Other developments in this area have involved perfecting superplasticizers which can be added at the batch plant.[16,18,61] The Japanese have developed slump-retentive superplasticizers that can maintain initial flowing concrete slumps through 90 minutes after batching. These admixtures can be added at much higher dosages while resisting tendencies toward segregation and excessive bleeding.

The last and perhaps most common method used to reinstate high workability of superplasticized concrete involves redosing. Researchers[30,32,43,51] agree that redosage can restore the high slump, but disagree on other effects. Ramakrishnan et al.[43] and Samarai, et al.[51], state that the rate of slump loss is higher for retempered concretes and that the ability of each additional superplasticizer dosage to keep the concrete workable is reduced as the number of retemperings is increased as shown in Fig. 2.8. Contrary to this work, Mailvaganam[32] and Malhotra[30] claim that redosed superplasticized concrete will experience more gradual decreases in slump as shown in Fig. 2.9.

2.6.2 Air Content. The use of superplasticizers is generally known to alter the air content of a concrete mix. Several studies[23,28,30,36,43] have concluded that naphthalene and melamine type superplasticizers will decrease the amount of entrained air. It is known that the loss of air in superplasticized concrete is greater than corresponding mixes with no superplasticizers.[59] MacInnis and Racic[28] found the average drop in air content was 1.8% for a nominal 5 % air content mix. Other investigators[30,41,43,52] have shown that repeated addition of these superplasticizers can result in further reductions of the air content of the concrete.

Malhotra[30] and Roberts and Adderson[49] investigated the effects of a lignosulfonate type superplasticizer on air content and found that this admixture would increase the air content of the mix. Still other authors[26,49,57] have found either no change in air content or an increase with superplasticizers other than lignosulfonates.

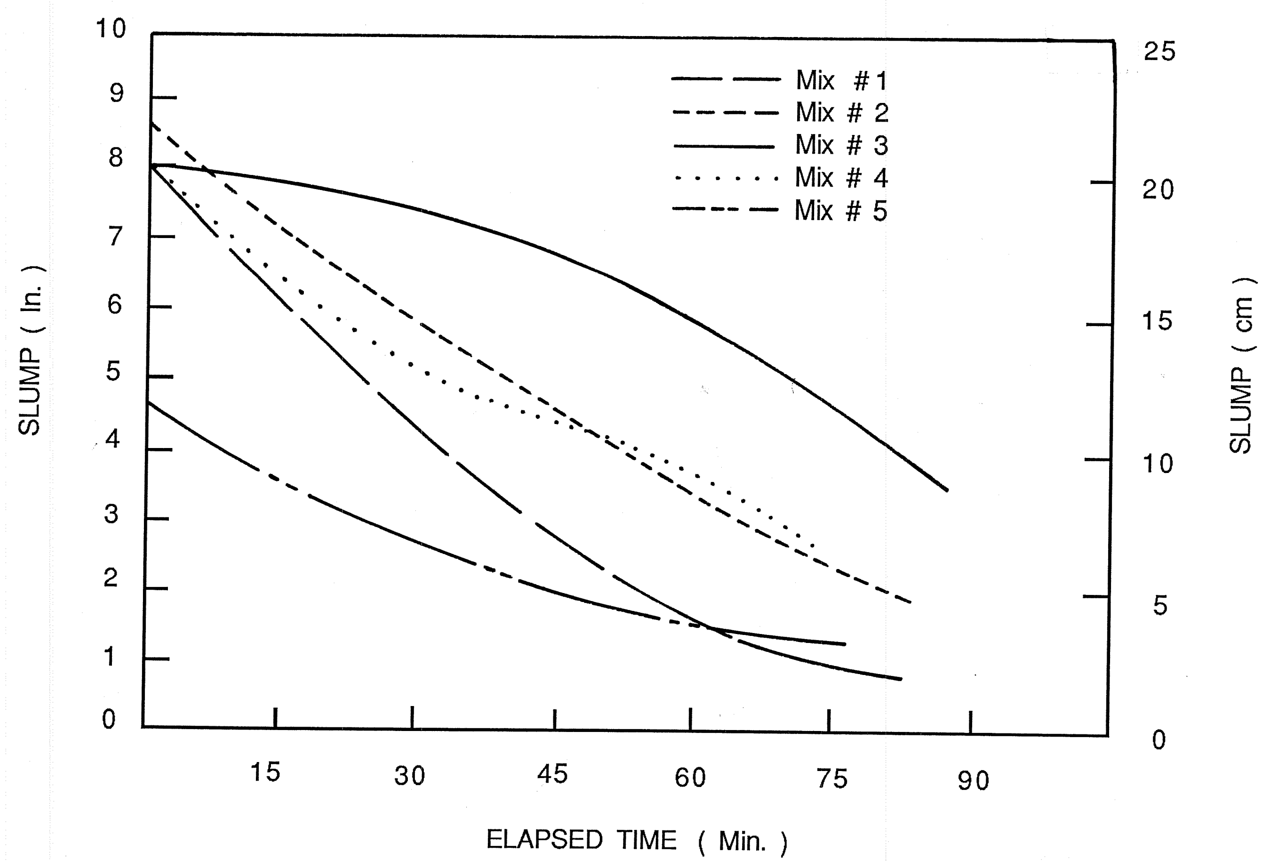


Fig. 2.7 Change in slump with elapsed time at 90° F for Mix #1: Superplasticizer alone, Mix #2: Superplasticizer plus retarder, Mix #3: Superplasticizer plus twice as much retarder, Mix #4: No superplasticizer, and Mix #5: No superplasticizer[17]

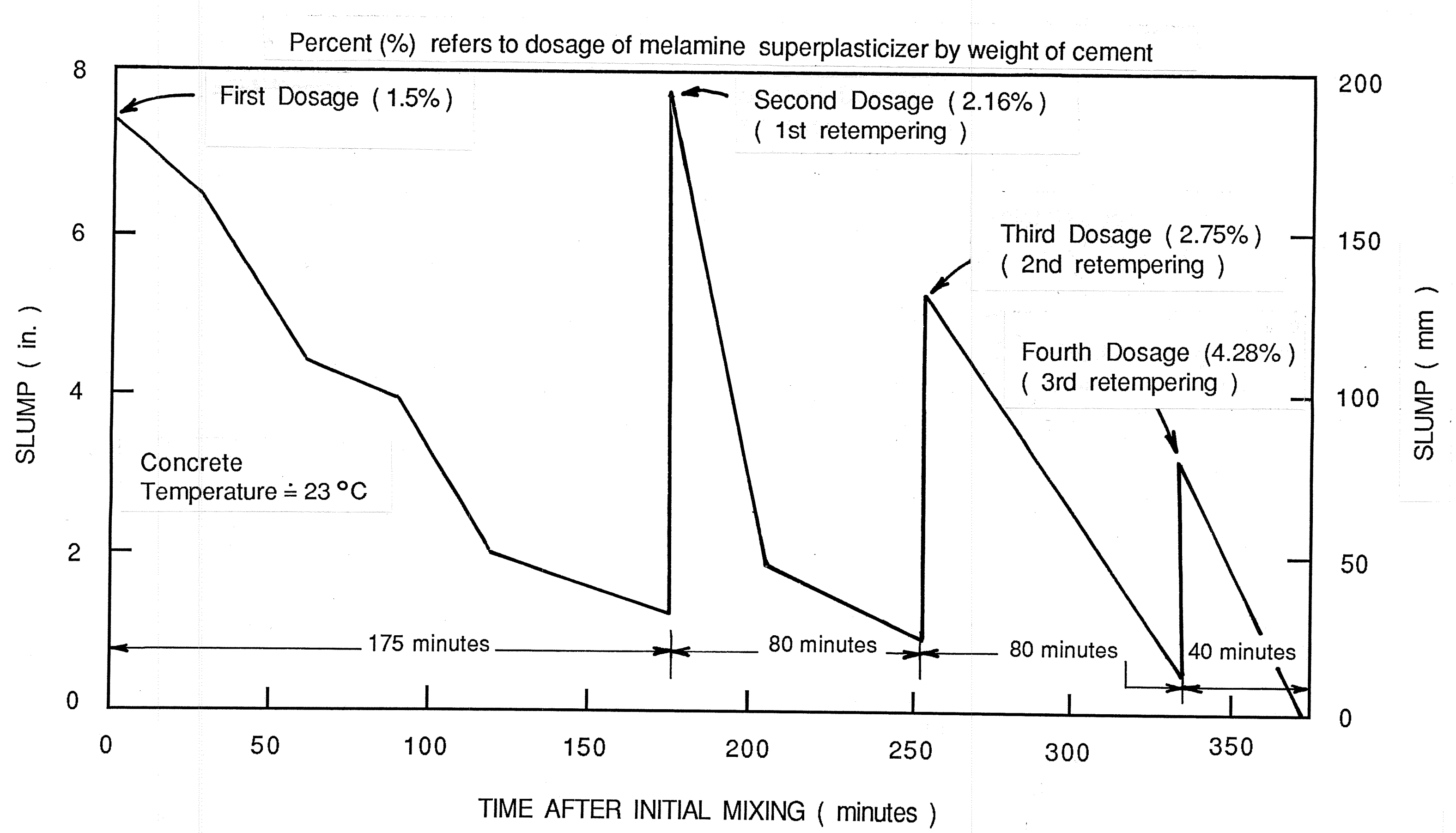


Fig. 2.8 Slump loss retempering study[43]

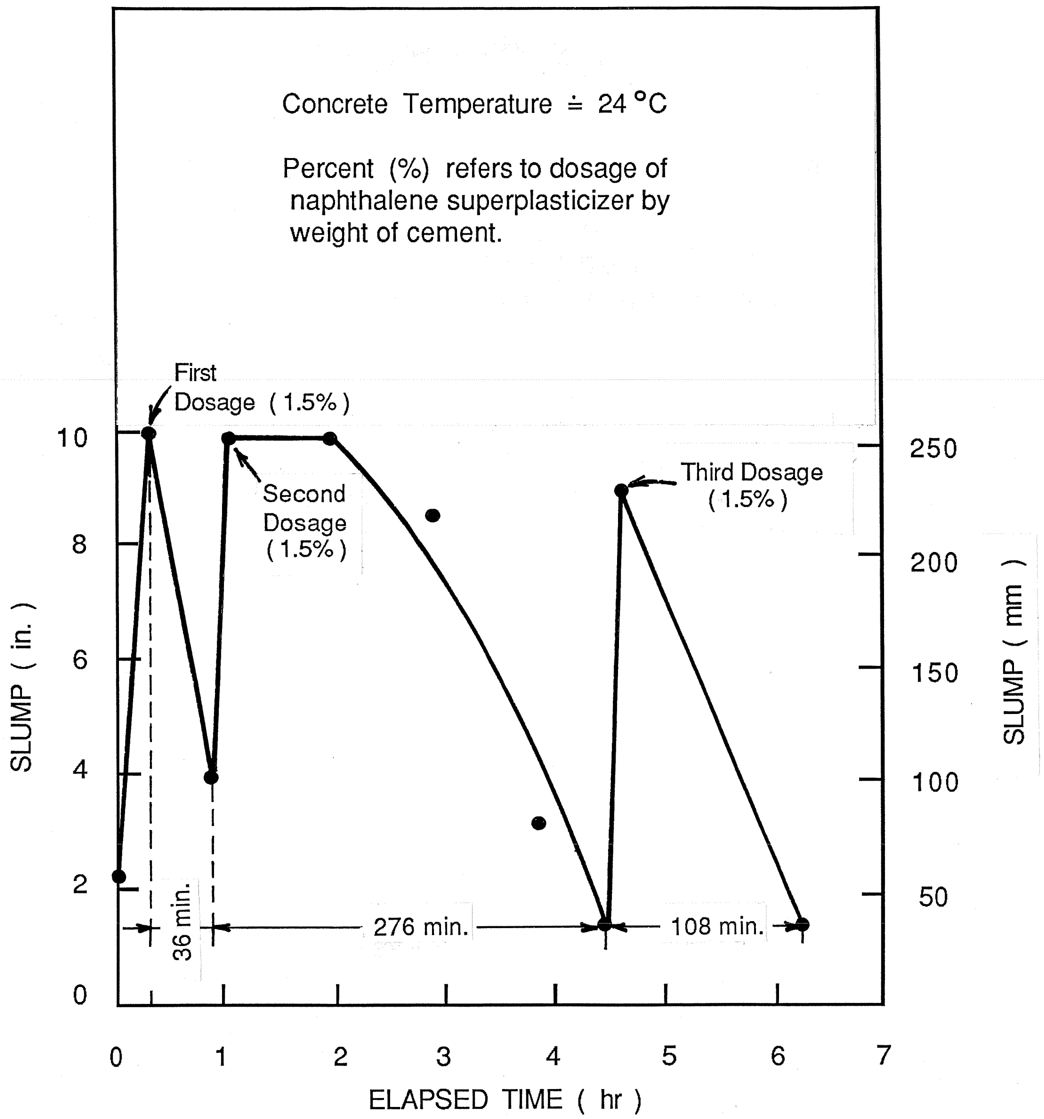


Fig. 2.9 Slump loss retempering study[30]

The loss of air is generally attributed to the increased slump. Hewlett[19] and Ramachandran[41] state that the fluidized or low viscosity mix facilitates the escape of air, and Whiting[59] hypothesizes that small bubbles may coalesce into larger bubbles. Eriksen and Anderson[14] recognized this problem and have proposed a method to determine the compatibility of different superplasticizers and air-entraining agents. This method involves measuring surface tension and foam stability of the admixtures in combination with and separate from one another.

2.6.3 Segregation and Bleeding. Segregation is defined as the separation of the individual components of a concrete mix. It occurs because of the differences in size and specific gravity of the constituents in concrete. Bleeding is a form of segregation in which some of the mixing water rises to the surface of the fresh concrete. Segregation can not be completely prevented and some degree of bleeding is desirable. However, excessive segregation or bleeding can cause problems such as honeycombing, difficulty in pumping and finishing, and decreased durability and strength. Superplasticizers have been blamed for amplifying these potential problems.

Malhotra and Malanka[31] found no significant segregation when superplasticizers were used at their maximum recommended dosages to yield 10-inch slumps for 6.8 sack concrete mixes at approximately 70°F. However, in a separate study, Malhotra[29] found considerable segregation in a 4.4 sack concrete mix at 70°F with a dosage of naphthalene superplasticizer within manufacturer's recommendations. Ramachandran[41] stated that superplasticizers may be likely to increase segregation and bleeding when the admixture is used to produce flowing concrete. Yamamoto and Kobayashi[62] found considerable increases in bleeding for 5.7 sack concrete mixes at lower temperatures on the order of 7°C (45°F). This trend was not continued for warmer mixes at 20 and 35°C (68 and 95°F). They concluded that this was due to the fact that setting times are considerably delayed at cooler temperatures and, therefore, the bleed water becomes more noticeable. Tsuji et al.[58] found that only the duration of bleeding was increased and not the bleed ratio by the addition of superplasticizers to the concrete.

Obviously, the current state of the art can be shown to vary with the peculiarities of each experimental program. Mindess and Young[34] have suggested the following to reduce segregation and bleeding in fresh concrete: 1) increasing cement fineness, 2) using pozzolans and other mineral admixtures, 3) increasing the rate of hydration, 4) including air entrainment, 5) reducing water content, 6) decreasing maximum aggregate size, and 7) using smooth, well-rounded aggregates.

2.6.4 Finishing Characteristics. One source[20] discusses how superplasticizers may affect the finishing of flatwork which is a common application for superplasticizers. Flowing concrete tends to have a proportionately large volume of mortar; thus, the surface is sticky, tears with the pass of a trowel and may tend to move under the finisher's weight. These problems may be solved by using a coarser fine aggregate or higher coarse aggregate content. Some admixture manufacturers recommend delaying the finishing process when superplasticizers are used.

2.6.5 Setting Times. As explained in Sec. 2.3.3, superplasticizers can delay the hydration process implying that initial and final setting times will be delayed when superplasticizers are used. This is indeed true. Many researchers[18,23,30,31,40,41,49,58,62] have presented data to support this hypothesis. The extent of this retardation depends on the type and dosage of superplasticizer, ambient temperature, presence of other admixtures, and repeated dosage.

Several researchers[30,31,49,58,62] have shown that all three types of superplasticizers will delay setting times. Increasingly larger dosages of a melamine superplasticizer will delay setting times further.[40] Malhotra[30] stated that repeated dosages of a superplasticizer may further delay stiffening. Ramakrishnan and Perumalswamy[42] and Yamamoto and Kobayashi[62] have demonstrated that setting times will be accelerated as the ambient and concrete temperatures rise. The use of other admixtures in conjunction with superplasticizers may either retard or accelerate setting times.[41] Using typical readymix trucks, Whiting[59] found that the use of superplasticizers in concrete mixes with reduced water-cement ratios will accelerate setting times.

2.6.6 Unit Weight. The literature concerning the effect of superplasticizers on the unit weight of fresh concrete is limited. Ramakrishnan, et al.[43], and Mukherjee and Chojnacki[36] attributed the increase in the unit weight of superplasticized concrete from that of plain concrete to the loss of air.

2.7 Effect of Superplasticizers on Hardened Concrete

Superplasticizers have also been found to affect the properties of hardened concrete including the air-void system, compressive and flexural strengths, and abrasion, freeze-thaw, and deicing-scaling resistance.

2.7.1 Air-void System. Though the ACI Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete[2] stipulates an air content for adequate durability, it is also necessary to have a good air-void system. This system has been characterized by three specific parameters, namely, the spacing factor, specific surface area, and number of voids. These parameters can only be measured and gauged from hardened concrete specimens; it is not possible to determine the characteristics of the air-void system while the concrete mix is in the plastic state.

In order to define the entrained air-void system, a specimen of hardened concrete is prepared for viewing under a microscope. The spacing factor has been defined as the average maximum distance from any point in the paste to the edge of a void.[34] In order to assure adequate frost protection, it has been determined that the spacing factor should not exceed 0.008 inches. The specific surface area is indicative of the size of the air bubbles. Mindess and Young[34] state that typical values should be in the range of 400 to 625 square inches of surface area per cubic inch of air. The third parameter is the number of voids per inch. Typical values range from one and a half to two times the numerical value of the percentage of air in the concrete.[10]

Research has been conducted on the effects of superplasticizers on the air-void system since it was discovered that the admixtures affected the air content of the plastic concrete mix. Several authors[23,28,29,31,41,48,55] have concluded that the addition of superplasticizers to air-entrained concrete will increase the spacing factor. In many cases, the factor exceeds the recommended values for adequate frost resistance. This is particularly true of naphthalene and melamine type superplasticizers.[41] Johnston, et al.[23], suggest this is due to bubble coagulation. In addition, MacInnis and Racic[28] and Tognon and Cangiano[57] found that the use of superplasticizers will result in a decrease in the specific surface area.

It is perhaps necessary to note that the total air contents measured in the plastic state using an air meter and in the hardened state by microscopic analysis often are not the same. Roberts and Scheiner,[48] Johnston, et al.,[23] and Reidenouer and Howe[46] acknowledge that hardened concrete air contents will be higher than those measured in fresh concrete. Reidenouer and Howe attribute this to different consolidation methods that in turn result in unequal entrapped air contents.

2.7.2 Compressive Strength. The effect of the addition of superplasticizers to a concrete mix on the compressive strength will vary with the type and number of dosages of the admixture, the time of molding, and the type of application, that is, flowing or high strength concrete.

Naphthalene and melamine type superplasticizers have generally been found to increase the compressive strength of concrete.[23,29,30,31,38,45,49,55] This has been attributed to the corresponding decrease in air content that accompanies their use and better compaction due to the increased workability. Lignosulfonate type superplasticizers have generally been found to decrease or have no effect on the compressive strength of concrete.[29,30,31,49] Similarly, this effect has been explained in terms of the change in air content since this type admixture can entrain air.

Several studies[30,43] have examined the effect of redosage on the compressive strength of the concrete. They have found that repeated addition of a superplasticizer will result in higher strengths each time. Malhotra[30] verified this for two redosages. In a related area, investigators[29,31,42,43] have found that the compressive strength will be higher for cylinders cast long after dosage to flowing concrete than those cast immediately after the superplasticizer is added to the concrete.

When superplasticizers are used to produce concretes of normal consistency, the water-cement ratio is decreased. As a result, the compressive strength of this mix compared to a mix having the same slump, but with no superplasticizer, will be higher.[7,49] Roberts and Adderson[49] and Johnston and Malhotra[23] concluded that the observed increase in compressive strength is greater than that which could be explained in terms of water reduction alone. The effects are most likely due to the dispersion of the hydration products.

When superplasticizers are used to produce flowing concrete, the water-cement ratio is not decreased, but researchers[30,38,41,45,49,55] have found that the compressive strength of the concrete will still increase. This increase may range anywhere from 2 to 11%. Sprinkel[55] has noted, however, that larger variations among companion cylinder strength test results will occur for superplasticized concrete.

2.7.3 Flexural Strength. It is generally agreed by researchers that the addition of superplasticizers will have little effect on the flexural strength of concrete.[22,23,29,31,36] This is particularly true for naphthalene and melamine type superplasticizers. The mechanism for the modulus of rupture depends primarily upon the paste-aggregate bond. It is, therefore, believed that superplasticizers do not modify this mechanism. Malhotra and Malanka[31] did find up to 10% decreases in flexural strength when a lignosulfonate type superplasticizer was used; it was attributed to the increased air content.

2.7.4 Abrasion Resistance. The abrasion resistance of concrete has been measured by many types of tests including the shotblast test,[60] the dressing wheel test,[59] and the rotating cutter method,[24] used in this project.

Researchers[24,41,60] have stated that the abrasion resistance is proportional to the compressive strength of the specimen. That is, as the compressive strength increases, the abrasion resistance of the hardened concrete specimen increases. Witte and Backstrom[60] have shown that the air content, density, maximum aggregate size, water-cement ratio, and cement content influence abrasion resistance only to the extent that they affect the compressive strength.

Kettle and Sadegzadeh[24] investigated the influences of different finishing and curing procedures on the abrasion resistance of concrete. Their program included hand finishing, power finishing, repeated power finishing, and vacuum dewatering and curing in air, under wet burlap, polythene sheeting, and with curing compounds. They concluded that power finishing and more efficient curing processes would increase the abrasion resistance of the concrete.

Whiting[59] presents the only data comparing the abrasion resistance of concrete specimens with and without a superplasticizer. The results show that a specimen with a naphthalene superplasticizer exhibited up to a 25% higher rate of abrasion although that same superplasticized concrete exhibited approximately 20% higher compressive strength at the age of testing. No explanation for the observed behavior was given by the researcher.

2.7.5 Freeze-Thaw Resistance. The main parameter used to compare the resistance of concrete to frost attack is the durability factor. The durability factor is based on the dynamic modulus of elasticity of the concrete.

Many researchers[7,12,23,27,29,30,31,36,38,41,48,49,54,61,59] have found that the durability factor for superplasticized concrete is equivalent or superior to that of the control concrete. Perenchio, et al.[38], showed this to be the case regardless of cement content. Whiting[59] was able to achieve good durability with specimens cast with a mobile mixer; however, the dosage of air-entraining agent was increased significantly (approximately 400%) when used in conjunction with superplasticizers. Smutzer and Zander[54] found retempered superplasticized concrete to possess significantly lower durability factors than concrete with only one dose of the admixture. Sprinkel,[55] Malhotra,[30] Robson,[50] and Johnston, et al.[23], have recorded results where the superplasticized concretes performed worse than the control concrete when subjected to freeze-thaw testing.

This generally superior performance is achieved in spite of the possible deleterious effects on the air content and air void system as described in Sec. 2.6.2 and 2.7.1. It has been proposed that the ASTM requirements for the spacing factor are not adequate.[41] Kobayashi, et al.[27], have listed other hypotheses to explain the increased resistance to freezing and thawing of superplasticized concrete. These include: 1) influence of reduction in free water, 2) improvement in the density of the hardened cement paste, 3) increases in the tensile strength of the hardened cement paste, and 4) improvement in the interfacial bond characteristics between the paste and aggregate.

In addition, MacInnis and Racic[28] and Roberts and Scheiner[48] have found that the chord length of the air-void system is unchanged with the addition of superplasticizer. They have suggested that the chord length may be the critical parameter for indicating the adequacy of the air-void system in predicting the capability of the concrete to resist frost attack. On the other hand, Whiting[59] has shown that the chord intercept measurements are deleteriously affected with the addition of superplasticizer.

2.7.6 Deicing-Scaling Resistance. This test simulates the application of deicing chemicals to highway pavements and bridge decks. Chemical attack of the exposed surface of the concrete is most likely accompanied by physical attack due to freezing and thawing.[8] This process can lead to deterioration of the surface, efflorescence, and corrosion of the reinforcement.

Perenchio, et al.[38], and Mukherjee and Chojnacki[36] found that superplasticized concrete specimens perform as well as control concrete under deicing-scaling testing. Mukherjee and Chojnacki[36] concluded testing at 50 cycles whereas Perenchio, et al.[38], continued testing until 300 cycles of freezing and thawing were complete. Perenchio, et al.[38], found this performance to be true regardless of cement content.

Whiting[59] has shown instances where superplasticized concrete performed as well as the control mix. In order to achieve this parity, however, it was necessary to increase the dosage of air- entraining agent approximately 400% when superplasticizers were used. Additional testing at decreased dosages of the air-entraining agent have shown specimens including a superplasticizer to perform poorly when compared to the control specimens.

2.8 Existing Guidelines for the Use of Superplasticizers

Three particular studies are discussed. One was carried out by the State of Indiana in 1986, another by the State of Virginia from 1974 to 1977, and the third study was conducted for the Federal Highway Administration (FHWA) in 1981. In addition, the existing federal workplan and subsequent submittal of a method by the Texas State Department of Highways and Public Transportation to meet these federal requirements are discussed in Chapter 6.

Smutzer and Zander[54] conducted a laboratory investigation of the effects of retempering portland cement concrete with a superplasticizer. Their recommendations have been adopted by the Indiana Department of Highways. Their conclusions state that retempering superplasticized concrete with additional amounts of the admixture to alleviate slump loss led to a significant reduction in the freeze-thaw durability. This practice is, therefore, discouraged, and not allowed in Indiana.

Sprinkel[55] conducted laboratory and field investigations of superplasticized concrete used for concrete pavements and bridge deck overlays for the Virginia Department of Highways and Transportation. The author found many portions of completed structures that exhibited inadequate consolidation, segregation, improperly entrained air, shrinkage cracks, and poor finishes due to the variability of the concrete. In addition, Sprinkel found that the freeze-thaw specimens exhibited low durability factors. His recommendations for guidelines for the use of superplasticizers include: 1) do not use superplasticized concrete where freeze-thaw durability is important, 2) add the superplasticizer immediately before discharge, 3) match the batch size to the placement rate, usually an amount that can be batched, placed, and finished in a 20 minute interval, and 4) specify an initial slump greater than zero inches. As of 1979, the work resulted in termination of the use of superplasticized concrete in construction by the Virginia Department of Highways and Transportation until: 1) satisfactory guidelines could be developed for batching, placing, consolidating, and finishing the concrete; 2) a satisfactory specification is prepared to allow for field acceptance; and 3) the durability of the concrete can be improved.

Whiting[59] conducted laboratory and field investigations of superplasticized concrete for the Federal Highway Administration. His recommendations for guidelines include: 1) if haul time exceeds 20 minutes, the addition of superplasticizer should be delayed until the truck has reached the jobsite, 2) delay in addition of superplasticizer up to 60 minutes after mixing will cause little loss of effectiveness, 3) small dosages of superplasticizer can be added in addition to the original dose in order to maintain the desired workability, 4) air contents should be increased to approximately 7 to 8%, and 5) variations in materials should not be permitted during the project. Whiting also recommends preparation and testing of trial batches with the specific job materials to determine: 1) dosage of superplasticizer necessary to achieve the desired slump, 2) dosage of air-entraining agent necessary to achieve the desired air content, 3) setting times, 4) compressive strengths at ages to 28 days, and 5) parameters of the air-void system. One full scale batch should follow the laboratory work to determine if any adjustments are necessary. As of the date of this publication, this report did not constitute a standard, specification, or regulation. It was, however, distributed to each FHWA regional and division office and to each state highway agency.

CHAPTER 3
MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Introduction

The materials and experimental program are described in this section for both the laboratory and field test programs. Mix proportion variables, experimental procedures, and fresh and hardened concrete tests are set forth.

3.2 Materials

3.2.1 Portland Cement. One type of portland cement was used throughout the entire project. A commercially available ASTM Type I portland cement meeting ASTM C150-86, *Standard Specification for Portland Cement* was used.[5] Table 3.1 contains the chemical and physical properties of the cement for the period from June through September 1987. These tests show little variance in cement composition for this period. All specimens were cast during the months of June through September 1987.

3.2.2 Coarse Aggregate. The coarse aggregate was of local commercial production. Normal weight crushed limestone and river gravel aggregates were used, both 3/4-inch nominal maximum size conforming to ASTM C33-86, *Standard Specification for Concrete Aggregates*. The limestone aggregate had a bulk specific gravity at SSD of 2.54 and the river gravel aggregate had a bulk specific gravity at SSD of 2.62.

3.2.3 Fine Aggregate. A natural river sand from the Colorado River was used for all readymix batches. It met all the performance requirements of ASTM C33-86 and had a bulk specific gravity at SSD of 2.62. A gradation analysis of samples was carried out in accordance with ASTM C136-84a, *Standard Method for Sieve Analysis of Fine and Coarse Aggregates.* Table 3.2 shows the sieve analyses for the samples taken on June 16, 1987, and September 10, 1987. The resulting fineness modulus calculations were 2.88 and 3.21, respectively, for the fine aggregate samples. Though significantly different, each sample met the gradation limitations set forth in ASTM C33-86.

3.2.4 Water. The water was drawn either directly from the Colorado River or from a well. The supply meets the criteria set forth in ASTM C94-86b, *Standard Specification for Ready-Mixed Concrete.*

3.2.5 Superplasticizers. Two commercially available superplasticizers were utilized for this study.

Table 3.1 Chemical and physical properties for Type I portland cement.

	June 1987	July 1987	August 1987	September 1987
Chemical Composition (%)				
Calcium Oxide (CaO)	65.22	64.90	65.31	64.87
Magnesium Oxide (MgO)	1.42	1.33	1.33	1.31
Silica Dioxide (SiO_2)	20.02	20.31	20.39	20.34
Aluminum Oxide (Al_2O_3)	5.15	5.41	5.29	5.28
Ferric Oxide (Fe_2O_3)	2.04	1.93	1.96	1.91
Sulfur Trioxide (SO_3)	2.91	3.08	3.03	3.06
Loss on Ignition (LOI)	1.77	1.62	1.23	1.70
Insoluble Residue (IR)	0.20	0.27	0.20	0.27
Total Alkalies as Na_2O	0.55	0.55	0.58	0.57
Tricalcium Silicate (C_3S)	67.54	61.97	63.94	62.58
Tricalcium Aluminate (C_3A)	10.20	11.07	10.70	10.76
Surface Area (ASTM C204-84)				
Blaine (sq. m/kg)	365	363	365	367
Turbidimeter (sq. m/kg)	195	---	---	---
Surface Area (Texas SDHPT 1982)				
Wagner (sq. cm/g)	1946	1905	1949	1911
Percent Passing #325 Sieve	96.3	95.7	97.0	95.7
Soundness				
Autoclave Expansion (%)	0.02	0.02	0.02	-0.01
Time of Setting (minutes)				
Gillmore: Initial	165	175	170	160
Gillmore: Final	300	345	315	305
Vicat: Initial	85	115	75	115
Vicat: Final	185	210	195	210

Table 3.2 Fine aggregate gradation

Sieve	Percent Retained (sample taken June 16, 1987)	Percent Retained (sample taken Sept. 10, 1987)
3/8 in	0.0	0.0
No. 4	0.40	0.48
No. 8	10.29	14.82
No. 16	20.61	25.83
No. 30	30.06	31.87
No. 50	24.79	19.06
No. 100	11.96	7.06
PAN	1.88	0.90

Superplasticizer A is approved for use by the Texas SDHPT and meets and exceeds all requirements for ASTM C494-86, *Standard Specification for Chemical Admixtures for Concrete*, Types A and F admixtures. It is a naphthalene sulfonate-based admixture having a specific gravity in the range of 1.18 to 1.23 at 77°F as reported by the manufacturer. The manufacturer's recommended dosage rate is 10 to 20 fluid ounces per hundred pounds of cement (oz/cwt).

Superplasticizer B is also approved for use by the Texas SDHPT and meets or exceeds all requirements of ASTM C494-86 Types F and G admixtures. This admixture is a naphthalene based admixture having a reported specific gravity of 1.21. The manufacturer's recommended dosage rate for this product is 6 to 12 fluid ounces per hundred pounds of cement (oz/cwt).

3.2.6 Retarders. A set retarder produced by the same manufacturer as the superplasticizer was used with each of the two superplasticizers. It was deemed necessary to include a retarder in the readymix concrete for this part of the study because the average ambient temperature during casting was above 90° F.

Retarder A exceeds the requirements of ASTM C494-86 for a Type B and D admixture and is approved for use by the Texas SDHPT. This admixture is based on a calcium salt of lignosulfonic acid. The manufacturer's recommended dosage rate is 3 to 5 fluid ounces per hundred pounds of cement (oz/cwt).

Retarder B satisfies all requirements of ASTM C494-86 for a Type D admixture and is approved for use by the Texas SDHPT. This admixture is a lignosulfonate based admixture. The manufacturer's recommended dosage rate is 3 to 5 fluid ounces per hundred pounds of cement (oz/cwt).

3.2.7 Air-entraining Agents. Three different air-entraining agents were utilized during this investigation. Air-entraining agent A is a neutralized vinsol resin and is approved for use by the Texas SDHPT and meets all requirements set forth in ASTM C260-86, *Standard Specification for Air-entraining Admixtures for Concrete.* Dosage rates varied from 0.54 to 1.00 fluid ounces per hundred pounds of cement (oz/cwt) as required to achieve the desired 4 to 6% air content.

Air-entraining agent B is an admixture developed for use with concrete mixes where it is difficult to entrain air. It consists of an aqueous solution of a mixture of fatty acids and sulfonate type surface active agents. A dosage rate of 0.60 to 0.75 fluid ounces per hundred pounds of cement (oz/cwt) was used to achieve the desired 4 to 6% air content.

Air-entraining agent C is an aqueous solution of neutralized vinsol resin with an approximate solids content of 14 ± 1/2%. It meets the requirements of ASTM C260-86 and is approved for use by the Texas SDHPT. The dosage rate used was 0.70 fluid ounces per hundred pounds of cement (oz/cwt).

3.3 Mixture Proportions

The mixture proportions are shown in Tables 3.3, 3.4, and 3.5. Table 3.3 lists the mixture proportions for the laboratory test program. In particular, weights of coarse and fine aggregate, cement and water, and admixture dosages are detailed. Relevant parameters for each mix, such as the water-cement ratio, slump at batching and delivery, travel time, and laboratory air temperature are also shown. Tables 3.4 and 3.5 contain similar mixture proportion data and relevant parameters for the field test program.

Part I: Laboratory Test Program

3.4 Mix Procedure

Each mix was batched at a local readymix concrete plant. The author was present during batching of each readymix concrete load produced for this project.

Each day the same procedure was followed. The readymix truck driver was asked to thoroughly rinse and clean the inside of the drum. Aggregates were weighed and all admixtures were added to the mix water. Weighing, dispensing, and mixing were all carried out in accordance with ASTM C94-86b, *Standard Specification for Ready-Mixed Concrete*. Samples of coarse and fine aggregates were taken directly from the plant silo storage.

After batching of all the materials, the driver then proceeded to rinse the exterior of the drum and the outermost fins. After completion of 5 to 10 minutes of initial mixing time, a slump test was carried out at the readymix plant. Water was added by the driver from the on board supply if the slump was not the desired target value. After the desired slump was achieved, the concrete was transported to the laboratory.

Upon arrival of the readymix truck at the laboratory, the concrete was mixed for approximately 2 to 3 minutes. One to two wheelbarrows of concrete, approximately 6 cubic feet, were discarded initially before any testing and sampling of the concrete was carried out as in accordance with ASTM C172-82, *Standard Method of Sampling Freshly Mixed Concrete.*

Table 3.3 Concrete mixture proportions for laboratory test program

(All amounts per cubic yard of concrete)

	Coarse Aggregate Type	Coarse Aggregate Weight[1] (lb)	Sand[1] (lb)	Cement (lb)	Water (lb)	Retarder Dosage[2] (oz)	AEA Dosage[3] (oz)	w/c (by weight)	Slump @ Batch[4] (in)	Slump @ Delivery[5] (in)	Air Temperature (°F)	Travel Time[6] (minutes)
Mix L1	Gravel	1880	1440	468	233	13.8	2.54	0.498	NA	2	90	30
Mix L2	Gravel	1890	1407	498	239	14.1	2.59	0.480	5	3	87	42
Mix L3	Limestone	1818	1317	468	250	14.2	3.20	0.534	2-1/2	1-1/2	90	44
Mix L4	Limestone	1800	1318	463	244	14.1	2.80	0.527	7	4	90	49
Mix L5	Limestone	1788	1316	468	234	14.2	2.80	0.500	4	1-3/4	90	56
Mix L6	Gravel	1928	1402	470	221	23.6	3.29	0.470	4	2-1/2	91	41
Mix L7	Gravel	1872	1378	476	214	23.6	3.52	0.450	1	3/4	93	37
Mix L8	Gravel	1712	1336	660	228	19.7	5.92	0.345	1-1/2	0	90	44
Mix L9	Gravel	1872	1371	466	206	14.3	3.52	0.442	1-1/2	3	90	58

1 All weights are saturated surface dry (SSD)
2 All mixes contain retarder A
3 Air entraining Agent B was used in Mix L9 (all other mixes contain air entraining Agent A)
4 Value for slump test conducted at the readymix plant after initial mixing
5 Value for slump test conducted at the Laboratory upon arrival of readymix truck
6 Elapsed time from batch time to time of arrival of the readymix truck at the laboratory

Table 3.4 Concrete mixture proportions for field test program

(September 21, 1987)

(All amounts per cubic yard of concrete)

	Coarse Agg.[1] (lb)	Sand[1] (lb)	Cement (lb)	Water (lb)	Retarder		AEA		W/C (by weight)	Initial[2] Slump(in.)
					Type	Dosage (oz)	Type	Dosage (oz)		
Mix F1	1896	1367	468	223	---	---	A	3.30	0.476	2-3/4
Mix F2	1854	1376	476	194	A	14.0	A	3.30	0.408	2-1/2
Mix F3	1884	1374	472	187	A	23.5	A	3.40	0.396	2-1/2
Mix F4	1908	1371	469	193	---	---	A	3.30	0.412	3
Mix F5	1836	1381	469	183	A	14.2	A	3.30	0.390	3-1/2
Mix F6	1890	1375	474	183	A	23.4	A	3.30	0.386	3
Mix F7	1890	1371	467	211	---	---	A	3.30	0.452	1-1/2
Mix F8	1878	1381	470	193	A	14.0	A	3.20	0.411	2-1/2
Mix F9	1860	1372	468	183	A	18.8	A	3.30	0.391	2-1/4
Mix F10	1884	1384	474	171	A	23.5	A	3.30	0.361	2-3/4

1 All weights are saturated surface dry

2 Slump test conducted after initial mixing prior to the addition of any superplasticizer

Table 3.5 Concrete mixture proportions for field test program

(September 25, 1987)

(all amounts per cubic yard of concrete)

	Coarse Agg.[1] (lb)	Sand[1] (lb)	Cement (lb)	Water (lb)	Retarder Type	Retarder Dosage (oz)	AEA Type	AEA Dosage (oz)	W/C (by weight)	Initial Slump(in.)[2]
Mix F11	1896	1374	473	204	B	23.5	C	3.30	0.431	3-1/2
Mix F12	1914	1379	467	194	B	14.1	C	3.30	0.415	1-3/4
Mix F13	1884	1392	473	193	B	23.5	C	3.30	0.408	3-1/2
Mix F14	1890	1371	467	221	A	14.1	B	2.82	0.473	2
Mix F15	1872	1393	473	225	A	23.5	B	2.82	0.476	3
Mix F16	1848	1383	474	202	A	23.4	A	4.70	0.426	1-3/4
Mix F17	1872	1381	472	249	---	---	A	3.30	0.528	6
Mix F18	1866	1392	472	225	A	14.2	A	3.30	0.477	5
Mix F19	1884	1371	469	238	A	23.5	A	3.30	0.507	7

1 All weights are saturated surface dry (SSD)

2 Slump test conducted after initial mixing prior to the addition of any superplasticizer

At the time of each sampling, the following tests were conducted and specimens were cast. Testing included slump, air content, unit weight, setting time, and concrete temperature. Specimens cast included seven cylinders for compression tests, seven beams for flexural tests, three slabs for deicing-scaling resistance tests, and three beams for freeze-thaw resistance tests.

The first specimens cast from each concrete mix contained no superplasticizer and are denoted as the control specimens. The initial addition of superplasticizer was scheduled for 50 to 55 minutes after batch time. This was not possible in all cases because of unexpected extended transit time. The average time for the first dosage of the nine laboratory mixes was 57 minutes. After the superplasticizer was added, the concrete was mixed for approximately 5 minutes.

The goal for this first addition of superplasticizer was for the fresh concrete to achieve a slump of approximately 8 inches. If flowing concrete was not achieved, more superplasticizer was added followed by approximately 5 minutes of mixing until the target slump was reached. The fresh concrete was then tested and specimens cast. Each testing and specimen molding cycle was identical to the one described previously.

The fresh concrete remaining in the readymix truck was then monitored for slump, temperature, and air content at approximately 15 minute intervals until either the slump had returned to the original slump of the control mix or one hour had passed since the first addition of superplasticizer. At this time, the concrete was redosed with the needed amount of superplasticizer to produce flowing concrete having approximately an 8 inch slump following the exact same procedures as described earlier. After flowing concrete was achieved, fresh concrete testing and specimen casting was completed. Although it would have been desirable to monitor slump and air content beyond this point, by this time the mix was about 2-1/2 hours old. All testing was thus concluded and the remaining concrete in the truck was discarded.

A procedure was established for finishing and curing the specimens and it was repeated for each of the nine laboratory mixes. The top surface of all specimens was leveled off with a wooden trowel after consolidation was completed. This was a rather quick strikeoff and no effort was made to finish the specimens. After the bleed water evaporated and the specimens had achieved a certain degree of set, they were finished with a minimum number of passes with a steel trowel. This certain degree of set was determined by punching the surface with an index finger. Wet burlap was placed around the specimens and plastic sheeting was draped over all the specimens. Nothing touched the finished surfaces; however, the intention was to provide an environment of 100% humidity.

3.5 Mix Variations

For each of the nine mixes that make up the laboratory test program, the test variables are outlined in Table 3.6.

3.5.1 Retarder Dosage. One retarder was used for all mixes; however, the dosage varied. Two dosages, 3.0 and 5.0 fluid ounces per hundred pounds of cement (oz/cwt), corresponding to the lower and upper limits recommended by the manufacturer were used. Primary interest to this study was the effect of this variable on initial and final setting times and rate of slump loss.

3.5.2 Water Content. The mixing water content was adjusted as needed to produce concrete having an initial slump of 1 to 2, 4 to 5, or 6 to 7 inches prior to the addition of any superplasticizers. The initial slump was determined and measurement carried out at the batch plant as described in Sec. 3.4.

3.5.3 Cement Content. Two cement contents were investigated in this program. Primarily, the mixes contained 5.0 sacks of cement per cubic yard; however, Mix L8 had a cement content of 7.0 sacks per cubic yard. A sack is defined as 94 pounds of cement, thus a 5.0 sack mix contains 470 pounds of cement per cubic yard of concrete. Similarly, a 7.0 sack mix contains 658 pounds of cement per cubic yard of concrete.

The 5.0 sack mix met the requirements for Texas SDHPT Class A regular concrete. General usage is for drilled shafts, bridge substructures, and culverts etc. The 7.0 sack mix met the requirements of Texas SDHPT specifications for a Class C-C special concrete. General usage is stated as bridge slabs and high strength concrete when a high-range water reducer is used. [56]

Considerations for increasing the cement content included examination of the effect of additional fines on the effectiveness of the superplasticizer. In addition, the effects of the cement content on finishing and setting times were investigated.

3.5.4 Coarse Aggregate. Both crushed limestone and river gravel were included in this study. Gravel was chosen as the primary aggregate type. Because of the rounded and less angular particle shape, river gravels were considered to have a higher tendency to produce more bleeding than crushed limestone. The limestone aggregate was

Table 3.6 Mix proportion information for laboratory test program

	Cement Content (sks)	Aggregate Type	Initial Slump (in) [1]	Retarder Type	Retarder Dosage (oz/cwt)	Air Entraining Agent Type	Superplasticizer Type
Mix L1	5.0	Gravel	1-2	A	3.0	A	A
Mix L2	5.0	Gravel	4-5	A	3.0	A	A
Mix L3	5.0	Limestone	1-2	A	3.0	A	A
Mix L4	5.0	Limestone	6-7	A	3.0	A	A
Mix L5	5.0	Limestone	4-5	A	3.0	A	A
Mix L6	5.0	Gravel	4-5	A	5.0	A	A
Mix L7	5.0	Gravel	1-2	A	5.0	A	A
Mix L8	7.0	Gravel	1-2	A	3.0	A	A
Mix L9	5.0	Gravel	1-2	A	3.0	B	A

[1] Refers to the acceptable range for initial slump immediately after batching and before any superplasticizer was added

included for thoroughness and secondly, to help determine aggregate contribution to abrasion resistance.

3.5.5 Air-entraining Agent. Mix L9 was included in the series to examine the capability of a different air-entraining agent to prevent the observed loss in air content that occurred when the superplasticizer was used in conjunction with the standard neutralized vinsol resin air-entraining admixture.

3.6 Fresh Concrete Tests

The following tests were performed for each mix tested at the laboratory.

3.6.1 Workability. This test was carried out in accordance with ASTM C143-78, *Standard Test Method for Slump of Portland Cement Concrete* and Tex-415-A, *Slump of Portland Cement Concrete.*

3.6.2 Air Content. Determination of air content was performed in accordance with ASTM C173-78, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method* and Tex-416-A, *Air Content of Freshly Mixed Concrete.*

3.6.3 Temperature. The concrete temperature was determined with a thermometer with a range from 25°F to 125°F and 1°F gradations.

3.6.4 Unit Weight. This procedure was carried out in accordance with ASTM C138-81, *Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete* and Tex-417-A, *Weight Per Cubic Foot and Yield of Concrete.*

3.6.5 Setting Time. Initial and final setting times were determined in accordance with ASTM C403-85, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.*

3.7 Hardened Concrete Tests

The following tests were performed as described for each mix tested at the laboratory. The procedures for making, consolidating, and curing the specimens were in accordance with ASTM C192-81, *Standard Method of Making and Curing Concrete Test Specimens in the Laboratory.*

3.7.1 Air-void Analysis. Though no tests have been conducted at this time, one specimen of each type from each mix is in storage for testing at a later age if this test is deemed necessary.

3.7.2 Compressive Strength. Testing for compressive strength of the 6 × 12 inch cylinders was carried out using unbonded neoprene caps. Three specimens were tested at an age of 7 days and three companion specimens were tested at 28 days. All procedures were in accordance with ASTM C39-86, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* and Tex-418-A, *Compressive Strength of Molded Concrete Cylinders.*

3.7.3 Flexural Strength. The 6 × 6 × 20 inch beams were tested in third point loading over an 18 inch span according to ASTM C78-84, *Standard Test Method for Flexural Strength of Concrete.* Three specimens were tested at 7 days and three companion specimens were tested at 28 days.

3.7.4 Abrasion Resistance. The abrasion resistance test was conducted in accordance with ASTM C944-80, *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating Cutter Method.* Three specimens consisting of the tested halves of the 7 day flexural strength beams were tested for each mix. The abrasion resistance test was conducted on the finished surface of the beam specimens. Testing was conducted at an age of 8 days.

3.7.5 Freeze-Thaw Resistance. The 3 × 4 × 16 inch beams were cast and are being tested in accordance with ASTM C666-84, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* and Tex-423-A, *Resistance of Concrete to Rapid Freezing and Thawing.* Procedure A, rapid freezing and thawing in water is being followed. The results will be published in a later report. The specimens were placed in a freezer maintained at or near 0°F after 14 days of moist curing and remained frozen until testing was started.

3.7.6 Deicing-Scaling Resistance. These slabs were cast and will be tested in accordance with ASTM C672-84, *Standard Test Method of Scaling Resistance of Concrete Surfaces exposed to Deicing Chemicals.* The specimens were moist cured for 14 days, followed by air curing for 14 days. On the 28th day, the specimens were placed in a freezer maintained at or near 0°F. The specimens will remain in the freezer until testing is started. The results will be published in a later report.

Part II: Field Test Program

3.8 Mix Procedure The second portion of the project reported herein was carried out in the field over a two day period. Ten readymix truck loads were batched the first day, and nine the second day. These nineteen mixes were batched at the same local readymix plant as the nine mixes that make up the laboratory test program using the same source of materials.

As before, the driver was instructed to thoroughly rinse and clean the inside of the drum. Aggregates were weighed cumulatively; admixtures were added to the mix water, and batching and mixing were carried out in accordance with ASTM C94-86b. The driver then completed the standard rinsing and cleaning procedure. Approximately 10 to 15 minutes after batching, the truck arrived at the testing site. The site was located in a flat, shadeless area within the readymix company's property.

Immediately upon arrival, the concrete was mixed for approximately 2 to 3 minutes. One to two wheelbarrows of concrete were discarded and a slump test was conducted to determine if the mix was within range of the desired initial slump. In some instances, water was added to achieve the desired initial slump and in a few cases, the mixes were already too wet, and thus were rejected. Additional initial testing included temperature and air content. Three cylinders were also molded at this time in accordance with ASTM C31-87a, *Standard Method of Making and Curing Concrete Test Specimens in the Field.*

Slump and concrete temperature were monitored at approximately 15 minute intervals until it was time to add the superplasticizer. If, at any time, the slump decayed to one inch or less during the hold period of 30, 60, or 90 minutes, the superplasticizer was added at this point. Addition of the superplasticizer was carried out following the same procedure described in Sec. 3.4. The air content of each mix was determined after the superplasticizer was added along with slump and concrete temperature. Slump and concrete temperature were then monitored again at 15 minute intervals. If the slump decayed to the original initial slump, the mix was redosed with superplasticizer to achieve flowing concrete.

All testing was stopped when the concrete mix reached the age of 120 minutes. At this time, three additional cylinders were cast, and final slump, air content, and concrete temperature tests were conducted.

3.9 Mix Variations

For each of the nineteen mixes that make up the field test program, the test variables are outlined for each mix in Tables 3.7 and 3.8.

Table 3.7 Mix proportion information for field test program (September 21, 1987)

	Initial Slump (in) [1]	Retarder		Air Entraining Agent		Superplasticizer Type	Time of Addition of Superplasticizer (minutes after batching)
		Type	Dosage (oz/cwt)	Type	Dosage (oz/cwt)		
Mix F1	2-3	--	None	A	0.70	A	30
Mix F2	2-3	A	3.0	A	0.70	A	30
Mix F3	2-3	A	5.0	A	0.70	A	30
Mix F4	2-3	--	None	A	0.70	A	60
Mix F5	2-3	A	3.0	A	0.70	A	60
Mix F6	2-3	A	5.0	A	0.70	A	60
Mix F7	2-3	--	None	A	0.70	A	90
Mix F8	2-3	A	3.0	A	0.70	A	90
Mix F9	2-3	A	4.0	A	0.70	A	90
Mix F10	2-3	A	5.0	A	0.70	A	90

[1] Refers to the acceptable range for initial slump immediately after batching and before any superplasticizer was added

Table 3.8 Mix proportion information for field test program (September 25, 1987)

	Initial[1] Slump (in)	Retarder		Air Entraining Agent		Superplasticizer Type	Time of Addition of Superplasticizer (minutes after batching)
		Type	Dosage (oz/cwt)	Type	Dosage (oz/cwt)		
Mix F11	2-3	B	5.0	C	0.70	B	30
Mix F12	2-3	B	3.0	C	0.70	B	60
Mix F13	2-3	B	5.0	C	0.70	B	60
Mix F14	2-3	A	3.0	B	0.60	A	60
Mix F15	2-3	A	5.0	B	0.60	A	60
Mix F16	2-3	A	5.0	A	1.00	A	60
Mix F17	5-6	--	None	A	0.70	A	90
Mix F18	5-6	A	3.0	A	0.70	A	90
Mix F19	5-6	A	5.0	A	0.70	A	90

1 Refers to the acceptable range for initial slump immediately after batching and before any superplasticizer was added

3.9.1 Superplasticizer Manufacturer. Two naphthalene superplasticizers were used in an attempt to determine if different commercially available products acted similarly under field conditions.

3.9.2 Time of Addition. Superplasticizers were added at three different times after batching, namely, 30, 60, and 90 minutes. The 30 minute time frame probably represents the earliest a readymix truck may reach the job site. Examples may be a precast operation or temporary job site batch plant. The 60 minute time frame represents the most likely circumstances for typical readymix concreting. The most extreme case, 90 minute dosage, may occur due to heavy traffic during transit or job site delays in unloading.

3.9.3 Retarder Dosage. The retarder dosages varied from the minimum to maximum recommended values, but, in addition, mixes were investigated that contained no retarder. The objective was to determine whether retarders were necessary in hot weather concreting and, if so, to gather information on how to determine the optimum dosage to minimize slump loss under field conditions.

3.9.4 Retarder Manufacturer. Two retarder types were investigated in the field study. Each retarder was matched with the superplasticizer marketed by the same manufacturer.

3.9.5 Air-entraining Agent. Three air-entraining agents were used in this study. Each air entraining agent was matched with the superplasticizer of the same manufacturer to ensure compatibility.

3.9.6 Water Content. Of the six field mixes held for 90 minutes, three had an initial slump of 2 to 3 inches whereas the others had a higher initial slump of 5 to 6 inches. The intention was to determine if a higher initial slump is required when superplasticizer addition will be substantially delayed. The higher initial slump may, however, be accompanied by segregation or unmanageable bleeding. All the remaining mixes were to have an initial slump of 2 to 3 inches. This was found to work well with the laboratory mixes.

3.10 Concrete Tests

The following tests were performed as described for each mix tested in the field. Slump tests were carried out in accordance with ASTM C143-78 and Tex-415-A. Determination of air content was performed by the volumetric method in accordance with ASTM C173-78 and Tex-416-A. Concrete temperature was determined using a thermometer with a range from 25°F to 125°F and 1 degree gradations. The cylinders for compression testing were made in accordance with ASTM C192-81 and tested in accordance with ASTM C39-86 and Tex-418-A. The specimens were brought to the laboratory within 48 hours, placed in moist curing conditions, and tested at the age of 28 days.

CHAPTER 4
EXPERIMENTAL RESULTS

4.1 Introduction

Experimental test results are presented in this chapter. In Chapter 5, the results are discussed and analyzed. This chapter is divided into two parts. Part I details the results of the laboratory mixes and Part II details the results of the field mixes. The results of Part I include change in slump, air content, temperature, and unit weight with time after batching, initial and final setting times, compressive and flexural strengths at 7 and 28 days, and abrasion resistance. The results of Part II include change in slump, air content, and temperature with time after batching, and 28 day compressive strengths.

Each of the figures presented in this chapter utilizes the following terminology. Admixture Group 1 includes Superplasticizer A, Retarder A, and Air-entraining Agent A. Admixture Group 2 includes Superplasticizer A, Retarder A, and Air-entraining Agent B. Admixture Group 3 includes Superplasticizer B, Retarder B, and Air- entraining Agent C. A description of each admixture is found in Chapter 3.

Part I: Laboratory Test Program

4.2 Fresh Concrete Tests

The following section describes the data recorded from all fresh concrete testing of each of the nine laboratory mixes. These mixes were batched between June 18, 1987 and September 10, 1987.

4.2.1 Workability. Figures 4.1 through 4.9 show the slump values for each laboratory mix throughout the monitoring period. In addition, each graph includes the amount and time of addition of the initial and second dosages of superplasticizer used to produce flowing concrete. The initial reading shown is the slump test conducted at the batch plant. There was no slump test conducted at the batch plant for Mix L1.

4.2.2 Air Content. Figures 4.10 through 4.18 show the air content values for each laboratory mix throughout the monitoring period. In addition, each graph includes the amount and time of addition of the initial and second dosages of superplasticizer. Initial air contents were measured when the readymix truck arrived at the laboratory.

4.2.3 Temperature. Figures 4.19 through 4.27 present the concrete temperature (°F) readings for each laboratory mix throughout the monitoring period. Each graph

