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16. Abstract

The main objective of the work described herein is to determine if the use of superplasticizing admixtures to produce high slump concrete affects the bond performance of deformed bars embedded in that concrete. Although many material properties of the concrete are affected by the addition of superplasticizer, it is intended that the research results will indicate which factors play a dominant role in determining the bond behavior. A research program was developed which would allow the study of the effect of naphthalene and melamine-based superplasticizers on not only the material properties of concrete, but also the bond behavior between concrete and reinforcement. Bond behavior was studied through pullout tests, in which the applied load and corresponding slips at the bar's free and loaded ends were recorded continuously throughout the test. Thirteen pullout specimens were cast, each containing nine pullout bars. The following material properties of the fresh concrete were monitored, both before and after the addition of superplasticizer to the concrete: slump, bleed, temperature, and air content. Also, the effect of superplasticizer on the compressive and tensile strengths of the concrete was determined. The results of this study indicate that the addition of naphthalene or melamine-based superplasticizer to concrete does not detrimentally affect the bond performance of reinforcing steel embedded in that concrete. However, the addition of superplasticizer to concrete does affect its rheological properties, namely bleed and air content. For this reason, trial batches should be made under the expected job conditions when superplasticizer is to be used in concrete in order to ensure proper performance of the concrete.

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# ANCHORAGE AND DEVELOPMENT OF REINFORCEMENT IN CONCRETE MADE USING SUPERPLASTICIZERS

by

P.L. Musser, R.L. Carrasquillo, J.O. Jirsa,
and R.E. Klingner

Research Report No. 383-1

Research Project No. 3-5-84-383
"Anchorage and Development of Reinforcement
in Concrete Made Using Superplasticizers"

Conducted for

Texas

State Department of Highways and Public Transportation

In Cooperation with the
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by

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

September 1985

# PREFACE

Superplasticizers, or high-range water-reducing admixtures, are currently being used mostly in precast plants, and also in the production of high strength concrete. The use of superplasticizer in the field as a workability agent offers savings in placing and finishing costs. However, due to the associated slump loss, the admixture must be added to the concrete at the jobsite. Because of the lack of specifications governing the field use of superplasticizer and questionable quality control, ready-mix producers have been hesitant to accept this relatively new type of admixture.

Since their introduction to North America, many researchers have investigated the effect of superplasticizers on the material properties of fresh and hardened concrete. However, no studies have been reported on the structural aspects of superplasticized concrete. The main objective of this research program is to determine which, if any, of the many material properties of concrete affected by the addition of superplasticizer may prove to be relevant to the concrete-reinforcing steel bond performance.

This study is part of a broad research project sponsored by the Texas State Department of Highways and Public Transportation, and administered by the Center for Transportation Research at The University of Texas at Austin.

## SUMMARY

The main objective of the work described herein is to determine if the use of superplasticizing admixtures to produce high slump concrete affects the bond performance of deformed bars embedded in that concrete. Although many material properties of the concrete are affected by the addition of superplasticizer, it is intended that the research results will indicate which factors play a dominant role in determining the bond behavior.

A research program was developed which would allow the study of the effect of naphthalene and melamine-based superplasticizers on not only the material properties of concrete, but also the bond behavior between concrete and reinforcement. Bond behavior was studied through pullout tests, in which the applied load and corresponding slips at the bar's free and loaded ends were recorded continuously throughout the test. Thirteen pullout specimens were cast, each containing nine pullout bars. The following material properties of the fresh concrete were monitored, both before and after the addition of superplasticizer to the concrete: slump, bleed, temperature, and air content. Also, the effect of superplasticizer on the compressive and tensile strengths of the concrete was determined.

The results of this study indicate that the addition of naphthalene or melamine-based superplasticizer to concrete does not detrimentally affect the bond performance of reinforcing steel embedded in that concrete. However, the addition of superplasticizer to concrete does affect its rheological properties, namely bleed and air content. For this reason, trial batches should be made under the expected job conditions when superplasticizer is to be used in concrete in order to ensure proper performance of the concrete.

# IMPLEMENTATION

The results of this study indicate that the use of superplasticizers in concrete does not adversely affect the concrete-reinforcing steel bond. However, the effect of superplasticizing admixtures on the material properties of concrete is highly dependent on the concrete age at the time the admixture is introduced. For this reason, admixture dosages and mix proportions should be based on the results of trial batches made under actual field conditions.

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# CHAPTER 1

## INTRODUCTION

### 1.1 General

A brief overview of the research program presented herein is given in this chapter. This includes a description of the basic problems which will be addressed and their importance to the design engineer. To facilitate the understanding of the research results and recommendations of this study, the fundamentals of the investigative program are discussed, and basic terms are defined.

### 1.2 Definition of Bond

Plain concrete has negligible tensile capacity. However, because of its low cost and high compressive strength, it is a valuable construction material. When reinforced with steel, the result is a relatively inexpensive and ductile material. Compressive stresses are carried by the concrete and tensile stresses by the steel. However, since the exterior loads are generally applied to the concrete, load must be transferred from the concrete to the reinforcement through shear bond stresses, or bond, between the concrete and steel. For a detailed explanation of the load transfer mechanism, see Ref. 17.

Load transfer to deformed bars occurs by the bearing of the lugs on the surrounding concrete. Thus, the quality of the surrounding concrete will have a significant effect on the bond capacity of the embedded bar. Factors which have been found to affect the bond performance of the concrete and reinforcing steel include casting depth, casting position, bleeding of concrete, and slump of concrete [17].

The effect of casting position on the concrete-steel interface is illustrated in Fig. 1.1. In this figure, the shaded regions are areas of water gain. The extent to which these areas occur is determined mainly by the amount the fresh concrete settles after placing, which is a function of the bleeding and slump of the concrete. It has been found that as the depth of concrete cast under a reinforcing bar increases, its bond capacity decreases [17]. This phenomenon is most likely due to the increase in water gain around the steel bars, resulting from increased bleeding.

### 1.3 Justification of Research

Superplasticizers or high-range water-reducing admixtures were introduced into North America in 1976 [20]. They are currently used

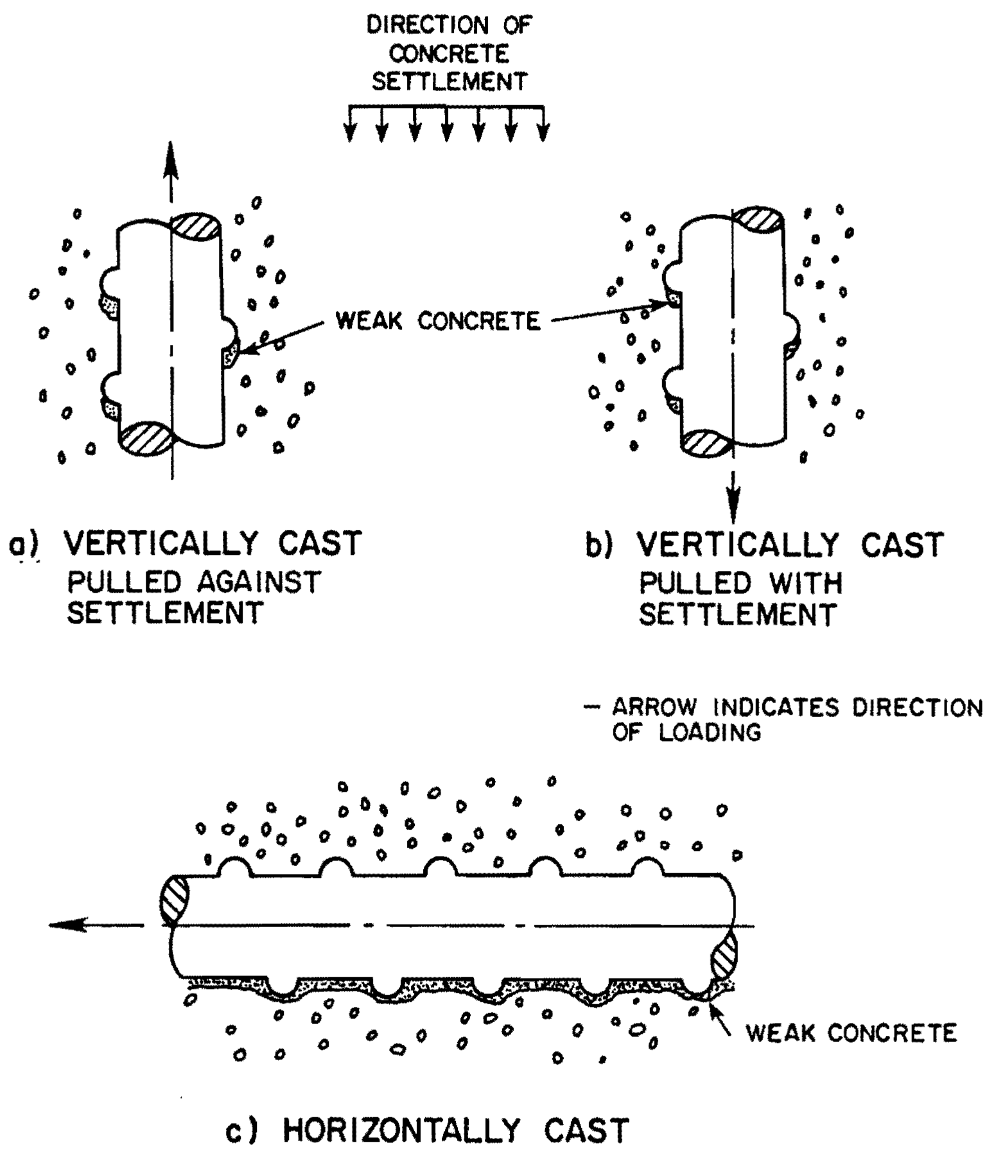



Fig. 1.1 Definition of casting position [17]

mostly in precast plants, and also in the field production of high strength concrete.

The use of superplasticizer in the field as a workability agent offers savings in placing and finishing costs. However, due to the associated slump loss, the admixture must be added to the concrete at the jobsite. Because of the lack of specifications governing the field use of superplasticizer and questionable quality control, ready-mix producers have been hesitant to accept this relatively new type of admixture.

Since their introduction to North America, many researchers have investigated the effect of superplasticizers on the material properties of fresh and hardened concrete. However, no studies have been reported on the structural aspects of superplasticized concrete.

The behavior of the bond between concrete and reinforcing steel depends on the bleeding and the slump of the concrete. When superplasticizer is used to produce high slump concrete, the slump is increased significantly and the bleeding could be increased as well. Therefore, it is uncertain whether current code provisions governing development length and anchorage of deformed bars are applicable in the case of superplasticized concrete.

## 1.4 Objectives of Research

The main objective of the work described herein is to determine if the use of superplasticizer to produce high slump concrete affects the bond performance of deformed bars embedded in that concrete. Although many material properties of the concrete are affected by the addition of superplasticizer, it is intended that the research results will indicate which factors play a dominant role in determining the bond behavior.

## 1.5 Research Plan

A research program was developed which would allow the study of the effect of superplasticizer on not only the material properties of concrete, but also the bond behavior between concrete and reinforcement.

Bond behavior was studied through pullout tests, in which the applied load and corresponding slips at the bar's free and loaded ends were recorded continuously throughout the test. The embedded length of the bars was purposely made less than the development length recommended by ACI 318-83 [3] in order to avoid yielding of the bars. Instead, the bond capacity was governed by shear bond failure, which is the shearing off of the concrete between the bar lugs. The pullout test results are not to be used for determination of the required development lengths. Rather, the pullout tests are simply a means for comparing the bond performance of steel reinforcement embedded in concrete with and without superplasticizer.

The following material properties of the fresh concrete were monitored: slump, bleed, temperature, and air content. These properties were measured both before and after the addition of superplasticizer to the concrete. Also, the 28-day compressive strength of the concrete with and without superplasticizer was determined.

Variables investigated in the research program were concrete slump before addition of superplasticizer, dosage of superplasticizer, type of superplasticizer, and depth of fresh concrete cast under the bar.

## 1.6 Format

A review of the technical literature relevant to the present study is presented in Chapter 2. Although the reader may consider the discussion on pullout tests to be sketchy, it should be kept in mind that for this research, the type of test was of little importance. The main objective was obtaining a means for comparing the bond behavior of reinforcing bars embedded in concrete with and without superplasticizers. The pullout tests simply provided the means to an end. However, the factors which affect concrete-reinforcing steel bond behavior have been determined through the use of pullout tests. Therefore, a presentation of the results of previous research incorporating pullout tests was made.

A detailed description of the experimental program and the results obtained are presented in Chapter 3 and 4.

The experimental procedure and results of a supplemental study on bleeding of concrete are presented in Chapter 5. This study was conducted to investigate the effect of time of addition of superplasticizer on the bleeding of the concrete.

The results from both the main research program and the supplemental study are discussed in Chapter 6, and Chapter 7 contains the conclusions and recommendations resulting from this investigative program.

This study is part of a broad research project on the anchorage and development of reinforcement in concrete made using superplasticizers conducted at the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas Balcones Research Center.

# C H A P T E R 2

# LITERATURE REVIEW

## 2.1 Introduction

The following is a review of relevant literature dealing with concrete-reinforcing steel pullout behavior and factors affecting that behavior. Topics covered include bleeding of concrete, results from previous pullout tests regarding development length of single deformed bars, types and uses of superplasticizer, and the effects of superplasticizer on the properties of plain concrete.

## 2.2 Bleeding of Concrete

The rising of water to the surface of concrete while in its plastic state is known as bleeding. It is mainly a sedimentation process, in which the heavier solid particles settle out of the plastic mass [16,23]. While bleeding is natural and desirable, excessive bleeding can lead to serious problems affecting the performance of the concrete.

One of the main factors to be considered in the determination of the development length of steel reinforcement is the tendency for some of the free water (bleed water) in the fresh concrete mix to become trapped under the aggregates and the reinforcing steel. This is shown in Fig. 2.1. The water gain under the aggregate particles creates discontinuities, or weak spots, in the concrete structure. The water gain under the steel reinforcement decreases the bonded area of the steel to the surrounding concrete, thereby affecting the effective bonded length of the steel reinforcement. The amount of water gain under the steel reinforcement would seem to be greater than under the aggregates since the steel reinforcement is not free to settle with the concrete. Instead, the concrete settles away from the steel bars, thus creating voids for water gain.

The two principal factors in determining the degree to which a fresh concrete mix will bleed are 1) the amount of free water in the mix, generally indicated by its slump (in the absence of admixtures), and 2) the percent air entrainment of the mix.

The free water in a concrete mix is that water which is free to migrate throughout the mix. Generally, as the slump of a mix is increased, so is the free water content and thus the amount of bleeding. The bleeding of concrete can be decreased by increasing the cement fineness or the percent of fines, increasing the rate of hydration of the cement, or simply by decreasing the water content of

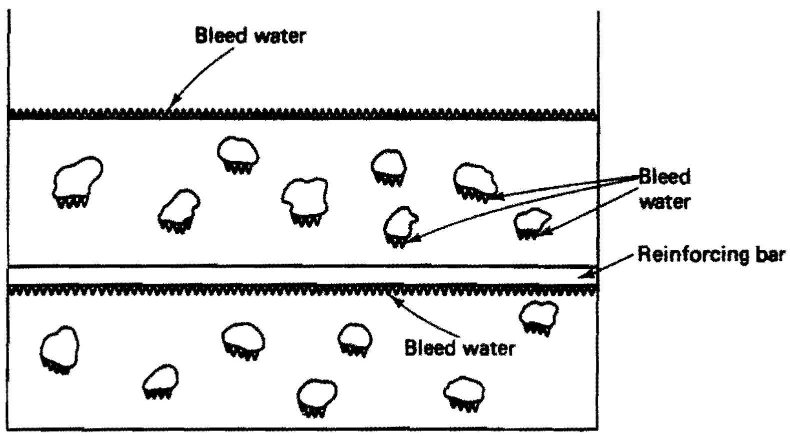



Fig. 2.1 Bleeding of concrete [23]

the mix [23]. All of these methods decrease the amount of free water in the mix.

On the other hand, the bleeding of a concrete mix can be decreased through the use of air entrainment [23]. The entrained air bubbles have electrically charged outer surfaces due to the polar hydrophilic groups there, which attract and trap the polar water molecules (Fig. 2.2). Thus, free water molecules are not allowed to migrate through the concrete mix, resulting in reduced bleed.

No information was found concerning the effect of the depth of fresh concrete on its bleed. It is unclear whether a column of concrete 1 ft high would bleed the same amount as a column 4 ft high. It seems that the bleed would be controlled by the rate of migration of the bleed water. How the migration of bleed water varies with concrete depth is unknown.

## 2.3 Pullout Tests

Many researchers have investigated the bond between concrete and reinforcing steel through pullout tests [1,4,5,6,7,8,9,16,20,25, 27]. In general, a steel reinforcing bar is cast in a block of concrete and the load required to pull it out or to cause a given level of slip is recorded. A typical test setup is shown in Fig. 2.3. Because most pullout tests induce a lateral compressive force in the concrete surrounding the bar near the loaded end [1], test results are best used for comparing bond performance, rather than for obtaining absolute values for bond strengths.

In 1928, Richart [26] and Edwards and Greenleaf [8] noted the possible importance of water gain under steel reinforcement on that steel's bond performance.

Menzel [21] was the first researcher to address the effect of casting depth on bond performance. He determined that the factors influencing the results of pullout bond tests were thickness of concrete cover, casting depth, casting position, and consistency of the concrete mix (slump). He found that the bond performance of bars decreased as the depth of concrete under them increased. From another set of tests he found that the bond performance of horizontal bars deteriorated with an increase in slump from 2 in. to 6 in., for a constant casting depth.

In 1949, Clark [5] investigated the effects of the following variables on bond performance: depth of concrete under the bar, length of embedment of the bar, strength of concrete, and diameter of the bar. His results were studied by ACI Committee 208 (Bond Stress), which then proposed a set of allowable unit stresses for bond. ACI Committee 318 approved the Committee 208 recommendations and incorporated them into

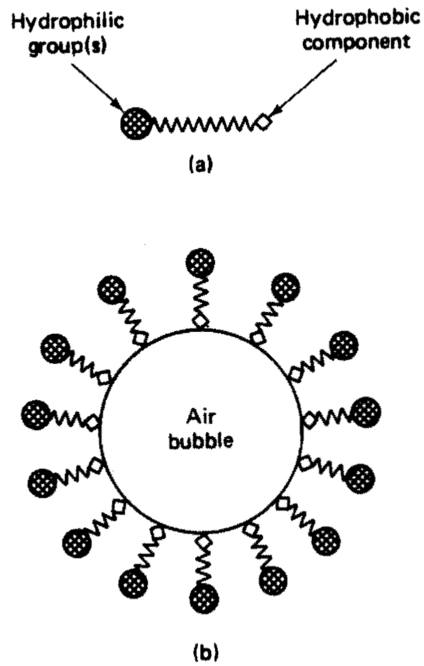



Fig. 2.2 Schematic representation of air entrainment by surface active molecules: (a) surface-active molecule; (b) stabilized air bubble [23]

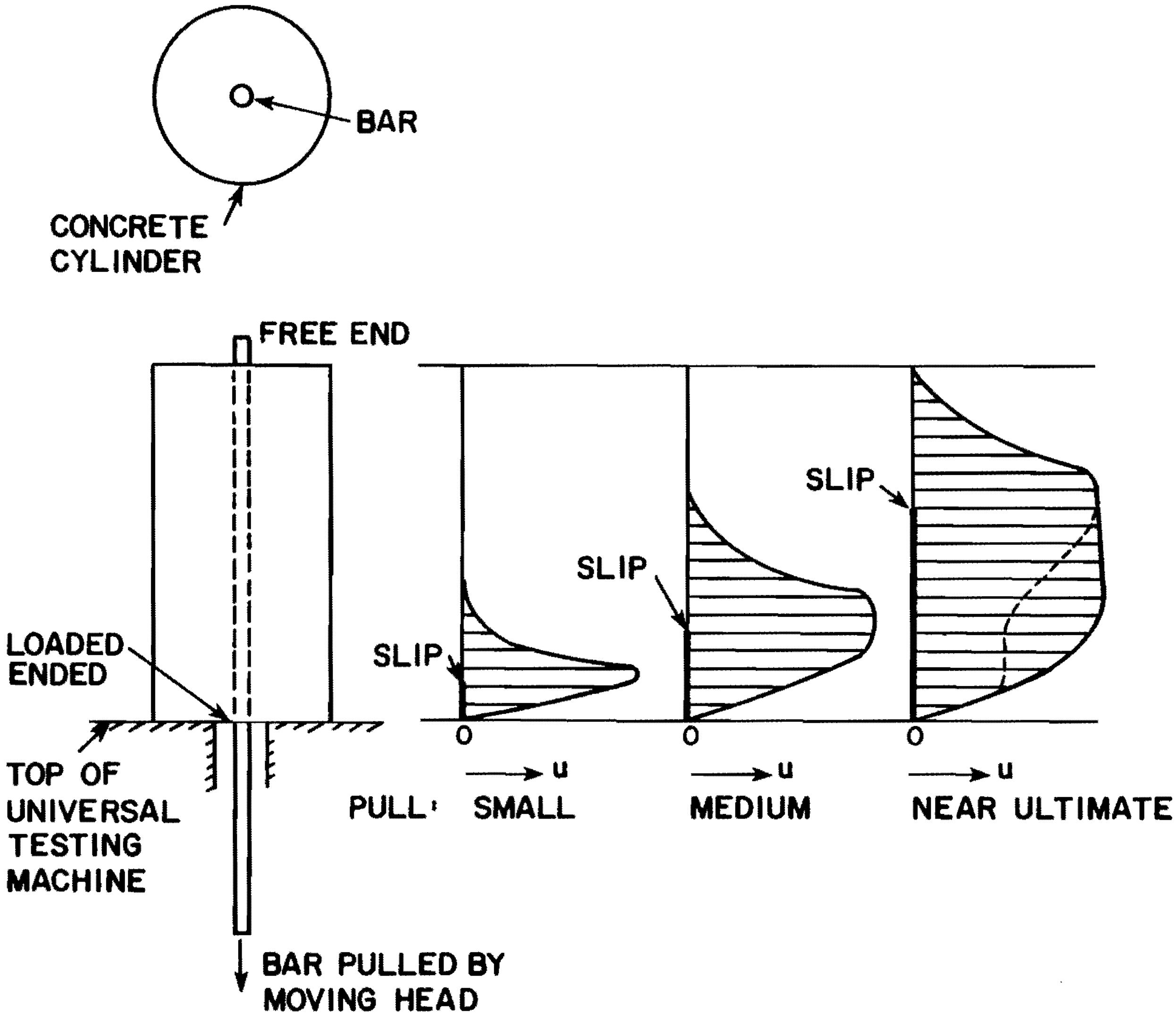



Fig. 2.3 Bond pullout test with bond stress distribution [9]

the 1951 ACI Code. Thus, the term "top bar" was introduced in ACI Code 318-51 [2], referring to any bar with more than 12 in. of fresh concrete cast below it. The allowable unit stresses of top cast bars were stated as 70% of those for bottom cast bars.

ACI Code 318-83 [3] still applies the 0.7 reduction factor to top cast bars in the form of a modification factor of 1.4 to be applied to the development length of top bars. Test results obtained by Ferguson and Thompson [10] indicated that this 0.7 reduction factor was conservative on a strength basis.

Many researchers investigated the influence of casting position on bond performance. However, no systematic investigation had been conducted to determine a quantitative relationship between bond performance and the variables affecting it until Luke, Hamad, Jirsa, and Breen [18] conducted a series of tests at The University of Texas at Austin. The variables they investigated included depth of concrete under the bar, concrete strength, concrete consistency (slump), concrete cover, and casting position. A typical test specimen from their investigation is shown in Fig. 2.4. Some results from their investigation are shown in Fig. 2.5. Except for the case of high slump concrete, they found the ACI Specifications for the development length modification factor to be conservative at casting depths less than 60 in. However, the results were highly dependent on concrete slump. For this reason, the recommendation of Luke, Hamad, Jirsa, and Breen was that the modification factor applied to the development length of reinforcing bars be a function not only of casting depth, but of concrete slump as well, as shown in Fig. 2.6. For high slump concrete, the ACI Specifications were found to be unconservative. In general, Luke et al. [18] recognized the deleterious effects on bond caused by additional water gain around steel reinforcing bars embedded in high slump concrete.

## 2.4 Superplasticizers

In order to understand the possible effects of superplasticizer on the bond between concrete and reinforcing steel, it is important to understand the effects of superplasticizer on plain concrete, particularly with respect to the bleeding of fresh concrete mixes. The following sections summarize information on the applications and types of superplasticizers, the mechanism by which they work, the behavior of superplasticized concrete, and factors which may affect this behavior.

2.4.1 Applications. Superplasticizers can be used in three ways in concrete production [14,20]. One application is in the production of high strength concrete. The water content of the mix is reduced while maintaining the cement content, resulting in a lower water to cement ratio. The reduced workability is then compensated for

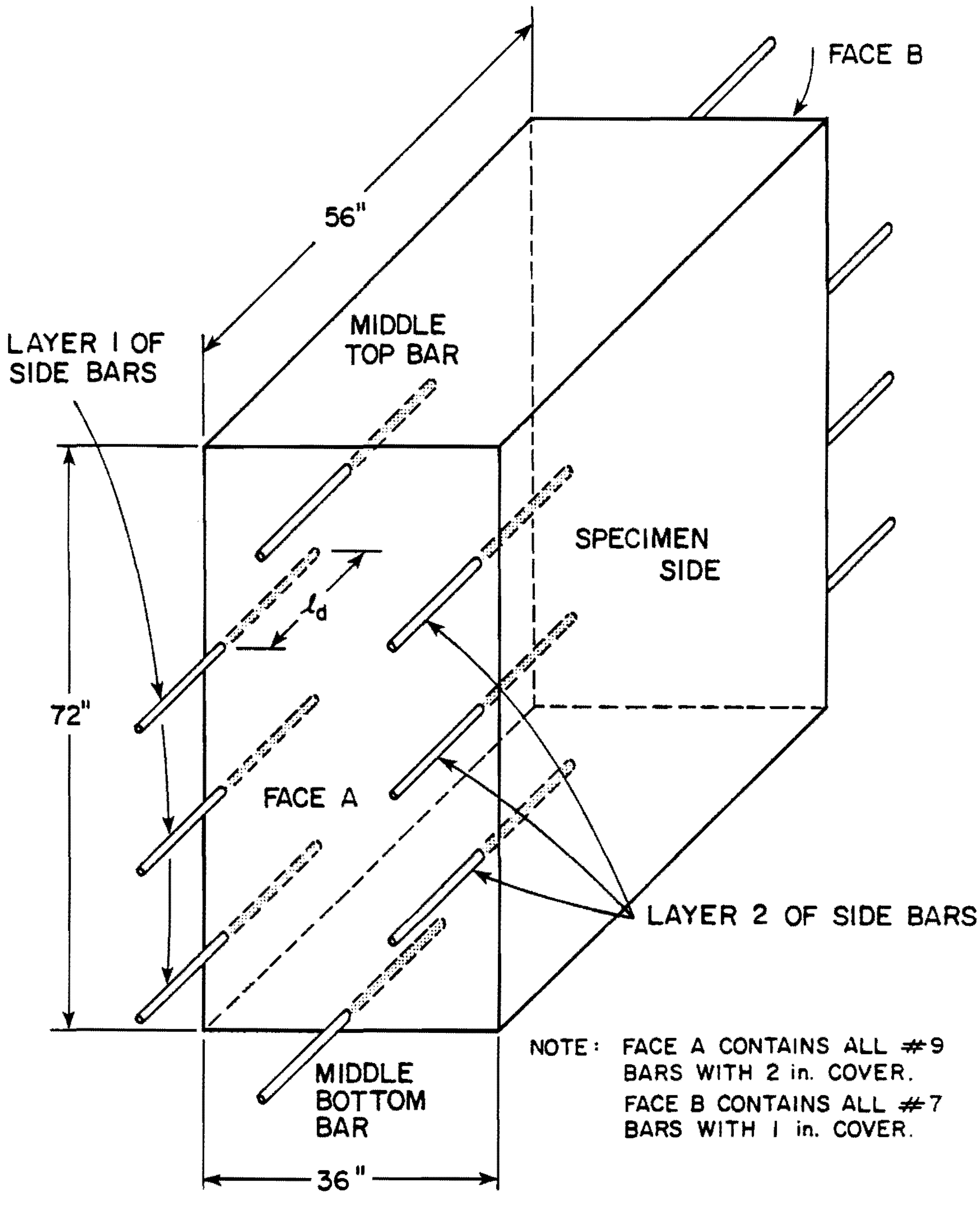



Fig. 2.4 Schematic representation of specimen for high slump tests [17]

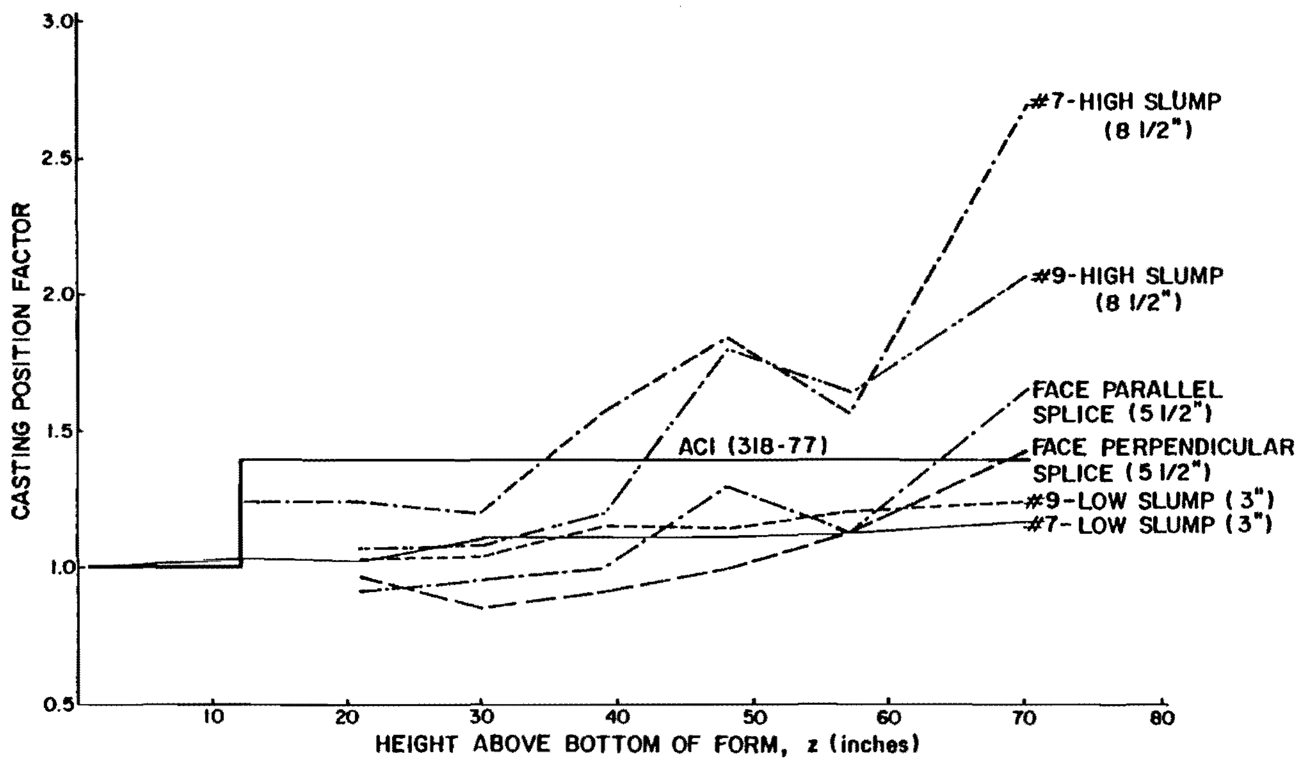



Fig. 2.5 Casting position factor versus bar height for all tests [17]

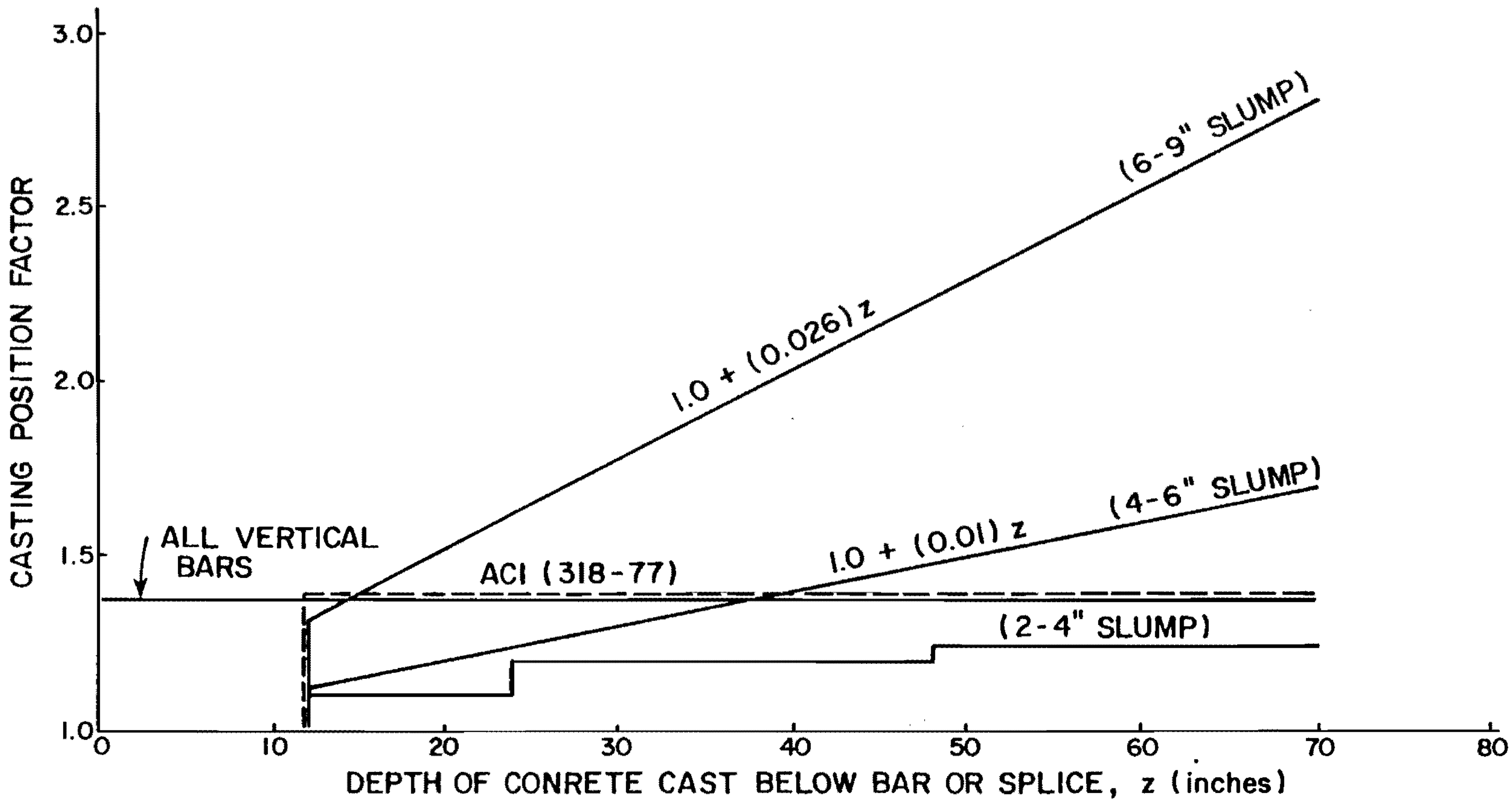



Fig. 2.6 Recommended casting position factors for all ranges of slump investigated [17]

by the use of superplasticizer. In this way, concretes with a water to cement ratio as low as 0.28 have been placed successfully [20].