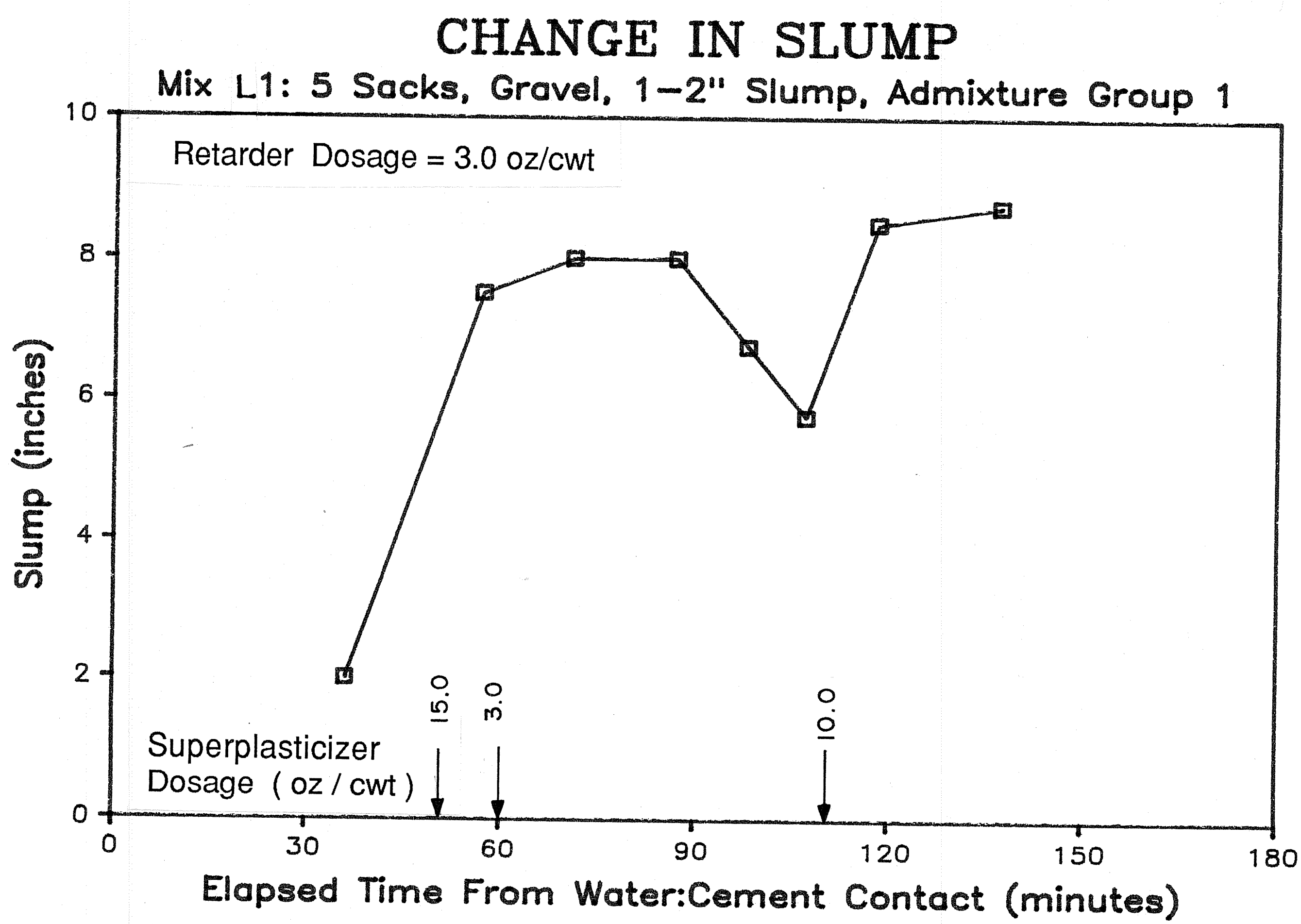


Fig. 4.1 Slump data for laboratory mix of June 18, 1987

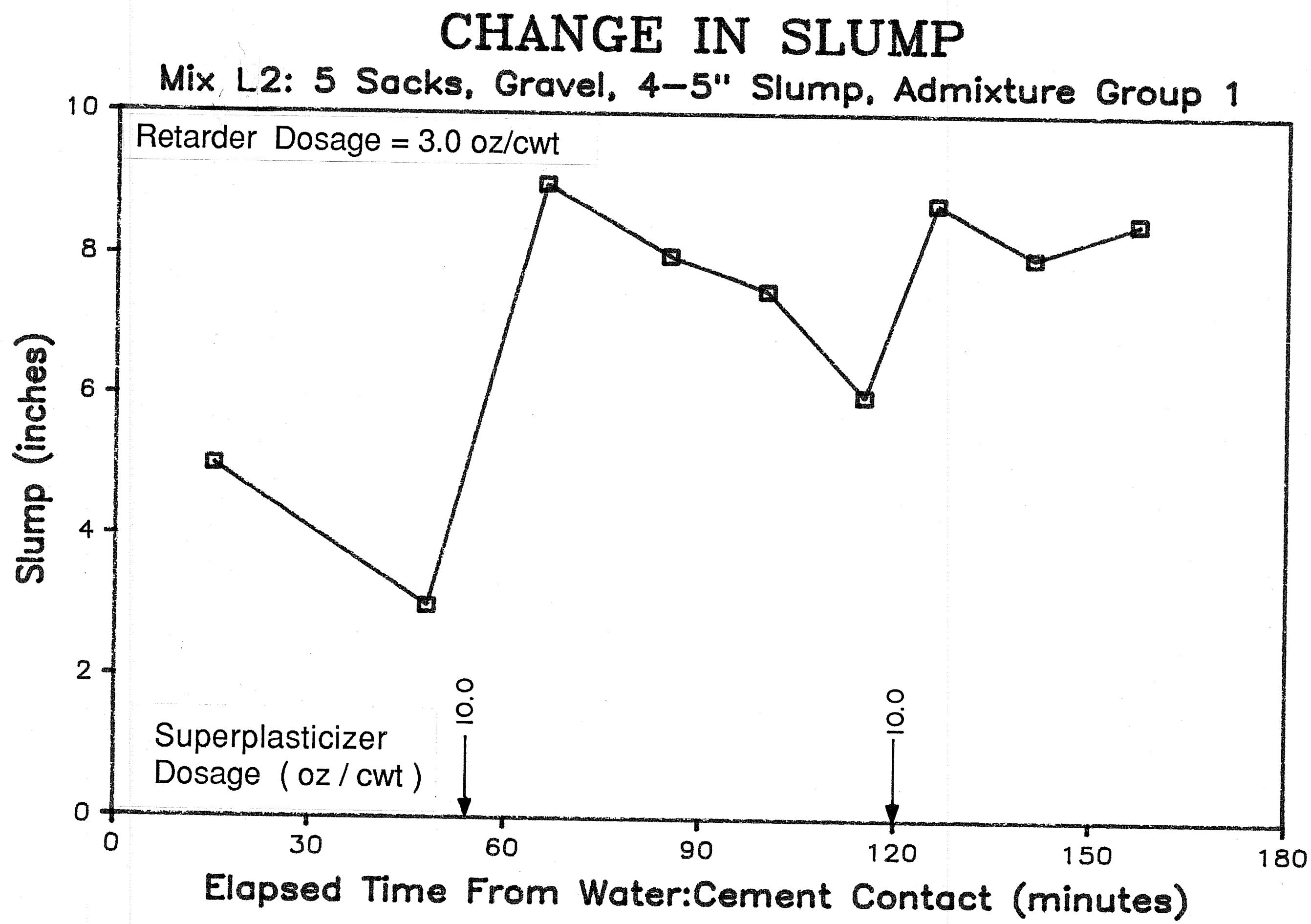


Fig. 4.2 Slump data for laboratory mix of June 23, 1987

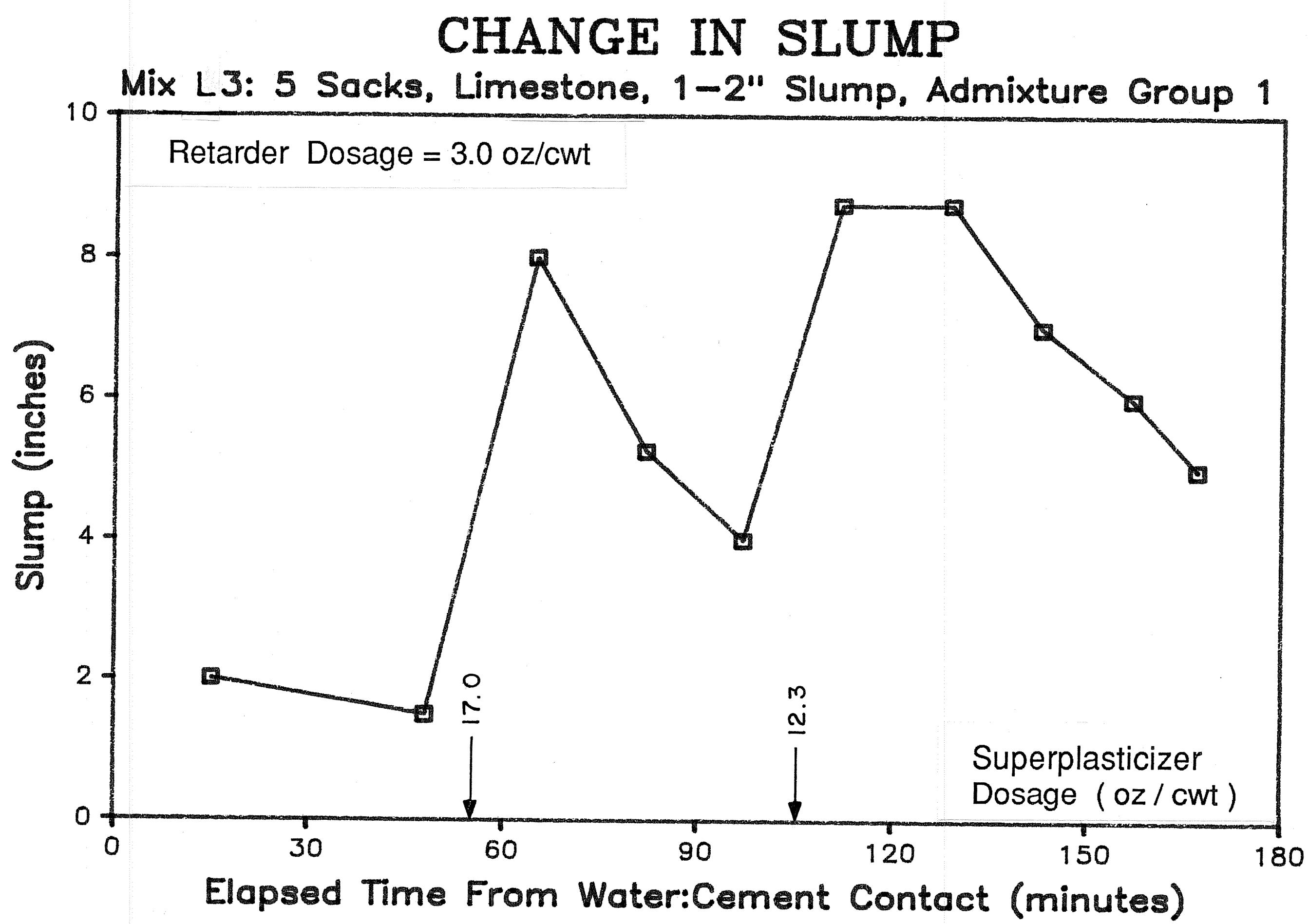


Fig. 4.3 Slump data for laboratory mix of July 2, 1987

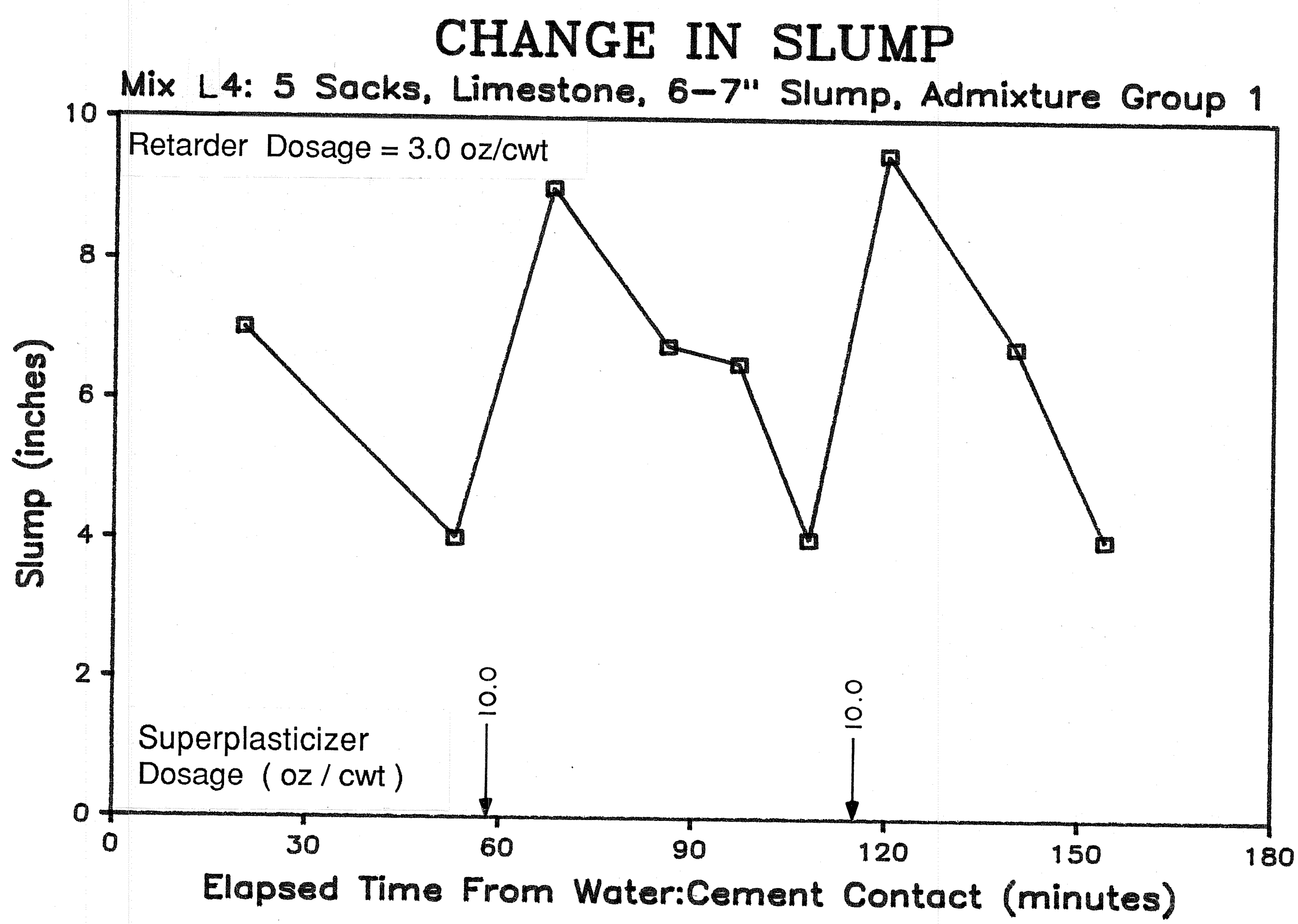


Fig. 4.4 Slump data for laboratory mix of July 16, 1987

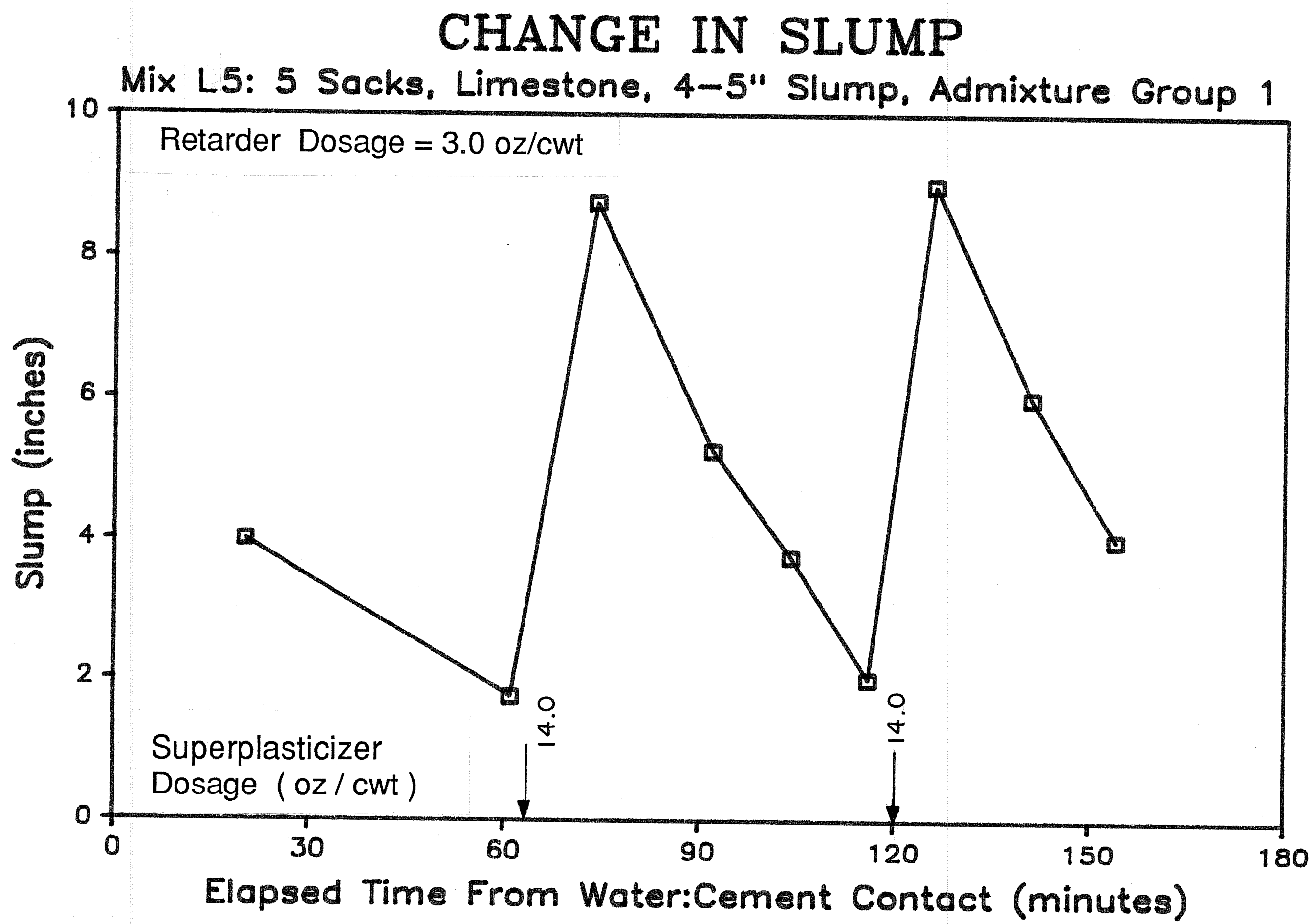


Fig. 4.5 Slump data for laboratory mix of July 21, 1987

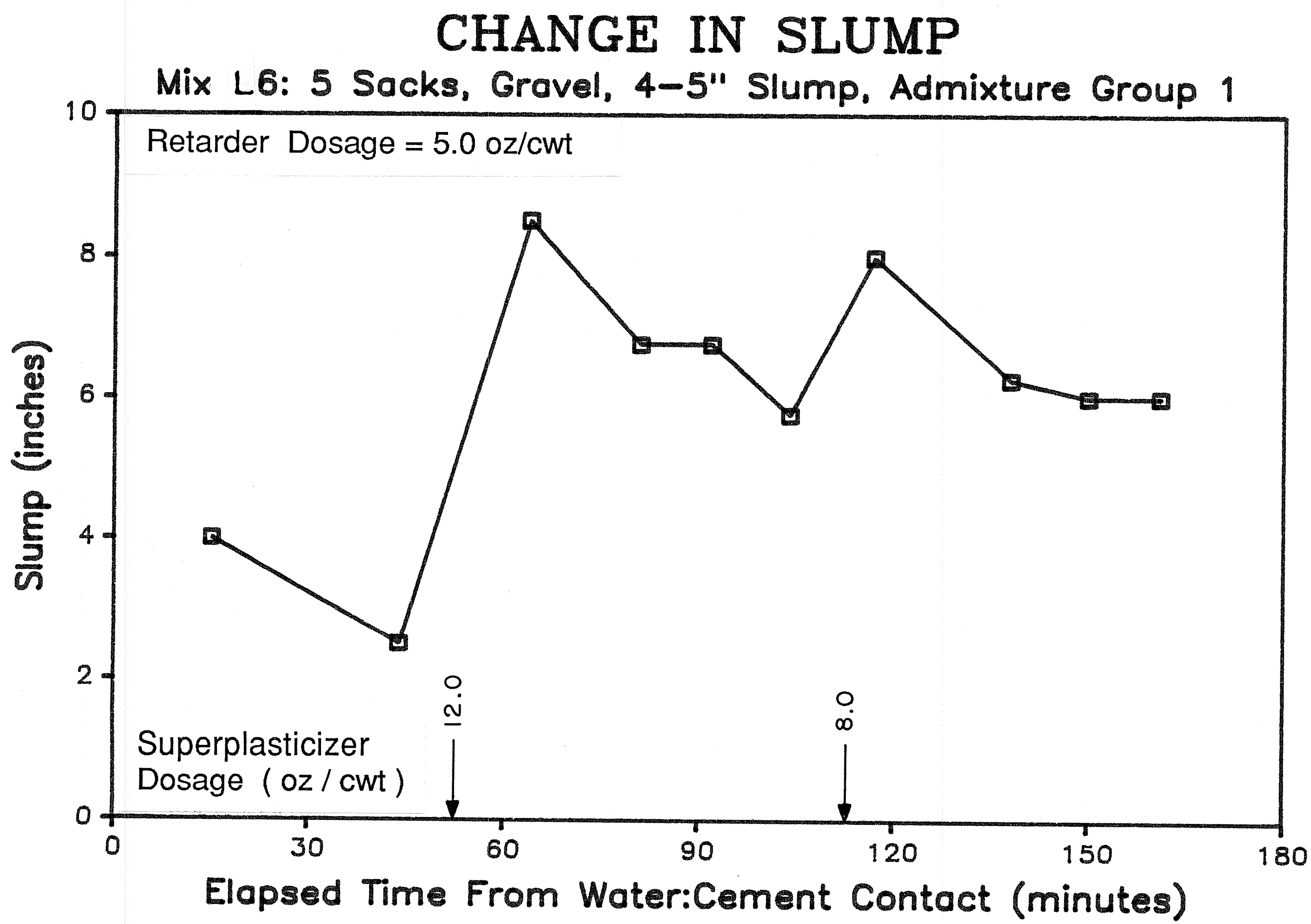


Fig. 4.6 Slump data for laboratory mix of July 23, 1987

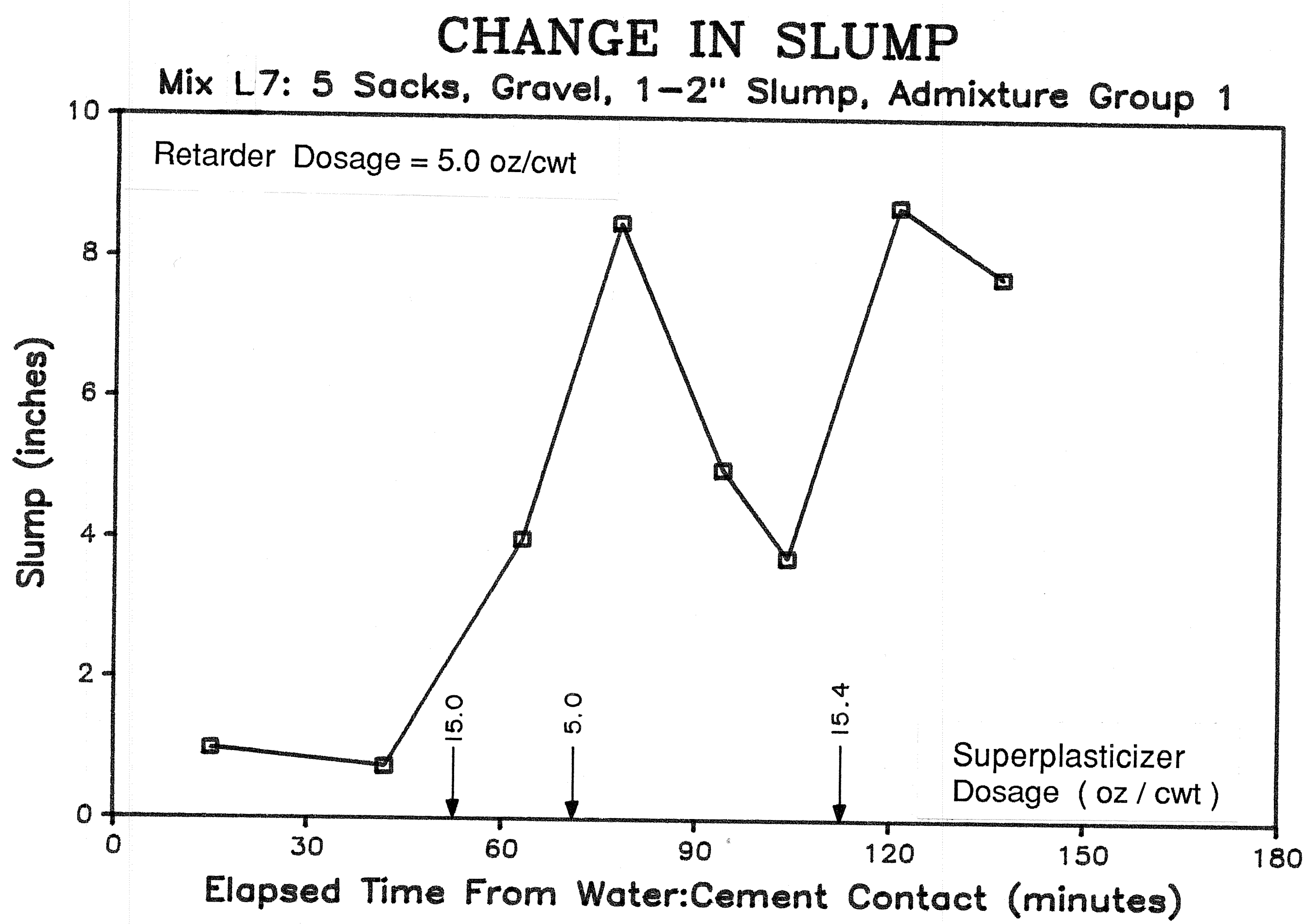


Fig. 4.7 Slump data for laboratory mix of August 25, 1987

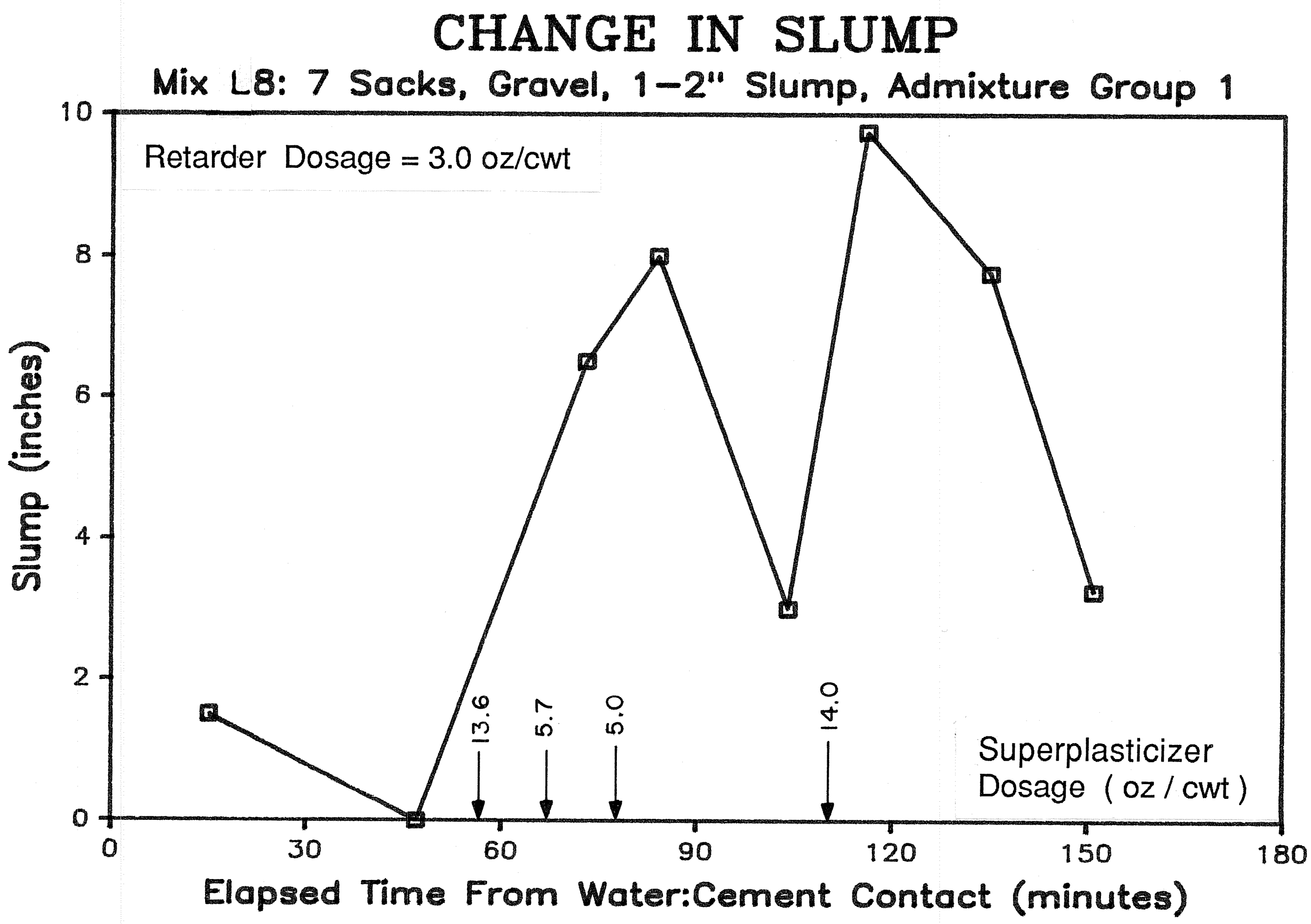


Fig. 4.8 Slump data for laboratory mix of September 3, 1987

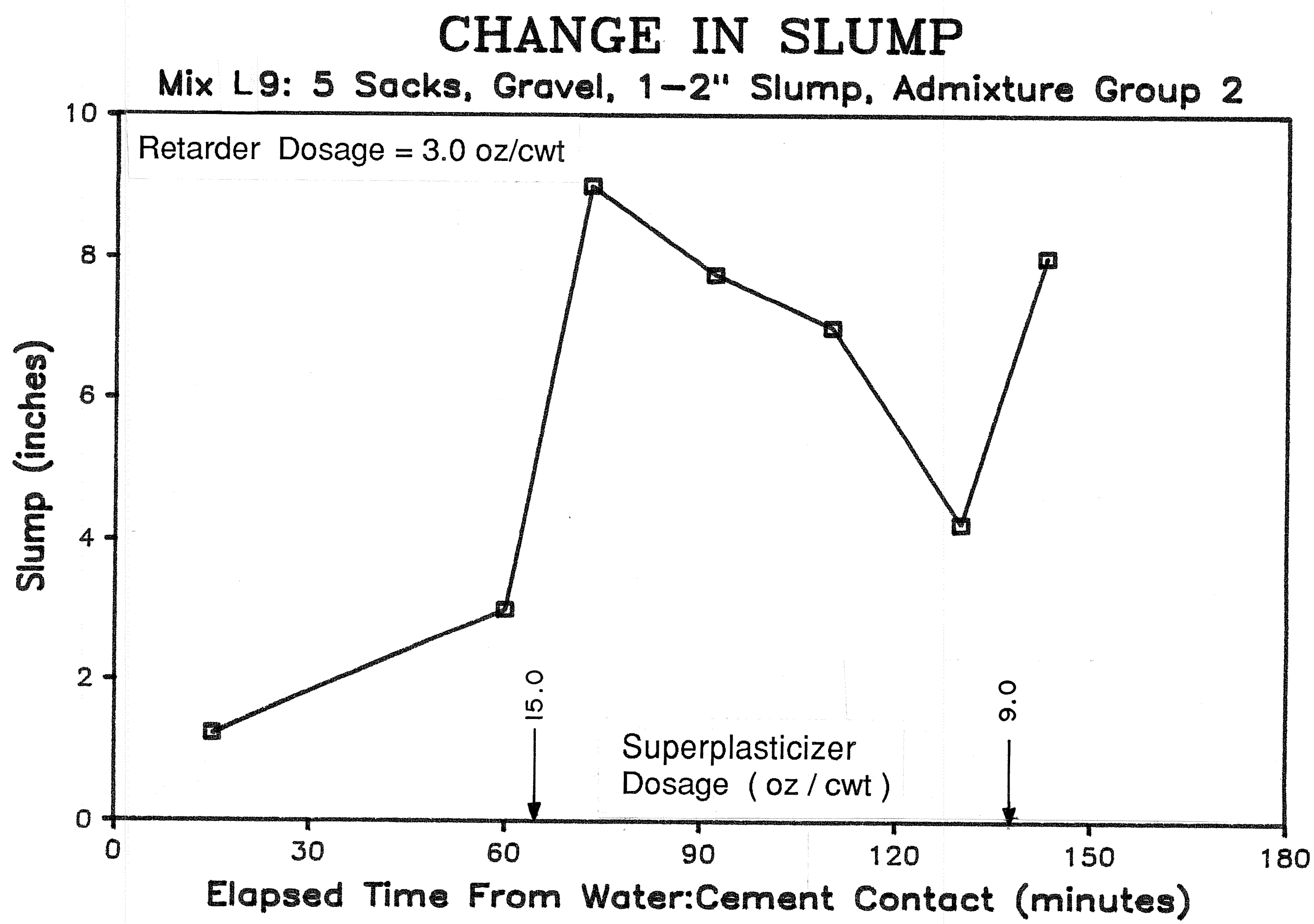


Fig. 4.9 Slump data for laboratory mix of September 10, 1987

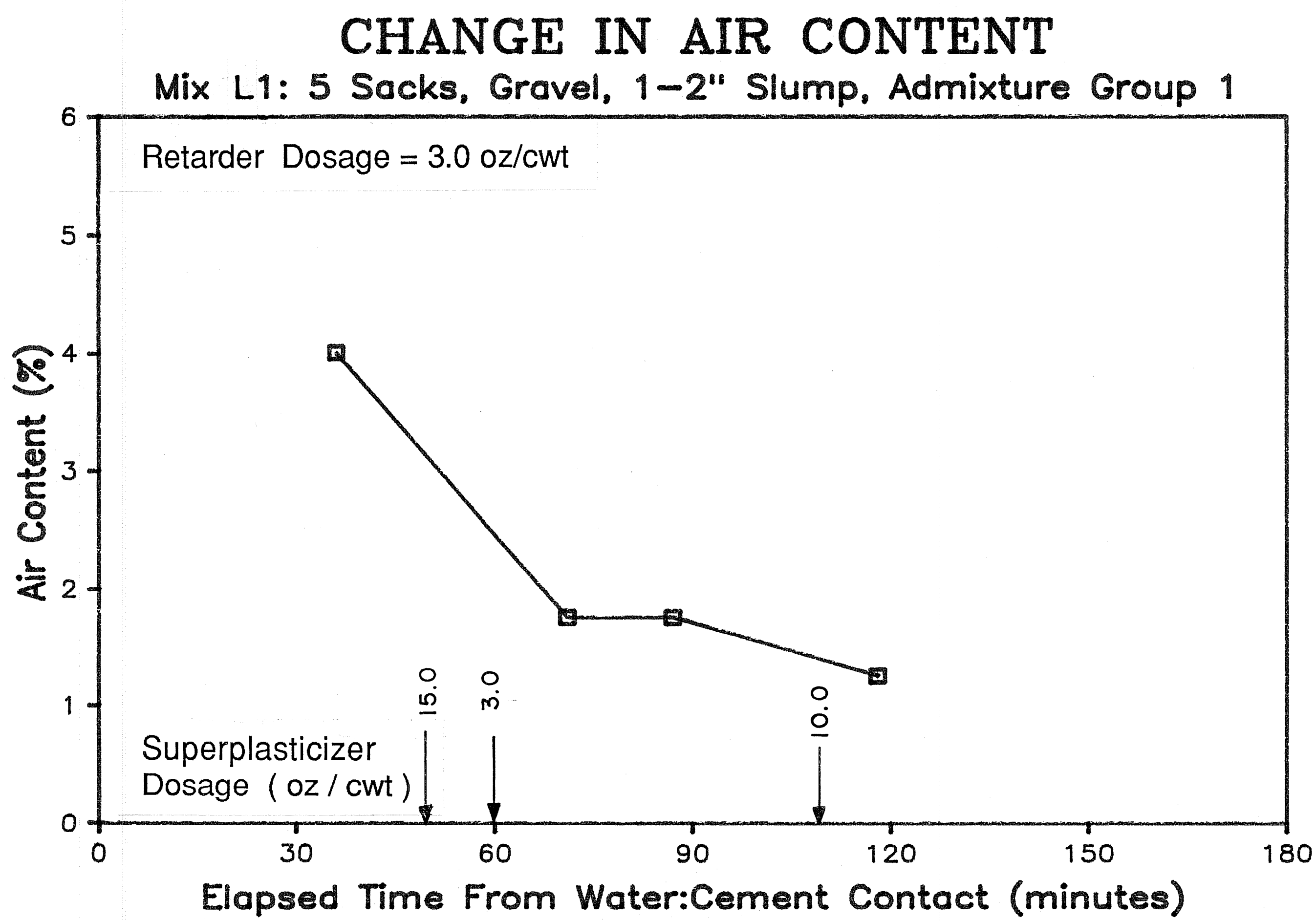


Fig. 4.10 Air content data for laboratory mix of June 18, 1987

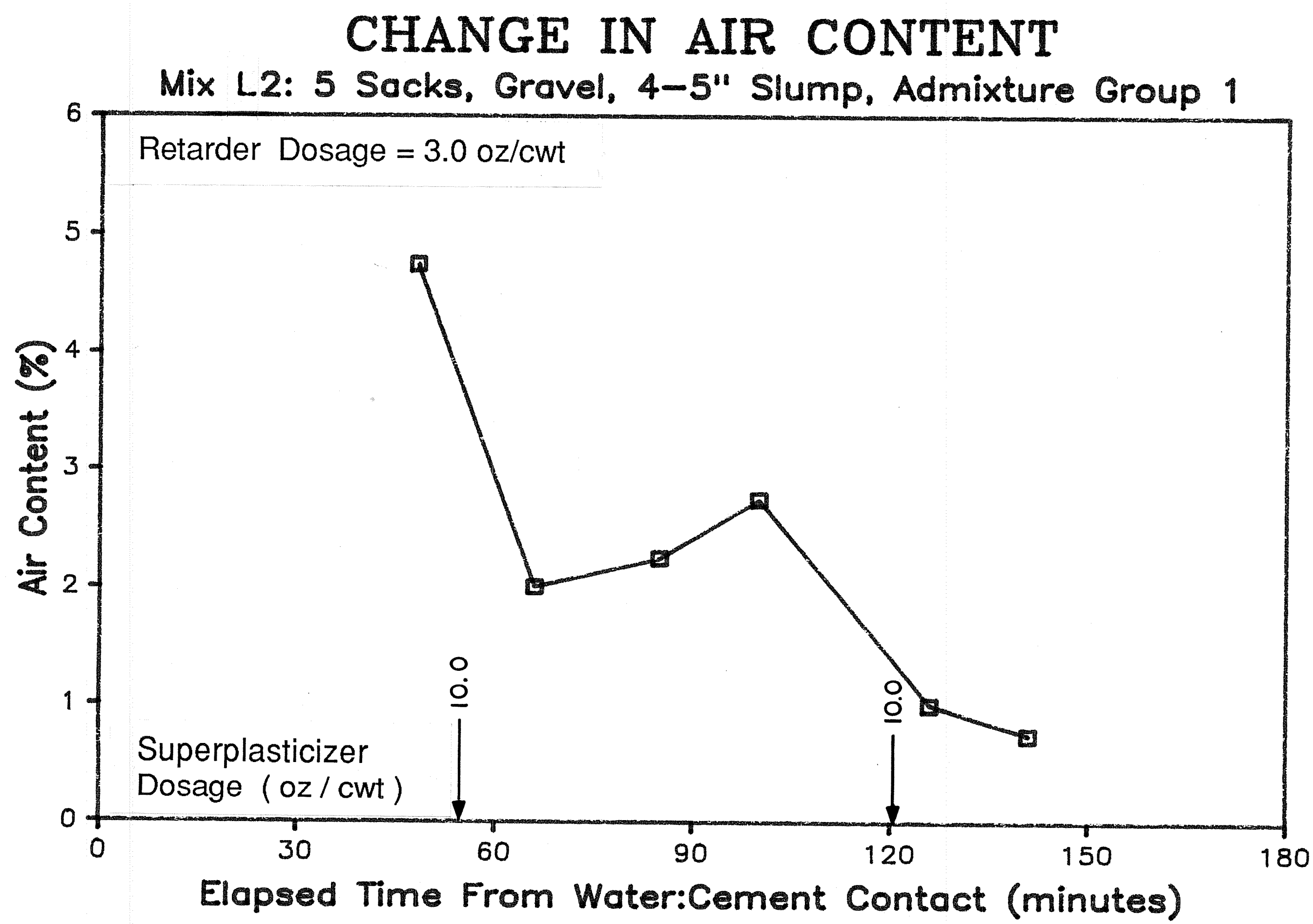


Fig. 4.11 Air content data for laboratory mix of June 23, 1987

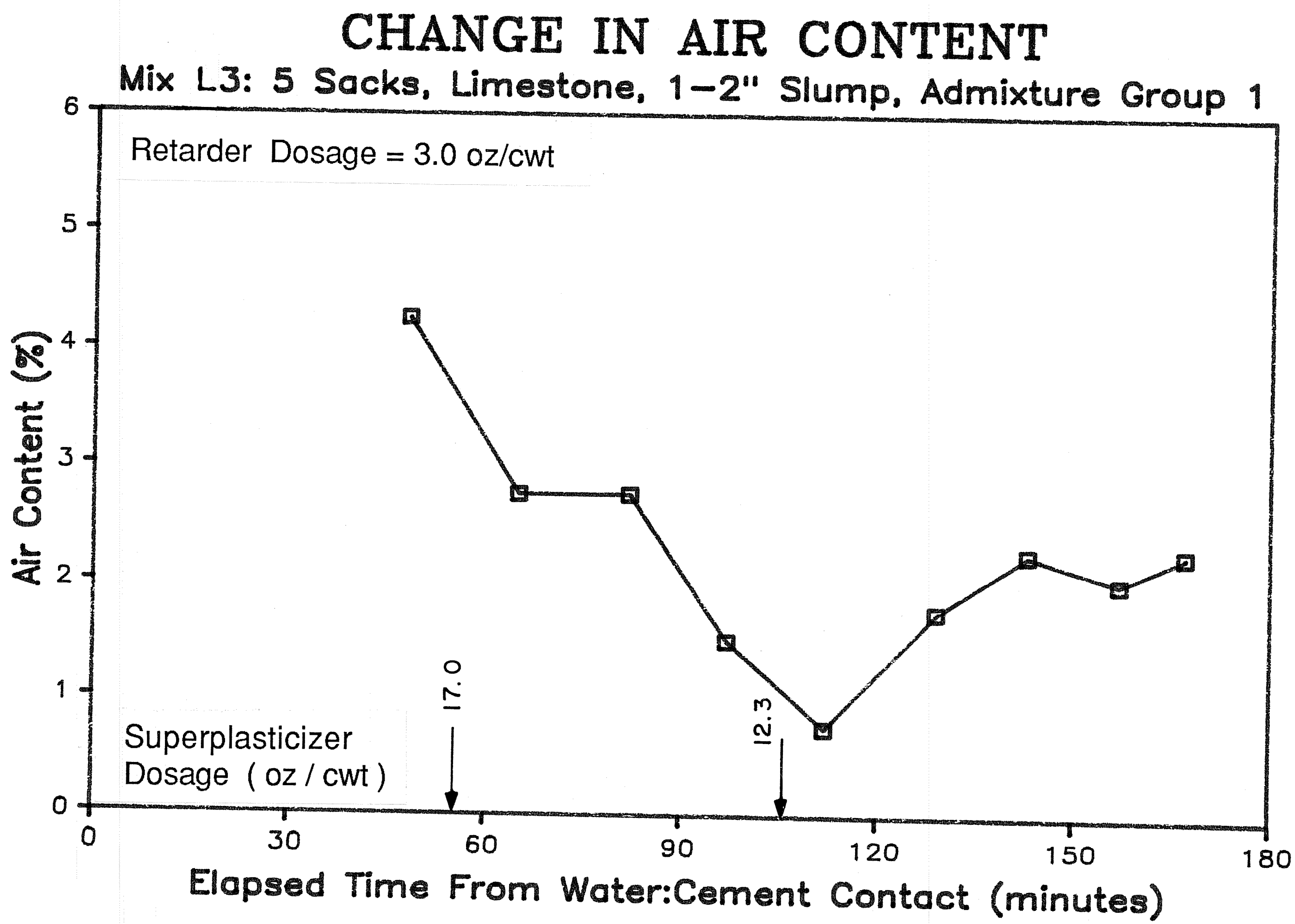


Fig. 4.12 Air content data for laboratory mix of July 2, 1987

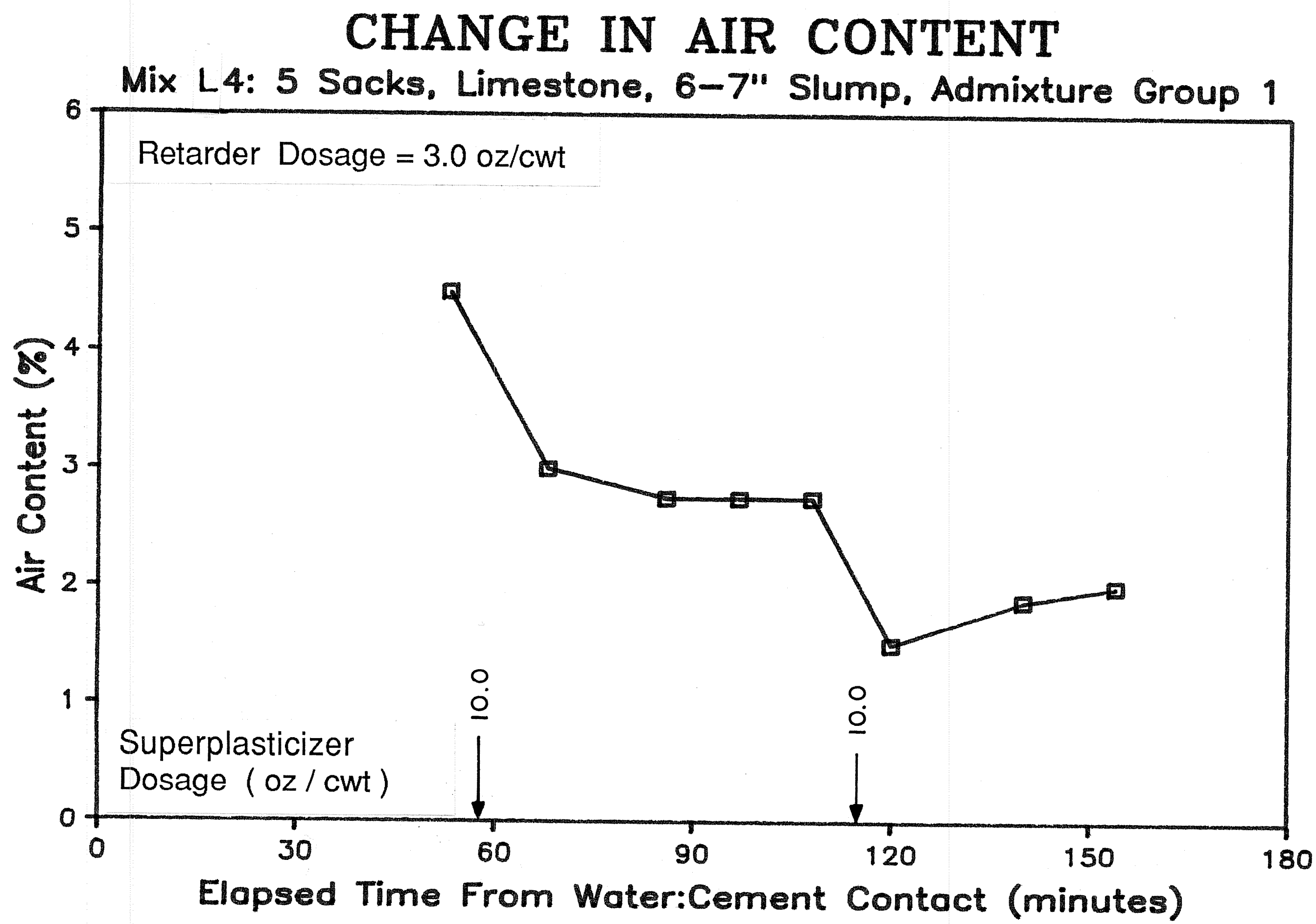


Fig. 4.13 Air content data for laboratory mix of July 16, 1987

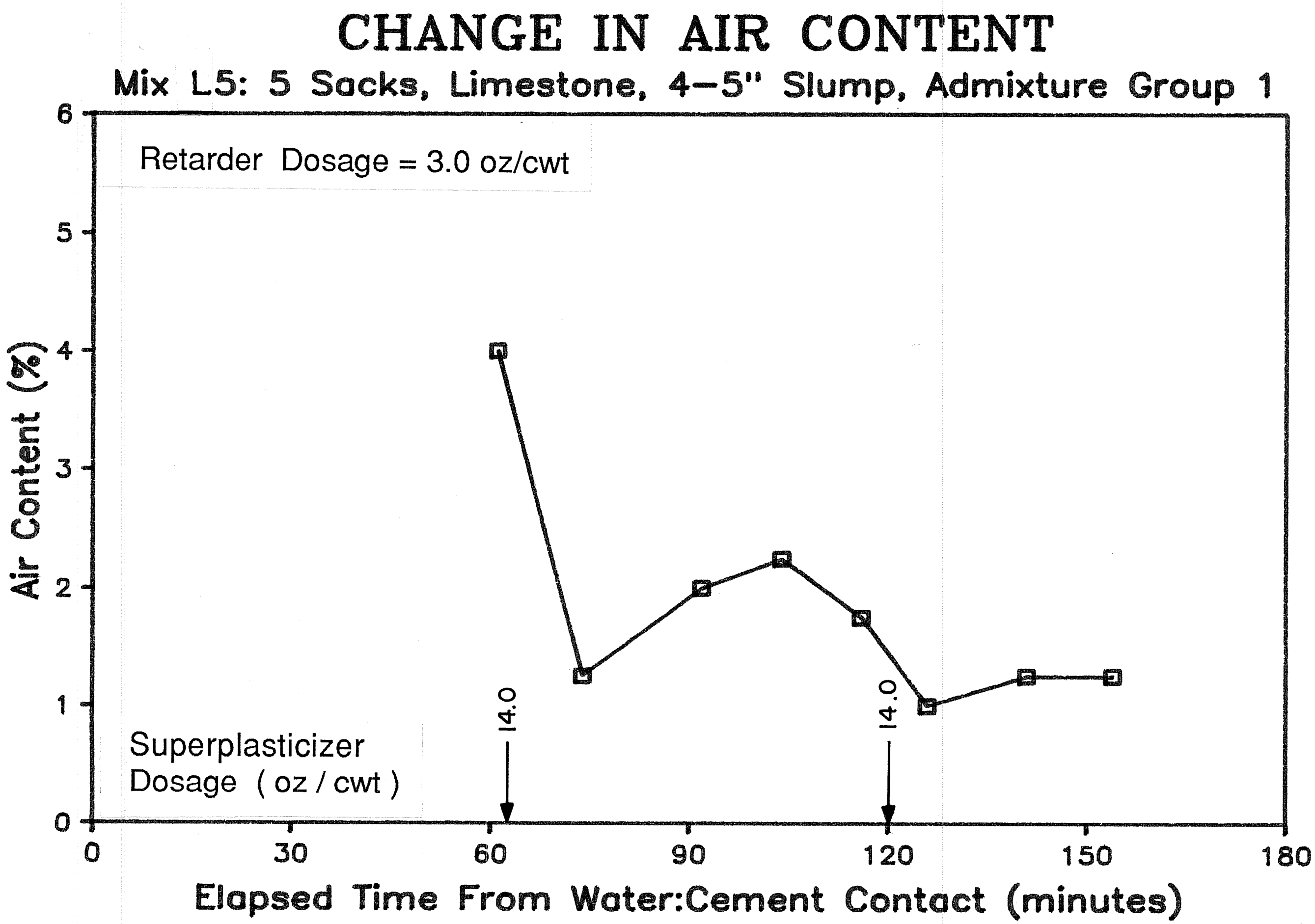


Fig. 4.14 Air content data for laboratory mix of July 21, 1987

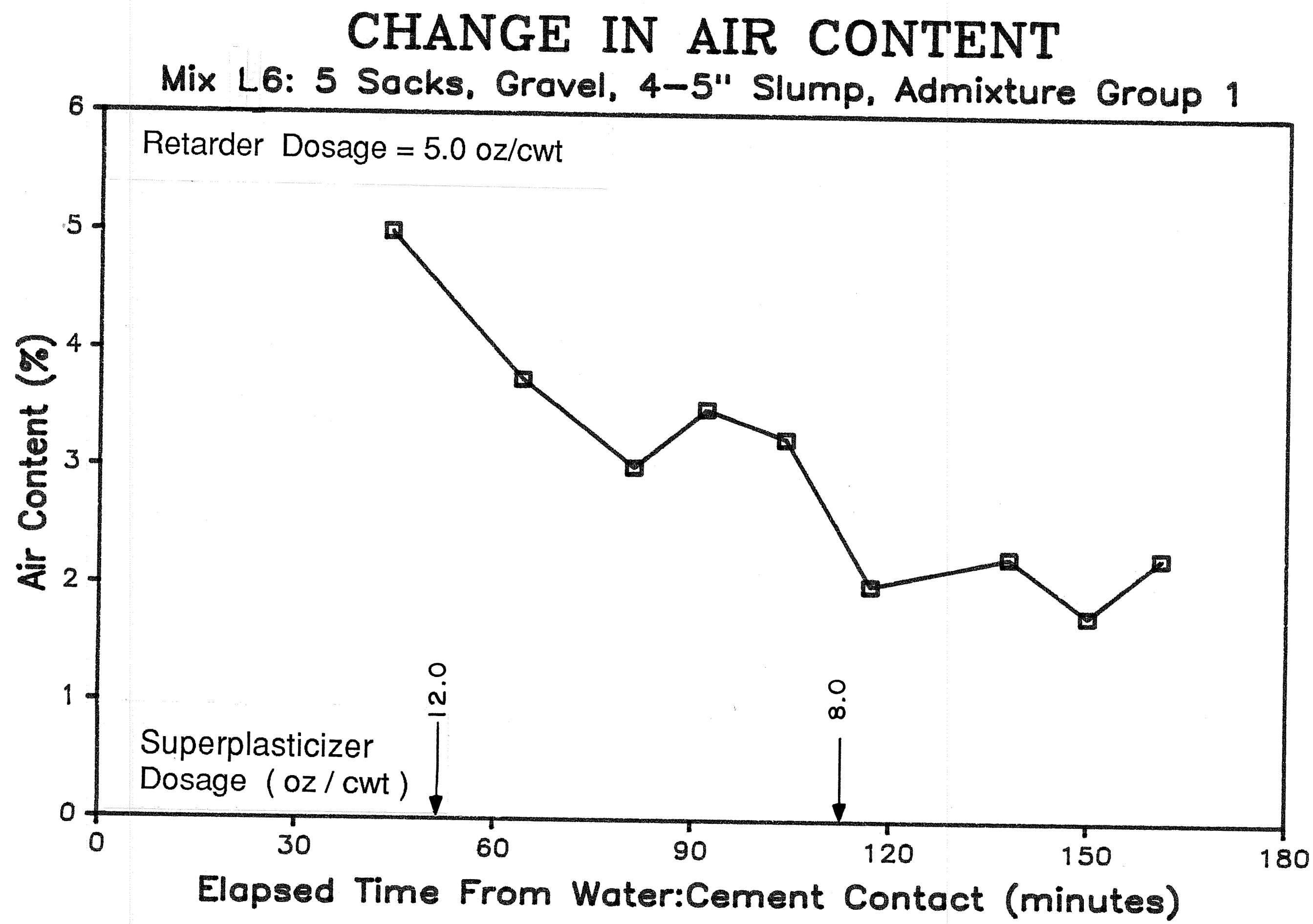


Fig. 4.15 Air content data for laboratory mix of July 23, 1987

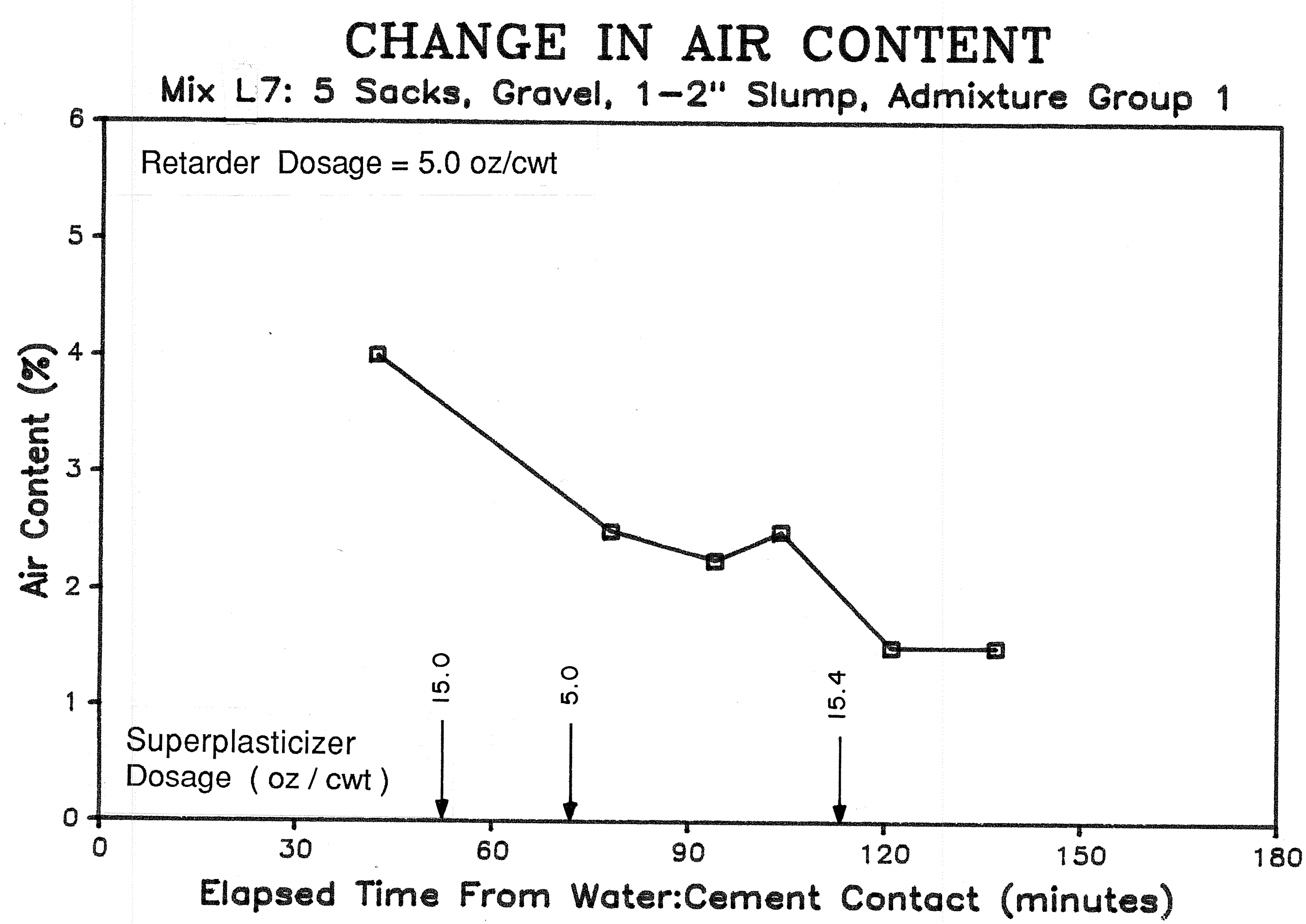


Fig. 4.16 Air content data for laboratory mix of August 25, 1987

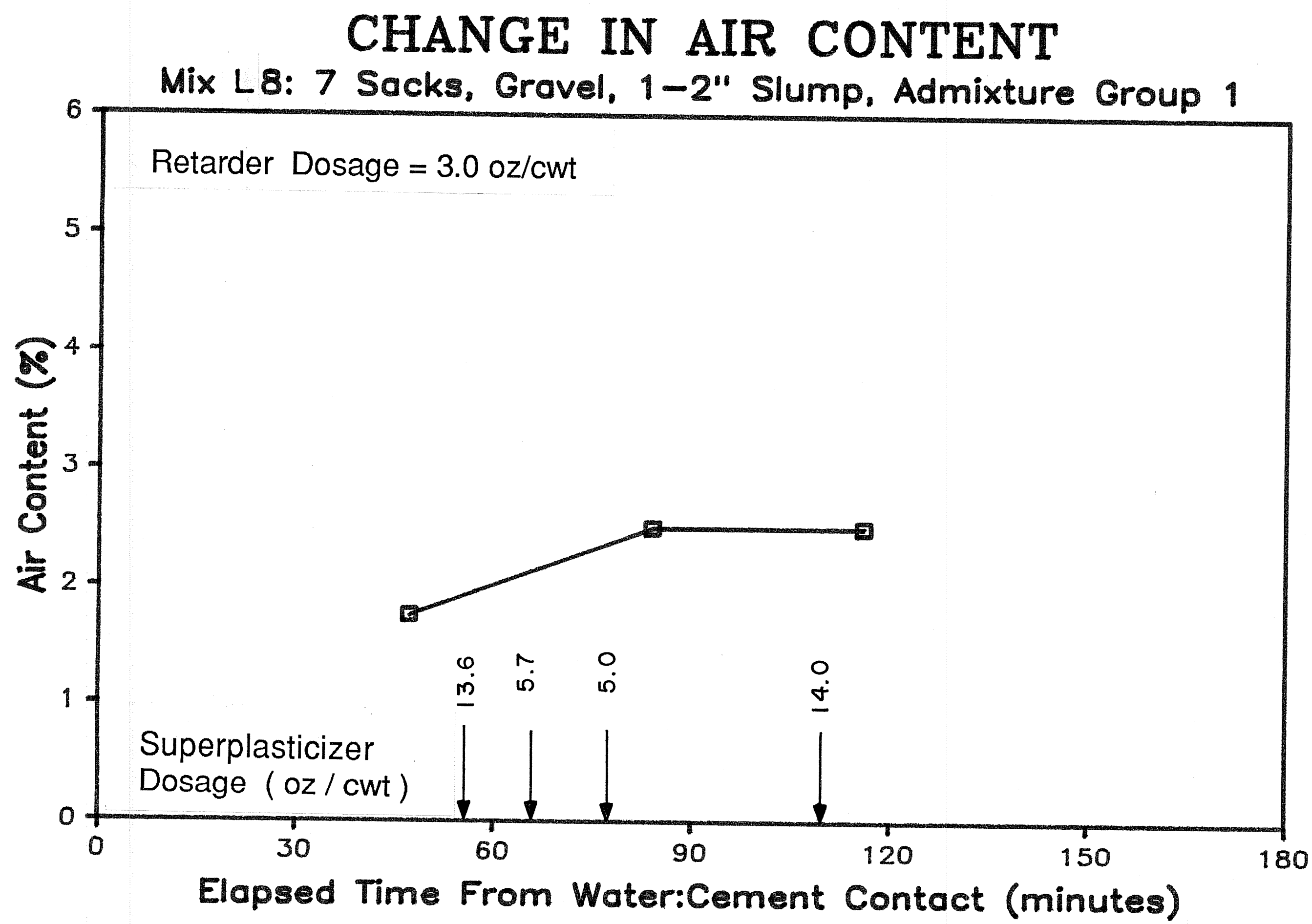


Fig. 4.17 Air content data for laboratory mix of September 3, 1987

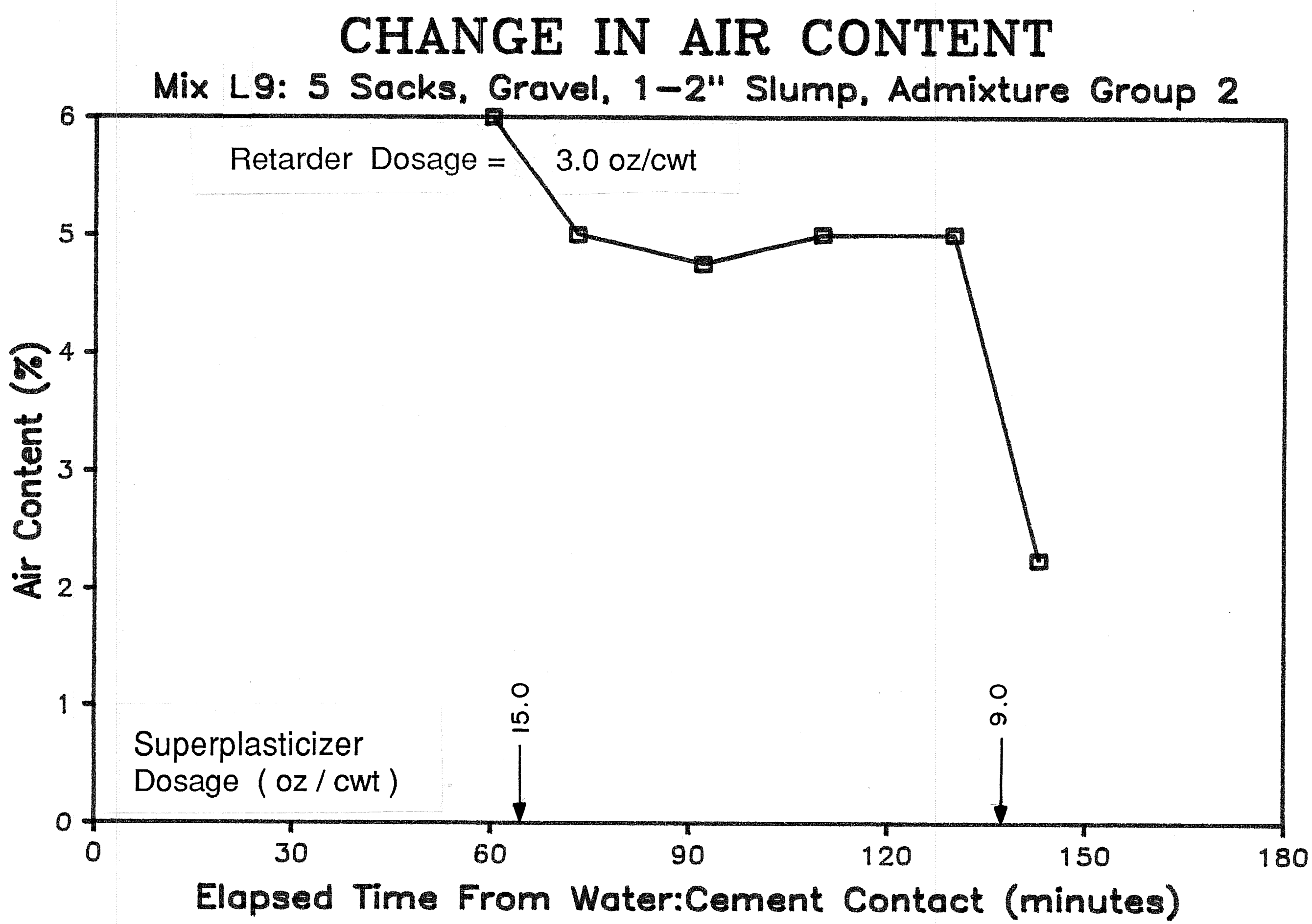


Fig. 4.18 Air content data for laboratory mix of September 10, 1987

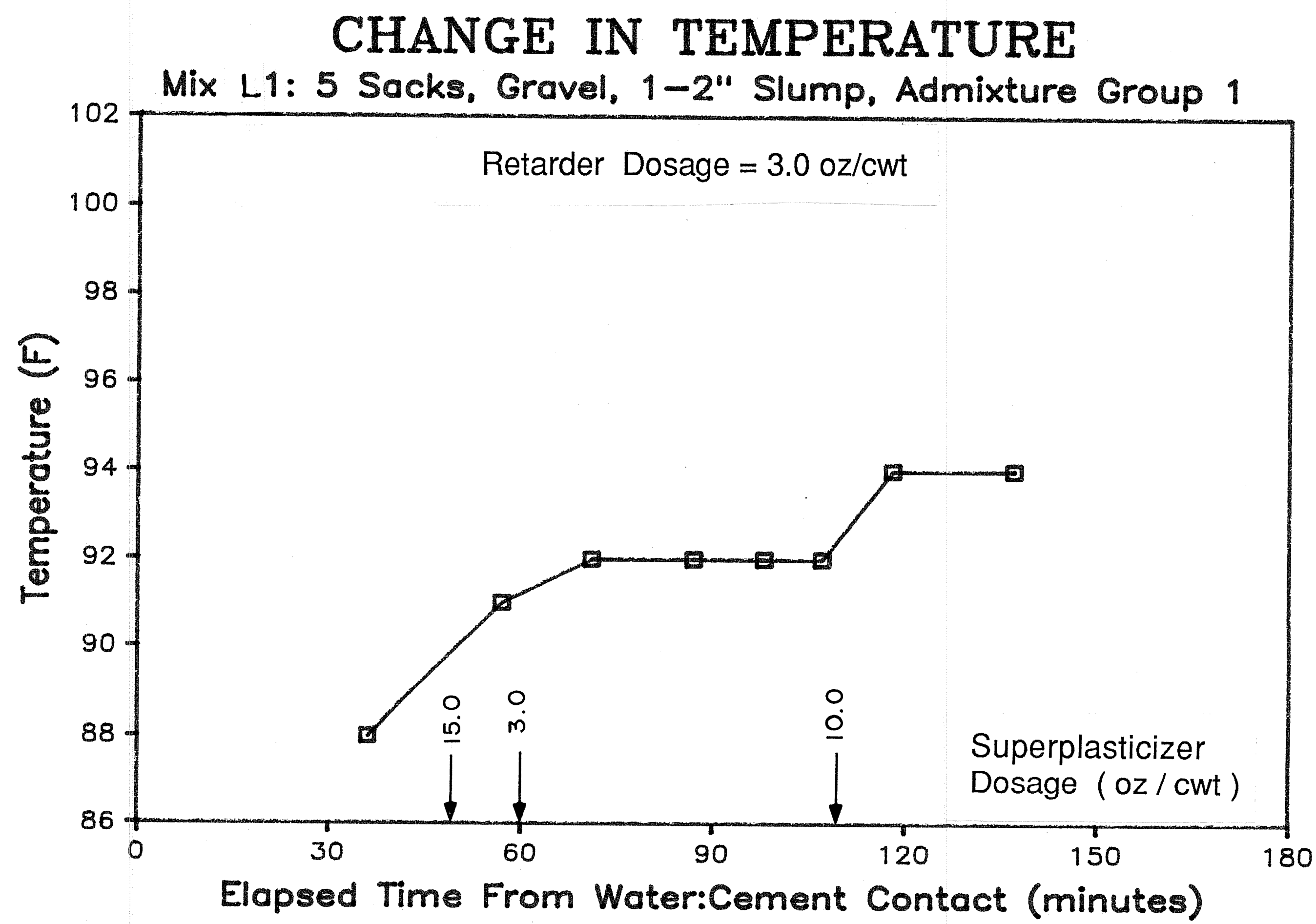


Fig. 4.19 Concrete temperature data for laboratory mix of June 18, 1987

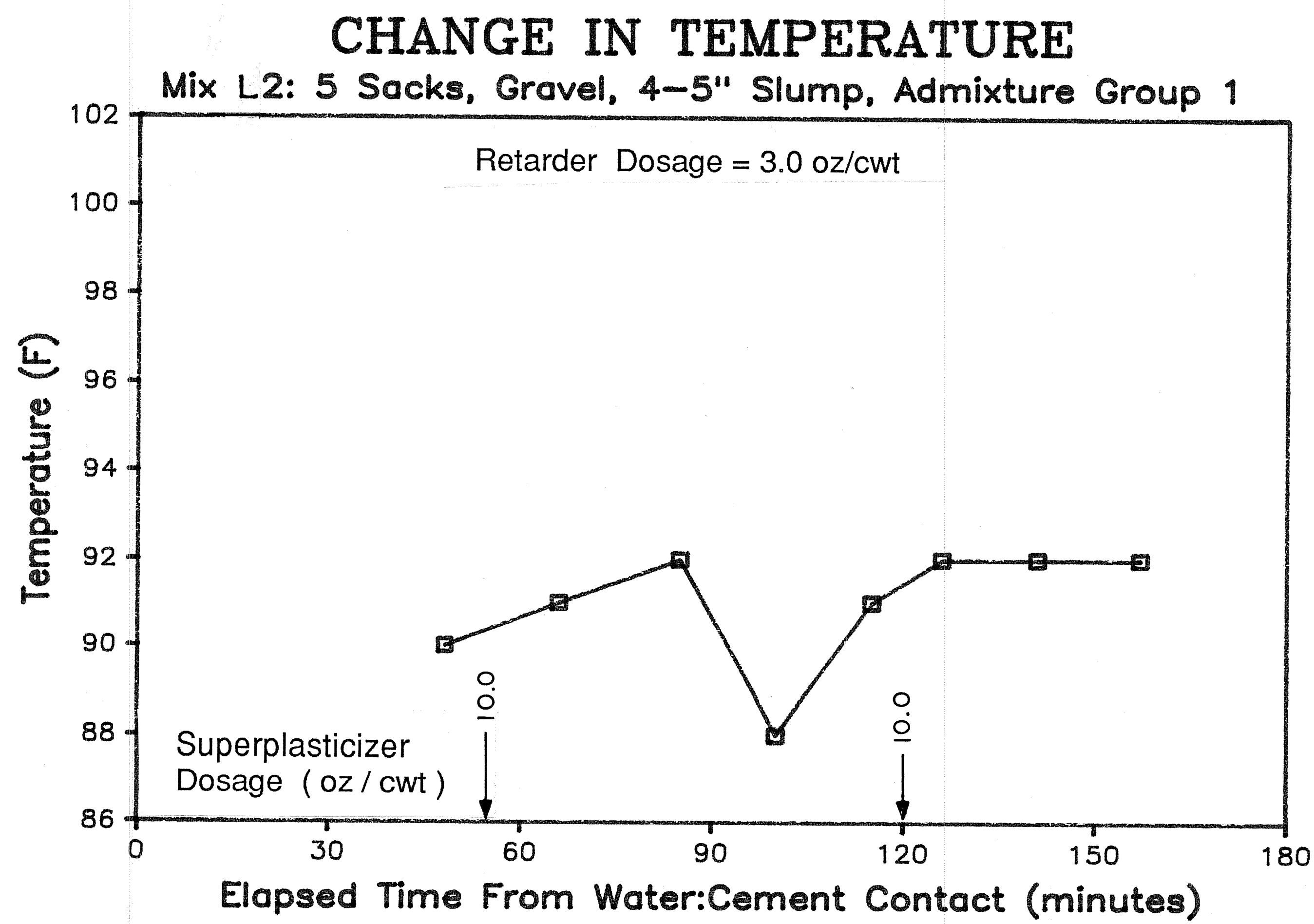


Fig. 4.20 Concrete temperature data for laboratory mix of June 23, 1987

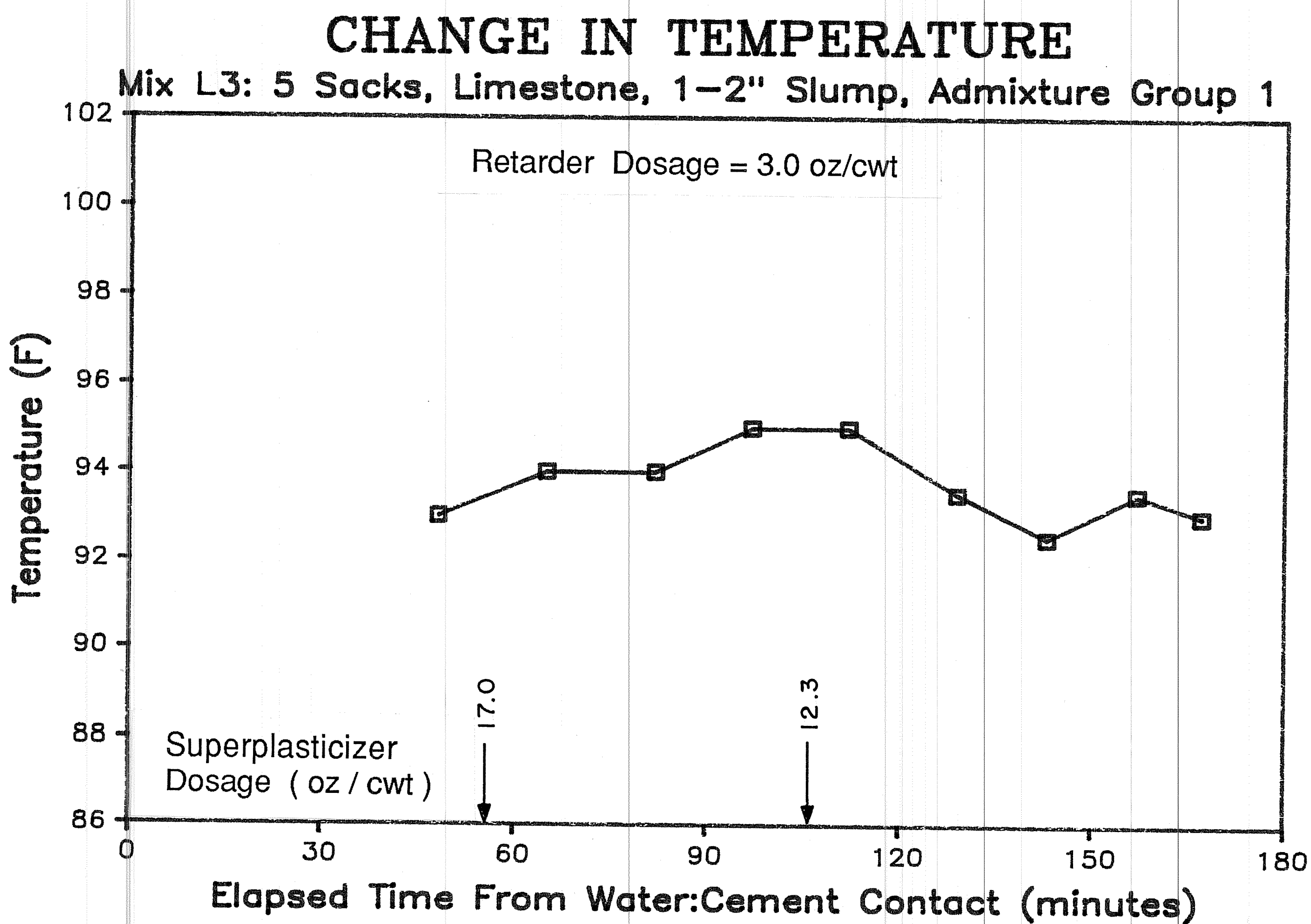


Fig. 4.21 Concrete temperature data for laboratory mix of July 2, 1987

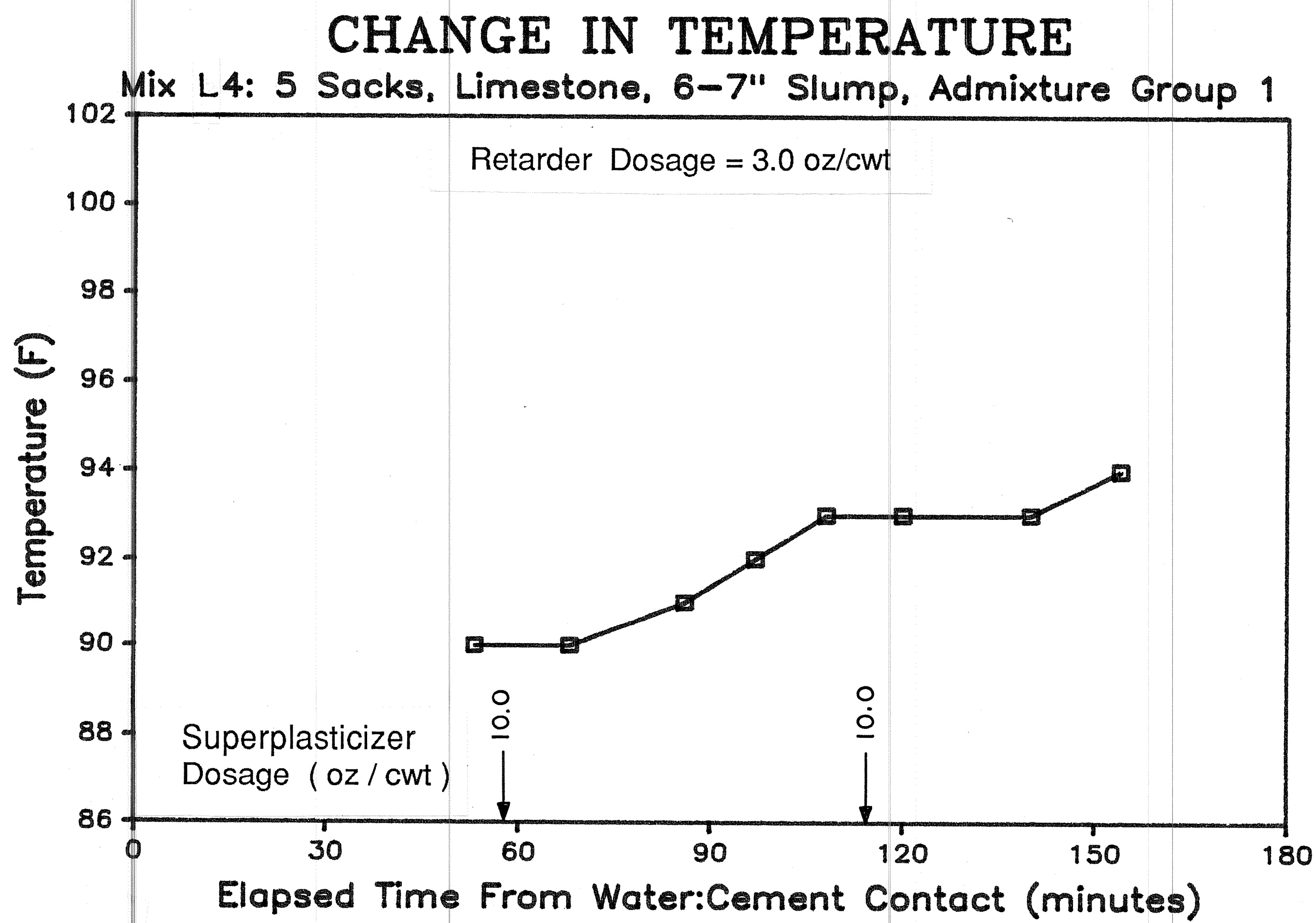


Fig. 4.22 Concrete temperature data for laboratory mix of July 16, 1987

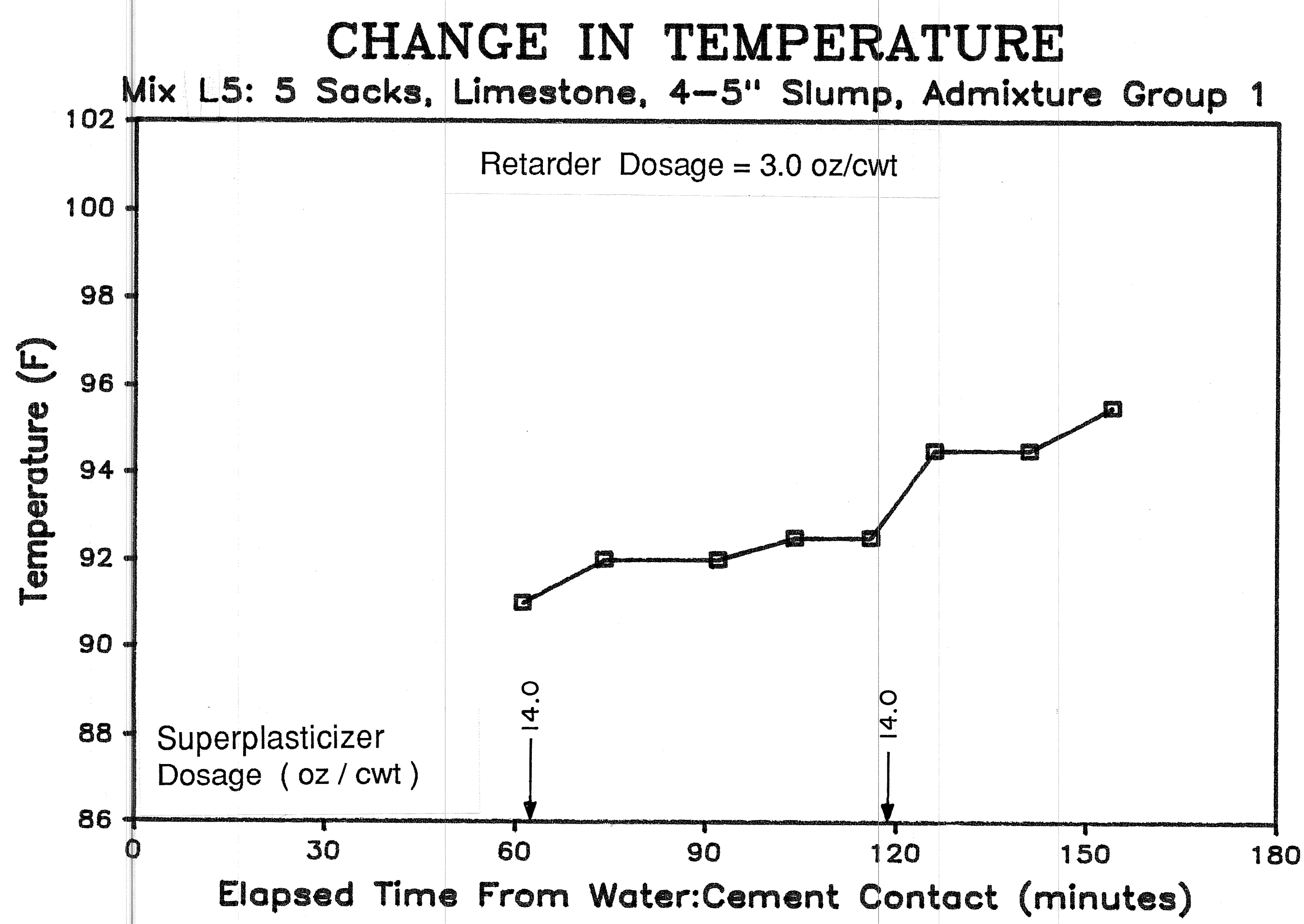


Fig. 4.23 Concrete temperature data for laboratory mix of July 21, 1987

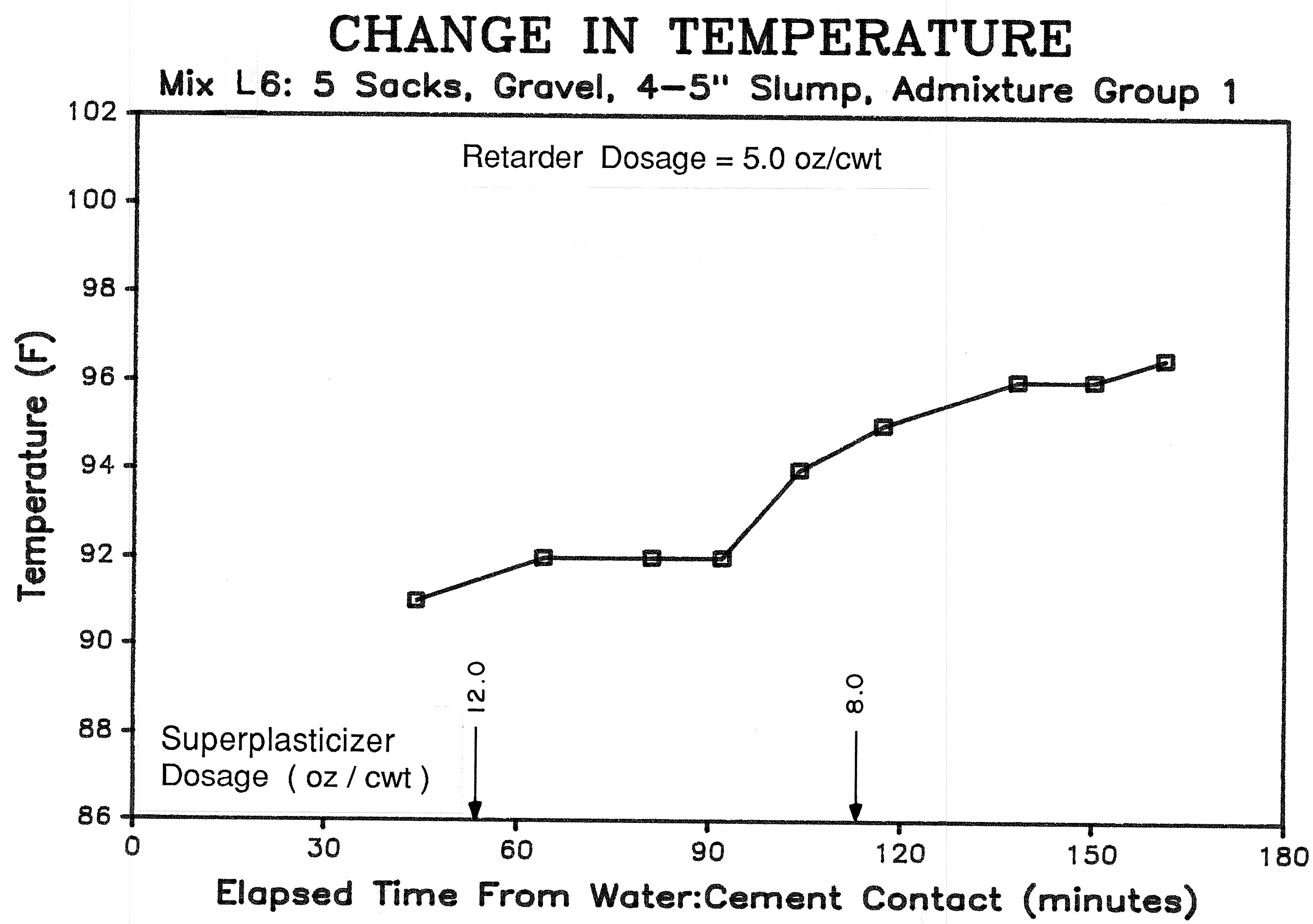


Fig. 4.24 Concrete temperature data for laboratory mix of July 23, 1987

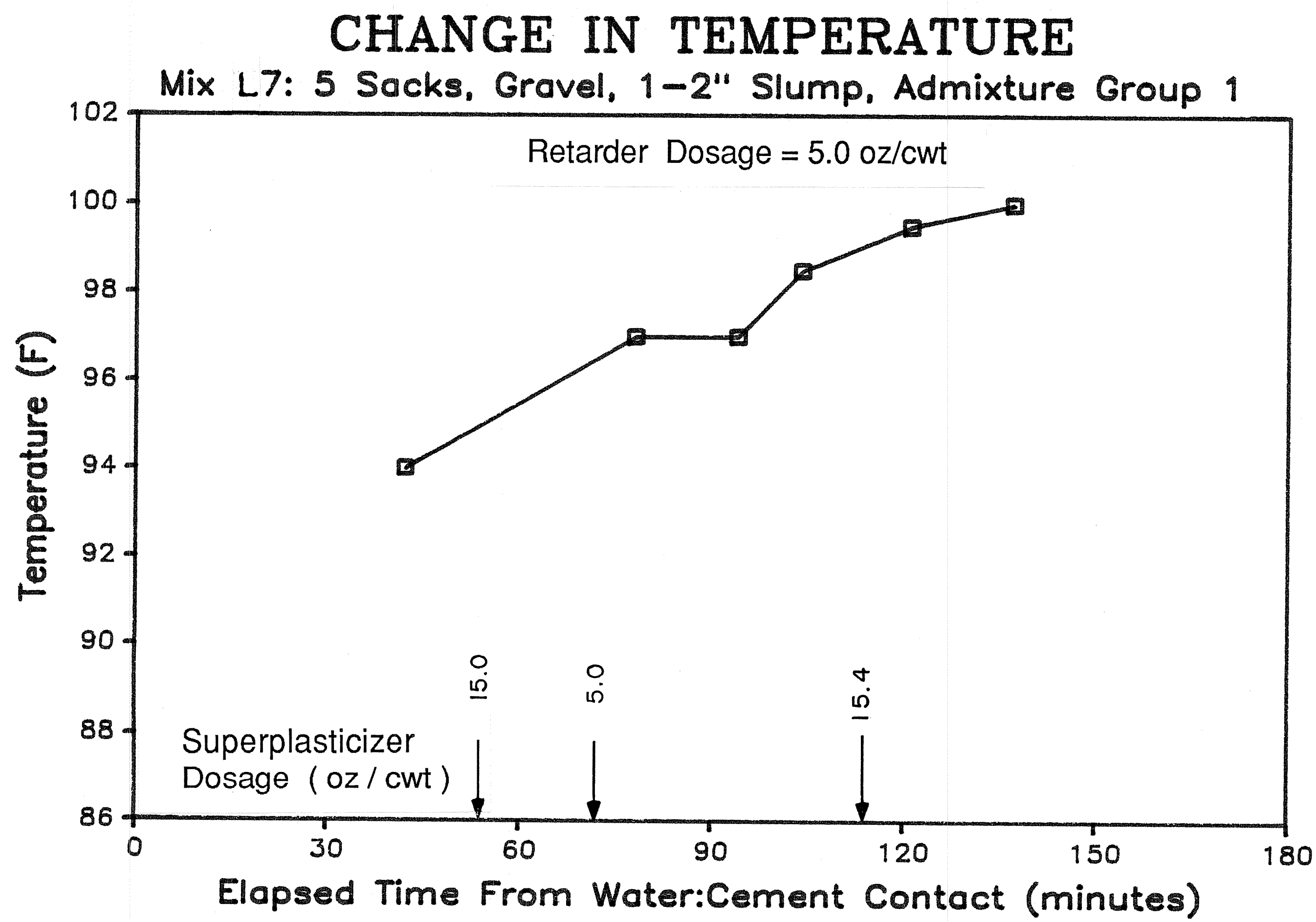


Fig. 4.25 Concrete temperature data for laboratory mix of August 25, 1987

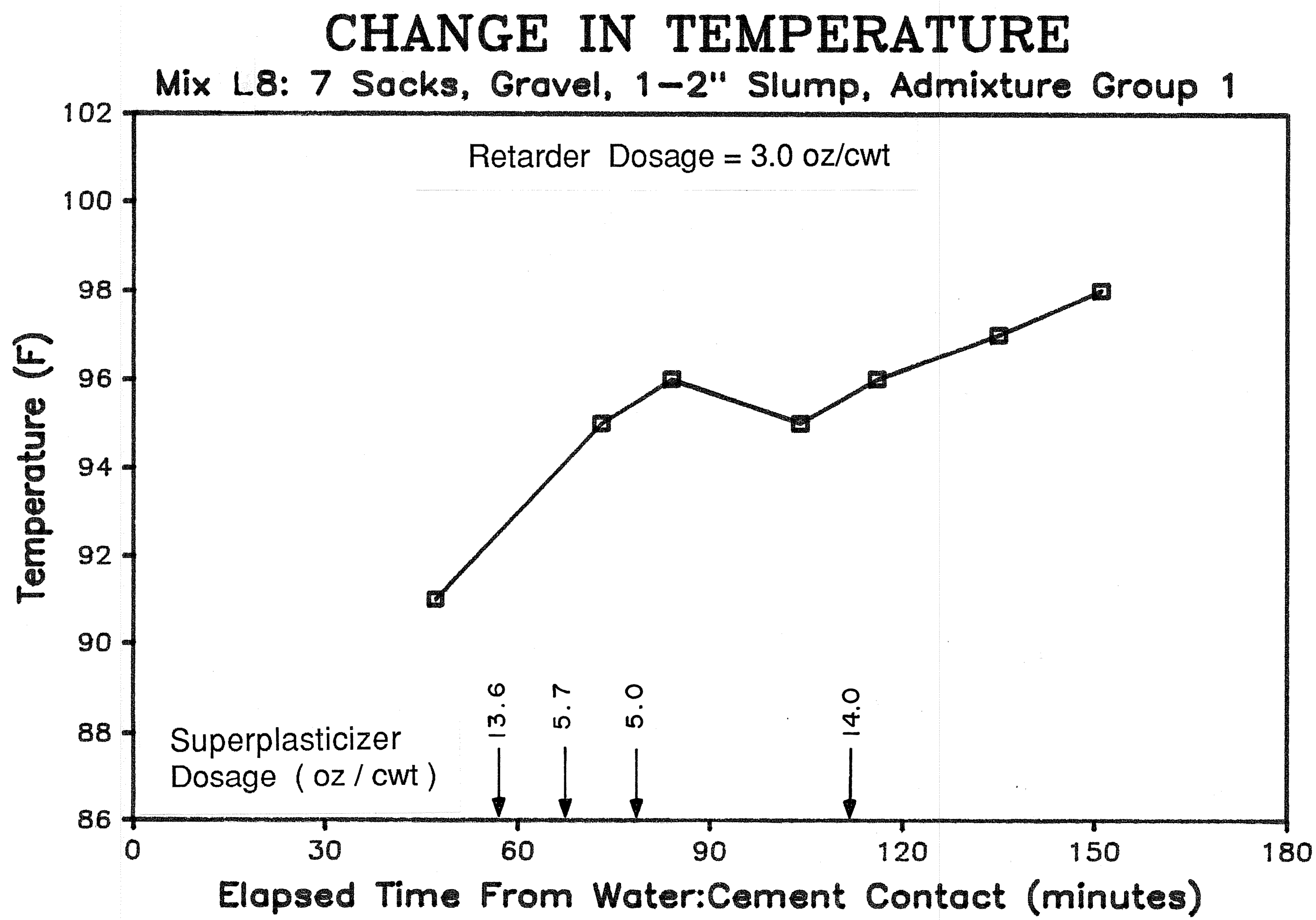


Fig. 4.26 Concrete temperature data for laboratory mix of September 3, 1987

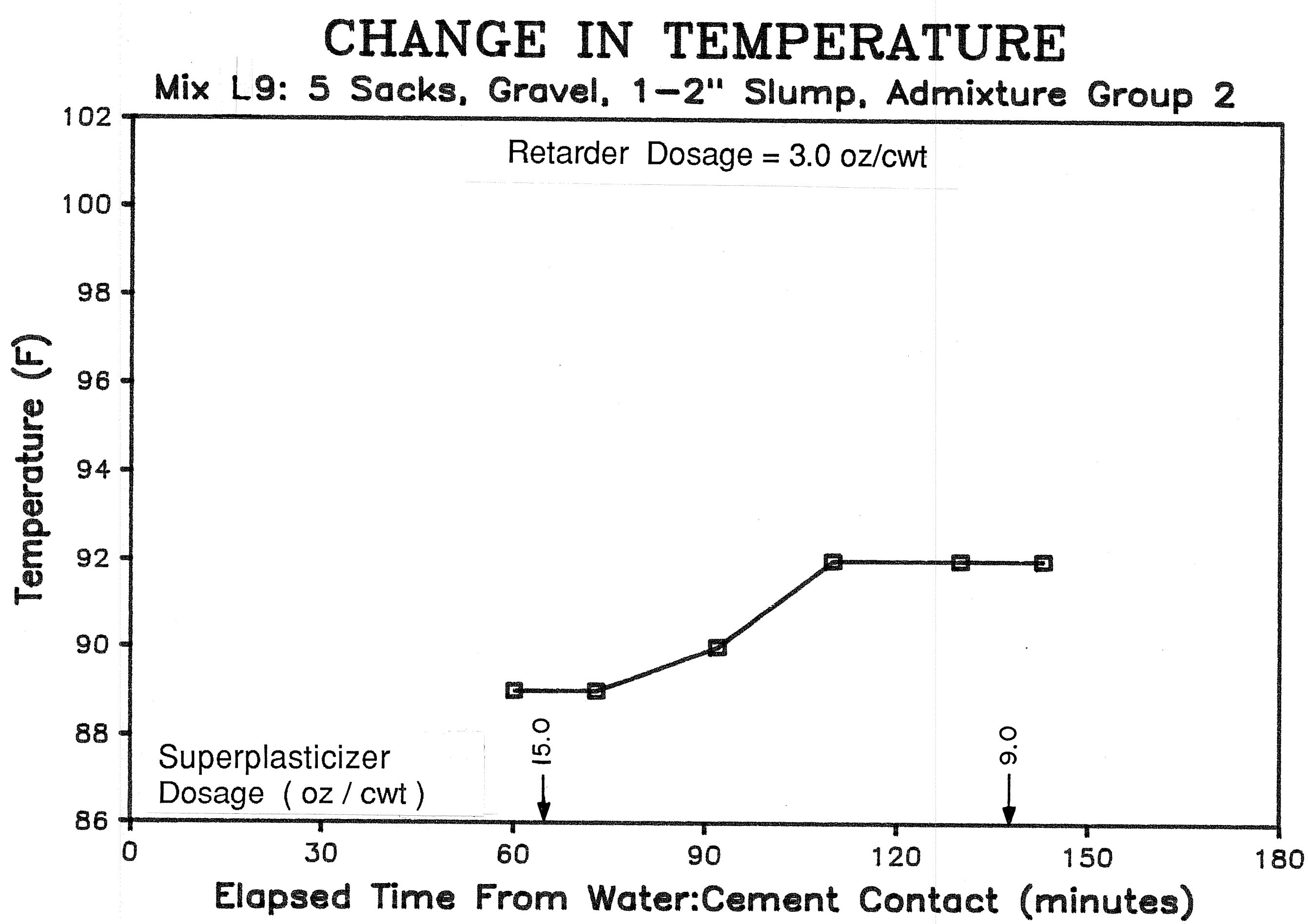


Fig. 4.27 Concrete temperature data for laboratory mix of September 10, 1987

also includes the amount and time of addition of the initial and second dosages of superplasticizer.

4.2.4 Unit Weight. Figures 4.28 through 4.36 present the unit weight values for each of the laboratory mixes. Results shown are for concrete samples taken prior to adding any superplasticizer and after the first and second dosages.

4.2.5 Setting Times. Figures 4.37 through 4.45 show the times for the initial and final setting times for each of the laboratory mixes. Results shown are for concrete samples taken prior to adding any superplasticizer and after the first and second dosages. Initial setting was defined as the time when the penetration resistance was 500 psi. Final setting was defined as the time when the penetration resistance was 4000 psi.

4.3 Hardened Concrete Tests

This section details the data recorded from the hardened concrete testing of each of the laboratory mixes.

4.3.1 Compressive Strength. Figure 4.46 through 4.54 show the compressive strengths at 7 and 28 days for each of the laboratory mixes. Results shown are for concrete samples taken prior to adding any superplasticizer and after the first and second dosages. Each data point represents the average of at least two to four companion specimens. In addition, each graph includes fresh concrete data detailing the slump, air content, mixing time, and fresh concrete temperature at the time the cylinders were cast. Table 4.1 lists the average values, standard deviations, and coefficients of variation for all 7- and 28-day compressive strength test results.

4.3.2 Flexural Strength. Figures 4.55 through 4.63 show the flexural strengths at 7 and 28 days for each of the laboratory mixes. Results shown are for concrete samples taken prior to adding any superplasticizer and after the first and second dosages. Each data point represents the average of at least three to four companion specimens. In addition, each graph includes fresh concrete data detailing the slump, air content, mixing time, and fresh concrete temperature at the time the beams were molded. Table 4.2 lists the average values, standard deviations, and coefficients of variation for all 7- and 28-day flexural strength test results.

4.3.3 Abrasion Resistance. Figures 4.64 through 4.72 show the abrasion resistance test results at 8 days for each of the laboratory mixes. Results shown are for

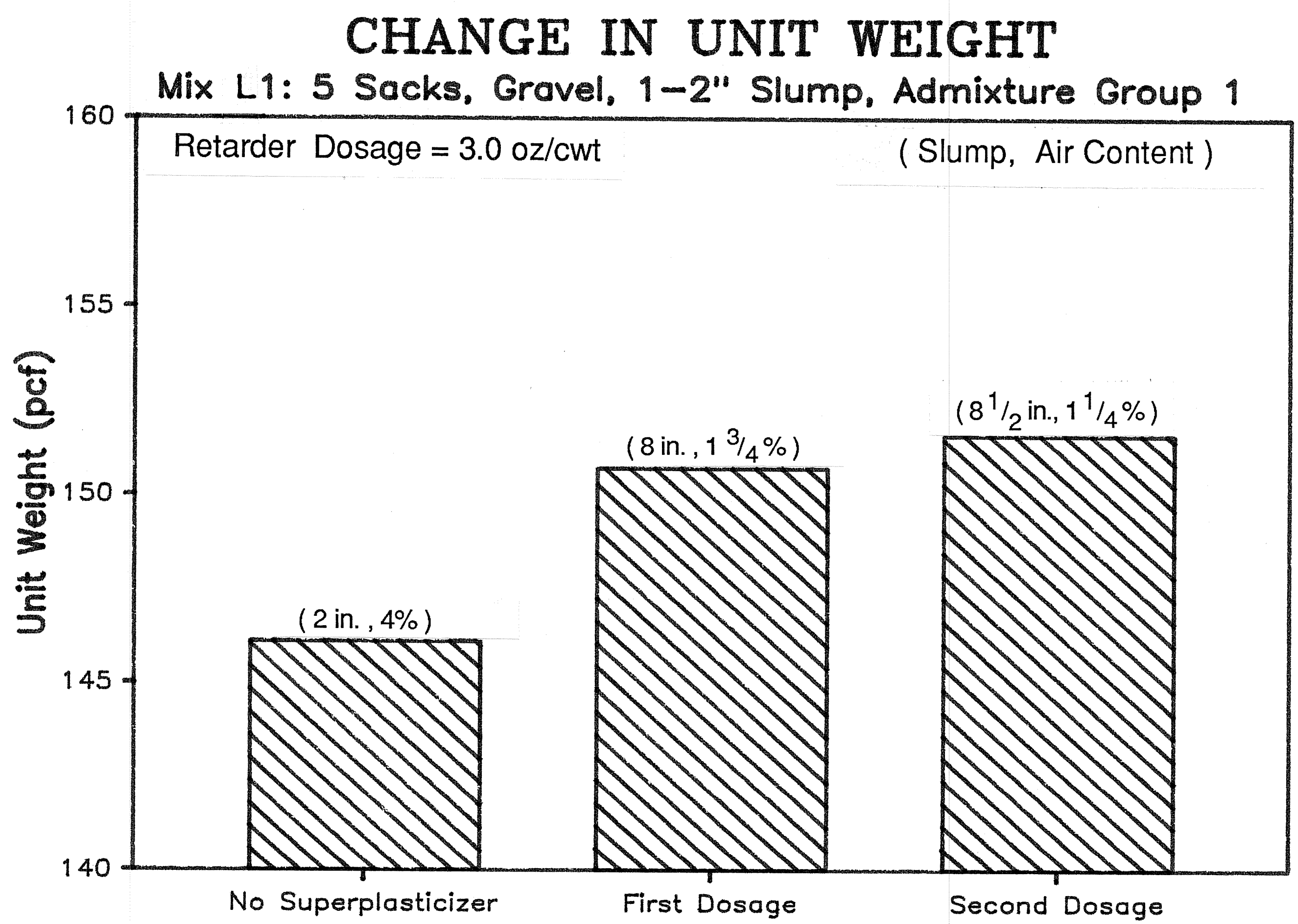


Fig. 4.28 Unit weight data for laboratory mix of June 18, 1987

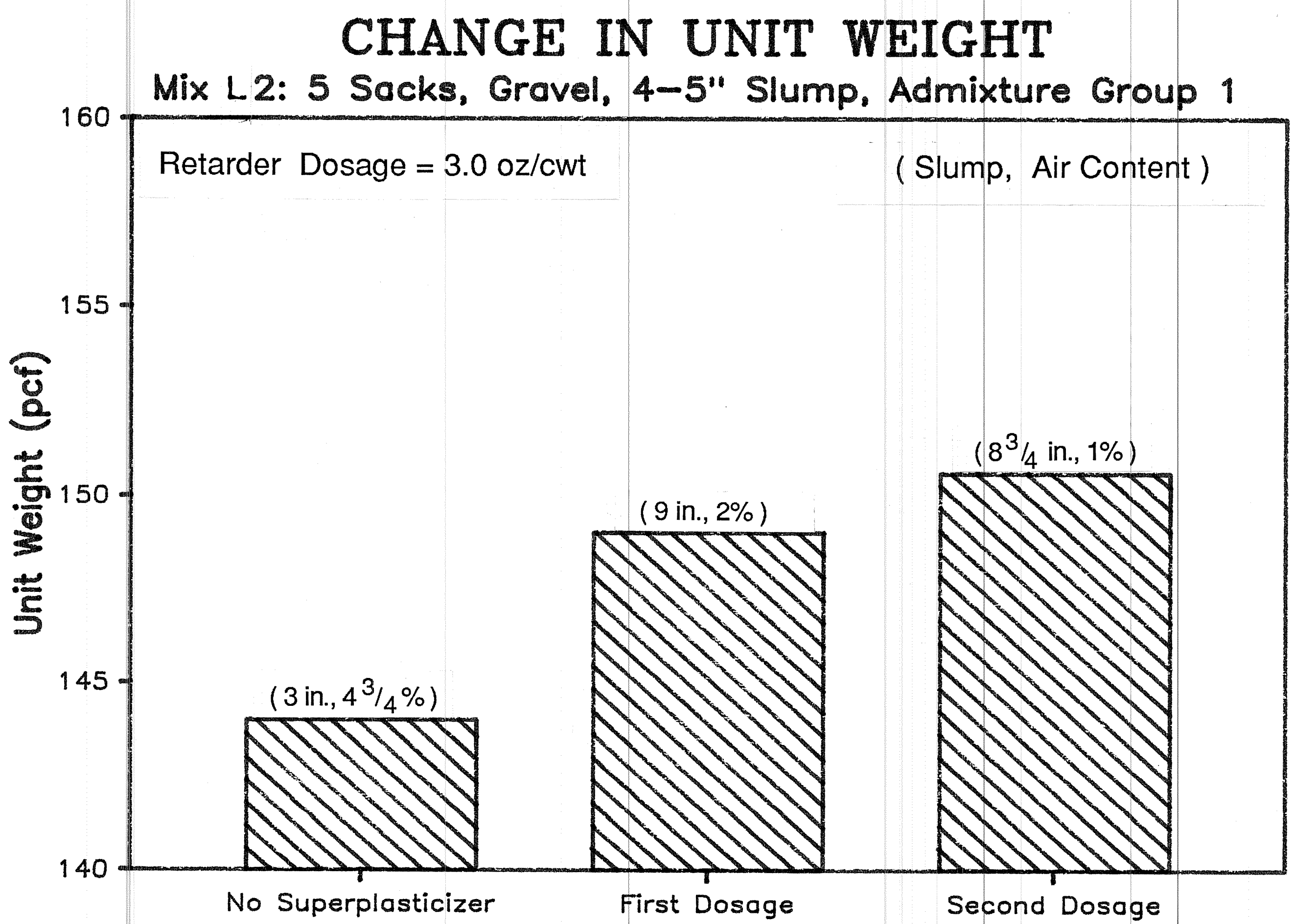


Fig. 4.29 Unit weight data for laboratory mix of June 23, 1987

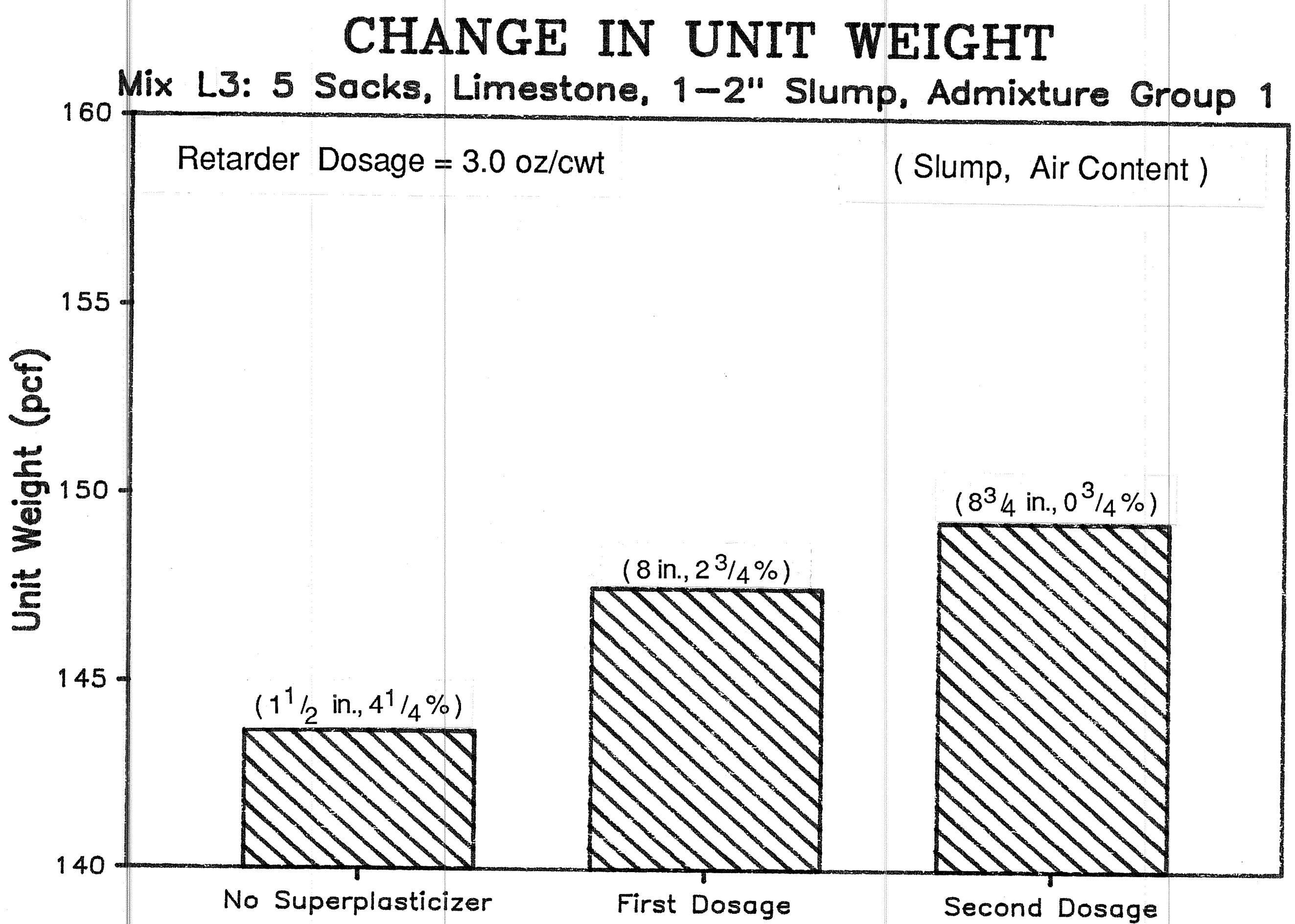


Fig. 4.30 Unit weight data for laboratory mix of July 2, 1987

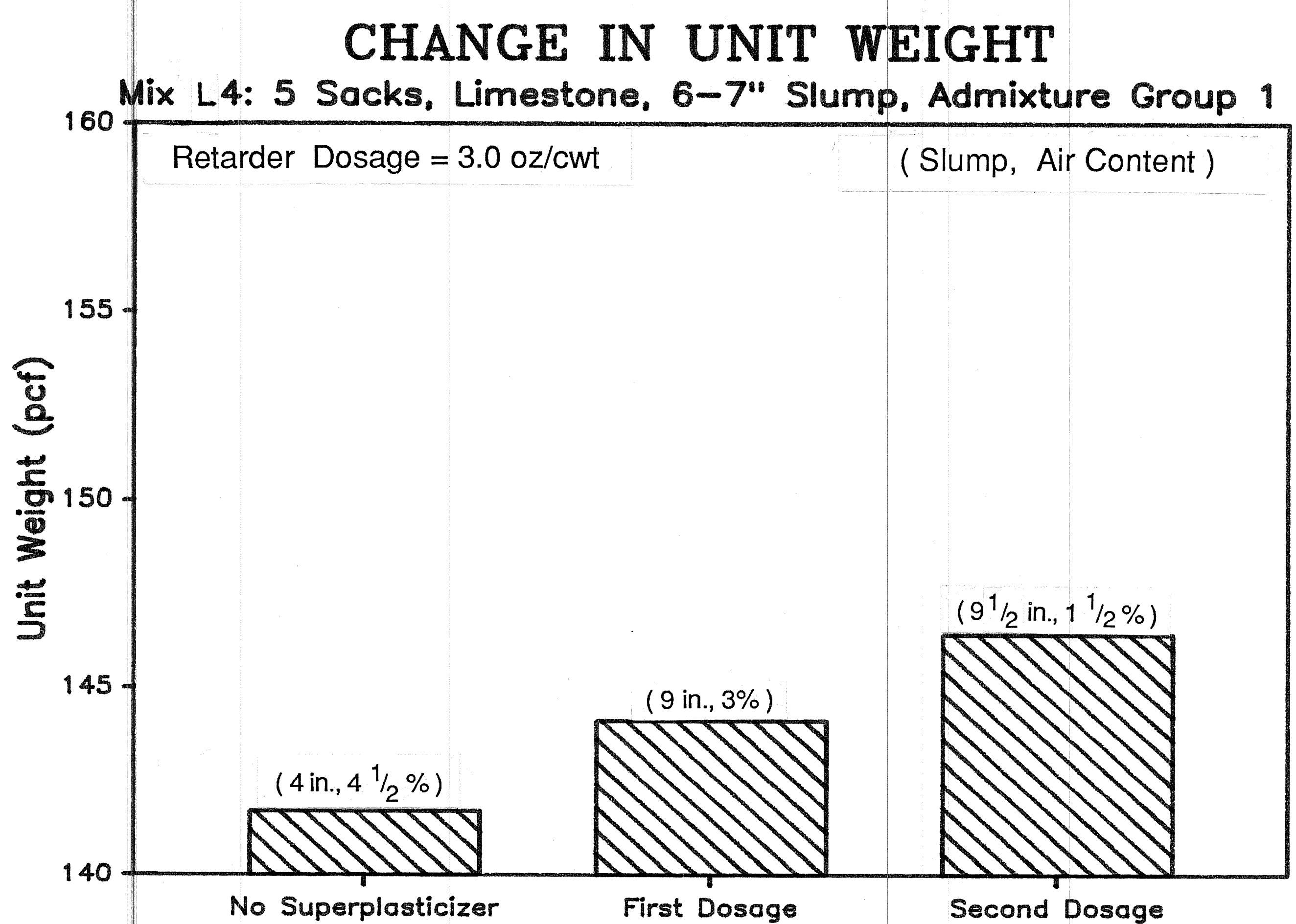


Fig. 4.31 Unit weight data for laboratory mix of July 16, 1987

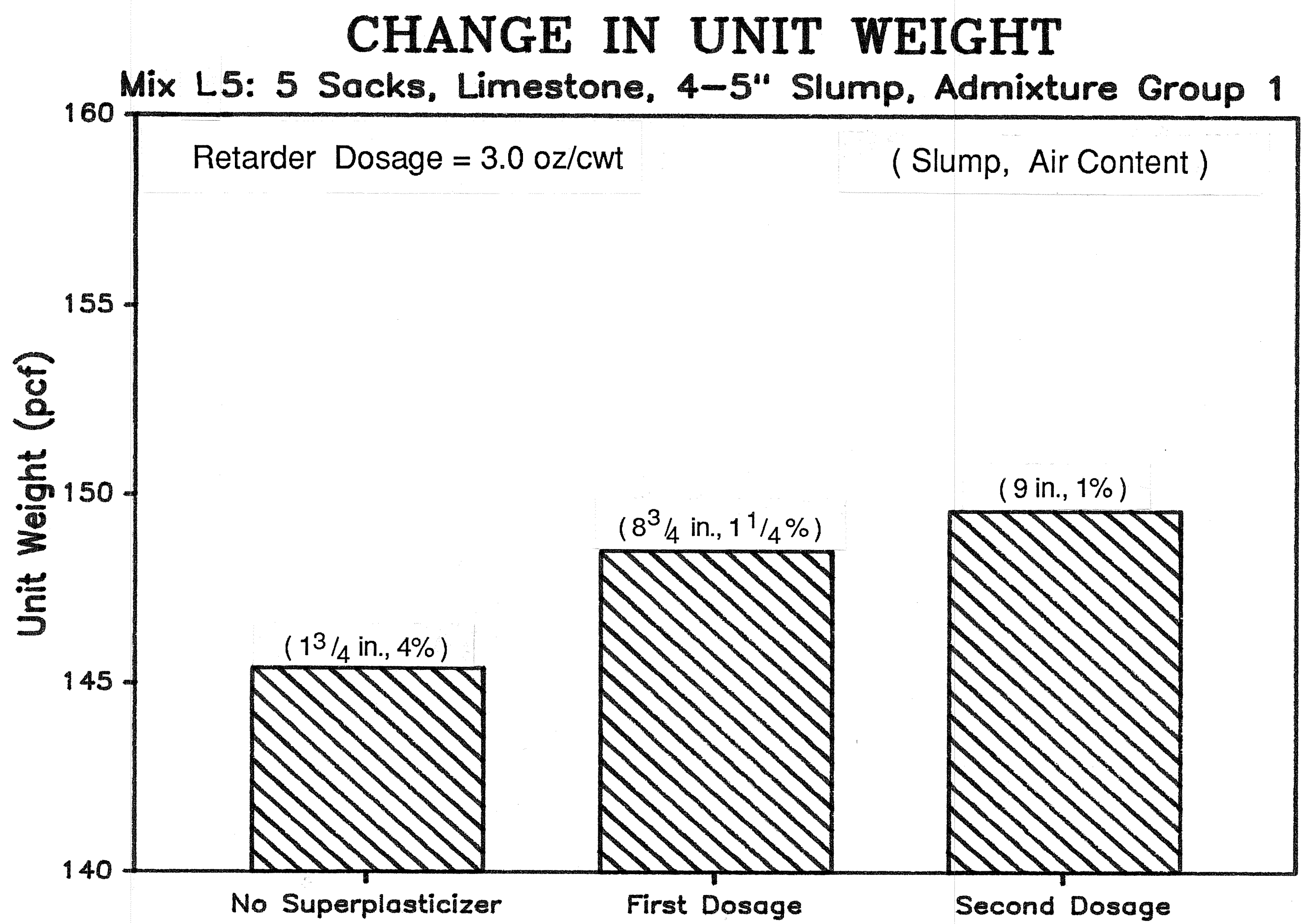


Fig. 4.32 Unit weight data for laboratory mix of July 21, 1987

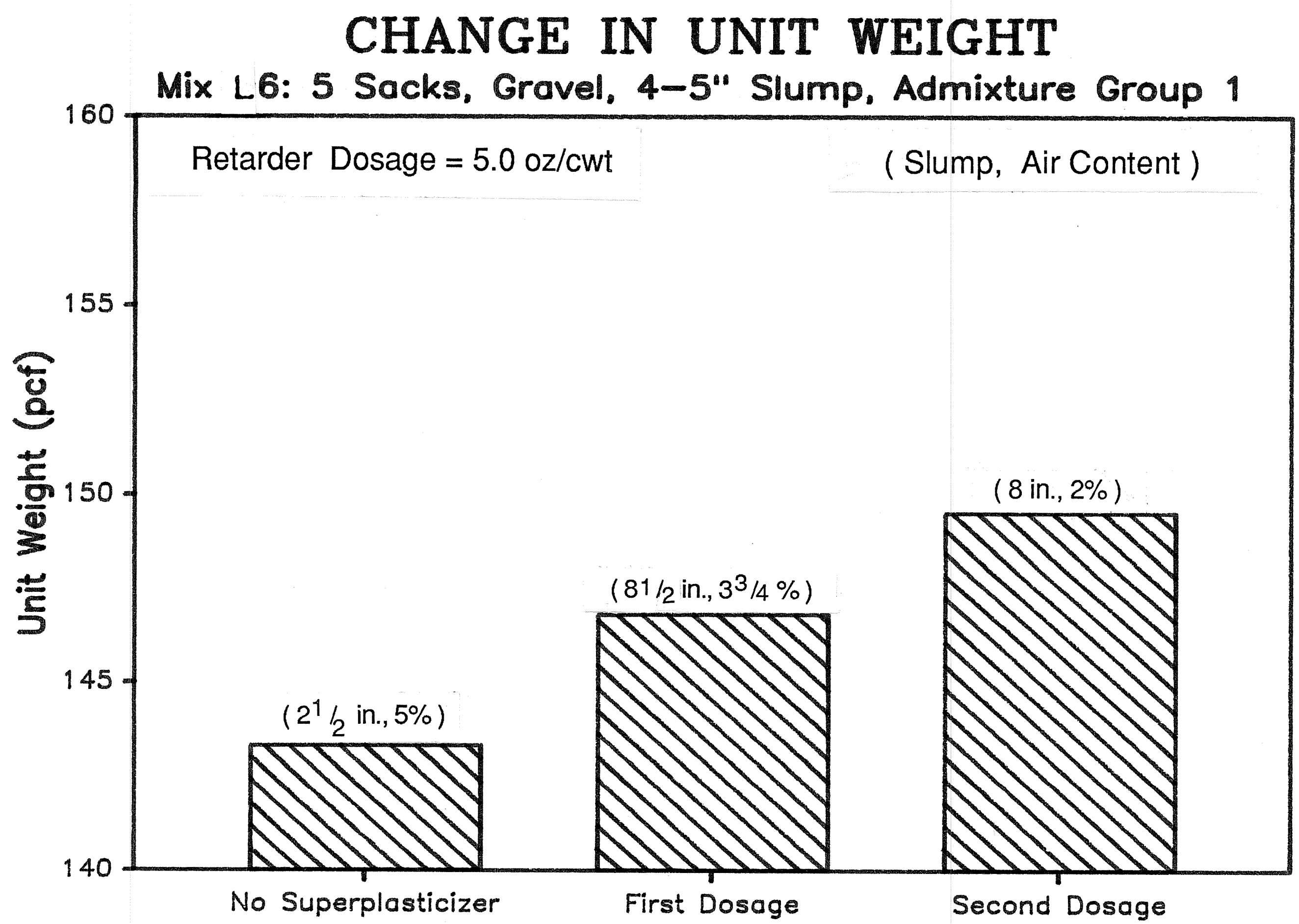


Fig. 4.33 Unit weight data for laboratory mix of July 23, 1987

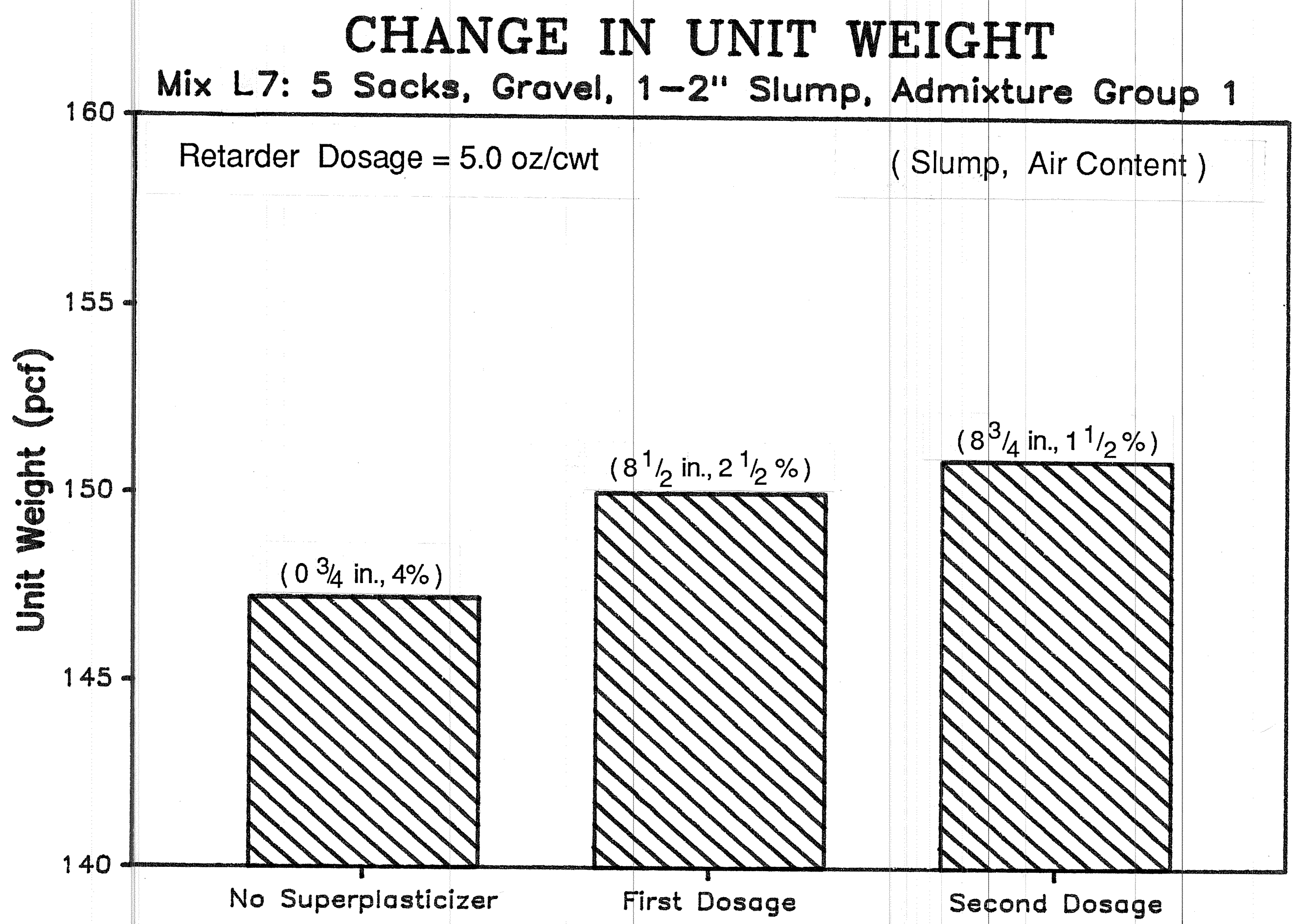


Fig. 4.34 Unit weight data for laboratory mix of August 25, 1987

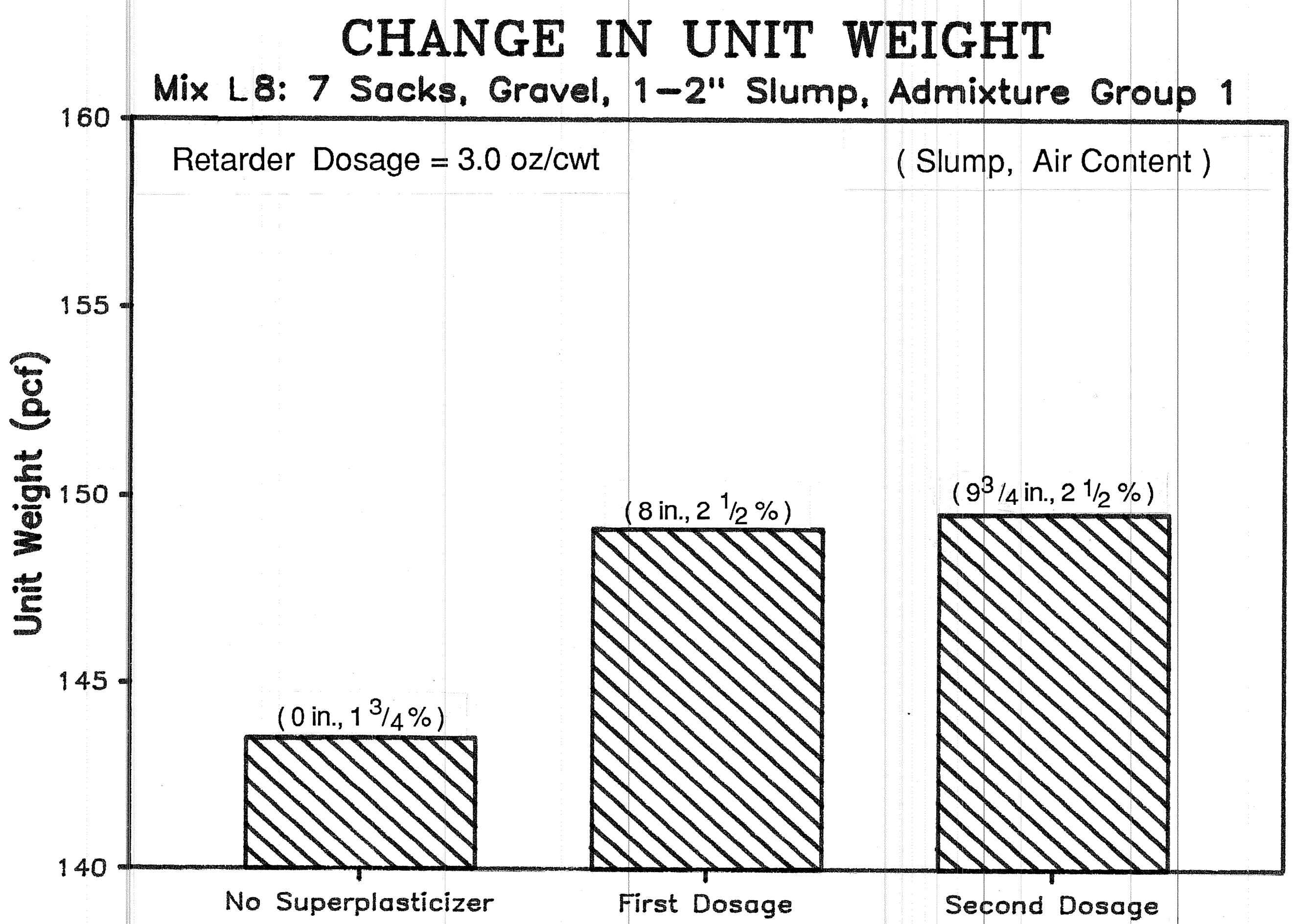


Fig. 4.35 Unit weight data for laboratory mix of September 3, 1987

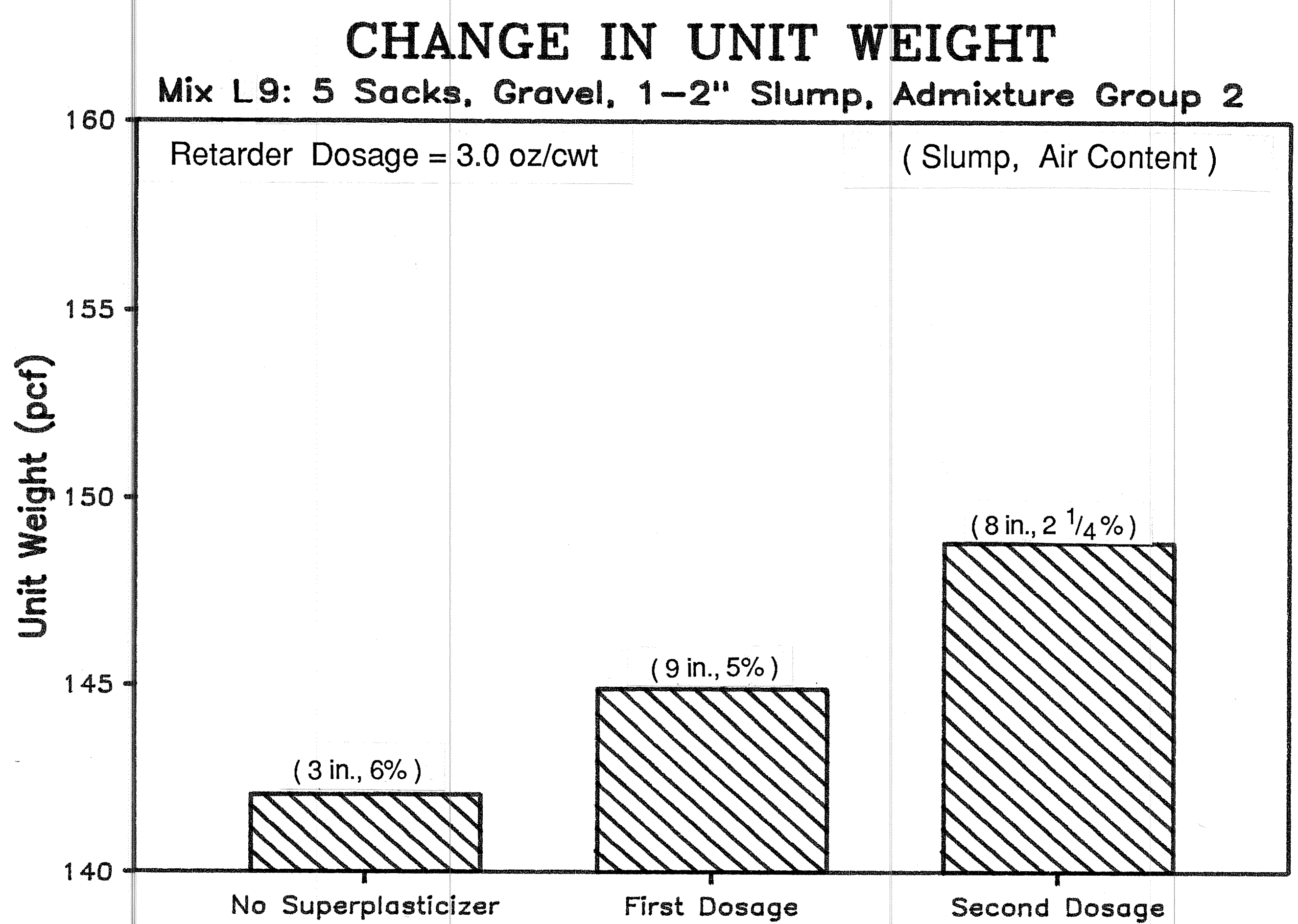


Fig. 4.36 Unit weight data for laboratory mix of September 10, 1987

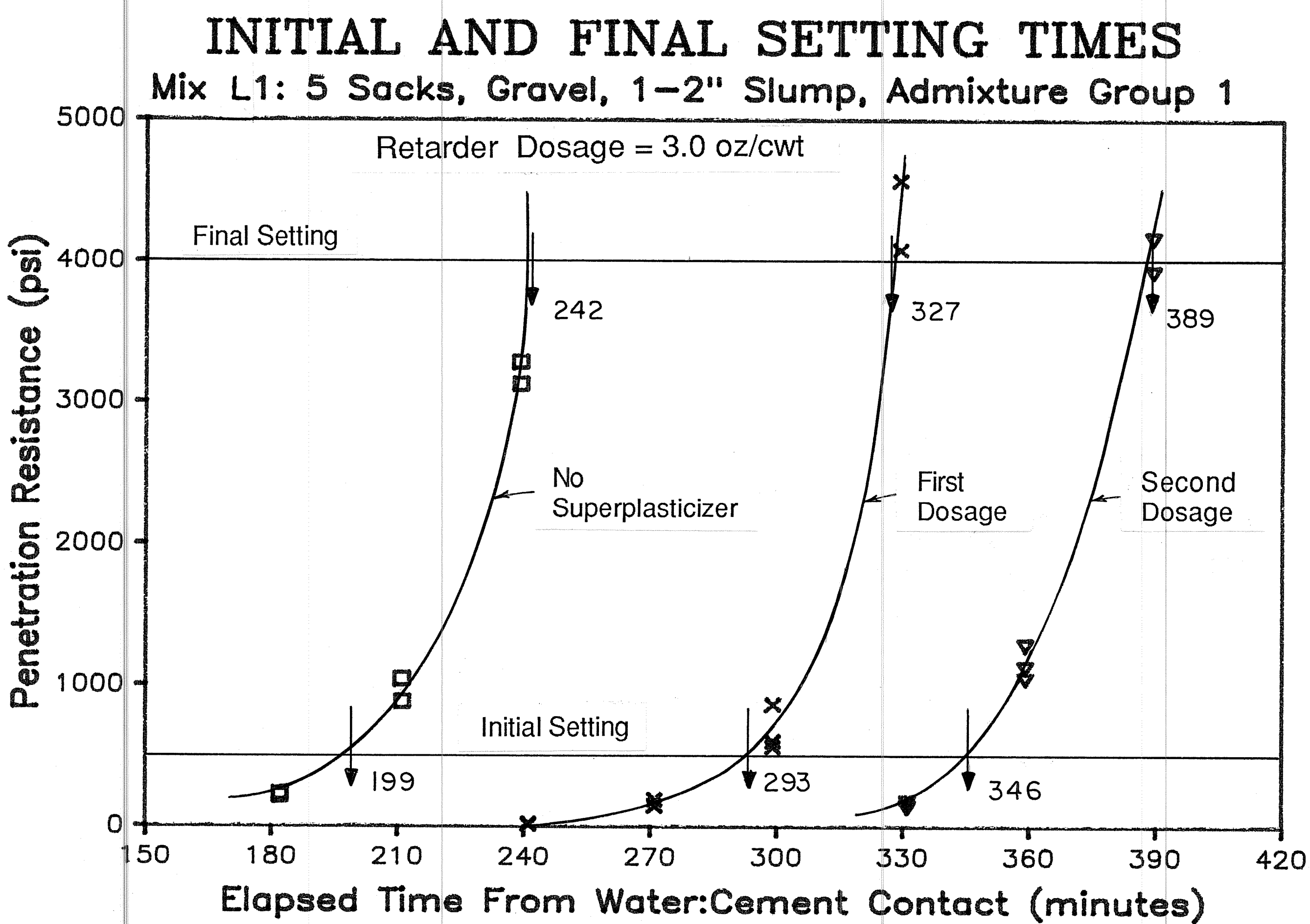


Fig. 4.37 Initial and final setting times data for laboratory mix of June 18, 1987

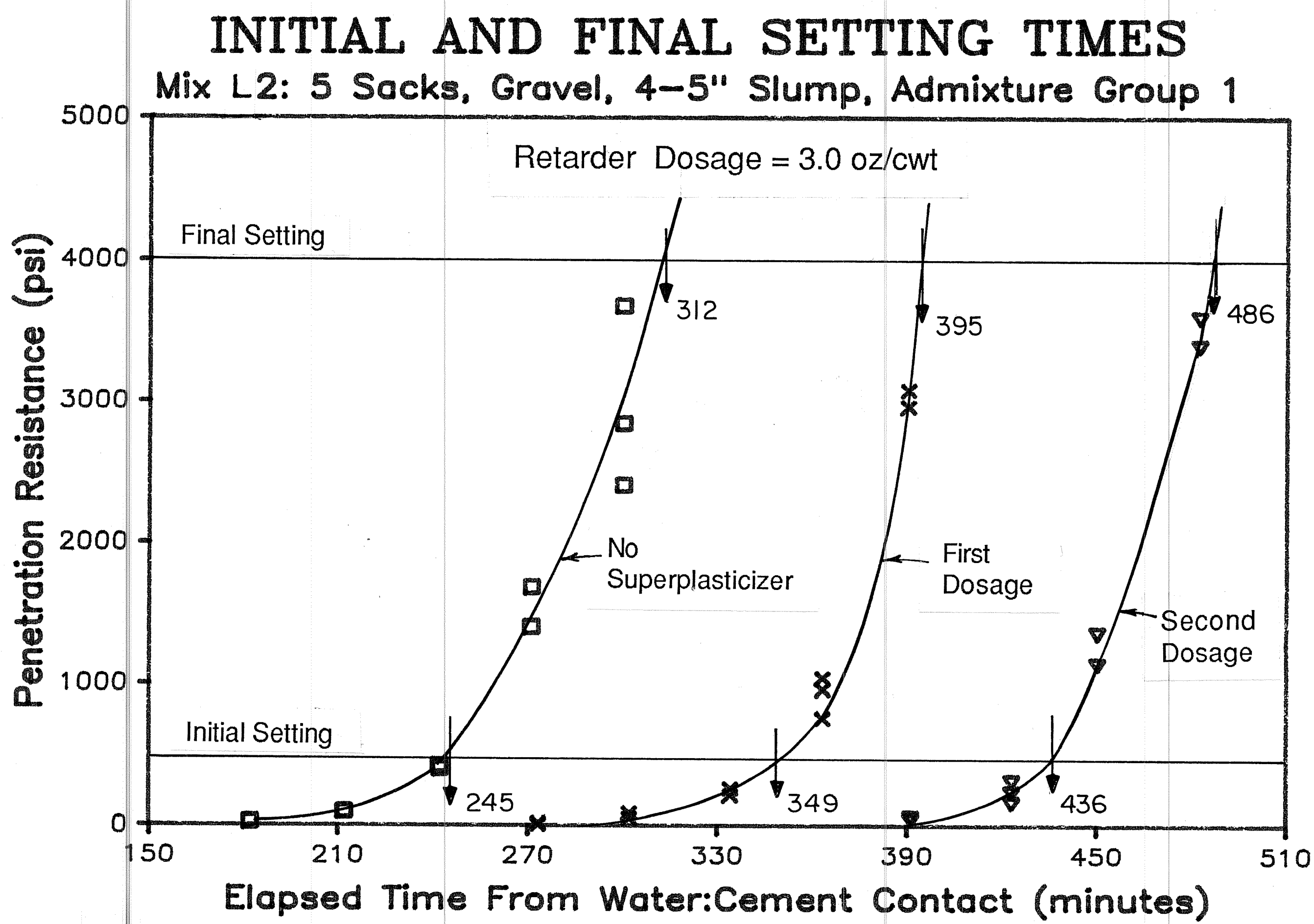


Fig. 4.38 Initial and final setting times data for laboratory mix of June 23, 1987

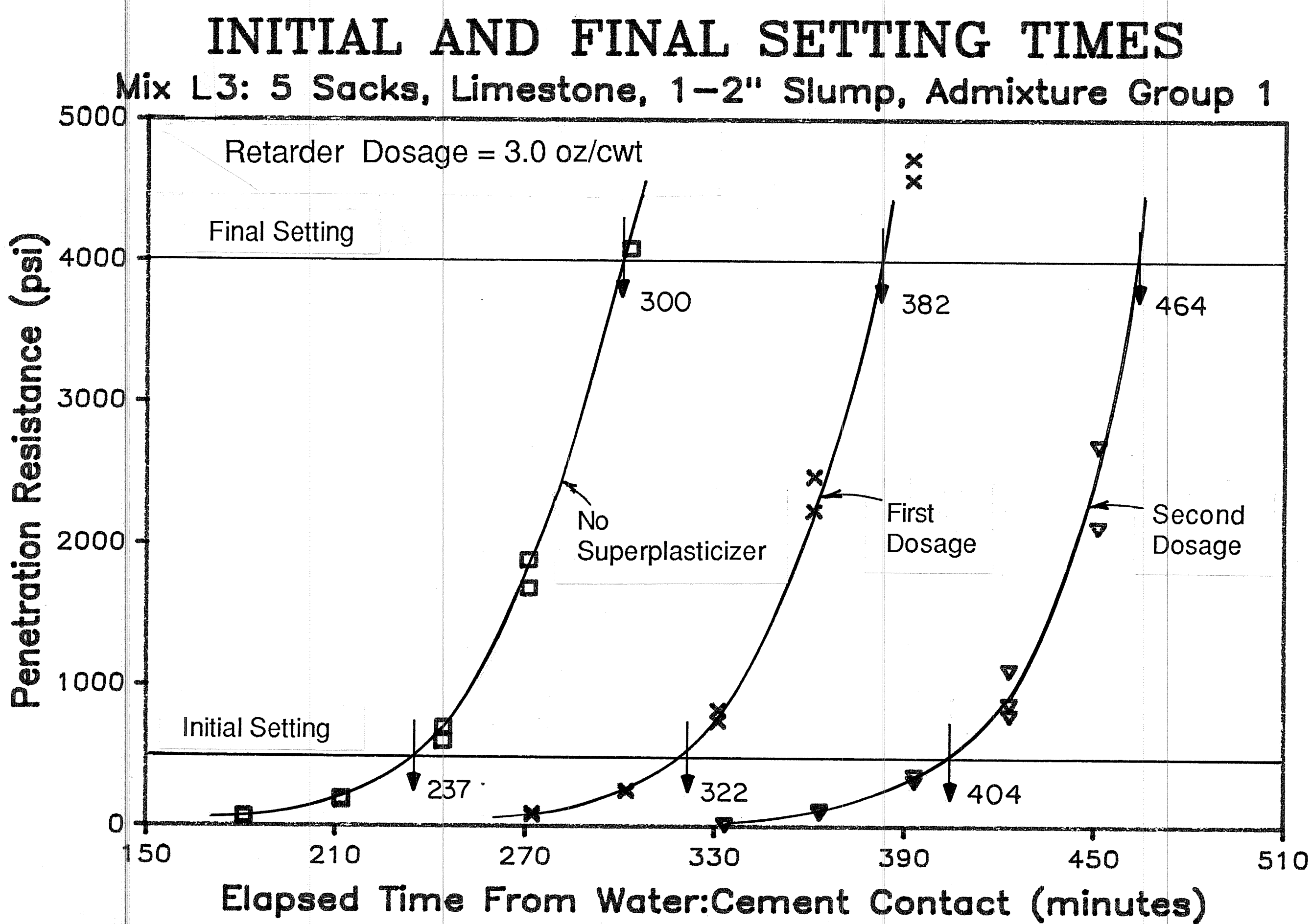


Fig. 4.39 Initial and final setting times data for laboratory mix of July 2, 1987

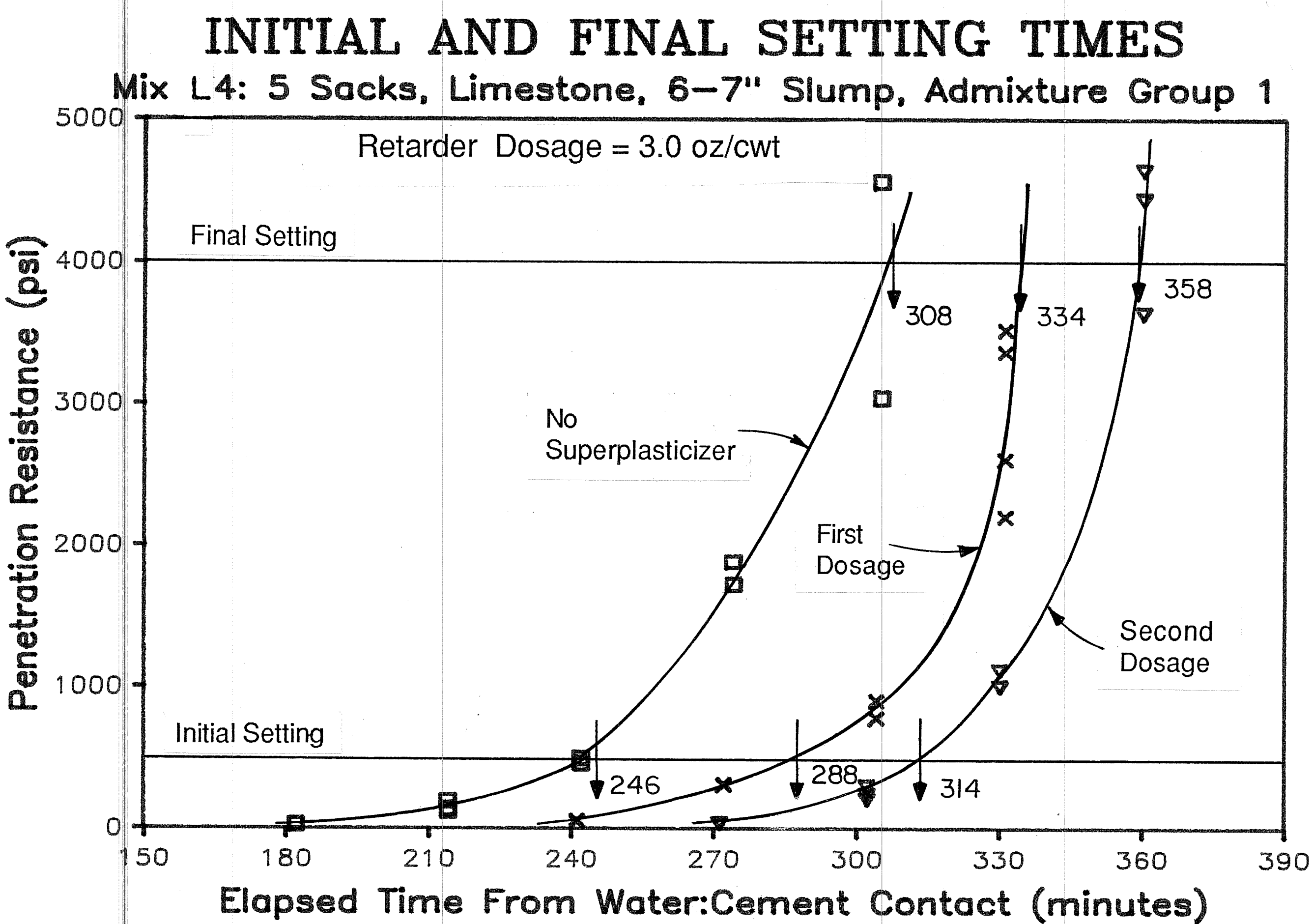


Fig. 4.40 Initial and final setting times data for laboratory mix of July 16, 1987

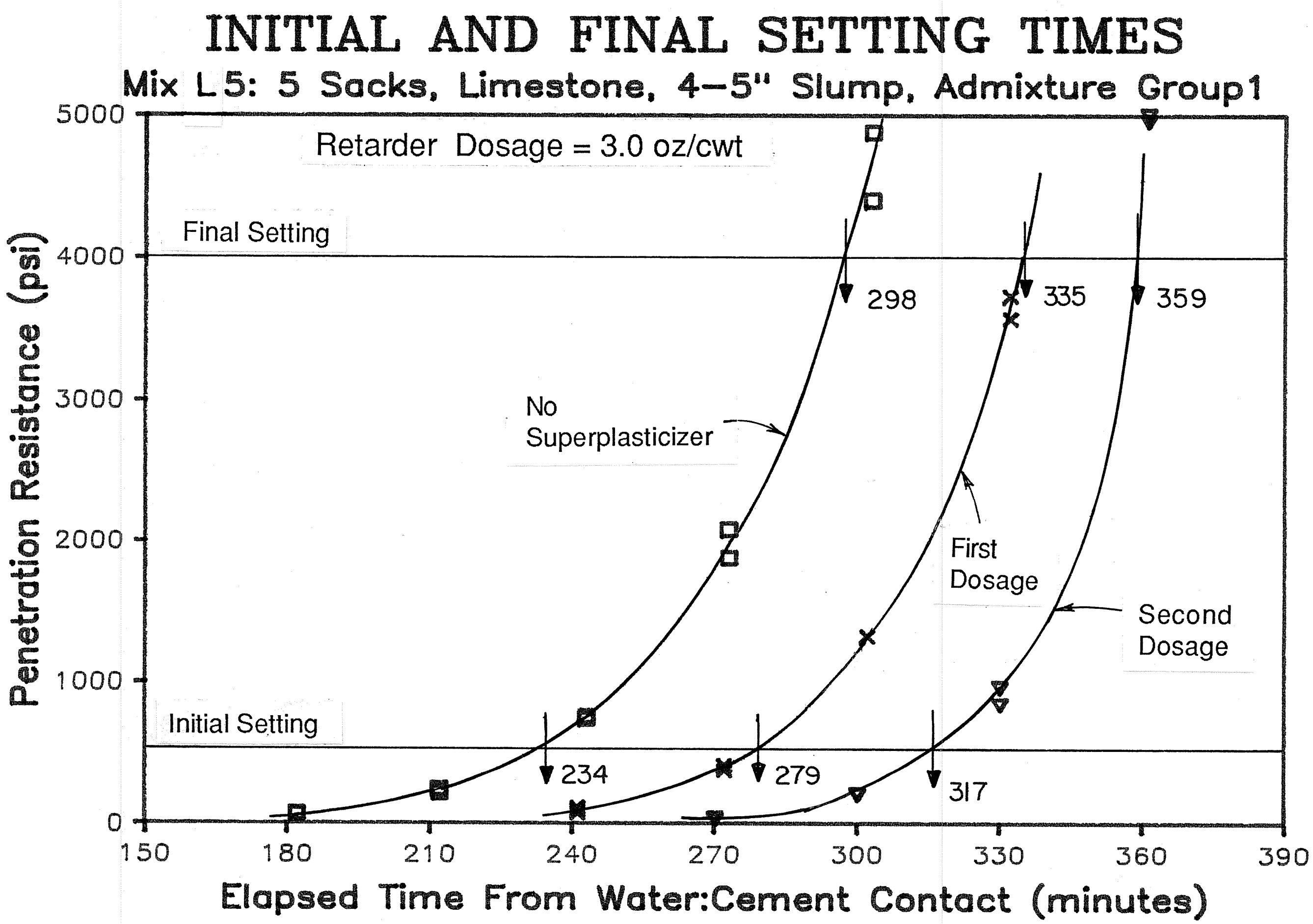


Fig. 4.41 Initial and final setting times data for laboratory mix of July 21, 1987

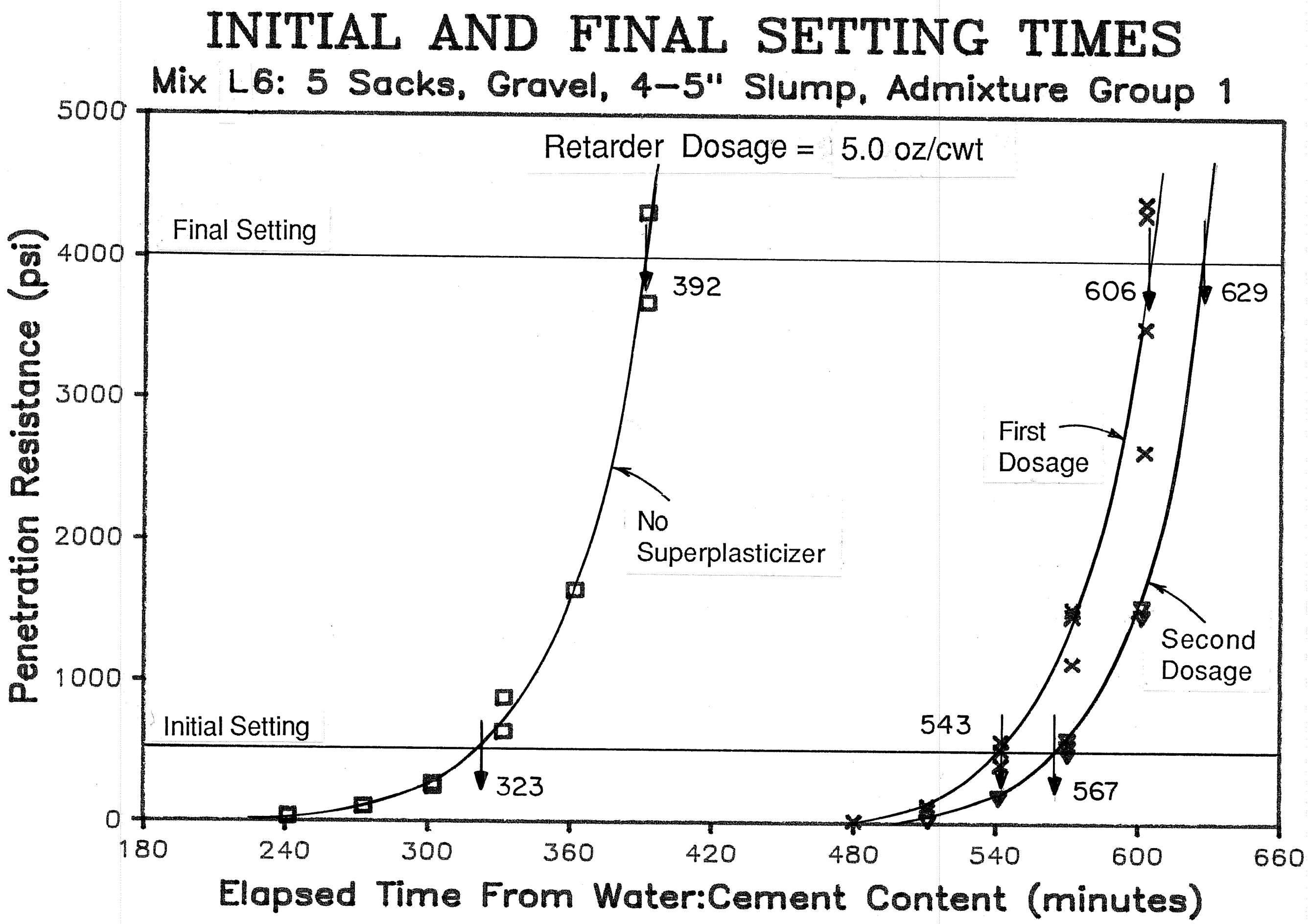


Fig. 4.42 Initial and final setting times data for laboratory mix of July 23, 1987

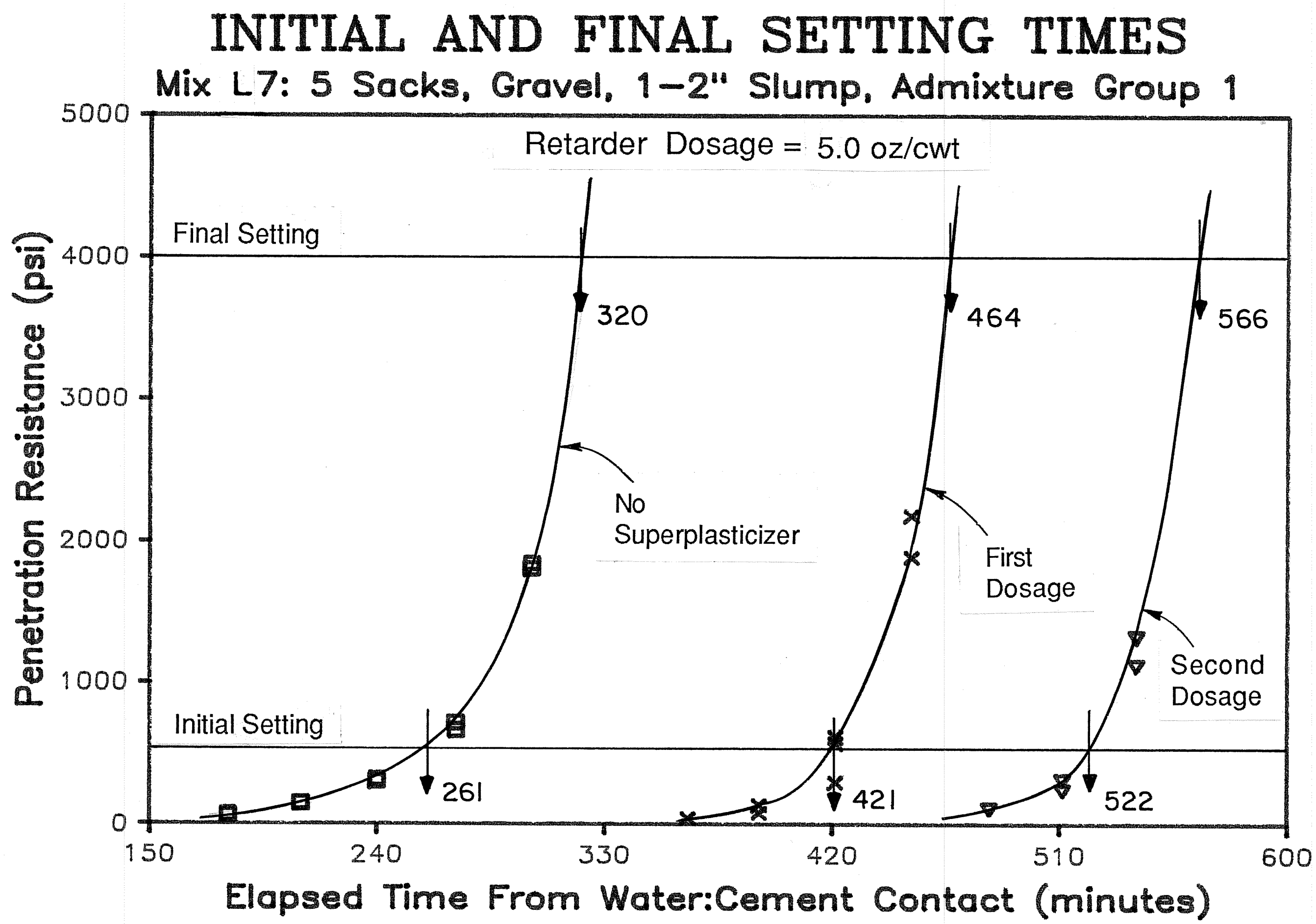


Fig. 4.43 Initial and final setting times data for laboratory mix of August 25, 1987