Another application of superplasticizers is in the production of concrete with a given strength using less cement, but maintaining a constant water to cement ratio. As in the case of high strength concrete, the reduced workability is corrected for by incorporating a superplasticizer into the concrete mix [20].

The third application of superplasticizers is in the production of flowing concrete. In this case, the superplasticizer is added to a normal slump concrete mix in order to achieve a self-leveling mix with good cohesion. When superplasticizers are used for this purpose, the water to cement ratio and cement content of the mix remain unaffected [20]. However, care must be taken that the mix does not segregate.

2.4.2 Types. Three types of superplasticizer are currently available in North America. Made from the salts of organic sulfonates, these three types are 1) sulfonated melamine formaldehyde condensates (melamine), 2) sulfonated naphthalene formaldehyde condensates (naphthalene), and 3) modified lignosulfonates (lignin).

2.4.3 Mode of Action. All three types of superplasticizer are surface agents which are adsorbed onto the cement particles and disperse the cement agglomerates, as shown in Fig. 2.7. How this dispersing action is achieved, however, is characteristic of the type of superplasticizer. Melamine-based superplasticizer is believed to form a lubricating film on the cement particles. Lignosulfonates decrease the surface tension of the water. The naphthalene-based superplasticizer, although decreasing the surface tension of the water slightly, acts mainly by giving the cement particles a negative charge. When the naphthalene molecules, which are negatively charged, are adsorbed onto the cement particles, the cement particles become negatively charged and thus repel one another [14,22].

2.4.4 Slump Loss of Superplasticized Concrete. Although the use of superplasticizing admixtures in concrete allows large increases in slump, these results are short-lived, and the concrete reverts back to its normal state within 30 to 90 minutes after being dosed with the superplasticizer [14,19,20,25]. This phenomenon is referred to as slump loss.

Perenchio, Whiting, and Kantro [25] investigated the effects of initial slump, dosage level of superplasticizer, and time of addition of superplasticizer on the slump loss characteristics of concrete. The percent slump loss versus time for two concretes are given in Fig. 2.8 and 2.9. In these figures, the solid lines represent the control concrete which contained no superplasticizers. The shaded regions

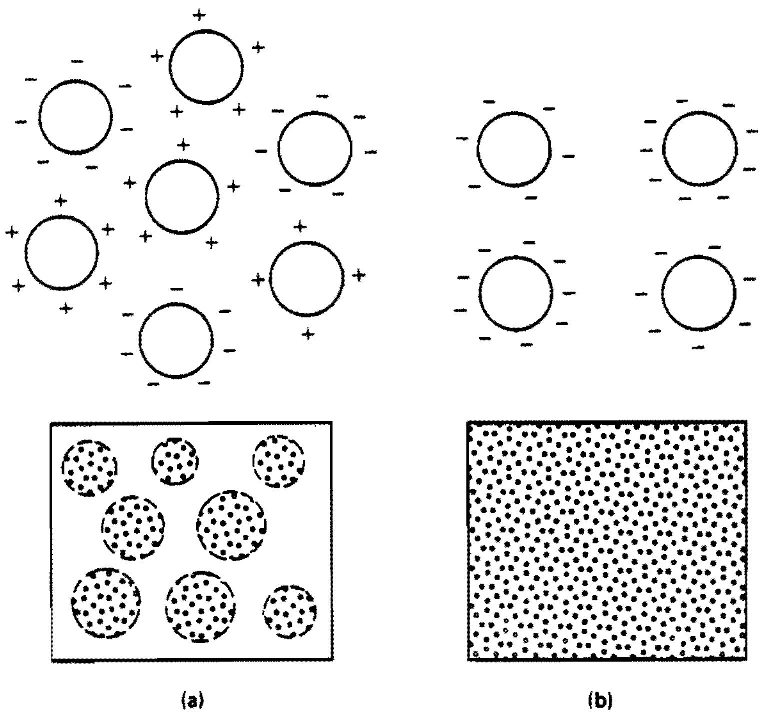



Fig. 2.7 Dispersing action of superplasticizer (schematic representation): (a) flocculated paste; (b) dispersed paste [23]

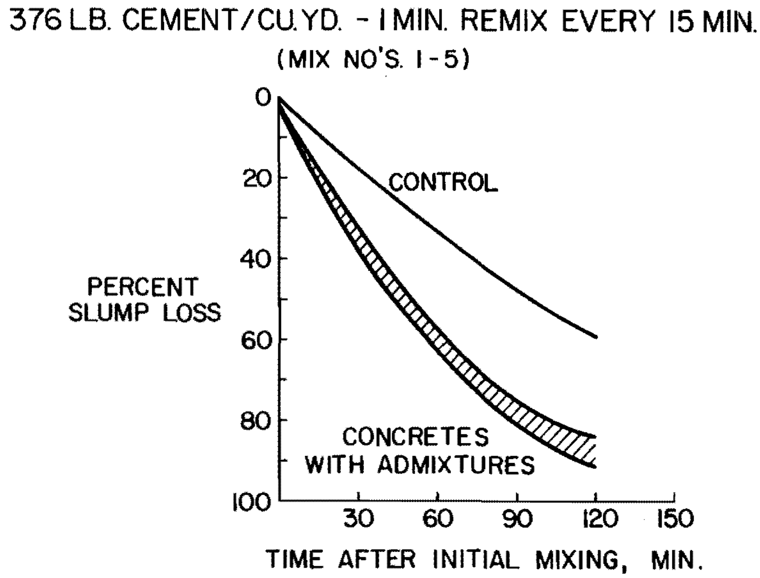



Fig. 2.8 Slump loss versus time for concrete containing 376 lbs cement per cubic yard [25]

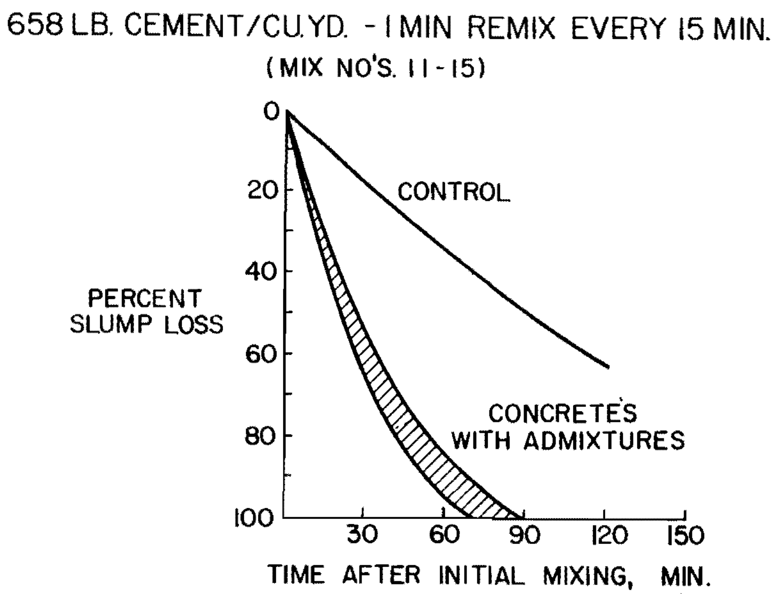



Fig. 2.9 Slump loss versus time for concrete containing 658 lbs cement per cubic yard [25]

represent the range of values obtained for similar concretes containing two naphthalene and two melamine type admixtures. It can be seen from these figures that the percent slump loss of the superplasticized concrete is more rapid than that of the control concrete. In Fig. 2.10 the effect of initial slump on the slump loss of concrete containing no superplasticizer is shown. It is evident that the time for 50% slump loss is nearly the same for all of the concretes tested. Figure 2.11 presents the same data as Fig. 2.10, except that the slump is given in absolute values rather than as a percentage of the slump resulting from the addition of superplasticizer. The "slump window" refers to the time required for the concrete to go from a slump of 3 in. to 1 in., and is fairly constant for all mixes. The effect of admixture dosage on slump loss is shown in Fig. 2.12. As the dosage of superplasticizer is increased, the slump of the concrete is increased, and the concrete maintains its workability longer. Likewise, the slump window is increased with the dosage of superplasticizer. The effect of delayed addition of superplasticizer on slump loss is negligible, as shown in Fig. 2.13.

Mailvaganum [19] conducted a series of tests investigating the effects of various factors on the rate of slump loss of superplasticized concrete. These factors included mix temperature, concrete consistency, cement content and type, and the time of addition of the superplasticizer. The mix temperatures included in the program were 60, 72, and 90° F. The times of addition of the superplasticizer were 20, 40 and 60 minutes after initial mixing.

As a result of his investigation, Mailvaganum [19] concluded that at the temperatures in excess of 90° F, the slump loss of superplasticized concrete is drastic, while at temperatures below 60°F the state of high workability is extended. These results are presented in Fig. 2.14. Like Perenchio, Whiting, and Kantro [25], Mailvaganum found that the rate of slump loss was independent of the time of addition of the superplasticizer, as illustrated in Fig. 2.15.

To date, the mechanism responsible for slump loss is not fully understood. It is not an acceleration of the hydration reaction of the cement [14]. Hattori [13] attributes the slump loss of superplasticized concrete to the coagulation of hydrated cement particles in the dormant stage rather than the hydration of those cement particles. However, while it may be true that the rapid slump loss of superplasticized concrete is a result of the recoagulation of the cement particles, this theory fails to address the question of why the superplasticizer loses its effectiveness; that is, why the cement particles, which have been coated with superplasticizer and dispersed, recoagulate. No information was found on what changes occurred with time in the superplasticizer coating.

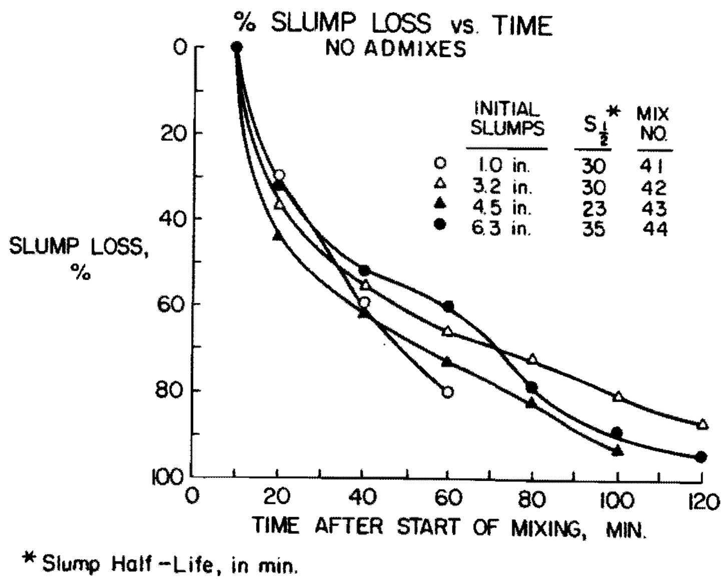



Fig. 2.10 Percent slump loss versus time for various initial slump values [25]

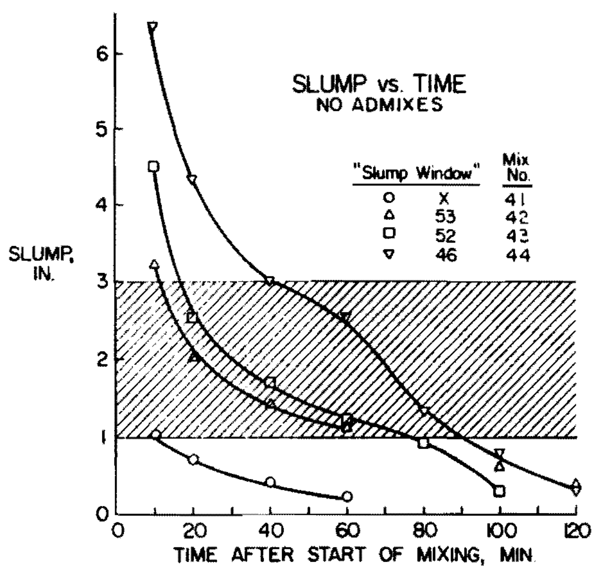



Fig. 2.11 "Slump windows" for concretes with various initial slump values [25]

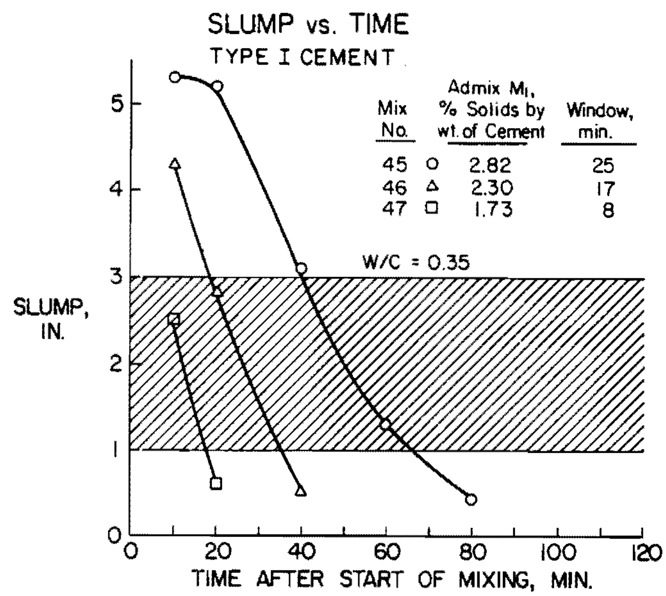



Fig. 2.12 "Slump windows" for concretes with various admixture dosages [25]

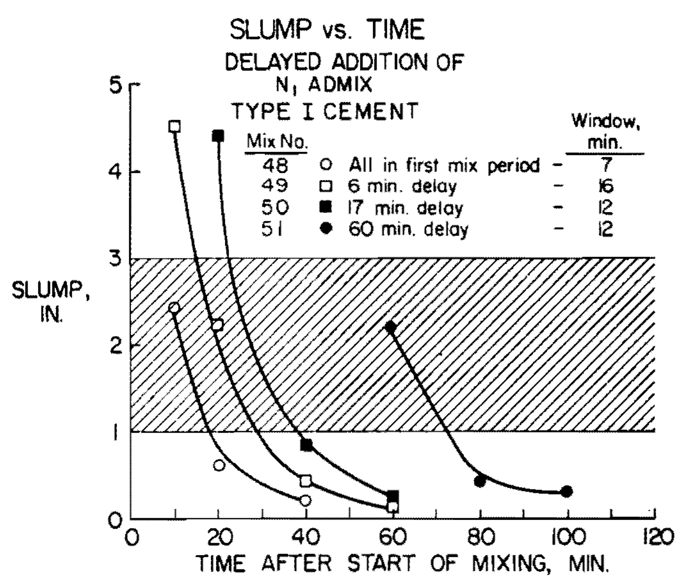



Fig. 2.13 "Slump windows" for concretes with various delay periods [25]

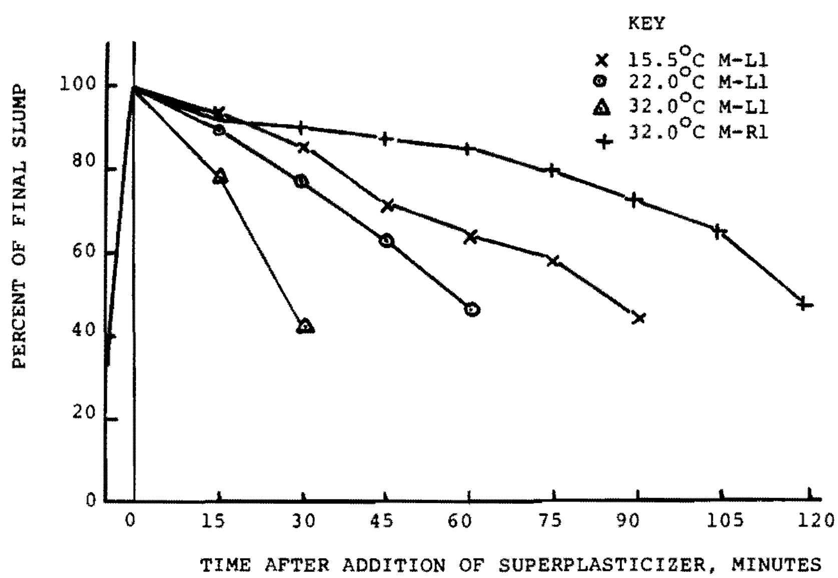



Fig. 2.14 Effect of temperature variation on slump loss [19]

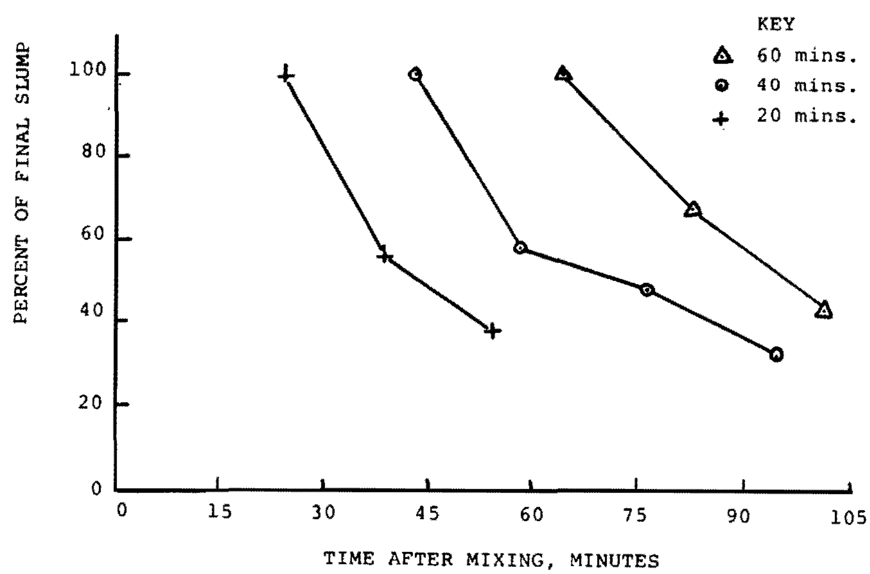



Fig. 2.15 Effect of time of addition of superplasticizer on slump loss [19]

2.4.5 Effect of Repeated Dosage on Slump. In order to overcome the problem of rapid slump loss, investigations have been made into the effects of repeated dosages of superplasticizer on slump loss [14,19,20,27].

Malhotra [20,27] states that the high slump of superplasticized concrete can be maintained for several hours with repeated doses of superplasticizer. However, he does not recommend more than two dosages. Generally, optimum performance of the concrete is achieved after the second dosing with superplasticizer, as shown in Fig. 2.16.

Mailvaganum [19] compared the effects of adding superplasticizer with those of adding water to concrete in order to maintain a given high slump over time, as shown in Fig. 2.17. The second dosage with superplasticizer resulted in a higher slump than the first dosage, as was shown in Fig. 2.16. Although the standard mix lost its initial slump more slowly than did the superplasticized concrete, its rate of slump loss accelerated after being retempered with water. Thus, the slump of the concrete could be maintained through repeated dosages of superplasticizer, avoiding possible strength problems resulting from the addition of water.

However, as pointed out by Hampton [12], repeated dosages of superplasticizer may be uneconomical and ineffective. This is especially true at high temperatures, where additional dosages of superplasticizer were not shown to increase the slump of the concrete.

2.4.6 Effect on Bleeding of Concrete. When superplasticizers are used to produce flowing concrete, there is a tendency for the fresh concrete mix to segregate and bleed [14,20]. To prevent this, the mix should be reproportioned to increase the fines content, thereby yielding a more cohesive concrete.

In a preliminary investigation conducted by Musser [24], factors affecting the bleeding of concrete were studied. The variables included were the type and dosage of superplasticizer. Two types of superplasticizer were used: sulfonated naphthalene formaldehyde condensate and sulfonated melamine formaldehyde condensate.

The superplasticizer was added to the concrete immediately after mixing. The control concrete mix was approximately 5 minutes old, with a 3-1/2 in. slump at the time of addition of the superplasticizer. The concrete and superplasticizer were then mixed for three more minutes, at which time the slump was measured and the bleed test started.

Results of the study are shown in Fig. 2.18 and 2.19. These figures show the effect of superplasticizer dosage on the bleed behavior of fresh concrete. In all cases, bleeding increased with the dosage of superplasticizer.

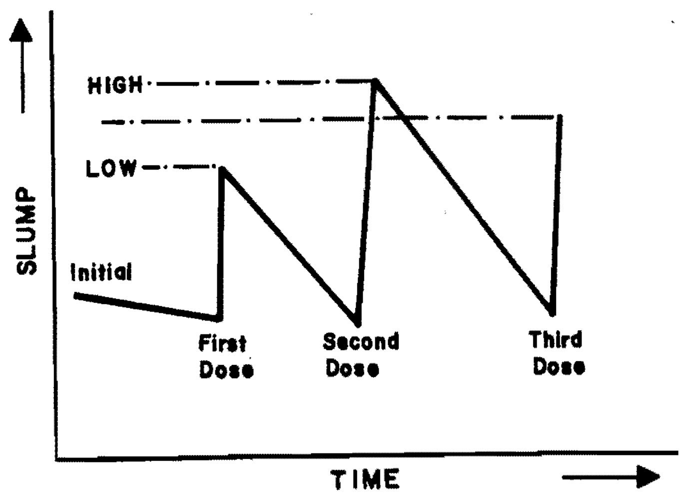



Fig. 2.16 Effect of repeated dosages of superplasticizer on slump of concrete [27]

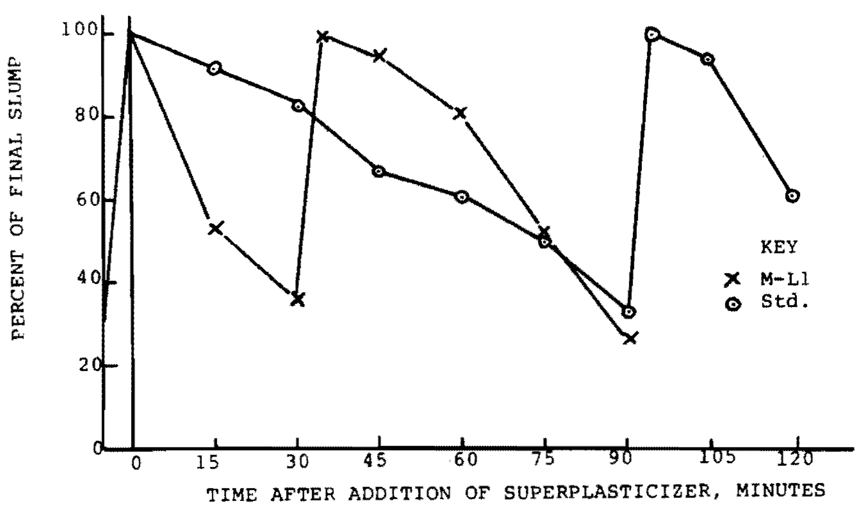



Fig. 2.17 Effect of redosage on slump loss [19]

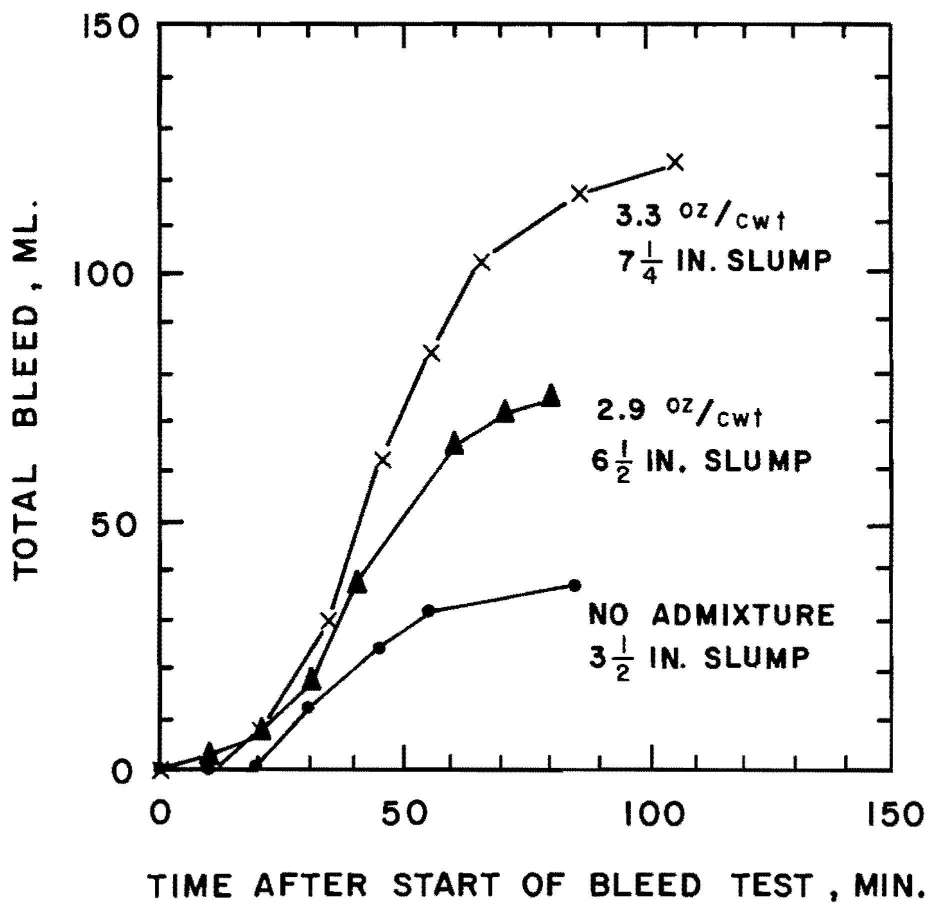



Fig. 2.18 Effect of naphthalene-based superplasticizer on bleeding of concrete for various dosage rates [24]

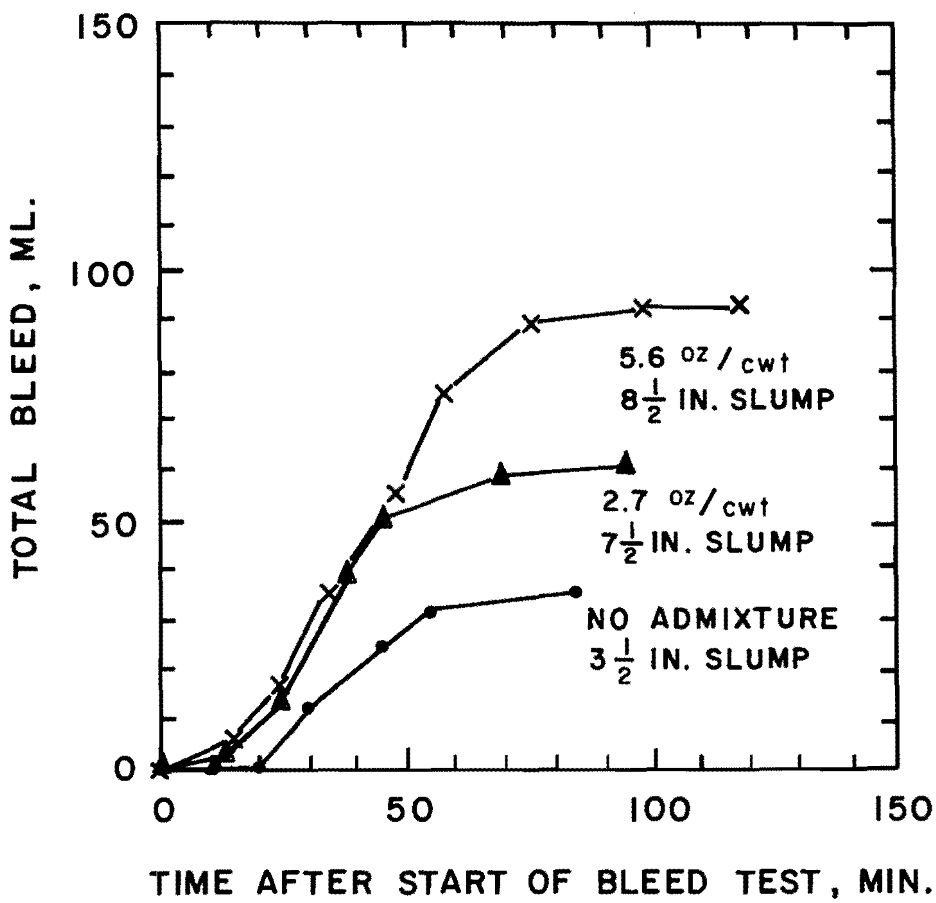



Fig. 2.19 Effect of melamine-based superplasticizer on bleeding of concrete for various dosage rates [24]

2.4.7 Effect on Air Content of Concrete. The addition of naphthalene or melamine-based superplasticizer to concrete causes a loss of entrained air [14,20]. The use of lignosulfonate-based superplasticizer, however, can cause an increase in the air content [20]. Results obtained by Seabrook and Malhotra [27] concerning the effect of superplasticizer on entrained air are shown in Figs. 2.20 and 2.21. From top to bottom, the plots of Fig. 2.20 represent the effect of melamine, lignosulfonate, and naphthalene-based superplasticizer on the slump and air content of concrete when these admixtures are added at a dosage rate of 1.5% by weight of cement at each addition to a concrete having a water to cement ratio of 0.42. Figure 2.21 presents similar information for a water to cement ratio of 0.55 and dosage rates of 2.5% for the melamine and lignosulfonate-based superplasticizer, and 1.5% for naphthalene-based superplasticizer. In all cases, the air content decreased with every addition of superplasticizer. However, in additional tests conducted when a lignosulfonate-based superplasticizer was added at a dosage rate of 2.20% to a concrete with a water to cement ratio of 0.50, the air content was found to increase by 0.5%. In this case, the slump increased from 1-1/2 in. to 7 in., and the air content from 5.0% to 5.5%.

2.4.8 Effect on Compressive Strength of Concrete. The addition of superplasticizer to concrete has been found to increase the 28-day compressive strength of concrete even if the water to cement ratio is unchanged [14]. This is thought to be caused by the dispersing action of the superplasticizer. The dispersed cement particles not only coat the aggregates better, but also achieve a more complete hydration. However, due to the tendency of lignosulfonate-based superplasticizer to increase the air content of the concrete, reductions in compressive strength are sometimes observed when using this admixture [20].

Typical effects of superplasticizer on the slump, air content, and compressive strength of concrete are shown in Fig. 2.22 [14]. Numerical values will depend on the concrete mixes and admixtures involved.

## 2.5 Summary

The use of superplasticizer to produce high slump concrete results in increased slump and increased bleed of the fresh concrete mix. The slump of concrete without superplasticizer has been shown to affect the bond between the concrete and reinforcing steel, and it is likely that this can be attributed to the water gain under the reinforcement due to the migration of the bleed water through the mix. However, the use of superplasticizer also increases the 28-day compressive strength of the concrete, which would lead to stronger concrete surrounding the reinforcement and thus better bond performance.