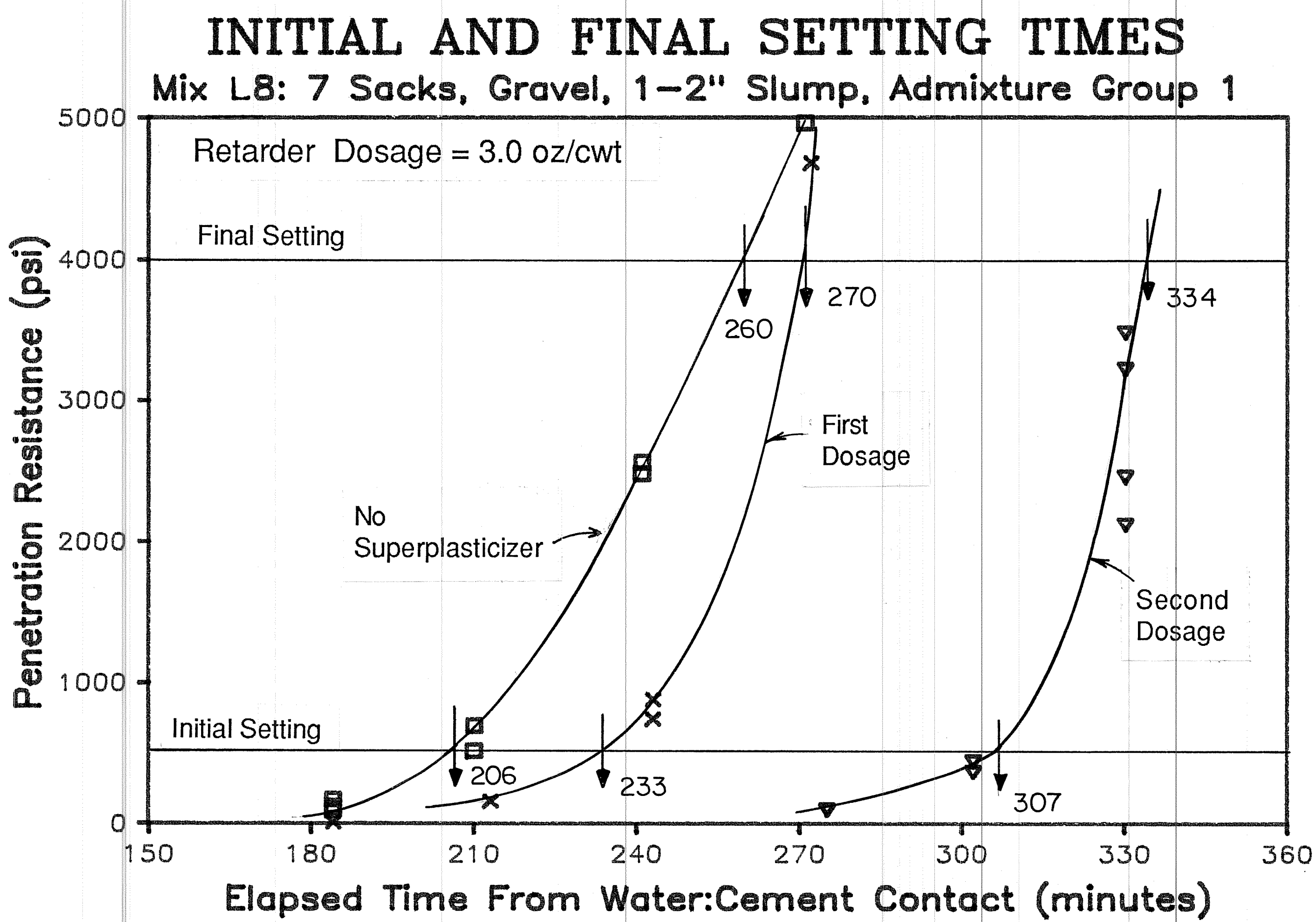


Fig. 4.44 Initial and final setting times data for laboratory mix of September 3, 1987

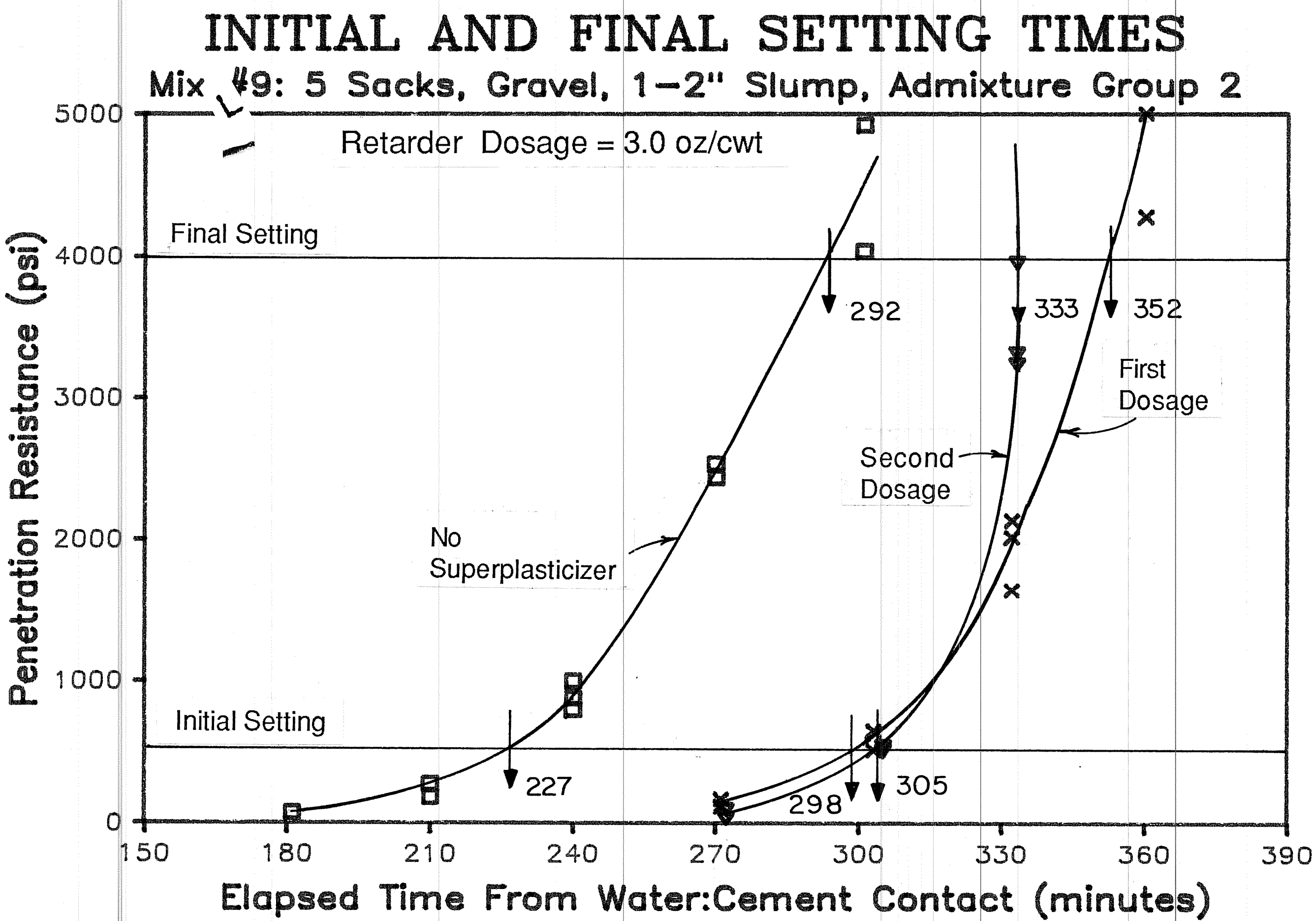


Fig. 4.45 Initial and final setting times data for laboratory mix of September 10, 1987

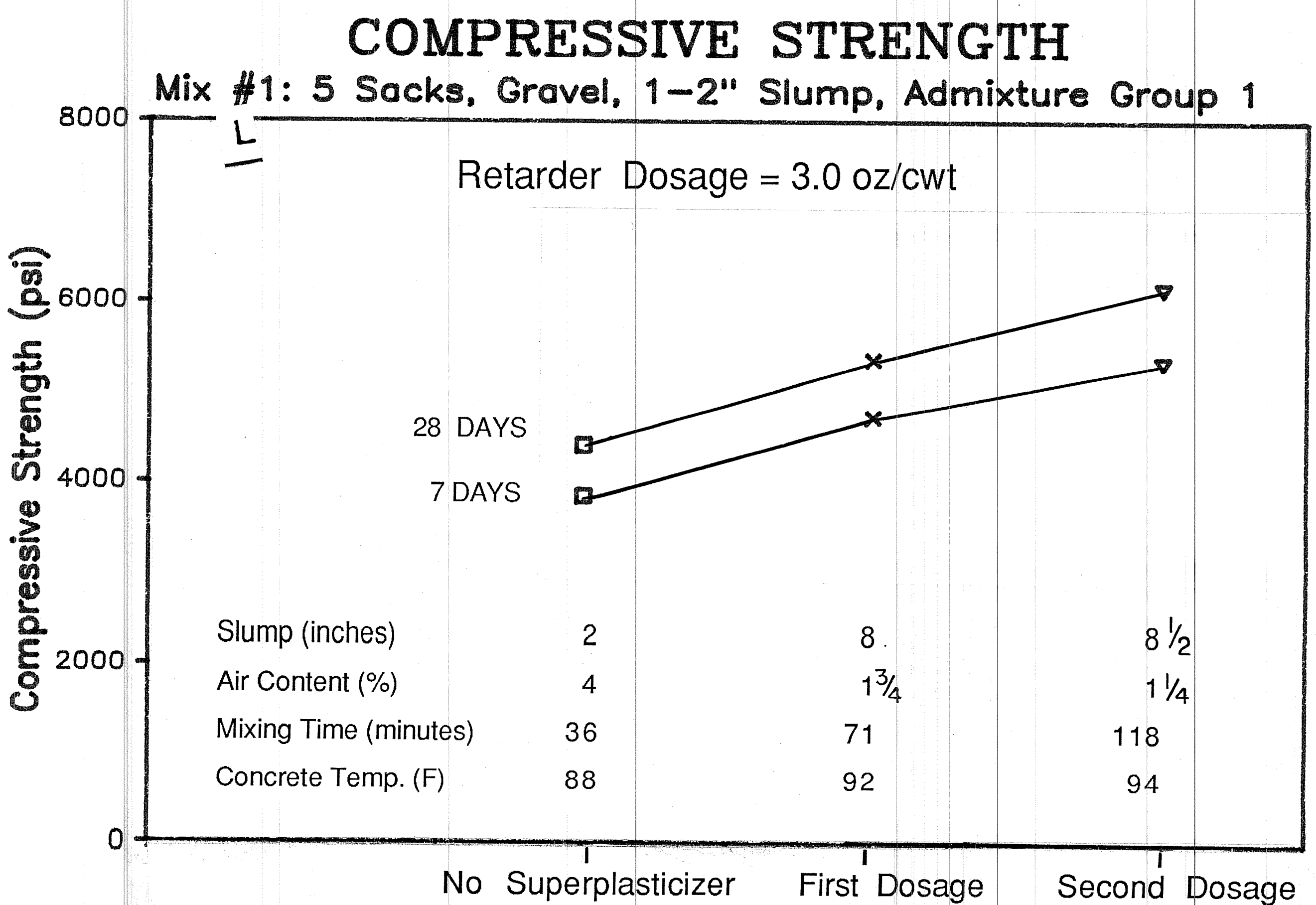


Fig. 4.46 Compressive strength results for laboratory mix of June 18, 1987

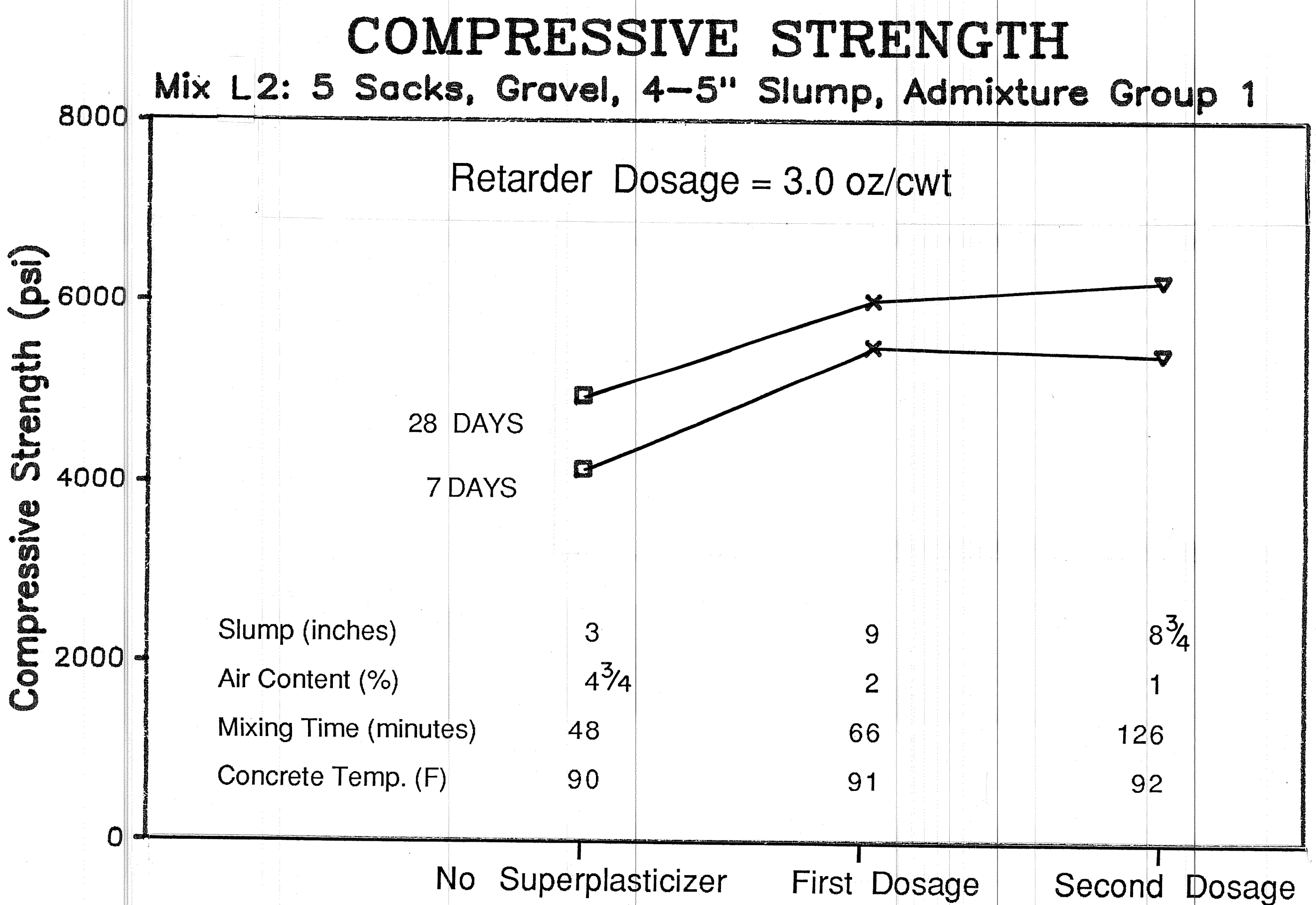


Fig. 4.47 Compressive strength results for laboratory mix of June 23, 1987

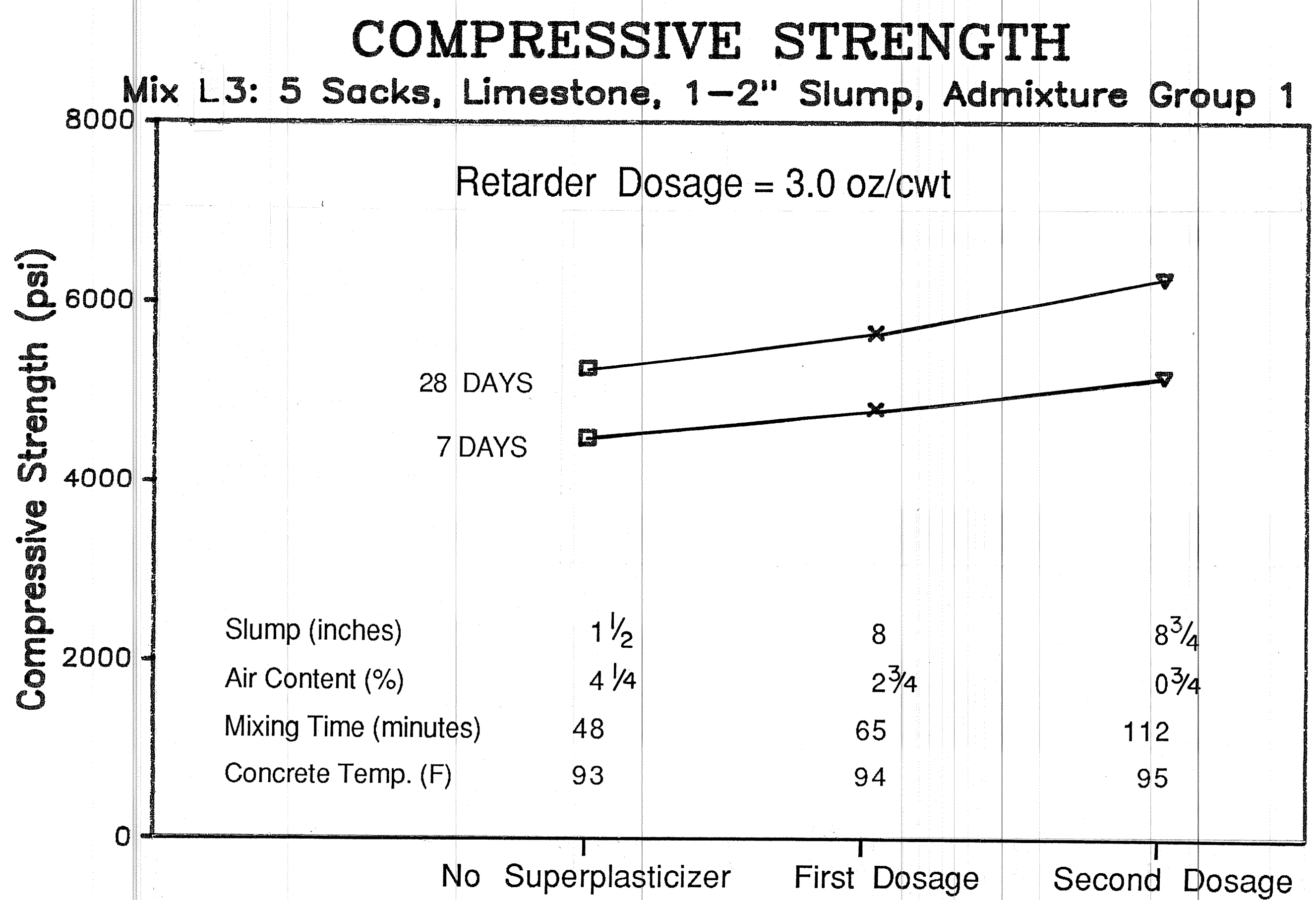


Fig. 4.48 Compressive strength results for laboratory mix of July 2, 1987

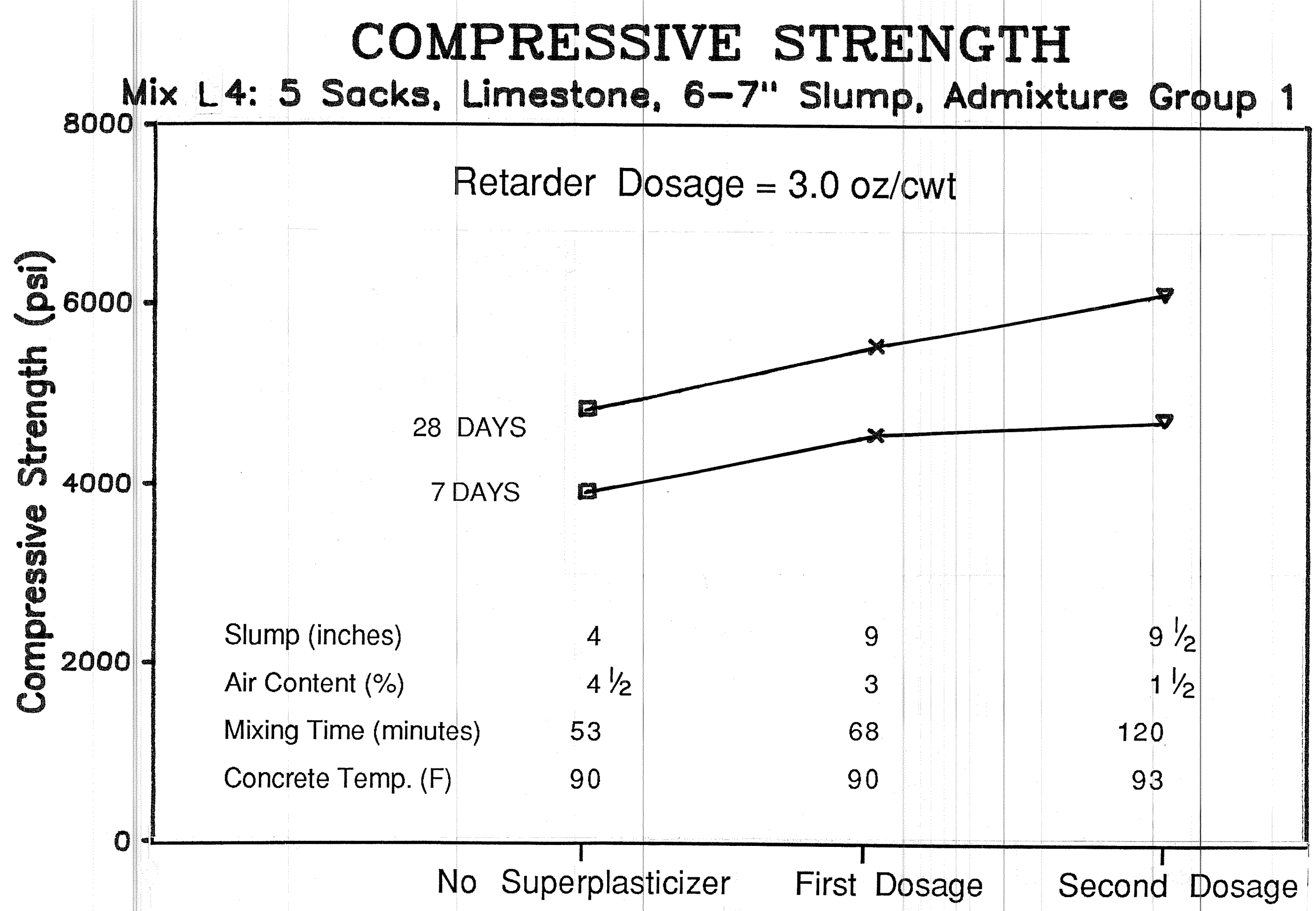


Fig. 4.49 Compressive strength results for laboratory mix of July 16, 1987

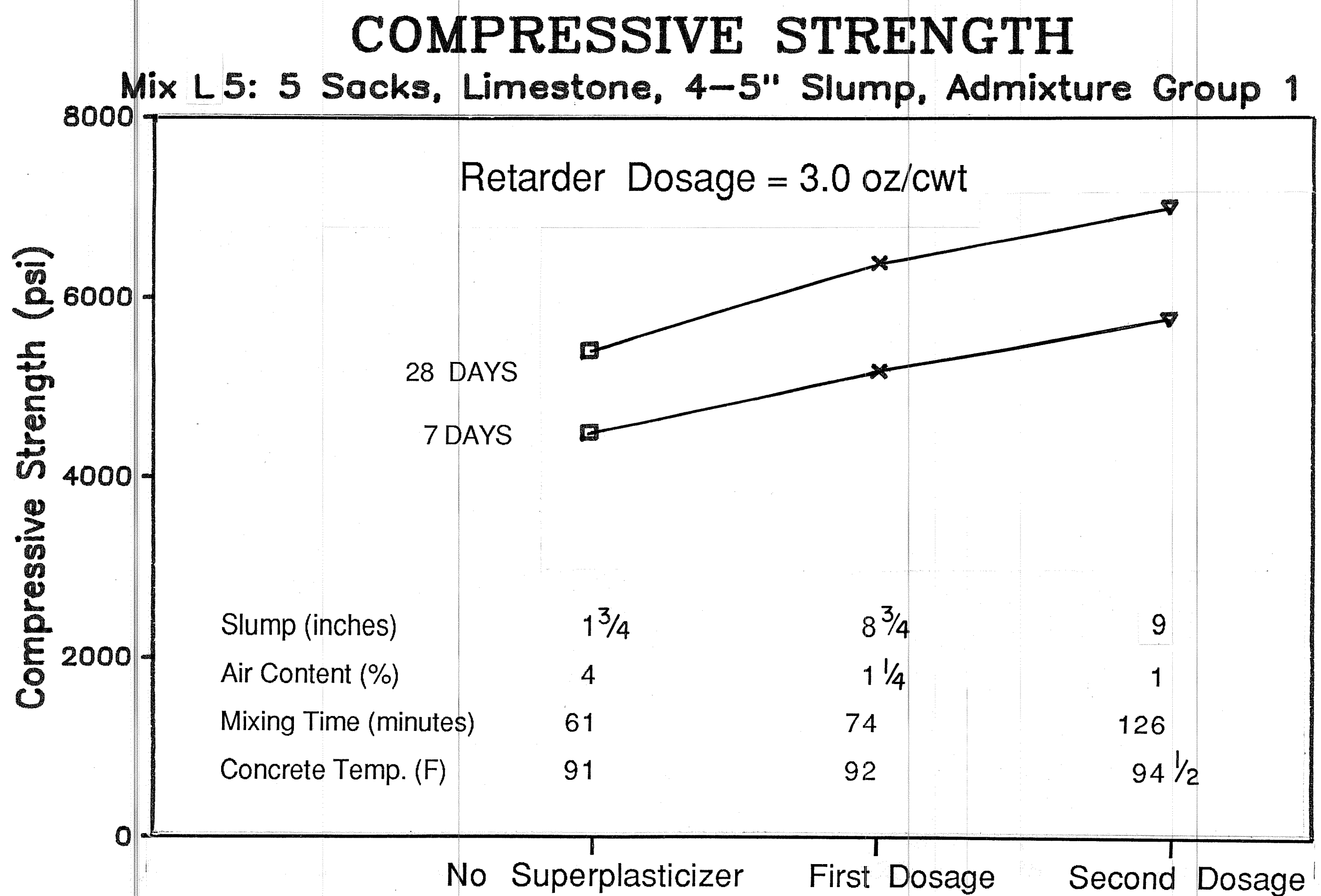


Fig. 4.50 Compressive strength results for laboratory mix of July 21, 1987

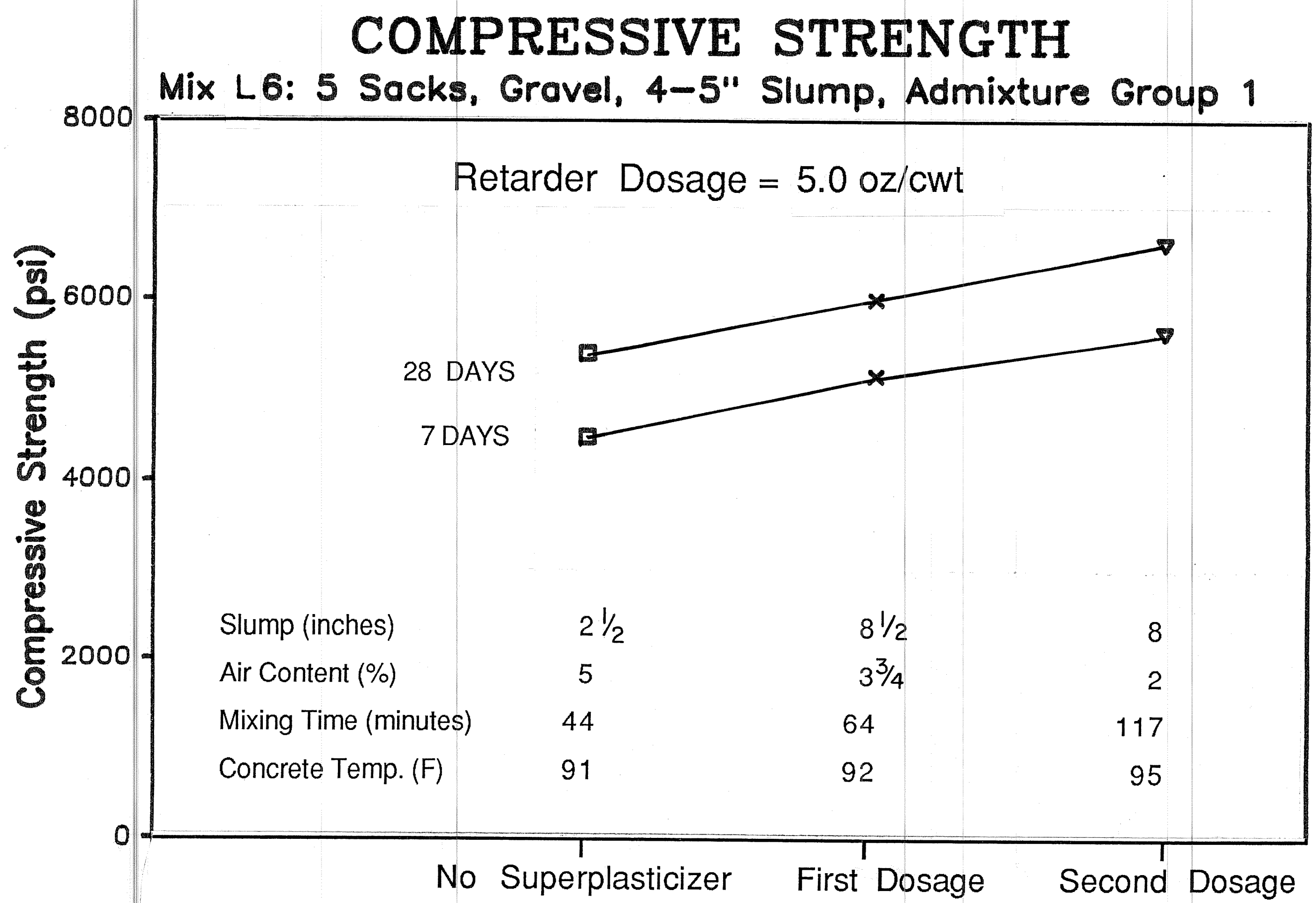


Fig. 4.51 Compressive strength results for laboratory mix of July 23, 1987

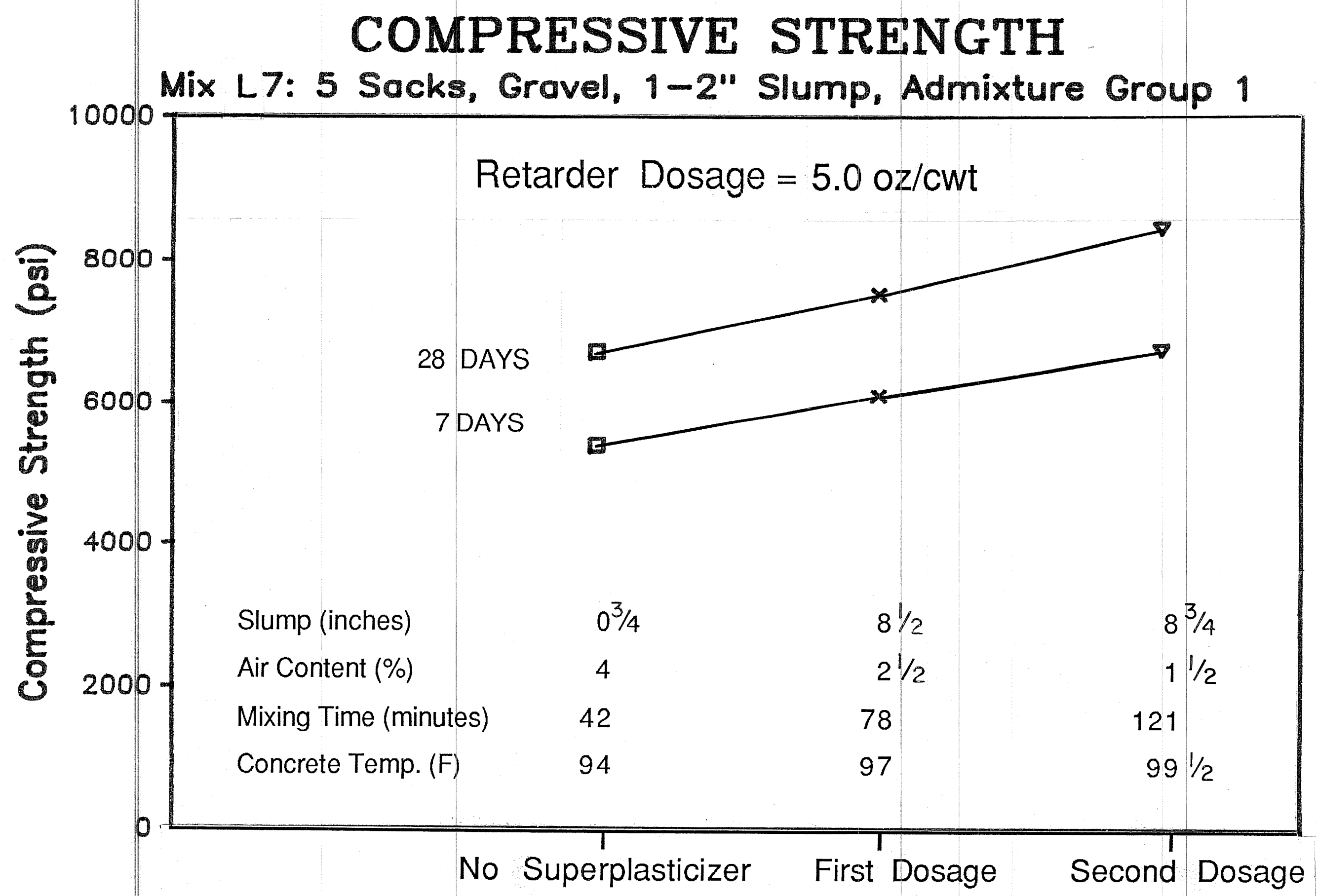


Fig. 4.52 Compressive strength results for laboratory mix of August 25, 1987

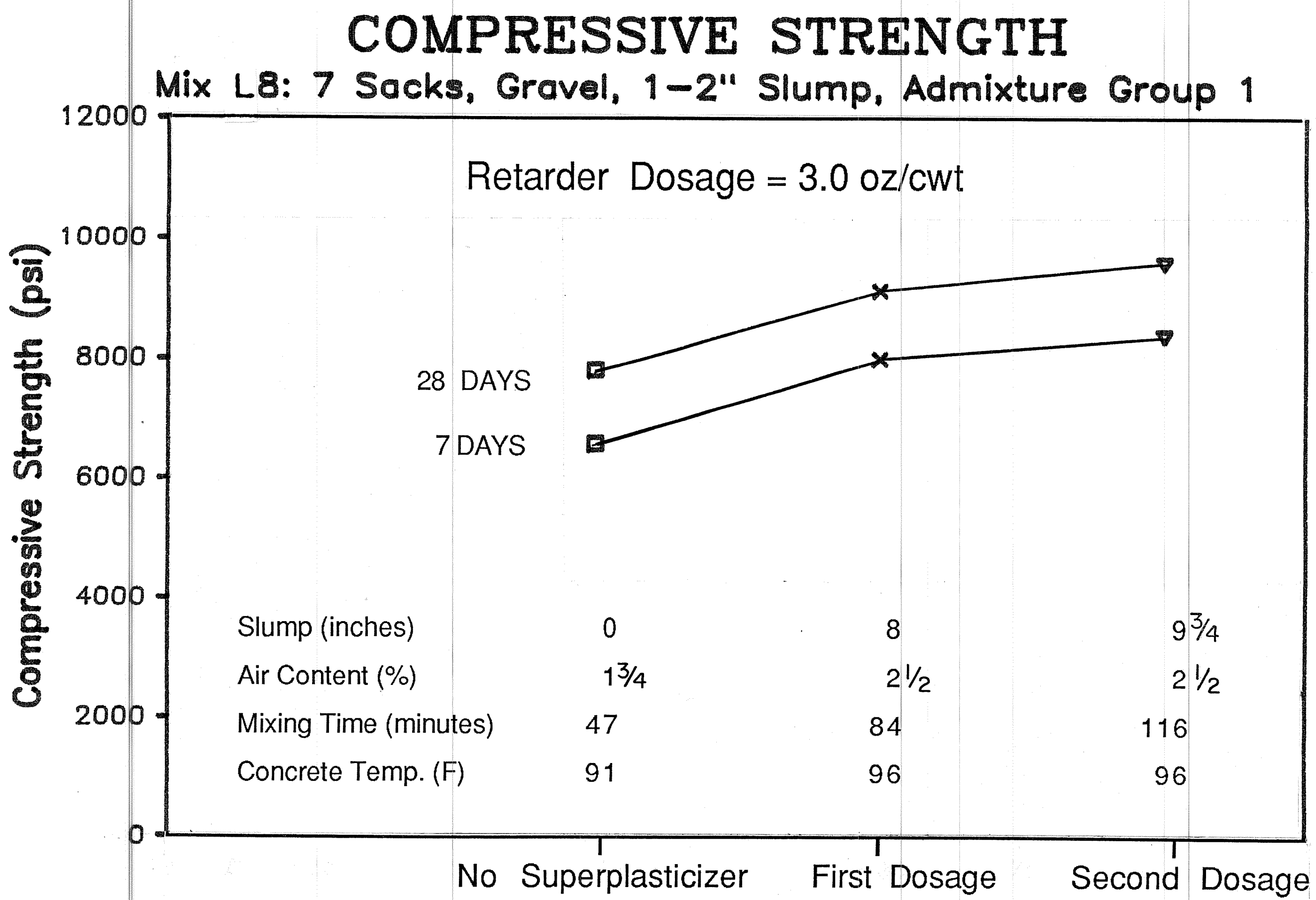


Fig. 4.53 Compressive strength results for laboratory mix of September 3, 1987

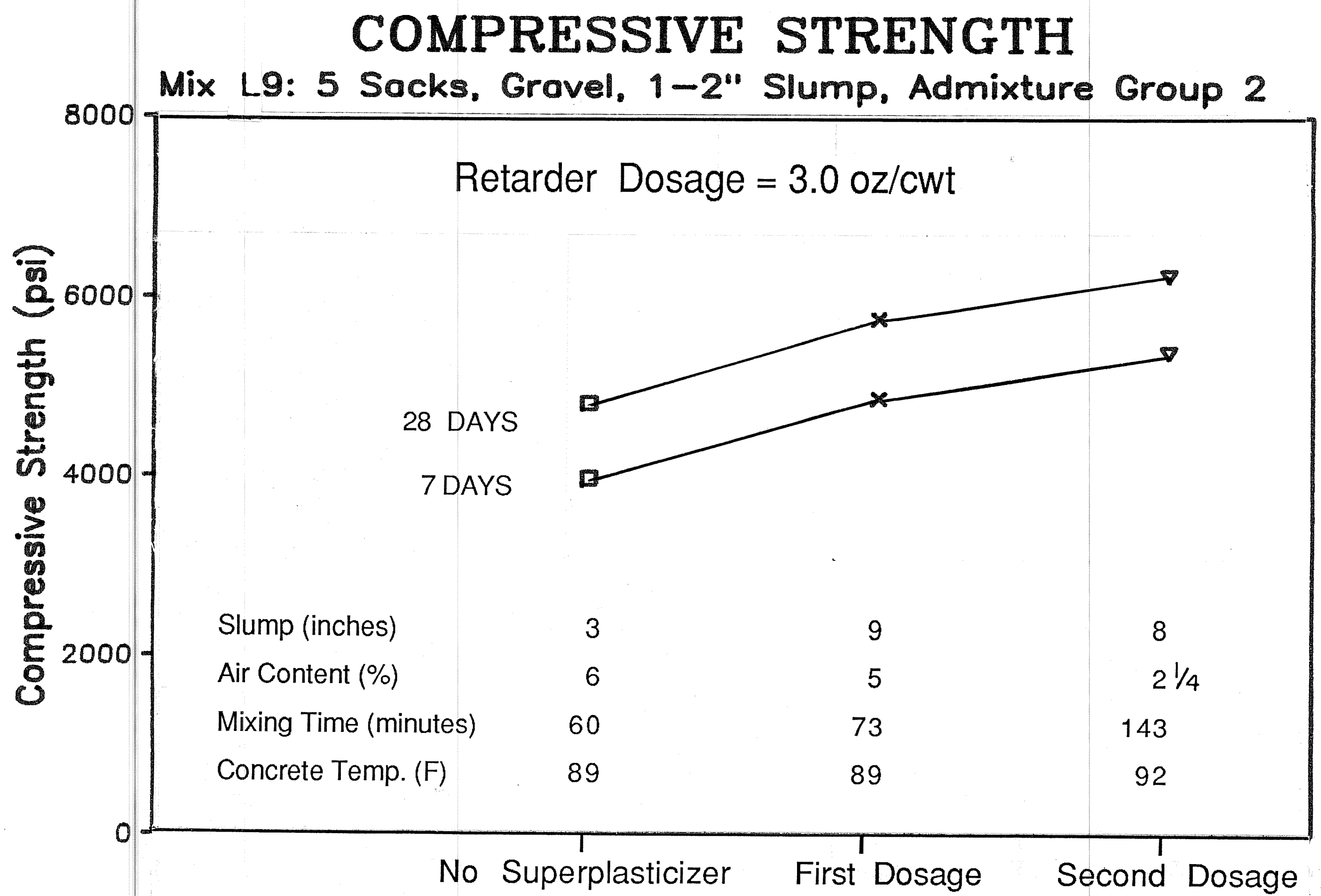


Fig. 4.54 Compressive strength results for laboratory mix of September 10, 1987

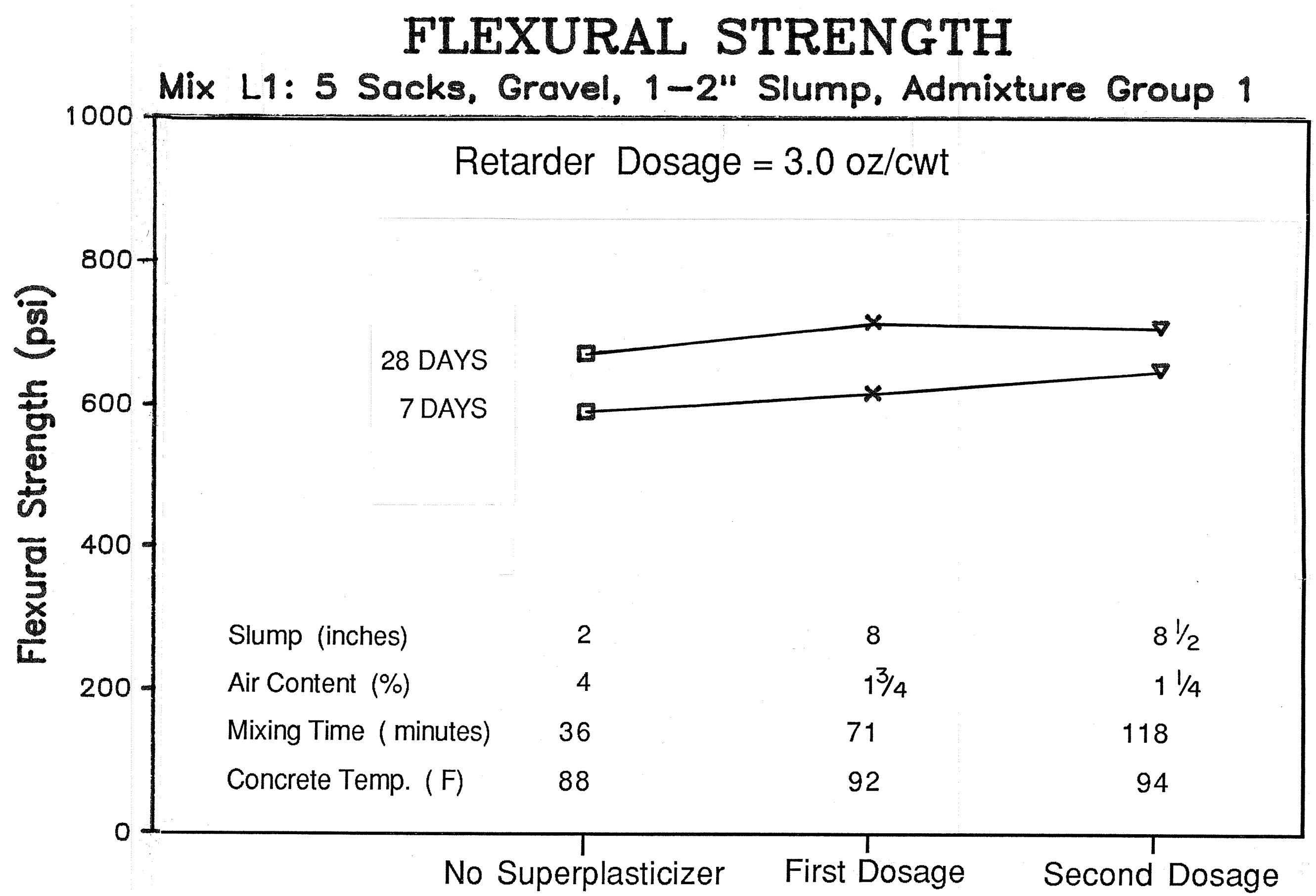


Fig. 4.55 Flexural strength results for laboratory mix of June 18, 1987

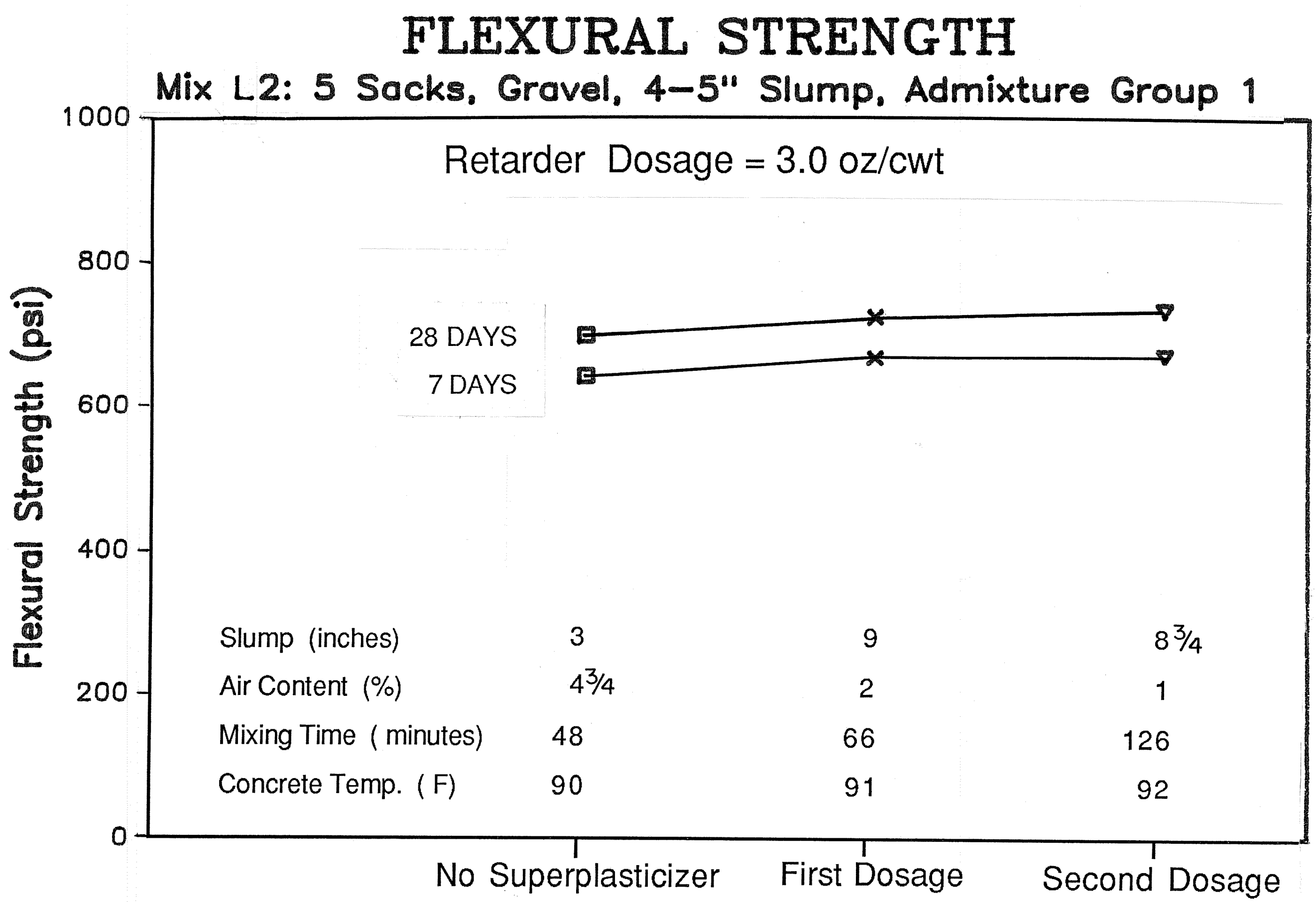


Fig. 4.56 Flexural strength results for laboratory mix of June 23, 1987

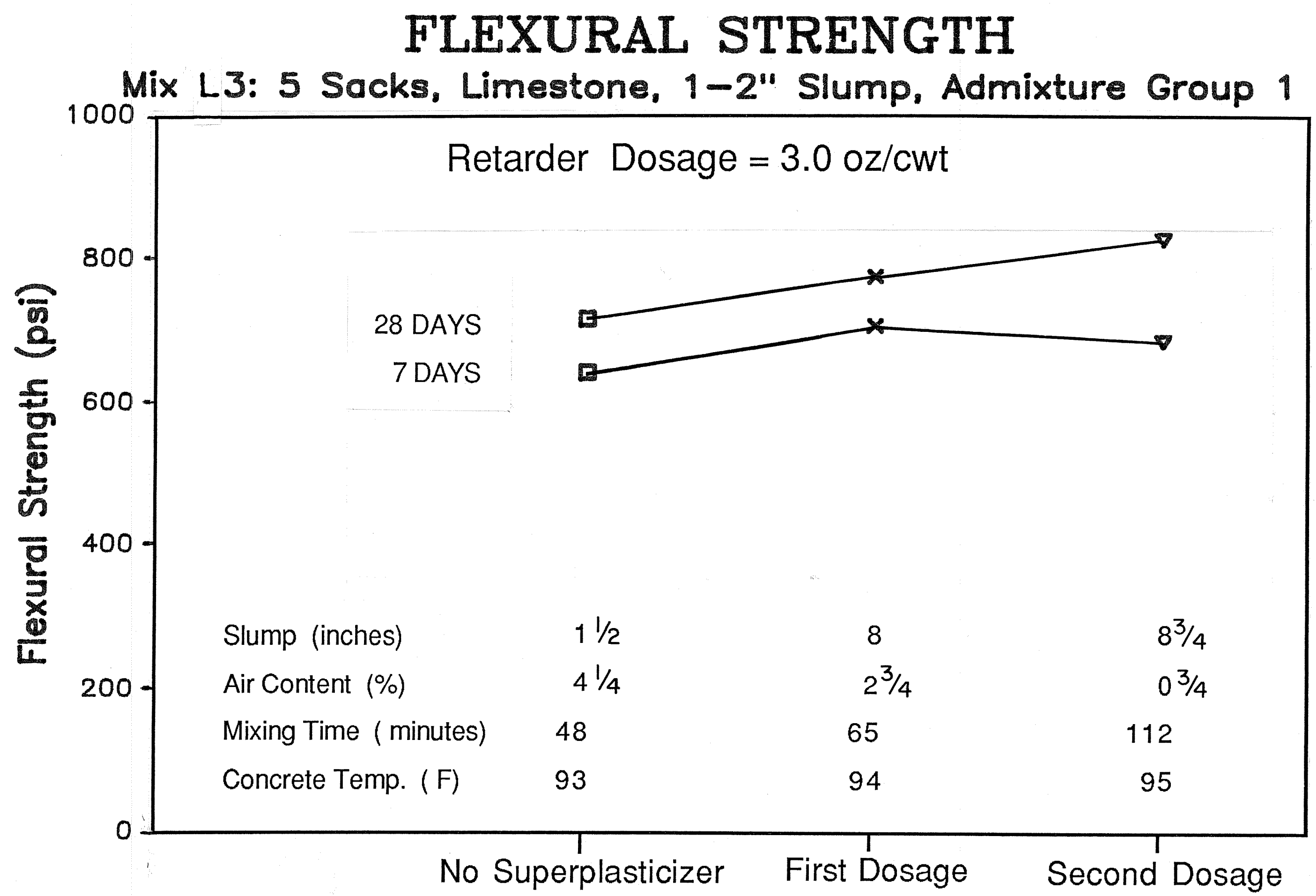


Fig. 4.57 Flexural strength results for laboratory mix of July 2, 1987

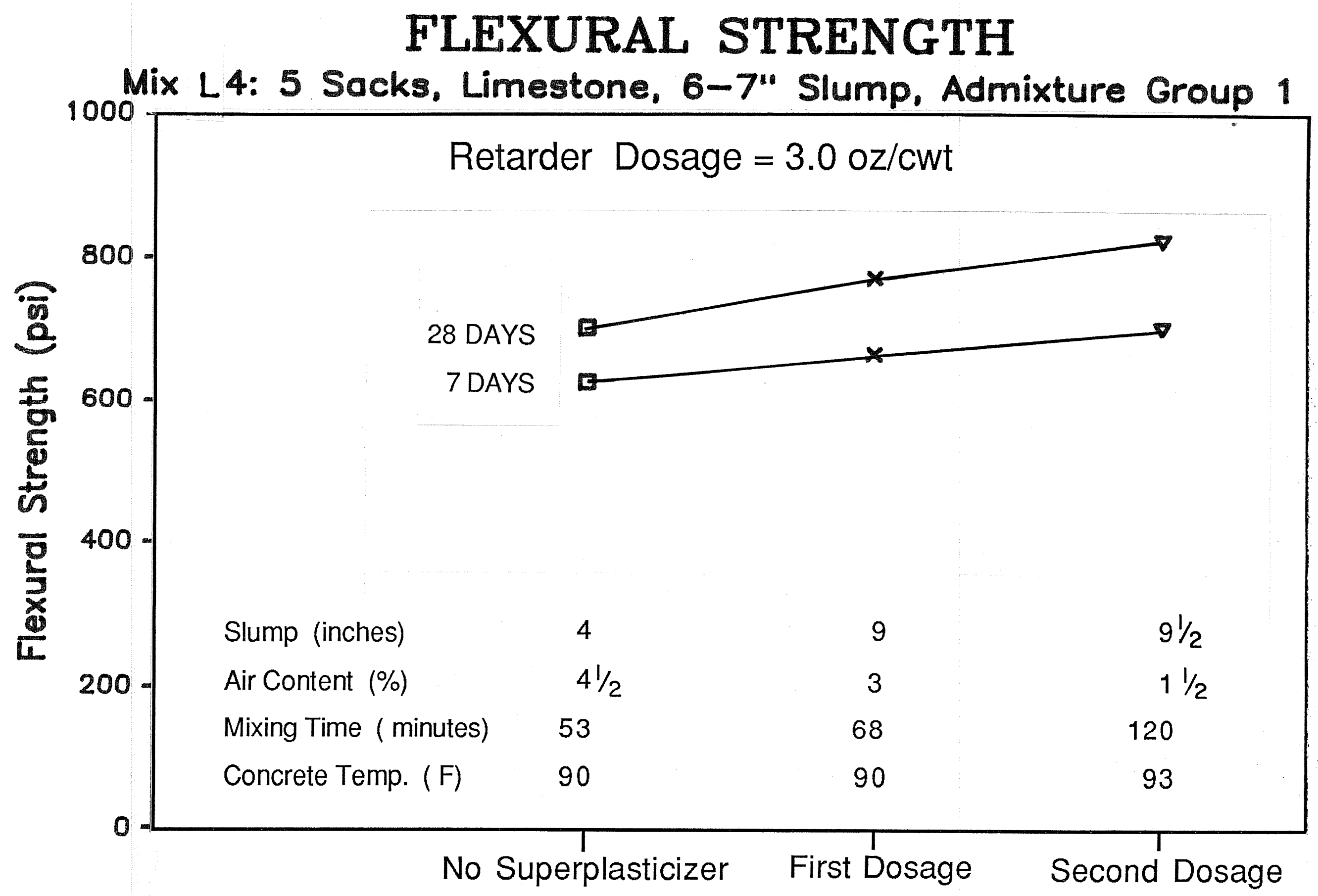


Fig. 4.58 Flexural strength results for laboratory mix of July 16, 1987

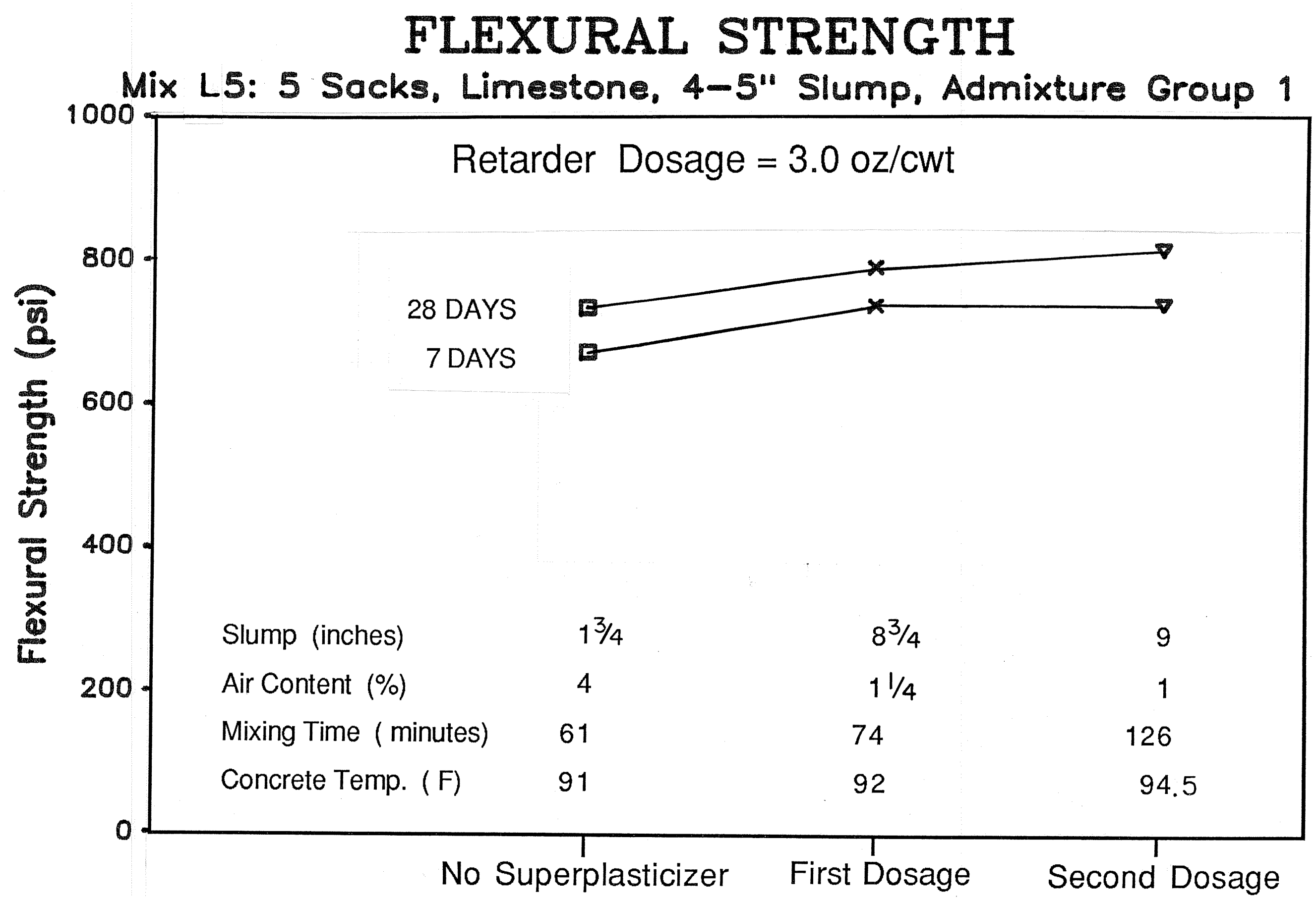


Fig. 4.59 Flexural strength results for laboratory mix of July 21, 1987

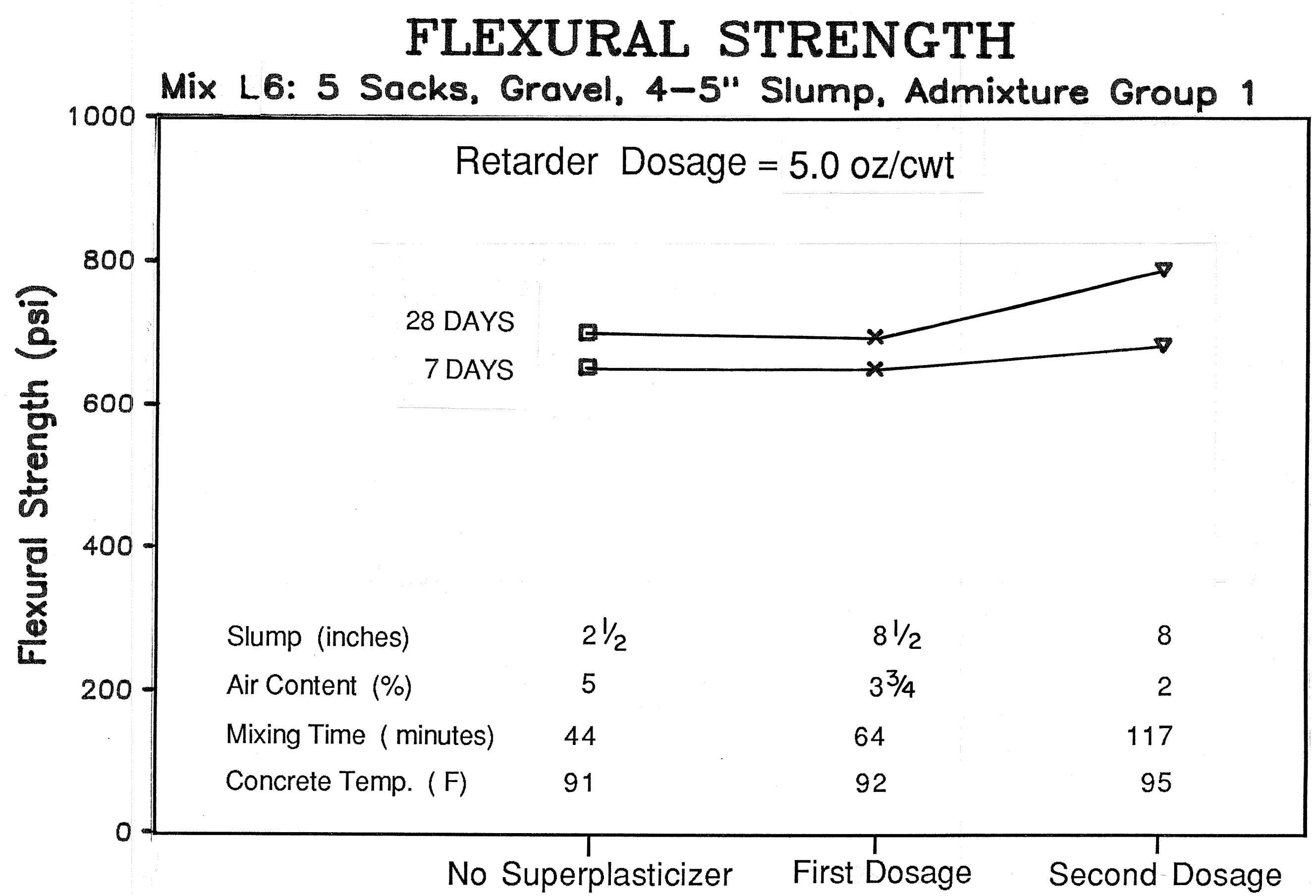


Fig. 4.60 Flexural strength results for laboratory mix of July 23, 1987

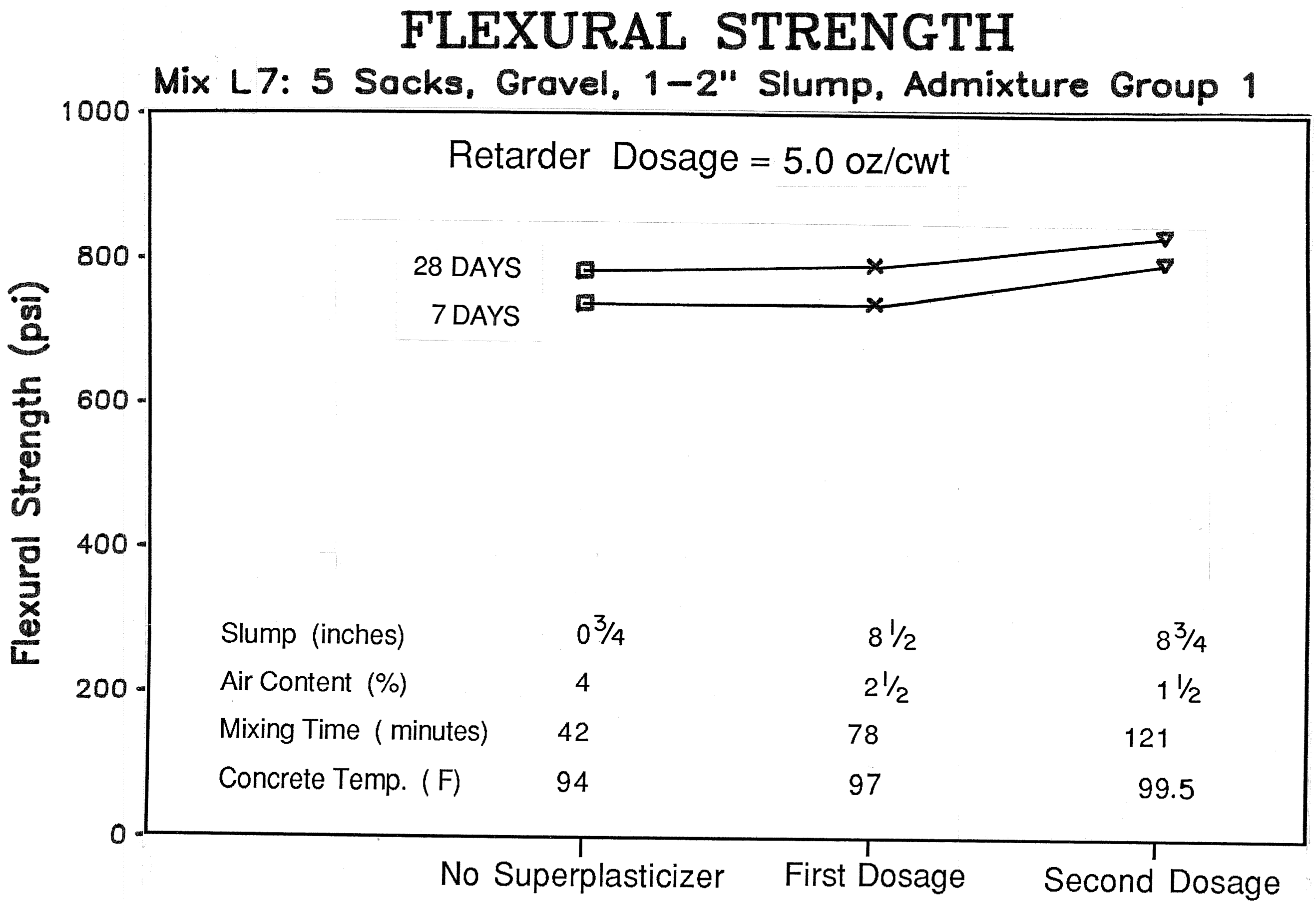


Fig. 4.61 Flexural strength results for laboratory mix of August 25, 1987

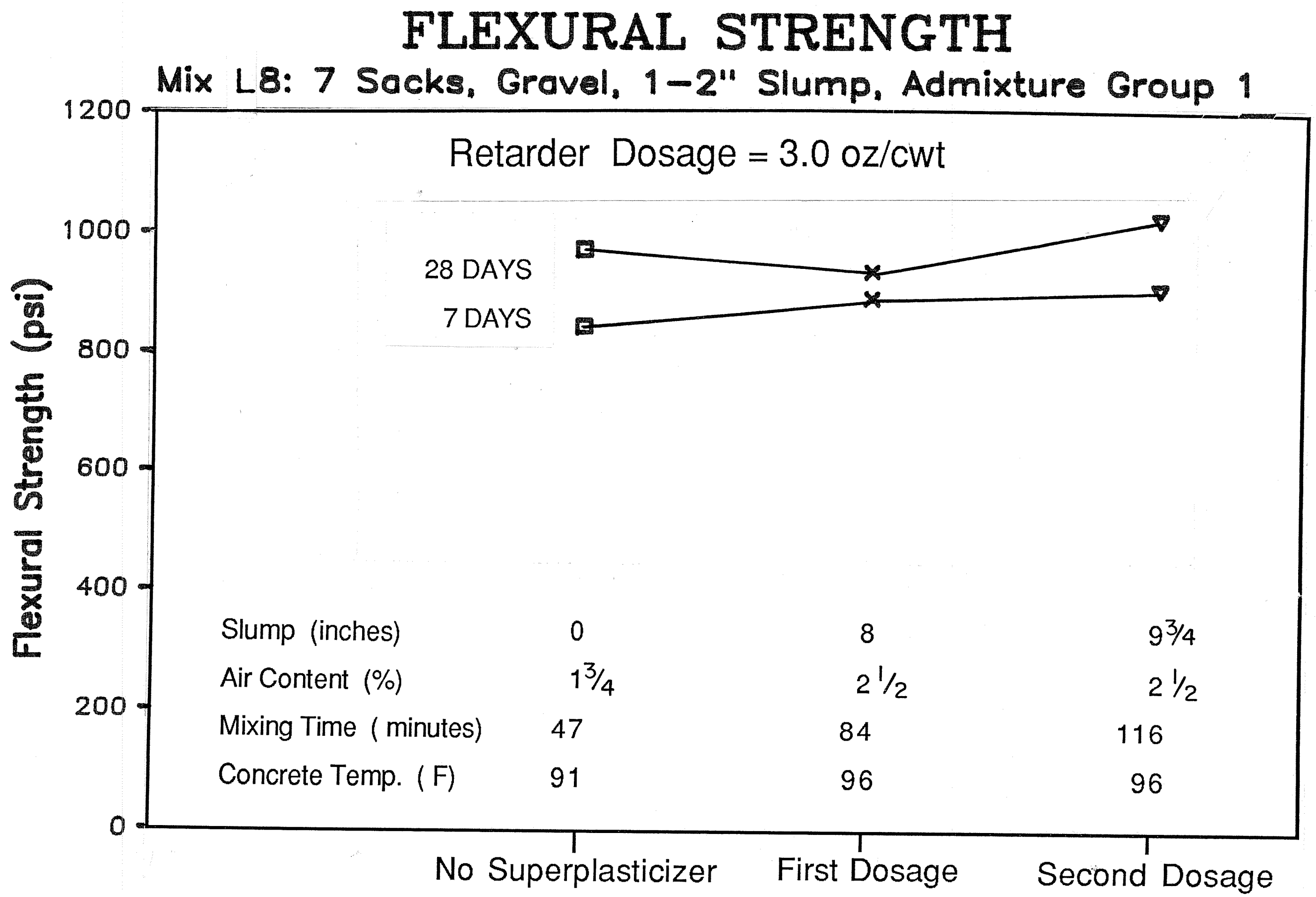


Fig. 4.62 Flexural strength results for laboratory mix of September 3, 1987

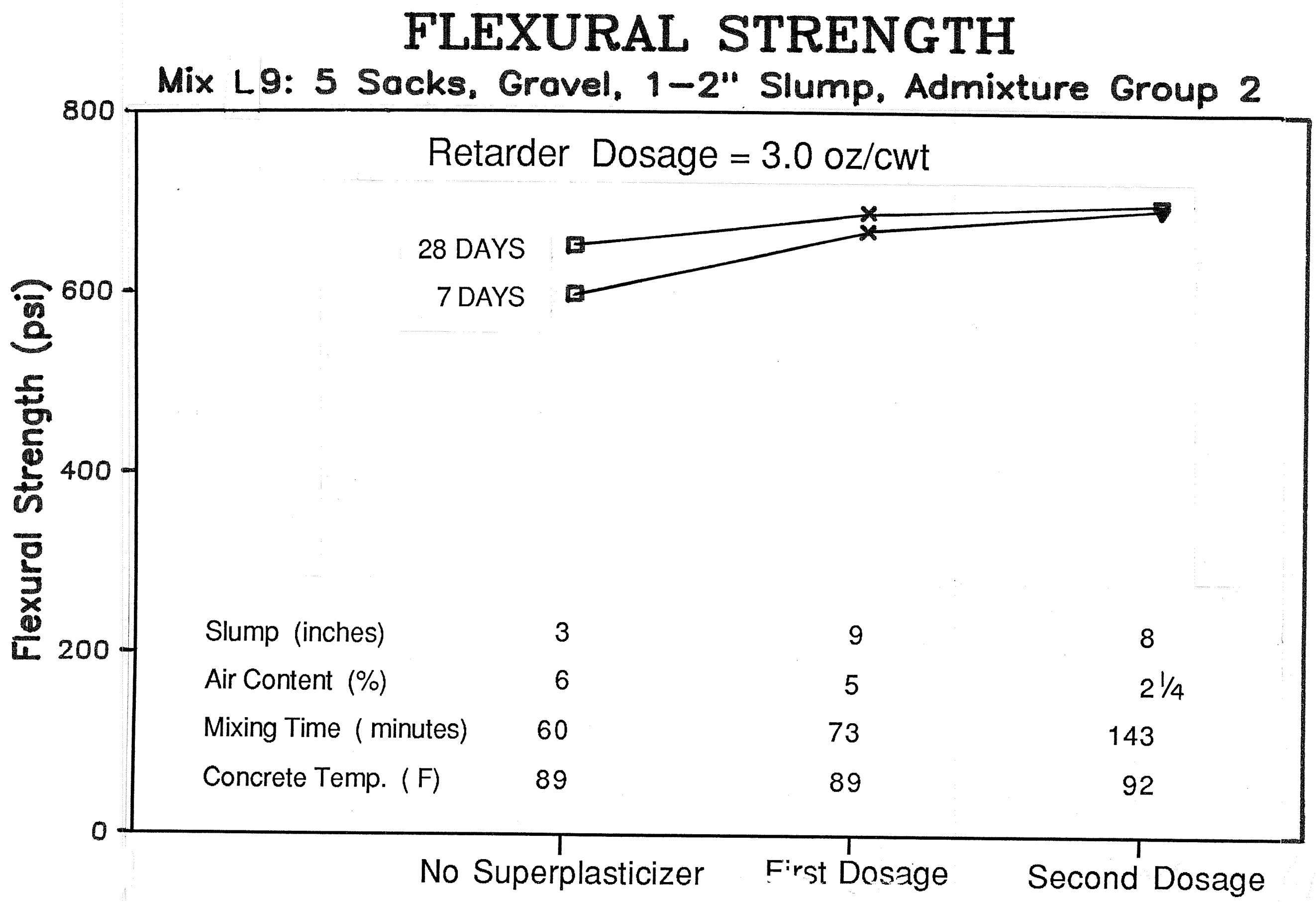


Fig. 4.63 Flexural strength results for laboratory mix of September 10, 1987

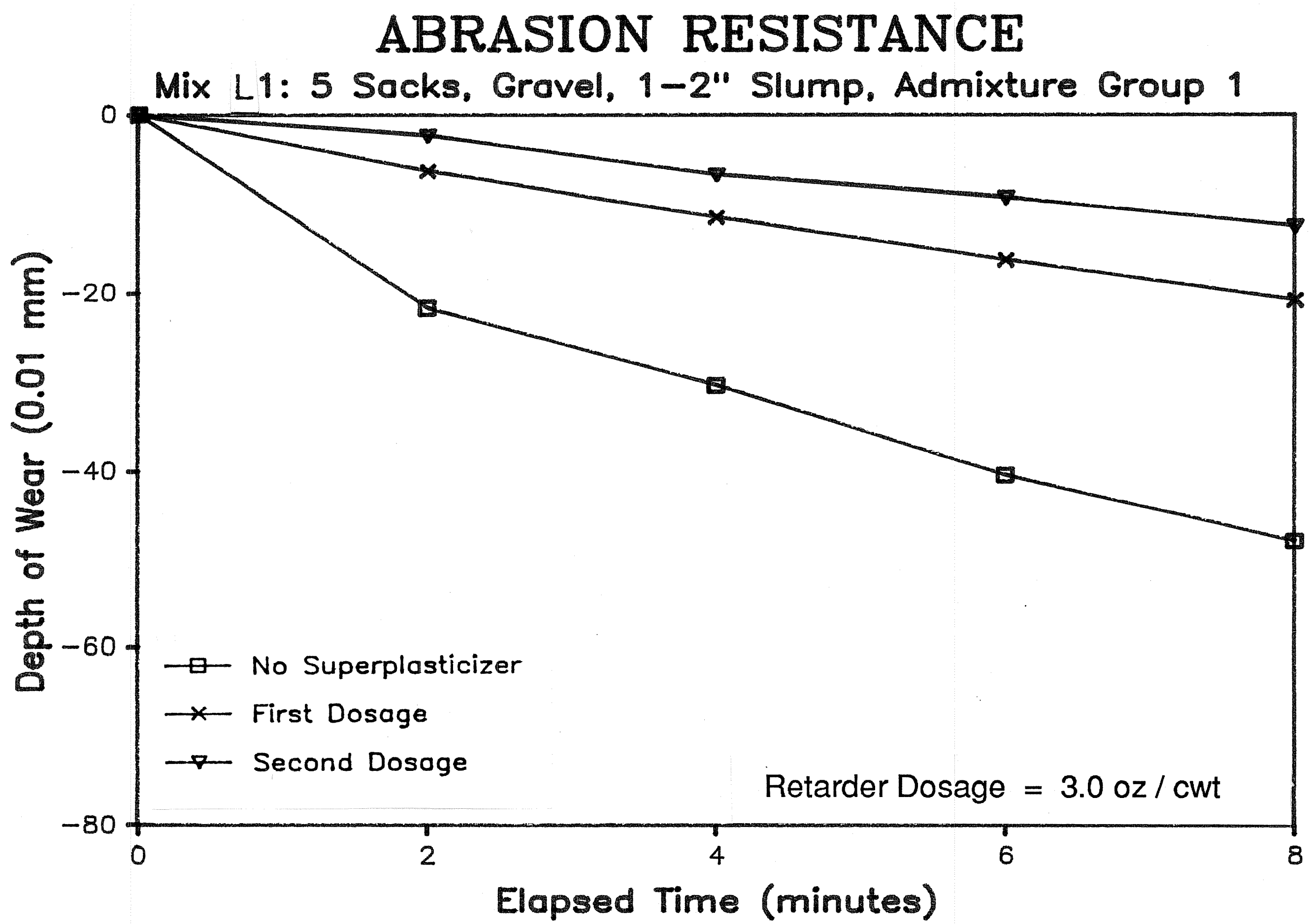


Fig. 4.64 Abrasion resistance data for laboratory mix of June 18, 1987. (Specimen Age - 8 Days)

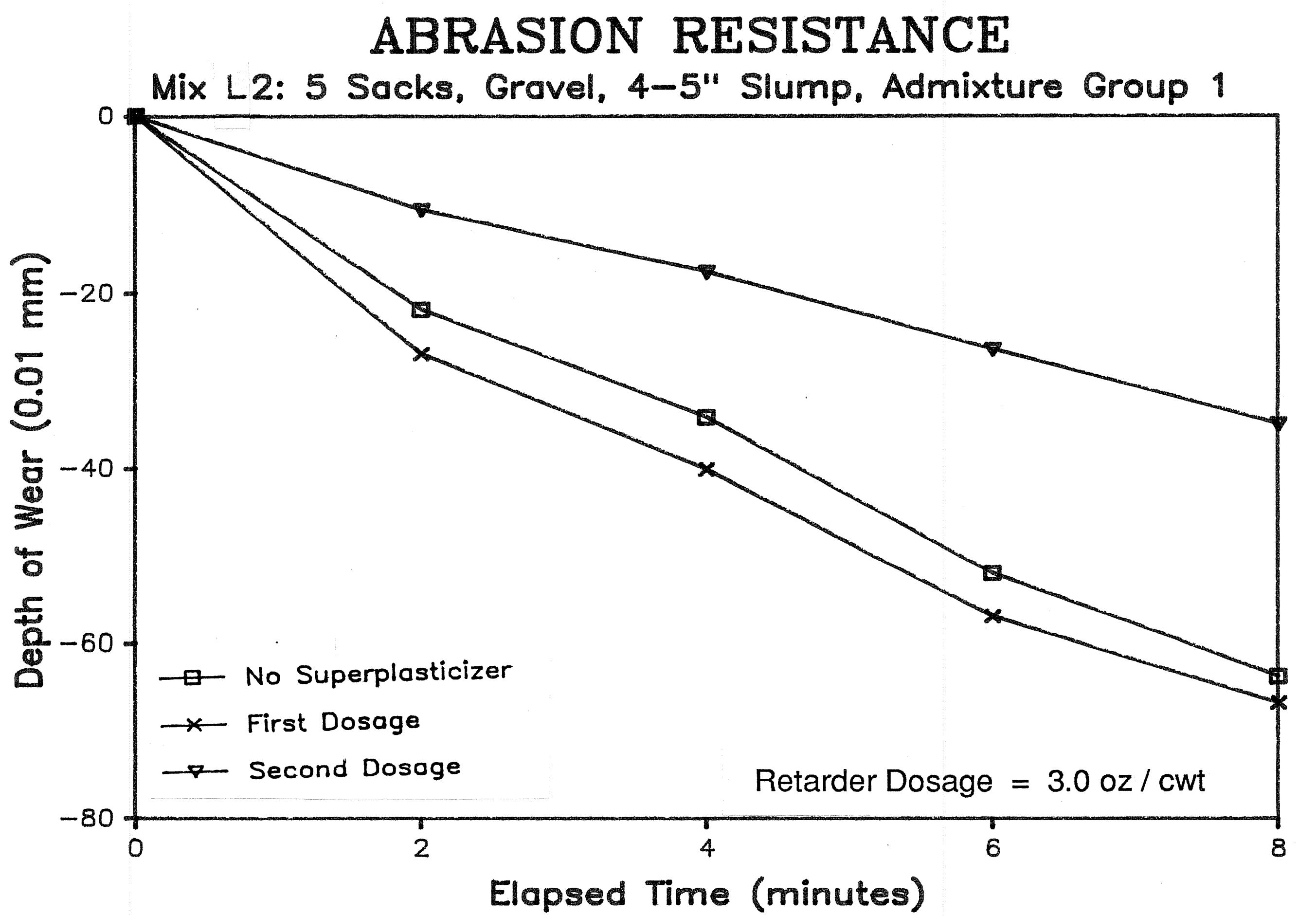


Fig. 4.65 Abrasion resistance data for laboratory mix of June 23, 1987. (Specimen Age - 8 Days)

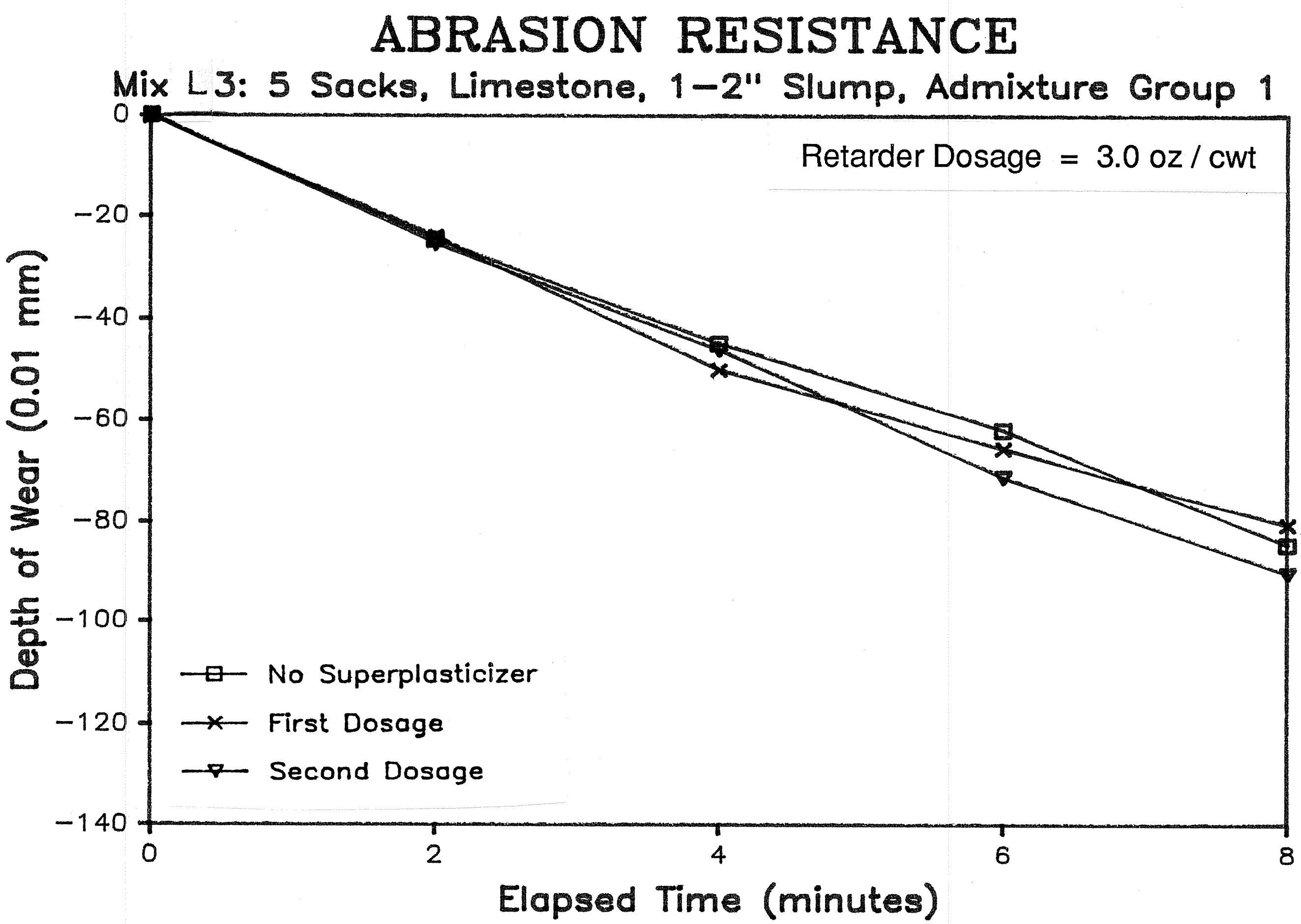


Fig. 4.66 Abrasion resistance data for laboratory mix of July 2, 1987. (Specimen Age - 8 Days)

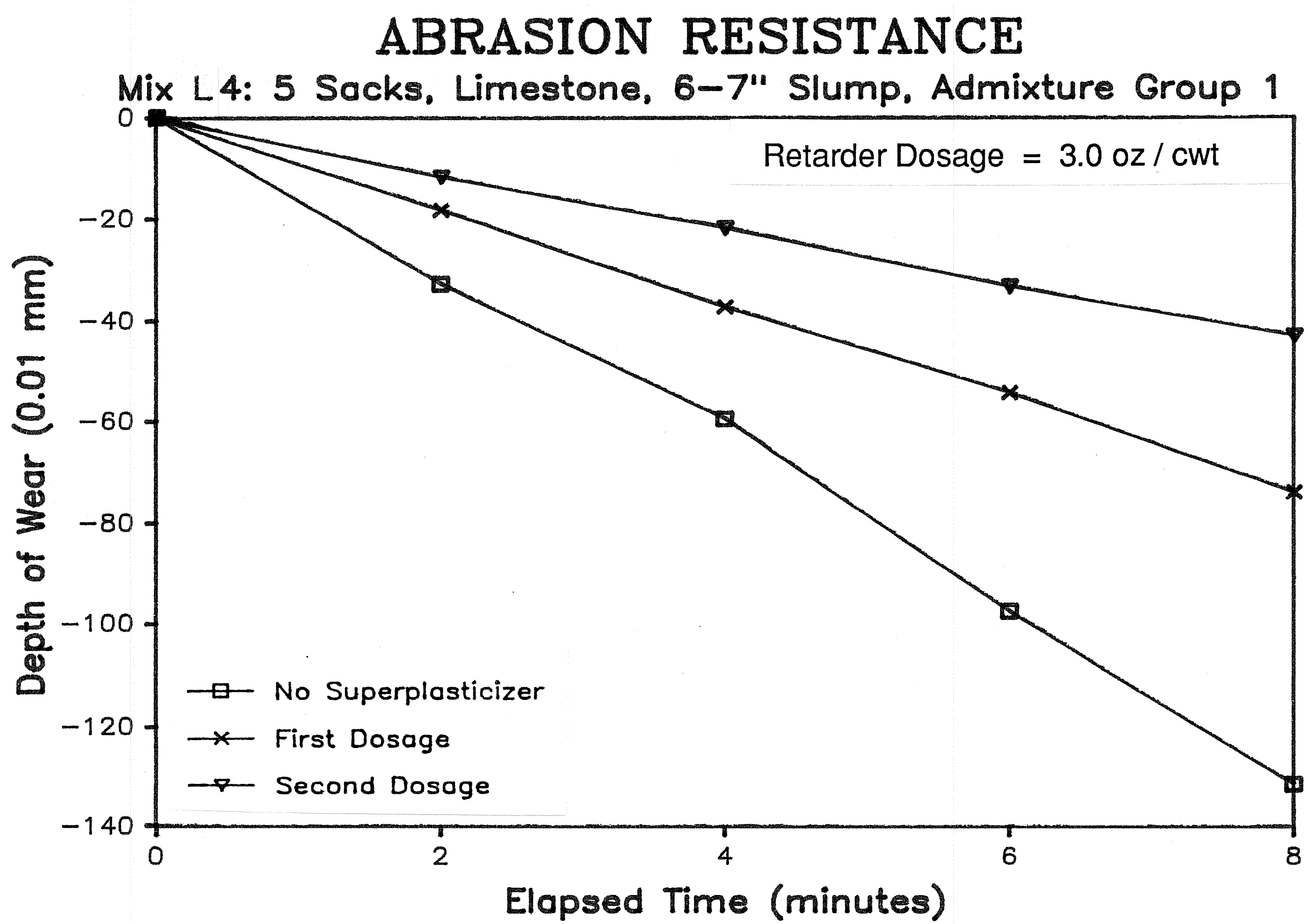


Fig. 4.67 Abrasion resistance data for laboratory mix of July 16, 1987. (Specimen Age - 8 Days)

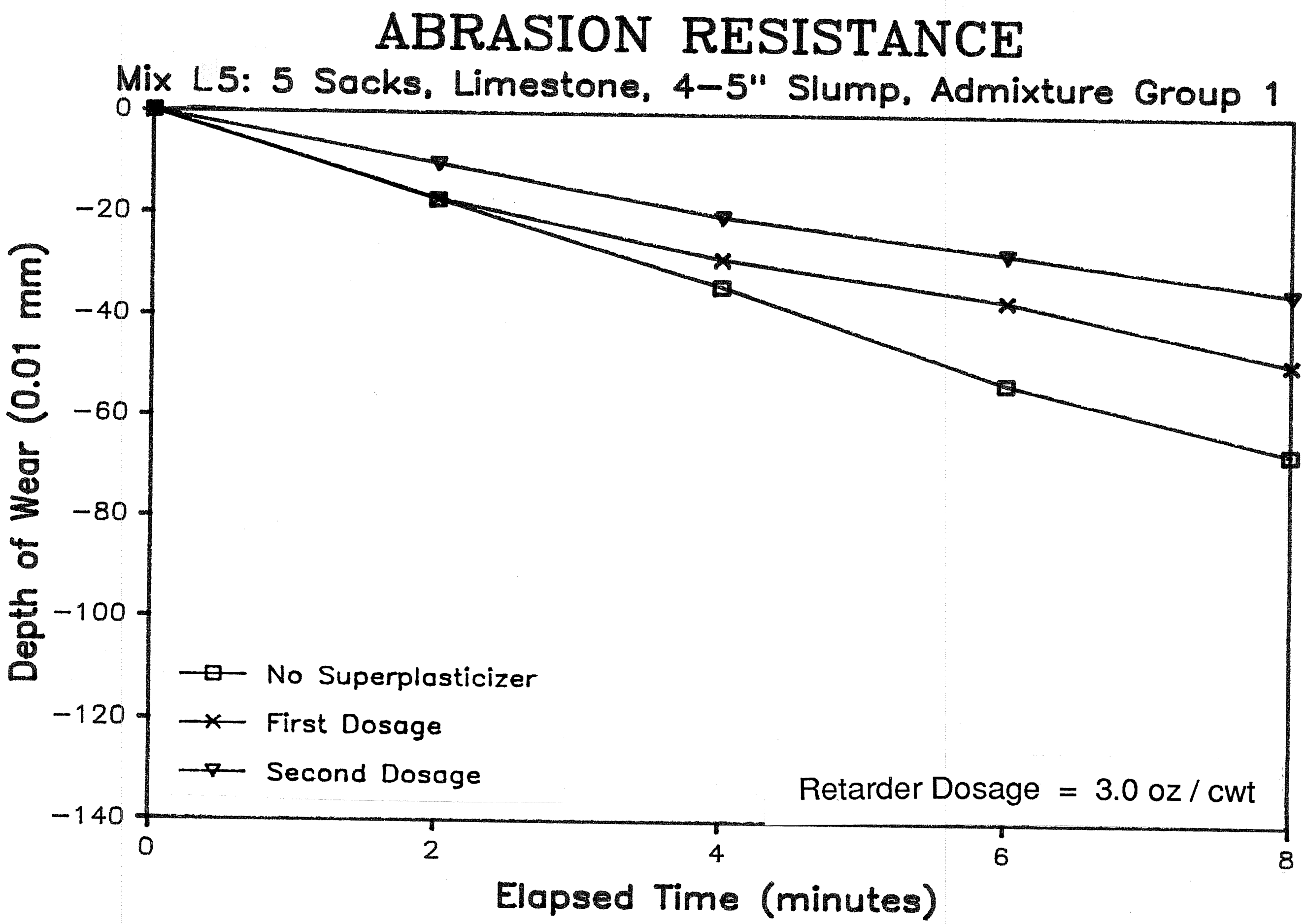


Fig. 4.68 Abrasion resistance data for laboratory mix of July 21, 1987. (Specimen Age - 8 Days)

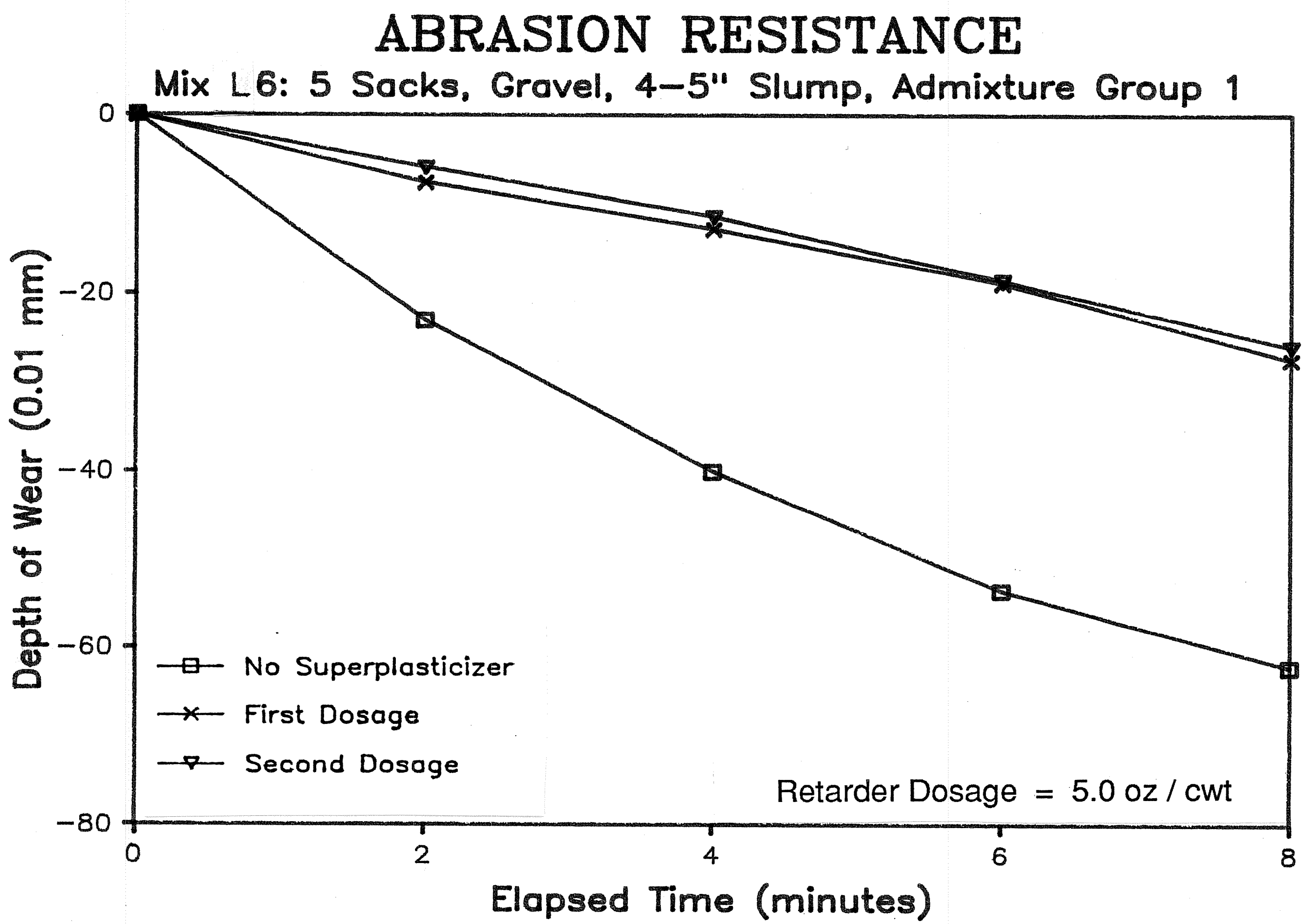


Fig. 4.69 Abrasion resistance data for laboratory mix of July 23, 1987. (Specimen Age - 8 Days)

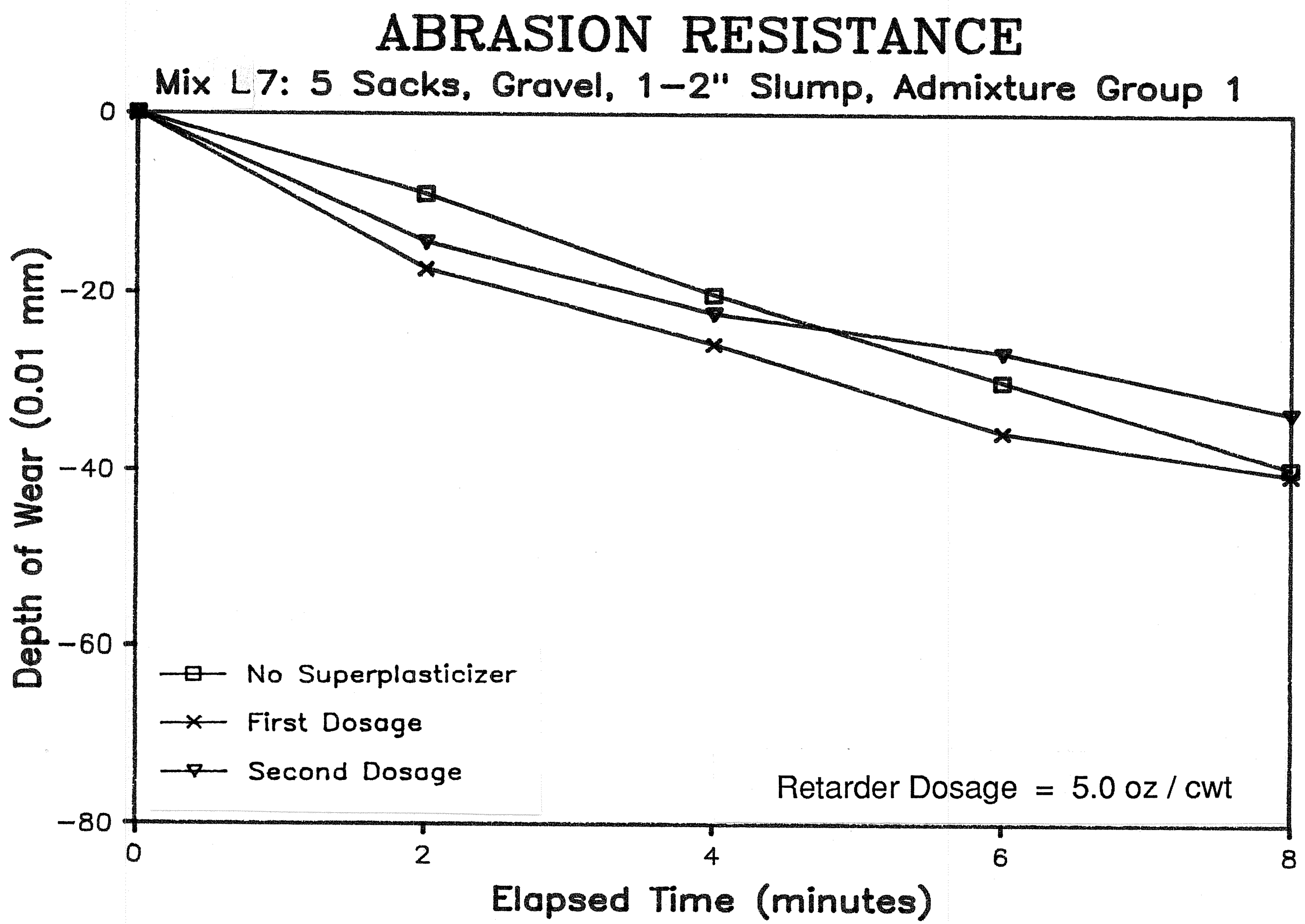


Fig. 4.70 Abrasion resistance data for laboratory mix of August 25, 1987. (Specimen Age - 8 Days)

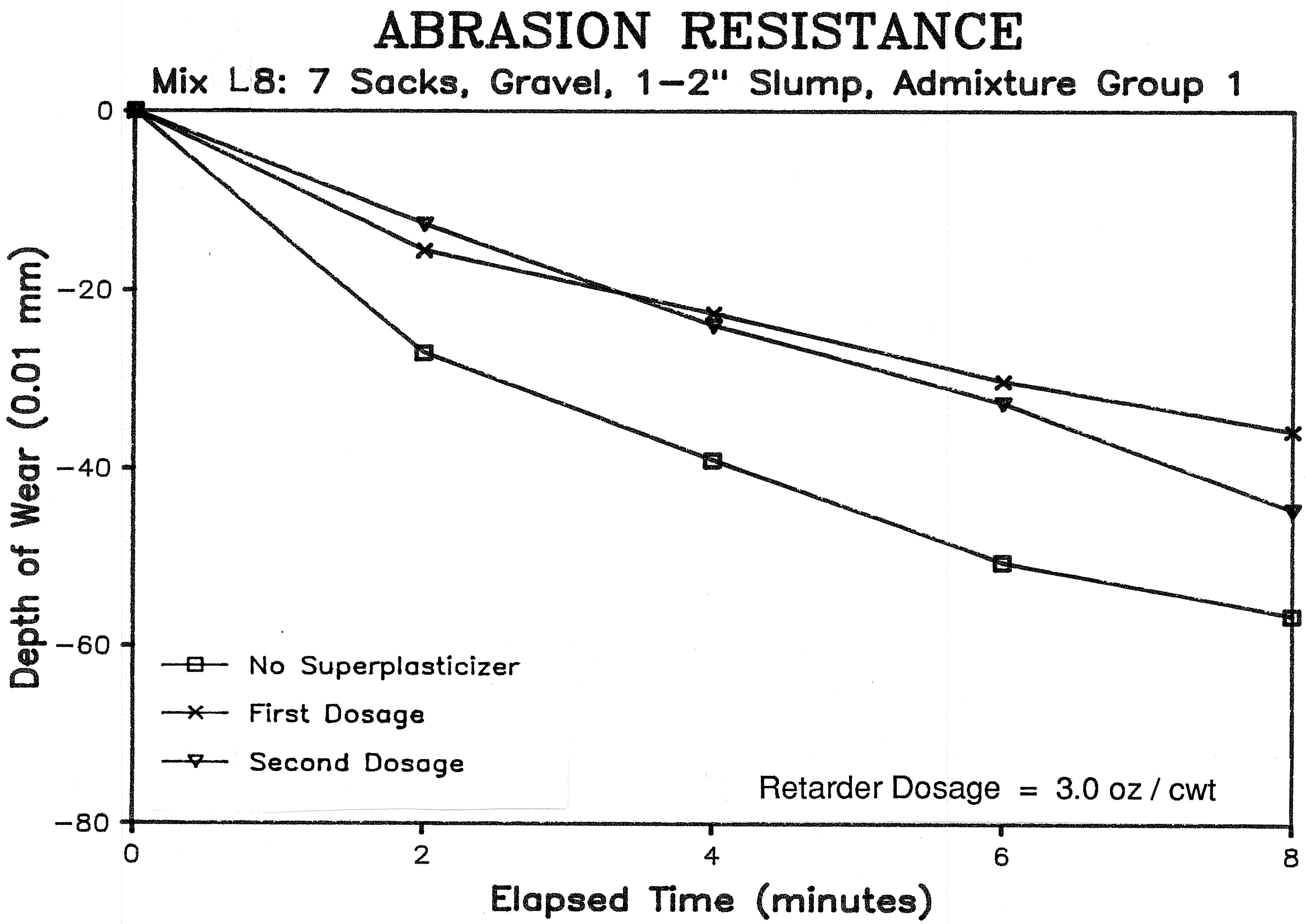


Fig. 4.71 Abrasion resistance data for laboratory mix of September 3, 1987. (Specimen Age - 8 Days)

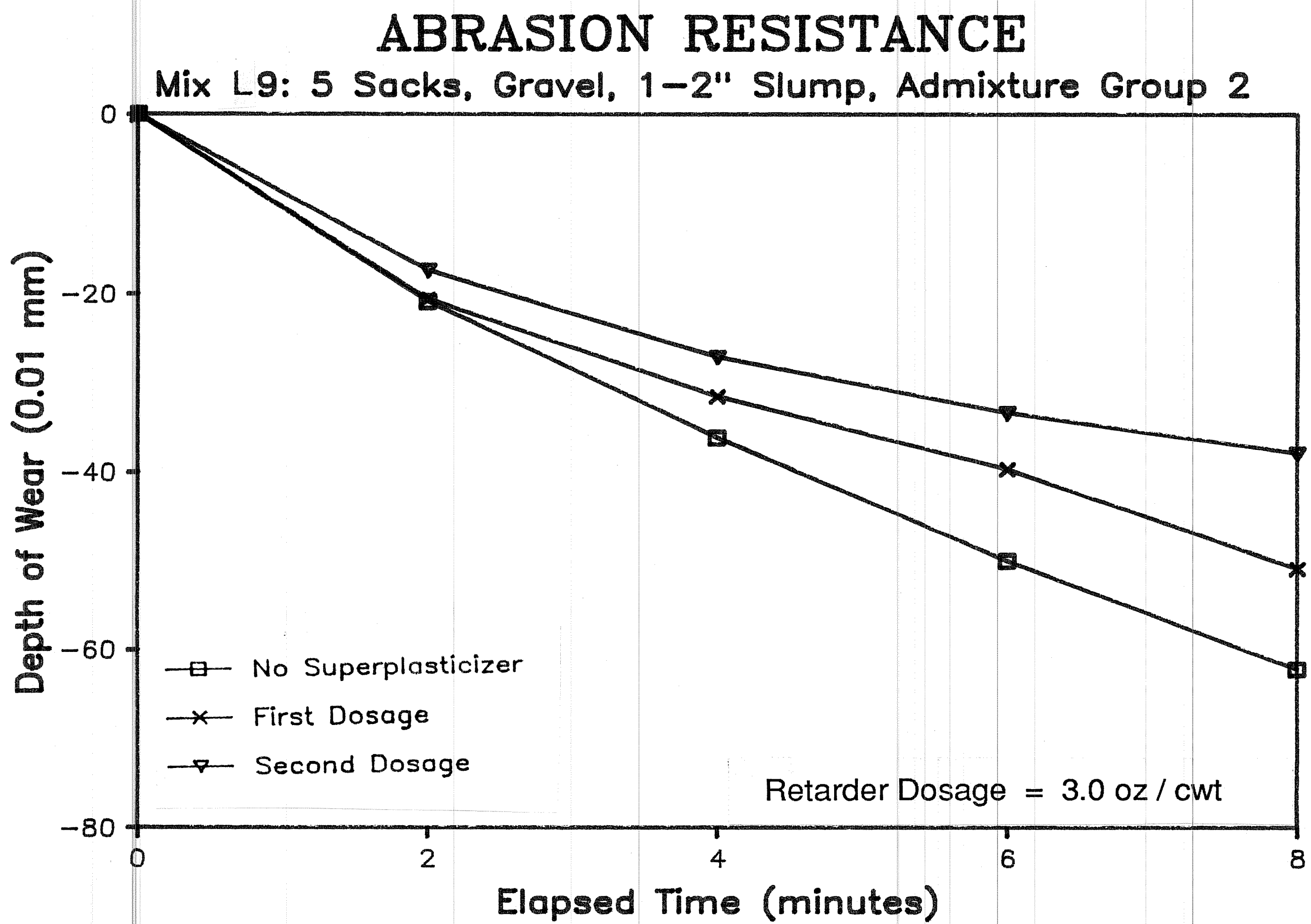


Fig. 4.72 Abrasion resistance data for laboratory mix of September 10, 1987. (Specimen Age - 8 Days)

Table 4.1 Statistical data for compressive strength tests from laboratory mixes

Mix #	Specimen Type	Age: 7 days			Age: 28 days		
		Average Value[1] (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	Average Value[1] (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
L1	Control	3850	148	3.9	4415	251	5.7
	1st Dosage	4725	178	3.8	5365	259	4.8
	2nd Dosage	5335	23	0.4	6155	154	2.5
L2	Control	4140	45	1.1	4960	94	1.9
	1st Dosage	5495	123	2.2	5995	44	0.7
	2nd Dosage	5415	103	1.9	6215	165	2.7
L3	Control	4485	22	0.5	5265	87	1.7
	1st Dosage	4810	97	2.0	5670	62	1.1
	2nd Dosage	5170	44	0.9	6265	112	1.8
L4	Control	3925	15	0.4	4845	26	0.5
	1st Dosage	4555	35	0.8	5545	65	1.2
	2nd Dosage	4725	146	3.1	6120	138	2.3
L5	Control	4505	24	0.5	5435	67	1.2
	1st Dosage	5210	90	1.7	6415	157	2.4
	2nd Dosage	5785	10	0.2	7045	77	1.1
L6	Control	4470	74	1.7	5405	75	1.4
	1st Dosage	5140	134	2.6	5990	71	1.2
	2nd Dosage	5615	27	0.5	6615	143	2.2
L7	Control	5390	44	0.8	6715	148	2.2
	1st Dosage	6110	118	1.9	7520	95	1.3
	2nd Dosage	6755	82	1.2	8485	100	1.2
L8	Control	6575	539	8.2	7800	270	3.5
	1st Dosage	7985	163	2.0	9110	140	1.5
	2nd Dosage	8360	109	1.3	9575	330	3.4
L9	Control	3975	245	6.2	4825	75	1.5
	1st Dosage	4880	30	0.6	5770	127	2.2
	2nd Dosage	5395	150	2.8	6250	262	4.2

(1) Refers to the average of three specimens

Table 4.2 Statistical data for flexural strength tests from laboratory mixes

Mix #	Specimen Type	Age: 7 days Average Value(1) (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	Age: 28 days Average Value(1) (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
L1	Control	591	11	1.9	671	32	4.7
	1st Dosage	617	14	2.3	717	23	3.3
	2nd Dosage	649	33	5.1	709	20	2.8
L2	Control	644	16	2.5	701	7	1.0
	1st Dosage	670	19	2.8	727	30	4.2
	2nd Dosage	673	23	3.5	735	12	1.7
L3	Control	644	15	2.3	718	29	4.1
	1st Dosage	709	23	3.3	777	12	1.5
	2nd Dosage	688	37	5.4	829	38	4.6
L4	Control	630	25	3.9	705	17	2.4
	1st Dosage	670	46	6.9	776	19	2.4
	2nd Dosage	707	16	2.2	830	11	1.4
L5	Control	674	2	0.3	734	27	3.7
	1st Dosage	738	34	4.7	792	14	1.8
	2nd Dosage	739	37	5.1	817	32	3.9
L6	Control	656	36	5.5	703	28	4.0
	1st Dosage	656	37	5.7	701	20	2.8
	2nd Dosage	691	40	5.7	797	22	2.7
L7	Control	738	7	1.0	783	19	2.4
	1st Dosage	736	44	5.9	790	24	3.0
	2nd Dosage	792	37	4.6	830	27	3.2
L8	Control	844	484	5.7	972	46	4.8
	1st Dosage	892	49	5.5	936	64	6.9
	2nd Dosage	905	23	2.5	1022	51	5.0
L9	Control	601	19	3.2	655	8	1.3
	1st Dosage	671	23	3.4	692	20	2.9
	2nd Dosage	693	17	2.5	699	38	5.4

(1) Refers to the average of three companion specimens

Part II: Field Test Program

4.4 Fresh Concrete Tests

The following section describes the data recorded from all fresh concrete testing of each of the field mixes. These mixes were batched on September 21 and 25, 1987.

4.4.1 Workability. Figures 4.73 through 4.78 show the slump values for all related field mixes throughout the monitoring period. Mixes that were batched within minutes of each other and had similar test variables are shown grouped together. In addition, each figure includes the amount and time of addition of the initial and, if necessary, second dosages of superplasticizer used to produce flowing concrete.

4.4.2 Air Content. Figures 4.79 through 4.84 show the air content values for each group of related field mixes throughout the monitoring period. These tests were conducted when the readymix truck arrived at the site, immediately after the addition of superplasticizer, and at 120 minutes after batching. In addition, each figure includes the amount and time of addition of the initial and, if necessary, second dosages of superplasticizer used to reach flowing concrete.

4.4.3 Temperature. Figures 4.85 through 4.90 present the concrete temperature (°F) readings for each group of related field mixes throughout the monitoring period. In addition, each figure includes the amount and time of addition of the initial and, if necessary, second dosages of superplasticizer used to produce flowing concrete.

4.5 Hardened Concrete Tests

This section details the data recorded from the compressive strength testing of all concrete cylinders cast from each of the field mixes. Table 4.3 lists the average values, standard deviations, and coefficients of variation for all 28 day compressive strength test results.

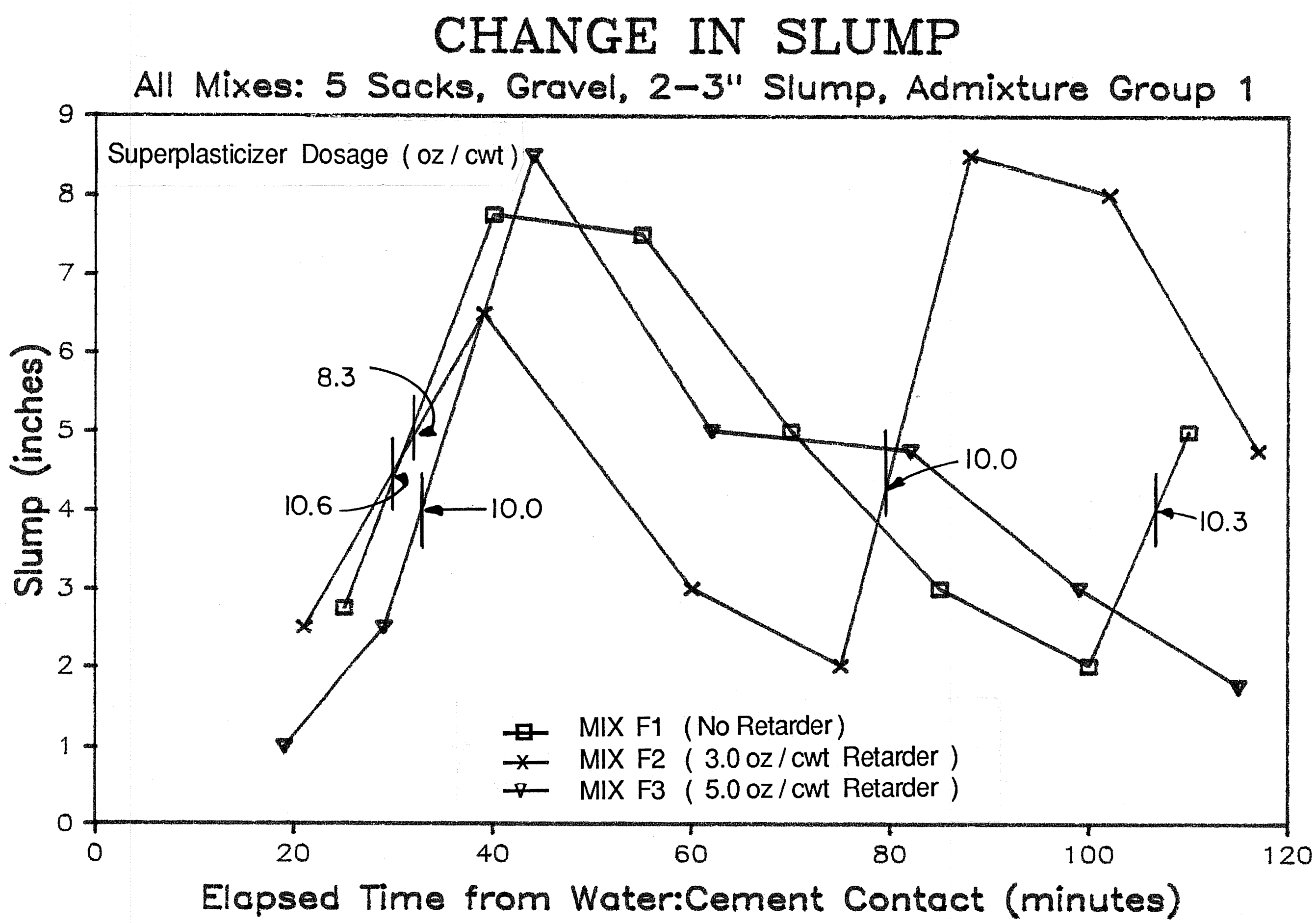


Fig. 4.73 Slump data for field mixes batched at 9:30 a.m. on September 21, 1987

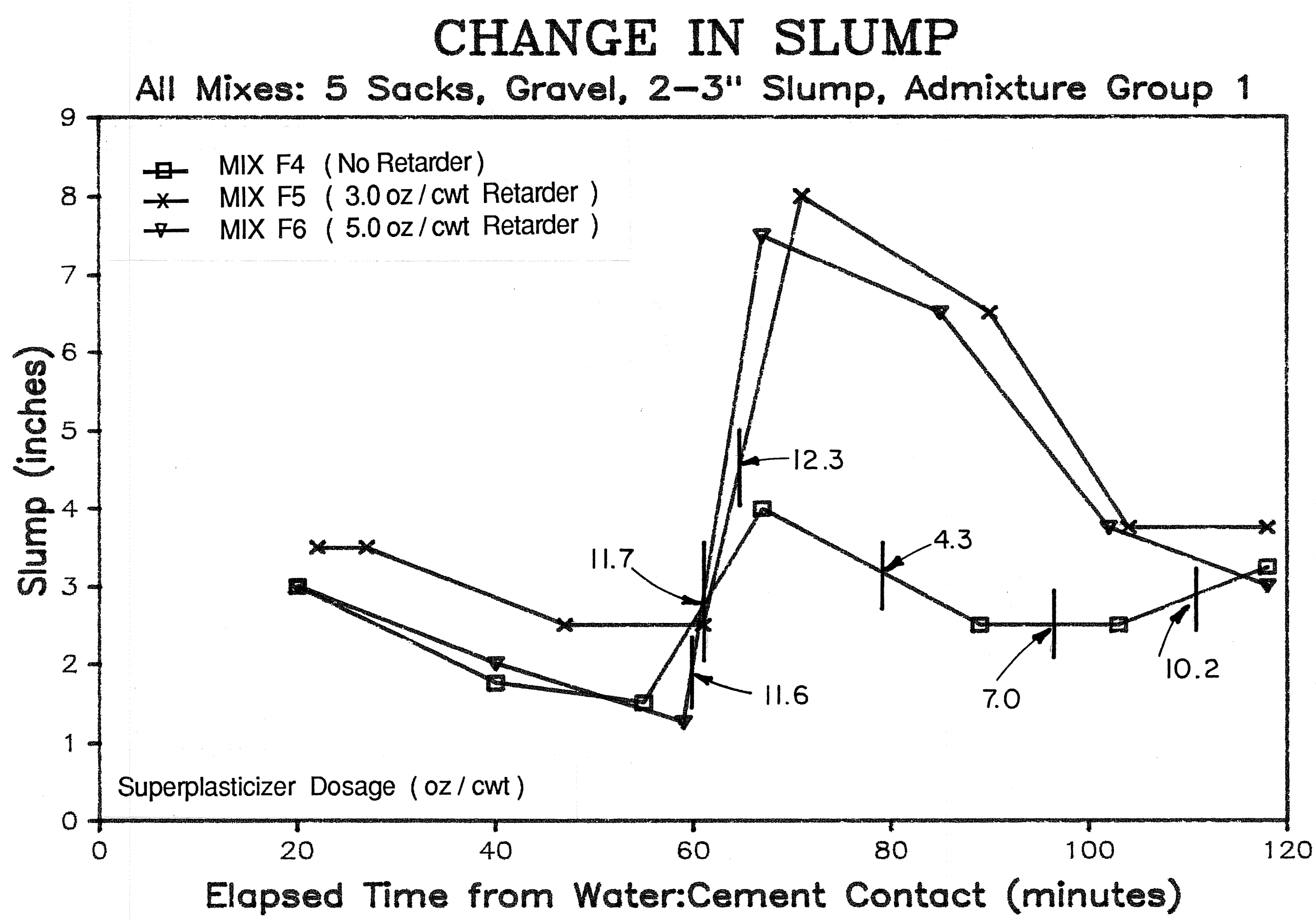


Fig. 4.74 Slump data for field mixes batched at 12:00 noon on September 21, 1987

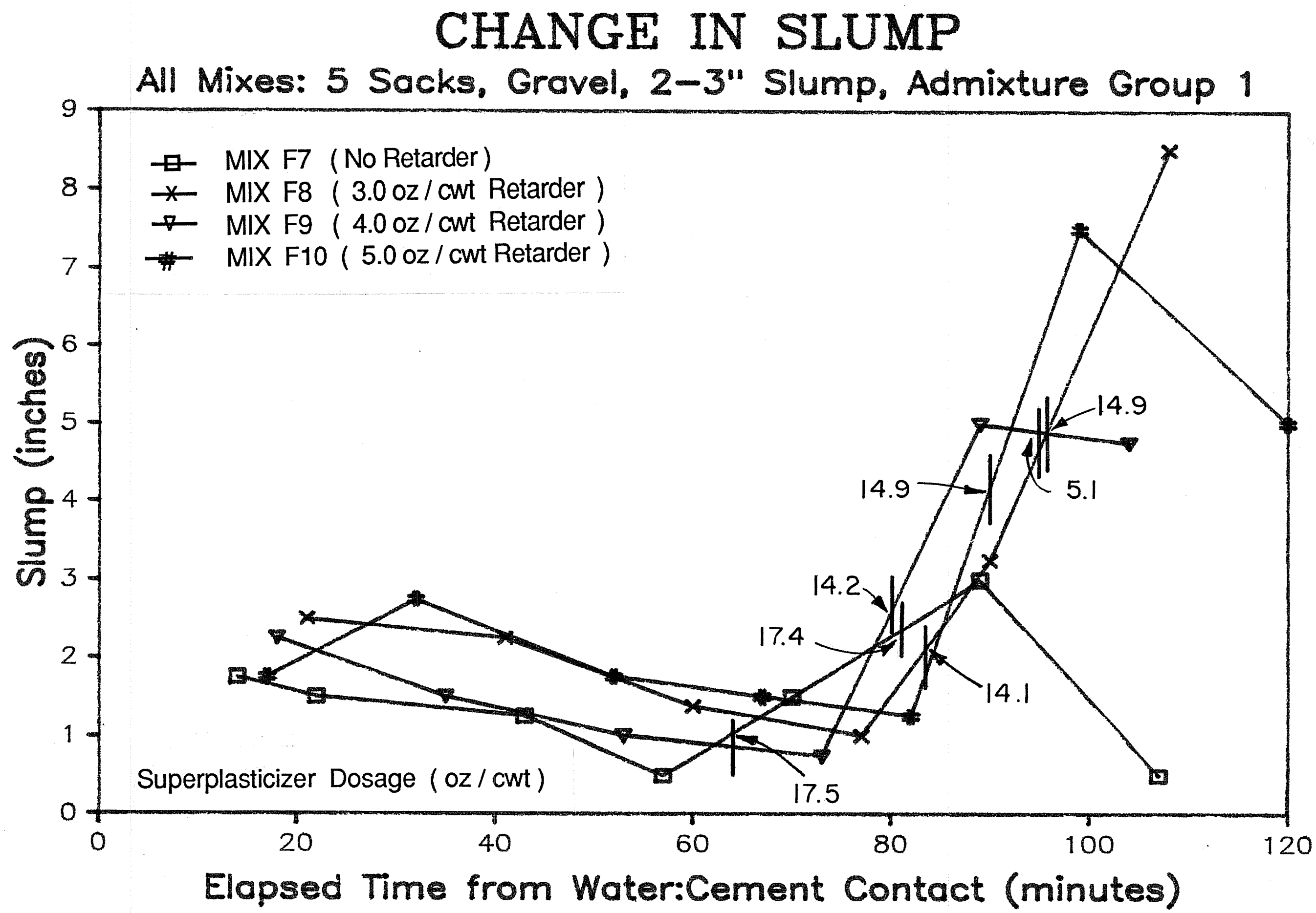


Fig. 4.75 Slump data for field mixes batched at 2:30 p.m. on September 21, 1987

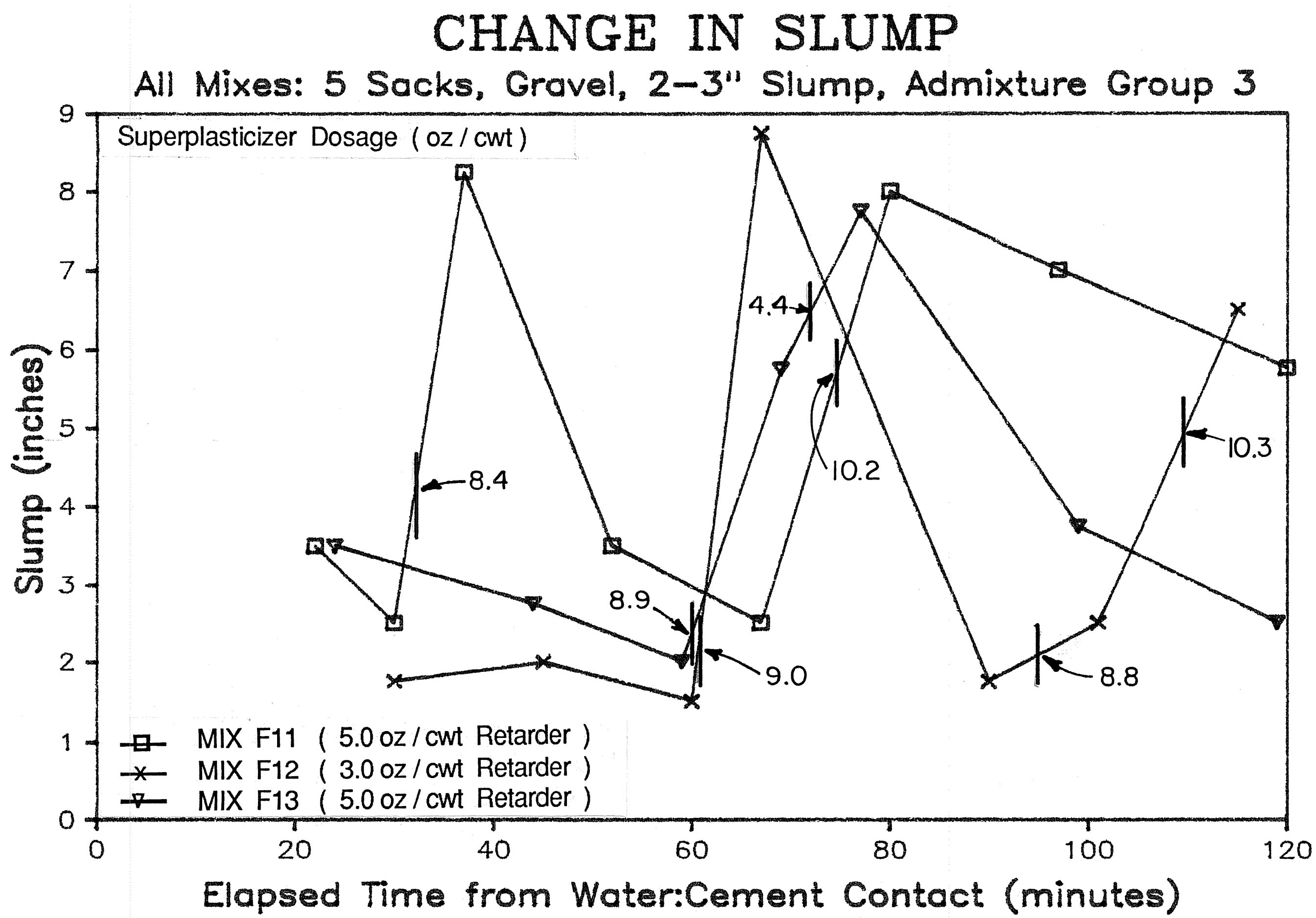


Fig. 4.76 Slump data for field mixes batched at 9:00 a.m. on September 25, 1987

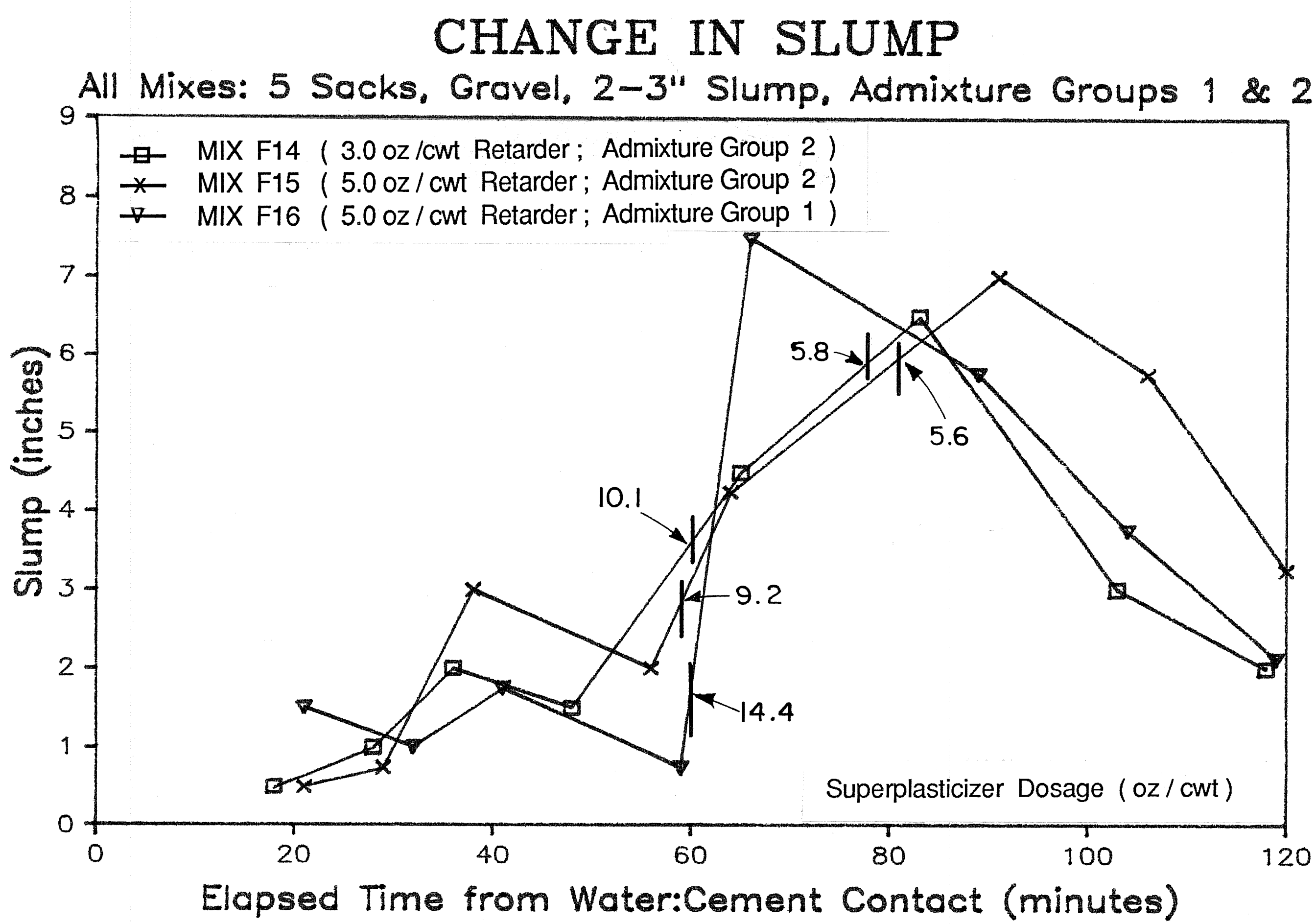


Fig. 4.77 Slump data for field mixes batched at 1:00 p.m. on September 25, 1987

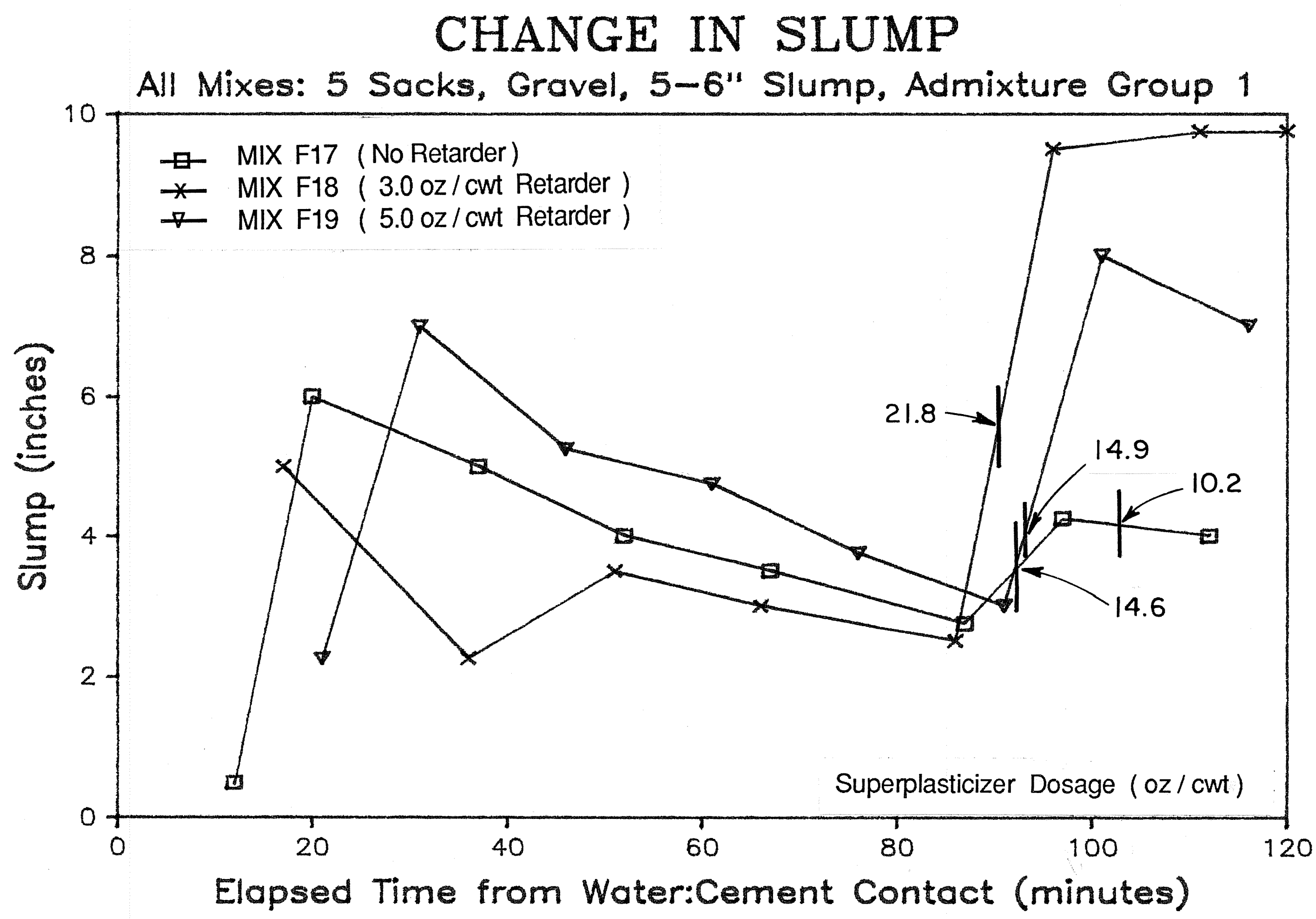


Fig. 4.78 Slump data for field mixes batched at 3:00 p.m. on September 25, 1987

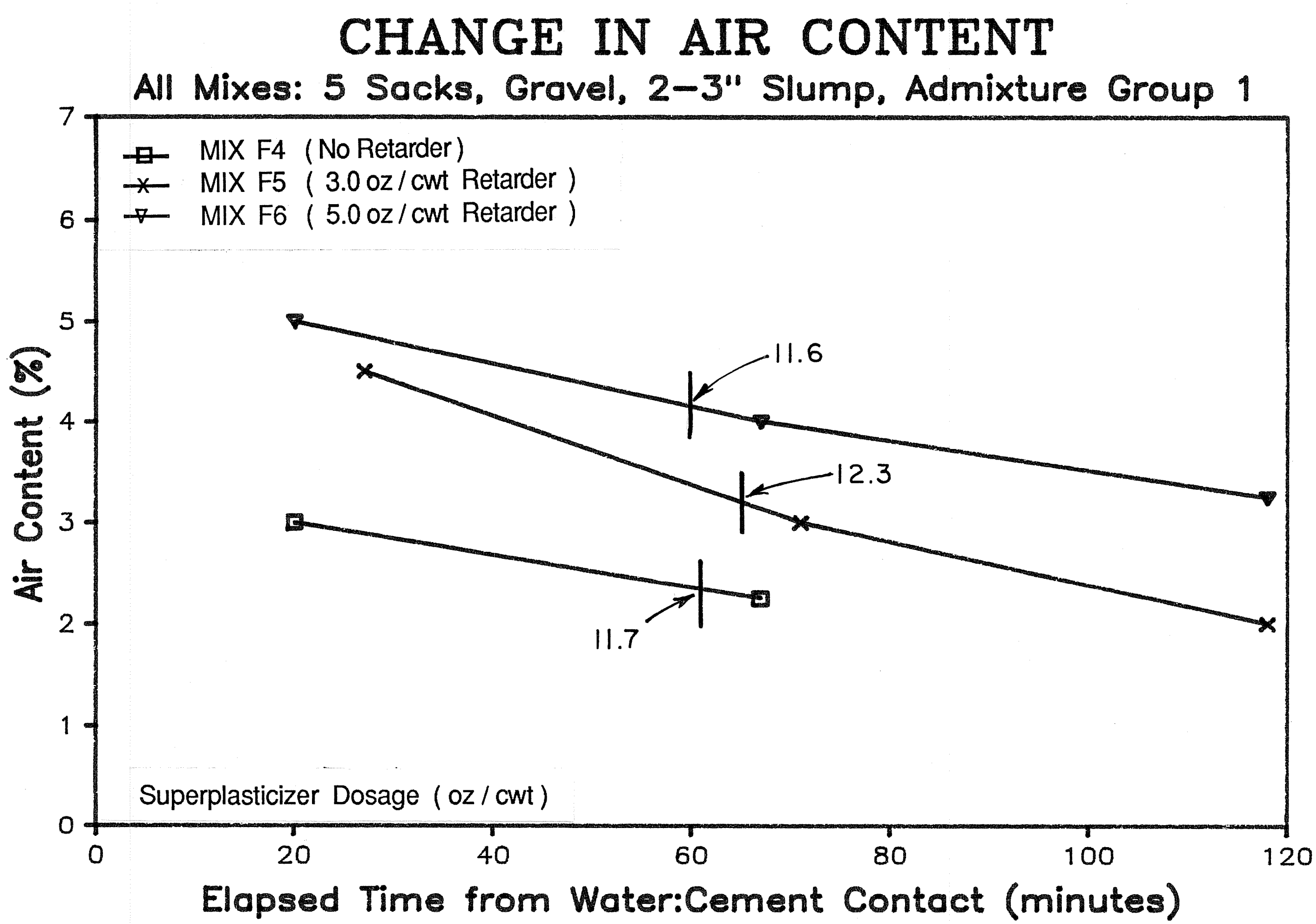


Fig. 4.79 Air content data for field mixes batched at 9:30 a.m. on September 21, 1987

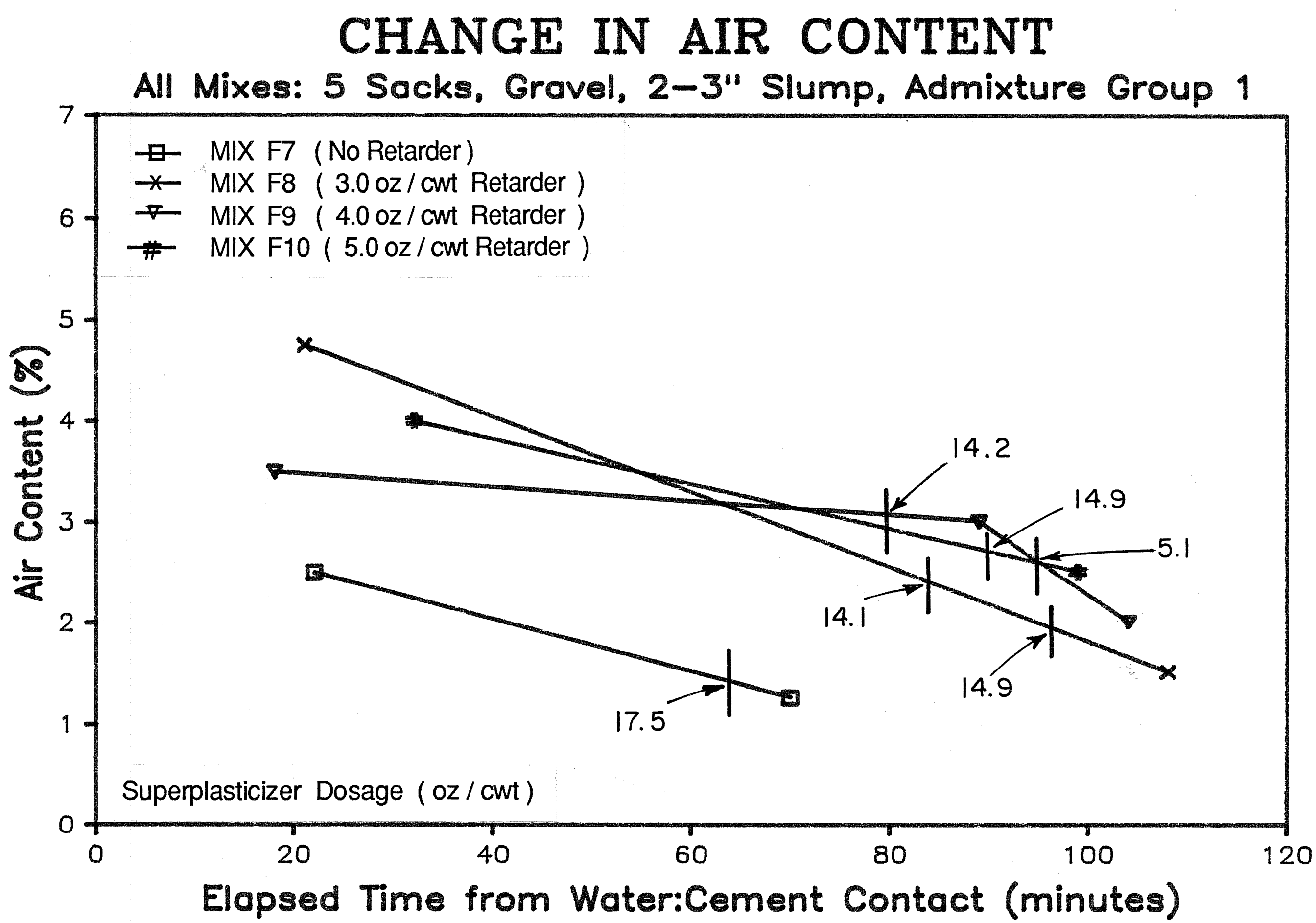


Fig. 4.80 Air content data for field mixes batched at 12:00 noon on September 21, 1987