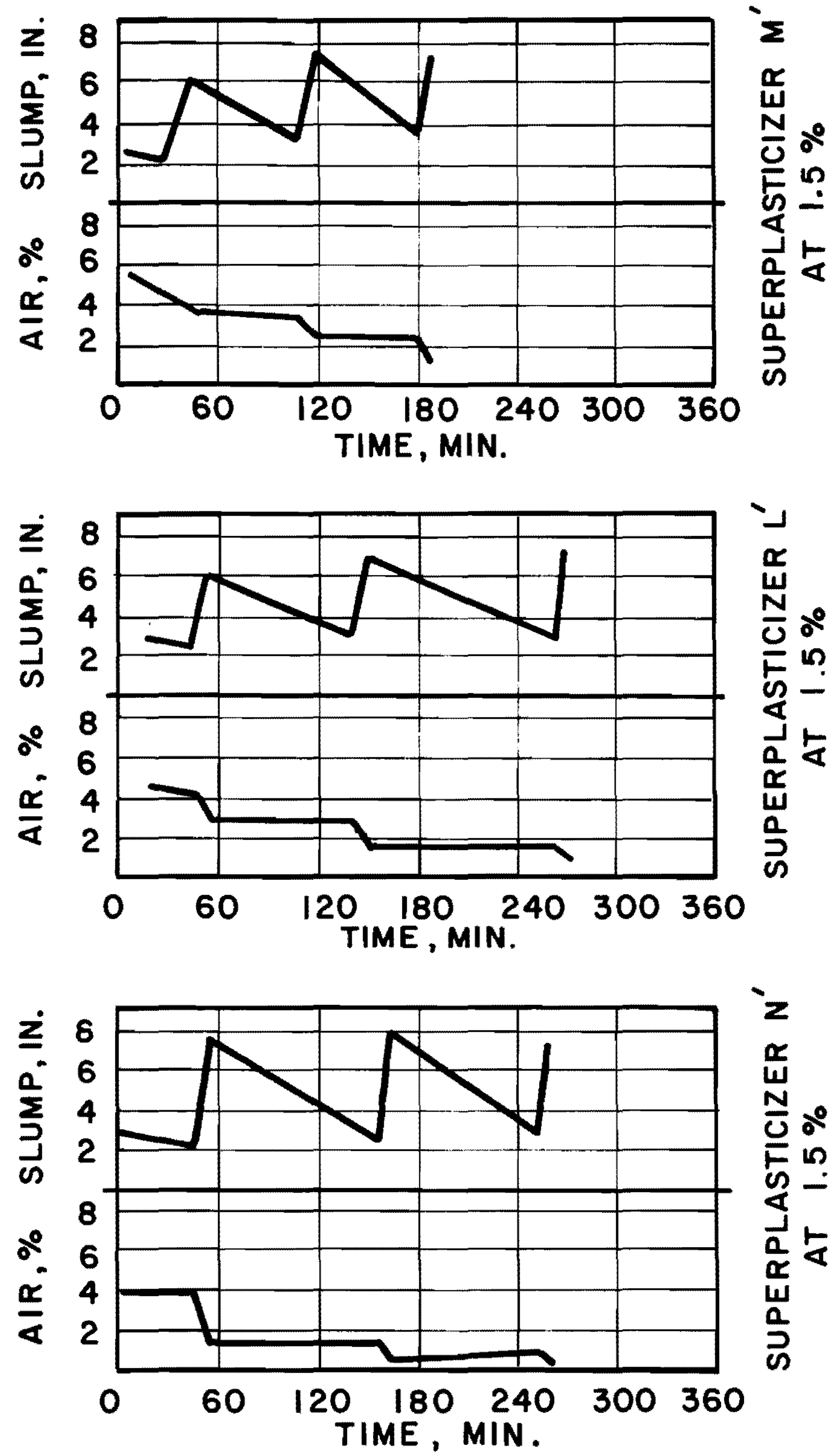



Fig. 2.20 Changes in plastic properties of concrete W/C = 0.42 due to repeated dosages of superplasticizer [27]

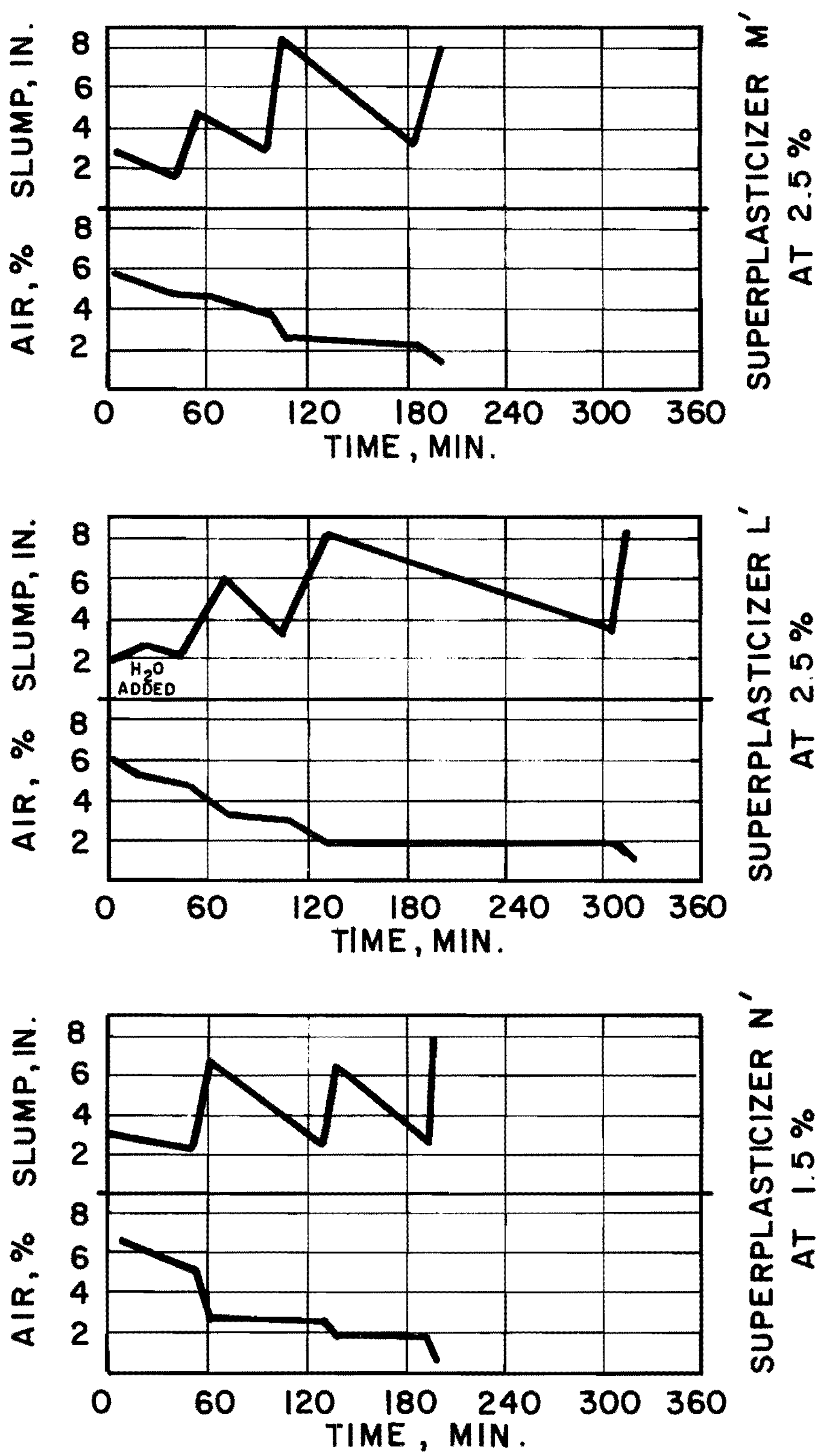



Fig. 2.21 Changes in plastic properties of concrete W/C = 0.55 due to repeated dosages of superplasticizer [27]

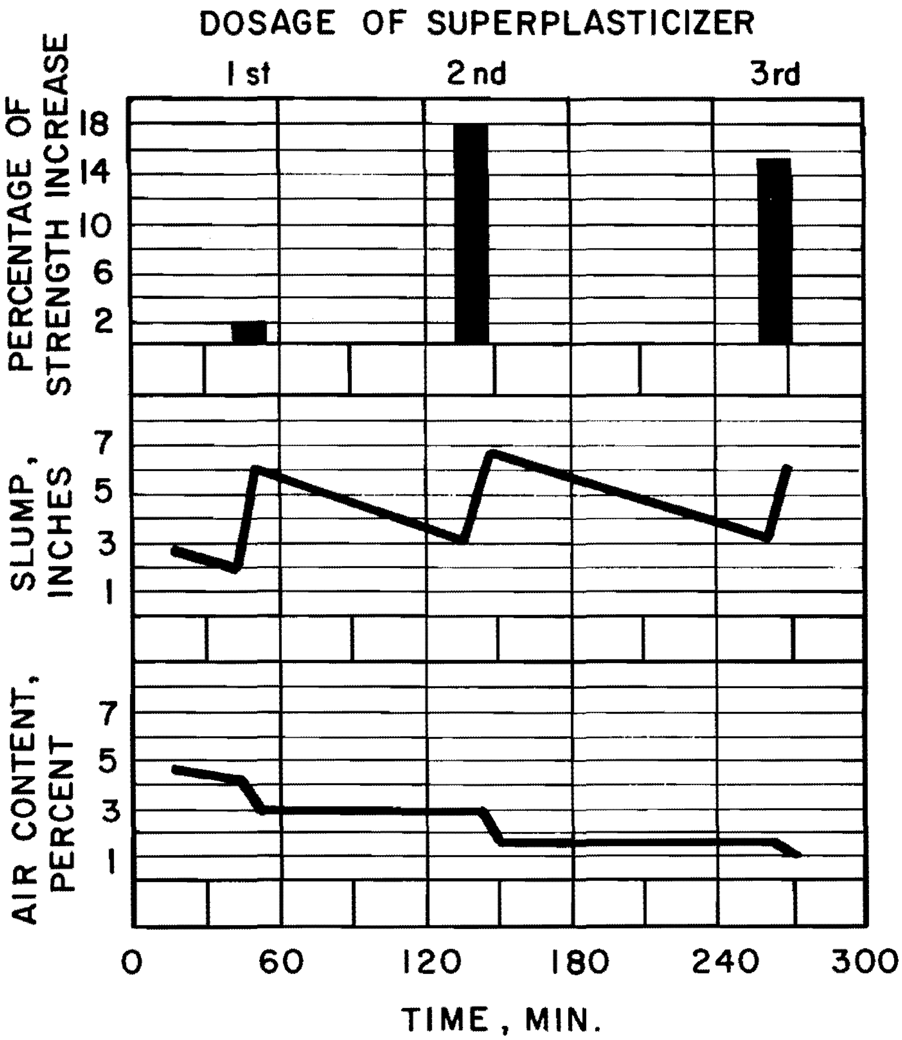



Fig. 2.22 Effect of repeated dosages of superplasticizer on slump, air content, and compressive strength of concrete [14]

It is understood that superplasticizer affects those properties of the concrete which determine the quality of the bond between concrete and reinforcement. However, the degree to which each of these factors is affected and how they interact to determine the bond strength is unknown.

# CHAPTER 3

## EXPERIMENTAL PROGRAM

### 3.1 Introduction

Thirteen specimens, each with nine pullout bars, were tested to investigate the effect of superplasticizers, when used as workability agents, on the bond between concrete and reinforcement. The variables studied included:

a) amount of mixing water in the concrete before adding superplasticizer;

b) slump increase induced using superplasticizer;

c) type of superplasticizer;

d) dosage of superplasticizer;

e) compressive strength of the concrete with and without superplasticizer;

f) tensile strength of the concrete with and without superplasticizer;

g) air content of the concrete with and without superplasticizer;

h) bleed characteristics of the concrete with and without superplasticizer;

i) casting depth;

j) compressive strength of the concrete as a function of casting depth; and

k) appearance of concrete-steel interface as a function of casting depth.

In this chapter, the test specimens and procedures will be described. Because the objectives of this study required a detailed study of the physical characteristics of the concrete used, it was necessary to conduct a number of basic tests on the concrete used for each specimen This chapter also contains brief descriptions of those test procedures. The mechanical characteristics so found, and the behavior of the specimens themselves, will be described in the next chapter.

## 3.2 Test Specimens

The dimensions of the test specimens are shown in Fig. 3.1. Each specimen contained nine #9 Grade 60 deformed bars embedded through the full thickness of the specimen. Thus, the thickness of the specimens was dictated by the embedment length desired for the pullout bars. The embedment length had to be consistent with the desired failure mode of shear bond failure. A longer embedment length would lead to premature yielding of the pullout bars, while a shorter embedment length would lead to conical pullout failure of the surrounding concrete.

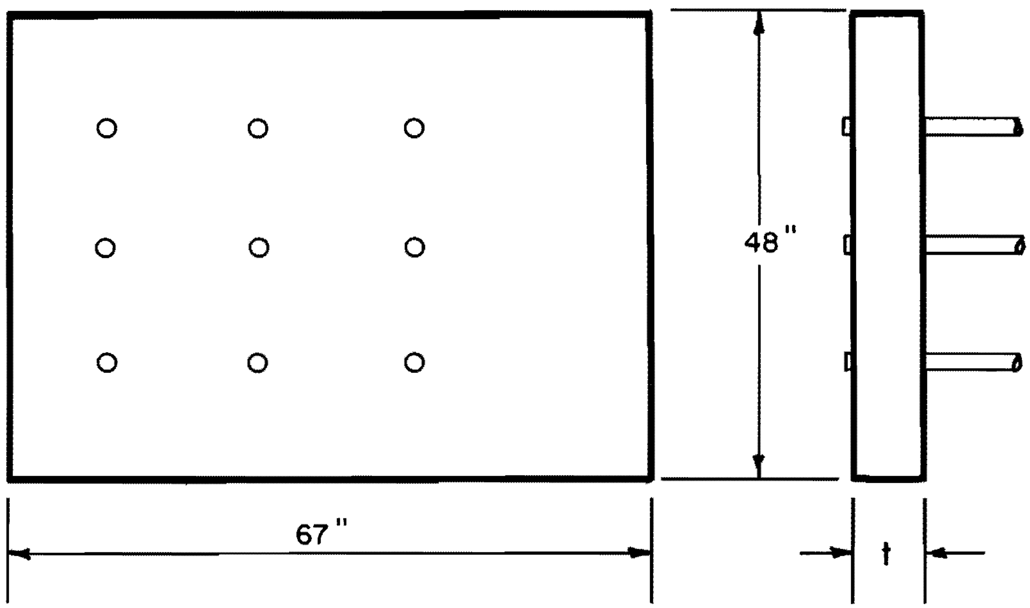
The equations used for predicting the loads corresponding to yielding of the pullout bar, and to conical failure of the surrounding concrete, are given in Appendix A. A sample calculation for determining the required embedment length is also provided.

Based on the calculations of Appendix A, it was found that a #9 bar with an embedment length of 8 in. would fail in bond rather than by yielding or cone pullout. However, during the testing of the first series of specimens, some of the pullout bars did yield for reasons which will be discussed later. As a result, the thickness of the test specimen was reduced to 6 in., as indicated in Fig. 3.1.

As shown in Fig. 3.2, the pullout bars in each specimen were placed at three different casting depths (12, 24, and 36 in.), with their longitudinal axes perpendicular to the casting direction. A slip wire was attached to each of these bars for recording the relative movement between the bar's loaded end and the concrete during testing, as shown in Fig. 3.3. To attach the slip wire, a small hole was drilled approximately 1/4 in. into each of the pullout bars, and a length of piano wire was inserted into each hole, bent to run parallel to the bar, and attached with epoxy cement. After the epoxy had set, the wire was covered with a plastic tubing and a small ball of rubber sealant was placed over the point where the wire was inserted into the bar, as shown in Fig. 3.4. This was done to avoid any bonding of the wire to the concrete, thus allowing the length of wire to move freely with the point of attachment to the pullout bar. To remove any impurities which could have affected their bond characteristics, all pullout bars were cleaned with acetone before being placed.

In order to arrest the propagation of cracks between adjacent pullout bars during testing, each specimen was provided with two mats of reinforcement, consisting of #4 Grade 60 deformed bars which entirely enclosed each pullout bar (Fig. 3.5).

In addition to the pullout bars, two short #9 bars were placed at each casting depth in the specimen (Fig. 3.6). After the pullout tests were completed, these shorter #9 bars were to be removed from the




<table>
<tr><th>SERIES</th><th>t (IN.)</th></tr>
<tr><td>I</td><td>8</td></tr>
<tr><td>II</td><td rowspan="5">6</td></tr>
<tr><td>III</td></tr>
<tr><td>IV</td></tr>
<tr><td>V</td></tr>
<tr><td>VI</td></tr>
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Fig. 3.1 Test specimen dimensions

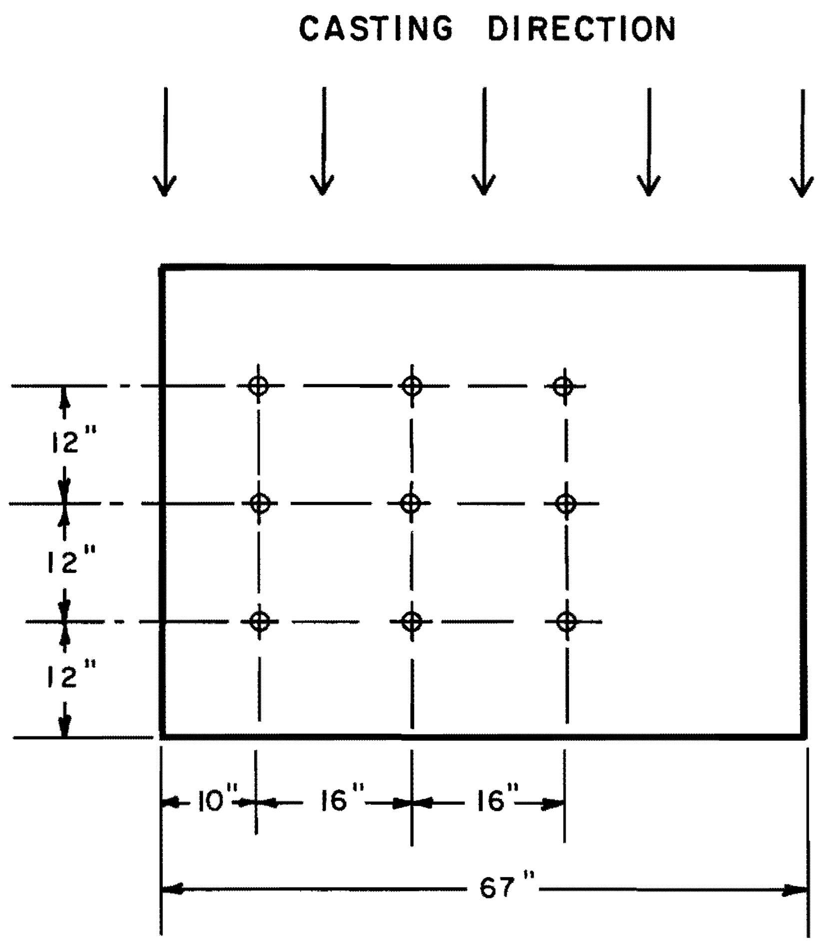



Fig. 3.2 Casting depth and casting direction

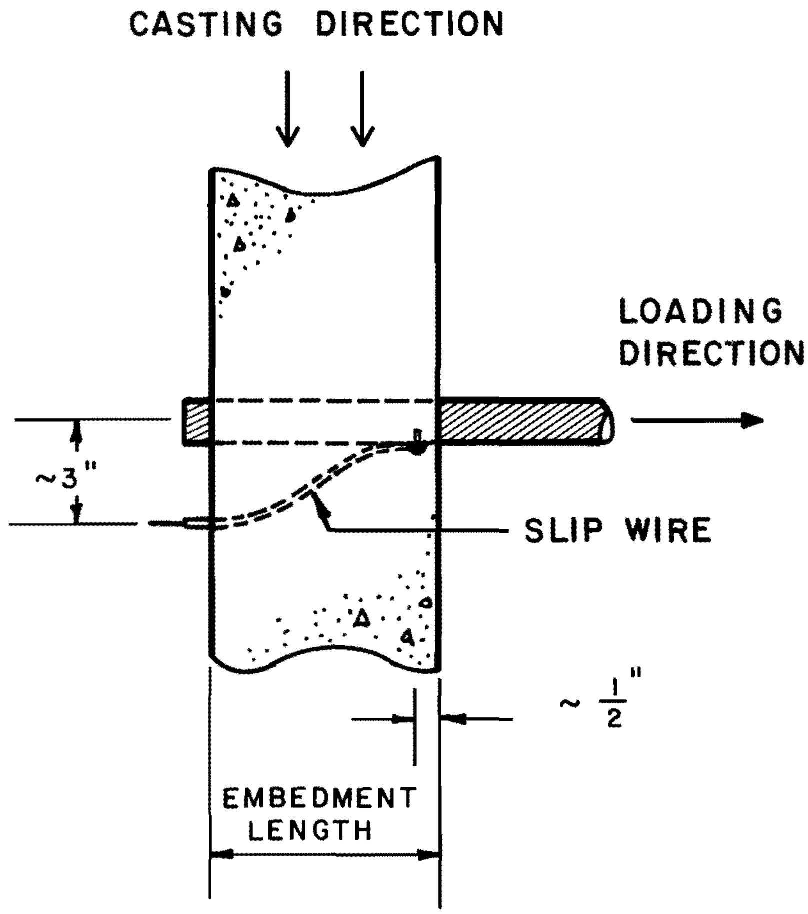



Fig. 3.3 Location of slip wire within specimen

Fig. 3.4 Slip wire attached to pullout bar

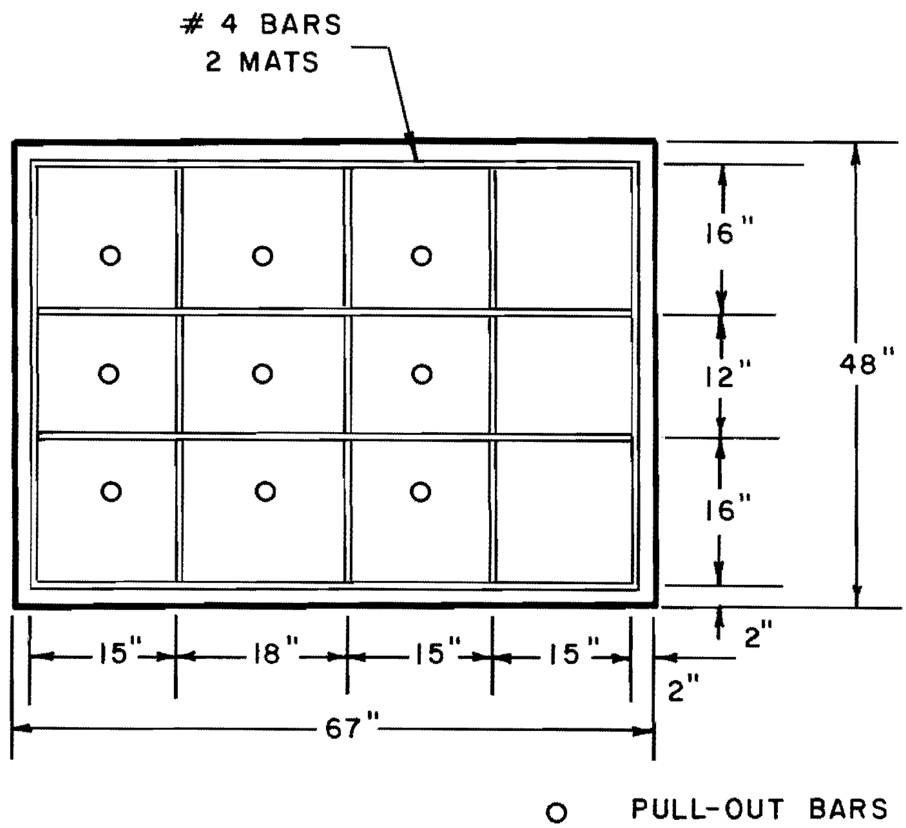



Fig. 3.5 Location of steel reinforcement

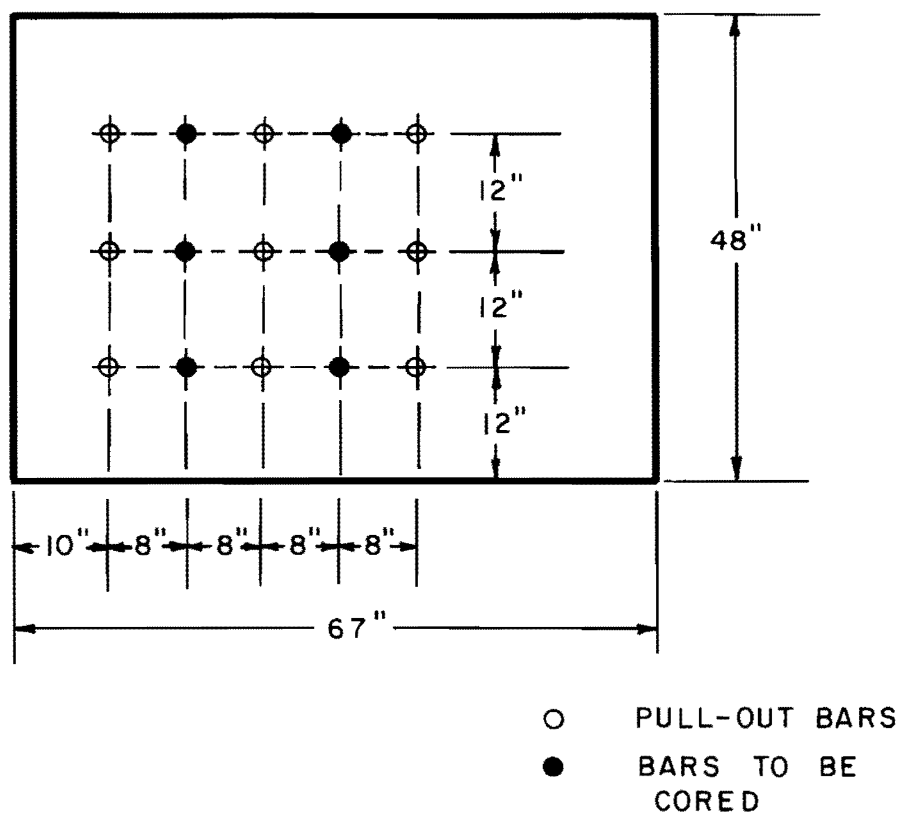



Fig. 3.6 Location of bars to be cored

specimens with a coring bit, and the cores were to be sliced transverse to the bar, permitting inspection of the concrete-steel interface. However, after completion of the pullout tests and examination of the test results, it was decided that no additional useful information would be gained from this inspection.

## 3.3 Materials

### 3.3.1 Formwork.

The formwork was constructed of 3/4-in. plywood and 2-in. x 4-in. wooden bracing. Details are shown in Figs. 3.7a through 3.7c. The front and back sides of the forms were tied together using 3/8-in. threaded rods while the sides were restrained by 2-in. x 4-in. toe boards. Uplift forces were resisted by 1/4-in. lag screws connecting the sides to the formwork bottom. One and one-half in. holes were drilled in the front and back sides for placement of the pullout bars. Pieces of 1-1/2 in. O.D. PVC tubing 3/4-in. long were placed in these holes to facilitate form removal. After placement of the pullout bars, wedges driven into these holes kept the bars perpendicular to the specimen surface, and the gaps between the bars and the PVC tubing were filled with silicone rubber caulking. In the back wall of the forms, directly below the holes for the pullout bars, 3/16 in. diameter holes were drilled to permit passage of the slip wires attached to the pullout bars.

### 3.3.2 Reinforcing Steel.

All bars were Grade 60 deformed bars conforming to ASTM A615.

### 3.3.3 Superplasticizers.

The effects of two types of superplasticizing admixtures were investigated in this research program. These two types are a sulfonated melamine formaldehyde condensate (melamine) and a sulfonated naphthalene formaldehyde condensate (naphthalene). Each of these was obtained from the same source throughout the duration of the research program to avoid any variability which may have existed between different brands of similar products.

Naphthalene-based superplasticizers are dark brown in color. The naphthalene used for this experimental work consisted of a 38 to 43% aqueous solution with a density of from 73.6 to 76.7 pcf. The chloride content was less than 0.1% by weight of admixture.

Melamine-based superplasticizers are generally clear to milky in appearance. The melamine used in this study consisted of a $33.0 \pm 0.5\%$ aqueous solution with a density of from 74.1 to 75.3 pcf. The chloride content was $0.020 \pm 0.009\%$ by weight of admixture.

### 3.3.4 Concrete.

The concrete used in all the specimens was supplied by the same commercial ready-mix company, which operated two dry-batch plants. The mix design was based on a specified compressive strength of 4000 psi. Mix proportions as batched at the ready-mix plant are shown in Table 3.1. Normal portland cement, ASTM Type I, and

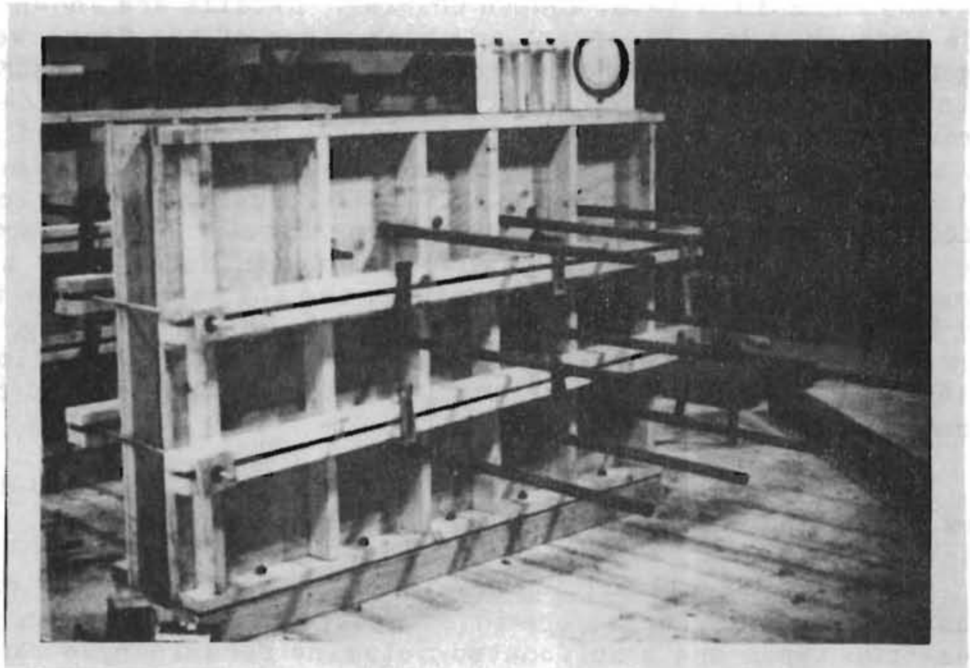


Fig. 3.7a Formwork ready for casting

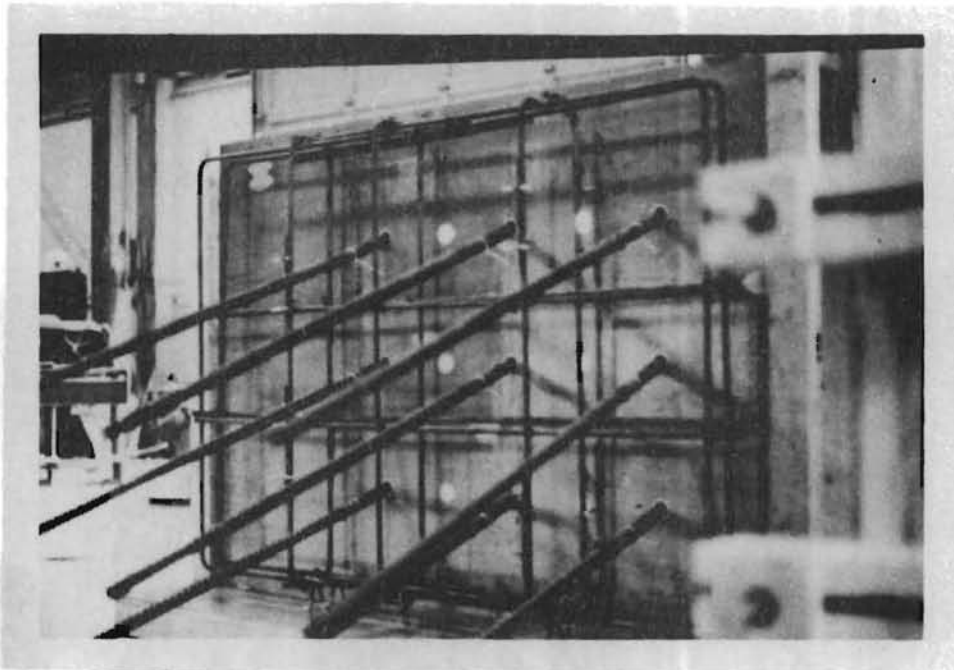


Fig. 3.7b

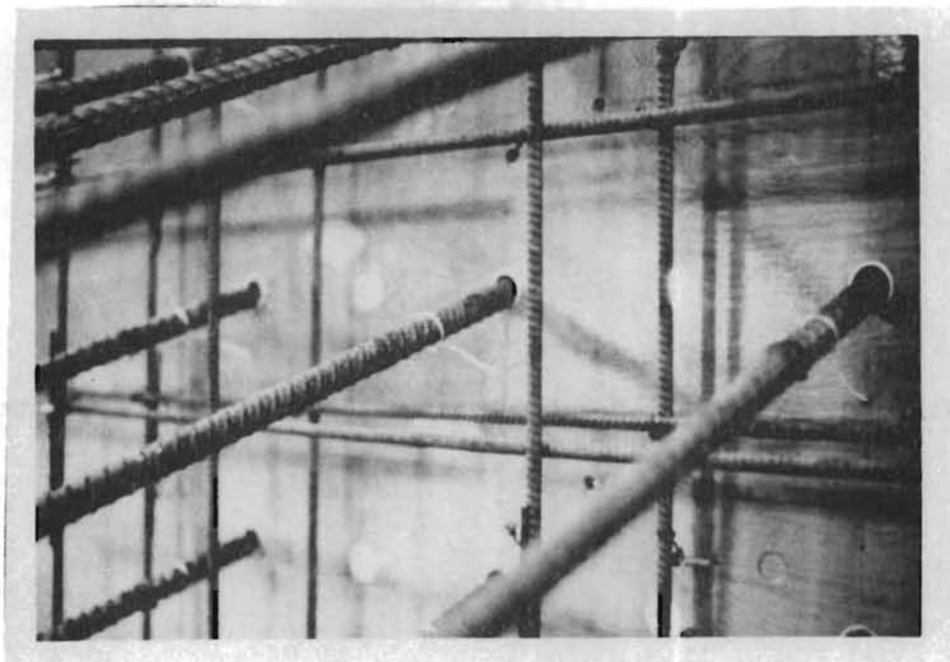


Fig. 3.7b PVC tubing in formwork

Fig. 3.7c Free end of pullout bar extending from form, with wedge, caulking, and slip wire

TABLE 3.1 Mix Proportions per Cubic Yard as Batched at the Ready-Mix Plant

| Component | Amount |
|---|---|
| Cement | 517 lbs |
| Fine Aggregate | 1350 lbs |
| Coarse Aggregate | 1695 lbs |
| Water | 31.5 gals |
| Retarding Admixture | 16.5 oz |
| Air Entraining Admixture | 3.0 oz |

TABLE 3.2 Details of the Casting Procedure of Each Series

| Series Number | Slump of Control Specimen, in. | Type of Super-Plasticizer Used | Slump of Second Specimen, in. | Slump of Third Specimen, in. |
|---|---|---|---|---|
| I | 3-1/4 | Naphthalene | 5-1/2 | 10 |
| II | 3 | Melamine | 6-1/2 | 9 |
| III | 3 | Naphthalene | 9 | -- |
| IV | 8-1/2 | --- | -- | -- |
| V | 5-1/2 | Naphthalene | 9 | -- |
| VI | 5 | Melamine | 8-1/2 | -- |

3/4-in. maximum size crushed limestone aggregate were used. In addition, the basic concrete mix design contained both an ASTM Type A retarding admixture and an air-entraining admixture.

## 3.4 Casting Procedure

In order to study the effects of adding superplasticizer to concrete, it is necessary to have a control specimen made of the same concrete without superplasticizer. Due to the variability inherent to the batching process at a typical ready-mix plant, both the control specimen and the specimens made with superplasticized concrete were cast from the same truckload of concrete. Although this method caused the superplasticized concrete to be poured at a slightly later age than the concrete of the control specimen, this difference in concrete age upon placing was considered to be of less importance than ensuring that all specimens of a given series would have the same mix proportions.

Six groups of specimens were poured. Two groups, denoted as Series I and Series II, consisted of three specimens each. Series III, V, and VI contained two specimens each. Series IV consisted of a single specimen. The details of the casting of each of the six series of specimens are given in Table 3.2, but the general procedure was as follows.

Upon the arrival of the ready-mix concrete truck at the laboratory, the slump of the concrete was measured. If the measured slump was less than the slump desired for the control specimen of the group being cast, water was added to the truck to achieve the desired slump. Once the desired slump had been achieved, the control specimen was cast, using a 1/2 cu.yd. capacity bucket. The forms were filled n three equal lifts, each lift being compacted using an internal vibrator having a 1-in. diameter round head. For all of the series except Series IV, the concrete remaining in the truck was then dosed with superplasticizer until a second target slump was achieved and the second specimen cast. When casting Series I and II, the concrete remaining in the truck after casting the first two specimens was again dosed with superplasticizer to a yet higher desired slump, and a third specimen was cast.

## 3.5 Concrete Properties Tested

In order to gain a more complete understanding of the pullout test results for each specimen, the following concrete properties were tested.

3.5.1 Slump. Each specimen was cast using concrete having a predetermined slump, achieved by the addition of either water or superplasticizer to the concrete. The slump was measured according to ASTM C143-78.

3.5.2 Air Content. The concrete used for each specimen was tested for air content, determined following the volumetric method as described in ASTM C173-78.

3.5.3 Bleeding. The bleed behavior of the concrete of each specimen was determined using the test procedure described in ASTM C232-71, except for the specified ambient temperature. According to that ASTM standard, the ambient temperature should be maintained between 65 and 75° F throughout the duration of the bleed test. Due to the conditions at the laboratory, however, control of the ambient temperature was not possible. Therefore, the bleed tests were carried out at temperatures significantly in excess of those values specified in ASTM C232-71.

3.5.4 Compressive Strength. The compressive strength of the concrete of each specimen was tested according to ASTM C39-81 as follows.

3.5.4.1 Molded Cylinders. Three 6-in. x 12-in. cylinders were tested at the time of the pullout tests, three 6-in. x 12 in. cylinders were tested at 56 days, and three 6-in. x 12-in. cylinders were tested at 104 days.

3.5.4.2 Drilled Cores. As shown in Fig. 3.8, three 6-in. x 12-in. cores were taken at each casting depth from specimens in Series IV and V. All cores were tested at 104 days.

3.5.5 Splitting Tensile Strength. Three 6-in. x 12-in. cylinders were tested according to ASTM C496-71 to determine the splitting tensile strength of the concrete cylinders cast with each specimen. These cylinders were tested at the time of the pullout tests.

## 3.6 Pullout Testing Procedure

All specimens were tested between 28 days and 35 days after casting, using the following procedure.