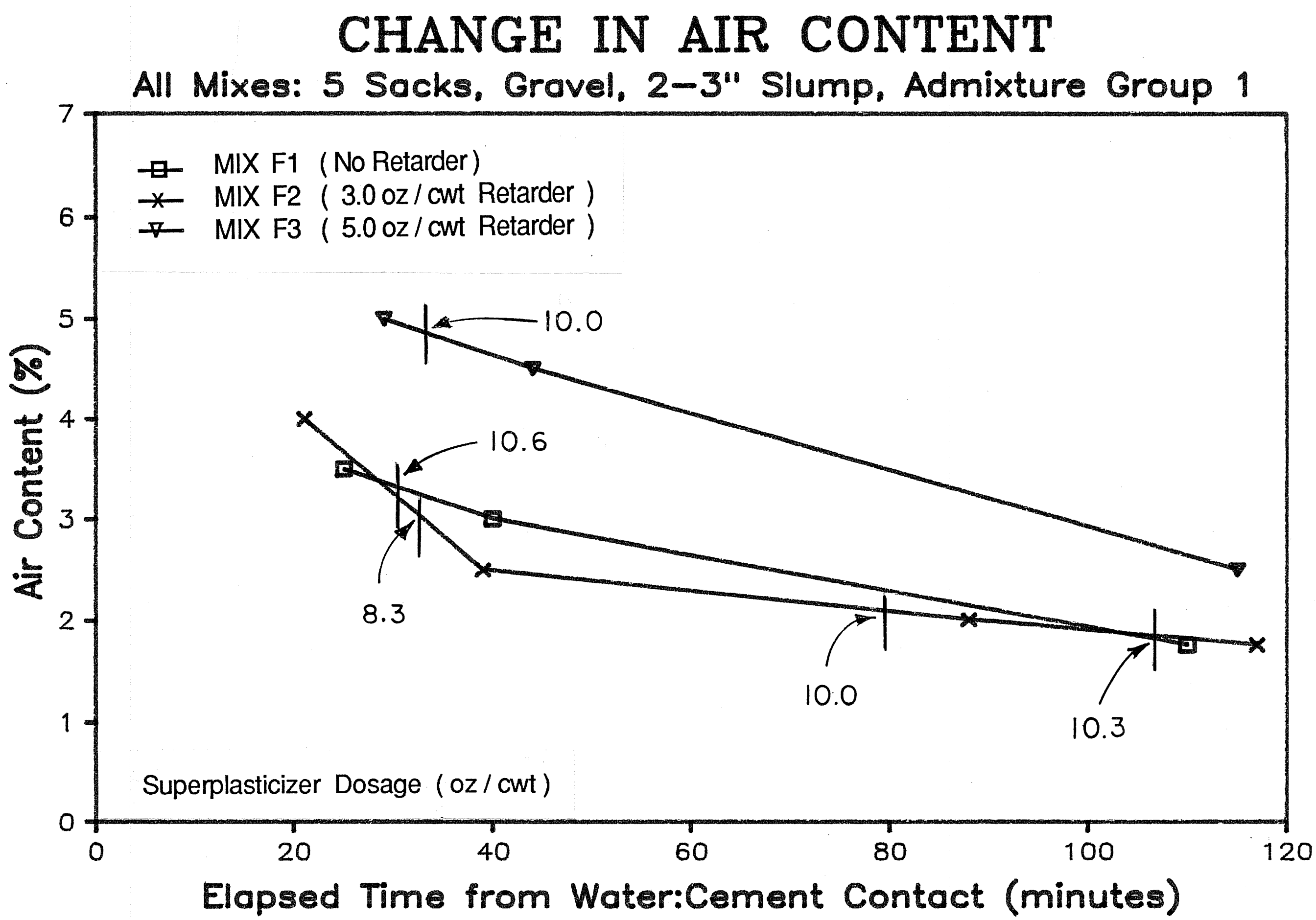


Fig. 4.81 Air content data for field mixes batched at 2:30 p.m. on September 21, 1987

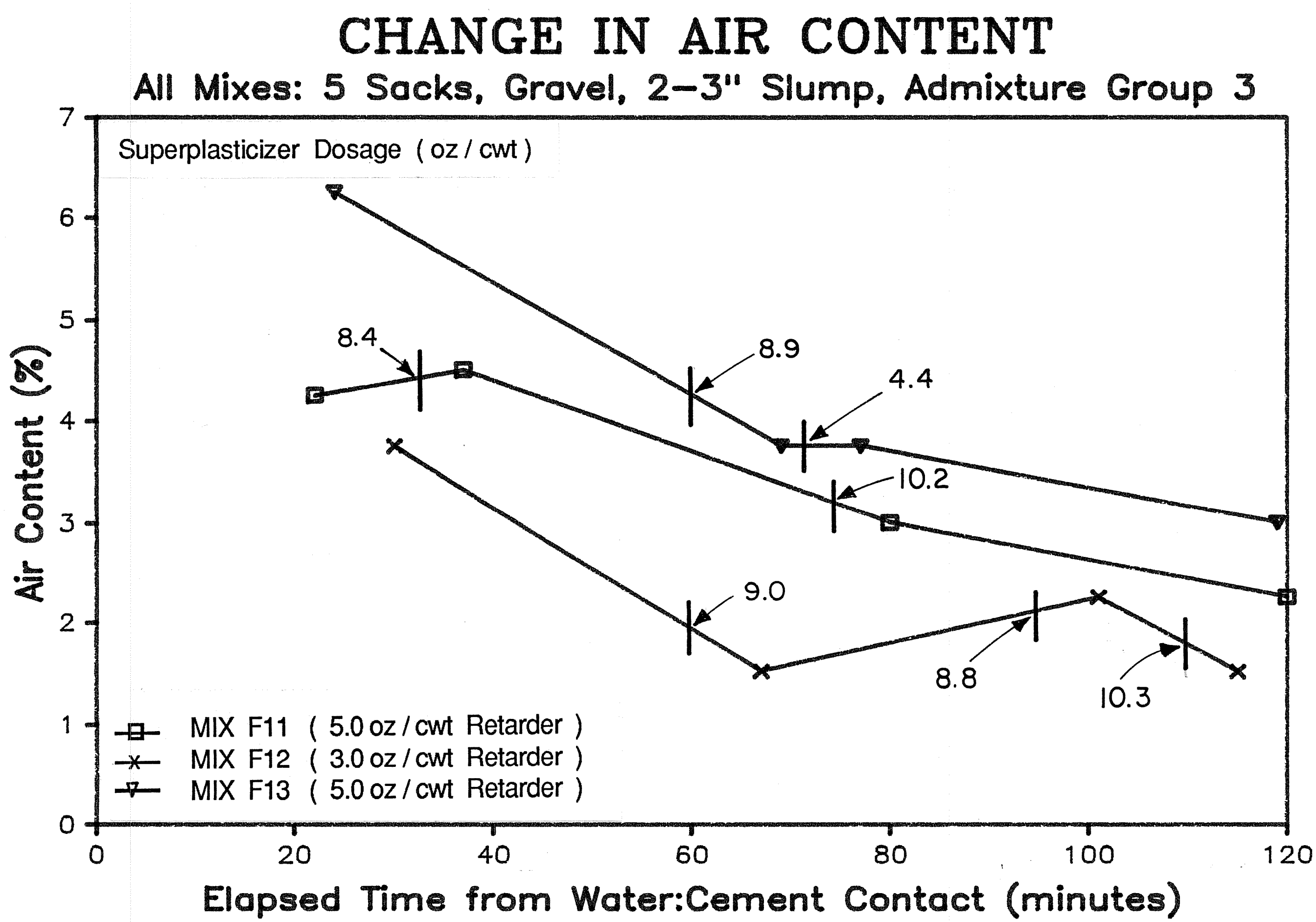


Fig. 4.82 Air content data for field mixes batched at 9:00 a.m. on September 25, 1987

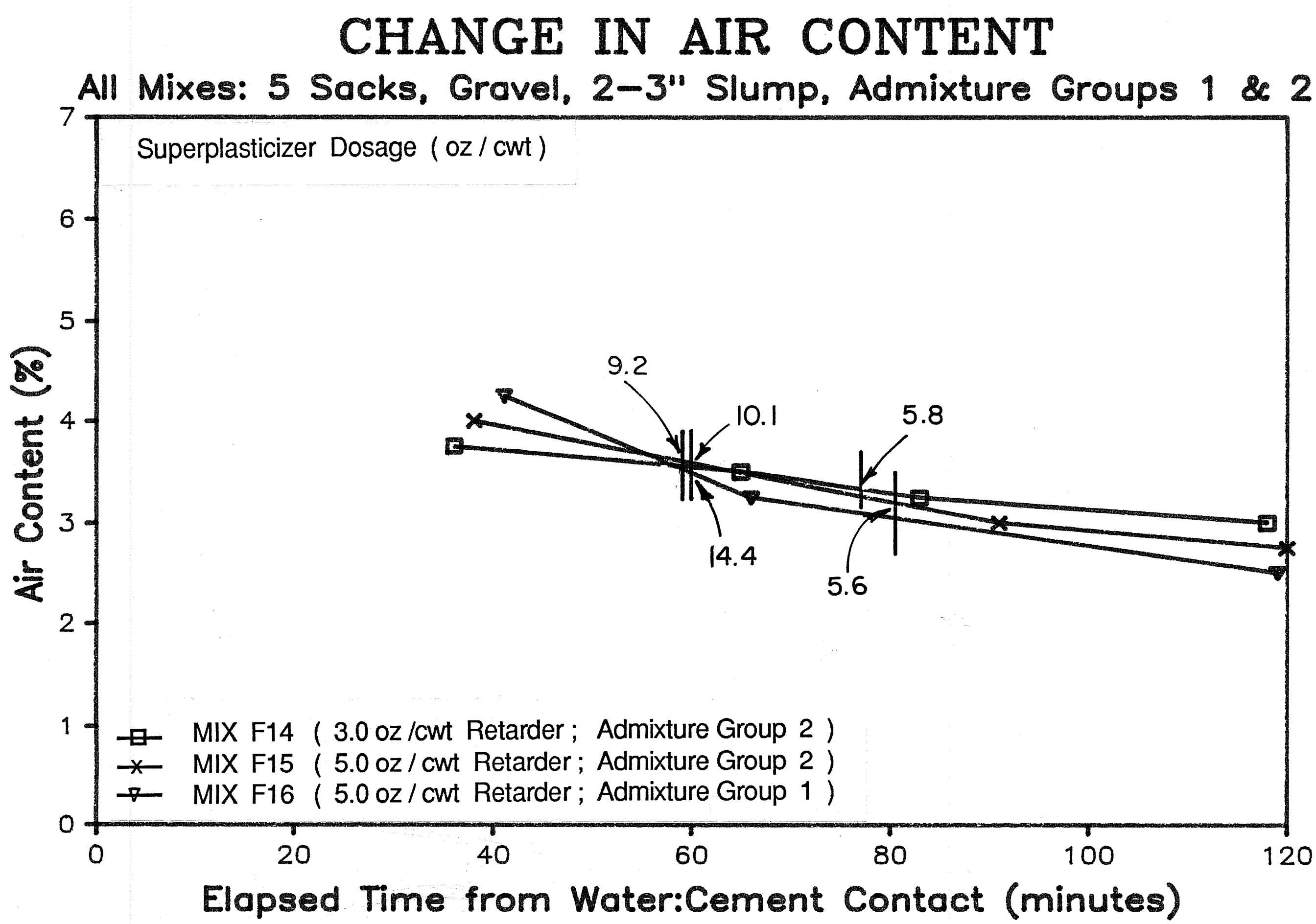


Fig. 4.83 Air content data for field mixes batched at 1:00 p.m. on September 25, 1987

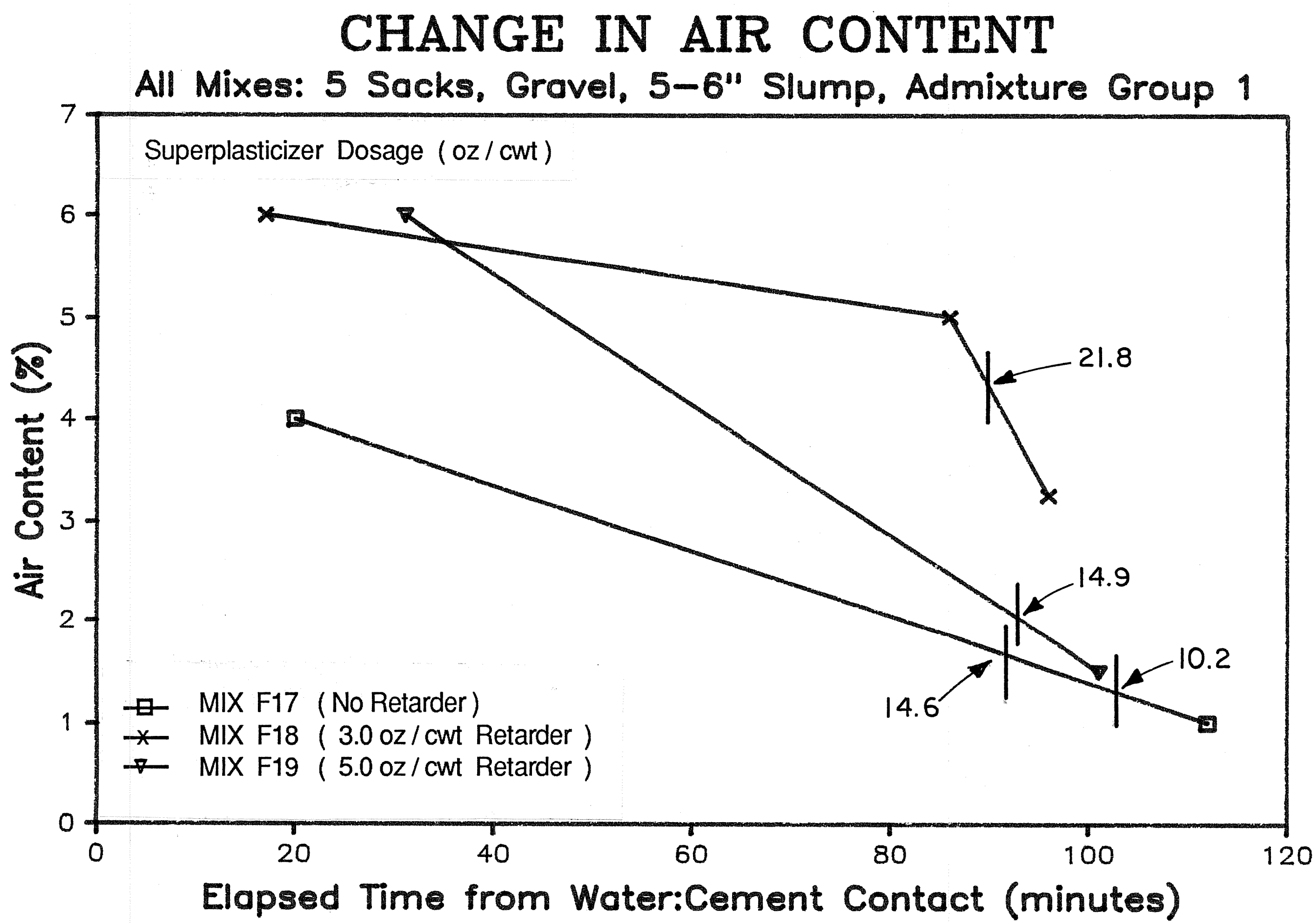


Fig. 4.84 Air content data for field mixes batched at 3:00 p.m. on September 25, 1987

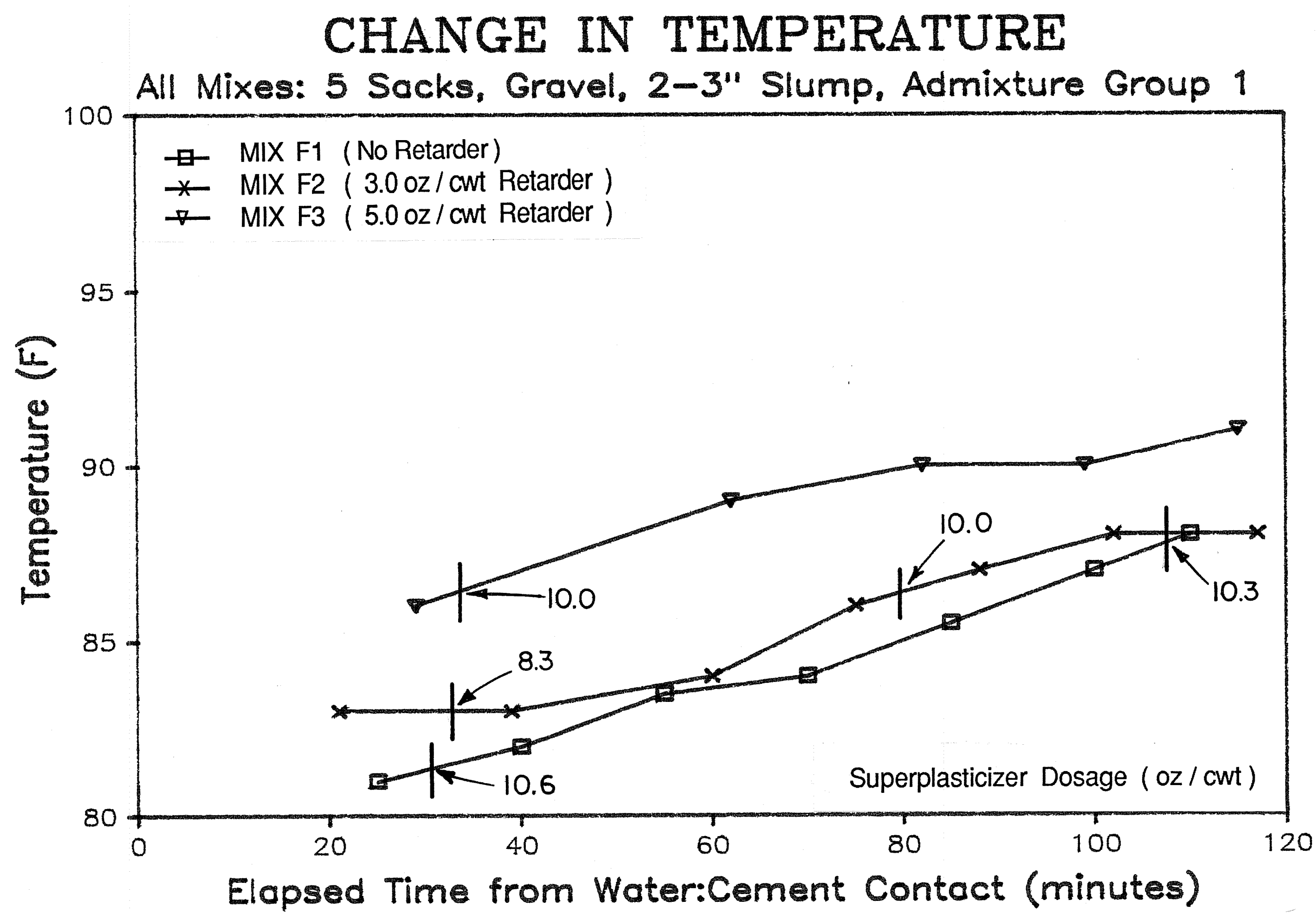


Fig. 4.85 Concrete temperature data for field mixes batched at 9:30 a.m. on September 21, 1987

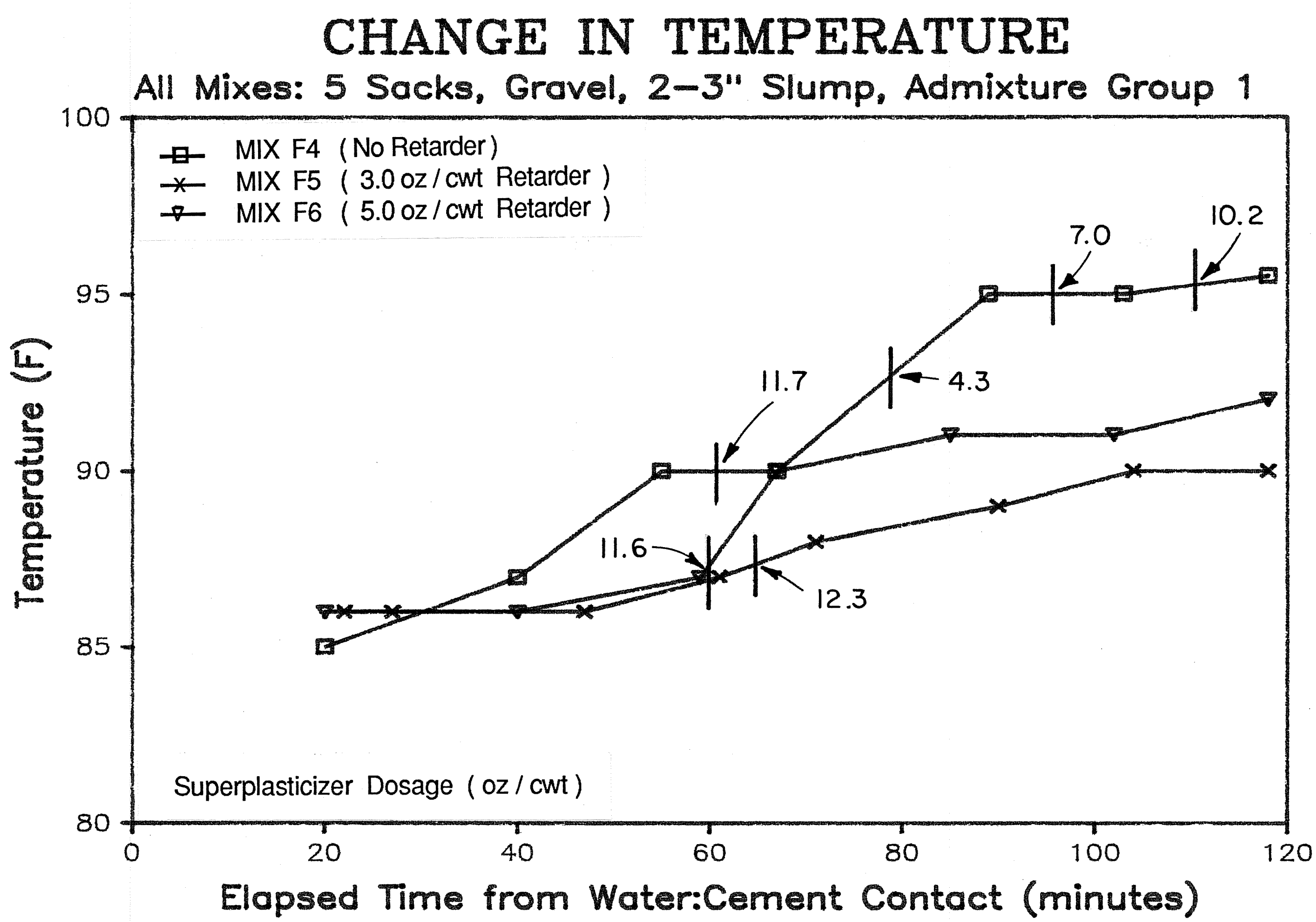


Fig. 4.86 Concrete temperature data for field mixes batched at 12:00 noon on September 21, 1987

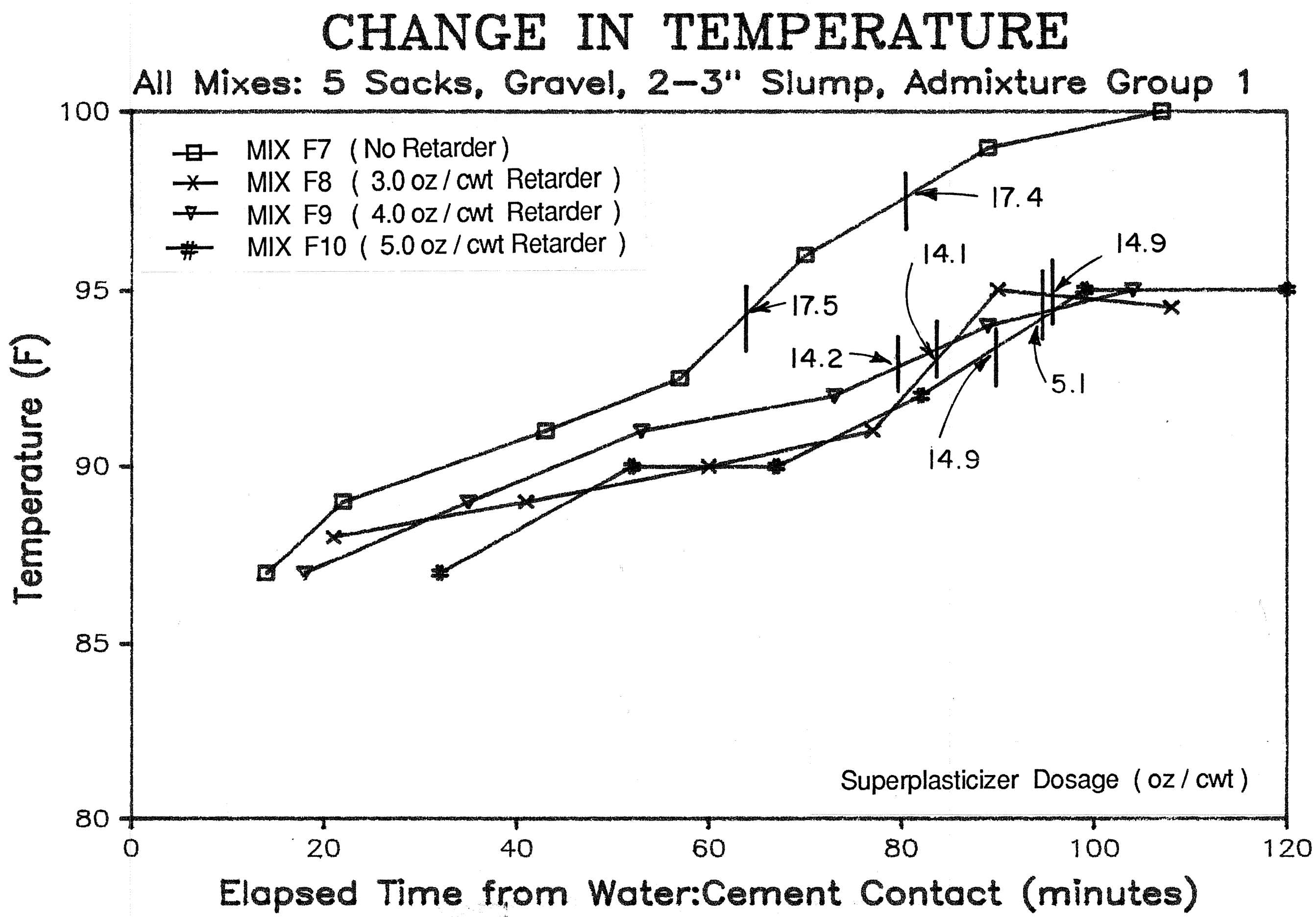


Fig. 4.87 Concrete temperature data for field mixes batched at 2:30 p.m. on September 21, 1987

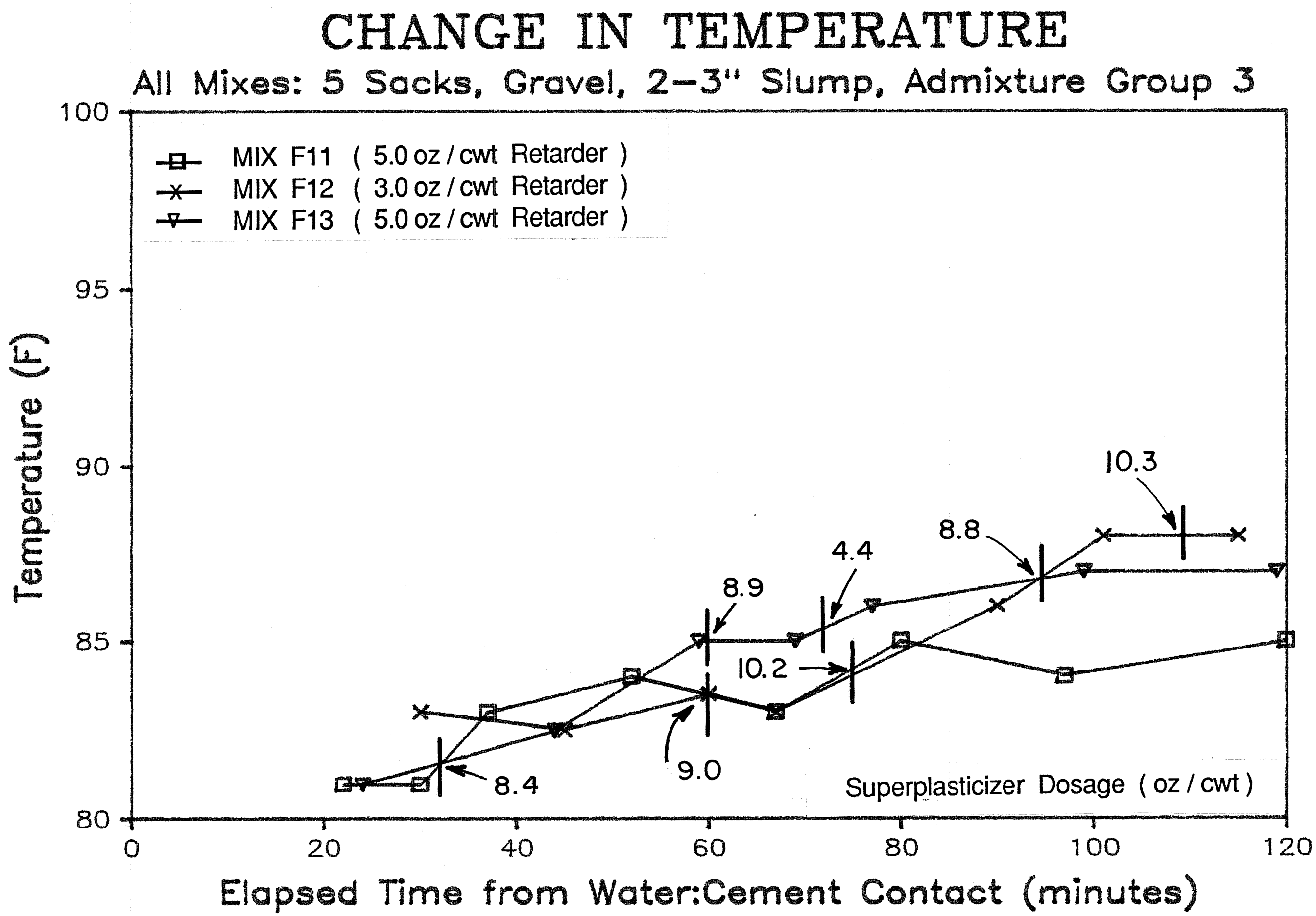


Fig. 4.88 Concrete temperature data for field mixes batched at 9:00 a.m. on September 25, 1987

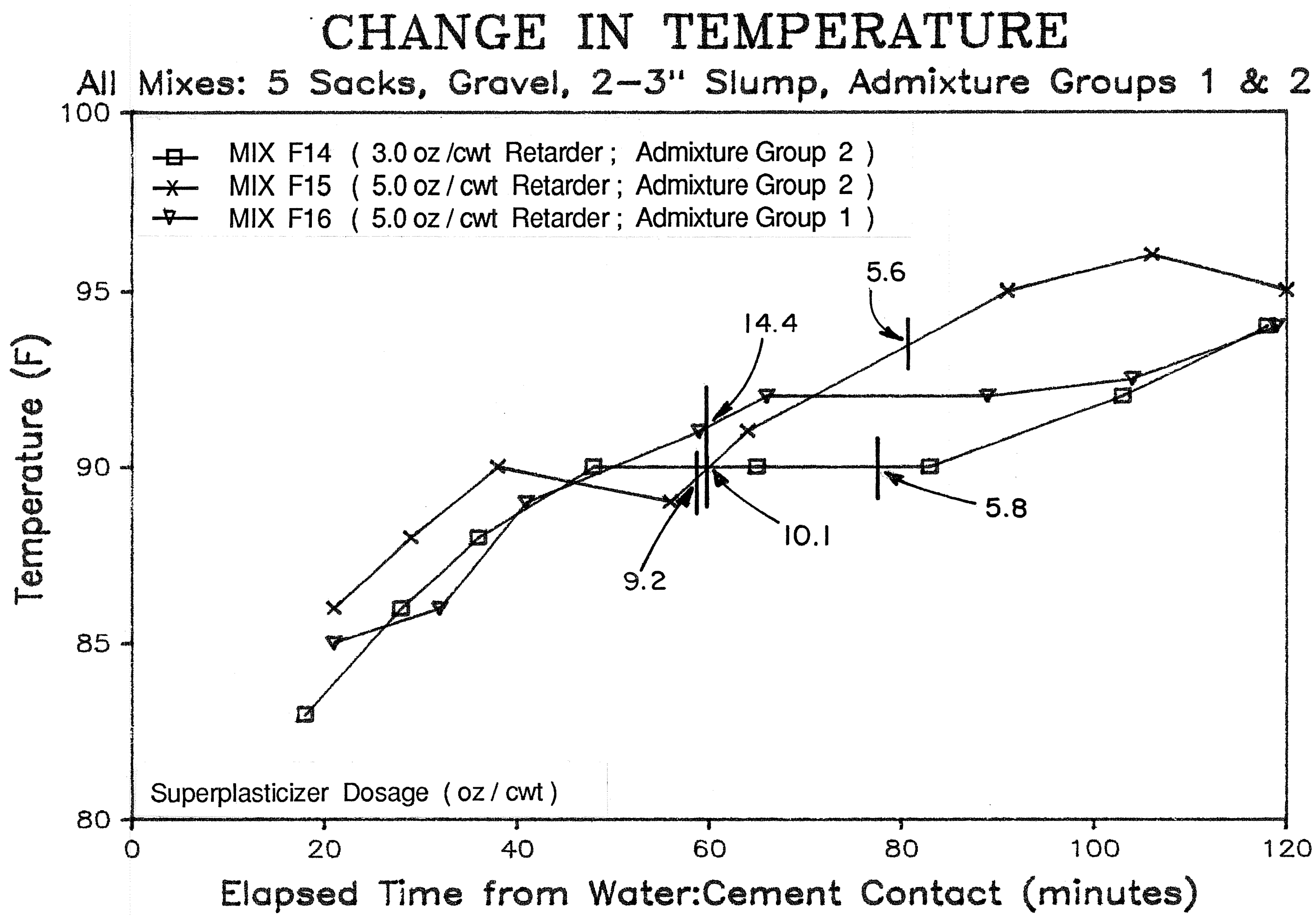


Fig. 4.89 Concrete temperature data for field mixes batched at 1:00 p.m. on September 25, 1987

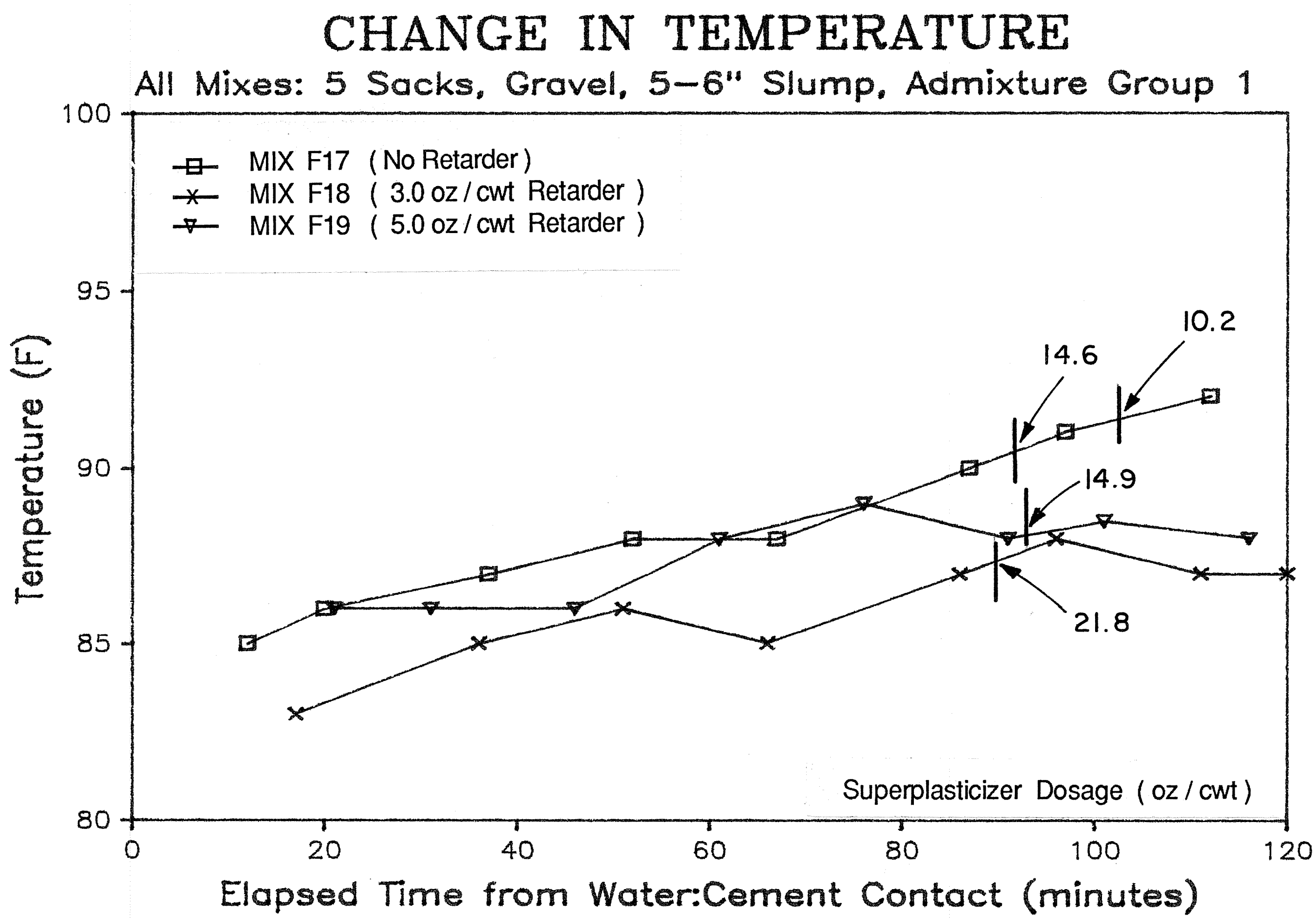


Fig. 4.90 Concrete temperature data for field mixes batched at 3:00 p.m. on September 25, 1987

Table 4.3 Statistical data for compressive strength tests from field mixes

Mix #	Age: 28 days			
	Specimen Designation[1]	Average Value[2]	Standard Deviation	Coefficient of Variation
F1	A	4385	111	2.5
	B	5120	86	1.7
F2	A	5245	61	1.2
	B	6010	140	2.3
F3	A	5320	218	4.1
	B	6580	163	2.5
F4	A	4245	23	0.5
	B	4505	150	3.3
F5	A	4490	75	1.7
	B	5230	27	0.5
F6	A	5160	149	2.9
	B	6520	75	1.1
F7	A	4425	170	3.8
	B	5690	91	1.6
F8	A	4970	137	2.8
	B	6385	129	2.0
F9	A	5365	47	0.9
	B	7475	102	1.4
F10	A	5730	179	3.1
	B	6965	86	1.2
F11	A	4205	207	4.9
	B	5530	97	1.8
F12	A	4260	55	1.3
	B	5045	62	1.2
F13	A	4060	76	1.9
	B	4800	68	1.4
F14	A	4445	154	3.5
	B	4950	63	1.3
F15	A	4250	71	1.7
	B	5565	107	1.9
F16	A	4610	134	2.9
	B	5730	145	3.5
F17	A	3770	53	1.4
	B	4685	115	2.4
F18	A	4480	57	1.3
	B	6445	189	2.9
F19	A	4675	126	2.7
	B	6045	104	1.7

1 Designation "A" refers to those specimens cast immediately, whereas designation "B" refers to those specimens cast 120 minutes after batching

2 Refers to the average of three companion specimens

CHAPTER 5
DISCUSSION OF EXPERIMENTAL RESULTS

5.1 Introduction

The experimental results presented in Chapter 4 are discussed in this chapter. The effects of the addition of a superplasticizer to readymix concrete will be discussed by analyzing and presenting dominant trends in the data collected from tests of fresh and hardened concrete.

5.2 Effects of Superplasticizers on Fresh Concrete

The following section is an analysis of the data recorded from all fresh concrete testing of each of the nine laboratory mixes and nineteen field mixes. The discussion specifically includes the effects of initial and second dosages of two superplasticizers on the workability, air content, temperature, segregation and bleeding tendencies, finishing characteristics, unit weight, and setting times of fresh concrete. In addition, the consequences of using different retarder dosages, air entraining agents, mixing water contents, cement contents, coarse aggregate types, and times of addition in conjunction with the superplasticizer are discussed.

5.2.1 Workability. Chiocchio and Paolini[9] have stated that the effectiveness of a superplasticizer varies with the admixture type and concentration, material types and proportions, temperature of the concrete, method of mixing, and time of addition. The effectiveness of a superplasticizer is better described by a discussion of the rate of slump gain and slump loss of the concrete after the first and second dosages of the superplasticizer with particular reference to the variables in this investigation. Discussions of slump loss characteristics for the second dosage of superplasticizer are limited because of concerns of the readymix company for possible damage to their equipment and Texas SDHPT specifications which place limitations on the placement of concrete when the air or concrete temperature exceeds 90°F. Concrete without a retarder may not be placed in the forms beyond 45 minutes after water-cement contact in hot weather. Similarly, concrete with a retarder may not be placed in the forms beyond 75 minutes after water-cement contact. [56]

5.2.1.1 Slump Gain Versus Initial Dosage. Figures 5.1 through 5.6 show a comparison of the increase in slump per ounce of superplasticizer per 100 pounds of cement required to produce flowing concrete for the laboratory and field mixes. In addition, each graph includes fresh concrete data detailing relevant parameters to aid in the discussion and analysis of results.

Figures 5.1 and 5.2 show that the rate of slump gain versus the initial dosage of superplasticizer is dependent on the retarder dosage. In five of the six groups of related mixes in which retarder dosage was incrementally increased, the superplasticizer became more effective in increasing the slump for mixes with larger retarder dosage. No data are shown for Mixes F4, F7, and F17 in Fig. 5.2 because repeated efforts to reach flowing concrete were unsuccessful even after substantial amounts of superplasticizer were added.

The observed trend of not reaching flowing concrete after addition of substantial amounts of superplasticizer for Mixes F4, F7, and F17 was attributed to the lack of a retarding admixture. As the time of addition for the initial dosage was delayed beyond 30 minutes, the hot weather and lack of retarder allowed a greater degree of cement hydration to occur. This in turn decreased the workability to a point that the slump test showed to be an average of approximately 1-1/2 inches. Correspondingly, these three mixes (F4, F7, and F17) experienced a larger rise in the fresh concrete temperature in comparison with related mixes which were of the same time of addition, but contained a retarder.

The temperature rise characteristics of the fresh concrete will be discussed further in a later section; however, it is believed that the advanced degree of hydration negated the ability of the superplasticizer to achieve a flowing concrete consistency. In the case of Mix F7, the total dosage administered eventually exceeded the manufacturer's maximum recommended value by 74%. Ideally, this mix was to be dosed at 90 minutes after batching; however, the initial slump dropped below one inch 57 minutes after batching at which time the first effort to reach flowing concrete was made.

In addition to these three mixes with no retarder, Mix F9, with a dosage of 4.0 oz/cwt of retarder, did not reach flowing concrete. This particular mix exhibited qualities similar to the three mixes with no retarder. The slump dropped below one inch 73 minutes after batching and a relatively large temperature rise accompanied the decrease in workability. Nothing out of the ordinary occurred during batching. It is believed a slightly higher superplasticizer dosage would have attained flowing concrete when a comparison is made to Mixes F8 and F10, and that, therefore, the data is irregular.

Figures 5.3 and 5.4 show the effect of initial slump on the rate of slump gain versus the initial dosage of superplasticizer. In general, a higher initial slump leads to a greater rate of slump gain for the initial dosage of superplasticizer. The exception to this

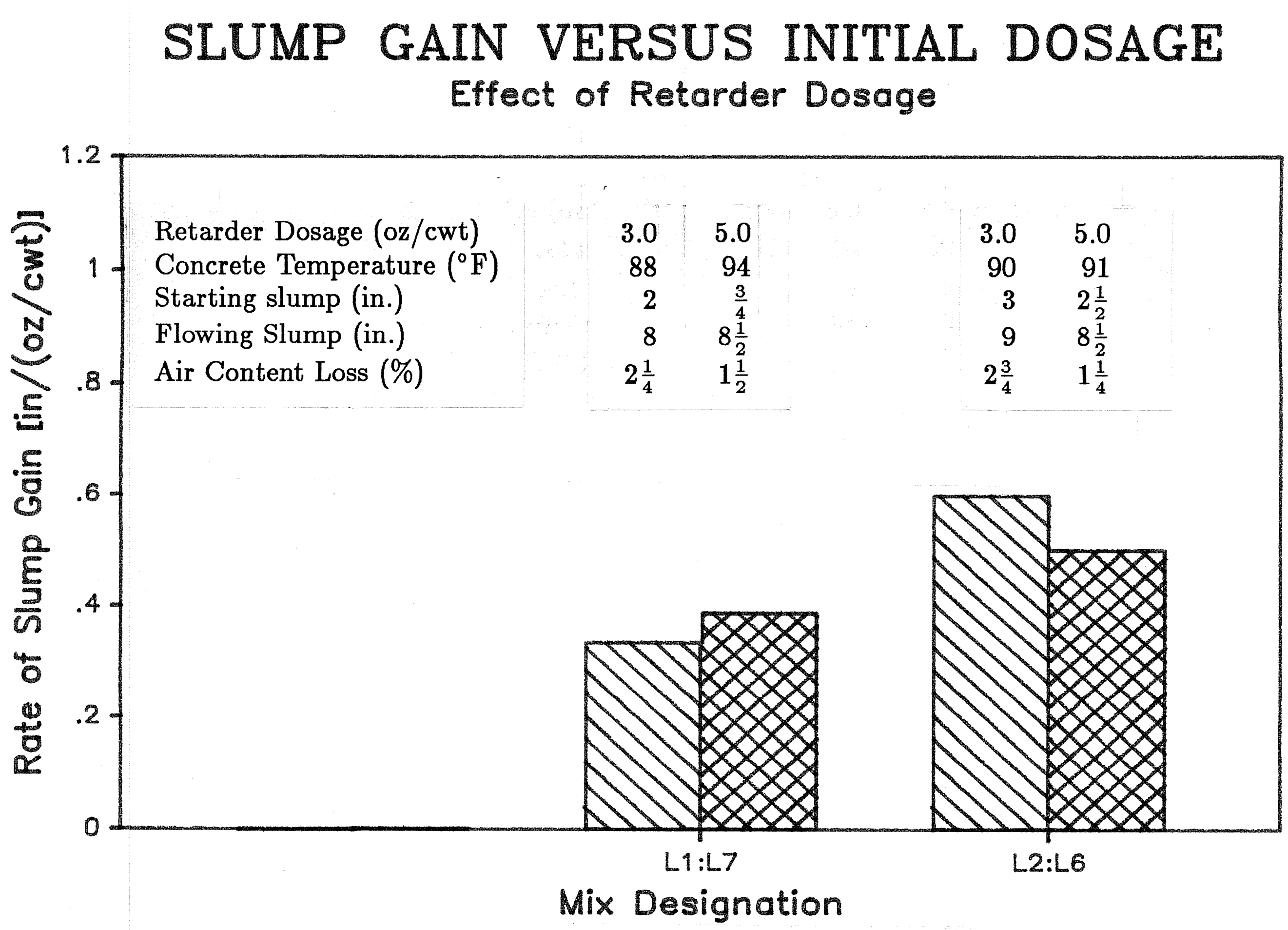


Fig. 5.1 Effect of retarder dosage on the rate of slump gain for the first superplasticizer dosage in the laboratory study

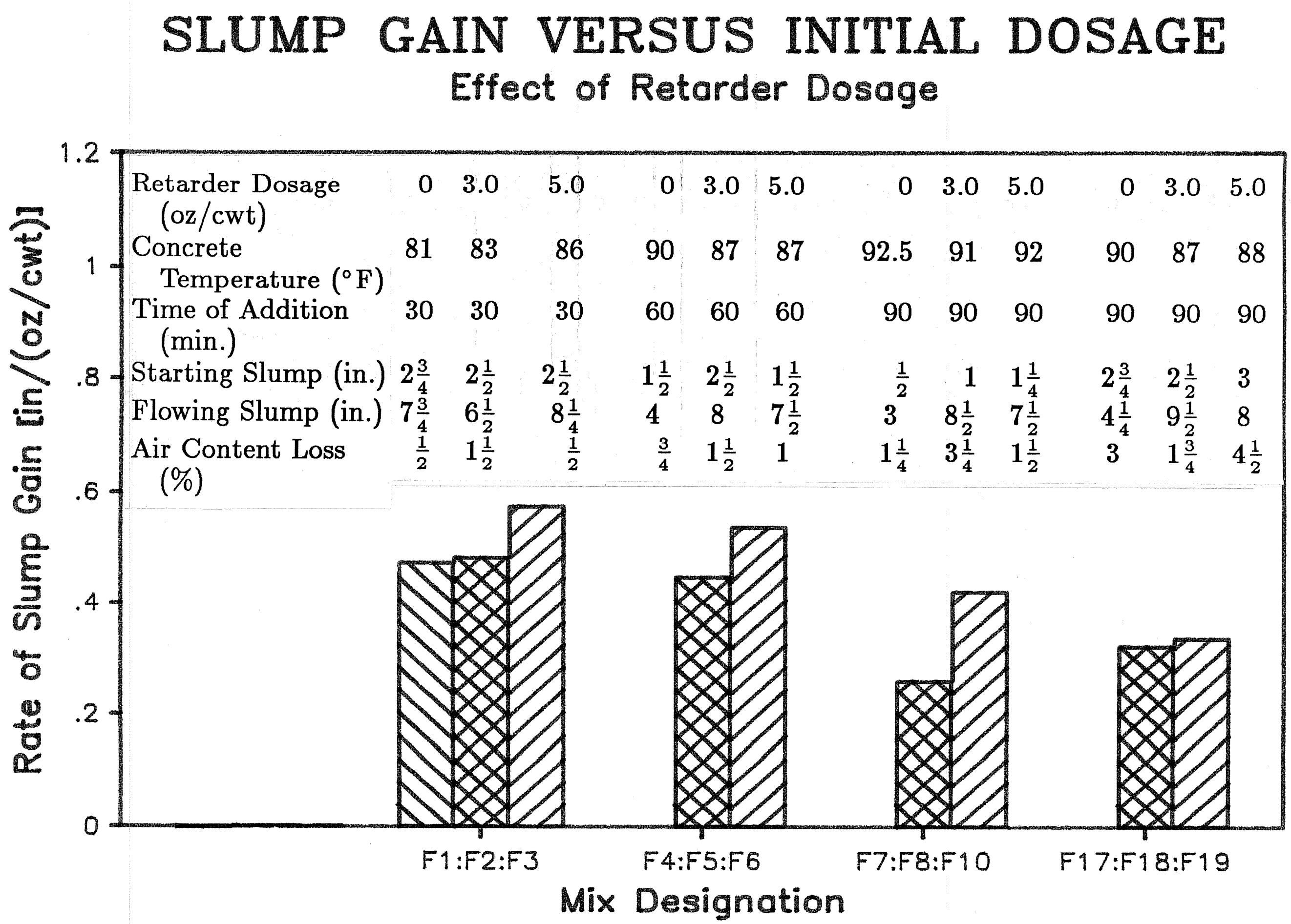


Fig. 5.2 Effect of retarder dosage on the rate of slump gain for the first superplasticizer dosage in the field study

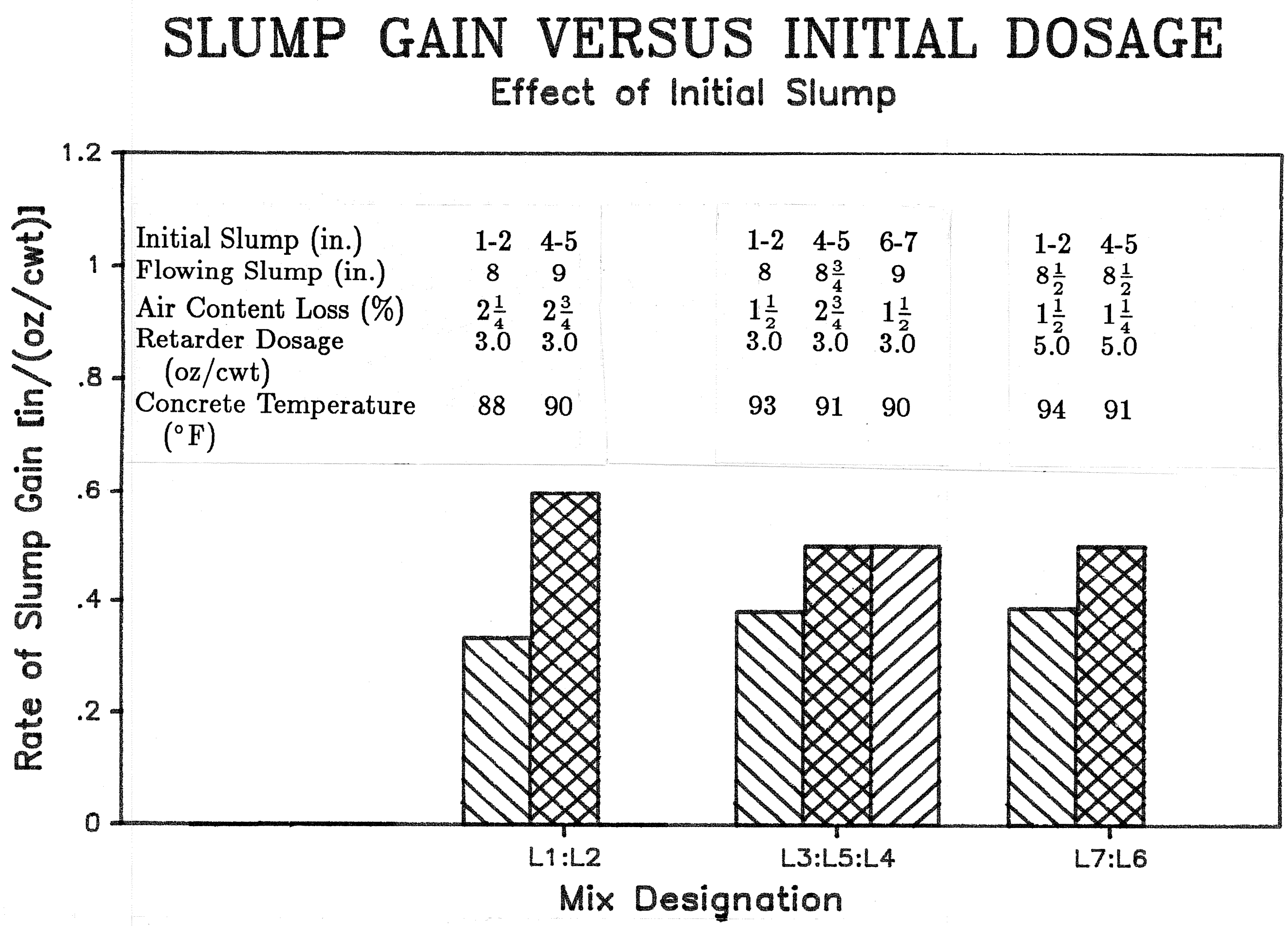


Fig. 5.3 Effect of initial slump on the rate of slump gain for the first superplasticizer dosage in the laboratory study

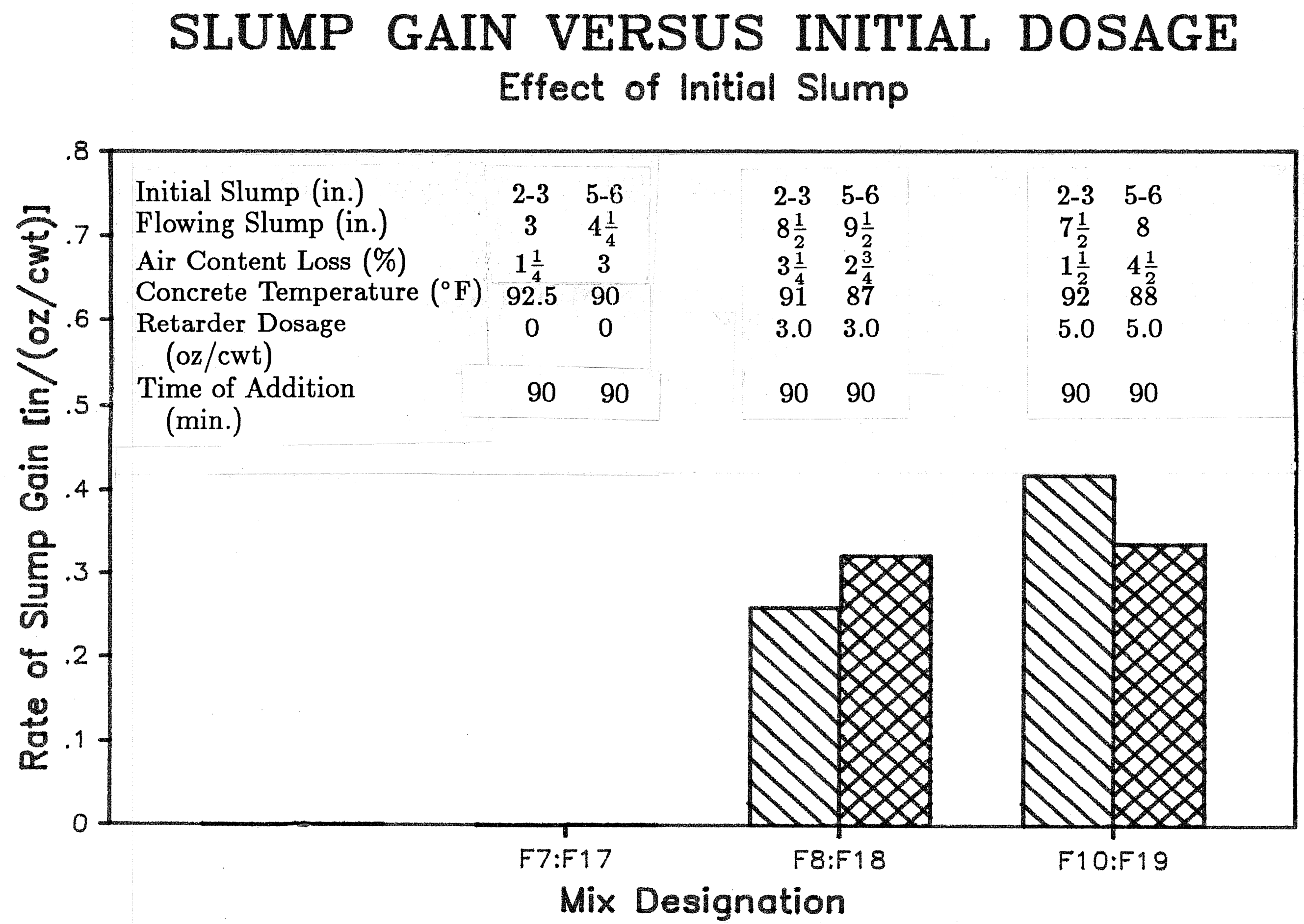


Fig. 5.4 Effect of initial slump on the rate of slump gain for the first superplasticizer dosage in the field study

trend of Mixes F10 and F19 may be attributable to the comparatively large loss of air entrainment with the superplasticizer dosage for Mix F19. Whereas the other groups of related mixes show similar losses in air entrainment, Mixes F10 and F19 do not. In the same manner as before, no data are shown for Mixes F7 and F17 because these mixes did not reach flowing concrete.

Figure 5.5 shows the effect of different times of addition of the superplasticizer on the rate of slump gain for that initial dosage. It can be seen that extending the time of addition to as late as 90 minutes slows the rate of slump gain per ounce of superplasticizer. This is believed to be due to further cement hydration which would occur during the time superplasticizer addition is withheld from 30 to 90 minutes after water-cement contact. The same superplasticizer dosage has less ability to disperse the cement particles and achieve flowing concrete as cement hydration proceeds. Similarly again, no data is shown for Mixes F7 and F17 because these mixes did not reach flowing concrete.

Figure 5.6 shows the effect of different manufacturer's products on the rate of slump gain for the initial superplasticizer dosage. For the materials used in this study, it is apparent that supposedly similar admixtures from different manufacturers can give significantly different results. This conclusion was also valid for those mixes where only the air entraining agent was changed such as L1:L9, F5:F14, and F6:F15.

Results from this study concerning the effect of cement content on the rate of slump gain for the initial superplasticizer dosage are limited. Mix L8 was the only mix with a cement content of 7.0 sacks. The data from this study will show that cement content has no effect on the rate of slump gain; however, such a conclusion would be inappropriate given the limited data for comparison.

No correlation was found in this study between the rate of slump gain for the initial dosage and the coarse aggregate type of each particular mix.

Previous researchers[31,37,38,44,49] have stated that as the dosage of superplasticizer was increased, the gain of slump was increased. These conclusions are based on companion mixes where the only variable was the superplasticizer dosage. Similar studies were not conducted as a part of this study.

The results of this portion of the study point out how the increase in workability depends on the peculiarities of each mix. Ravina and Mor[44] conducted tests where superplasticizer addition was delayed for up to 90 minutes after batching. They concluded that minimum dosages may become ineffective in producing flowing concrete as early as 30

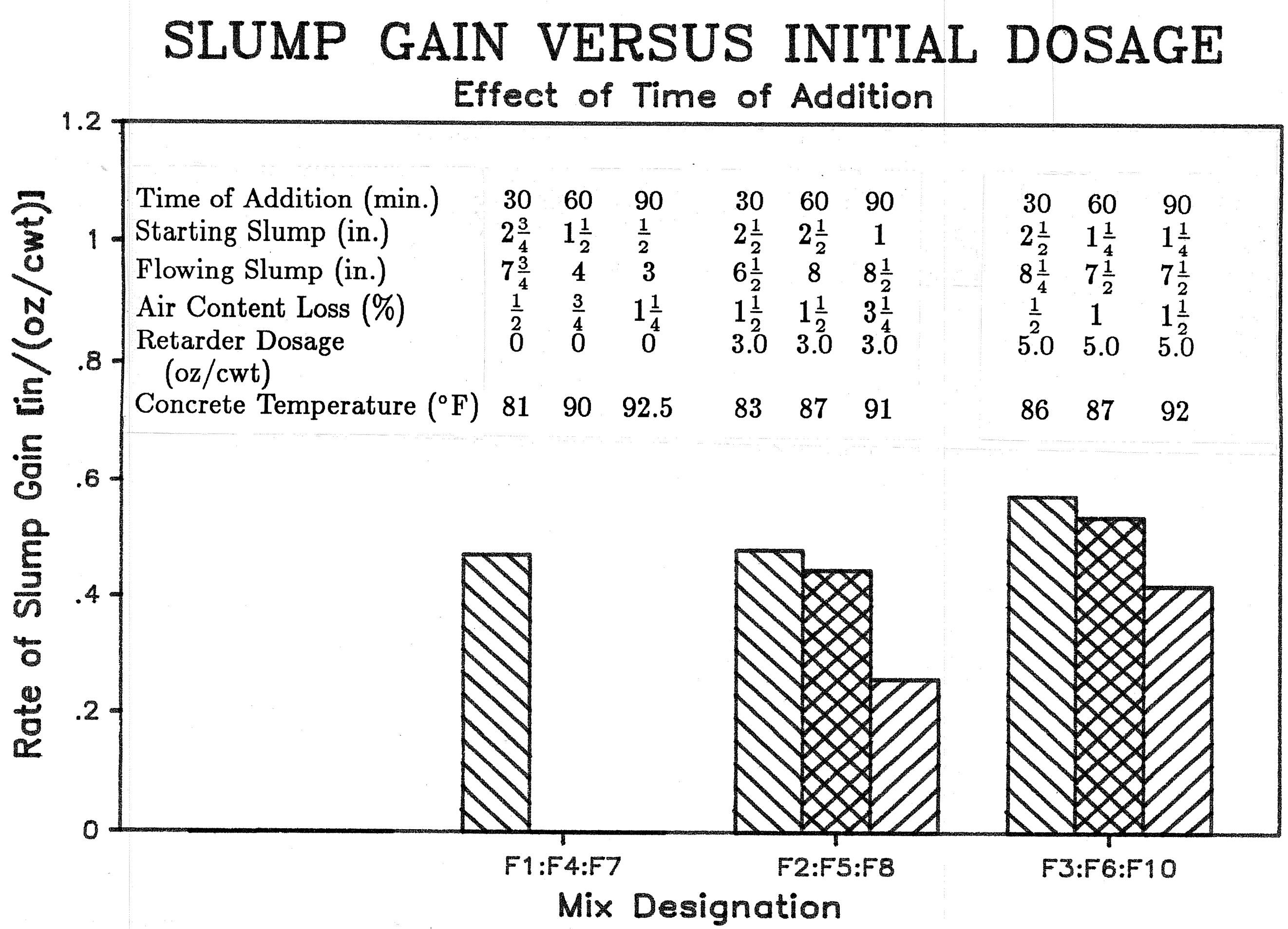


Fig. 5.5 Effect of time of addition of superplasticizer on the rate of slump gain for the first superplasticizer dosage in the field study

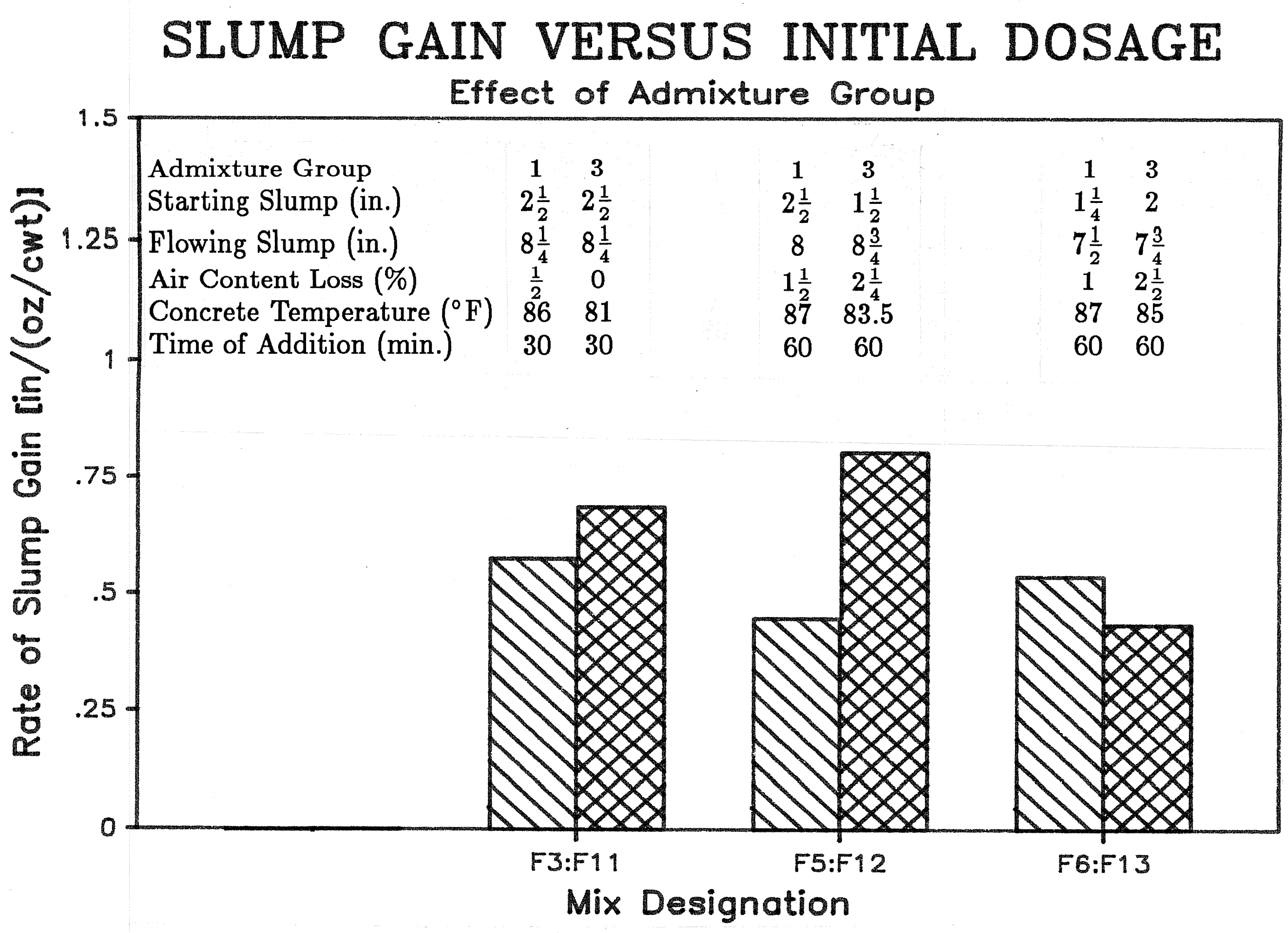


Fig. 5.6 Effect of admixture group on the rate of slump gain for the first superplasticizer dosage in the field study

minutes after batching whereas maximum dosage will allow achievement of flowing concrete up to 90 minutes later. This study has shown that for the production of flowing concrete in hot weather, the retarder dosage may be more important than the maximum or minimum superplasticizer dosage as the time from batching equals or exceeds 60 minutes. The initial slump of the mix can also affect the superplasticizer dosage requirements.

5.2.1.2 Slump Loss Versus Initial Dosage. Figures 5.7 through 5.12 show a comparison of the rate of slump loss after the initial superplasticizer dosage to flowing concrete.

Figures 5.7 and 5.8 are representative graphs of the relationship between different retarder dosages and the rate of slump loss from flowing concrete. Figure 5.7 shows that the slopes of the descending lines after the first superplasticizer dosage to flowing concrete at 30 minutes after batching are nearly equal for each of the three mixes. Figure 5.8 shows similar rates of slump loss for Mixes F5 and F6 which were dosed with superplasticizer 60 minutes after batching. Mix F4 does not follow the trend because flowing concrete was not attained. This similarity in slump loss, regardless of the retarder dosage, is repeated for other groups of similar mixes in this investigation, such as F12:F13, F14:F15, and L2:L6.

The data presented in Figures 5.7 and 5.8 contradict Hampton[17] and Yamamoto and Kobayashi[62] who have found significant improvements in delaying slump loss by using retarders. Edmeades and Hewlett's[13] contention that a 3:1 blend of superplasticizer to retarder would give significant improvements in workability retention is not in agreement with this data. Mixes L1, L2, and L6 all have similar rates of slump loss and fresh concrete temperatures; however, their respective superplasticizer:retarder ratios are 6:1, 3.3:1, and 2.4:1. Mix L7 has a superplasticizer:retarder ratio near the median of these values at 4:1, but the accompanying rate of slump loss is approximately three times the value of the three similar mixes. Mix L7 was 5°F warmer than the other three mixes, however.

The effect of different times of addition on the rate of slump loss from flowing concrete after the initial dosage can be seen by examining Fig. 5.9. This graph shows, for Mixes F11 and F13, that extending the time of addition for the first superplasticizer dosage from 30 to 60 minutes has little effect on the rate of slump loss from flowing concrete. The descending lines for the two mixes (F11 and F13) are essentially parallel. This similarity in slump loss regardless of the time of addition of the superplasticizer is repeated for other groups of similar mixes in this investigation, such as F2:F5 and F3:F6.