3.6.1 Preparation for Testing. In preparation for testing, a specimen was laid horizontally on four concrete blocks, one at each corner of the specimen. The blocks were approximately 42-in. tall, thus elevating the specimen and giving access to the back (now the bottom) of the specimen, from which protruded the free ends of the pullout bars and the slip wires. The bars would be loaded vertically at the front (top) face of the specimen.

Once in place, the bottom of the specimen was roughened with a wire brush and cleaned with acetone prior to attaching the aluminum

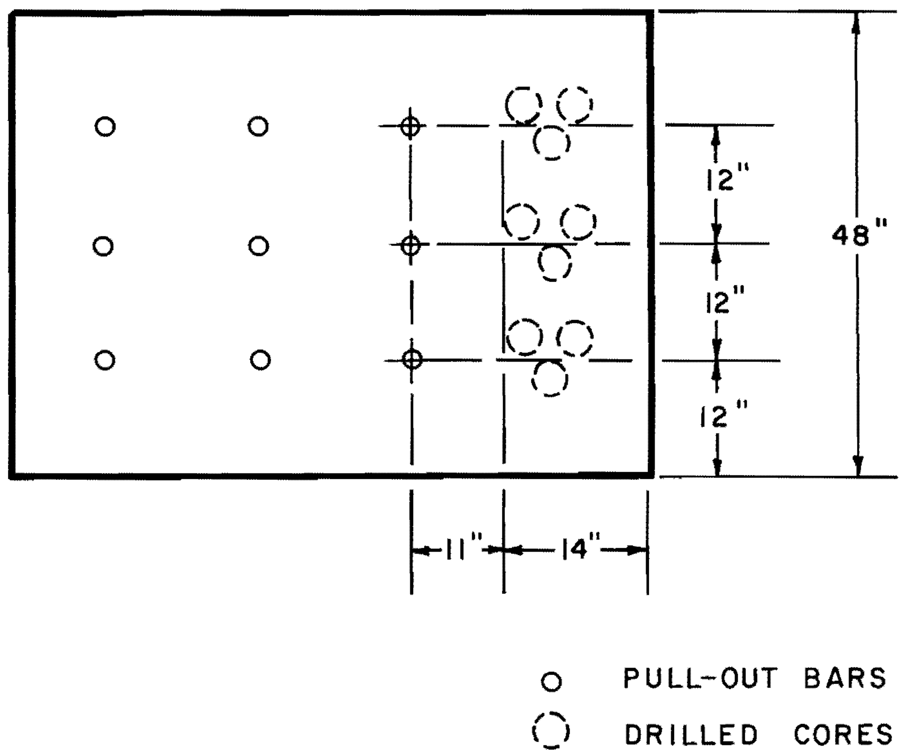



Fig. 3.8 Location of drilled cores

stands on which linear potentiometers would be mounted. The aluminum stands were attached to the specimen using 5-min. epoxy.

The specimen was then readied for the placement of the loading setup. All surface irregularities were removed from the top surface of the specimen around the pullout bars. The loading assembly consisted of a 60-ton capacity centerhole hydraulic ram, a 100-kip capacity load cell, a grip assembly, and a 1-in. thick steel plate having a 6-in. diameter hole placed concentrically around the pullout bar. This plate transferred the reaction from the concrete surface to the ram. Details of the loading assembly are shown in Figs. 3.9 and 3.10.

3.6.2 Instrumentation. During the pullout tests, slip at the loaded and free ends of the bar was measured using linear potentiometers. These were mounted on the aluminum stands attached to the bottom of the specimen, as shown in Fig. 3.10. One linear potentiometer was placed so that its plunger rested directly on the exposed free end of the pullout bar, and was used to measure free end slip. The other potentiometer was attached to the slip wire, and was used to measure loaded end slip.

3.6.3 Testing. The load was applied using a hand pump. In general, the duration of each pullout test was 5 min. The tests were terminated when the bond capacity of the system was reached, and slip occurred with no further increase in load. However, in the first series of specimens some of the bars tested, having an 8-in. embedment length, did not exhibit bond failure. Instead, these bars were fully developed, and yielded. This can be attributed to the decrease in cross-sectional area and stress concentration caused by drilling the holes for attachment of the slipwires to the pullout bars. For this reason, the embedment length of later specimens was reduced to 6 in.

3.6.4 Data Acquisition. The load-slip data from the pullout tests were recorded at the time of testing, using two X-Y plotters. Thus, the results of each pullout test were recorded in two plots, one giving the applied load versus free end slip, the other giving the applied load versus loaded end slip.

3.6.5 Data Reduction. Since the plunger of the linear potentiometer measuring free end slip rested directly against the free end of the test bar, the plots of applied load versus free end slip could be used directly. However, due to the small amount of initial slack in the slip wire, some loaded end slip occurred before the linear potentiometer recorded any movement. Therefore, the plots of applied load versus loaded end slip had to be corrected for this. An example of this correction procedure is given in Appendix B.

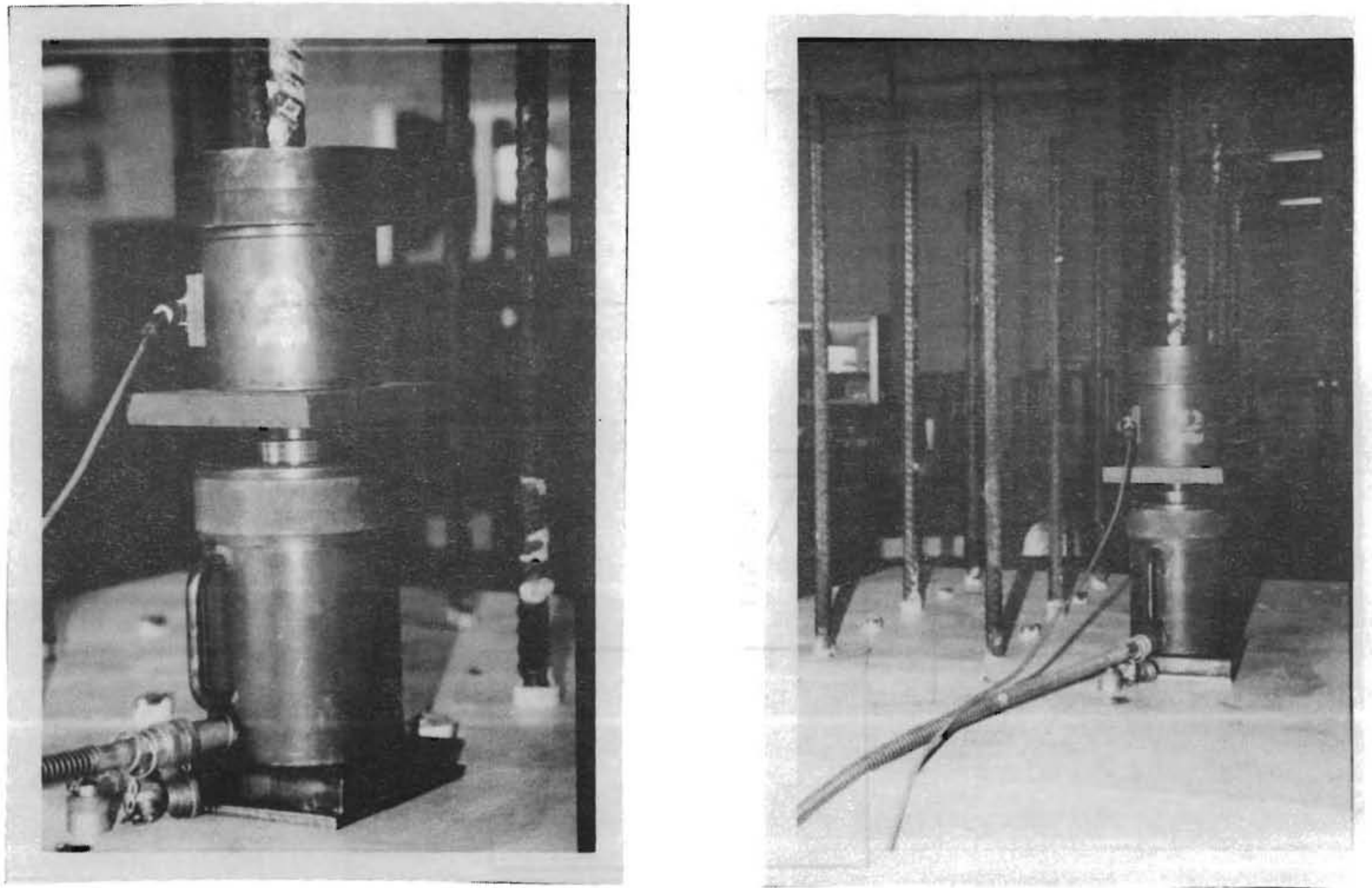


Fig. 3.9 Loading assembly

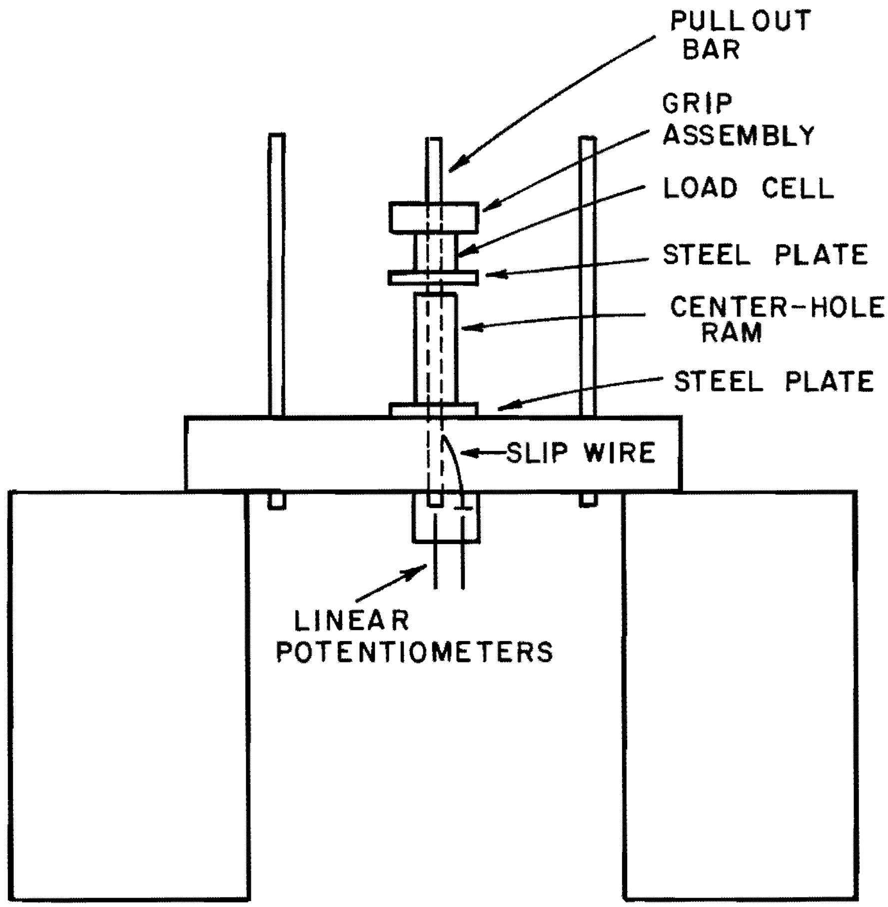



Fig. 3.10 Specimen in place prior to testing

# CHAPTER 4

## EXPERIMENTAL RESULTS

### 4.1 Introduction

In this chapter, the experimental results obtained from this study are presented. These include details of the casting procedure (such as concrete temperature and superplasticizer dosage), the material properties of the concrete of each specimen, and the pullout test results. The test results are discussed in Chapter 6.

The nomenclature of Table 4.1 is used to refer to individual specimens within each series tested. The nomenclature consists of three parts: 1) a Roman numeral denoting the series in which the specimen was cast; followed by 2) an Arabic numeral denoting the slump of the concrete of the specimen; and 3) a letter denoting if the concrete of the specimen contained no superplasticizer (U), naphthalene-based superplasticizer (N), or melamine-based superplasticizer (M).

### 4.2 Details of Casting Procedures

Details of the casting procedure for each of the six series are given in Table 4.2 through 4.7. Table 4.8 presents the superplasticizer dosage rates used for each specimen. The age of the concrete was measured starting at the time it left the ready-mix plant. The volume of concrete remaining in the ready-mix truck after casting each specimen was estimated by subtracting, from the original volume in the truck, the volume of concrete used to cast each specimen and to conduct the necessary quality control tests on each mix. This estimate is accurate to within plus or minus 1/4 of a cubic yard.

### 4.3 Air Content Test

The concrete of each specimen was tested for air content at the time of placing. The results of these tests are presented in Table 4.9.

### 4.4 Mix Proportions

The mix design supplied by the ready-mix concrete producer (Table 3.1) was based on an air content of 5%. As shown in Table 4.9, the actual air content of the fresh concrete ranged from 0.8% to 7.5%. In addition, water was added to the fresh concrete at the laboratory in order to achieve the design slump of each control mix. As a result, the mix proportions were recalculated to account for the actual air content of the fresh concrete and the retempering water added to each

TABLE 4.1 Test Specimen Nomenclature

| Series in Which Specimen Was Cast | Slump of Control Concrete[a], in. | Type of Super-Plasticizer Used | Super-Plasticizer Induced Slump[b], in. | Nomenclature |
|---|---|---|---|---|
| I | 3-1/4 | None | ----- | I3-1/4U |
| I | 3-1/4 | Naphthalene | 5-1/2 | I5-1/2N |
| I | 3-1/4 | Naphthalene | 10 | I10N |
| II | 3 | None | ----- | II3U |
| II | 3 | Melamine | 6-1/2 | II6-1/2M |
| II | 3 | Melamine | 9 | II9M |
| III | 3 | None | ----- | III3U |
| III | 3 | Naphthalene | 9 | III9N |
| IV | 8-1/2 | None | ----- | IV8-1/2U |
| V | 5-1/2 | None | ----- | V5-1/2U |
| V | 5-1/2 | Naphthalene | 9 | V9N |
| VI | 5 | None | ----- | VI5U |
| VI | 5 | Melamine | 8-1/2 | VI8-1/2M |

[a] Refers to the slump of the control concrete mix containing no superplasticizer.
[b] Refers to the slump of the concrete mix after adding the superplasticizer.

TABLE 4.2 Casting Procedure for Series I

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--5 $yd^3$ | 0 | 60 | a |
| 10 gal. water added | 2 | | |
| Additional 8 gal. water added | 3-1/4 | | |
| Specimen I3-1/4U cast | 3-1/4 | 69 | 84 |
| 56 oz. super added to 4 $yd^3$ concrete remaining in truck | 3 | | |
| Additional 56 oz. super added | 4-1/2 | | |
| Additional 96 oz. super added | 3 | | |
| Additional 176 oz. super added | 5-1/2 | | |
| Specimen I5-1/2N cast | 5-1/2 | 105 | 92 |
| 336 oz. super added to 2-3/4 $yd^3$ concrete remaining in truck | 10 | | |
| Specimen I10N cast | 10 | 120 | 93 |

[a] Not recorded

TABLE 4.3 Casting Procedure for Series II

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--6 $yd^3$ | 0 | 11 | a |
| 10 gal. water added | 1-1/2 | | |
| Additional 6 gal. water added | 2 | | |
| Additional 3 gal. water added | 3 | | |
| Specimen II3U cast | 3 | 32 | 86 |
| 232 oz. super added to 5 $yd^3$ concrete remaining in truck | 5 | | |
| Additional 24 oz. super added | 6-1/2 | | |
| Specimen II6-1/2M cast | 6-1/2 | 57 | 88 |
| 176 oz. super added to 4 $yd^3$ concrete remaining in truck | 8 | | |
| Additional 36 oz. super added | 6-1/2 | | |
| Additional 60 oz. super added | 9 | | |
| Specimen II9M cast | 9 | 87 | 89 |

[a] Not recorded

TABLE 4.4 Casting Procedure for Series III

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--6 $yd^3$ | 0 | 23 | a |
| 20 gal. water added | 2 | | |
| Additional 8 gal. water added | 3 | | |
| Specimen III3U cast | 3 | 38 | 88 |
| 288 oz. super added to 5 $yd^3$ concrete remaining in truck | 8 | | |
| Additional 96 oz. super added | 9 | | |
| Specimen III9N cast | 9 | 73 | 90 |

[a] Not recorded

TABLE 4.5 Casting Procedure for Series IV

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--4 $yd^3$ | 0 | 43 | a |
| 25 gal. water added | 4 | | |
| Additional 10 gal. water added | 6 | | |
| Additional 9 gal. water added | 8 | | |
| Additional 3 gal. water added | 8-1/2 | | |
| Specimen IV8-1/2U cast | 8-1/2 | 63 | 90 |

[a] Not recorded

TABLE 4.6 Casting Procedure for Series V

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--6 $yd^3$ | 1 | 15 | a |
| 15 gal. water added | 5-1/2 | | |
| Specimen V5-1/2U cast | 5-1/2 | 25 | 86 |
| 192 oz. super added to 5 $yd^3$ concrete remaining in truck | 9 | | |
| Specimen V9N cast | 9 | 37 | 86 |

[a] Not recorded

TABLE 4.7 Casting Procedure for Series VI

| Description | Slump, in. | Concrete Age, min. | Concrete Temp., °F |
|---|---|---|---|
| Arrival of concrete at lab--5 $yd^3$ | 3 | 19 | a |
| 8 gal. water added | 5 | | |
| Specimen VI5U cast | 5 | 24 | 84 |
| 150 oz. super added to 4 $yd^3$ concrete remaining in truck | 7 | | |
| Additional 72 oz. super added | 8-1/2 | | |
| Specimen VI8-1/2M cast | 8-1/2 | 49 | 85 |

[a] Not recorded

TABLE 4.8 Dosage Rates of Superplasticizer

| Specimen | Dosage of Superplasticizer, fl.oz./cwt |
|---|---|
| I3-1/4U | ---- |
| I5-1/2N | 19.6 |
| I10N | 43.2 |
| II3U | ---- |
| II6-1/2M | 9.9 |
| II9M | 22.5 |
| III3U | ---- |
| III9N | 15.0 |
| IV8-1/2U | ---- |
| V5-1/2U | ---- |
| V9N | 7.4 |
| VI5U | ---- |
| VI8-1/2M | 10.6 |

TABLE 4.9 Air Content

| Specimen | Air Content, % |
|---|---|
| I3-1/4U | 2.5 |
| I5-1/2N | 1.4 |
| I10N | 0.8 |
| II3U | 5.9 |
| II6-1/2M | 6.5 |
| II9M | 5.5 |
| III3U | 4.5 |
| III9N | 3.5 |
| IV8-1/2U | 7.4 |
| V5-1/2U | 6.6 |
| V9N | 4.4 |
| VI5U | 1.2 |
| VI8-1/2M | 1.1 |

mix, and are presented in Table 4.10.

## 4.5 Bleed Test

Bleed versus time curves for each of the series are presented in Figs. 4.1 through 4.6. Table 4.11 shows the duration of the bleed test for each specimen in relation to the age of the concrete during the test and the total amount of bleeding which occurred.

## 4.6 Compressive Strength Test

The results of the concrete compressive strength tests are divided into two groups: molded cylinders and drilled cores.

4.6.1 Molded Cylinders. The compressive strengths of the 6-in. x 12-in. cylinders cast with each specimen are given in Table 4.12. The concrete cylinder compressive strength tests were conducted at the time each corresponding pullout specimen was tested, rather than at the standard test age of 28 days. All results shown are the average strengths of three cylinders tested.

4.6.2 Drilled Cores. Three 3-in. x 6-in. cores were taken at each casting depth from specimens IV8-1/2U, V5-1/2U, and V9N, and tested in compression. For each specimen, the average value of the core strengths from each casting depth is presented in Table 4.13.

## 4.7 Splitting Tensile Strength Test

The results of the split cylinder tests for each concrete mix are shown in Table 4.14. Values reported in Table 4.14 correspond to average values determined from the tests of three 6-in. x 12-in. molded cylinders. The cylinders were tested at the time the corresponding pullout specimen was tested.

## 4.8 Pullout Tests

The load versus slip behavior between concrete and reinforcement from each pullout test will be presented in this section. To differentiate among the nine bars embedded in each specimen for pullout tests, each bar will be designated by the column and row number in which it was located, as shown in Fig. 4.7. For example, using this designation system, the bottom cast middle bar would be referred to as bar 1B.

Typical load versus slip curves for the bars tested are shown, and the load versus slip behavior of each pullout bar tested is presented in tabular form. Also included in this section is a description of the observed failure mechanism of the pullout test bars and of the failure surface.

TABLE 4.10 Mix Proportions of Pullout Specimens

| Specimen | Water Added to Basic Concrete Mix[a], gal/c.y. | Air Cont., % | Mix Proportions per Cubic Yard | | | | |
|---|---|---|---|---|---|---|---|
| | | | Cement, lbs | Fine Agg., lbs-SSD | Coarse Agg., lbs-SSD | Water, gal | W/C Ratio by wt |
| Basic Mix Design | 0.0 | 5.0 | 517 | 1350 | 1695 | 31.5 | 0.51 |
| I3-1/4U | 3.71 | 2.5 | 521 | 1360 | 1708 | 35.5 | 0.57 |
| I5-1/2N | 3.71 | 1.4 | 527 | 1375 | 1727 | 35.8 | 0.57 |
| I 10N | 3.71 | 0.8 | 530 | 1383 | 1737 | 36.0 | 0.57 |
| II3U | 3.15 | 5.9 | 505 | 1318 | 1655 | 33.9 | 0.56 |
| II6-1/2M | 3.15 | 6.5 | 502 | 1310 | 1645 | 33.7 | 0.56 |
| II9M | 3.15 | 5.5 | 507 | 1323 | 1661 | 34.0 | 0.56 |
| III3U | 4.66 | 4.5 | 508 | 1326 | 1665 | 35.6 | 0.59 |
| III9N | 4.66 | 3.5 | 513 | 1339 | 1682 | 36.0 | 0.59 |
| IV8-1/2U | 11.2 | 7.4 | 477 | 1247 | 1564 | 40.3 | 0.71 |
| V5-1/2U | 2.46 | 6.6 | 502 | 1310 | 1644 | 33.1 | 0.55 |
| V9N | 2.46 | 4.4 | 513 | 1339 | 1680 | 33.8 | 0.55 |
| VI5U | 1.68 | 1.2 | 533 | 1393 | 1748 | 34.2 | 0.53 |
| VI8-1/2M | 1.68 | 1.1 | 534 | 1394 | 1750 | 34.2 | 0.53 |

[a] Refers to the amount of retempering water added to the fresh concrete at the laboratory in order to achieve the design slump.

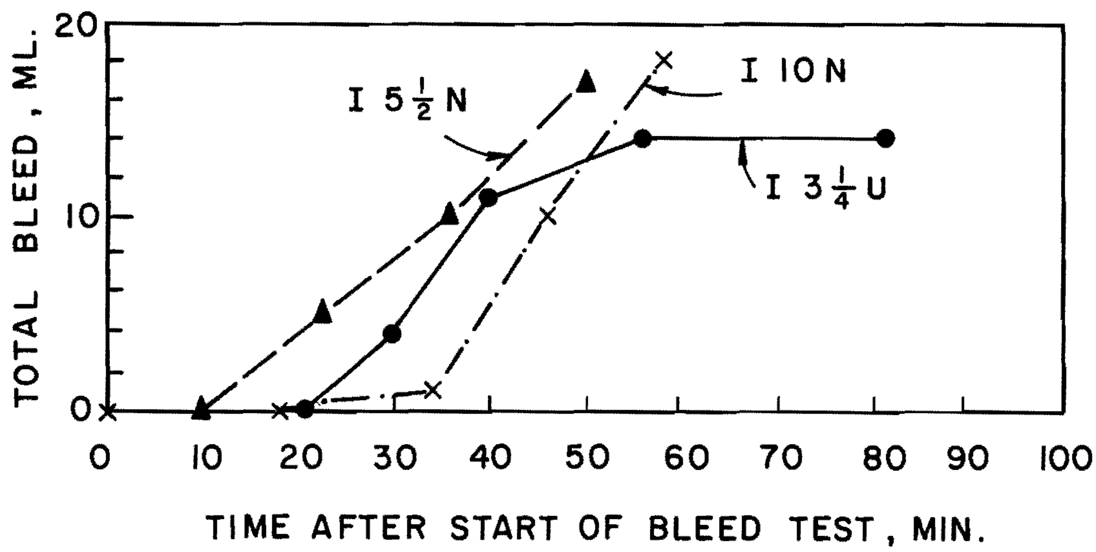



Fig. 4.1 Bleed versus time curves for specimens of Series I

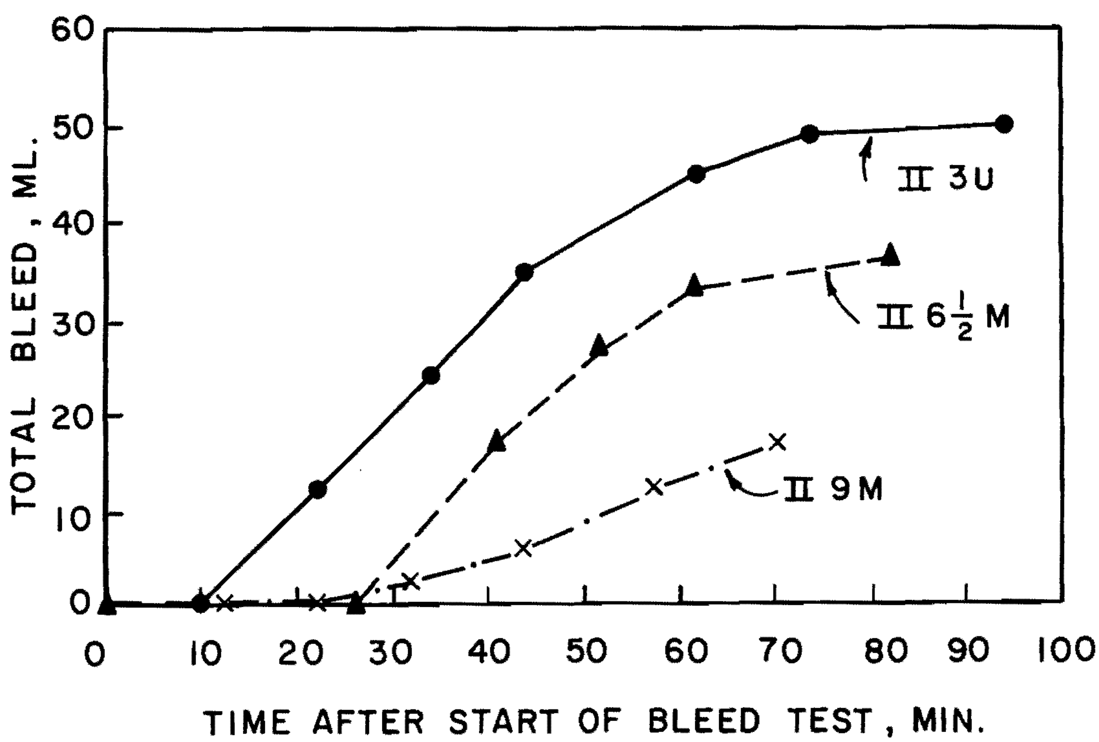



Fig. 4.2 Bleed versus time curves for specimens of Series II

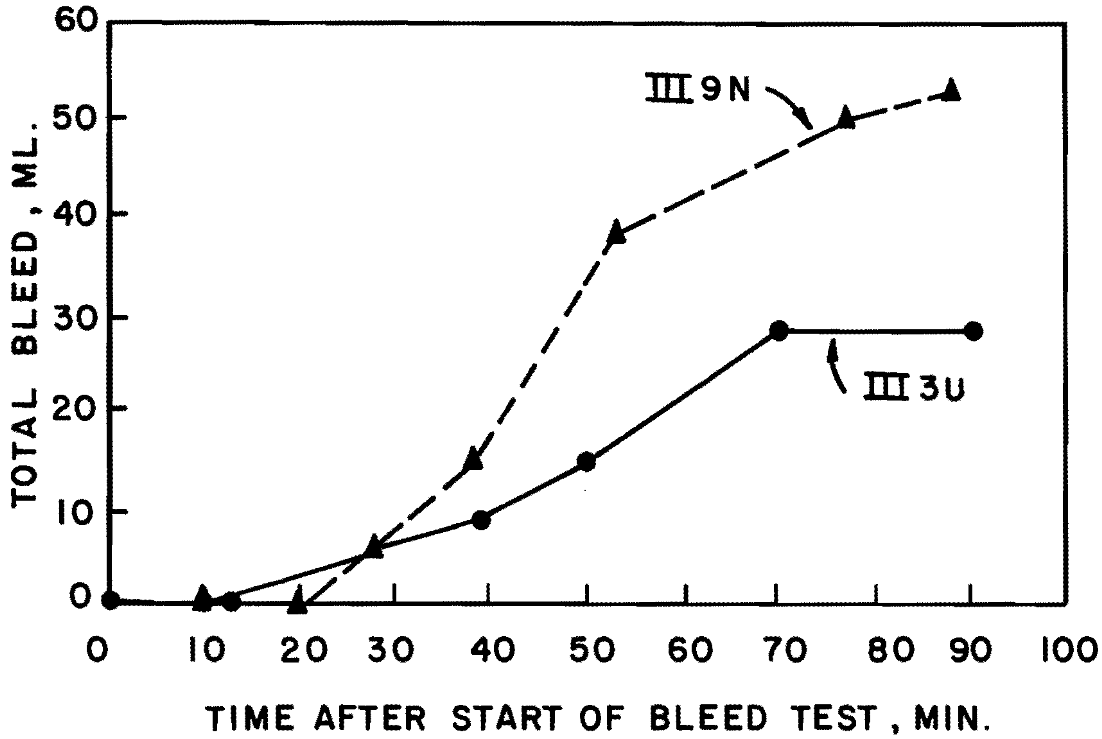



Fig. 4.3 Bleed versus time curves for specimens of Series III

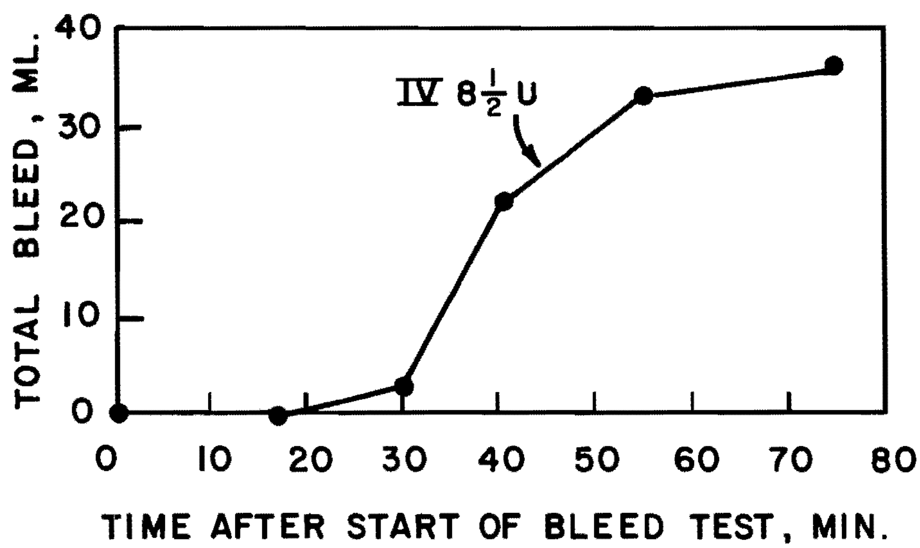



Fig. 4.4 Bleed versus time curve for specimen of Series IV

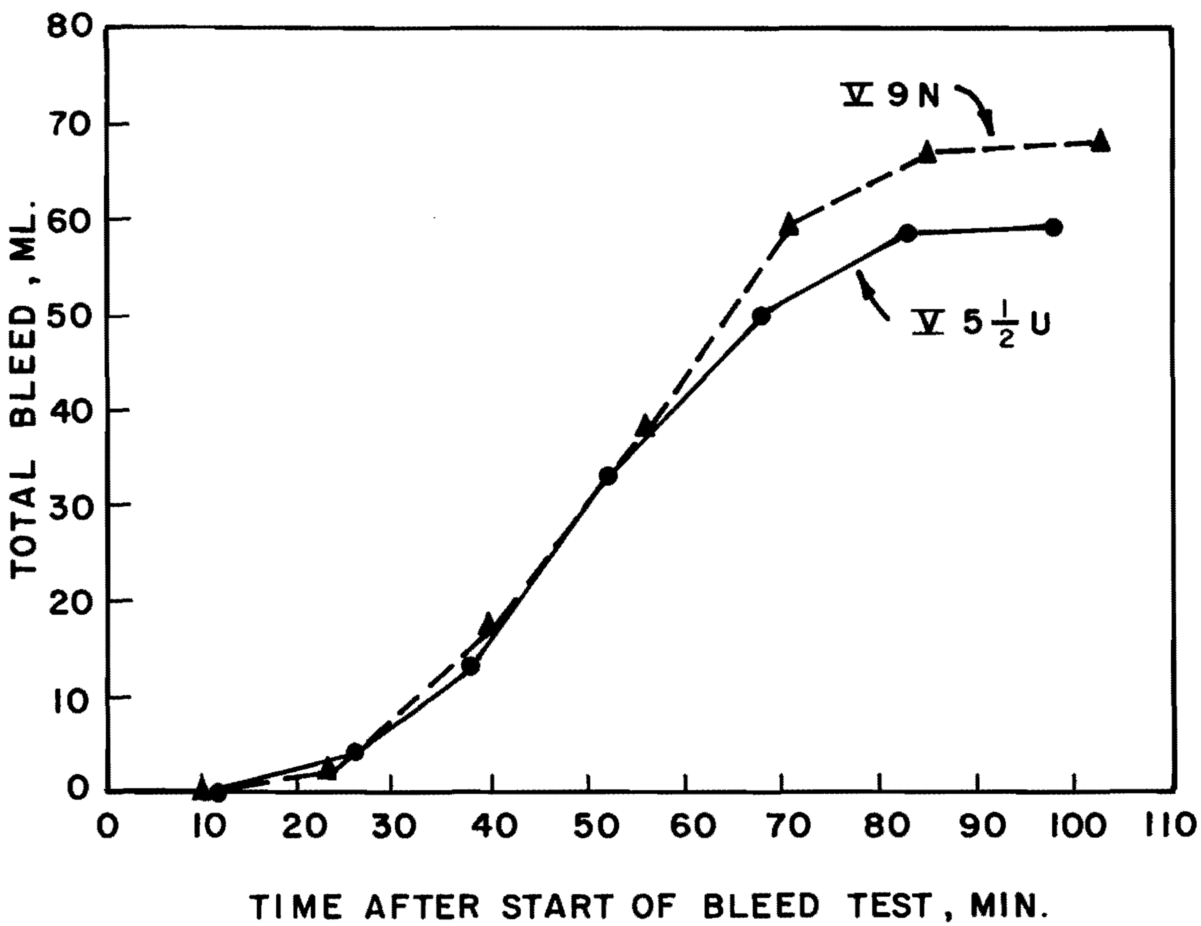



Fig. 4.5 Bleed versus time curves for specimens of Series V

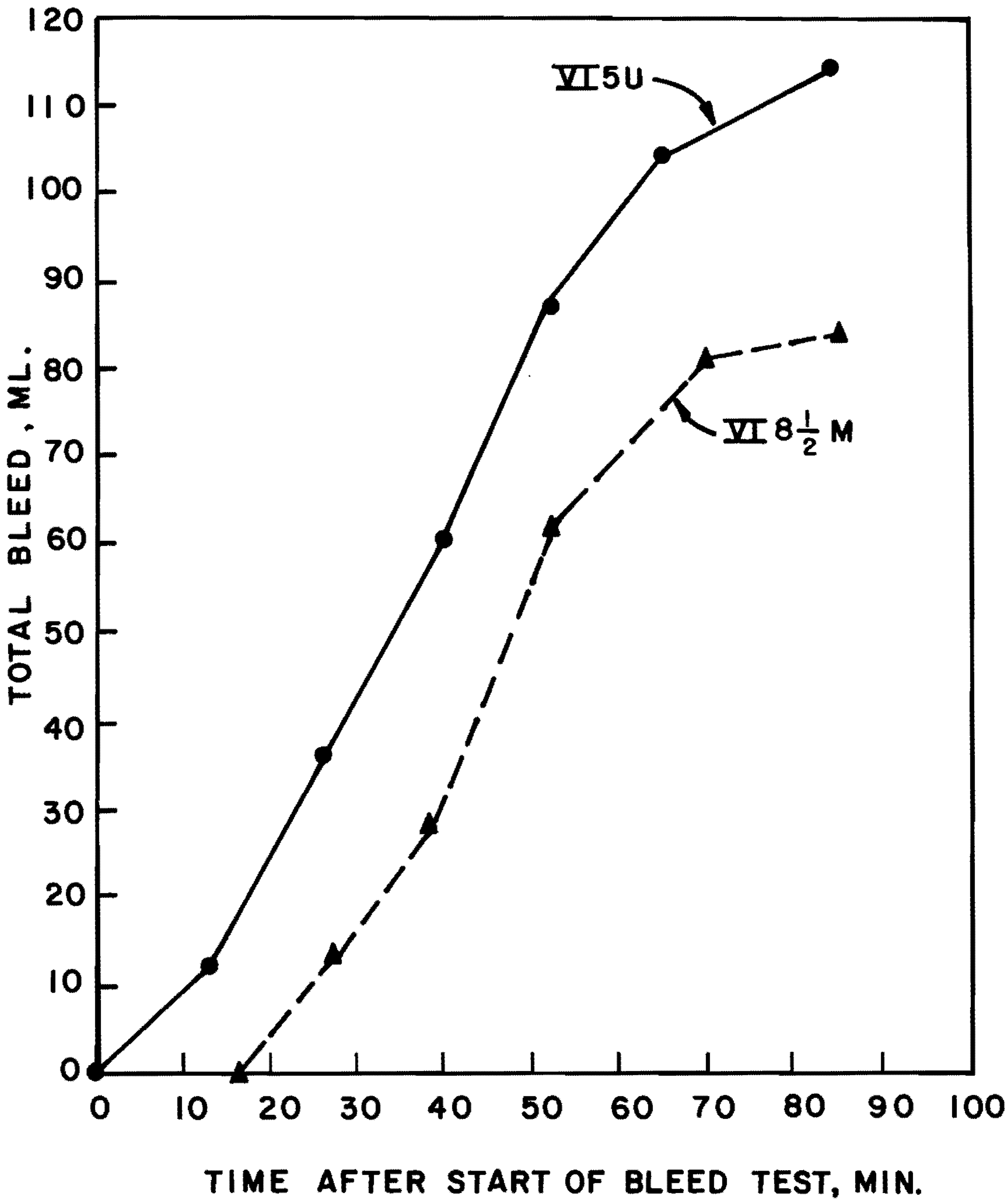
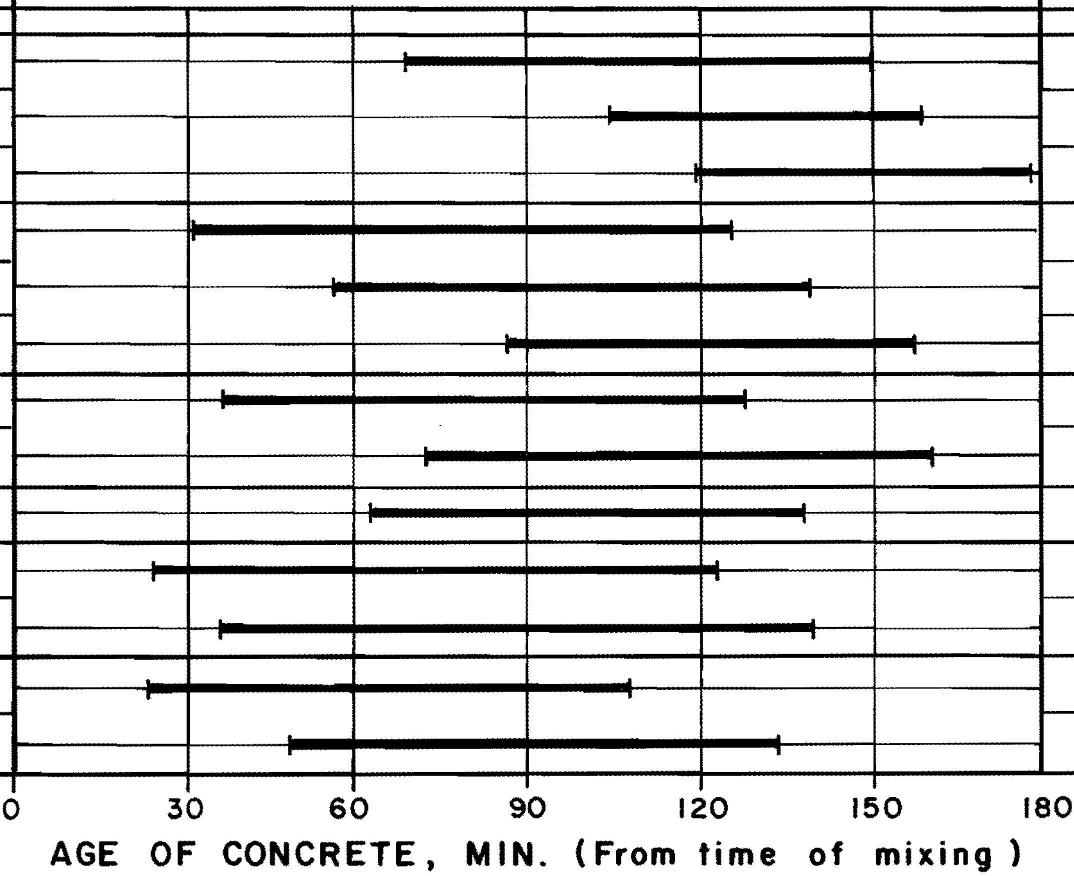



Fig. 4.6 Bleed versus time curves for specimens of Series VI

TABLE 4.11 Bleed Test Results With Respect to Age of Concrete

| SPECIMEN | BLEED VERSUS TIME BEHAVIOR FOR TEST SPECIMENS | Duration of Bleed Test min. | Total Amount of Bleed ml. |
|---|---|---|---|
| I 3 $\frac{1}{4}$ U | | 81 | 14 |
| I 5 $\frac{1}{2}$ N | | 54[a] | 17 |
| I 10 N | | 58[a] | 18 |
| II 3 U | | 94 | 50 |
| II 6 $\frac{1}{2}$ M | | 82 | 36 |
| II 9 M | | 70 | 17 |
| III 3 U | | 90 | 28 |
| III 9 N | | 88 | 53 |
| IV 8 $\frac{1}{2}$ U | | 75 | 36 |
| V 5 $\frac{1}{2}$ U | | 98 | 59 |
| V 9 N | | 103 | 68 |
| VI 5 U | | 84 | 114 |
| VI 8 $\frac{1}{2}$ M | | 85 | 84 |




a. Bleed test stopped before concrete had stopped bleeding.

TABLE 4.12 Compressive Strengths of Molded Cylinders

| Specimen | Age at Time of Pullout Testing, days | Cylinder Compressive Strength[a], psi | | |
|---|---|---|---|---|
| | | At Time of Pullout Testing | At 56 Days | At 104 Days |
| I3-1/4U | 31 | 4600 | ---- | ---- |
| I5-1/2N | 34 | 5500 | ---- | ---- |
| I10N | 35 | 5400 | ---- | ---- |
| II3U | 28 | 5900 | 5900 | ---- |
| II6-1/2M | 29 | 6100 | 6300 | ---- |
| II9M | 30 | 6100 | 6200 | ---- |
| III3U | 31 | 5100 | 5700 | 6000 |
| III9N | 28 | 6300 | 6500 | 6700 |
| IV8-1/2U | 35 | 3400 | 3700 | 3800 |
| V5-1/2U | 35 | 4900 | 4800 | 4500 |
| V9N | 34 | 5300 | 5500 | 5200 |
| VI5U | 31 | 5200 | 5400 | 5200 |
| VI8-1/2M | 28 | 5300 | 5400 | 4600 |

[a] Refers to the average of three cylinder tests.

TABLE 4.13 Compressive Strength of Drilled Cores

| Specimen | Casting Depth, in. | Core Compressive Strength[a], psi |
|---|---|---|
| | 36 | 3900 |
| IV8-1/2U | 24 | 4600 |
| | 12 | 4300 |
| | 36 | 5400 |
| V5-1/2U | 24 | 5600 |
| | 12 | 5500 |
| | 36 | 5000 |
| V9N | 24 | 5500 |
| | 12 | 5700 |

[a] Refers to the average of three tests.

TABLE 4.14 Splitting Tensile Strength of Molded Cylinders

| Specimen | Age at Testing, days | Splitting Tensile Strength at Time of Testing[a], psi |
|---|---|---|
| I3-1/4U | 31 | 500 |
| I5-1/2N | 34 | 500 |
| I10N | 35 | 580 |
| II3U | 28 | 480 |
| II6-1/2M | 29 | 460 |
| II9M | 30 | 460 |
| III3U | 31 | 400 |
| III9N | 28 | 460 |
| IV8-1/2U | 35 | 370 |
| V5-1/2U | 35 | 340 |
| V9N | 34 | 400 |
| VI5U | 31 | 440 |
| VI8-1/2M | 28 | 470 |

[a] Refers to average of three tests.

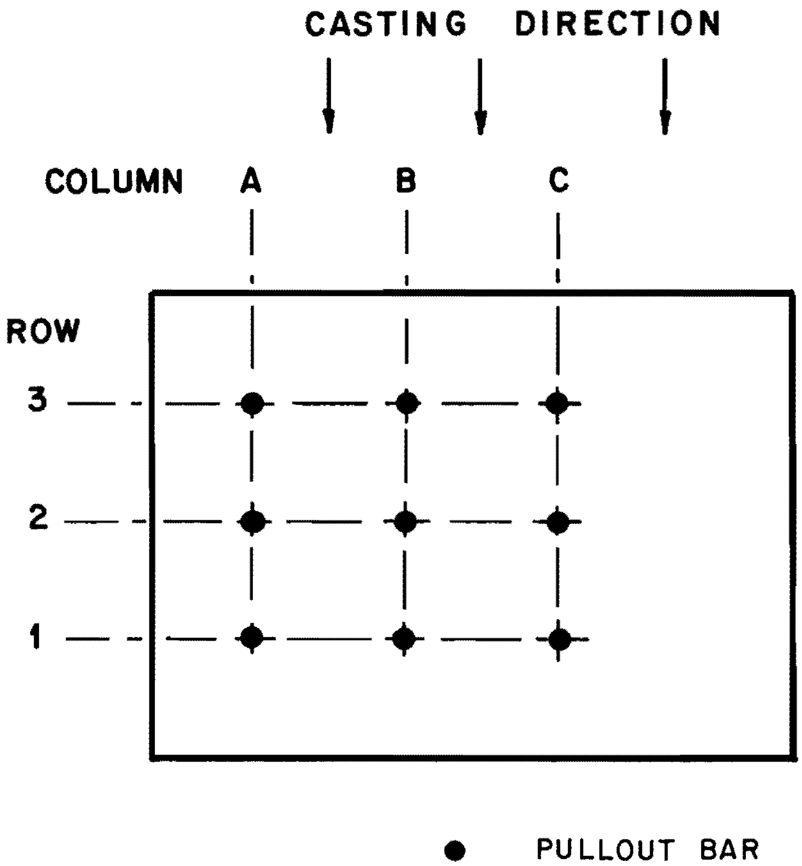



Fig. 4.7 Pullout bar designation system

4.8.1 Typical Curves. The curves shown in Figs. 4.8 through 4.11 represent typical load versus slip curves obtained from the pullout tests. Both free end slip and loaded end slip test data are plotted in each figure. The loaded end slip curves have been corrected as described in Appendix B.

4.8.2 Tabulated Results. The pullout test results presented in Tables 4.15 through 4.20 summarize the applied load versus slip behavior of all pullout bars tested. Normalized pullout test results are presented in Tables 4.21 through 4.26. In those tables, the variation in splitting tensile strength of concrete among specimens was compensated for by normalizing the loads for each specimen with respect to a concrete tensile strength of 400 psi as follows:

$$\text{(applied load)} \times (400/T_{(\text{specimen})}) = \text{(normalized load)}$$

The above factor is based on the generally accepted hypothesis that bond strength is directly related to the tensile capacity of the concrete.

4.8.3 Failure Mechanism. A typical observed crack pattern resulting from a pullout test is shown in Fig. 4.12. As shown in this figure, the cracks extended radially from the pullout bar to the encompassing circular crack. The circular crack followed the opening in the steel plate, bearing against the specimen surface, which transferred the reaction from the specimen to the actuator. Pulling the bar completely out of the specimen resulted in the failure surface shown in Figs. 4.13 and 4.14.

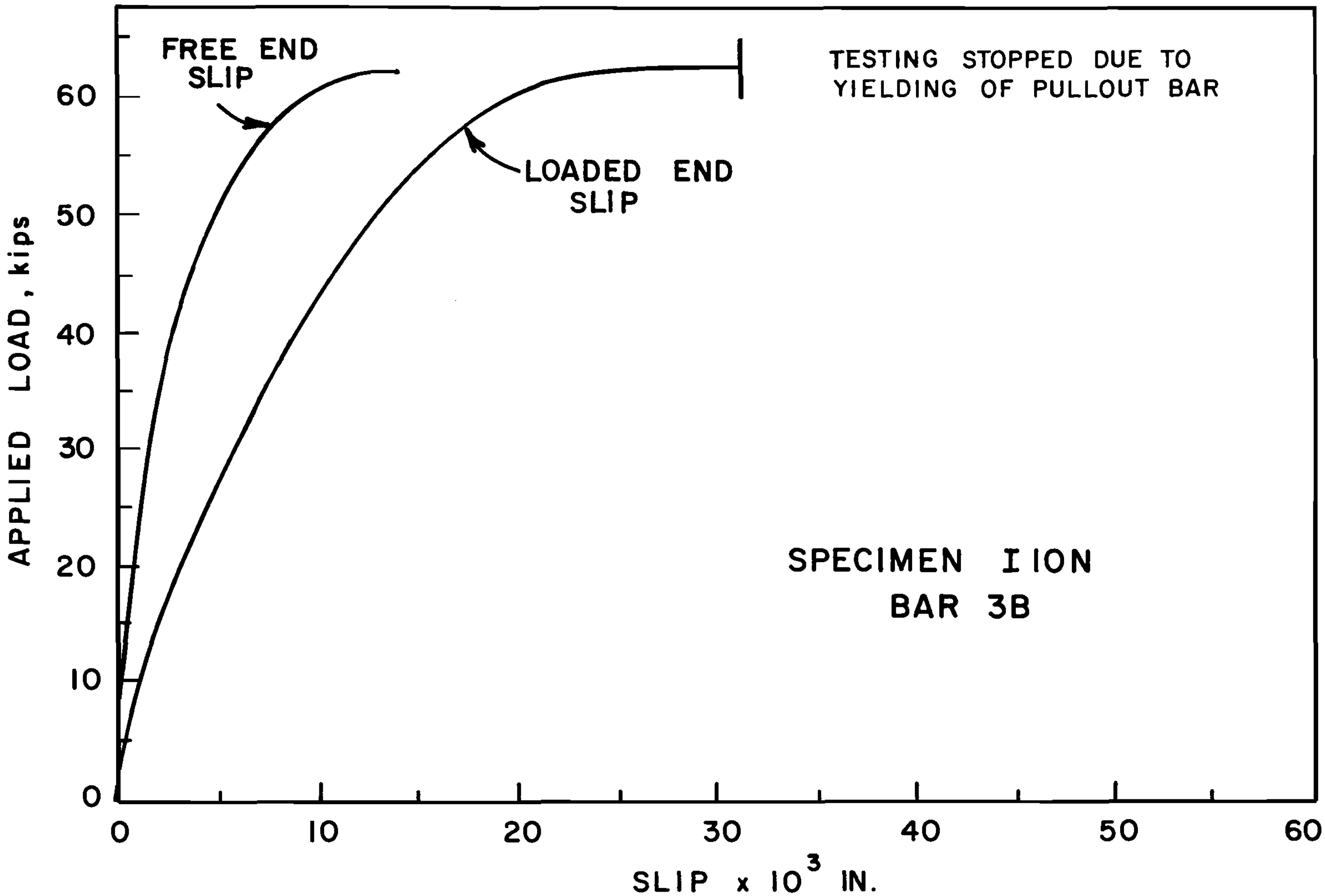



Fig. 4.8 Typical load-slip curve

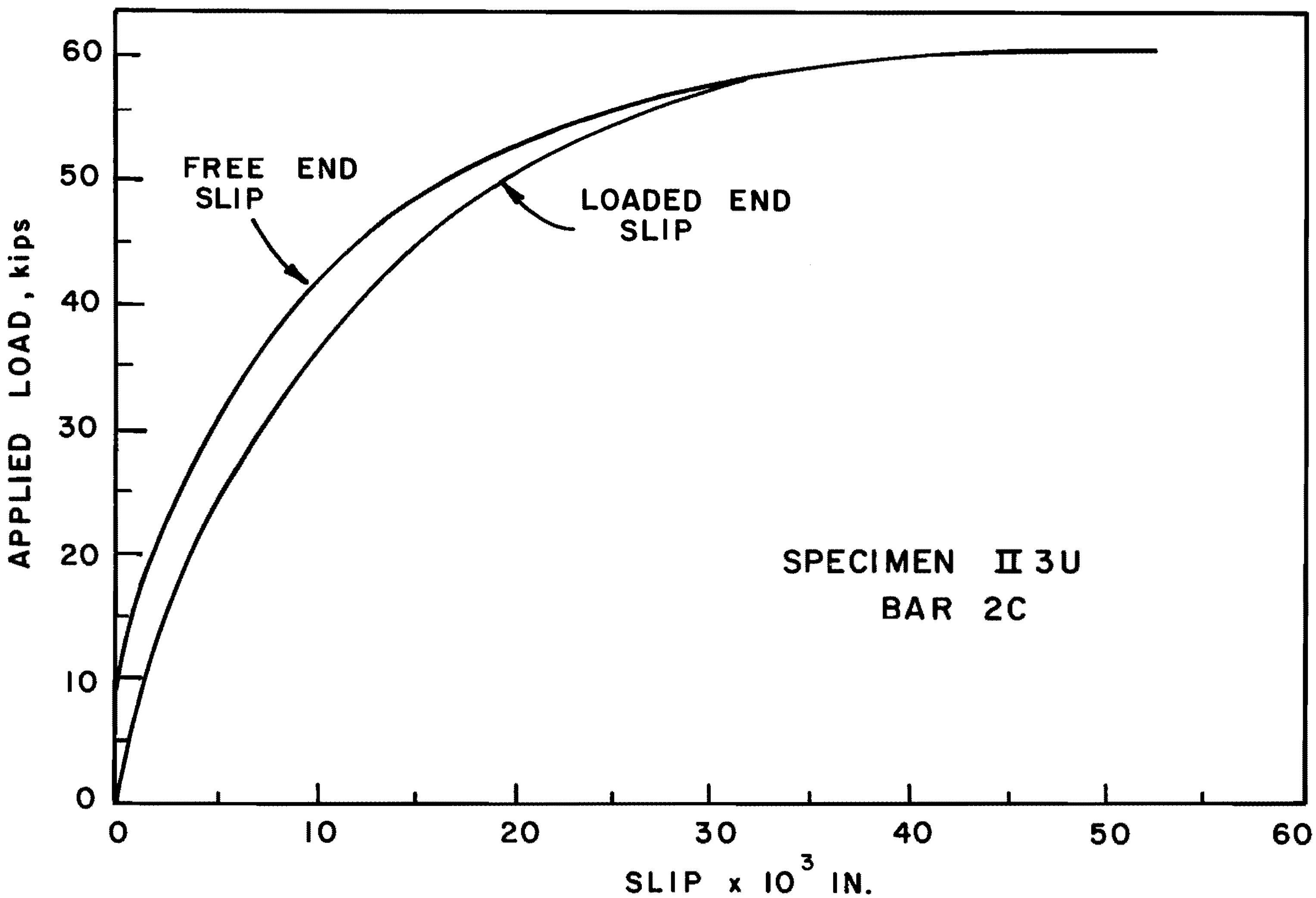



Fig. 4.9 Typical load-slip curve

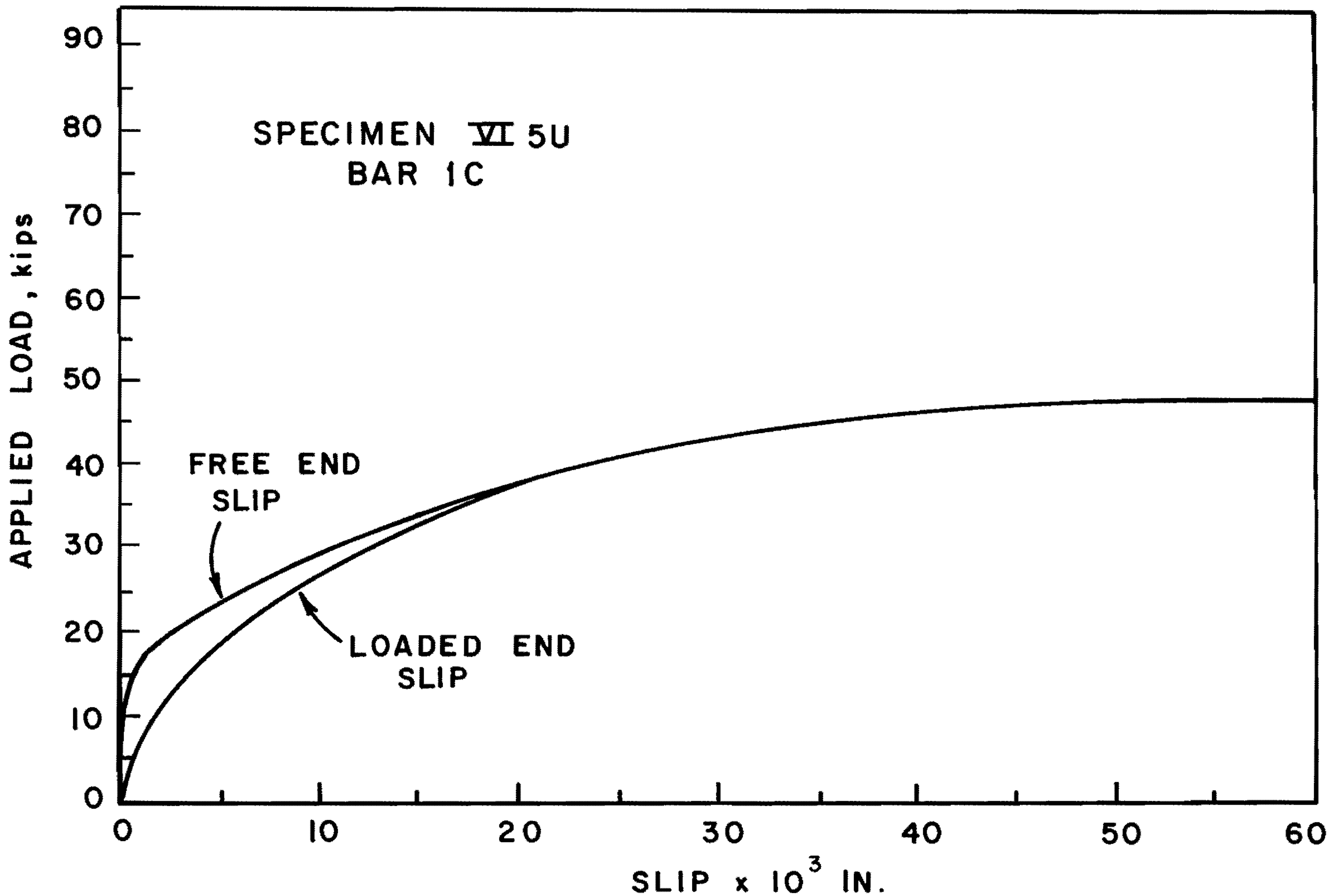



Fig. 4.10 Typical load-slip curve

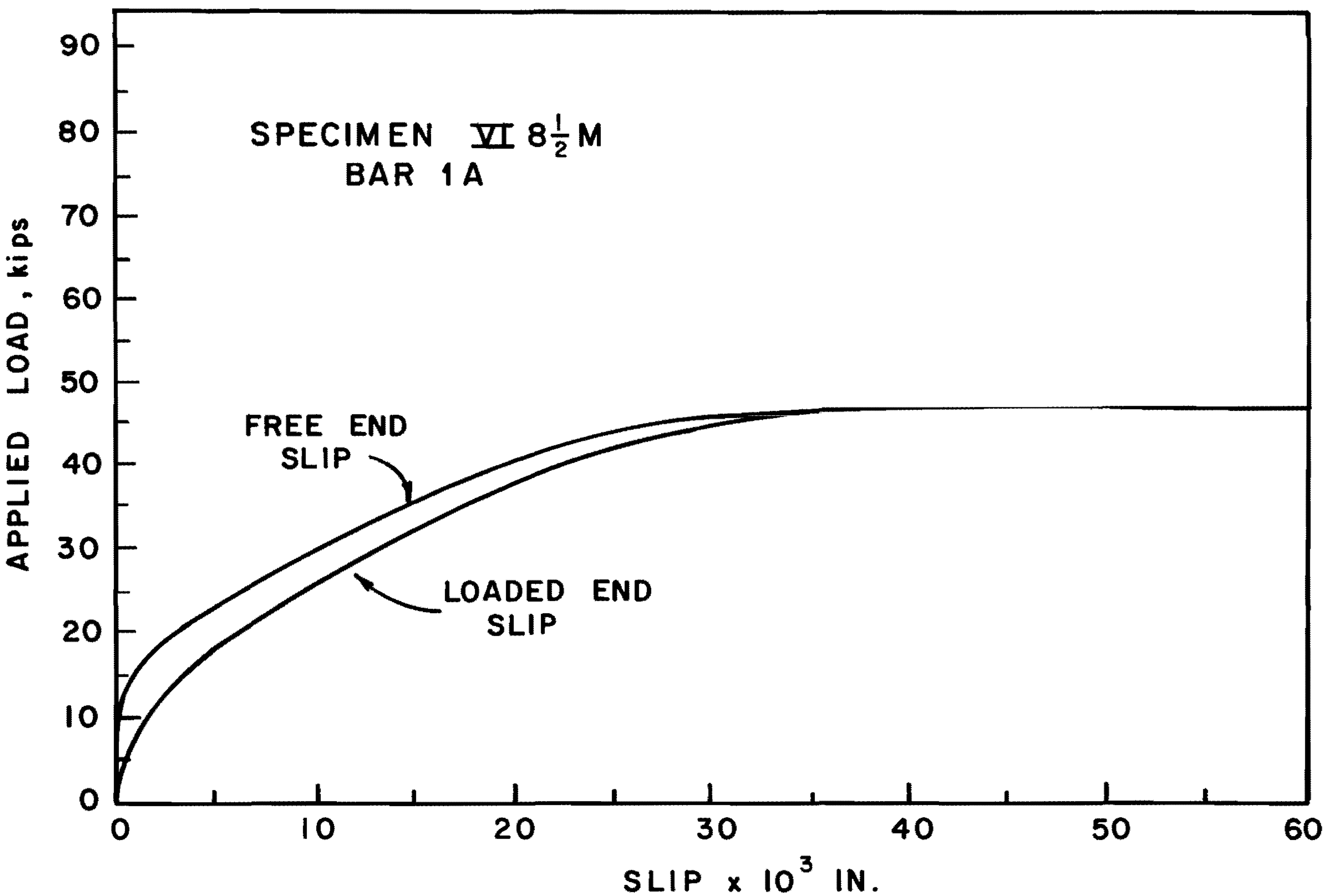



Fig. 4.11 Typical load-slip curve

TABLE 4.15 Pullout Test Results for Series I

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A[a] | 54.1 | | 36.5 | | 23.6 | |
| | 1B | 59.1 | 56.6 | 38.2 | 37.4 | 53.7 | 38.7 |
| | 1C | b | | b | | b | |
| | 2A | 56.8 | | 40.2 | | 22.4 | |
| I3-1/4U | 2B | 60.5 | 57.5 | b | 44.4 | 19.6 | 25.9 |
| | 2C[a] | 55.1 | | 48.6 | | 35.8 | |
| | 3A[a] | 61.8 | | 38.9 | | 17.6 | |
| | 3B[a] | 54.1 | 56.1[d] | 35.4 | 36.5 | 14.5 | 17.2 |
| | 3C[a] | 52.4 | | 35.1 | | 19.6 | |
| | 1A | 65.9 | | 44.3 | | 24.3 | |
| | 1B[c] | 66.2 | 66.1 | 49.7 | 44.2 | 45.3 | 31.2 |
| | 1C[c] | (61.8) | | 38.5 | | 24.0 | |
| | 2A[c] | (60.8) | | 47.3 | | 28.7 | |
| I5-1/2N | 2B[c] | 65.9 | 65.7 | 47.3 | 46.5 | 27.0 | 25.3 |
| | 2C | 65.5 | | 44.9 | | 20.3 | |
| | 3A | 66.9 | | 41.2 | | b | |
| | 3B[c] | (62.2) | 64.7 | 45.6 | 41.2 | 32.4 | 25.9 |
| | 3C | 62.5 | | 36.8 | | 19.3 | |
| | 1A[c] | 62.2 | | 47.3 | | 20.9 | |
| | 1B[c] | 61.5 | 62.3[e] | b | 45.6 | 18.6 | 23.9 |
| | 1C[c] | 63.2 | | 43.9 | | 32.1 | |
| | 2A | 65.9 | | 42.6 | | 15.9 | |
| I10N | 2B[c] | 67.6 | 67.0 | 44.3 | 42.7 | 30.7 | 22.7 |
| | 2C | 67.6 | | 41.2 | | 21.6 | |
| | 3A[c] | 62.5 | | 42.2 | | 23.0 | |
| | 3B[c] | 62.8 | 62.6[e] | 61.5 | 51.3 | 35.5 | 31.4 |
| | 3C[c] | 62.5 | | 50.3 | | 35.8 | |

() Value not included in average.
[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Test results not recorded due to instrumentation problems.
[c] Testing stopped due to yielding of pullout bar.
[d] Average value of loads at loaded end slip of 0.06 in.
[e] Average value of loads at which pullout bars yielded.

TABLE 4.16 Pullout Test Results for Series II

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A | 72.6 | | 53.7 | | 29.7 | |
| | 1B | b | 67.3 | 53.5 | 50.4 | 33.0 | 26.7 |
| | 1C | 61.9 | | 44.0 | | 17.3 | |
| | 2A | 74.0 | | 45.3 | | 33.5 | |
| II3U | 2B | b | 67.4 | 45.6 | 42.0 | 33.6 | 28.4 |
| | 2C | 60.7 | | 35.2 | | 18.2 | |
| | 3A | 70.7 | | b | | b | |
| | 3B | 67.6 | 66.9 | 46.8 | 46.2 | 26.9 | 25.8 |
| | 3C | 62.3 | | 45.6 | | 24.7 | |
| | 1A | 66.5 | | 40.5 | | 13.5 | |
| | 1B | 67.0 | 67.9 | 49.0 | 48.2 | 25.0 | 31.8 |
| | 1C | 70.3 | | 55.2 | | 57.0 | |
| | 2A | 61.3 | | 37.2 | | 16.0 | |
| II6-1/2M | 2B[a] | 68.4 | 66.6 | 36.8 | 39.9 | 16.5 | 17.4 |
| | 2C | 70.0 | | 45.7 | | 19.8 | |
| | 3A | 63.2 | | 38.8 | | 15.6 | |
| | 3B | 67.9 | 64.6 | 44.0 | 41.3 | 24.0 | 21.7 |
| | 3C | 62.7 | | 41.2 | | 25.5 | |
| | 1A | 72.0 | | 46.2 | | 42.9 | |
| | 1B | 79.7 | 73.2 | 52.3 | 45.3 | 25.0 | 31.6 |
| | 1C | 67.9 | | 37.4 | | 26.9 | |
| | 2A | 72.6 | | 43.4 | | 14.6 | |
| II9M | 2B | 69.3 | 70.7 | 45.7 | 44.3 | 26.4 | 20.6 |
| | 2C | 70.3 | | 43.7 | | 20.7 | |
| | 3A | 64.8 | | 39.1 | | 25.5 | |
| | 3B | 60.8 | 63.9 | 40.1 | 39.1 | 20.2 | 21.4 |
| | 3C | 66.0 | | 38.2 | | 18.4 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.

[b] Test results not recorded due to instrumentation problems.

TABLE 4.17 Pullout Test Results for Series III

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A | 54.4 | | 36.3 | | 13.8 | |
| | 1B | 58.0 | 56.6 | 42.0 | 38.4 | 27.3 | 17.9 |
| | 1C | 57.5 | | 37.0 | | 12.7 | |
| | 2A | 66.0 | | 50.0 | | 17.9 | |
| III3U | 2B | 61.8 | 62.1 | 45.9 | 45.5 | 43.8 | 26.2 |
| | 2C | 58.5 | | 40.5 | | 16.8 | |
| | 3A | 64.6 | | 45.3 | | 13.2 | |
| | 3B | 61.5 | 64.0 | 46.9 | 46.9 | 28.3 | 25.8 |
| | 3C | 66.0 | | 48.6 | | 35.8 | |
| | 1A | 64.8 | | 43.8 | | 15.4 | |
| | 1B | 76.1 | 72.5 | 66.5 | 55.1 | 49.5 | 35.2 |
| | 1C | 76.7 | | 54.9 | | 40.7 | |
| | 2A | 61.6 | | 46.5 | | 21.7 | |
| III9N | 2B | 63.2 | 65.5 | 40.5 | 43.5 | 30.4 | 23.5 |
| | 2C | 71.7 | | a | | 18.4 | |
| | 3A | 67.9 | | 40.1 | | 15.8 | |
| | 3B | 73.1 | 69.7 | 48.7 | 41.9 | 14.8 | 16.3 |
| | 3C | 68.1 | | 36.8 | | 18.4 | |

[a] Value not recorded due to instrumentation problems.

TABLE 4.18 Pullout Test Results for Series IV

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A[a] | 50.0 | | 34.9 | | 19.3 | |
| | 1B | 45.7 | 46.5 | 26.9 | 32.4 | 27.3 | 22.2 |
| | 1C | 43.8 | | 35.4 | | 20.0 | |
| | 2A | 53.3 | | 38.8 | | 36.8 | |
| IV8-1/2U | 2B | 45.9 | 47.6 | 36.3 | 36.7 | 32.1 | 31.2 |
| | 2C | 43.6 | | 34.9 | | 24.6 | |
| | 3A | 44.3 | | b | | 28.8 | |
| | 3B | 43.6 | 44.8 | 33.9 | 34.7 | 22.2 | 22.3 |
| | 3C | 46.5 | | 35.4 | | 16.0 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.