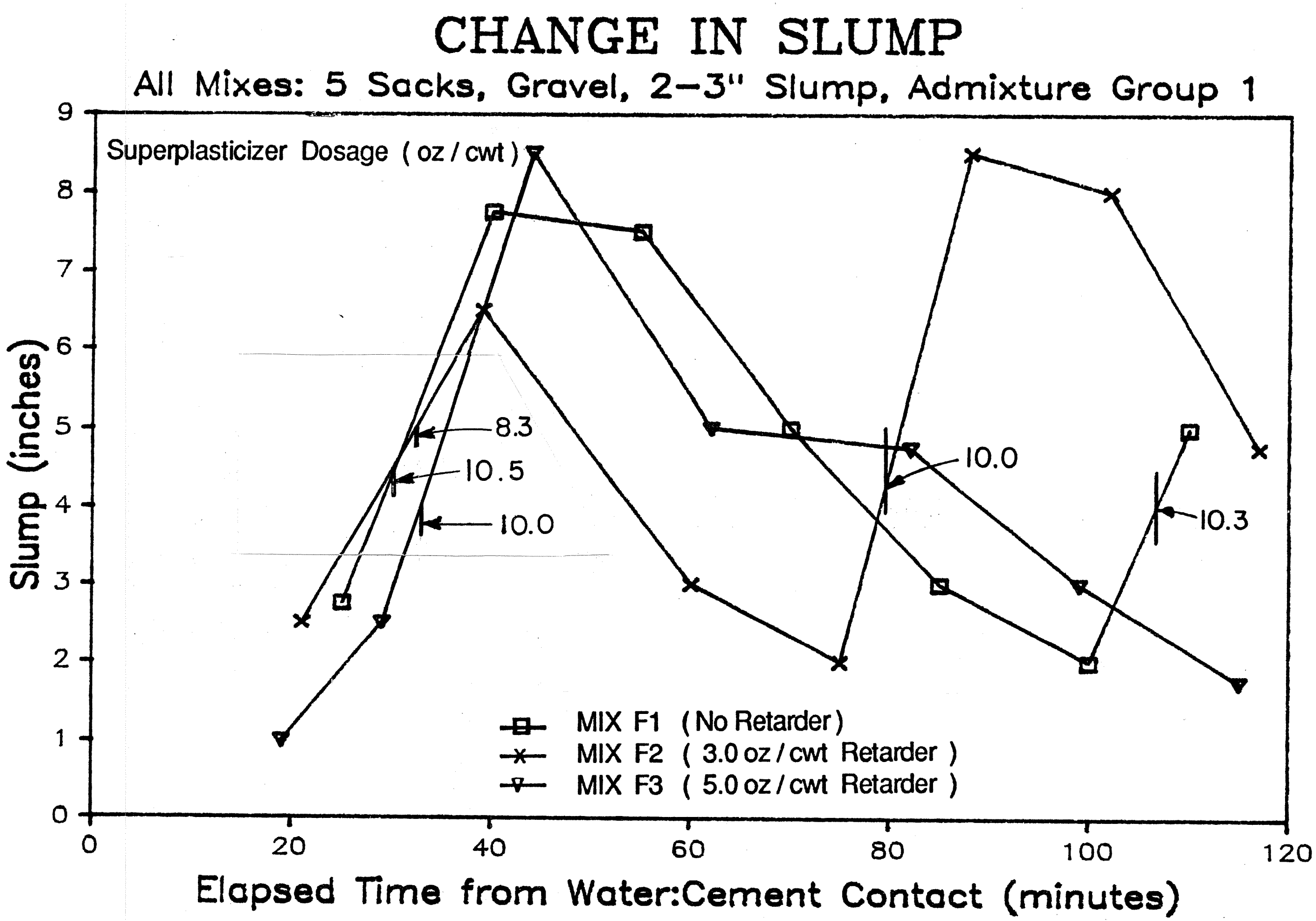


Fig. 5.7 Slump loss study from initial superplasticizer dosage to flowing concrete for mixes with different retarder dosages at a time of addition of 30 minutes after batching

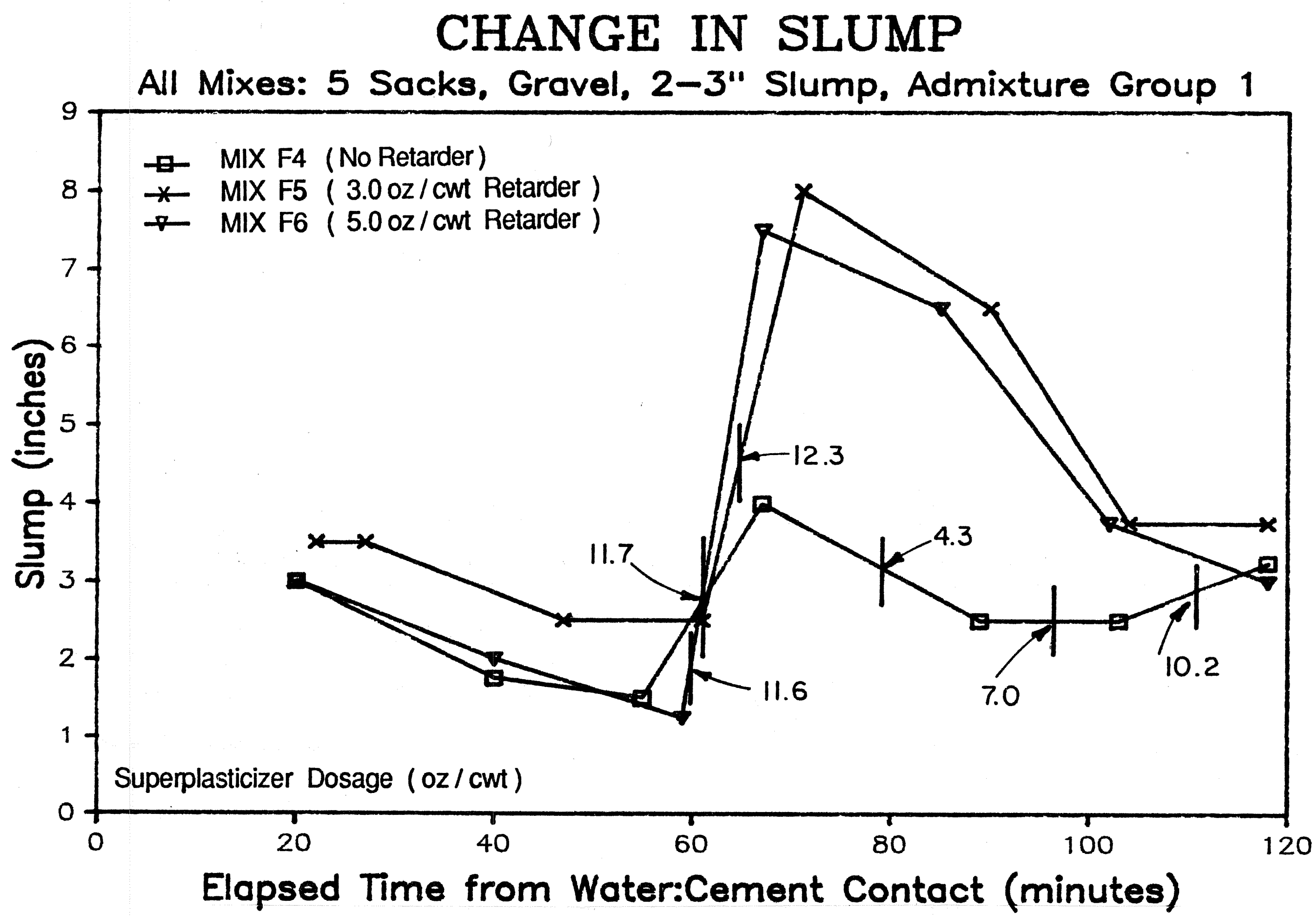


Fig. 5.8 Slump loss study from initial superplasticizer dosage to flowing concrete for mixes with different retarder dosages at a time of addition of 60 minutes after batching

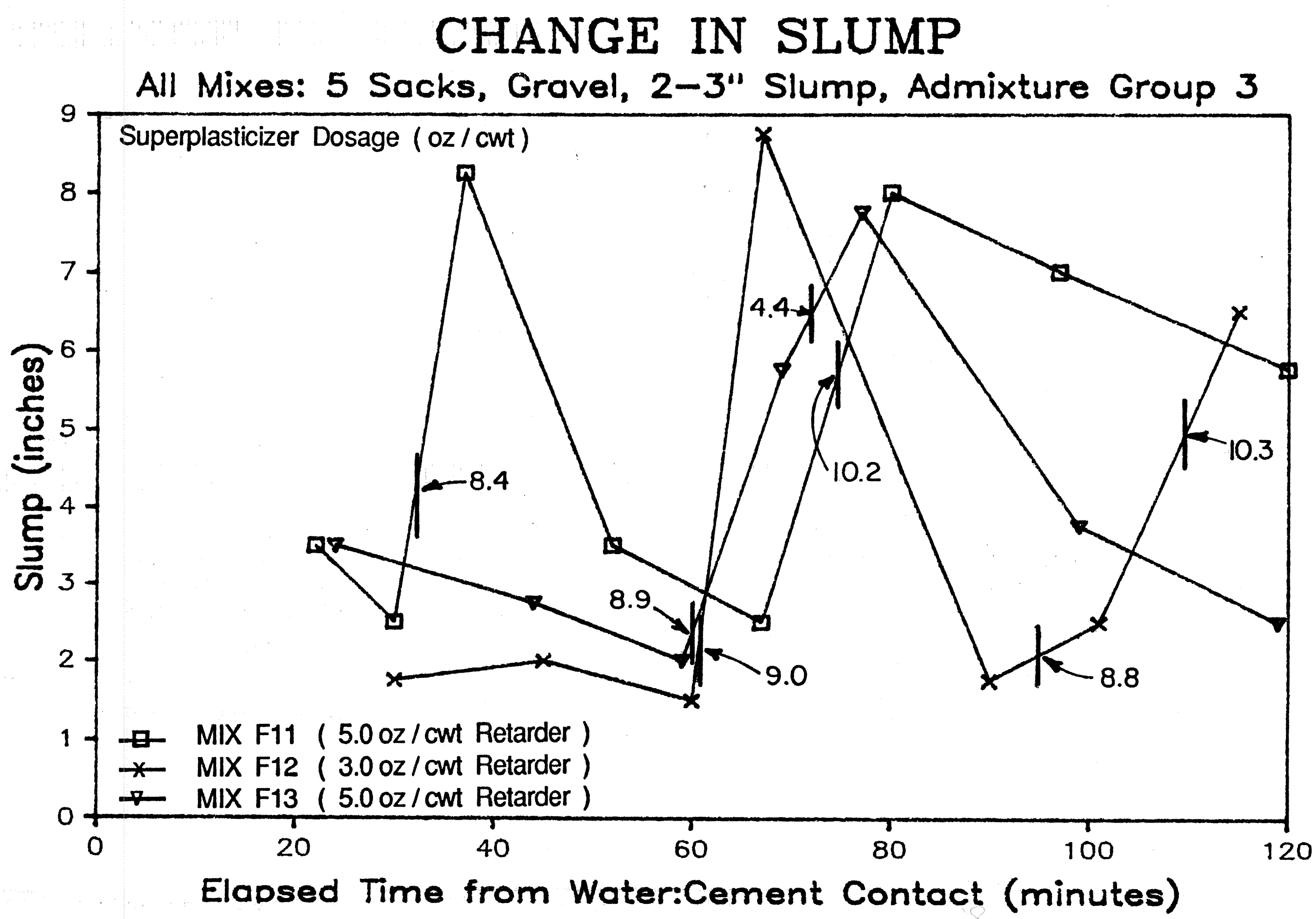


Fig. 5.9 Slump loss study from initial superplasticizer dosage to flowing concrete for mixes of identical retarder dosage at different superplasticizer times of addition (F11 and F13)

Figure 5.9 is in agreement with Mailvaganam[32] and Perenchio et al.[38] who found no clear trends and insufficient improvements in efforts to decrease the rate of slump loss by varying the time for addition of the superplasticizer.

Figure 5.10 shows the effect of changes in coarse aggregate type on the rate of slump loss from flowing concrete after the first superplasticizer dosage. It is apparent that those mixes with the rounder and smoother river gravel coarse aggregate experienced less slump loss. As the paste begins to lose fluidity, the rough surface texture of the crushed limestone attracts and monopolizes more of the paste. The sooner the paste becomes attached to the aggregate, the less paste there is available for maintaining flow and workability.

Though limited in scope, Fig. 5.11 shows the effect of cement content on the rate of slump loss from flowing concrete after the first superplasticizer dosage. The results show that the mix with a cement content of 7.0 sacks lost slump more quickly than the mix with a cement content of 5.0 sacks. This was attributed to the larger cement hydration reaction which can decrease workability sooner. The data presented in Fig. 5.11 are in agreement with Perenchio et al.[38], but in contradiction with other researchers[32,36,41,59] who state that an increase in cement content should decrease the rate of slump loss.

Figure 5.12 shows the effect of different manufacturer's products on the rate of slump loss after the initial superplasticizer dosage. It is again the case, that for the materials used in this study, supposedly similar admixtures from different manufacturers can give significantly different results. The performance of admixture group 1 was very stable whereas the performance of admixture group 3 shows a less constant and always higher rate of slump loss. This compatibility difference was also valid for those mixes where only the air-entraining agent was changed such as L1:L9, F5:F14, and F6:F15.

No correlation was found in this study between the rate of slump loss from the initial superplasticizer dosage to flowing concrete and the initial slump for each particular mix. The conclusion of Ramakrishnan and Perumalswamy[42] that higher rates of slump loss would accompany higher initial slumps can not be substantiated with the available information from this investigation.

5.2.1.3 Slump Gain Versus Second Dosage. Figures 5.13 and 5.14 show a comparison of the increase in slump per ounce of superplasticizer per 100 pounds of cement required to produce flowing concrete for the second superplasticizer dosage in the laboratory study. No summary of information about the rate of slump gain versus the second

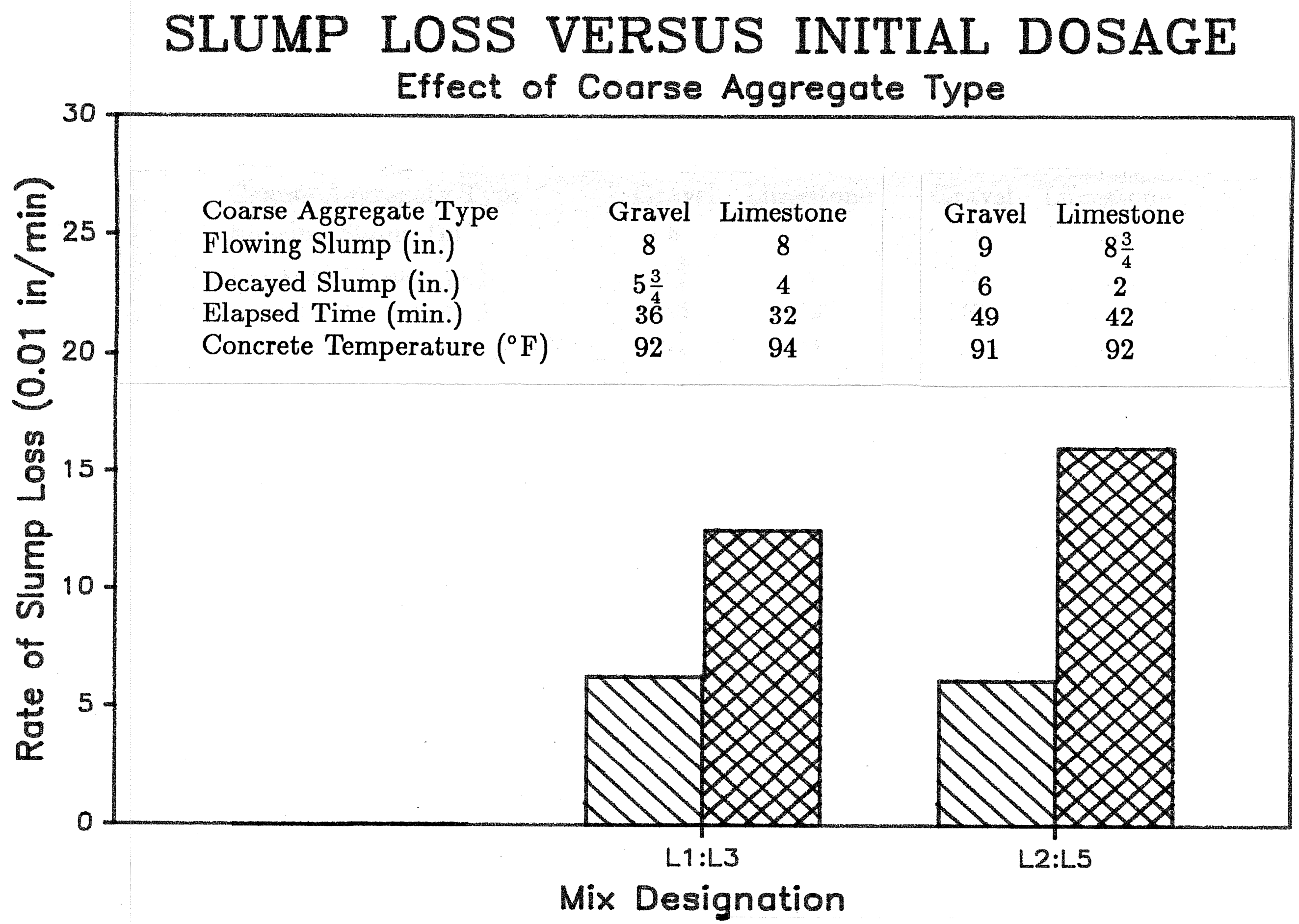


Fig. 5.10 Effect of coarse aggregate type on the rate of slump loss from the first superplasticizer dosage to flowing concrete in the laboratory study

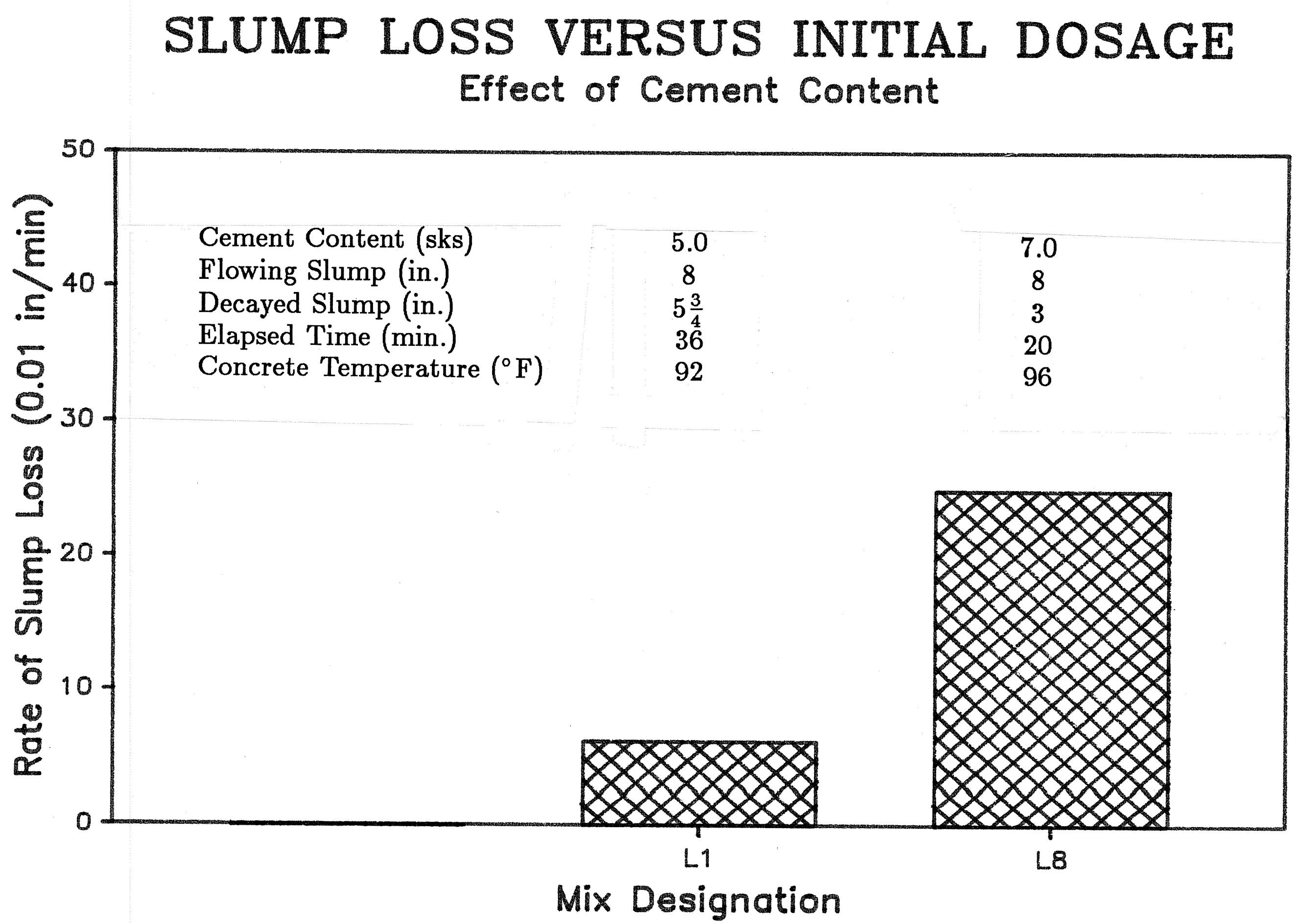


Fig. 5.11 Effect of cement content on the rate of slump loss from the first superplasticizer dosage to flowing concrete in the laboratory study

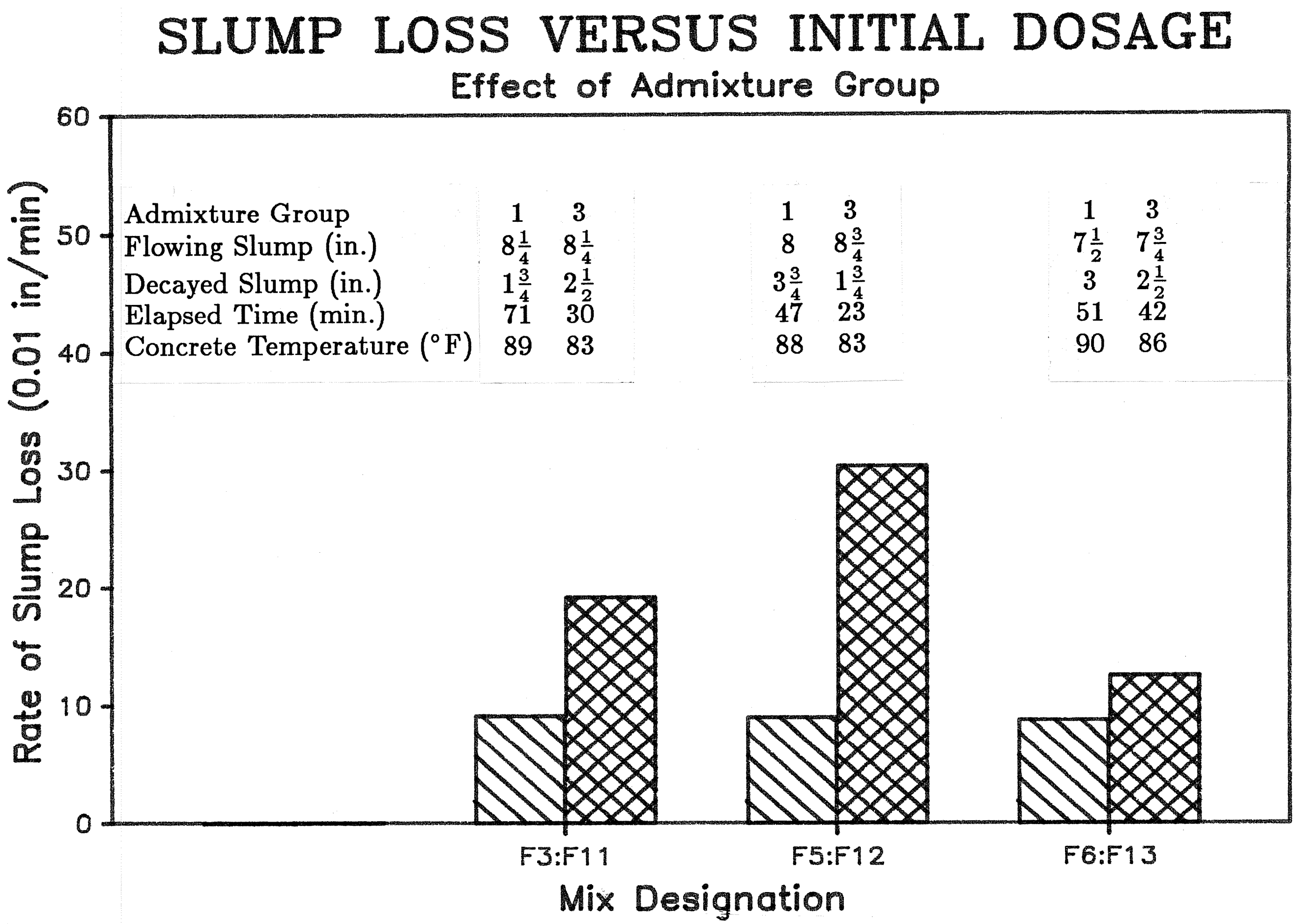


Fig. 5.12 Effect of admixture group on the rate of slump loss from the first superplasticizer dosage to flowing concrete in the field study

dosage of superplasticizer is shown for the field mixes because only four of nineteen mixes were dosed a second time. This few a number does not permit any valid comparisons.

It was shown earlier that changes in retarder dosage and initial slump had repeatable patterns of influence on the rate of slump gain for the initial superplasticizer dosage to flowing concrete. These trends are not repeated for the second superplasticizer dosage.

Figure 5.13 shows that those mixes with crushed limestone coarse aggregate exhibited a greater rate of slump gain per ounce of superplasticizer than similar mixes with river gravel coarse aggregates. Figure 5.14 shows that the mix with a cement content of 7.0 sacks had a greater rate of slump gain per ounce of superplasticizer than a similar mix with a cement content of 5.0 sacks. Each of these two factors, coarse aggregate type and cement content, were the only variables to show definite trends in the study of slump loss after the first superplasticizer dosage. Those mixes with crushed limestone coarse aggregate and the mix with 7.0 sacks of cement experienced the greatest rate of slump loss from the first superplasticizer dosage to flowing concrete and, then correspondingly, were more easily restored to a flowing concrete consistency with the second superplasticizer dosage.

This experimental program has shown that redosage of a concrete mix with a superplasticizer can restore a flowing consistency in hot weather, provided the first dosage was capable of producing flowing concrete. This is in agreement with other researchers [30,32,43,51] who have studied this phenomenon. Flowing concrete was restored up to two hours and 15 minutes after the readymix concrete was batched in each of the nine laboratory mixes.

5.2.1.4 Slump Loss Versus Second Dosage. As described earlier, the data for the rate of slump loss after the second superplasticizer dosage to flowing concrete is limited. It can be shown by examining the slump data in Chapter 4 that the greatest rates of slump loss from the second superplasticizer dosage occurred in those mixes with crushed limestone coarse aggregate and the mix with a cement content of 7.0 sacks. Figures 5.15 and 5.16 present evidence of these trends.

Recalling the observations regarding the rate of slump loss from the first superplasticizer dosage to flowing concrete, those mixes with crushed limestone coarse aggregate and a cement content of 7.0 sacks experienced a greater rate of slump loss also. Therefore, to summarize, for each of the two superplasticizer additions utilized to produce flowing concrete for the mixes and materials used in this study, those mixes with crushed limestone coarse aggregate and a higher cement content experienced a greater rate of slump loss.

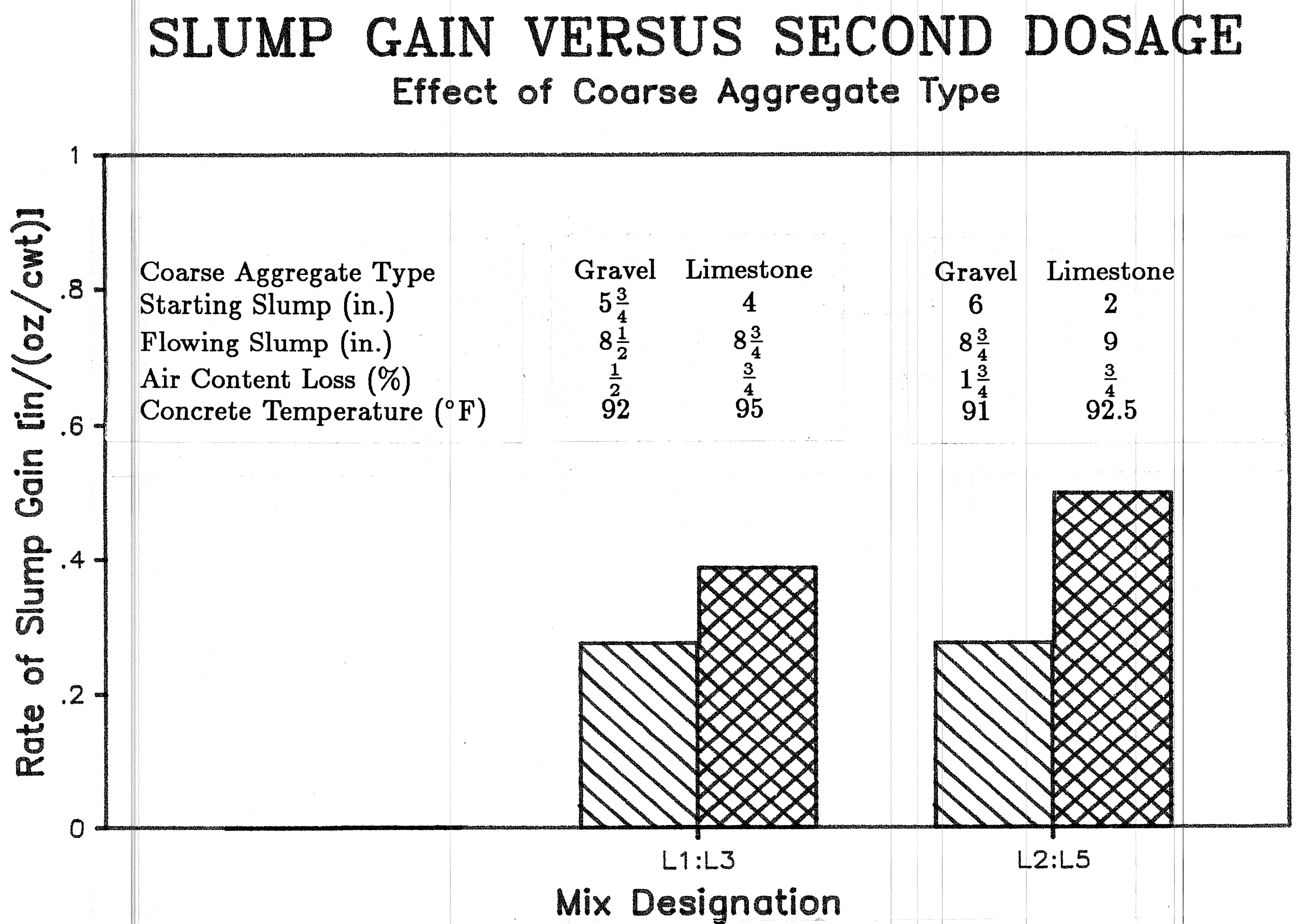


Fig. 5.13 Effect of coarse aggregate type on the rate of slump gain for the second superplasticizer dosage in the laboratory study

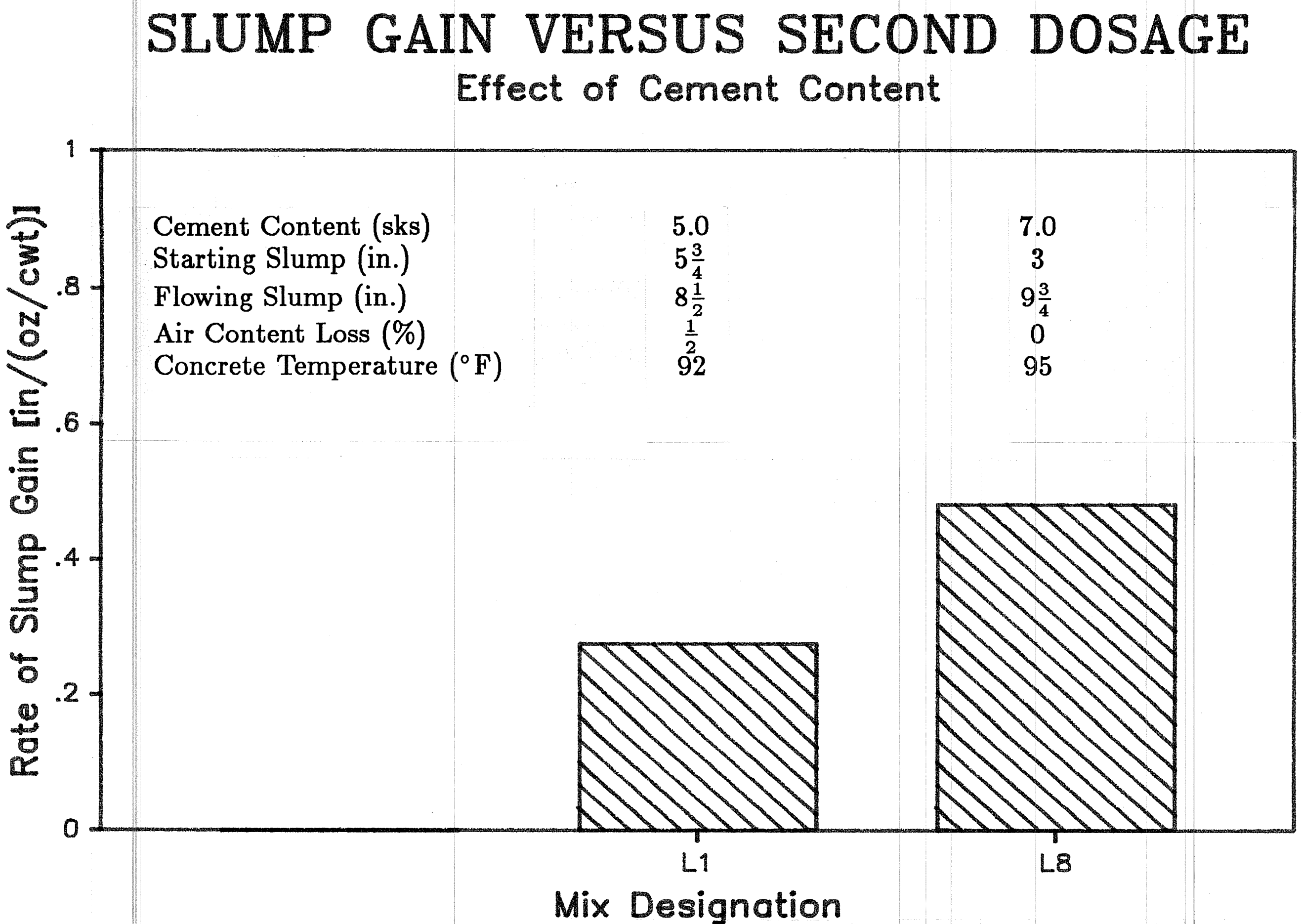


Fig. 5.14 Effect of cement content on the rate of slump gain for the second superplasticizer dosage in the laboratory study

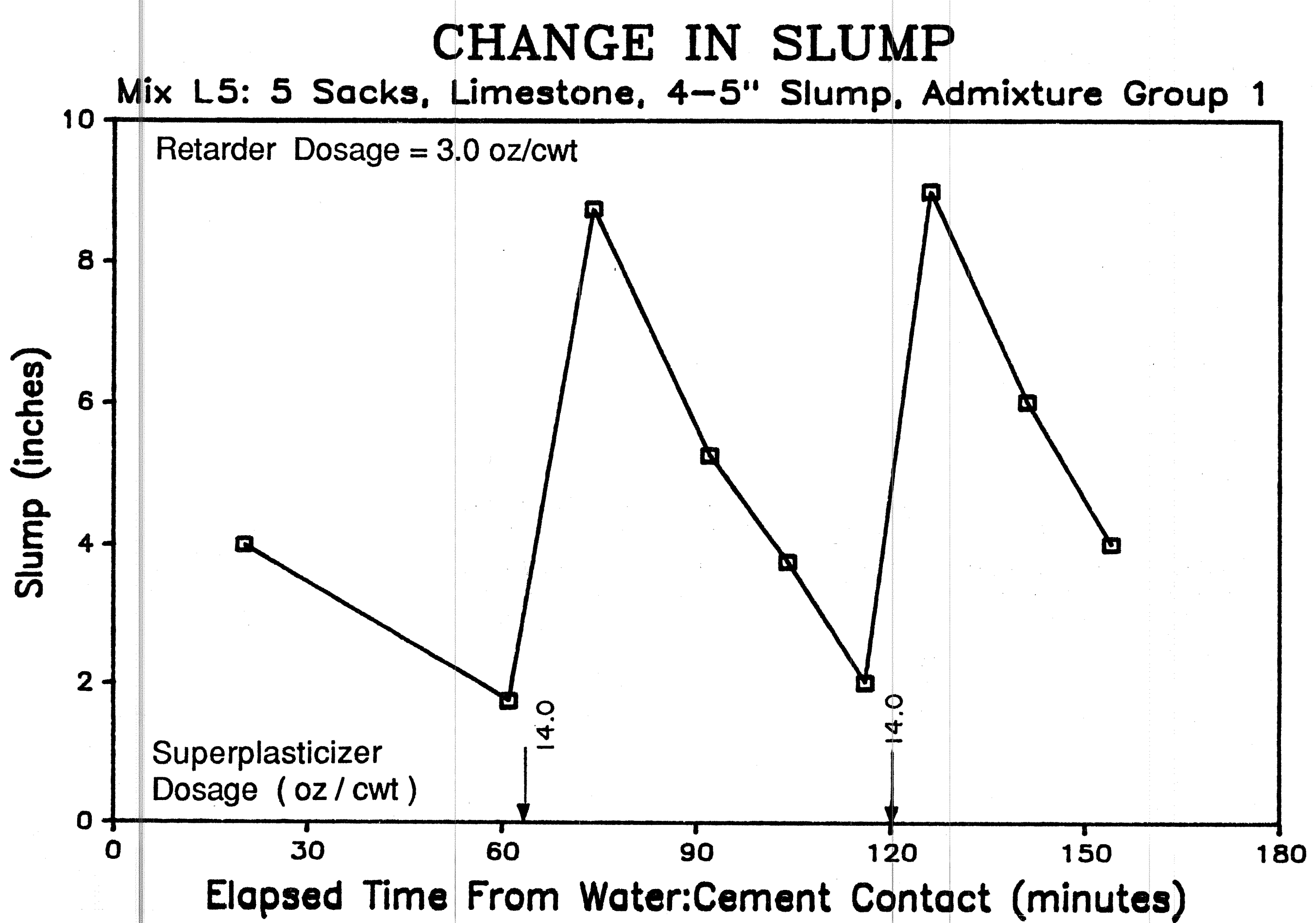


Fig. 5.15 Slump loss from the second superplasticizer dosage to flowing concrete for a representative laboratory mix with crushed limestone coarse aggregate

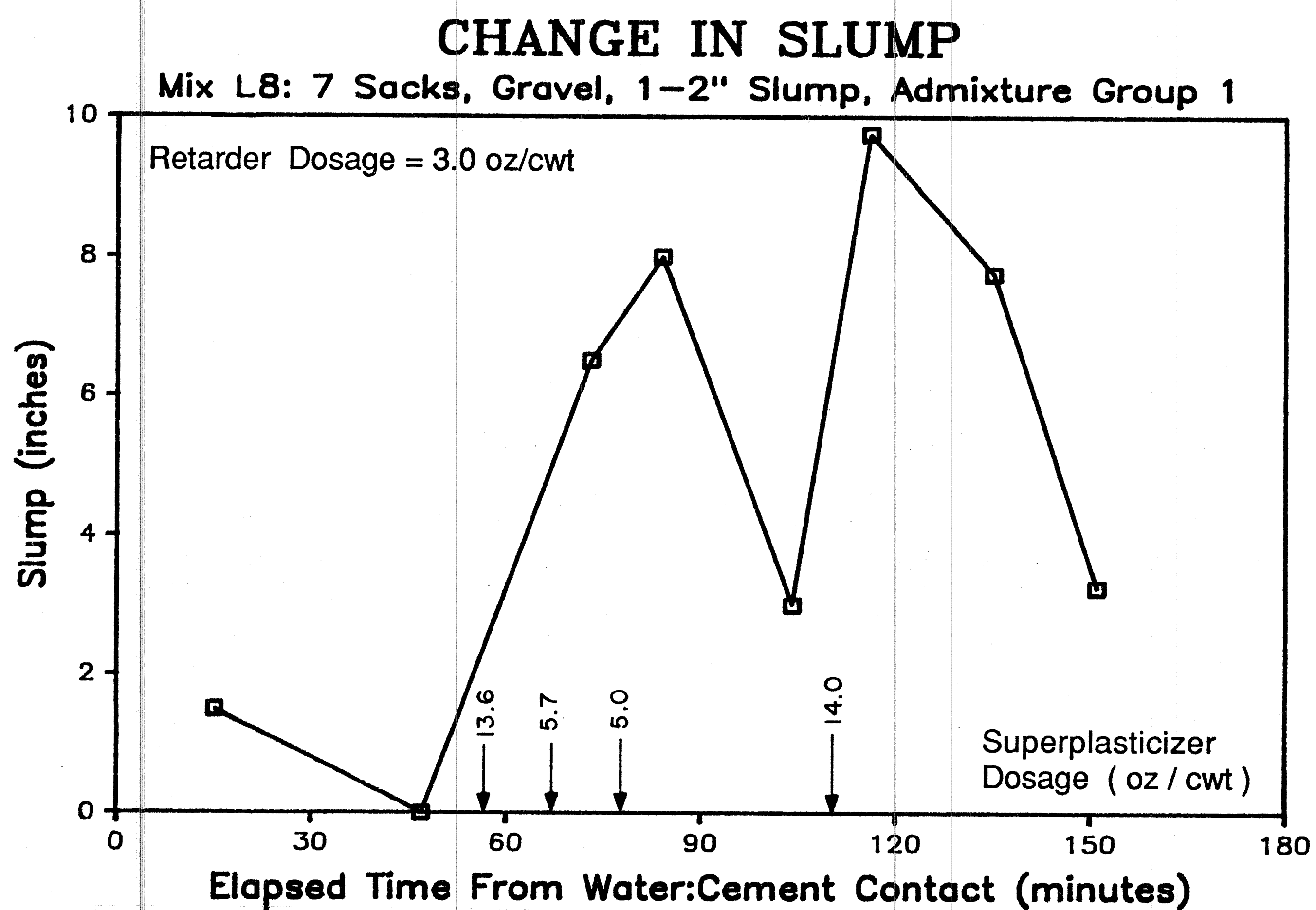


Fig. 5.16 Slump loss from the second superplasticizer dosage to flowing concrete for the laboratory mix with a cement content of 7.0 sacks

The literature contains contradictory conclusions regarding the rate of slump loss after redosage. Malhotra[30] and Mailavganam[32] state that the rate of slump loss is more gradual after redosage with a superplasticizer, but Ramakrishnan et al.[43] and Samarai et al.[51] state that the rate of slump loss will be higher after the concrete has been redosed to a flowing consistency. No particular pattern was found regarding a comparison in the rates of slump loss for the mixes in this research program.

5.2.2 Air Content. Figures 5.17 through 5.20 summarize the change in the air content of the fresh concrete mixes due to the first and second dosages of superplasticizer.

Figure 5.17 shows that, for the average of nine laboratory mixes, the air content of the fresh concrete mix declined with each dosage of superplasticizer. For an average initial air content of 4-1/4%, the first superplasticizer dosage decreased the value about 35% to an average air content of 2-3/4%. The second dosage resulted in an additional average decrease of approximately 45% to an air content of 1-1/2%.

Each laboratory mix followed this trend of air loss with each superplasticizer dosage regardless of coarse aggregate type, retarder dosage, or initial slump, except Mix L8. This particular mix, one with a cement content of 7.0 sacks, arrived at the laboratory with a zero inch slump. Though the dosage of air- entraining admixture was similar to other mixes, it is virtually impossible to entrain air in such a dry paste. The air content of the control sample for Mix L8 was 1-3/4%. After the first dosage of superplasticizer, the air content rose to 2-1/2%. It is believed the increase in slump due to the superplasticizer freed some water molecules to interact with the air-entraining agent. This produced a net increase in air content.

The summarized results of change in air content for the mixes in the field study are not shown; however, they are similar to the findings of the laboratory study. The 35% decrease in air content from the control mix to that after the first superplasticizer dosage for the field mixes was identical to that for the laboratory mixes. Second dosages of superplasticizer were rare in the field study, but of the four mixes that were retempered, three exhibited a loss of air after the second superplasticizer dosage. The air content was unchanged for the fourth field mix.

These findings are in agreement with previous researchers [23,28,30,36,43] who have found that a naphthalene based superplasticizer will decrease the air content of the fresh concrete mix. The results of the laboratory study also verify earlier work by researchers[30,41,43,52] who stated that repeated additions of superplasticizer will further

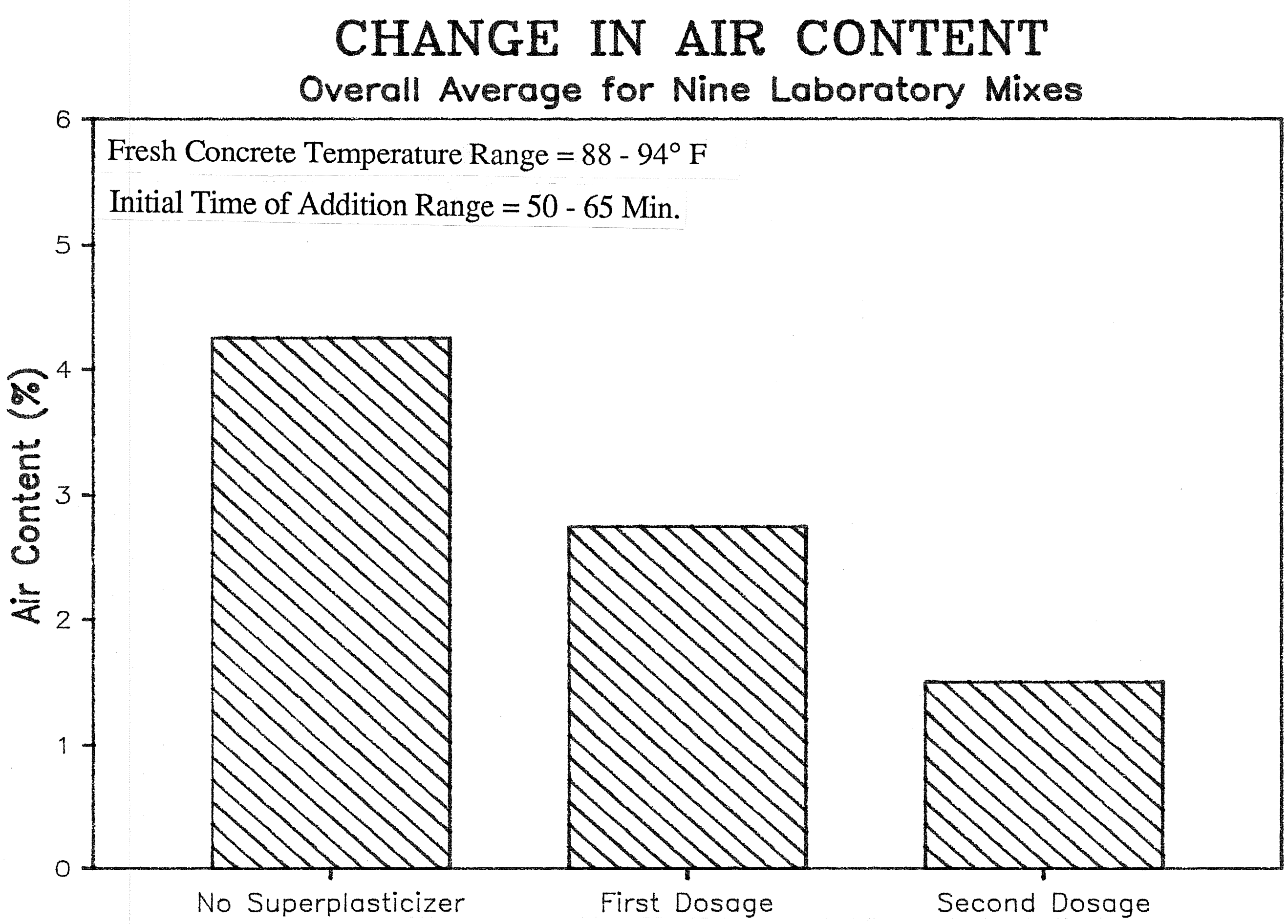


Fig. 5.17 Average change in air content for each superplasticizer dosage for the nine laboratory mixes

reduce the air content. Various researchers have attributed this loss of air to increased workability and bubble coalescence. These two events create decreased resistance to an increased buoyant force and, thus, the escape of air is facilitated.

It is suspected that these losses in air content would not allow the specimens to exhibit adequate durability to freezing and thawing cycles or the application of deicing salts. The literature review has shown, however, that exceptions to this are numerous.

The testing for air content by the volumetric method was continued during the period of time when the workability decreased after flowing concrete had been achieved. It can be shown from Figs. 4.10 through 4.18 that this loss of air was not a temporary phenomenon. As the slump decayed from a flowing consistency to a less workable mix, the initial air content of the control mix was never reattained.

Figures 5.18 and 5.19 summarize the effect of the retarder dosage on the loss of air. In general, it is shown that mixes with a larger retarder dosage do not lose as much air with the first superplasticizer dosage. This was attributed to the lignosulfonate based retarder which can entrain air. Thus, the larger retarder dosages result in lower air loss.

Figure 5.20 summarizes the average behavior of the two air- entraining admixtures investigated in this study for the two superplasticizer dosages. As stated in Chapter 2, air-entraining agent B was developed especially for situations where it is difficult to entrain air. These results show that significant air loss accompanied each superplasticizer dosage regardless of the type of air-entraining agent used.

Figure 5.21 shows that as the time of addition for the first superplasticizer dosage is delayed from 30 to 90 minutes, a greater amount of air is lost. This trend may be attributable to an increase in the fresh concrete temperature as the mix is held for longer times.

No correlation was found in this study between the amount of air-entrainment lost and the initial slump of the particular mix.

5.2.3 Temperature. Figures 4.19 through 4.27 document the fresh concrete temperatures for the nine laboratory mixes. Figures 4.85 through 4.90 show similar information for the nineteen field mixes. This information is presented primarily as verification that all mixes were indeed conducted in hot weather. The average temperature for the nine laboratory mixes when the readymix truck arrived at the laboratory was 91°F, with each mix varying by no more than 3°F in either direction. The average temperature for

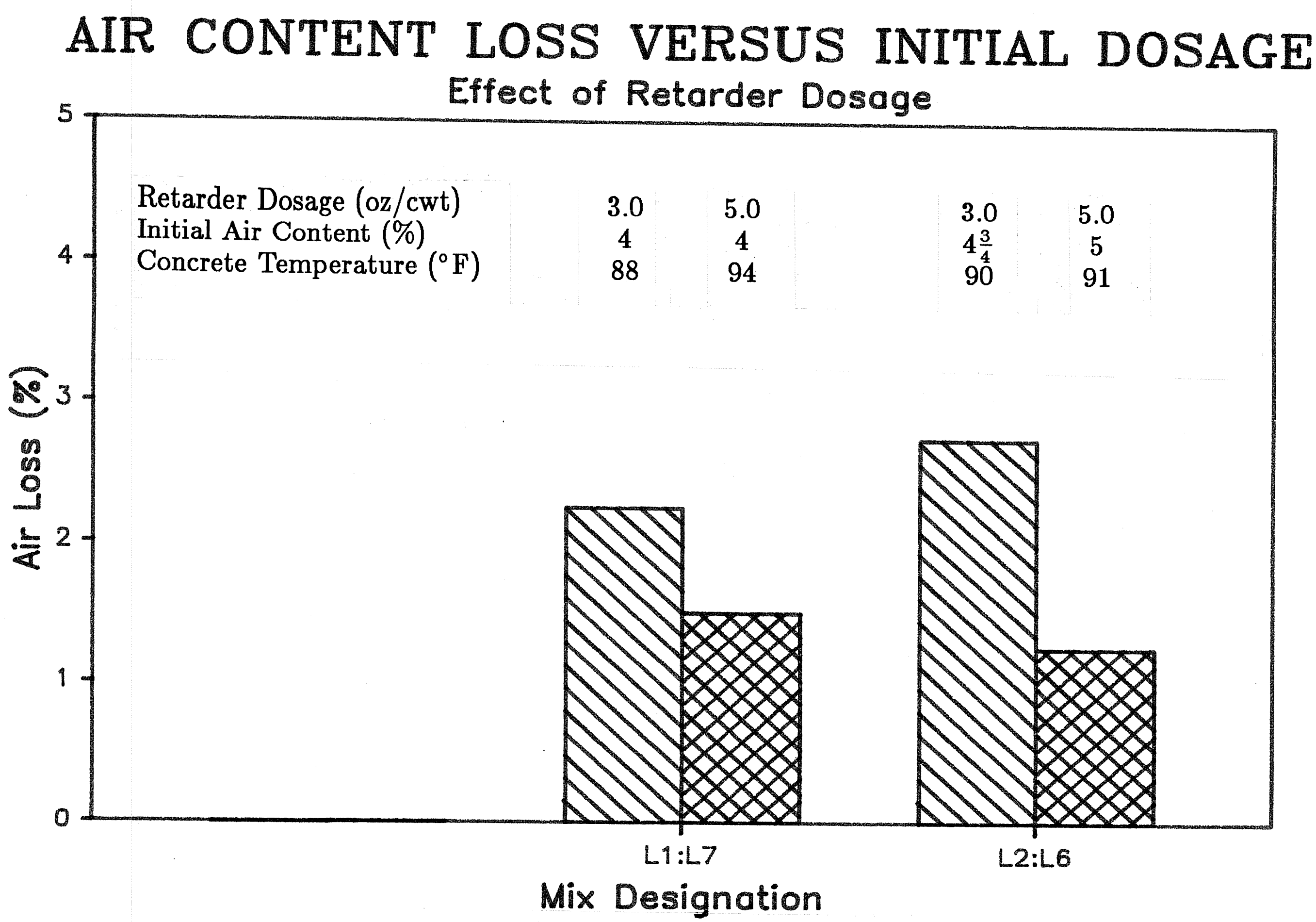


Fig. 5.18 Effect of retarder dosage on air loss from the first superplasticizer dosage to flowing concrete in the laboratory study

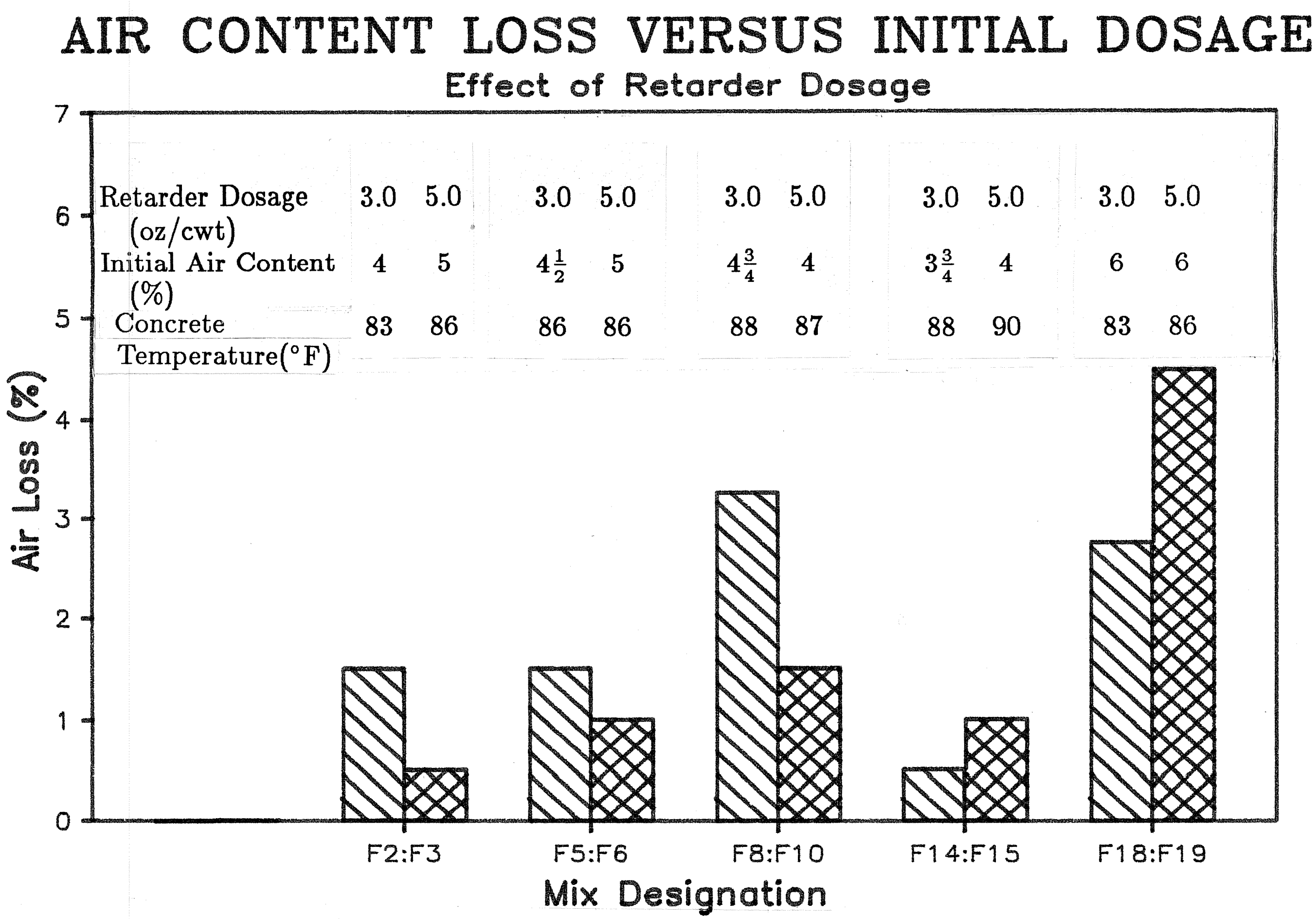


Fig. 5.19 Effect of retarder dosage on air loss from the first superplasticizer dosage to flowing concrete in the field study

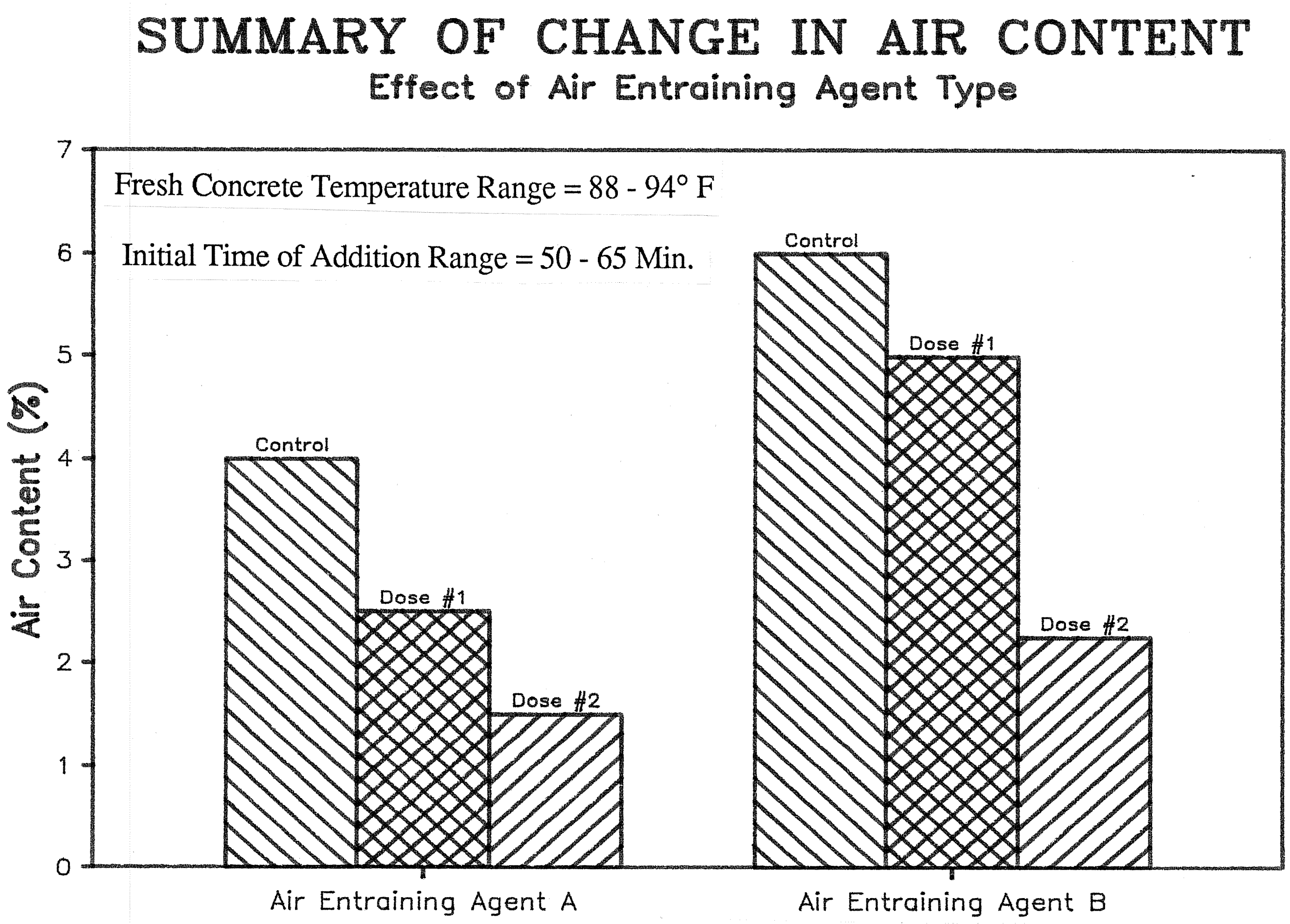


Fig. 5.20 Effect of air entraining agent on the change in air content for each superplasticizer dosage in the laboratory study

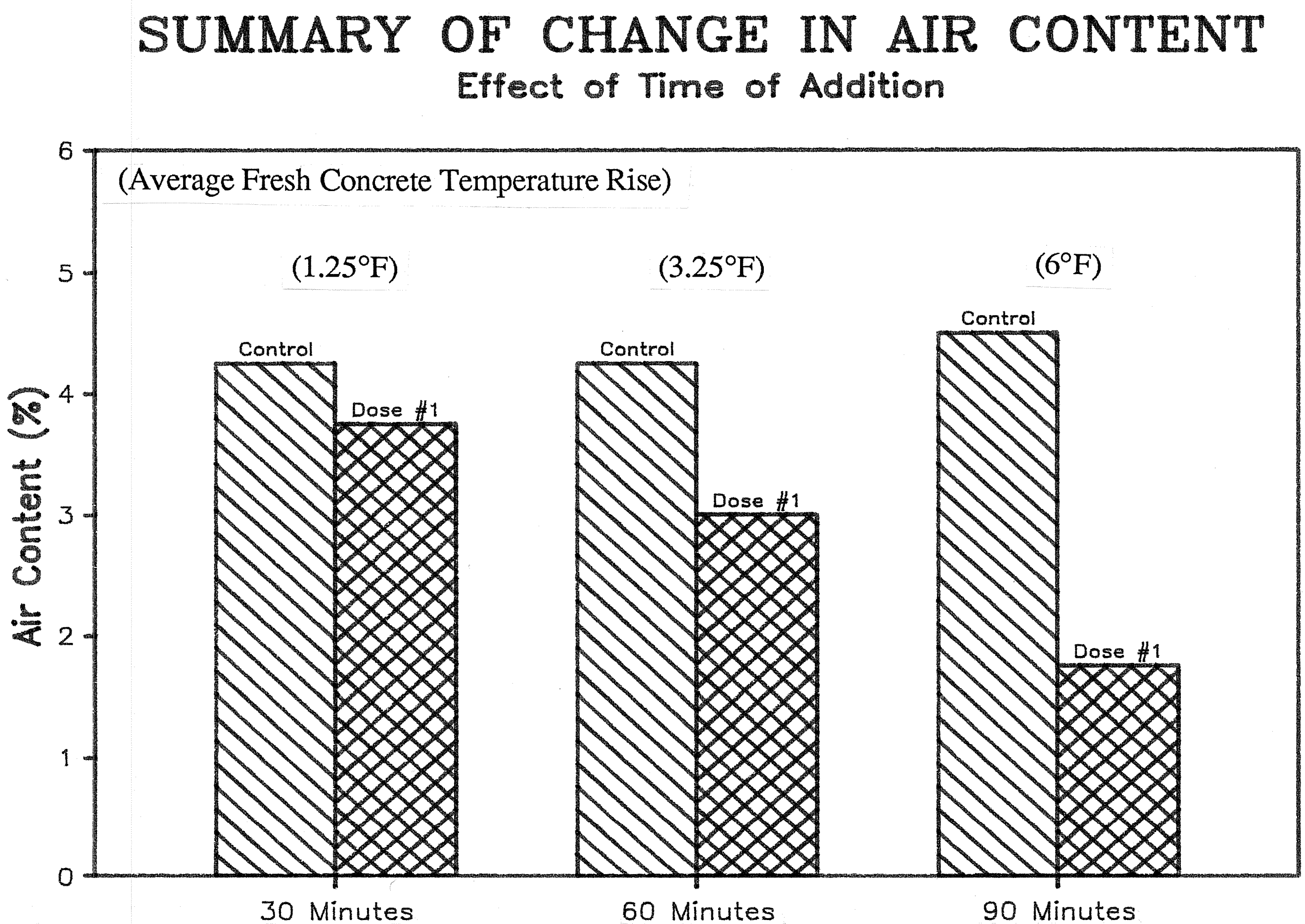


Fig. 5.21 Effect of time of addition on the change in air content for the first superplasticizer dosage in the field study

the nineteen field mixes, when the readymix truck arrived at the testing site and the target slump was achieved, was 85.5°F, with each mix varying by no more than 4.5°F in either direction.

Temperature rise is no apparent explanation for the rate of slump loss; however, it is most likely related to the capability of a superplasticizer to attain flowing concrete. It became apparent that excessive superplasticizer dosages would not yield a flowing concrete consistency in three particular mixes of the field study. Mixes F4, F7, and F17 contained no retarder and, though initial temperatures were similar to the related mixes with retarder, the final temperatures of mixes with no retarder showed an average 69% greater temperature rise during the two hour time period. Thus, it is believed this greater and faster temperature rise is due to the lack of a retarder and that, subsequently, when the initial time of addition exceeded 30 minutes, it prevented the achievement of flowing concrete.

It is also noted that the change in initial slump from 2 to 3 inches to 5 to 6 inches decreased the heat gain characteristics of the mixes by approximately 50% for the 90 minute hold time in the field study. This was attributed to the higher water- cement ratios of these higher slump mixes which consequently slowed the early cement hydration reactions. However, in each case, the mix with no retarder did not reach flowing concrete.

The effects of superplasticizers on readymix concrete in cooler weather are currently being studied in a similar investigation. Significant conclusions can then be made regarding the effect of temperature on the amount of superplasticizer required to reach flowing concrete, rate of slump loss, initial and final setting times, flexural and compressive strengths, and durability.

5.2.4 Segregation and Bleeding. No test was conducted to determine if a mix exhibited excessive segregation or bleeding. This discussion evolved primarily from observations by the author. It is necessary to restate that 3 to 6 cubic feet of concrete was discarded initially, prior to any sampling, after the superplasticizer was added.

All fresh concrete testing and specimen casting consisted of concrete discharged from the mixer after the two discarded wheelbarrows. The concrete was remixed in the wheelbarrow with a scoop or shovel. All specimens were consolidated identically to the control specimens. Usually consolidation was accomplished with a tamping rod, but a vibrating table was used for the casting of specimens when required due to a concrete slump of less than one inch.

The superplasticized concrete did show occasional patches of bleed water on the struck off surfaces and water filling the needle indentations in the mortar used for the setting time test. However, a point was make to examine the broken flexural strength specimens. In no case did the ruptured section exhibit obvious coarse aggregate settlement.

5.2.5 Finishing. For each of the nine laboratory mixes, each superplasticizer dosage further delayed the time when steel trowel finishing could be properly performed. The low initial slump mixes in particular were difficult to finish. There was very little paste; the surface would split and pull away from the mold edges. This is in agreement with the description of a sticky finish that would tear with the pass of the trowel.[20] All finishing was done with a hand trowel; therefore, conclusions relating to the finishing of large flatwork by experienced personnel are limited.

5.2.6 Unit Weight. Figure 5.22 summarizes the average values from the unit weight test for each of the nine laboratory mixes with no superplasticizer and after the first and second dosages. Included with each test result is the average slump and air content value of the nine laboratory mixes at these particular times. The information in this figure shows that the unit weight increased with each addition of the superplasticizer. This can be attributed to the decrease in air content and increase in slump which allowed better compaction.

This finding is in agreement with Mukherjee and Chojnacki [36] and Ramakrishnan et al.[43] who found that the unit weight of superplasticized concrete would be greater. The results are probably of little significance, however. Designers assume the unit weight of plain concrete to be 145 pounds per cubic foot. In the worst case, the data presented only vary from that assumption by approximately 3%.

5.2.7 Initial and Final Setting Times. Figures 5.23 and 5.24 summarize the results for determination of the initial and final setting times for the nine laboratory mixes.

Figures 5.23 and 5.24 show that for the average of laboratory mixes grouped by retarder dosage, initial and final setting times were each delayed with each superplaticizer dosage. For each particular retarder dosage, the delays from the control to the first dosage and again to the second dosage specimens were similar for initial and final setting times. However, those mixes with the greater retarder dosage (5.0 oz/cwt) showed greater delays between all specimens for initial and final setting times when compared with the averages for those mixes with a retarder dosage of 3.0 oz/cwt.