[b] Value not recorded due to instrumentation problems.

TABLE 4.19 Pullout Test Results for Series V

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: | | | |
|---|---|---|---|---|---|---|---|
| | | | | 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A[a] | 46.2 | | 23.1 | | 16.6 | |
| | 1B | 51.4 | 51.6 | 28.8 | 32.2 | 17.0 | 16.9 |
| | 1C | 57.2 | | 44.8 | | 17.0 | |
| | 2A | 53.0 | | 43.8 | | 24.5 | |
| V5-1/2U | 2B | 56.6 | 56.5 | 41.5 | 42.6 | 29.7 | 27.6 |
| | 2C | 59.9 | | 42.4 | | 28.5 | |
| | 3A | 44.3 | | 32.5 | | 16.5 | |
| | 3B | 55.4 | 51.3 | 41.0 | 37.2 | 15.1 | 18.5 |
| | 3C | 54.2 | | 38.2 | | 24.0 | |
| | 1A | 53.5 | | 26.9 | | 21.0 | |
| | 1B | 47.6 | 50.8 | 25.5 | 26.2 | 12.2 | 15.5 |
| | 1C | 51.4 | | b | | 13.2 | |
| | 2A | 52.8 | | 31.1 | | 19.3 | |
| V9N | 2B | 60.4 | 55.7 | 36.8 | 31.9 | 14.1 | 16.2 |
| | 2C | 53.9 | | 27.9 | | 15.1 | |
| | 3A | 55.4 | | 31.6 | | 32.1 | |
| | 3B | 54.2 | 54.4 | 26.4 | 29.7 | 8.2 | 18.5 |
| | 3C | 53.7 | | 31.1 | | 15.1 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to instrumentation problems.

TABLE 4.20 Pullout Test Results for Series VI

| Specimen | Bar | Maximum Load, kips | | Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Each Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A | 41.5 | | 17.4 | | 11.3 | |
| | 1B[a] | 38.7 | 43.1 | b | 22.2 | 11.3 | 13.3 |
| | 1C | 49.0 | | 26.9 | | 17.4 | |
| | 2A | 43.4 | | 19.8 | | 12.3 | |
| VI5U | 2B[a] | 44.3 | 45.7 | 20.3 | 20.3 | 9.0 | 10.6 |
| | 2C | 49.3 | | 20.7 | | 10.4 | |
| | 3A | 45.7 | | 19.3 | | 9.9 | |
| | 3B | 43.4 | 44.9 | 22.2 | 25.5 | 12.7 | 13.3 |
| | 3C | 45.5 | | 34.9 | | 17.4 | |
| | 1A | 47.6 | | 25.9 | | 16.0 | |
| | 1B | 47.1 | 44.3 | 18.9 | 22.3 | 14.1 | 16.2 |
| | 1C | 38.2 | | 22.2 | | 18.4 | |
| | 2A | 44.5 | | 30.6 | | 20.3 | |
| VI8-1/2M | 2B | 48.3 | 47.4 | 24.5 | 27.6 | 15.5 | 16.6 |
| | 2C | 49.5 | | b | | 14.1 | |
| | 3A | 51.1 | | 26.4 | | 16.5 | |
| | 3B | 47.6 | 48.3 | 26.9 | 25.9 | 17.4 | 14.9 |
| | 3C | 46.2 | | 24.5 | | 10.8 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to instrumentation problems.

TABLE 4.21 Normalized Pullout Test Results for Series I

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| I3-1/4U | 1A[a] | 43.3 | | 29.2 | | 18.9 | |
| | 1B | 47.3 | 45.3 | 30.6 | 29.9 | 43.0 | 31.0 |
| | 1C | b | | b | | b | |
| | 2A | 45.4 | | 32.2 | | 17.9 | |
| | 2B | 48.4 | 46.0 | b | 35.5 | 15.7 | 20.7 |
| | 2C[a] | 44.1 | | 38.9 | | 28.6 | |
| | 3A[a] | 49.4 | | 31.1 | | 14.1 | |
| | 3B[a] | 43.3 | 44.9[d] | 28.3 | 29.2 | 11.6 | 13.8 |
| | 3C[a] | 41.9 | | 28.1 | | 15.7 | |
| I5-1/2N | 1A | 52.7 | | 35.4 | | 19.4 | |
| | 1B[c] | 53.0 | 52.9 | 39.8 | 35.4 | 36.2 | 25.0 |
| | 1C[c] | (49.4) | | 30.8 | | 19.2 | |
| | 2A[c] | (48.6) | | 37.8 | | 23.0 | |
| | 2B[c] | 52.7 | 52.6 | 37.8 | 37.2 | 21.6 | 20.2 |
| | 2C | 52.4 | | 35.9 | | 16.2 | |
| | 3A | 53.5 | | 33.0 | | b | |
| | 3B[c] | (49.8) | 51.8 | 36.5 | 33.0 | 25.9 | 20.7 |
| | 3C | 50.0 | | 29.4 | | 15.4 | |
| I10N | 1A[c] | 42.9 | | 32.6 | | 14.4 | |
| | 1B[c] | 42.4 | 43.0[e] | b | 31.4 | 12.8 | 16.5 |
| | 1C[c] | 43.6 | | 30.3 | | 22.1 | |
| | 2A | 45.4 | | 29.4 | | 11.0 | |
| | 2B[c] | 46.6 | 46.2 | 30.6 | 29.4 | 21.2 | 15.7 |
| | 2C | 46.6 | | 28.4 | | 14.9 | |
| | 3A[c] | 43.1 | | 29.1 | | 15.9 | |
| | 3B[c] | 43.3 | 43.2[e] | 42.4 | 35.4 | 24.5 | 21.7 |
| | 3C[c] | 43.1 | | 34.7 | | 24.7 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to instrumentation problems.
[c] Testing stopped due to yielding of pullout bar.
[d] Average value of loads at loaded end slip of 0.06 in.
[e] Average value of load at which pullout bars yielded.
() Value not included in average.

TABLE 4.22 Normalized Pullout Test Results for Series II

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A | 60.5 | | 44.8 | | 24.8 | |
| | 1B | b | 56.1 | 44.6 | 42.0 | 27.5 | 22.3 |
| | 1C | 51.6 | | 36.7 | | 14.4 | |
| | 2A | 61.7 | | 37.8 | | 27.9 | |
| II3U | 2B | b | 56.2 | 38.0 | 35.0 | 28.0 | 23.7 |
| | 2C | 50.6 | | 29.3 | | 15.2 | |
| | 3A | 58.9 | | b | | b | |
| | 3B | 56.3 | 55.8 | 39.0 | 38.5 | 22.4 | 21.5 |
| | 3C | 51.9 | | 38.0 | | 20.6 | |
| | 1A | 57.8 | | 35.2 | | 11.7 | |
| | 1B | 58.3 | 59.0 | 42.6 | 41.9 | 21.7 | 27.7 |
| | 1C | 61.1 | | 48.0 | | 49.6 | |
| | 2A | 53.3 | | 32.3 | | 13.9 | |
| II6-1/2M | 2B[a] | 59.5 | 57.9 | 32.0 | 34.7 | 14.3 | 15.1 |
| | 2C | 60.9 | | 39.7 | | 17.2 | |
| | 3A | 55.0 | | 33.7 | | 13.6 | |
| | 3B | 59.0 | 56.2 | 38.3 | 35.9 | 20.9 | 18.9 |
| | 3C | 54.5 | | 35.8 | | 22.2 | |
| | 1A | 62.6 | | 40.2 | | 37.3 | |
| | 1B | 69.3 | 63.7 | 45.5 | 39.4 | 21.7 | 27.5 |
| | 1C | 59.0 | | 32.5 | | 23.4 | |
| | 2A | 63.1 | | 37.7 | | 12.7 | |
| II9M | 2B | 60.3 | 61.5 | 39.7 | 38.5 | 23.0 | 17.9 |
| | 2C | 61.1 | | 38.0 | | 18.0 | |
| | 3A | 56.3 | | 34.0 | | 22.2 | |
| | 3B | 52.9 | 55.6 | 34.9 | 34.0 | 17.6 | 18.6 |
| | 3C | 57.4 | | 33.2 | | 16.0 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to instrumentation problems.

TABLE 4.23 Normalized Pullout Test Results for Series III

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load, kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| III3U | 1A | 54.4 | | 36.3 | | 13.8 | |
| | 1B | 58.0 | 56.6 | 42.0 | 38.4 | 27.3 | 17.9 |
| | 1C | 57.5 | | 37.0 | | 12.7 | |
| | 2A | 66.0 | | 50.0 | | 17.9 | |
| | 2B | 61.8 | 62.1 | 45.9 | 45.5 | 43.8 | 26.2 |
| | 2C | 58.5 | | 40.5 | | 16.8 | |
| | 3A | 64.6 | | 45.3 | | 13.2 | |
| | 3B | 61.5 | 64.0 | 46.9 | 46.9 | 28.3 | 25.8 |
| | 3C | 66.0 | | 48.6 | | 35.8 | |
| III9N | 1A | 56.3 | | 38.1 | | 13.4 | |
| | 1B | 66.2 | 63.0 | 57.8 | 47.9 | 43.0 | 30.6 |
| | 1C | 66.7 | | 47.7 | | 35.4 | |
| | 2A | 53.6 | | 40.4 | | 18.9 | |
| | 2B | 55.0 | 57.0 | 35.2 | 37.8 | 26.4 | 20.4 |
| | 2C | 62.3 | | a | | 16.0 | |
| | 3A | 59.0 | | 34.9 | | 13.7 | |
| | 3B | 63.6 | 60.6 | 42.3 | 36.4 | 12.9 | 14.2 |
| | 3C | 59.2 | | 32.0 | | 16.0 | |

[a] Value not recorded due to instrumentation problems.

TABLE 4.24 Normalized Pullout Test Results for Series IV

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A[a] | 54.1 | | 37.7 | | 20.9 | |
| | 1B | 49.4 | 50.3 | 29.1 | 35.0 | 29.5 | 24.0 |
| | 1C | 47.4 | | 38.3 | | 21.6 | |
| | 2A | 57.6 | | 41.9 | | 39.8 | |
| IV8-1/2 U | 2B | 49.6 | 51.5 | 39.2 | 39.7 | 34.7 | 33.7 |
| | 2C | 47.1 | | 37.7 | | 26.6 | |
| | 3A | 47.9 | | b | | 31.1 | |
| | 3B | 47.1 | 48.4 | 36.6 | 37.5 | 24.0 | 24.1 |
| | 3C | 50.3 | | 38.3 | | 17.3 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.

[b] Value not recorded due to instrumentation problems.

TABLE 4.25 Normalized Pullout Test Results for Series V

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| | 1A[a] | 54.4 | | 27.2 | | 19.5 | |
| | 1B | 60.5 | 60.7 | 33.9 | 37.9 | 20.0 | 19.9 |
| | 1C | 67.3 | | 52.7 | | 20.0 | |
| | 2A | 62.4 | | 51.5 | | 28.8 | |
| V5-1/2U | 2B | 66.6 | 66.5 | 48.8 | 50.1 | 34.9 | 32.5 |
| | 2C | 70.5 | | 49.9 | | 33.5 | |
| | 3A | 52.1 | | 38.2 | | 19.4 | |
| | 3B | 65.2 | 60.4 | 48.2 | 43.8 | 17.8 | 21.8 |
| | 3C | 63.8 | | 44.9 | | 28.2 | |
| | 1A | 53.5 | | 26.9 | | 21.0 | |
| | 1B | 47.6 | 50.8 | 25.5 | 26.2 | 12.2 | 15.5 |
| | 1C | 51.4 | | b | | 13.2 | |
| | 2A | 52.8 | | 31.1 | | 19.3 | |
| V9N | 2B | 60.4 | 55.7 | 36.8 | 31.9 | 14.1 | 16.2 |
| | 2C | 53.9 | | 27.9 | | 15.1 | |
| | 3A | 55.4 | | 31.6 | | 32.1 | |
| | 3B | 54.2 | 54.4 | 26.4 | 29.7 | 8.2 | 18.5 |
| | 3C | 53.7 | | 31.1 | | 15.1 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to instrumentation problems.

TABLE 4.26 Normalized Pullout Test Results for Series VI

| Specimen | Bar | Normalized Maximum Load, kips | | Normalized Applied Load kips, at a Slip of: 0.01 in. @ Loaded End | | 0.001 in. @ Free End | |
|---|---|---|---|---|---|---|---|
| | | Per Bar | Average | Ea.Bar | Avg. | Ea.Bar | Avg. |
| VI5U | 1A | 37.7 | | 15.8 | | 10.3 | |
| | 1B[a] | 35.2 | 39.2 | b | 20.2 | 10.3 | 12.1 |
| | 1C | 44.5 | | 24.5 | | 15.8 | |
| | 2A | 39.5 | | 18.0 | | 11.2 | |
| | 2B[a] | 40.3 | 41.5 | 18.5 | 18.5 | 8.2 | 9.6 |
| | 2C | 44.8 | | 18.8 | | 9.5 | |
| | 3A | 41.5 | | 17.5 | | 9.0 | |
| | 3B | 39.5 | 40.8 | 20.2 | 23.2 | 11.5 | 12.1 |
| | 3C | 41.4 | | 31.7 | | 15.8 | |
| VI8-1/2M | 1A | 40.5 | | 22.0 | | 13.6 | |
| | 1B | 40.1 | 37.7 | 16.1 | 19.0 | 12.0 | 13.8 |
| | 1C | 32.5 | | 18.9 | | 15.7 | |
| | 2A | 37.9 | | 26.0 | | 17.3 | |
| | 2B | 41.1 | 40.3 | 20.9 | 23.5 | 13.2 | 14.1 |
| | 2C | 42.1 | | b | | 12.0 | |
| | 3A | 43.5 | | 22.5 | | 14.0 | |
| | 3B | 40.5 | 41.1 | 22.9 | 22.0 | 14.8 | 12.7 |
| | 3C | 39.3 | | 20.9 | | 9.2 | |

[a] Maximum load not reached before loaded end slip = 0.06 in. and testing stopped.
[b] Value not recorded due to problems with instrumentation.

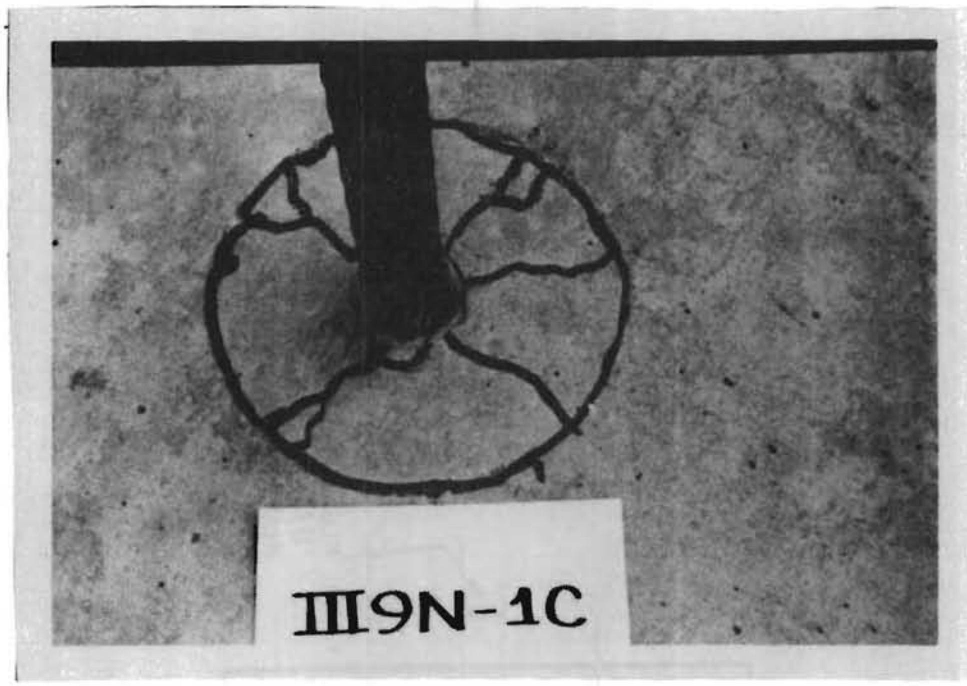



Fig. 4.12 Typical crack pattern

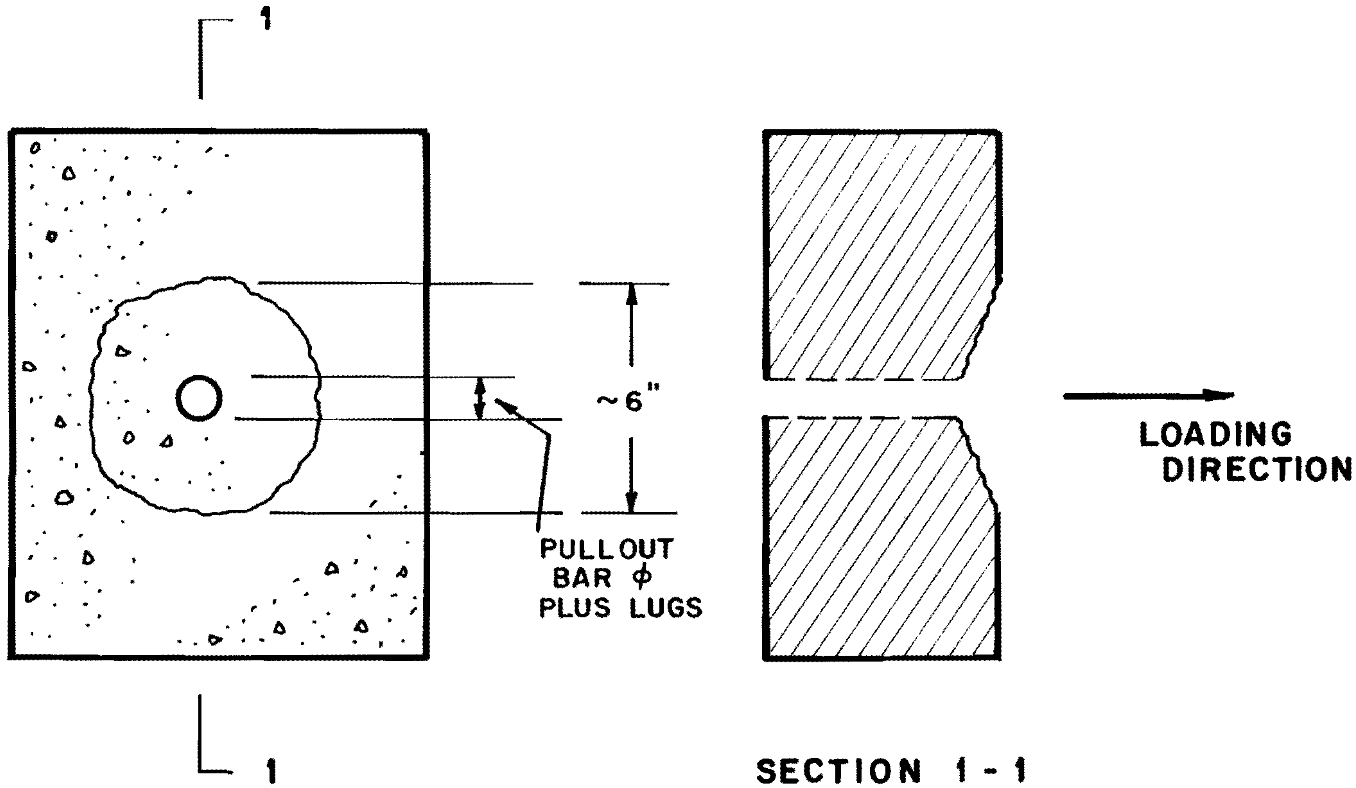



Fig. 4.13 Appearance of failure surface resulting from pullout test

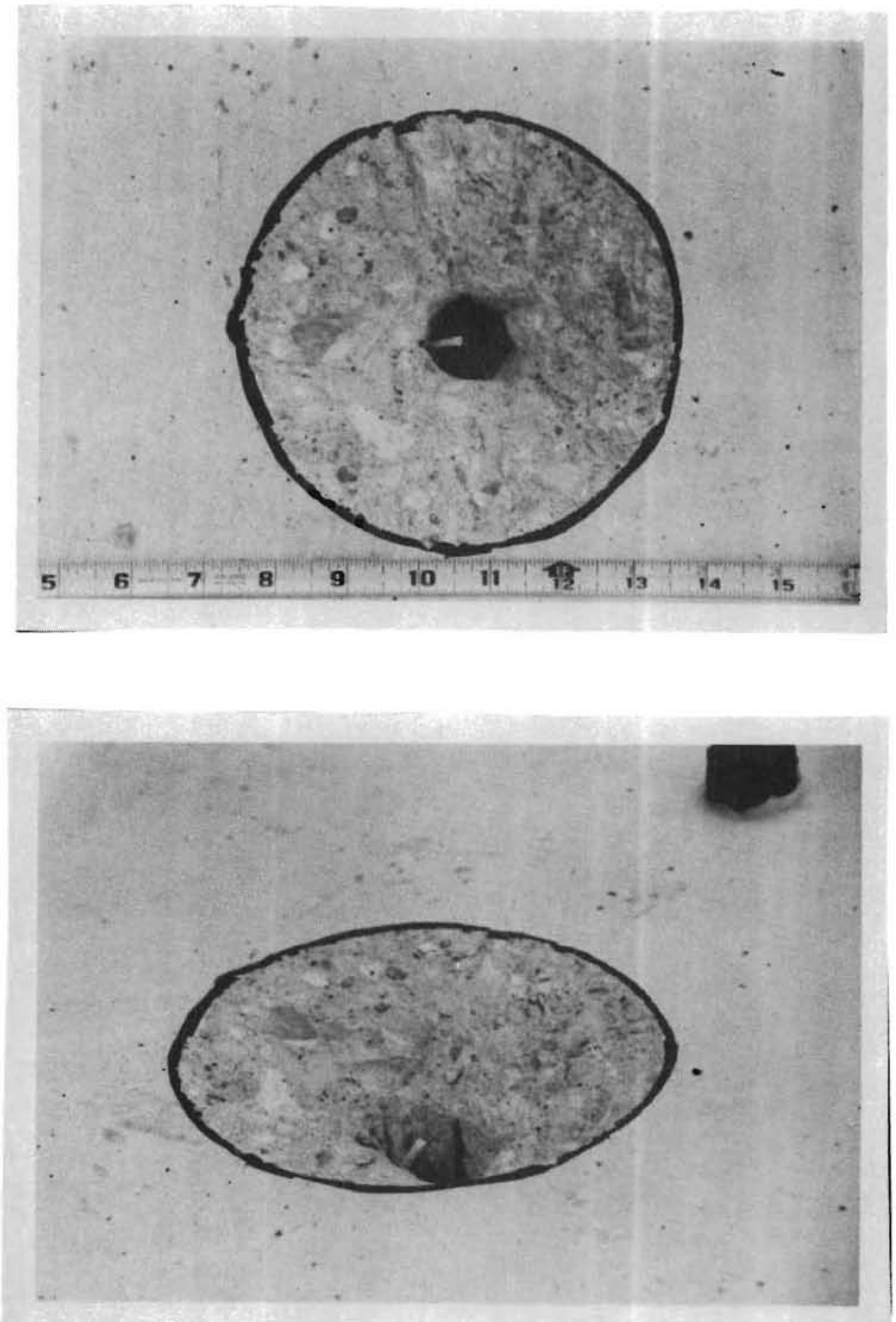



Fig. 4.14 Appearance of failure surface resulting from pullout test

# CHAPTER 5

# EFFECT OF TIME OF ADDITION OF SUPERPLASTICIZER ON CONCRETE BLEED

## 5.1 Introduction

Preliminary study of data showed that results did not conform to expected patterns. In assessing possible reasons for this discrepancy, the factors which distinguished this investigation from others were focused on: the high temperature of the concrete mix and the delayed time of addition of the superplasticizer. As part of a class project in CE383L (Advanced Reinforced Concrete Members), the author conducted a supplementary study of the effects of delayed time of addition of superplasticizer. The study and its principal results are described in this chapter. The results will be discussed in Chapter 6.

A typical heat of hydration curve for portland cement is shown in Fig. 5.1. This curve illustrates the effect of time on the rate at which water is consumed by cement. Stage I lasts roughly 10 to 15 min. The end of Stage II marks the time of initial set of the concrete, and occurs from two to four hours after initial mixing [23], depending on the temperature of the concrete. In the current research program, the time of addition of superplasticizer to the concrete ranged from 25 min. to 110 min. after initial mixing, as shown in Tables 4.2 through 4.7. Thus, the cement particles could have been in the dormant stage Stage II) or the stage of increased hydration (Stage III) at the time the superplasticizer was added.

## 5.2 Supplementary Experimental Program

Details of the supplementary experimental program described in this section include the concrete mix proportions and mixing procedure, type of superplasticizer used, and the testing procedures followed.

5.2.1 Concrete. The mix proportions of the concrete used in this supplementary study are given in Table 5.1. A coarse fresh concrete mix was desirable since bleed behavior was to be studied. The concrete had a water to cement ratio of 0.45, and was batched in a 6-cu.ft. capacity mixer.

5.2.2 Superplasticizer. The naphthalene-based superplasticizer used for this supplementary study was from the same manufacturer as that used in the main research program.

5.2.3 Testing Procedure. Three sets of tests were conducted. For each of these, 3 cu.ft. of concrete were batched, having a slump of

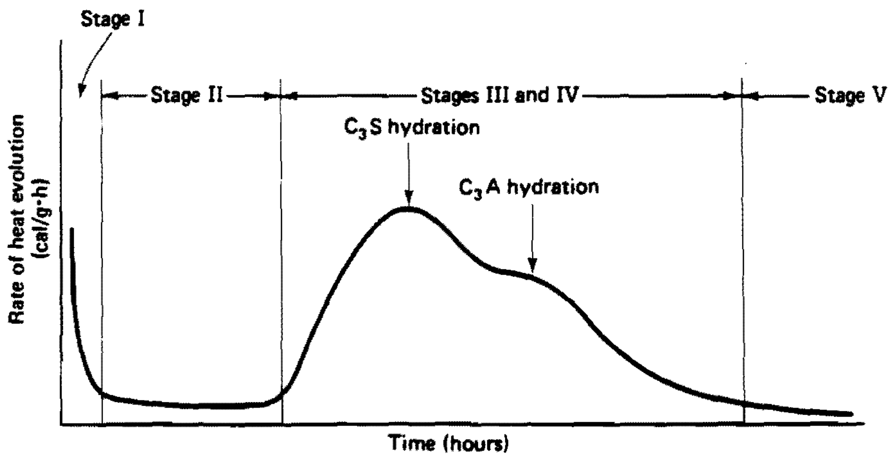



Fig. 5.1 Rate of heat evolution during the hydration of portland cement [23]

TABLE 5.1 Concrete Mix Proportions per Cubic Yard

| Component | Amount/c.y. |
|---|---|
| Cement, lb. | 584 |
| Coarse Aggregate @ SSD, lb | 1919 |
| Fine Aggregate @ SSD, lb | 1256 |
| Water, gal | 31.7 |

approximately 4-1/2 in. After initial mixing, the concrete was left in the mixer for a given length of time, and was mixed for 2 min. out of every 5 min. The concrete of Test Set I remained in the mixer for 30 min., Test Set II for 55 min., and Test Set III for 85 min. after initial mixing. At the end of those times, the slump and air content of the concrete were determined following ASTM Specification C143-78 (Slump of Portland Cement Concrete) and ASTM C231-82 (Air Content of Freshly Mixed Concrete by the Pressure Method). Also, a bleed test was conducted following the procedure in ASTM Specification C232-71 (Bleeding of Concrete), except for the ambient temperature constraint as discussed in Section 3.5.3. The concrete remaining in the mixer, slightly less than 2-1/2 cu.ft., was then dosed with superplasticizer to a slump of approximately 8-1/2 in. This concrete, also, was tested for air content and bleed, as described above.

## 5.3 Results of Supplementary Experimental Program

The results of this study are presented in this section. Included are the concrete mix information, air content test results, and bleed test results.

5.3.1 Concrete Mix Information. Information regarding each of the three test sets is shown in Table 5.2. The identification system used to refer to individual mixes in this study is identical to that of the main research program for individual specimens.

5.3.2 Air Content Test. The results of the air content tests for each of the mixes are shown in Table 5.3.

5.3.3 Bleed Test. The bleed test results are shown in Figs. 5.2 through 5.6. A comparison of the bleeding of superplasticized concrete to that of concrete with no superplasticizer is shown in Figs. 5.2, 5.3, and 5.4 for the time of addition of 30, 55, and 85 min., respectively. Figures 5.5 and 5.6 show the effect of concrete age on bleeding of concrete with and without superplasticizer.

TABLE 5.2 Concrete Mix Information, Supplementary Study

| Mix | Orig. Slump, in. | Age of Conc. at Dosing, min. | Dosage Rate of Super-plasticizer, oz/cwt | Slump After Addn. of Super-plasticizer, in. | Slump at Start of Bleed Test, in. | Age of Conc. at Start of Bleed Test, min. | Conc. Temp. at Start of Bleed Test, °F |
|---|---|---|---|---|---|---|---|
| I4-1/2U | 4-1/2 | -- | 0.0 | ----- | 4-1/2 | 25 | 76 |
| I9N | 4-1/2 | 35 | 6.5 | 9 | 9 | 40 | 76 |
| II2U | 4-1/2 | -- | 0.0 | ----- | 2 | 60 | 76 |
| II8N | 4-1/2 | 60 | 8.3 | 8 | 8 | 65 | 76 |
| III2-1/2U | 5 | -- | 0.0 | ----- | 2-1/2 | 90 | 76 |
| III8-1/2N | 5 | 95 | 8.6 | 8-1/2 | 8-1/2 | 100 | 76 |

TABLE 5.3 Air Content Test Results

| Mix | Air Content, % |
| --- | --- |
| I4-1/2U | 1.1 |
| I9N | 1.2 |
| II2U | 1.2 |
| II8N | 1.0 |
| III2-1/2U | 1.5 |
| III8-1/2N | 1.1 |

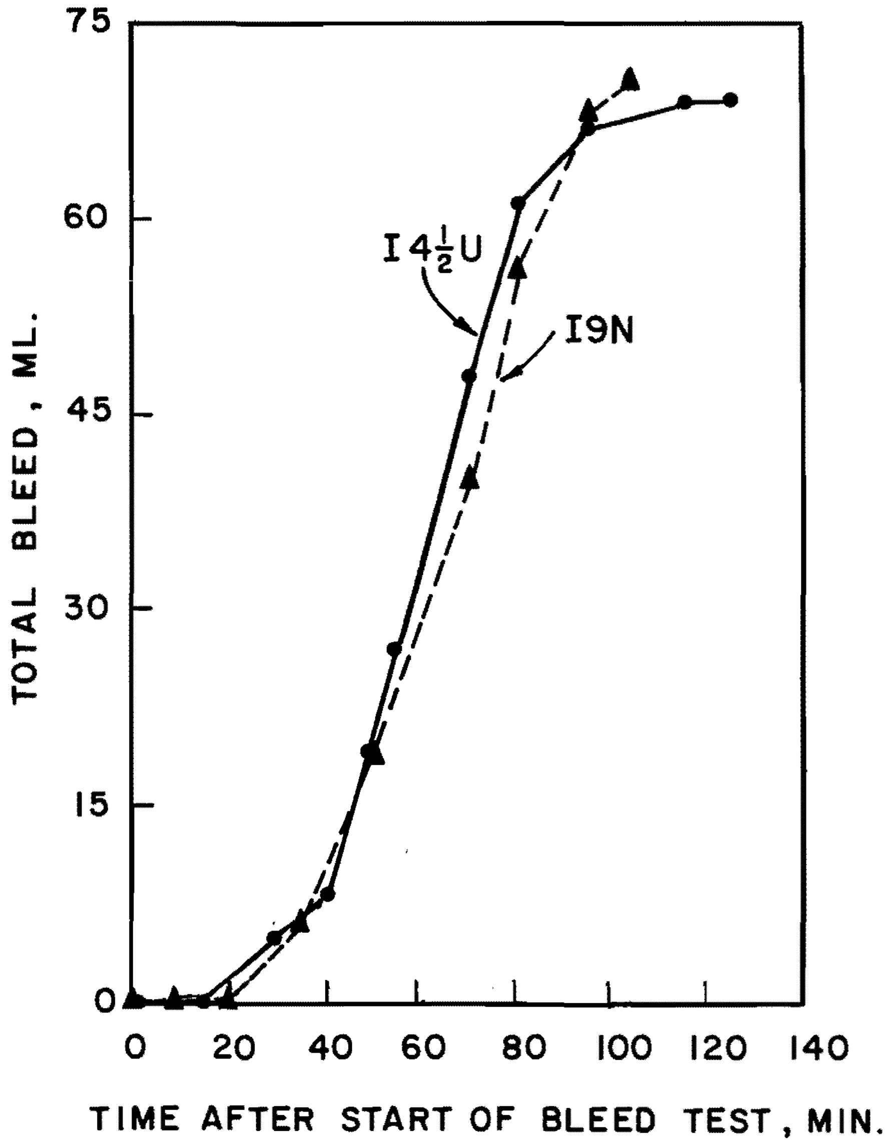



Fig. 5.2 Bleed test results for time of addition of 30 minutes

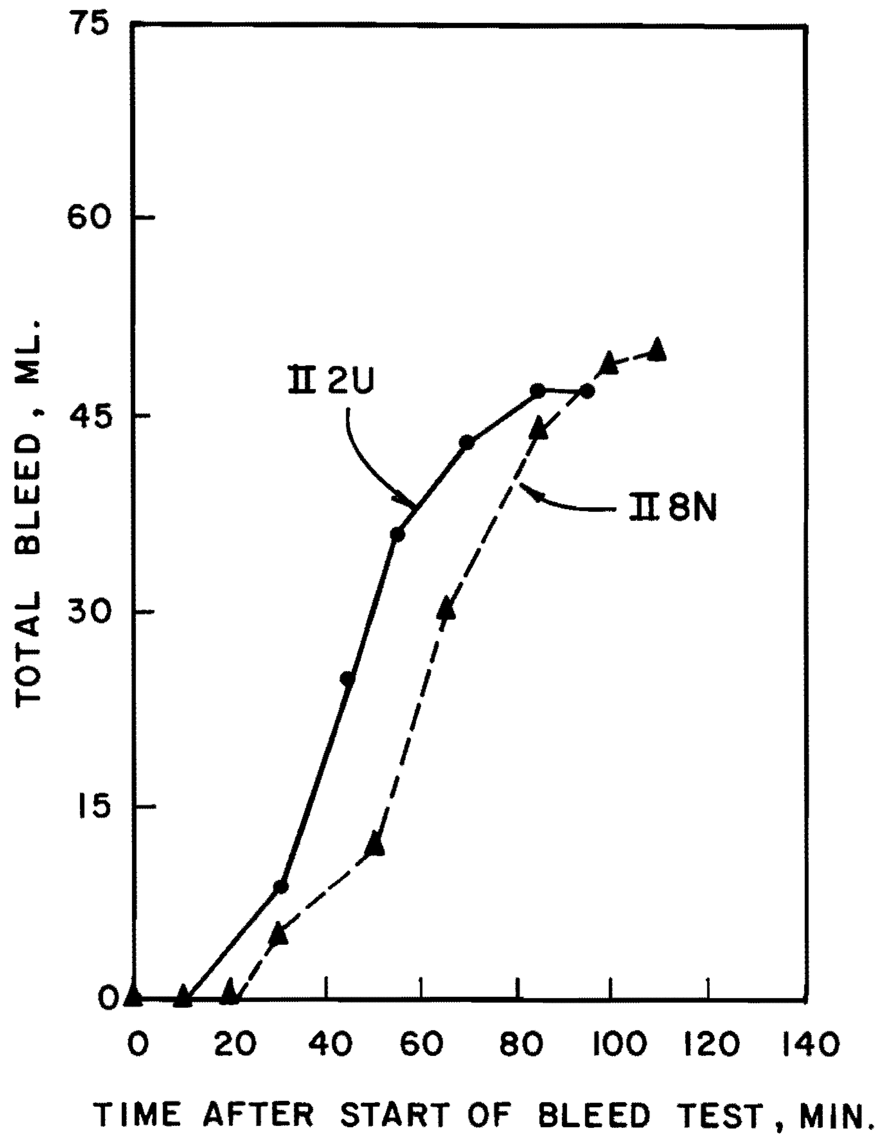



Fig. 5.3 Bleed test results for time of addition of 55 minutes

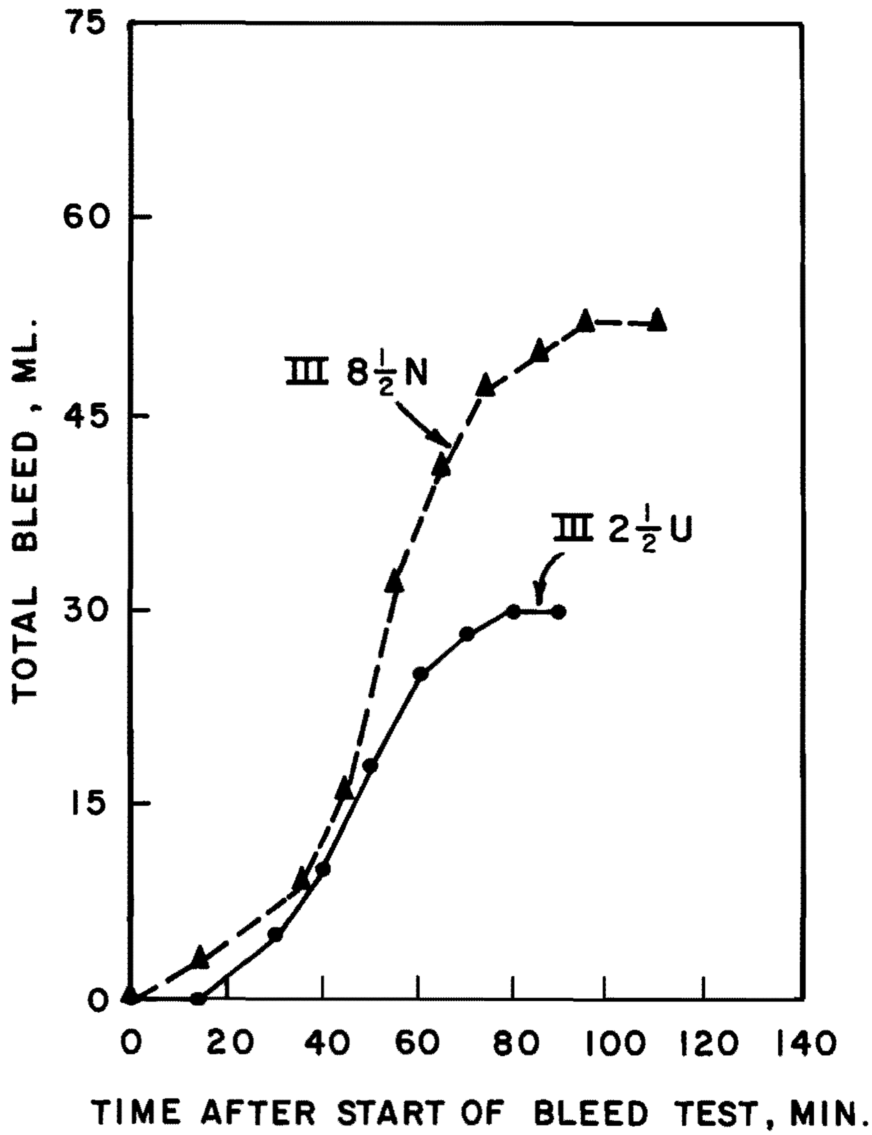



Fig. 5.4 Bleed test results for time of addition of 85 minutes

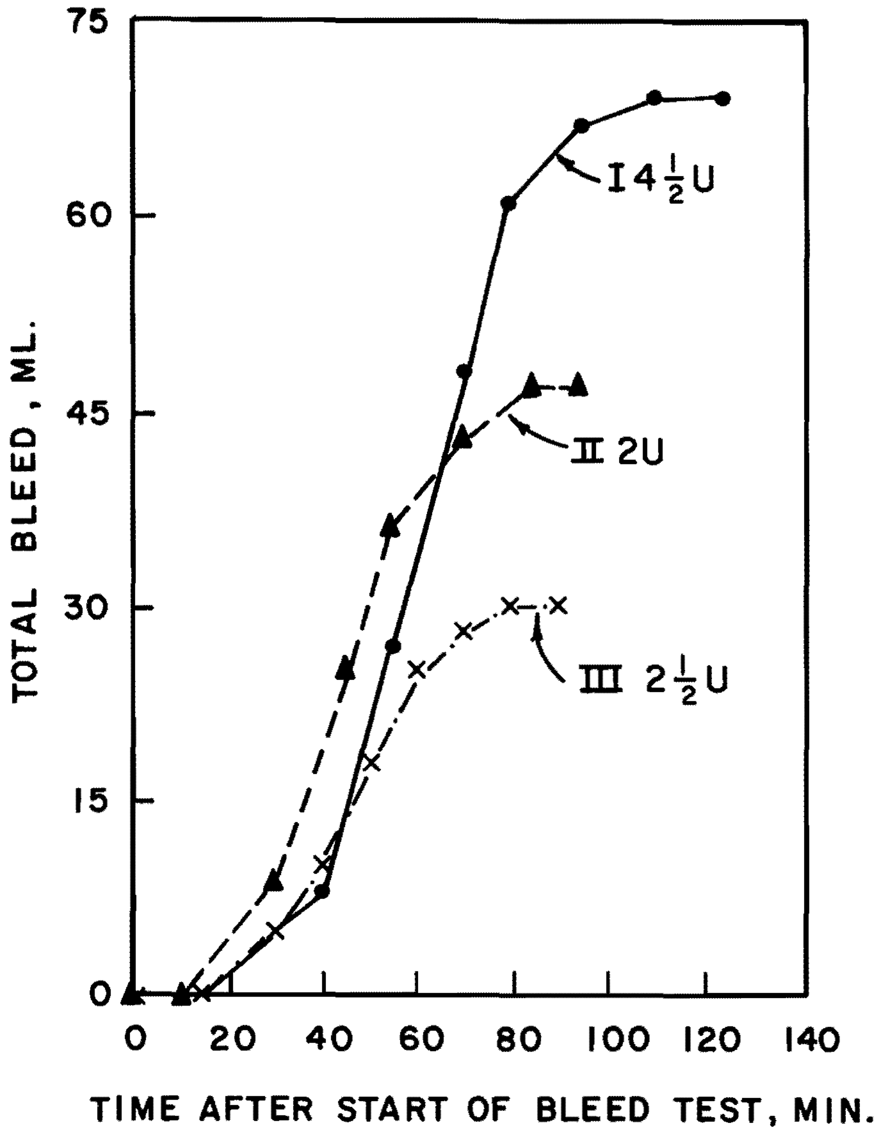



Fig. 5.5 Effect of concrete age on its bleed characteristics (no superplasticizer added)

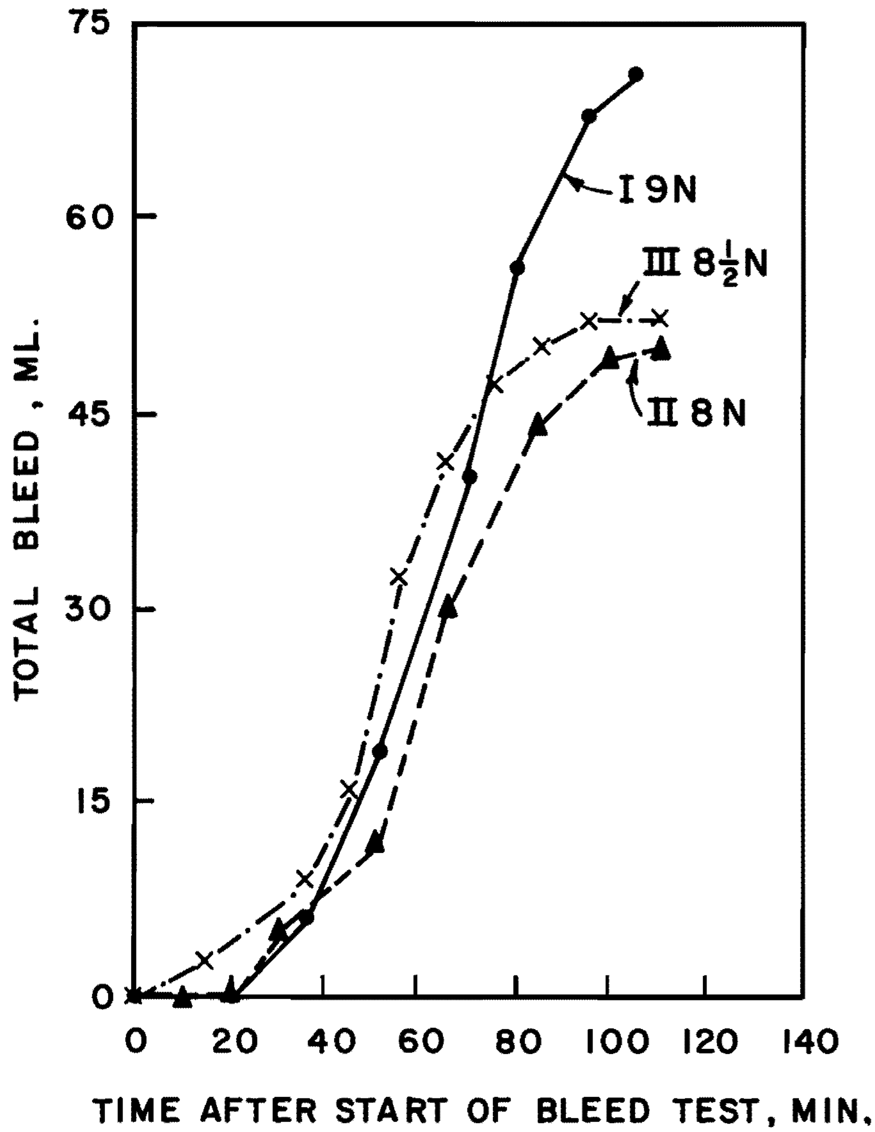



Fig. 5.6 Effect of concrete age on the bleeding of concrete containing superplasticizer

# CHAPTER 6

# DISCUSSION OF EXPERIMENTAL RESULTS

## 6.1 Introduction

The experimental test results presented in Chapters 4 and 5 are discussed herein. The effects of superplasticizers on the properties of both fresh and hardened concrete, and on the bond pullout performance of reinforcing steel in concrete, are examined.

In order to discuss the experimental results obtained from the main research program, it is important to understand the findings of the supplementary study on the effects of time of addition of superplasticizer on the material properties of concrete. Those findings will be discussed first.

## 6.2 Effect of Time of Addition of Superplasticizer on Properties of Concrete

This section contains a discussion of the experimental results of the supplementary study, including the behavior of the fresh concrete mix itself, and the results of the air content and bleed tests.

6.2.1 Concrete Mix Information. The slump versus time behavior of each of the three concrete mixes used in the study is shown in Fig. 6.1. As shown by the dashed lines in this figure, it was assumed that like Test Set I, Test Sets II and III would exhibit no slump loss during the first 30 minutes following initial mixing. The increase in slump shown in these curves was due to the addition of superplasticizer at the dosage rate indicated by each curve.

In general, the dosage of superplasticizer per 100 lb of cement required to increase the slump of the concrete to 8-1/2 in. ± 1/2 in. increased as the age of concrete at the time of addition increased, as shown in Fig. 6.2. However, the required dosage of superplasticizer per inch of increase in slump remained constant for all mixes, independent of the age of the concrete at the time of addition of the superplasticizer, as shown in Fig. 6.3. This is probably due to the condition of the cement particles at the time of addition of the superplasticizer. As the concrete gets older, the decrease in slump is due to two factors: the decrease in free water in the mix; and the increase in interparticle friction, due to formation of hydration products. As the slump of the concrete decreases due to these two factors, the dosage rate of superplasticizer required to overcome their effects increases. Thus, the ratio of dosage rate of superplasticizer to slump increase remains roughly constant. The

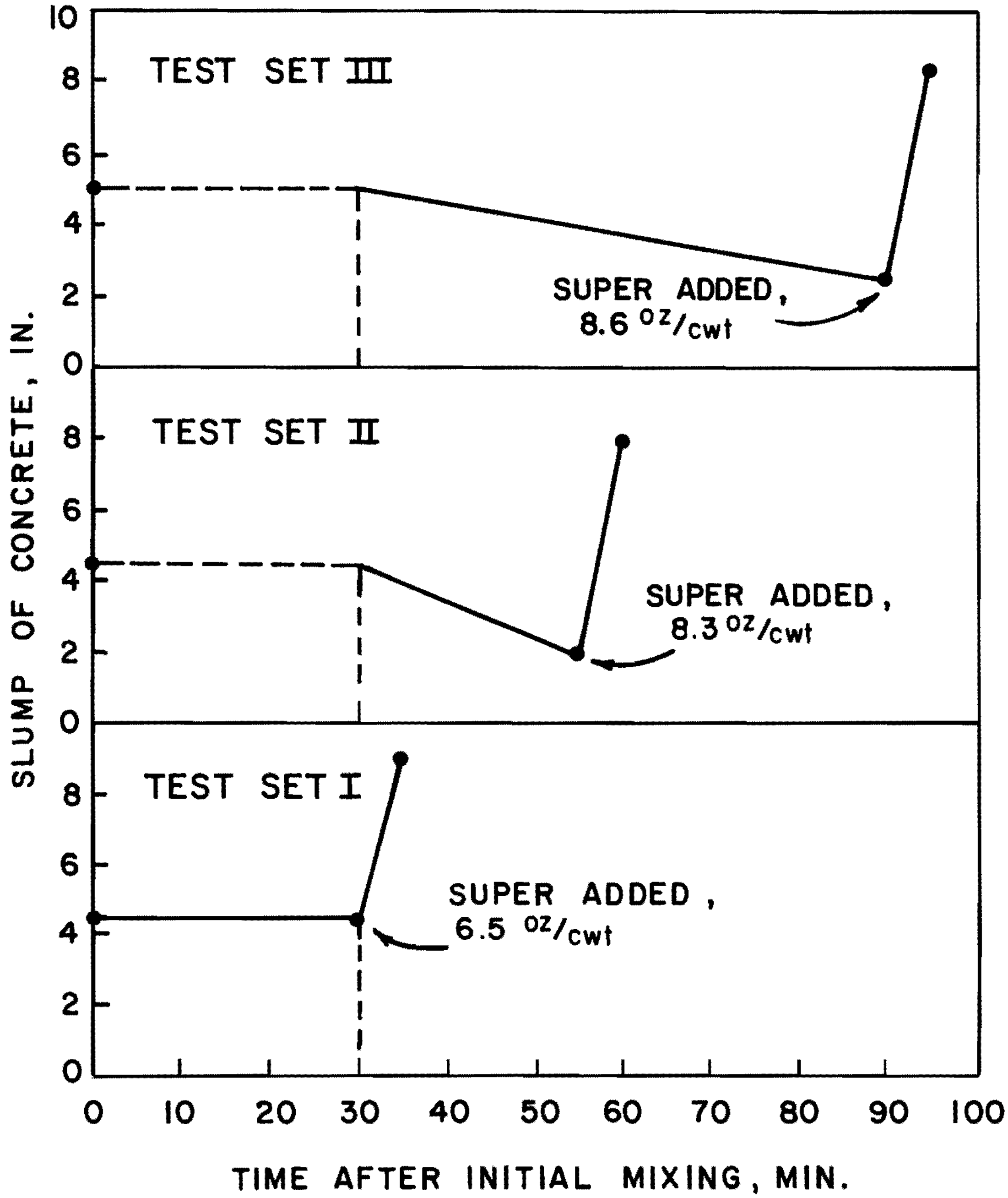



Fig. 6.1 Slump behavior of concrete from time of initial mixing to time of addition of superplasticizer for each test set

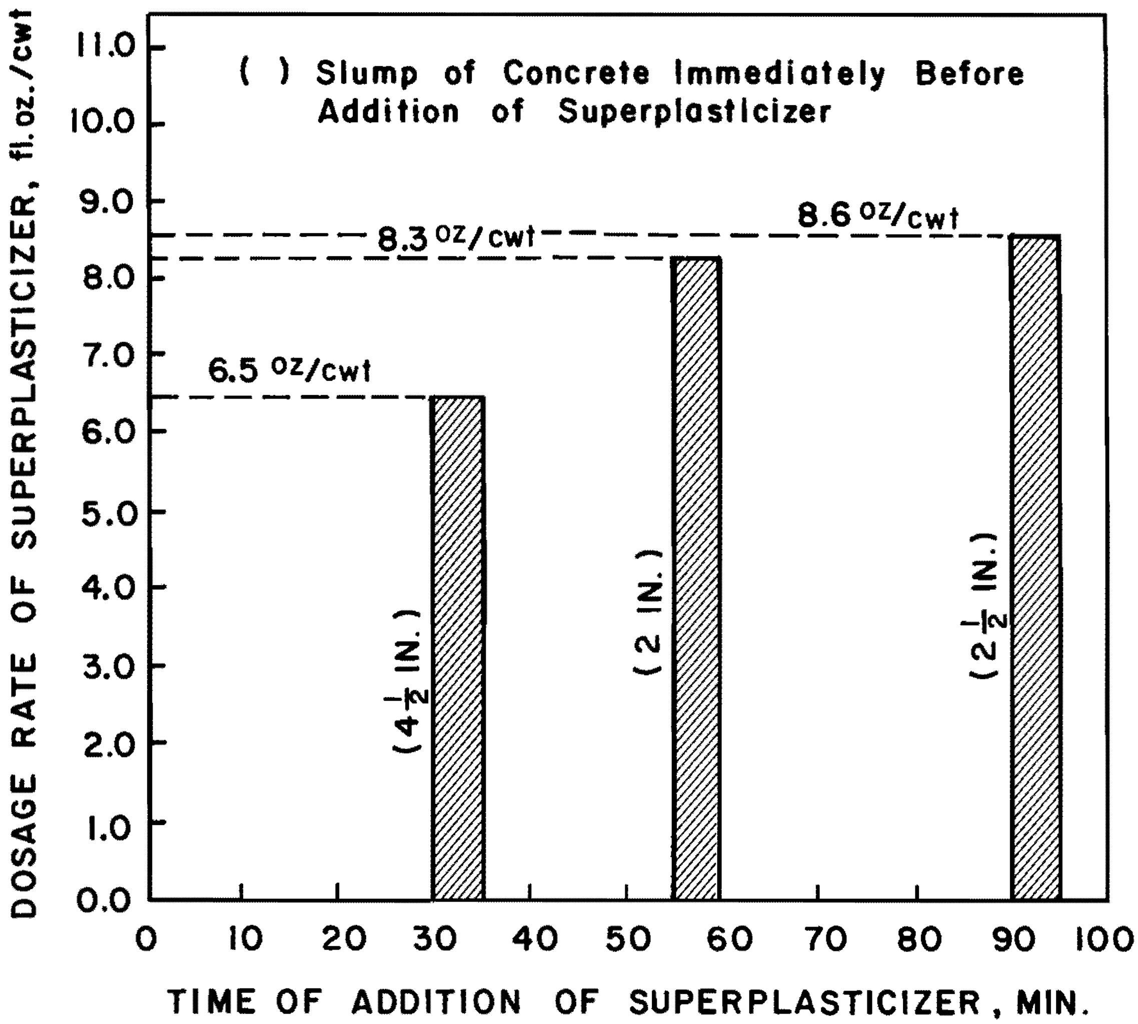



Fig. 6.2 Dosage rate of superplasticizer required to increase the concrete slump to 8-1/2 in. ± 1/2 in. as a function of time of addition

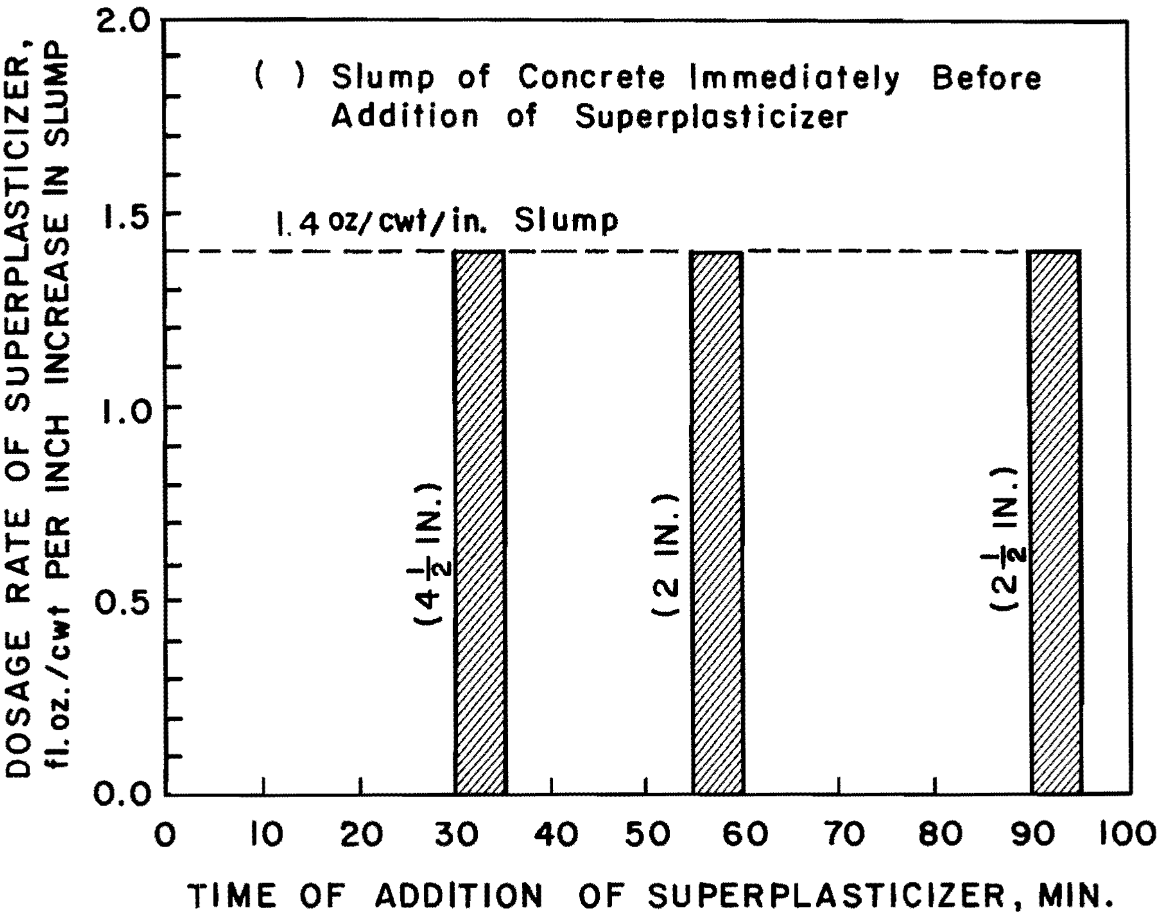



Fig. 6.3 Dosage rate of superplasticizer required per inch increase in slump to increase the concrete slump to 8-1/2 in. ± 1/2 in. as a function of time of addition

effect of concrete age on the condition of the cement particles and the action of superplasticizer will be discussed further in later sections.

6.2.2 Air Content Test. The results of the air content tests for each of the three non-air entrained concrete mixes are shown in Fig. 6.4. The air content of the concrete decreased with the addition of superplasticizer in Test Sets II and III. There was a negligible increase in air content when the superplasticizer was added in Test Set I. In general, the total air content of non-air entrained concrete decreased slightly for mixes containing superplasticizer, mainly due to the increased workability of the superplasticized mixes. This increased workability allows for a better compaction of the fresh concrete mix, resulting in a lower entrapped air content. However, the effect of superplasticizer on the air content of non-air entrained concrete is unimportant since the air involved is entrapped air, which has no beneficial effect on the properties of the concrete, such as freeze-thaw resistance.

6.2.3 Bleed Test. The effect of concrete age on bleed behavior is shown in Fig. 6.5. The total bleed of the concrete decreased as the age of the concrete at the start of the bleed test increased. Concrete specimen III2-1/2U bled less than II2U, even though the former had a greater slump when the bleed test was begun. The decrease in bleeding of concrete as the age at the start of the test increases can be attributed to two factors:

The first of these factors is the evaporation of water from the concrete mix. When the plastic concrete is sitting in the mixer, a portion of the free water evaporates. The longer the concrete sits, the more water evaporates. Therefore, the free water remaining in the mix is lessened, decreasing the amount of available bleed water. The second factor is the condition of the cement particles. As the concrete gets older, more of the mixing water is bound to the cement particles through hydration. Also, as the hydrated cement structure becomes more developed, water becomes entrapped in the structure.

The effect of concrete age at the time of addition of superplasticizer on the bleeding of concrete is shown in Fig. 6.6. The concrete mixes which were treated with superplasticizer at 55 and 85 minutes after initial mixing bled roughly equal amounts. However, the bleeding of the concrete when superplasticizer was added at 30 minutes after initial mixing was the greatest of the three superplasticized mixes.

The total amounts of bleeding of each of the three mixes, with and without superplasticizer, are shown in Fig. 6.7. From this figure, it is apparent that addition of superplasticizer to concrete 85 minutes after initial mixing increased significantly the bleeding of the concrete over that of a similar concrete mix containing no superplasticizer, whereas addition at the earlier times did not.

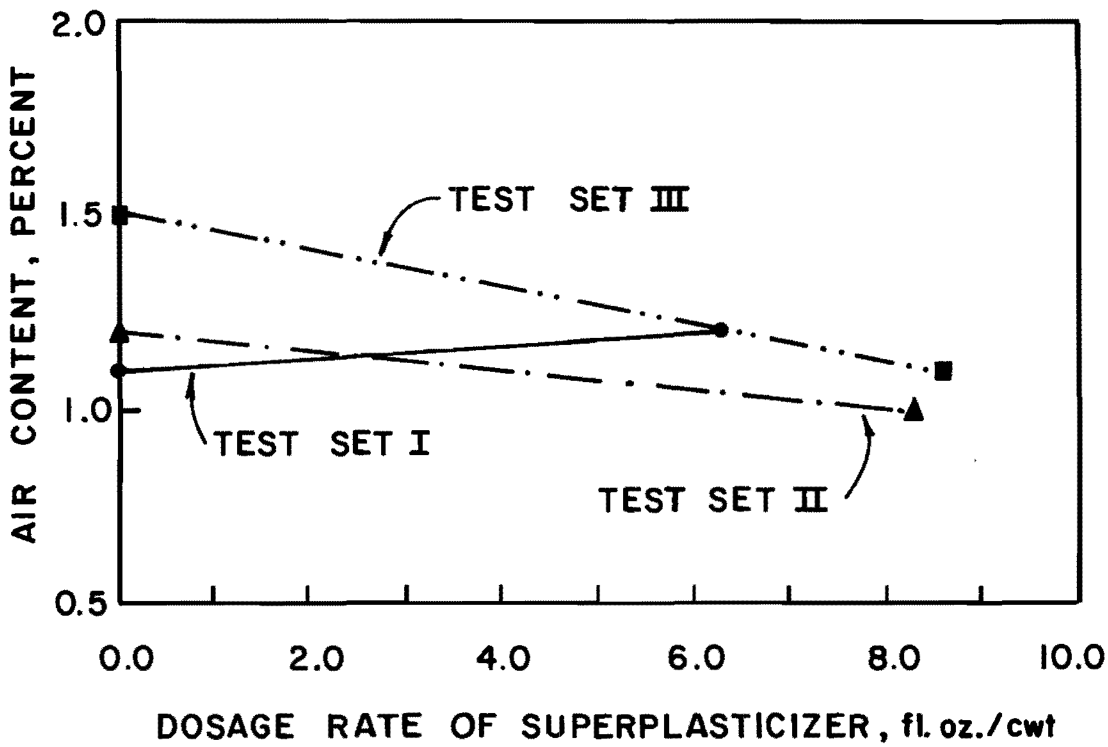



Fig. 6.4 Air content of concrete as a function of dosage rate of superplasticizer

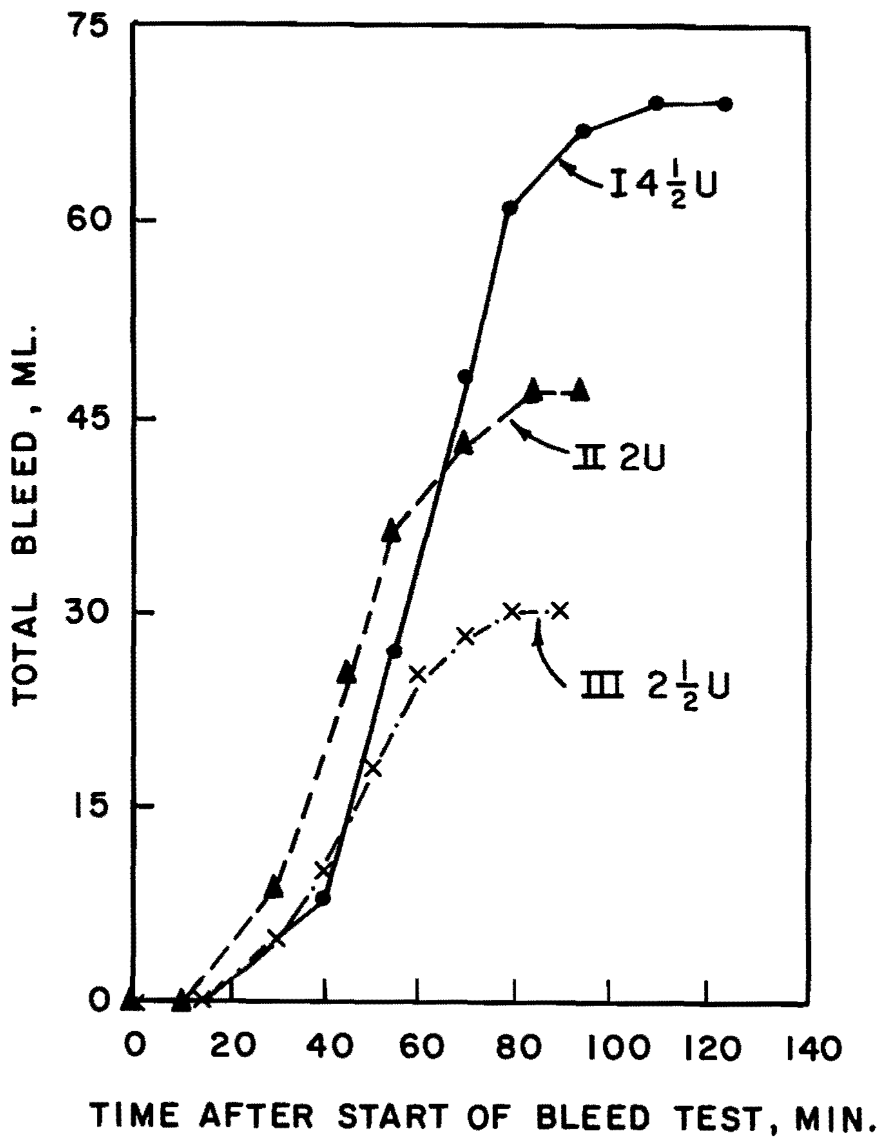



Fig. 6.5 Effect of concrete age on its bleed characteristics (no superplasticizer added)

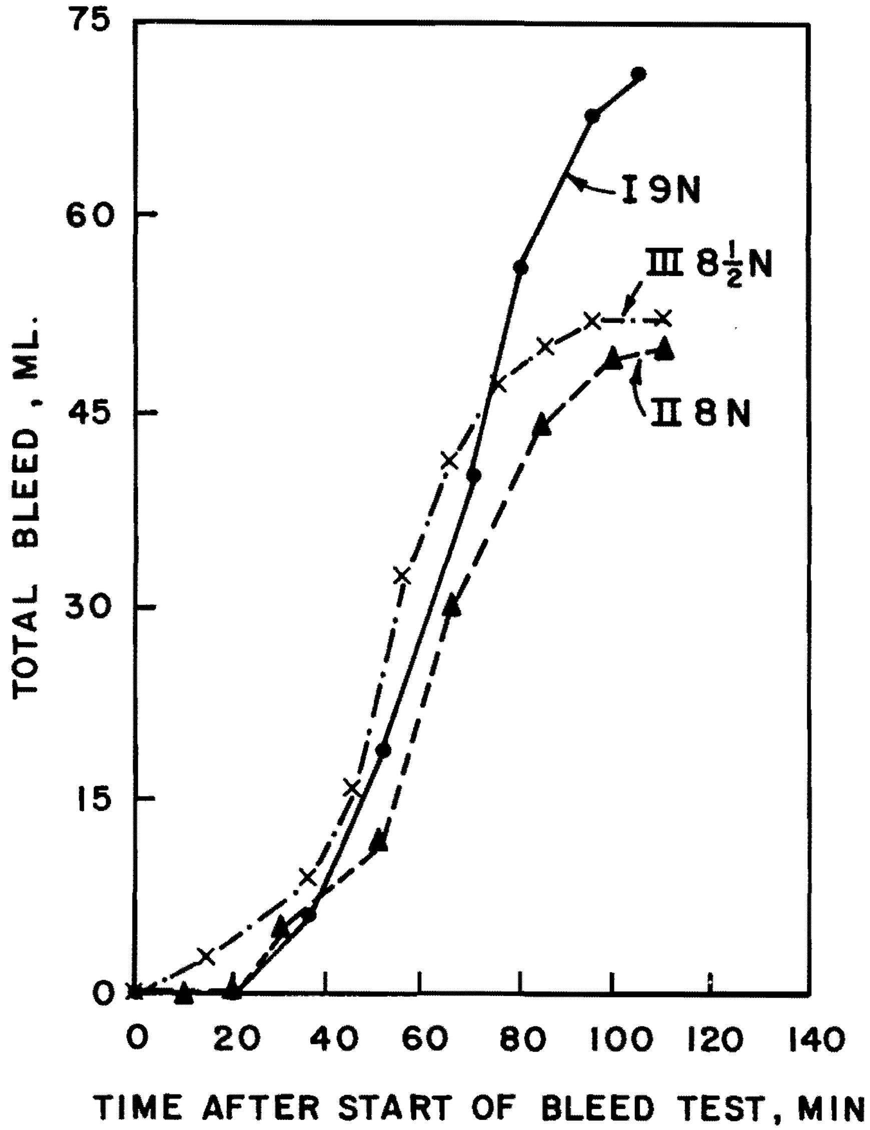



Fig. 6.6 Effect of concrete age on the bleeding of concrete containing superplasticizer

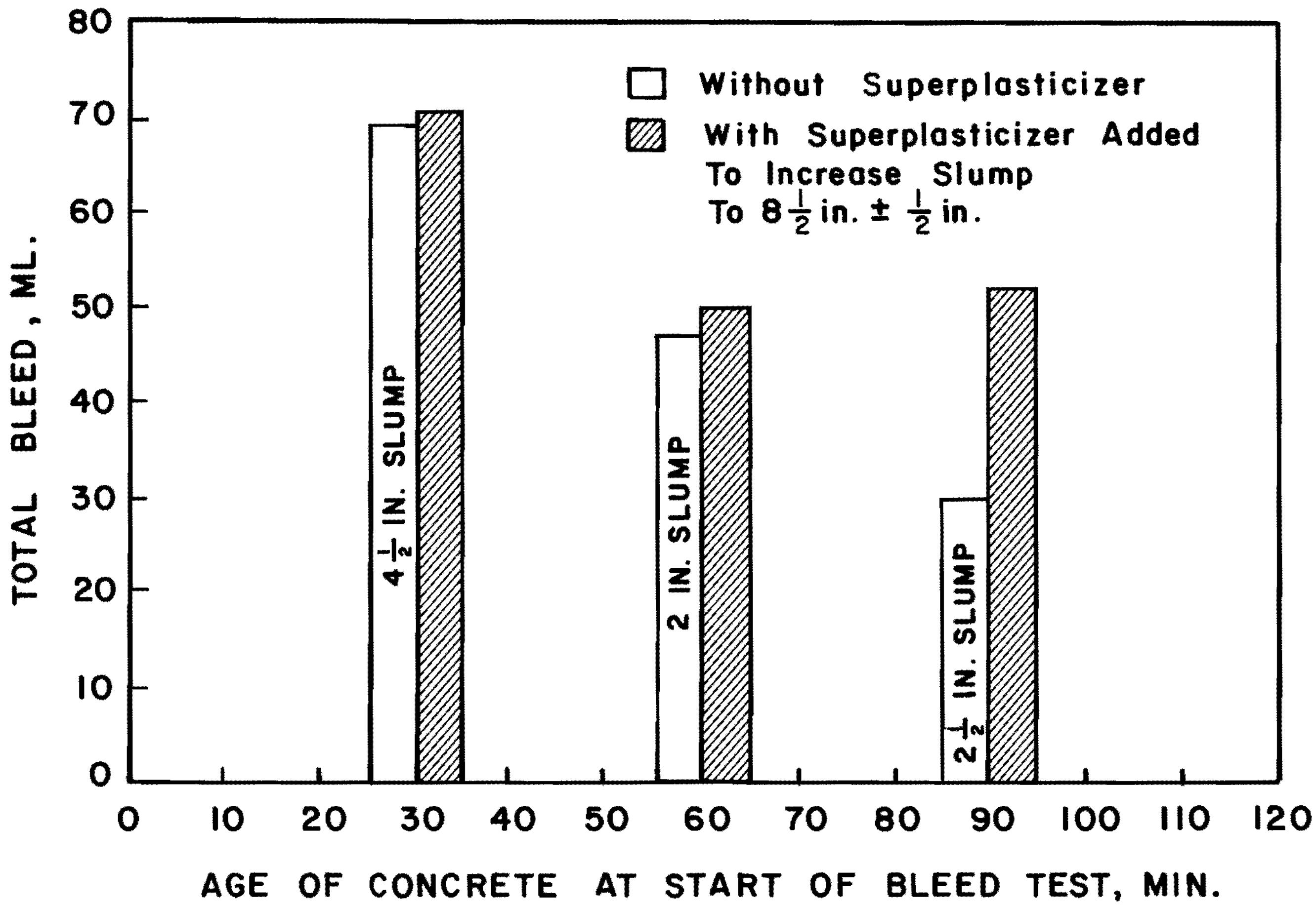



Fig. 6.7 Effect of time of addition of superplasticizer on bleeding of concrete

Therefore, it can be concluded that either a change occurred in the concrete between the ages of 55 and 85 minutes which affects the action of superplasticizer when added at those ages, or a change occurred in the concrete during the bleed tests.