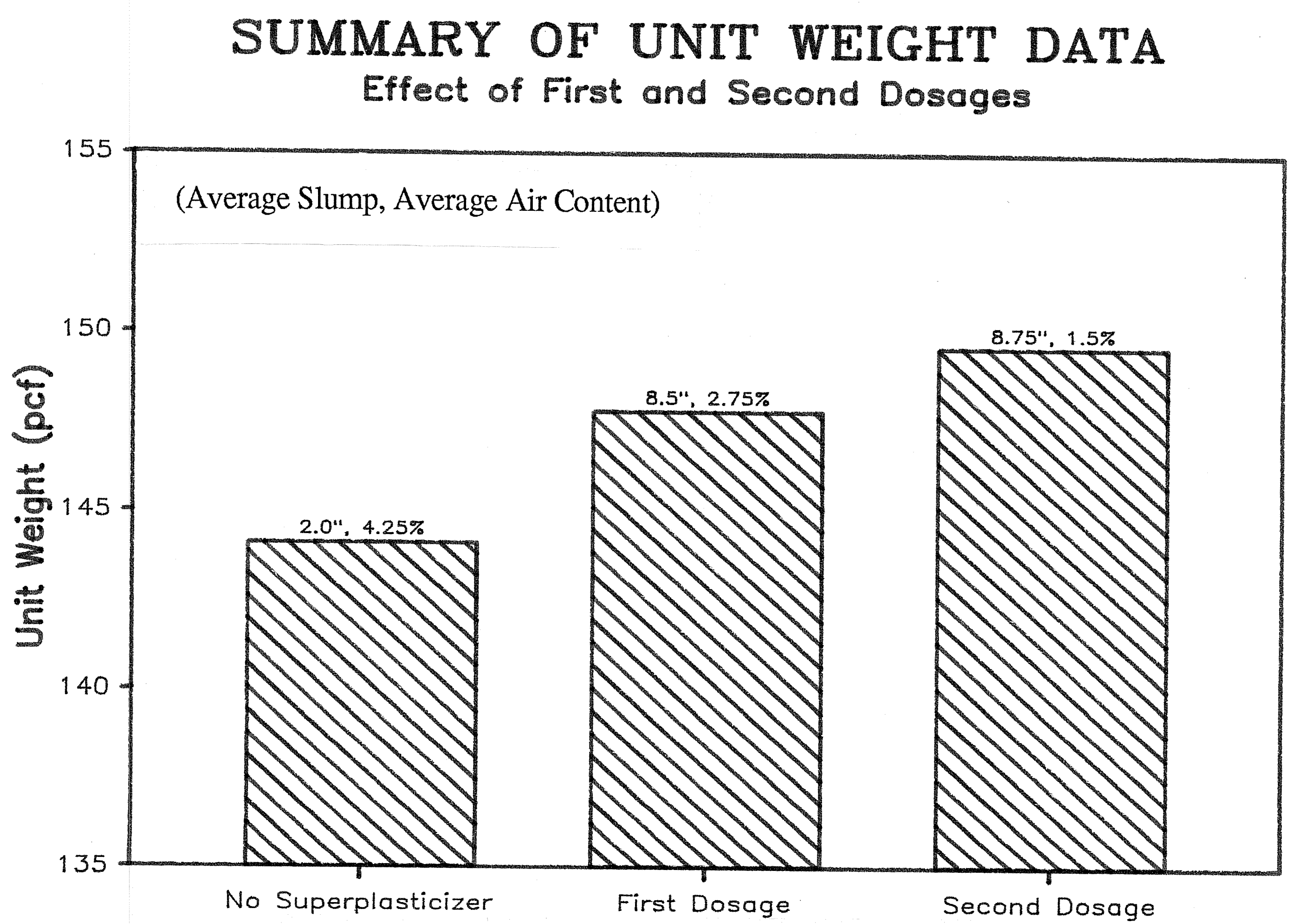


Fig. 5.22 Summary of average unit weight for control and both superplasticizer dosage specimens in the laboratory study

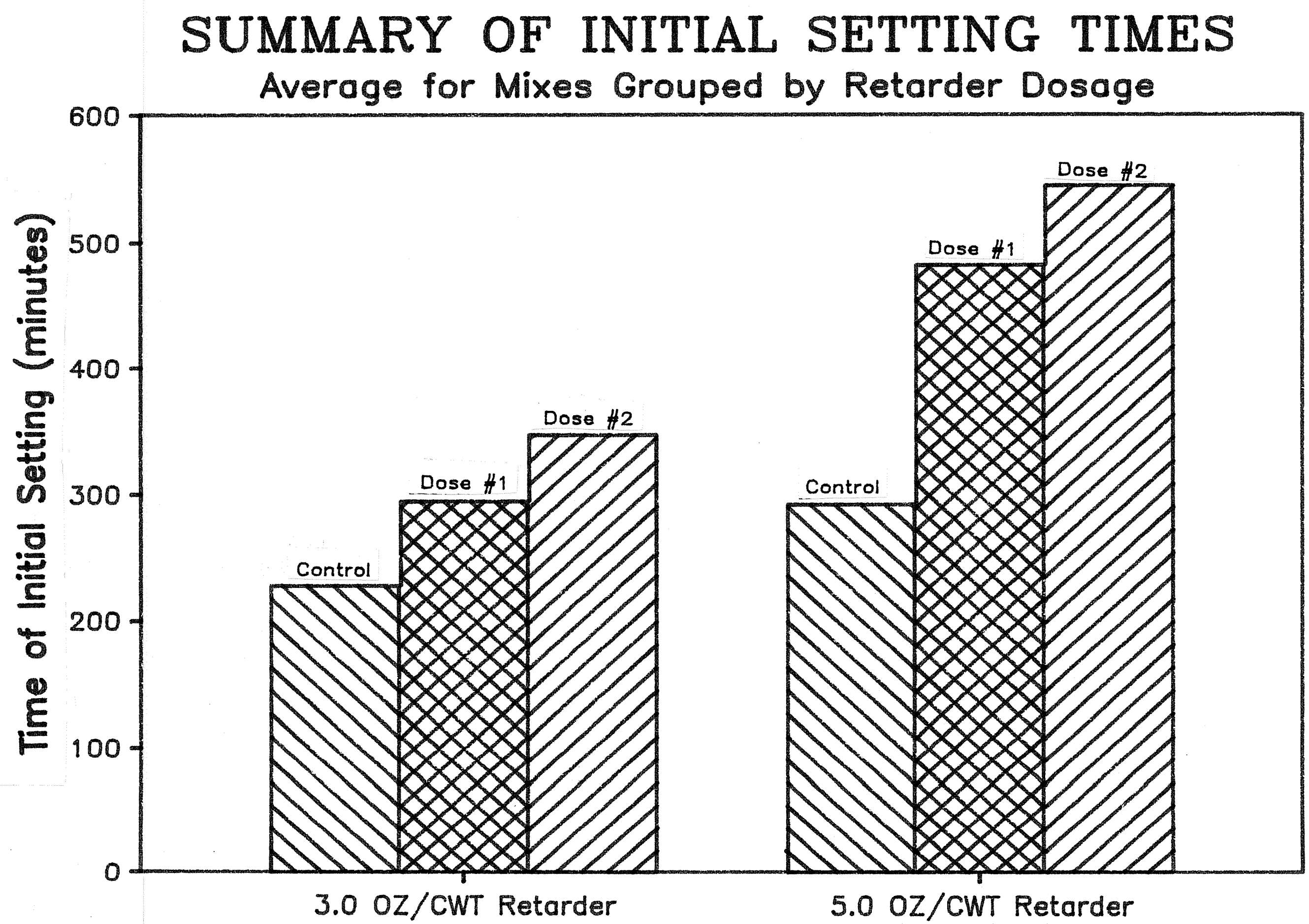


Fig. 5.23 Summary of average initial setting times for control and both superplasticizer dosage specimens for the nine laboratory mixes grouped by retarder dosage

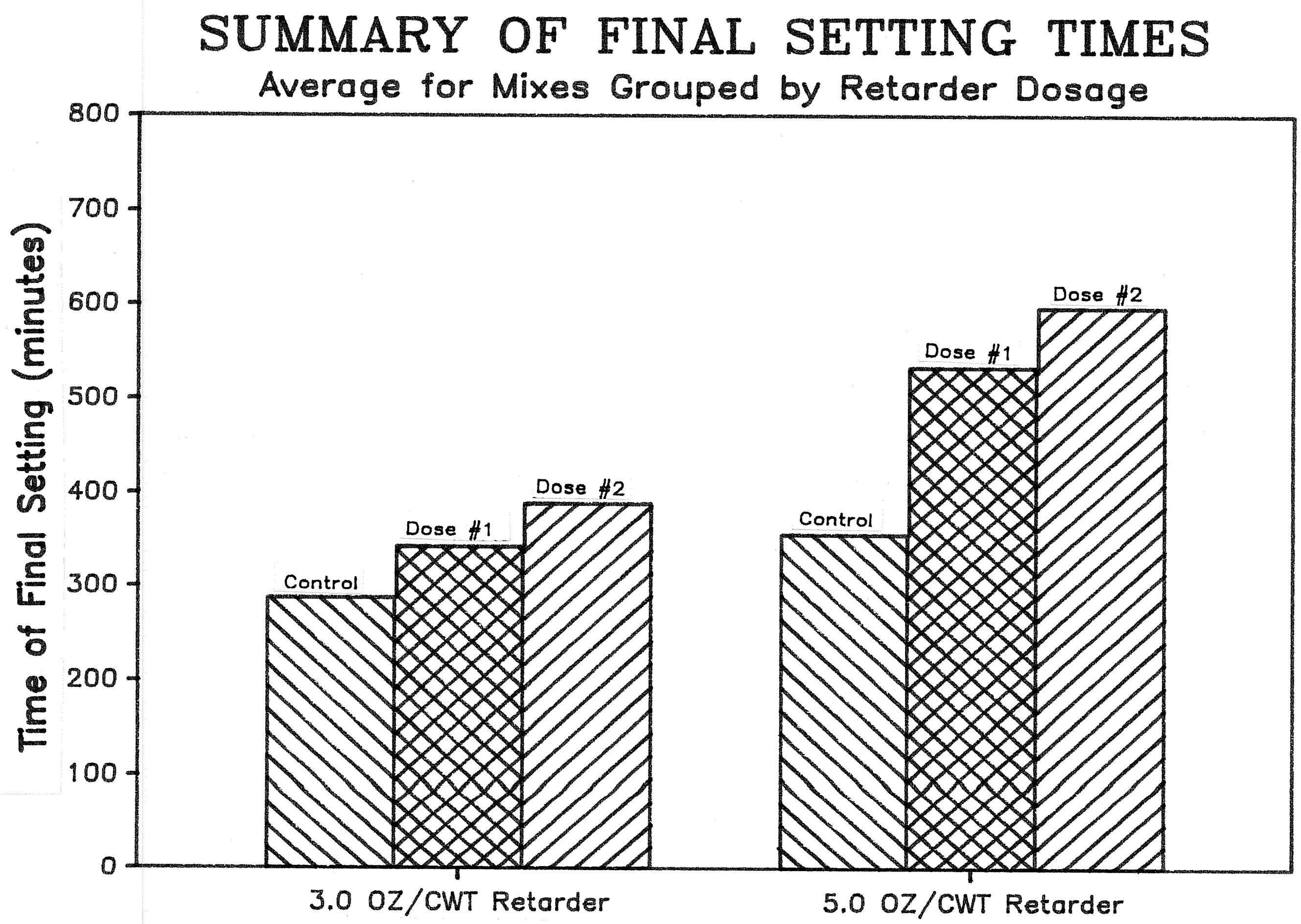


Fig. 5.24 Summary of average final setting times for control and both superplasticizer dosage specimens for the nine laboratory mixes grouped by retarder dosage

Limitations are placed on the deviation from the control sample for initial and final setting times in ASTM C494-86 for Type F admixtures. Initial and final setting times for the superplasticized sample may not be more than one hour earlier nor 1-1/2 hours later than the control sample. Mixes L3, L4, L5, L8, and L9 pass this specification for the first superplasticizer dosage. Mixes L4, L5, L8, and L9 pass this specification for the second superplasticizer dosage. These mixes include those of each cement content, coarse aggregate type, initial slump, air entraining agent, and minimum and maximum superplasticizer dosages.

The most indicative factor in whether the particular mix met the ASTM specifications was retarder dosage. It should be noted, however, that the increase in retarder dosage did not affect the time lapse between initial and final setting of one particular sample.

No correlations were found between the delays in setting times for each laboratory mix and the amount of superplasticizer that was added in order to produce flowing concrete. Neither were any correlations found between the water-cement ratios of the control specimens and accompanying setting times.

These results agree with other researchers [18,23,30,31,40,41,49,58,62] who have stated that initial and final setting times will be delayed when superplasticizers are used. The data is also in accordance with the findings of Malhotra[30] who found that repeated dosages of superplasticizers will further delay stiffening.

5.3 Effects of Superplasticizers on Hardened Concrete

The following section is an analysis of the data recorded from all hardened concrete testing of each of the nine laboratory mixes and nineteen field mixes. The discussion specifically includes the effects of initial and second dosages of two superplasticizers on the compressive strength, flexural strength, and abrasion resistance of the hardened concrete specimens.

5.3.1 Compressive Strength. Figure 5.25 summarizes the results from the compressive strength testing for the nine laboratory mixes at ages of 7 and 28 days. At each test age, the average compressive strength increased from the control specimens to the first dosage specimens and again to the second dosage specimens. The average increase from the control specimens to the first dosage specimens for test ages of 7 and 28 days was 18 and 16%, respectively. The average increase from the control specimens to the second dosage specimens for test ages of 7 and 28 days was 27 and 26%, respectively.

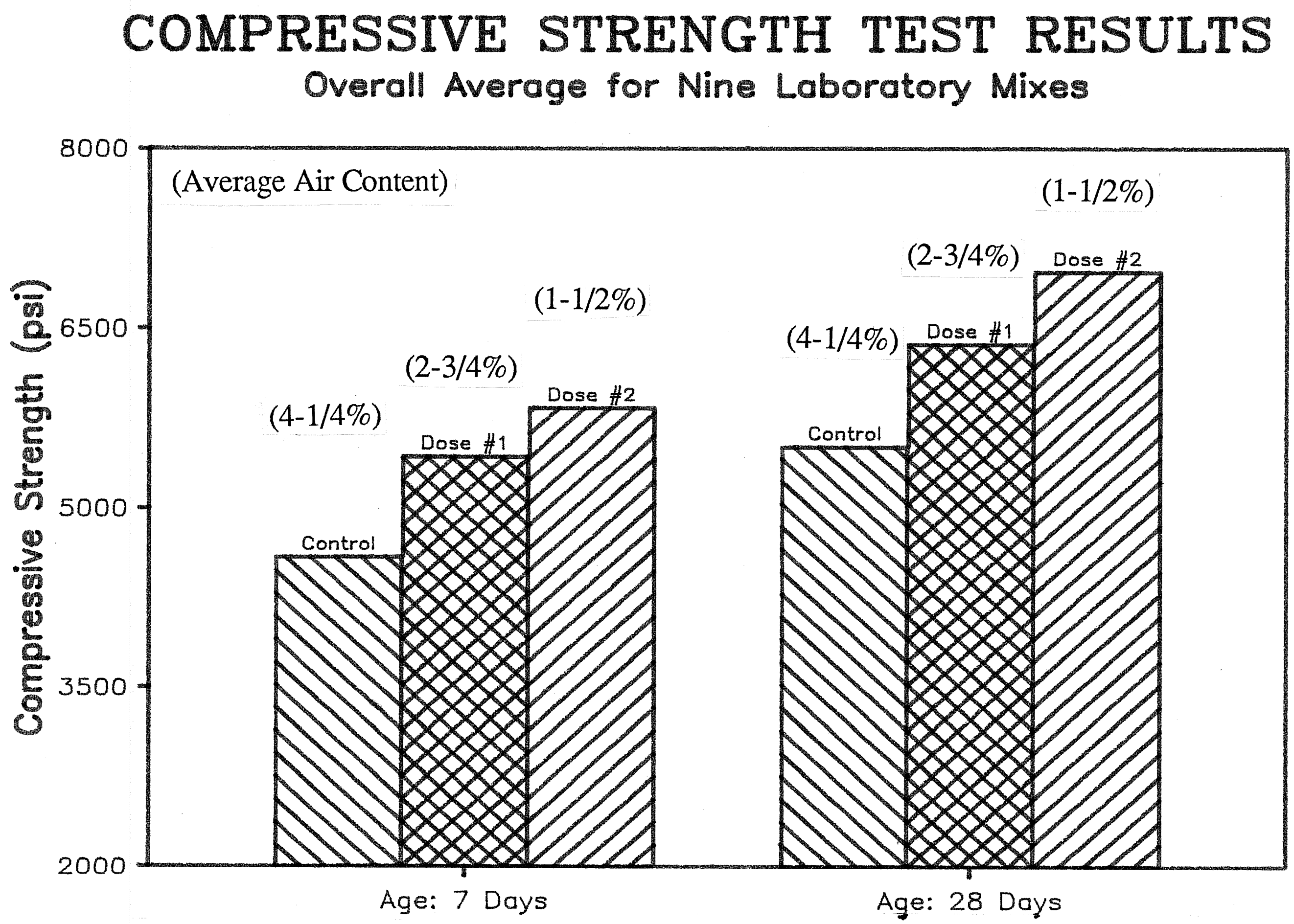


Fig. 5.25 Summary of average compressive strengths at ages of 7 and 28 days for control and both superplasticizer dosage specimens for the nine laboratory mixes

In each case, all companion cylinder compressive strength values met the Texas SDHPT specifications for minimum strength at 28 days. The specifications require a minimum compressive strength of 3000 psi for the 5.0 sack mix and 5500 psi for the 7.0 sack mix.

Additionally, all the superplasticized concrete specimens gave higher strengths than the control specimens at 7 and 28 days. However, ASTM specifications (C494-86) stipulate that concrete with Type F admixtures must provide 15% greater strength than the control specimens at a test age of 7 days and similarly, 10% greater strength at a test age of 28 days. The average values presented in Fig. 5.25 meet these stipulations, but several individual mixes do not. First dosage specimens for Mixes L3 and L7 provide only 7 and 13% increases over the control specimens at a test age of 7 days. First dosage specimens for Mix L3 provide only an 8% increase over the control specimens at a test age of 28 days.

The compressive strength testing for the field mixes will show that, in each case, the compressive strength of the cylinders cast at the end of the 120 minute cycle exceeded the strength of the companion control cylinders cast approximately 15 to 20 minutes after batching. This shows that the compressive strength of concrete dosed with a superplasticizer to a flowing consistency, but cast up to two hours after batching and after the high slump has decayed, can still exceed the compressive strength of the control specimens.

The average increase in compressive strength for these field mix cylinders cast 120 minutes after batching over the control cylinders was 24%. This meets the ASTM specifications of a minimum of 10% increase in compressive strength at 28 days when Type F admixtures are used. Only Mix F4, with an increase of 6% from the control specimens, did not meet the specifications. In each case, companion cylinders met the Texas SDHPT specifications for minimum strength at 28 days.

No correlations were found between the increase in compressive strength for each particular mix and the amount of superplasticizer that was added.

In general, this information is in agreement with previous research. Many investigators[23,29,30,31,38,45,49,55] have found that the addition of a naphthalene based superplasticizer will increase the compressive strength of the concrete. Various researchers have attributed this to the decreases in air content that usually accompany the use of superplasticizers, the likelihood of better consolidation due to the increased workability, and more complete cement hydration due to the dispersing abilities of the superplasticizer. Malhotra [30] and Ramakrishnan et al.[43] have previously shown that repeated addition of and more complete cement hydration due to the dispersing abilities of the superplasticizer. Malhotra [30] and Ramakrishnan et al.[43] have previously shown that repeated addition of a superplasticizer will result in higher strengths each time. This was found to be true for two additions in this investigation.

Sprinkel[55] found larger variations among companion cylinder compressive strength test results for superplasticized concrete; however, examination of Tables 4.1 and 4.3 will show this not the case for this investigation. The standard deviations and coefficients of variation varied both ways, not uniformly worse for the superplasticized concrete. In general, companion cylinder agreement was good. The average standard deviation and coefficient of variation for all the cylinders of each mix was 114 psi and 2.1%, respectively.

5.3.2 Flexural Strength. Figures 5.26 and 5.27 summarize the results from the flexural strength testing for the nine laboratory mixes.

Figure 5.26 shows the overall average results of flexural strength testing for the nine laboratory mixes at ages of 7 and 28 days. At each test age, the average flexural strength increased from the control specimens to the first dosage specimens and again to the second dosage specimens. The average increase from the control specimens to the first dosage specimens for test ages of 7 and 28 days was 6 and 4%, respectively. The average increase from the control specimens to the second dosage specimens for both test ages of 7 and 28 days was 9%.

In all cases except one, companion beam flexural strengths met the Texas SDHPT specifications for minimum strength at 7 days. The specifications require a flexural strength of 500 psi for the 5.0 sack mix and 900 psi for the 7.0 sack mix using center-point loading. Mix L8, with a cement content of 7.0 sacks, only had a flexural strength of 844 psi.

Additionally, all the superplasticized concrete specimens gave equivalent or higher flexural strengths than the control specimens at 7 and 28 days, except for the first dosage specimens of Mix L8 at 28 days. This particular flexural strength was four percent less than the control specimens. ASTM specifications (C494-86) stipulate that concrete with Type F admixtures must provide equal or greater flexural strengths than the control specimens at test ages of 7 and 28 days. These stipulations are satisfied for each mix except Mix L8, as previously described.

Figure 5.27 shows the relationship between the coarse aggregate type and the corresponding percentage increase in flexural strength from the control to first dosage specimens at ages of 7 and 28 days. Those mixes with a crushed limestone coarse aggregate

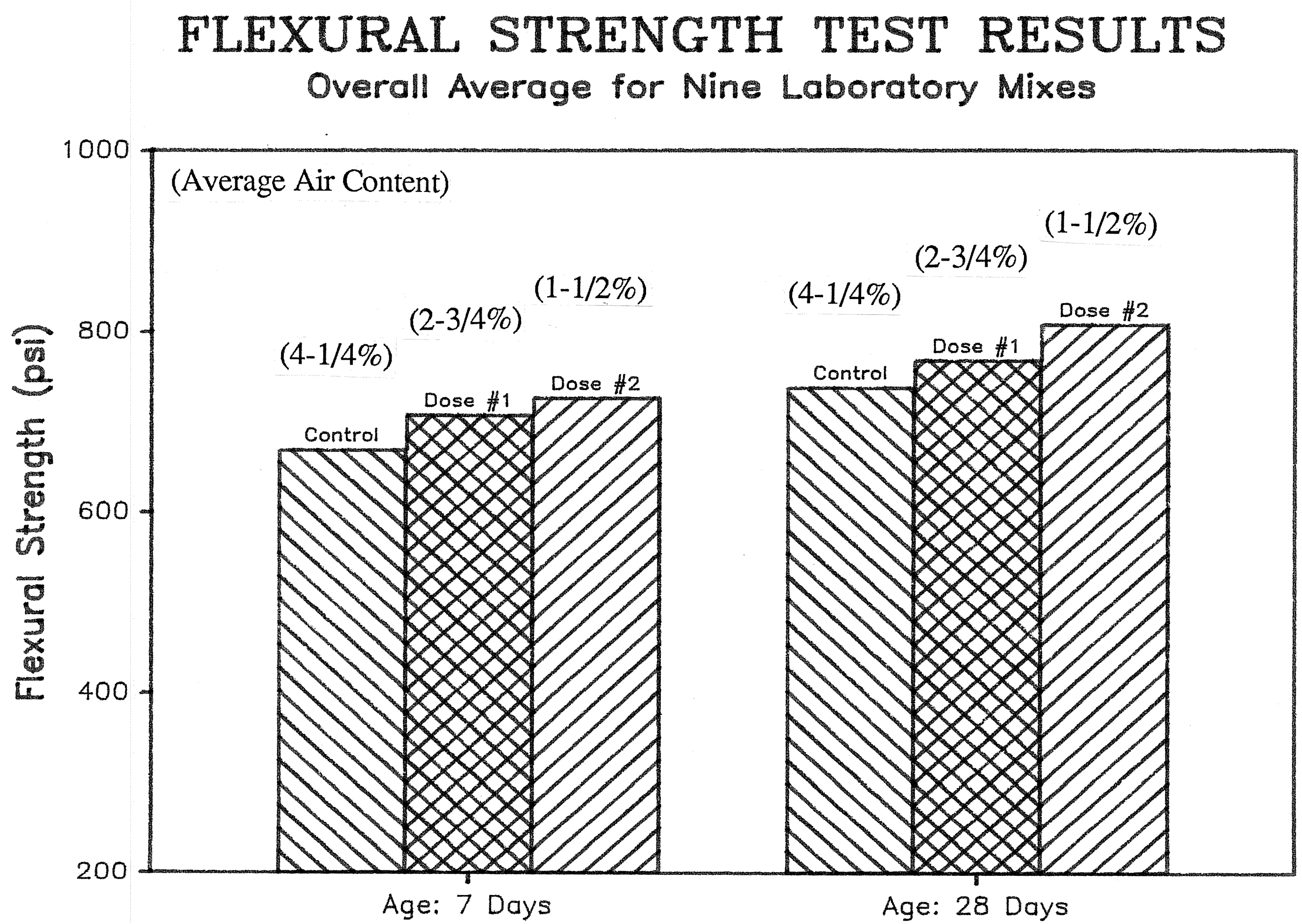


Fig. 5.26 Summary of average flexural strengths at ages of 7 and 28 days for control and both superplasticizer dosage specimens for the nine laboratory mixes

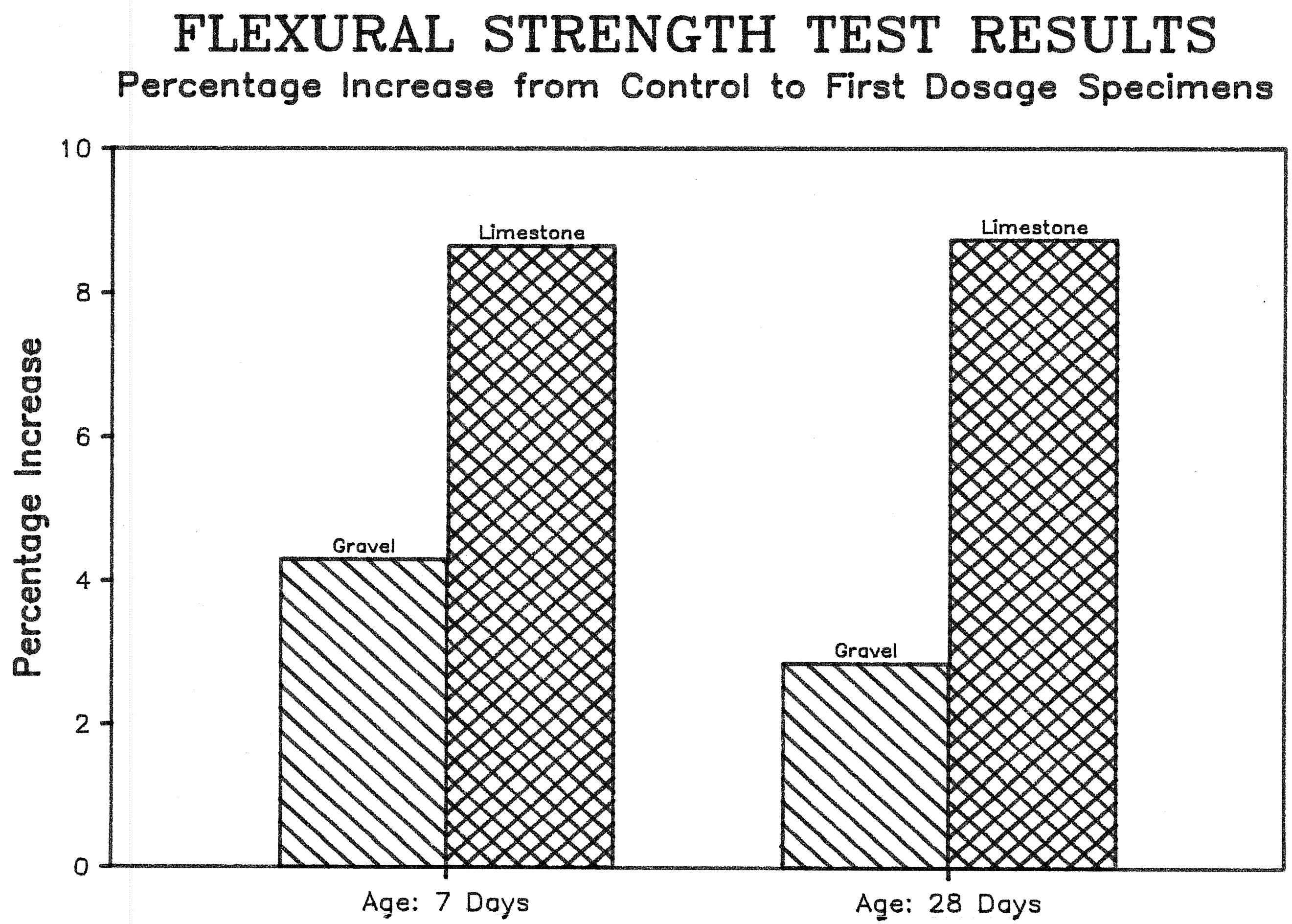


Fig. 5.27 Percentage increase in flexural strengths at 7 and 28 days due to the first superplasticizer dosage for specmiens of the nine laboratory mixes grouped by coarse aggregate type

experienced a much greater increase in flexural strength when the superplasticizer was added, regardless of the test age. This was attributed to the known tendencies for angular rough aggregates to contribute more to the flexural strength of the specimen than a smoother aggregate.

Researchers[22,23,29,31,36] have found that superplasticizers have little effect on the flexural strength of concrete. In this study, however, the superplasticized specimens generally exceeded the control specimens. As with the increase in compressive strength, this may be attributed to the decrease in air content, better compaction, and more complete cement hydration.

The statistical scatter for the flexural strength testing was fairly low. The average standard deviation and coefficient of variation was 34 psi and 3.5%, respectively.

5.3.3 Abrasion Resistance. Figures 5.28 and 5.29 summarize the results from the abrasion resistance testing for the nine laboratory mixes.

Figure 5.28 shows the effect of coarse aggregate type on the average depth of wear after eight minutes for the control specimens with no superplasticizer and the specimens with first and second dosages of superplasticizer. For each specimen type, the mixes with a crushed limestone coarse aggregate exhibited approximately 72% more wear than mixes with gravel coarse aggregate. It is also apparent from Fig. 5.28 that the average abrasion resistance improves with each superplasticizer addition, regardless of the coarse aggregate type.

When examining the mixes individually, it will be found that five of the nine mixes (L1, L4, L5, L6, and L9) show increased resistance to the rotating cutter as each dosage of superplasticizer is added. The abrasion resistance of Mixes L3 and L7 are essentially unaffected by either addition of the admixture. The two remaining mixes, L2 and L8, show varying results. Mix L2 shows that the first dosage specimens performed slightly worse than the control specimens, but that the second dosage specimens performed significantly better than either of the others. Mix L8 shows the first and second dosage specimens to be essentially identical, with both exhibiting increased abrasion resistance beyond the control specimens.

Figure 5.29 summarizes the relationship between the abrasion resistance and compressive strength of the control specimens after eight minutes of testing. The abrasion specimens were tested at an age of eight days; thus, seven day compressive strength values are shown. It is shown that for those mixes with crushed limestone coarse aggregates (L4,

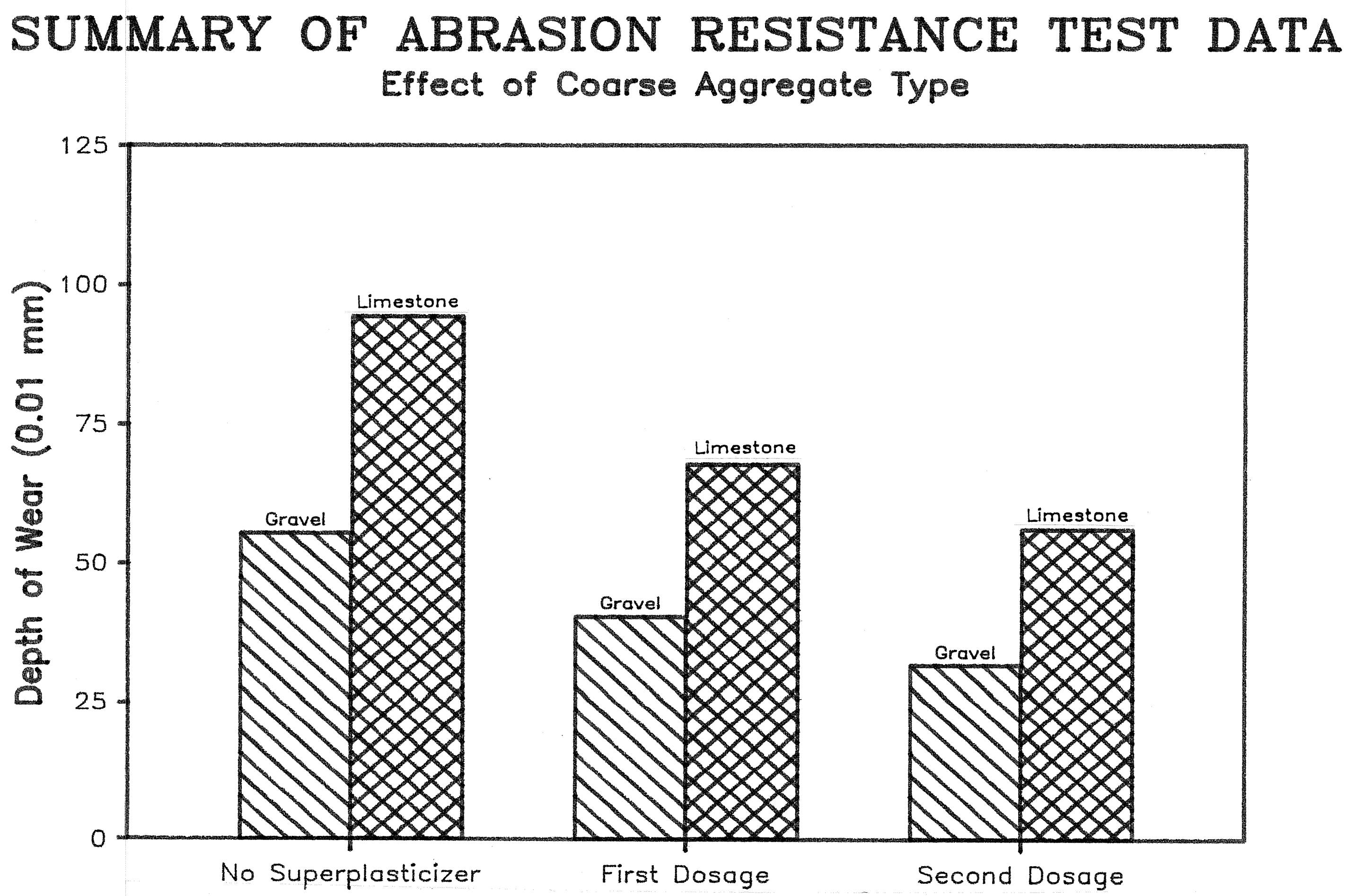


Fig. 5.28 Effect of coarse aggregate type on the average depth of wear due to abrasion after eight minutes for control and both superplasticizer dosage specimens in the laboratory study

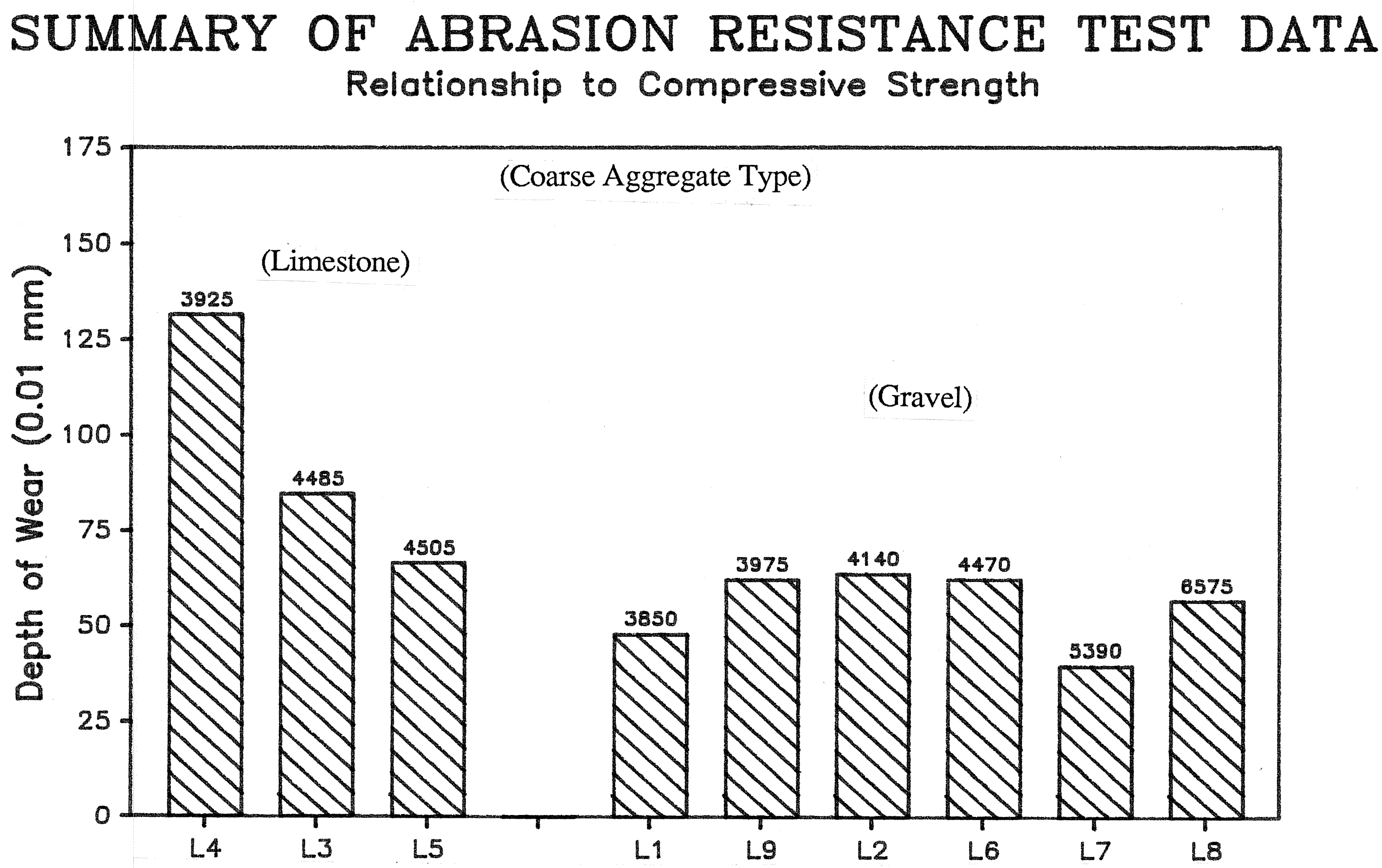


Fig. 5.29 Summary of effect of compressive strength on the depth of wear due to abrasion after eight minutes for the control specimens of each of the nine laboratory mixes grouped by coarse aggregate type

L3, and L5), where the wear from abrasion is greater, an increase in strength does increase the abrasion resistance. For those remaining mixes with the harder river gravel coarse aggregates, an increase in strength does not necessarily increase the abrasion resistance. In fact, the wear is relatively constant for 7 day compressive strengths ranging from 3850 psi to 6575 psi.

The effect of superplasticizers on the abrasion resistance has not been the subject of many investigations. In general, researchers have found abrasion resistance to be dependent on the compressive strength and finishing and curing methods. The data from these nine laboratory mixes has shown that, though the abrasion resistance of all control specimens is not directly related to compressive strength, the superplasticized specimens will generally show improved abrasion resistance. As stated earlier, the compressive strength of the superplasticized specimens was always improved.

These results are in repeated disagreement with the only source found on the effect of superplasticizers on abrasion resistance. Whiting[59] found decreased resistance for a superplasticized specimen compared to the control specimen, even though the compressive strength was improved for the superplasticized specimen.

CHAPTER 6
CASE STUDY

6.1 Introduction

A case study describing the use of superplasticizers in a construction project for the TSDHPT is presented in this chapter. The current existing federal workplan for the use of superplasticizers is discussed as it applied to the casting of segmental bridge elements for a bridge near Beaumont, Texas, over the Neches River. The segments were cast in Victoria, Texas.

6.2 Federal Highway Administration Workplan

The existing guidelines suggested for use by the Federal Highway Administration are presented below. These describe minimum details and the content for a plan to support the elective use of high range water reducers (superplasticizers) in structural concrete. The following steps are part of the proposed procedure for developing a workplan.

(Item 1) Contractor or Supplier to prepare and test at least eight small volume batches containing high range water reducer (HRWR) and recording this information in a manner similar to Table 6.1; four batches with a slump of approximately 4 to 5 inches as shown in Table 6.2, and four batches with a slump of approximately 5 to 6 inches as shown in Table 6.3. It would be desirable for a Department of Highways and Transportation (DHT) representative to witness these tests.

(Item 2) Contractor or Supplier to prepare and test at least one full batch using equipment and batch design representative of that proposed for job based on Item 1 above. Record information the same as in Item 1. DHT to witness all testing, preferable with the project inspection team that will be responsible for job control.

(Item 3) Contractor or Supplier to plan, hold, and document a special preconstruction and training conference on this item to discuss results of testing, proposed mix design, anticipated site conditions, and potential problems during pour using HRWR. DHT project personnel responsible for material control to participate.

(Item 4) DHT to prepare and submit field changes as needed to modify concrete specs as result of trial batches and plan for use.

(Item 5) Report results of usage for a minimum of first two pours or until usage is no longer problematic. Report to be a short narrative description of the process,

I. General Data

A. Project Number(s) ________________

B. Structure Name(s) ________________

C. Structural Element(s) ________________

D. Contractor ________________

E. Conc. Supplier ________________

F. Cement Type and Brand ________________

G. Course Agg. Source ________________

H. Fine Agg. Source ________________

I. Admixtures & Recommended Dosage Range

1. Air ________________

2. Retarder ________________

3. Water Reducer ________________

4. High Range WR ________________

J. Narrative on recommended charging sequence and mixing times at plant and job site, maximum batch size, dosage rates, maximum and desired slump, special procedures to control segregation.

K. If pumping is proposed, slump before and after pumping and air content before and after pumping should be considered and documented.

L. If multiple dosing with HRWR is allowed at site, this procedure should be modeled and tested on the full volume trial batch with appropriate air and slump testing, including air and slump loss with time.

Table 6.1 Suggested form to be used for recording the eight small volume batches

II. **MIX DESIGN USING HRWR**

BASE MIX		TRIAL___#	TRIAL___#	TRIAL___#	TRIAL___#
A. Course Aggregate	______lbs.				
B. Fine Aggregate	______lbs.				
C. Cement	______lbs.				
D. Water	______lbs.				
E. Admixtures					
1. Air	______oz.				
2. Retarder	______oz.				
3. Water Reducer	______oz.				
4. High Range WR	______oz.				
F. Cement Factor	______sacks/yard				
G. Workability Factor	______				
H. Cement Water Ratio	______gal/sack				
I. Slump (initial)	______in.	5 to 6	5 to 6	5 to 6	5 to 6
J. Air Content	______%				
K. Concrete Temperature	______F	65	75	85	95
L. Air Temperature	______F				
M. Strength					
1. 7 Day Beam	______psi				
2. 28 Day Cylinder	______psi				
N. Slump Loss					
1. Initial + 15 min.	______in.				
2. Initial + 30 min.	______in.				
3. Initial + 45 min.	______in.				
O. Time to Set	______hrs.				
P. Air Content I + 30 min.	______%				

Table 6.2 Suggested form to be used for mix design and material testing for 5 to 6 inch slump mixes at varying temperatures

II. MIX DESIGN USING <u>HRWR</u> (continued)

BASE MIX		TRIAL ___ #	TRIAL ___ #	TRIAL ___ #	TRIAL ___ #
A. Course Aggregate	___ lbs.	___	___	___	___
B. Fine Aggregate	___ lbs.	___	___	___	___
C. Cement	___ lbs.	___	___	___	___
D. Water	___ lbs.	___	___	___	___
E. Admixtures					
1. Air	___ oz.	___	___	___	___
2. Retarder	___ oz.	___	___	___	___
3. Water Reducer	___ oz.	___	___	___	___
4. High Range WR	___ oz.	___	___	___	___
F. Cement Factor	___ sacks/yard	___	___	___	___
G. Workability Factor	___	___	___	___	___
H. Cement Water Ratio	___ gal/sack	___	___	___	___
I. Slump (initial)	___ in.	4 to 5	4 to 5	4 to 5	4 to 5
J. Air Content	___ %	___	___	___	___
K. Concrete Temperature	___ F	65	75	85	95
L. Air Temperature	___ F	___	___	___	___
M. Strength					
1. 7 Day Beam	___ psi	___	___	___	___
2. 28 Day Cylinder	___ psi	___	___	___	___
N. Slump Loss					
1. Initial + 15 min.	___ in.	___	___	___	___
2. Initial + 30 min.	___ in.	___	___	___	___
3. Initial + 45 min.	___ in.	___	___	___	___
O. Time to Set	___ hrs.	___	___	___	___
P. Air Content I + 30 min.	___ %	___	___	___	___

Table 6.3 Suggested form to be used for mix design and material testing for 4 to 5 inch slump mixes at varying temperatures

problems encountered, resolutions reached and the results of all job control testing performed during pour.

The implementation of the guidelines for developing a workplan as presented by the FHWA has been faced with limited success in the field. One of the main obstacles faced by the contractor in meeting the FHWA requirements is the need to conduct trial batches at temperatures ranging from 65°F to 95°F prior to the start of the job. Although there is no question that concrete temperature is one of the most relevant variables affecting the performance of superplasticizers in concrete, there are limited facilities available where a contractor can conduct trial mixes over the specified temperature range. This will require the availability of environmental chambers with enough capacity to allow for mixing of concrete inside.

6.3 Case Study: Neches River Bridge

This section contains a description of the process followed for achieving the development of a workplan with the approval of state and federal agencies for use of superplasticizers in concrete. The concrete produced was to be used in the casting of precast segmental bridge box sections for the construction of the Neches River Bridge in Texas. The plan incorporated the following provisions:

(1) Information relating to the equipment, materials, and concrete mixture design,

(2) Main Work Plan for the production of superplasticized concrete with a desired slump of 5 to 8 inches,

(3) Modified Work Plan for the production of superplasticized concrete with a desired slump of 3 to 5 inches,

(4) Precautions for hot weather, and

(5) Precautions for cold weather.

The Main Work Plan required a highly workable mix for casting of the top slabs of the typical box segments, the struts, the superstructure pylons, and the top slabs of the pier deck segments. A total of four trial batches were made. Figure 6.1 shows the variation in slump with time as observed at the jobsite prior to the development of an adequate workplan. From this figure, it can be observed that the slump loss of the concrete was significant and the variations in slump with time were unpredictable. Without a doubt, the use of superplasticizers under these conditions would not result in a successful concreting

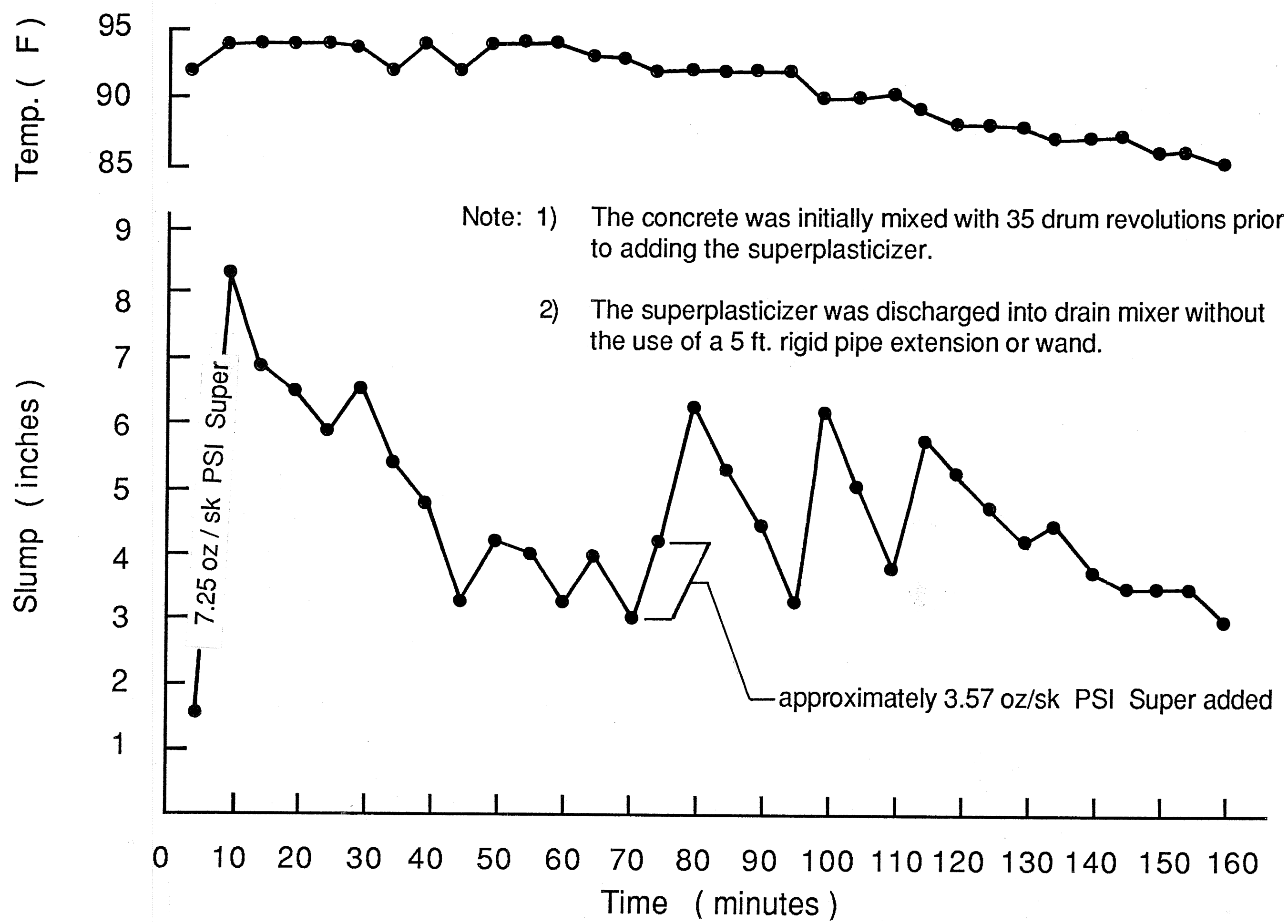


Fig. 6.1 Slump loss and concrete temperature change study carried out prior to the development of an adequate workplan

operation. The results of change in slump and temperature with time for the four trial batches are shown in Fig. 6.2 through 6.5. Compressive strength results are shown for the trial batches in Table 6.4. The data indicates the concrete strengths were adequate since they significantly surpassed the required strength range of 5500 to 6000 psi at 7 days.

The main objective in developing the workplan was to establish a procedure and practice that will allow the consistent production of superplasticized concrete in agreement with the concrete specifications and specific conditions of this job including materials selection and their proportions and batching, mixing, and casting operations.

As a result of the trial batches, the following guidelines were established:

("1) Superplasticizer will not be allowed to be added to the concrete until after initial mixing is achieved.

(2) The initial mixing of the concrete will involve 50 drum revolutions.

(3) The concrete must contain 7.0 OZ/SK of Type D admixture that will be added during initial batching for every load.

(4) Superplasticizer will be added to concrete having a desired slump range of 1-1/2 to 2-1/2 inches.

(5) The first addition of superplasticizer to the concrete must be made within 30 minutes after initial mixing.

(6) If the slump of the concrete prior to the first addition of superplasticizer is below one inch, the contractor can adjust the slump of the concrete to within the desired slump range of 1-1/2 to 2-1/2 inches by the addition of hold water as per existing specifications. The addition of hold water will be performed prior to the addition of superplasticizer. After the addition of hold water, the concrete will be mixed a minimum of 25 drum revolutions.

(7) Add the superplasticizer, approximately 7.25 OZ/SK or less, after the mixer drum is reversed to a point just short of discharge and stopped. Discharge the superplasticizer at the front end of the drum through a five-foot rigid pipe extension or wand.

(8) After the first addition of superplasticizer, no water will be added to the concrete.

(9) After the first and any following addition of superplasticizer, the concrete shall be mixed for 70 drum revolutions prior to sampling for slump.

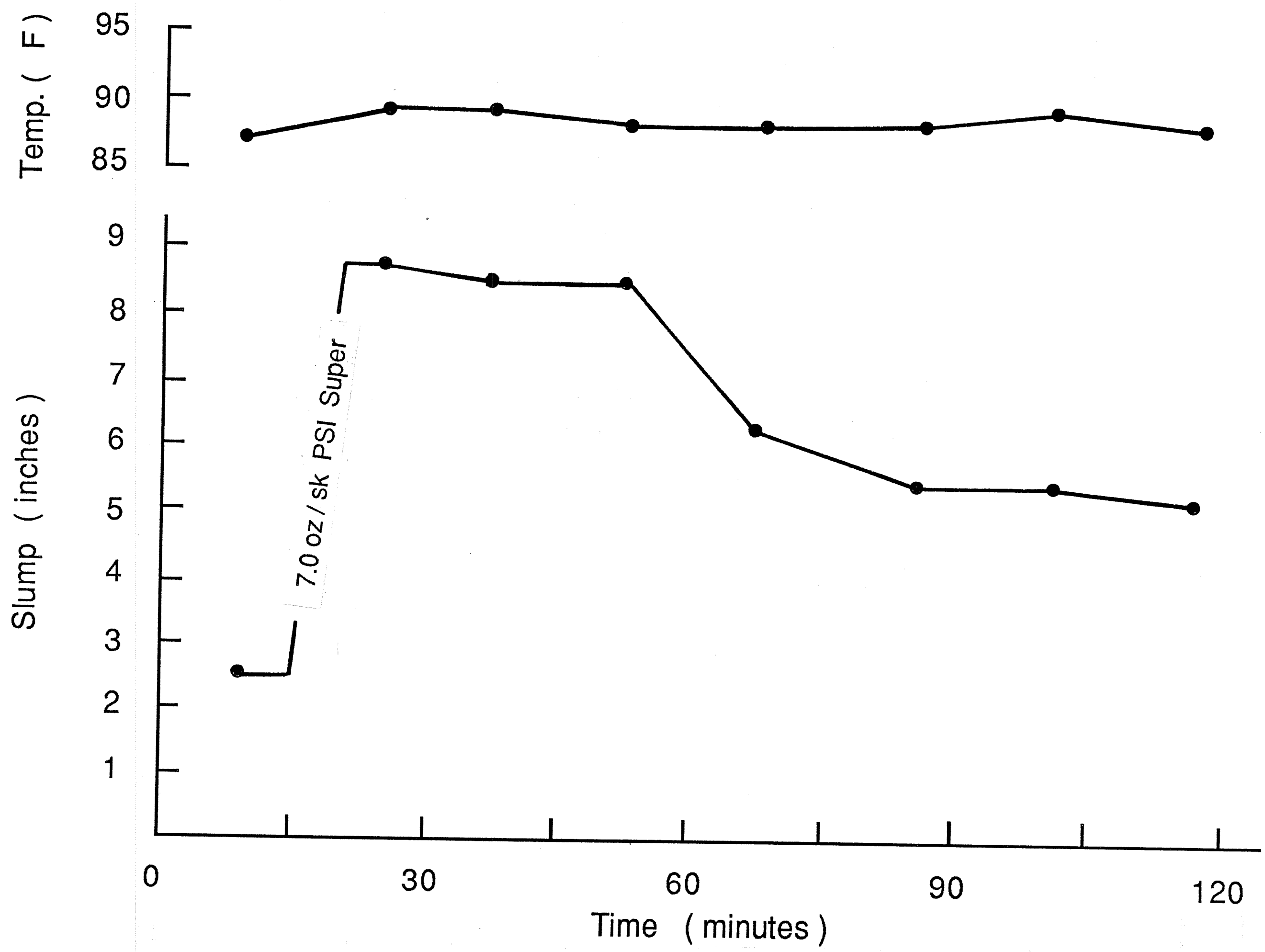


Fig. 6.2 Slump loss and concrete temperature change for trial batch #1

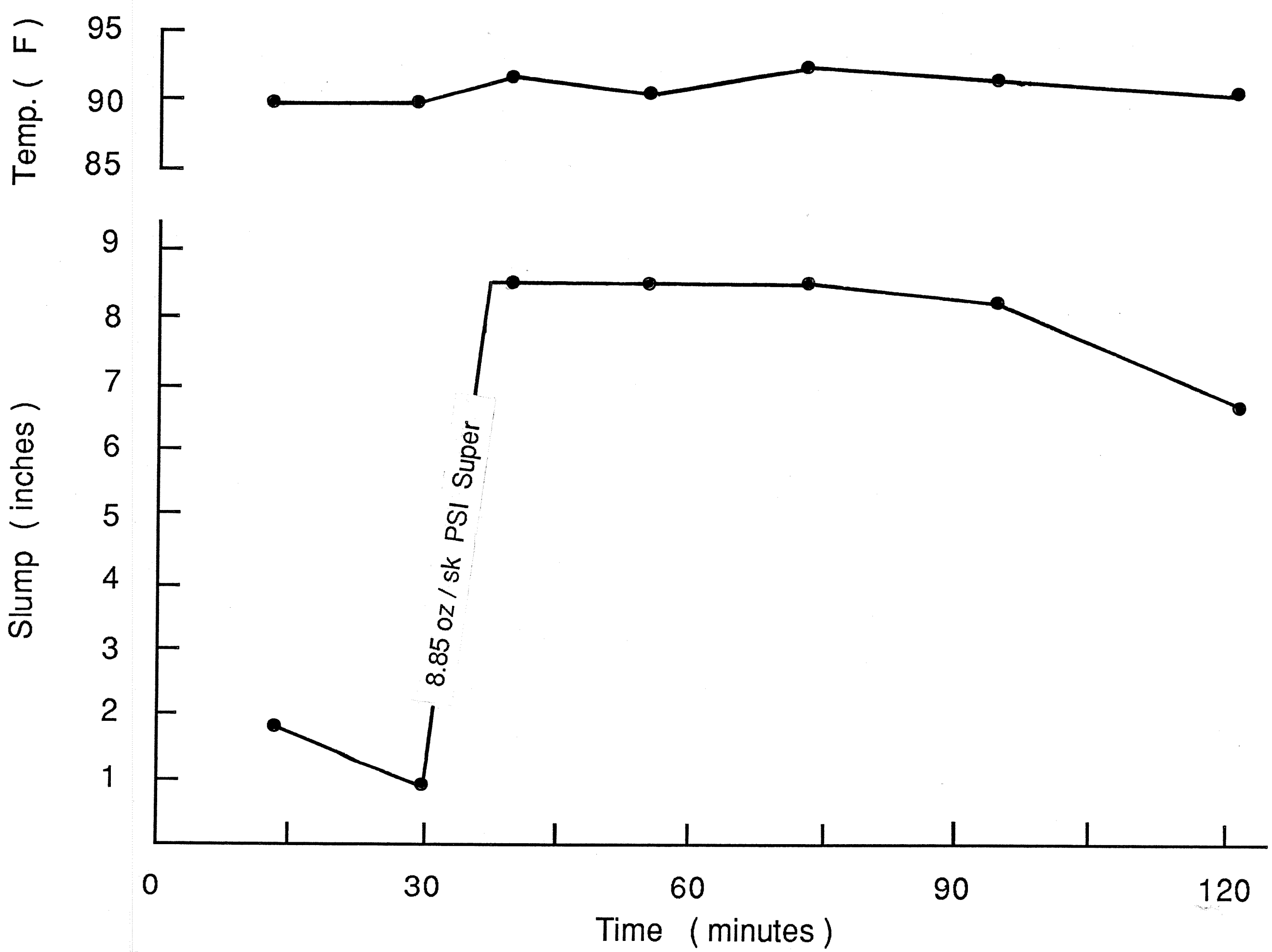


Fig. 6.3 Slump loss and concrete temperature change for trial batch #2

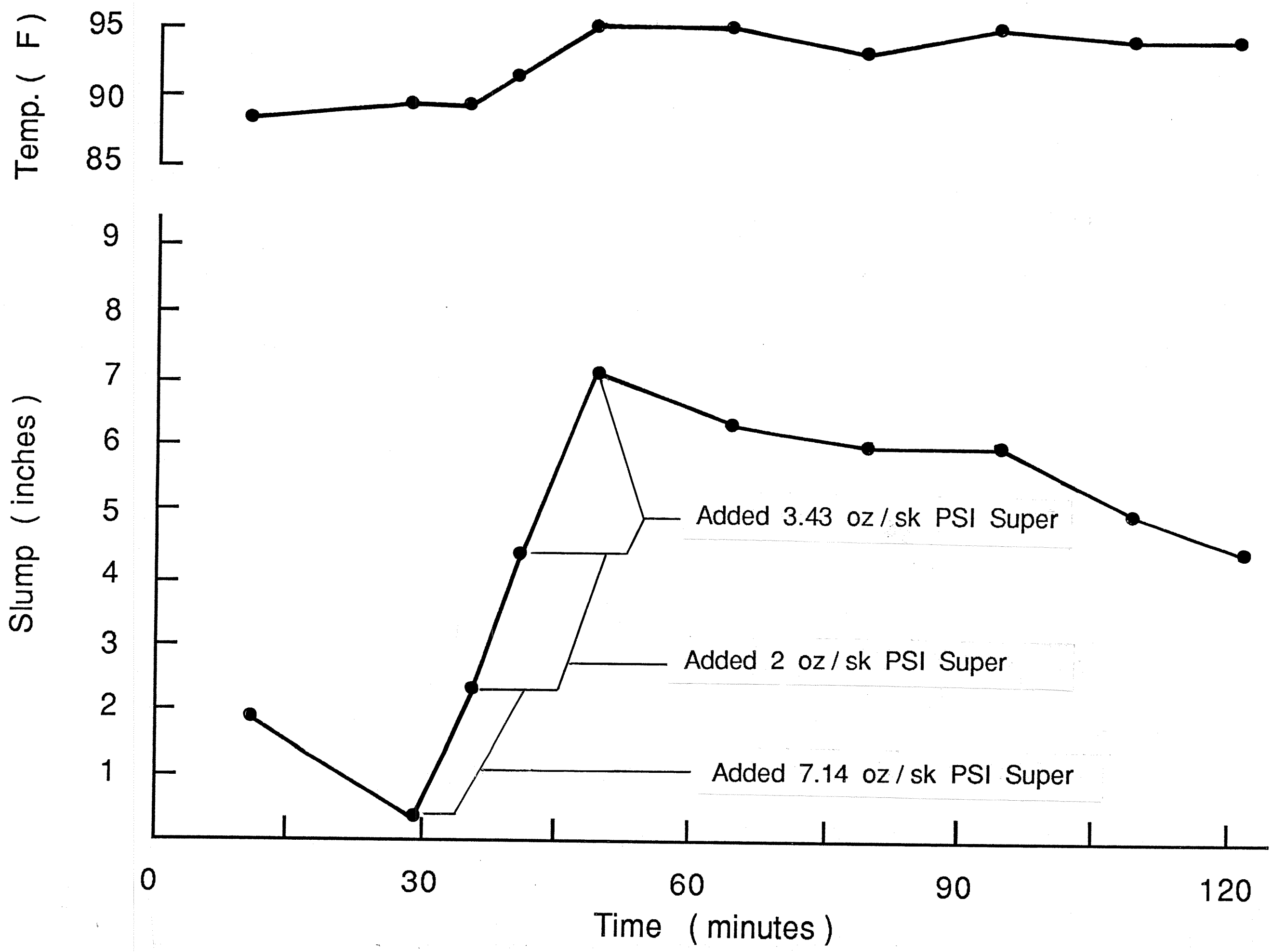


Fig. 6.4 Slump loss and concrete temperature change for trial batch #3

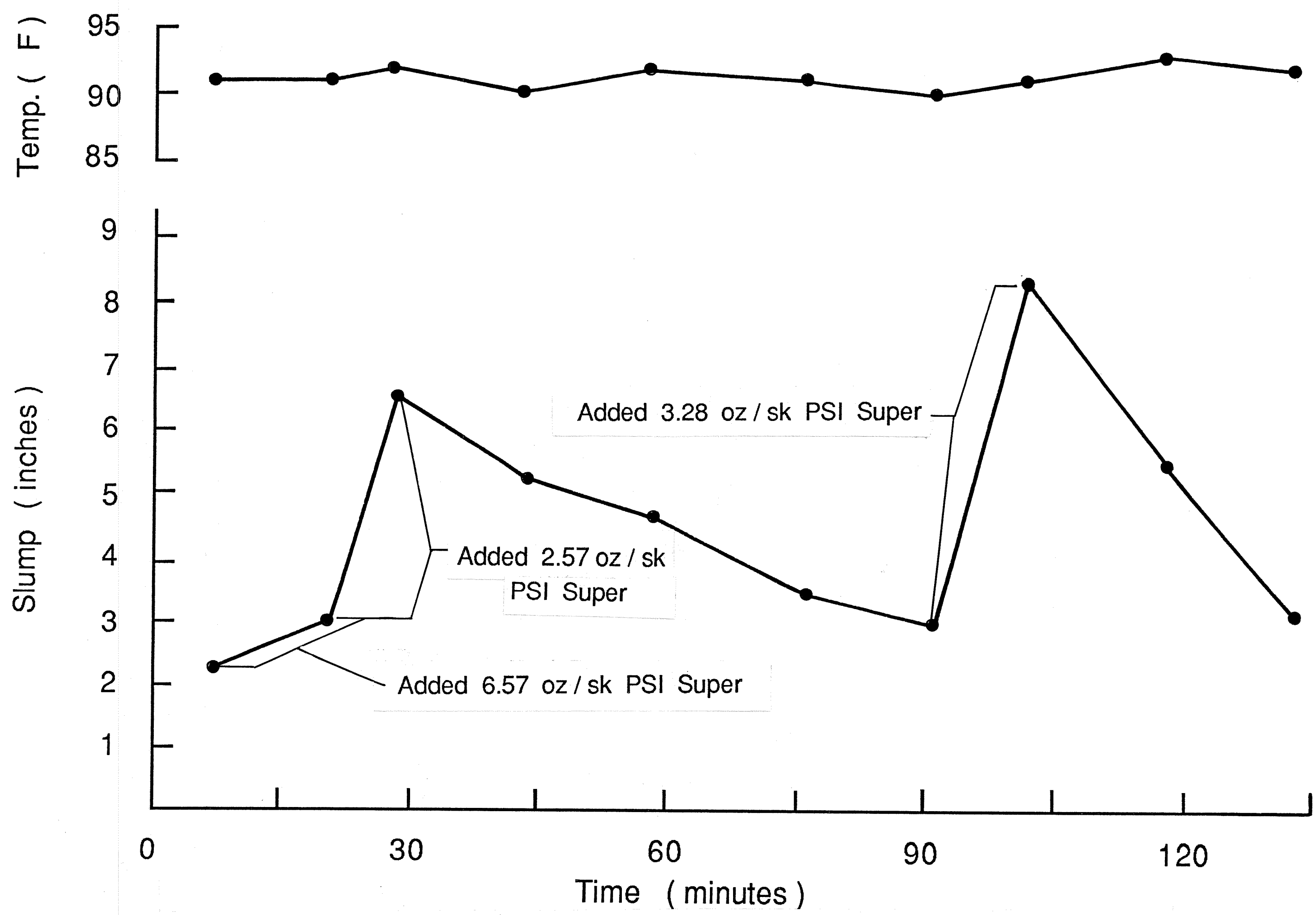


Fig. 6.5 Slump loss and concrete temperature change for trial batch #4

Table 6.4 Compressive Strengths for Trial Batches

Trail Batch	Description When Cylinders Were Cast	Test Age 1 Day	7 Days	28 Days
#1	As Flowing Concrete	4870 psi	7580 psi	8280 psi
	92 Minutes After Flowing Concrete	4540 psi	7210 psi	N/A
#2	Immediately	N/A	7050 psi	N/A
	As Flowing Concrete	4890 psi	7780 psi	8700 psi
	81 Minutes After Flowing Concrete	5160 psi	6910 psi	N/A
#3	Immediately	N/A	7600 psi	N/A
	As Flowing Concrete	5910 psi	8820 psi	9610 psi
	72 Minutes After Flowing Concrete	6330 psi	8360 psi	9160 psi
#4	Immediately	N/A	6060 psi	N/A
	As Initial Flowing Concrete	5080 psi	6930 psi	7470 psi
	As Second Dosage to Flowing Concrete	5800 psi	7380 psi	8620 psi

(10) If the slump of the concrete after the addition of superplasticizer is between 8 and 9 inches, acceptance of the concrete will be dependent on the material not exhibiting segregation or excessive bleeding as determined by the Materials and Tests inspector. However, it will be the responsibility of the contractor to make necessary adjustments in the superplasticizer dosage rate for subsequent batches in order for the concrete not to exceed an 8 inch slump. Subsequent batches will not be allowed to be placed with over an 8 inch slump during the continuous casting operation.

(11) Concrete with an original slump of over 9 inches will not be accepted for use.

(12) If the concrete has a slump of less than the desired slump range of 5 to 8 inches after mixing with superplasticizer, an immediate redose may be allowed to achieve the desired slump.

(13) A second redose of the concrete will be allowed if the slump of the concrete falls below 3 inches and can still be placed within 90 minutes after initial mixing.

(14) The maximum size concrete batches will be 75% of the readymix truck rated capacity."

The Modified Work Plan required a less workable mix for the sloped web sections of certain pier deck segments. The desired minimum compressive strength was 7000 psi at 7 days. Compressive strength values at 28 days averaged 8820 psi for the pilot test. Two exceptions to the Main Work Plan were found to be necessary for the Modified Work Plan.

("1) The concrete will have approximately 5.0 OZ/SK of superplasticizer added into the drum after initial mixing.

(2) The concrete, after addition of the HRWR, should have a desired slump range of 3 to 5 inches."

Precautions for hot weather included the following:

("1) During charging and initial mixing speeds, the outside of the readymix truck drum may be cooled by spraying water on the rotating drum.

(2) The coarse aggregate stockpiles may be watered with a soaker hose to created a mist covering as large an area as possible. Watering of the stockpiles will not be allowed within six hours prior to casting to insure fairly uniform coarse aggregate moisture."

Precautions for cold weather included the following:

> For cold weather concreting, where the expected concrete temperature will be below 60°F, adjustments in the amount of retarder and superplasticizer required will be determined on the basis of trial batches. These trial batches will be performed when cooler weather approaches in order that an adjusted design is prepared in advance.

CHAPTER 7
SUMMARY, CONCLUSIONS, GUIDELINES, AND RECOMMENDATIONS

7.1 Summary

The main objective of this research was to provide field personnel with guidelines for avoiding the potential problems that accompany the use of superplasticizers in readymix concrete and to ensure the production of good quality and durable concrete containing superplasticizers. Tests for workability, air content, unit weight, setting times, strength, and durability were conducted for nine readymix truck loads in the laboratory study. Tests for workability, air content, and strength were conducted for nineteen readymix truck loads in the field study. Variables for these mixes included initial slump, coarse aggregate type, cement content, retarder dosage, time of addition, and admixture combinations.

This study is part of continuing research being conducted at the Phil M. Ferguson Structural Engineering Laboratory. Whereas this study was limited to hot weather mixes, a successive study will report the effects due to the use of superplasticizers in cooler weather. The results of this first study show that superplasticizers can provide desirable characteristics for a concrete mix, such as increased workability, increased compressive and flexural strengths, and increased resistance to abrasion. However, superplasticizers can also produce undesirable and deleterious characteristics for a concrete mix, such as rapid slump loss, loss of air, and delayed finishing due to delayed setting times.

The decision of whether to use superplasticizers is a choice that should be based on considerations for each specific application. The admixture can be an advantageous component for the concrete mix, but may just as easily create more problems than the situations that led to the consideration for use of the admixture. The field engineer must be aware that the use of superplasticizers is not a substitute for good concrete practice and job control testing. In a consideration of the technical benefits or shortcomings, an economic analysis should not be ignored.

7.2 Conclusions

The following conclusions are based on an analysis of the results of this research project presented in Chapter 4 and discussed in Chapter 5.

(1) The rate of slump gain for the first superplasticizer dosage to flowing concrete is increased for greater retarder dosages, higher initial slumps, and earlier times of addition.

(2) The rate of slump loss after the first superplasticizer dosage to flowing concrete is decreased for mixes with river gravel coarse aggregates and lower cement contents. The amount of retarder did not affect the rate of slump loss as long as flowing concrete was achieved.

(3) The capability of achieving flowing concrete through the use of superplasticizing admixtures during hot weather is dependent on the use of an adequate amount of retarding mixture.

(4) Air contents of the fresh concrete were decreased with each dosage of the naphthalene based superplasticizer; however, larger retarder dosages and earlier times of addition decreased the magnitude of these losses.

(5) The use of superplasticizers to produce flowing concrete will delay proper finishing and setting times.

(6) The use of superplasticizers to produce flowing concrete is not deleterious to compressive or flexural strengths at ages of 7 and 28 days.

(7) The use of superplasticizers to produce flowing concrete will usually increase the resistance to abrasion of the concrete.

7.3 Guidelines for the Proper Use of Superplasticizers

This section consists of guidelines for the proper use of superplasticizers when producing flowing concrete in hot weather. These guidelines will be of particular interest to field personnel and resident engineers who are involved in projects where the use of the admixture is being contemplated or has been approved. Once testing for both hot weather and cold weather conditions, a complete and detailed set of guidelines would be published as a separate report. At this time, this report contains test results to date as these affect or influence the proper use of superplasticizers in the field.

(1) Choose material suppliers who can provide cement, aggregates, and admixtures with fairly consistent physical and chemical properties.

(2) Evaluate in-place strength and durability requirements for the structural concrete. In particular, what amount, if any, of air entrainment is required?

(3) Evaluate job site location with respect to readymix facilities for estimation of a reasonable transit time to establish a time of addition for the superplasticizer to the fresh concrete mix.

(4) This experimental program has shown that, unless the superplasticizer can be added 30 minutes after initial water:cement contact, some retarding admixture is needed.

(5) If it is necessary for the concrete to be air-entrained, it has been shown that a naphthalene based superplasticizer can significantly reduce the effectiveness of vinsol resin and specially developed air-entraining agents. Therefore it is most likely necessary that the mix be proportioned for an air content of 2 to 4 percent higher than that recommended by the specifications.

(6) Establish mix proportions for production of readymix concrete with an initial slump of 2 to 4 inches when the time of addition is approximately 60 minutes; if the time of addition is delayed to approximately 90 minutes, an initial slump of 4 to 6 inches is more appropriate. In either case, the slump of the concrete should not fall below approximately one inch before the superplasticizer is added.

(7) Execute at least one full trial batch using actual materials to determine material compatibility and the adequacy of air-entrainment after the initial dosage to flowing concrete at the estimated time of addition. Conduct intermittent tests for air content before and after the addition of superplasticizer up until the time when placement is estimated to have been completed.

(8) In addition to tests for air content, it is desirable to conduct intermittent slump tests, to monitor the fresh concrete temperature, and to cast cylinders and/or flexural beams. This will allow determination of a reasonable working time, detection of a temperature rise in the concrete, and a method to ensure that minimum strength specifications are met.

(9) Evaluate the slump test results and limit the readymix truck load to a volume that may be placed and consolidated within the time frame for continuing acceptable workability.

(10) If it is not necessary for the concrete to be air- entrained, a second superplasticizer dosage would not be detrimental to the properties of the concrete mix except for setting times. This, however, can extend finishing to significantly later times.

This would not be a consideration for members with formed finishes, such as columns.

(11) The study of different retarder dosages in this research program has shown that while a larger retarder dosage can not delay slump loss, it can decrease the amount of superplasticizer required to produce flowing concrete. Larger retarder dosages will delay setting times further.

(12) The concrete should be mixed thoroughly, at least five minutes, after the addition of superplasticizer. Placement should begin immediately.

(13) No changes are necessary in standard recommendations for adequate consolidation and curing.

7.4 Recommendations for Further Research

A complete listing of guidelines for the proper use of superplasticizers is not possible from this research. However, the research program has provided a basis for further research and has raised a few specific questions that further research can address. Additional topics for research that may help meet the objective for the development of guidelines for the proper use of superplasticizers are the following:

(1) Examine variables and mix proportion changes for readymix loads similar to this research program in cooler weather to determine the effect of temperature change on rates of slump loss, required dosages of superplasticizer to achieve flowing concrete, interaction of superplasticizers with other admixtures, other fresh concrete properties, and strength and durability.

(2) Examine effects of newer plant-added slump-retentive superplasticizers on similar properties of fresh and hardened concrete tested in this research program.

(3) Examine effects of pozzolans such as fly ash on concrete mixes to which a superplasticizer is added to examine changes in tendencies for segregation and excessive bleeding, rates of slump loss, and air loss.

(4) Conduct tests to determine the air-void system of the hardened concrete specimens for inclusion with results of freeze-thaw and deicing-scaling testing.

(5) Conduct placement and finishing of full scale flatwork and use experienced personnel to determine differences in finishing characteristics.

(6) Examine more mixes of varying cement contents and include cements with different sulfate contents to determine the effects on rates of slump loss.

(7) Conduct accelerated strength testing for correlation with strengths at 28 days from standard curing as this method of quality control becomes more common.

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