## 6.3 Proposed Action of Superplasticizer for Varying Times of Addition

In this section, an explanation is proposed of the action of superplasticizer when added to concrete mixes of different ages. The times of addition which will be considered are immediately following initial mixing, and 30, 55, and 85 minutes after initial mixing.

### 6.3.1 Hydration of Portland Cement in Fresh Concrete.

Before investigating the effects of superplasticizer on concrete of different ages, it is important to understand how the structure of the hydrating cement particles changes during the time superplasticizer can be added to fresh concrete in the field. A typical heat of hydration curve for portland cement is shown in Fig. 6.8, of which Stages I and II are of interest to this research study.

Stage I of the hydration process of portland cement begins immediately upon contact of the mixing water with the cement particles. The rate of hydration of the cement, initially very rapid, quickly decreases with time until a slow but constant rate of hydration is achieved. This marks the start of Stage II, the dormant stage of the hydration process Throughout the dormant stage, hydration of the cement particles proceeds very slowly. The end of Stage II is designated as "initial set" of the concrete, and is indicated by a gradual increase in the temperature of the concrete. The time of initial set, typically from 2 to 4 hours after initial mixing, is that time after which no further mixing of the concrete can be done without damaging the hydrated cement structure.

The proposed appearance of the cement particle surface at each time of addition to be considered is shown schematically in Figs. 6.9a through 6.9d. In Fig. 6.9a, the cement particle is shown immediately after initial mixing. At this time, the layer of hydration products at the particle surface is very thin, but hydration is occurring rapidly. Therefore, the hydrated layer thickens, forming a diffusion barrier, and the hydration reaction slows. The layer of hydration products consists of ettringite, which is the product of the expansive reaction of the tricalcium aluminates in the cement with gypsum and water. The heat of evolution curve for this reaction is shown in Fig. 6.10.

In Figs. 6.9b and 6.9c, the layer of ettringite is shown to be developing further through hydration. The well-developed, needle-like ettringite structure is shown in Fig. 6.9d. At this time, the diffusion of the water molecules through the ettringite structure has

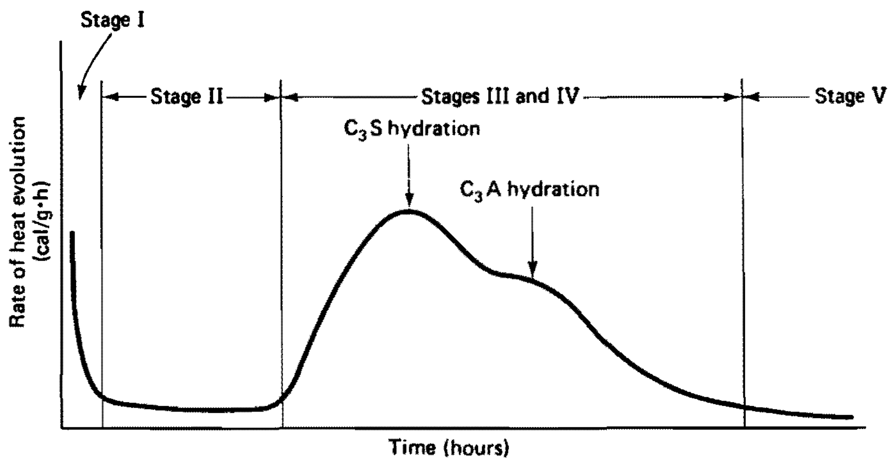



Fig. 6.8 Rate of heat evolution during the hydration of portland cement [23]

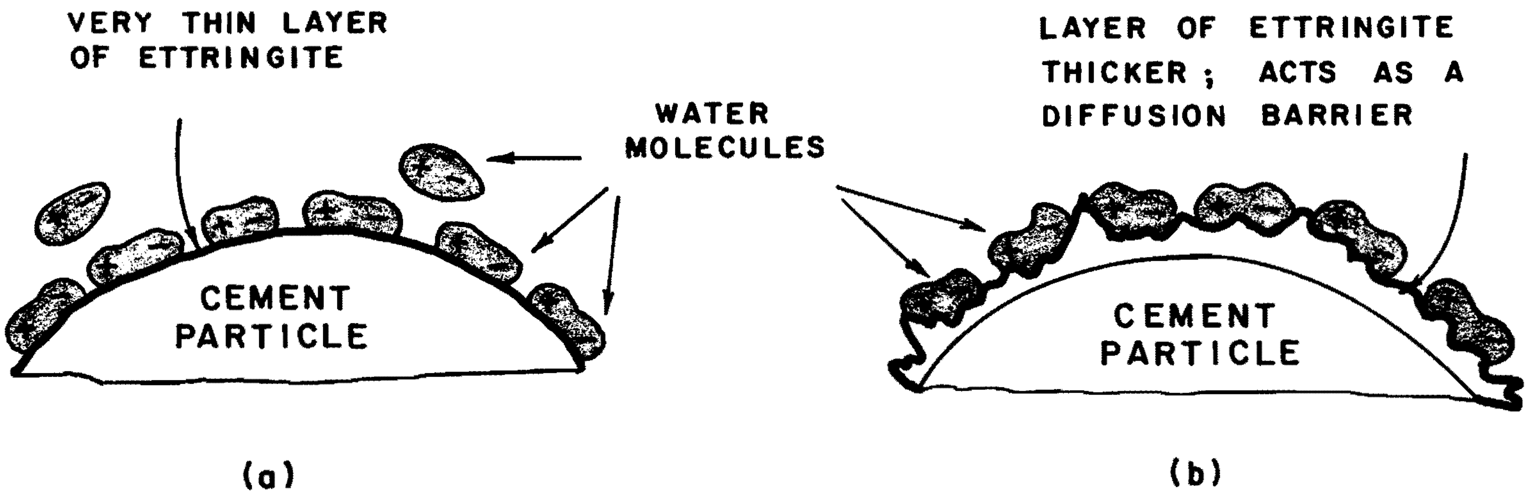



Fig. 6.9 Proposed appearance of cement particle surface:
(a) immediately after initial mixing;
(b) 30 minutes after initial mixing

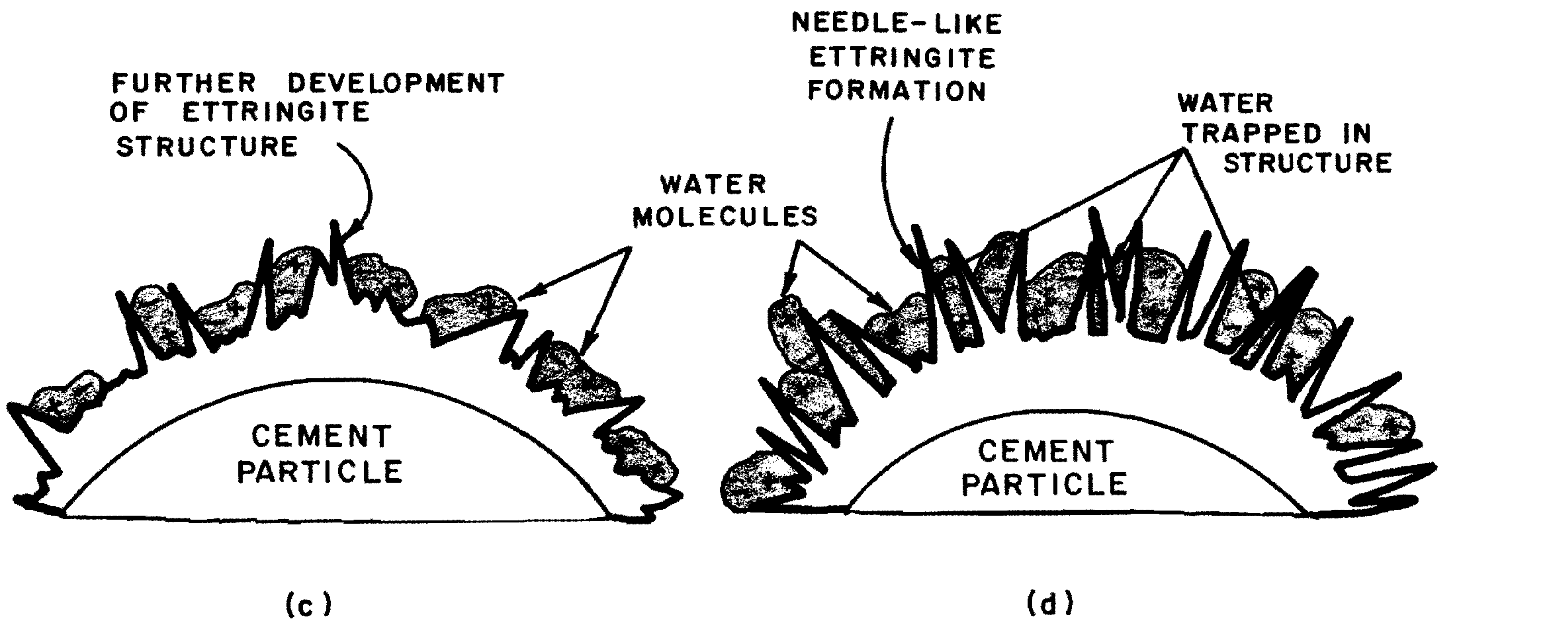



Fig. 6.9 Proposed appearance of cement particle surface:
(c) 55 minutes after initial mixing;
(d) 85 minutes after initial mixing

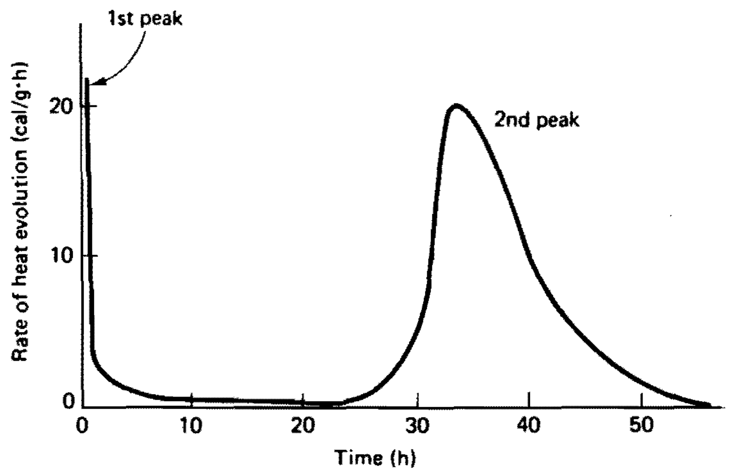



Fig. 6.10 Rate of heat evolution during the hydration of tricalcium aluminate with gypsum [23]

slowed considerably, as indicated by the amount of heat evolution shown in Fig. 6.10. Also, water molecules are trapped within the structure itself through surface tension.

Throughout all this time, the calcium silicates in the cement have also been reacting with water. No hydration products are formed, however. Instead, calcium and hydroxide ions are released into solution at a slowing rate. When the concentration of $Ca^{++}$ and $OH^{-}$ ions in solution reaches a certain value, the hydration products crystallize out of solution and the reaction of the calcium silicates proceeds at an increasing rate [23]. The crystallization of the hydration products from solution marks the initial set of the concrete.

The time after initial mixing at which each of these stages occurs is dependent on the chemical composition and fineness of the cement, and the temperature of the concrete mix. For a concrete at 75$^{o}$F, Stage II begins at approximately 10 to 15 minutes after initial mixing, and ends at approximately two to four hours after initial mixing. The lengths of the stages shorten with finer-ground cement and higher concrete temperatures.

6.3.2 Addition of Superplasticizer to Concrete. The addition of superplasticizer to concrete allows the constituent parts of the concrete to move freely with respect to one another. In the case of naphthalene-based superplasticizer, this is achieved by imparting a net negative surface charge to the cement particles.

When a naphthalene-based superplasticizer is added to concrete immediately following initial mixing, the cement particles become coated with the admixture. This is shown in Fig. 6.11. The coating acts as a barrier to the water molecules, stopping the hydration of the cement particles. As a result, the water which would normally have reacted with the cement particles during the first 10 to 15 minutes after initial mixing (Stage I) is free to migrate through the plastic concrete, and becomes bleed water.

The proposed effects of addition of a superplasticizer to concrete 30 minutes after initial mixing are shown schematically in Fig. 6.12. The addition of superplasticizer to the concrete after 30 minutes temporarily stops the hydration process. However, since the rate of hydration is slow at 30 minutes after initial mixing, stopping the hydration of the cement particles does very little to increase the free water content of the mix. Therefore, no significant increase in the bleeding of the concrete is observed as a result of the addition of the superplasticizer.

Instead of increasing the free water content of the concrete, the superplasticizer increases the slump of the concrete by reducing the interparticle friction among the components of the concrete, as shown schematically in Fig. 6.13. Without surface friction to resist

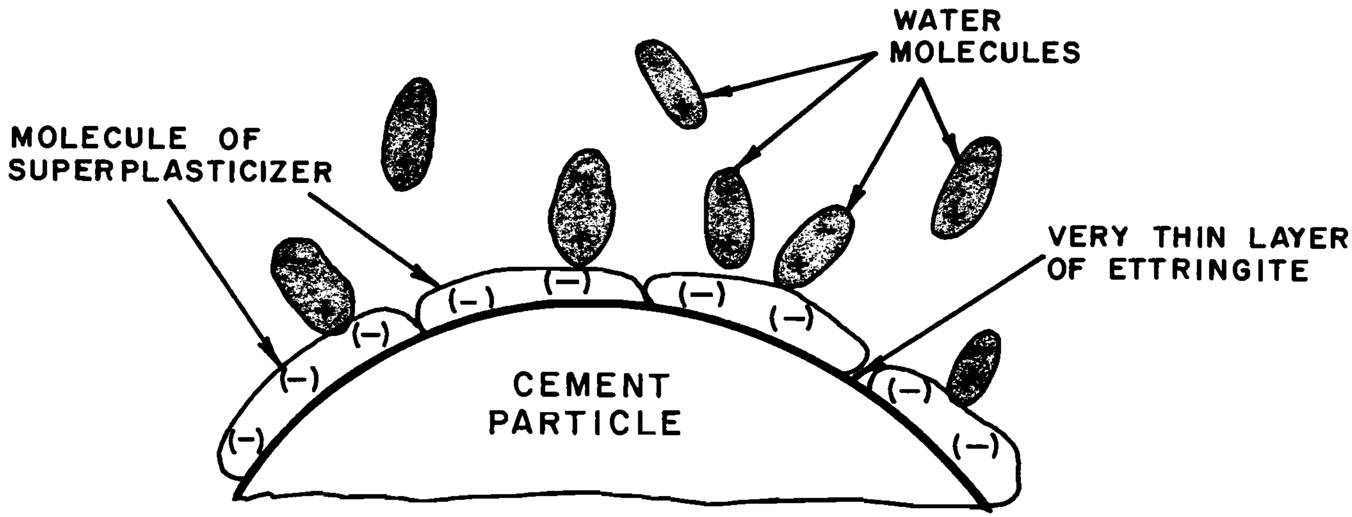



Fig. 6.11 Proposed action of a naphthalene-based superplasticizer when added to concrete immediately after initial mixing

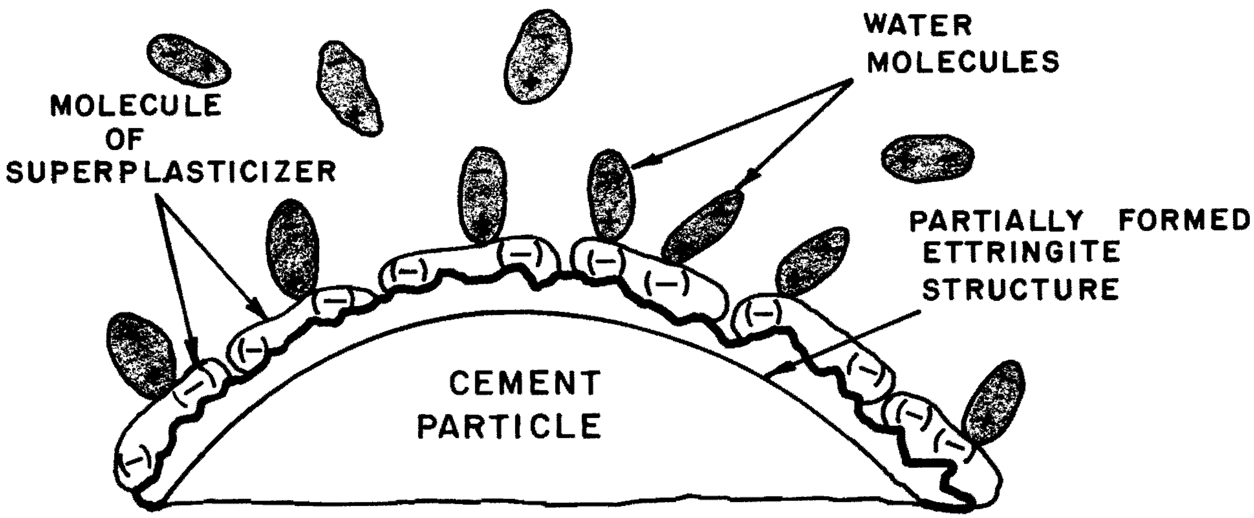



Fig. 6.12 Proposed action of a naphthalene-based superplasticizer when added to concrete 30 minutes after initial mixing

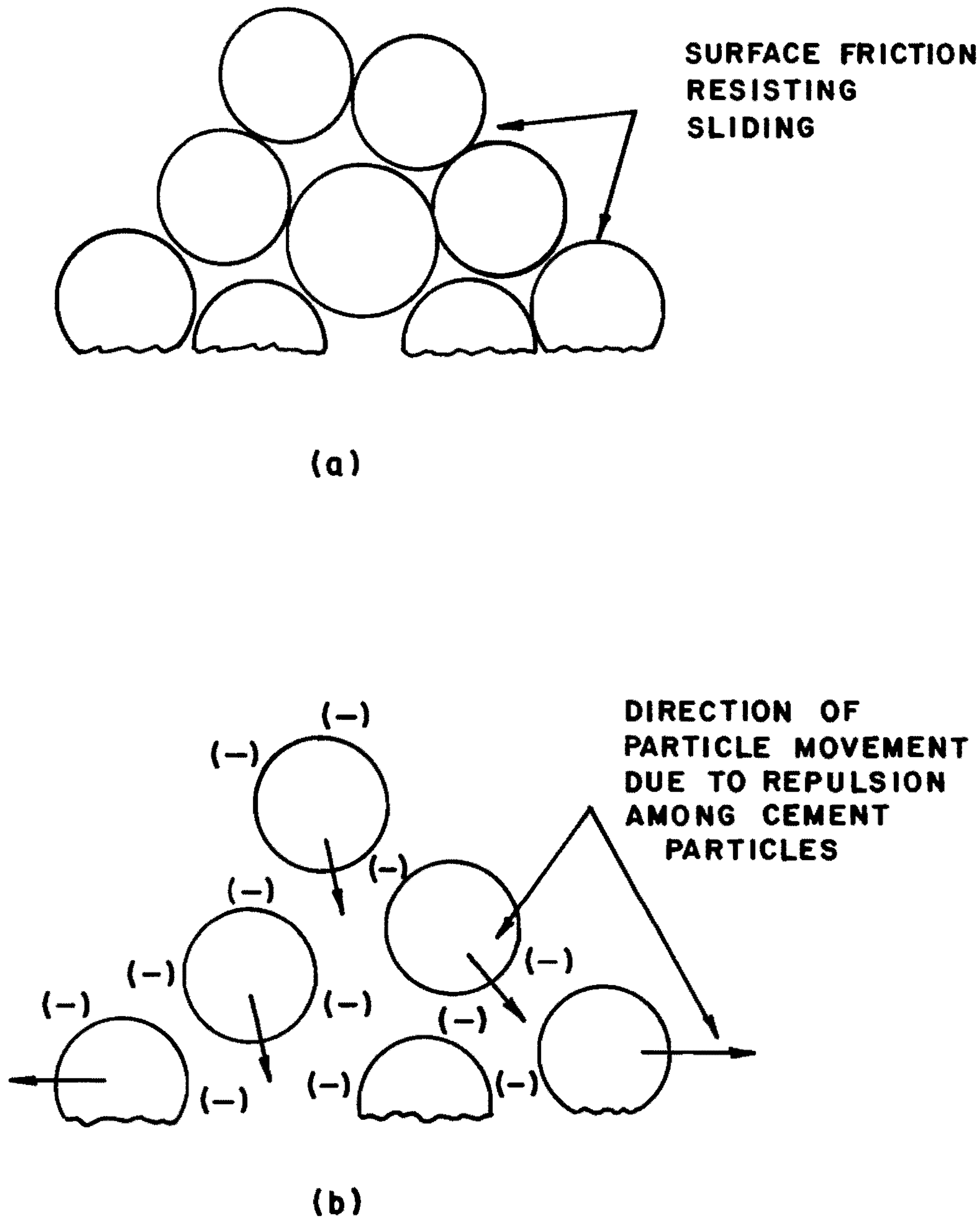



Fig. 6.13 Process by which naphthalene-based superplasticizer increases slump of concrete: (a) stacking of cement particles due to surface friction; (b) sliding of cement particles after addition of superplasticizer

movement, the sand and cement particles slide easily with respect to each other.

When superplasticizer is added to concrete 55 minutes after initial mixing, the results are very similar to those obtained when superplasticizer is added 30 minutes after initial mixing, as shown in Fig. 6.14. At 55 minutes after initial mixing, the ettringite structure is more developed. However, the rate of hydration is still extremely slow, so stopping the hydration frees very little water. The increase in slump of the concrete is due to removal of surface friction among the particles.

The addition of a superplasticizer to concrete 85 minutes after initial mixing, however, was found to increase significantly the bleeding of the concrete. The proposed action of a superplasticizer added to concrete 85 minutes after initial mixing is shown schematically in Fig. 6.15. The increased bleeding for this time of addition is attributable to two factors.

One of these is the release of trapped water from the ettringite structure by the addition of superplasticizer. As the ettringite structure becomes more developed, water molecules are trapped by surface tension among the needle-like ettringite growths. The superplasticizer removes this surface tension and the water is freed. Also, since the concrete is 85 minutes old when the bleed test is begun, it is likely that the hydration rate of the cement particles normally would increase during the course of the bleed test due to the onset of Stage III of the hydration process. Thus, an increasing amount of water would be removed from the mix through hydration. However, the barrier formed around the cement particle surface by the superplasticizer delays the onset of Stage III, thereby freeing water which would normally be used for hydration. This water can then become bleed water.

## 6.4 Details of Casting Procedure

The casting procedures for each of the six series of specimens cast in the main research program are discussed in this section. Included are details which may prove to be significant in determining the properties of the concrete and in understanding the concrete-reinforcing steel bond performance.

6.4.1 Series I. The concrete for Series I was 60 minutes old and very stiff when it arrived at the laboratory. The addition of 18 gallons of water increased the slump of the concrete to 3-1/4 in., and Specimen I3-1/4U was cast. The age and temperature of the concrete were 69 minutes and 89°F.

Difficulty was encountered in increasing the slump of the concrete with addition of superplasticizer. In some cases, the slump

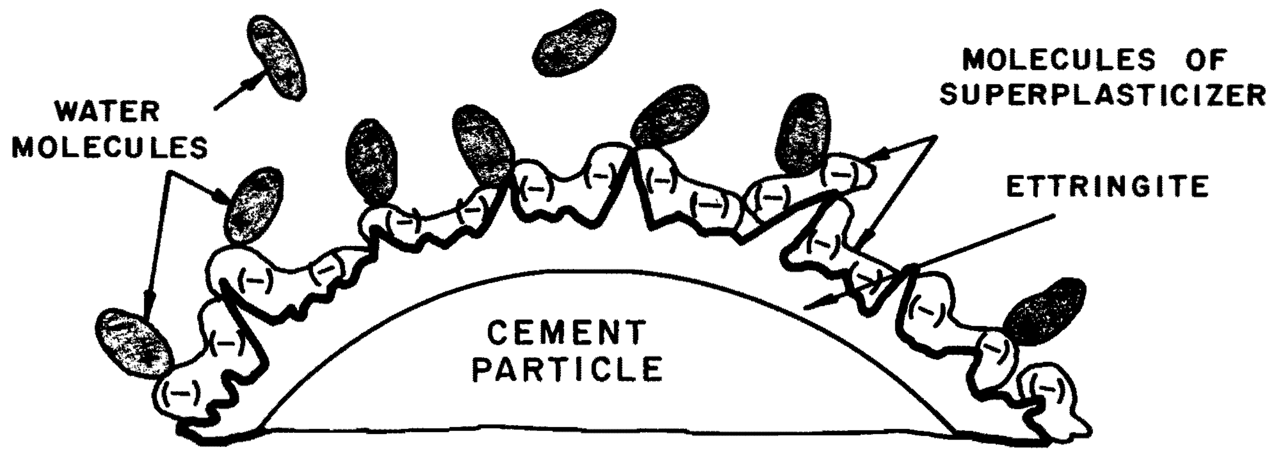



Fig. 6.14 Proposed action of a naphthalene-based superplasticizer when added to concrete 55 minutes after initial mixing

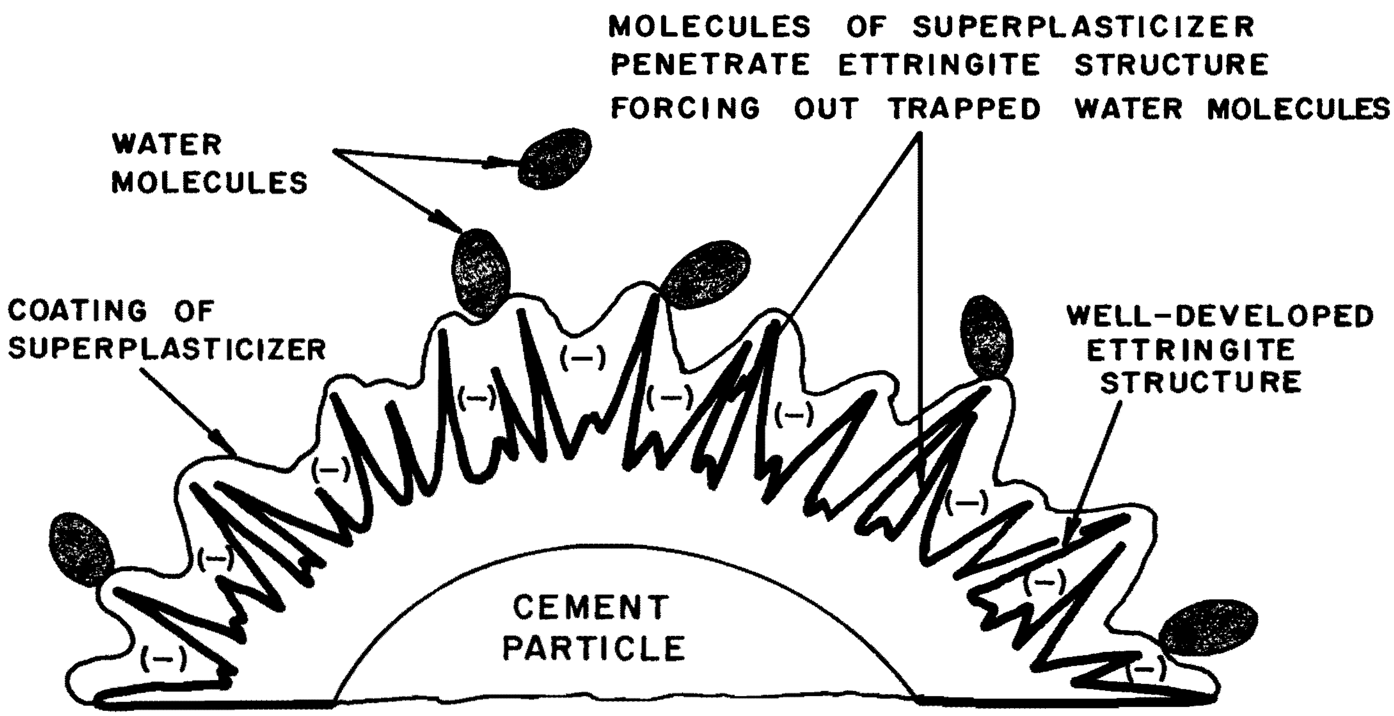



Fig. 6.15 Proposed action of a naphthalene-based superplasticizer when added to concrete 85 minutes after initial mixing

of the concrete decreased after the superplasticizer was added. Finally, a slump of 5-1/2 in. was achieved with a dosage rate of 19.6 fluid ounces of superplasticizer per 100 lb of cement, and Specimen I5-1/2N was cast. The age and temperature of the concrete were 105 minutes and 92°F. The problems with the slump of this concrete were probably due to the age and temperature of the concrete, as discussed by Hampton [12]. The temperature of the concrete increased from 84°F at 69 minutes after initial mixing to 92°F at 105 minutes after initial mixing. This indicates that the rate of hydration of the cement particles was increasing and that the time of initial set was imminent. Therefore, more superplasticizer was required to coat the cement particles and the hydration products which were crystallizing out of solution. Also, due to the increasing rate of hydration of those cement particles not coated with superplasticizer, the time period of effectiveness of the superplasticizer was shortened.

The slump of the concrete was then further increased to 10 in. by adding superplasticizer at a dosage rate of 43.2 fluid ounces per 100 lb of cement. When specimen I10N was cast, the age and temperature of the concrete were 120 minutes and 93°F. The further increase in temperature of the concrete indicates that the hydration rate of the cement was still increasing, even after addition of the superplasticizer.

6.4.2 Series II. The concrete for Series II was only 11 minutes old when it arrived at the laboratory. However, the casting of the three specimens took 76 minutes and the concrete temperature ranged from 86°F to 89°F. Therefore, problems arose in increasing the slump of the concrete using superplasticizer.

The slump of the concrete was increased from 0 to 3 in. with the addition of 19 gallons of water, and Specimen II3U was cast. At this time, the age and temperature of the concrete were 32 minutes and 86°F.

Superplasticizer was added to the concrete at a dosage rate of 9.9 fl.oz. per 100 lb of cement, increasing the slump of the concrete to 6-1/2 in., and Specimen II6-1/2M was cast. No problems with slump loss were encountered during the casting procedure of this specimen. The age of the concrete was 57 minutes. However, the temperature of the concrete had increased to 88°F., indicating that the rate of hydration of the cement was increasing.

When superplasticizer was added to increase the slump of the concrete in preparation for casting specimen II9M, the slump decreased after one of the additions of superplasticizer. Finally, after the addition of superplasticizer at a dosage rate of 22.5 fl.oz. per 100 lb of cement, the slump of the concrete was increased to 9 in. and Specimen II9M was cast. The age and temperature of the concrete were

87 minutes and 89°F. Again, the temperature of the concrete had increased.

6.4.3 Series III. The age and temperature of the concrete after pouring Series III were 73 minutes and 90°F. No problems were encountered with the effect of superplasticizer on the slump of the concrete: a dosage rate of only 15 fl.oz. of superplasticizer per 100 lb of cement was sufficient to increase the slump from 3 to 9 in. However, the temperature of the concrete increased, in 35 minutes, from 88°F to 90°F.

6.4.4 Series IV. The concrete for casting Specimen IV8-1/2U was delivered to the laboratory 43 minutes after initial mixing and had zero slump. The addition of 47 gallons of water increased the slump of the concrete to 8-1/2 in. and the specimen was cast. The age and temperature of the concrete were 63 minutes and 90°F.

6.4.5 Series V. The casting of the specimens for Series V proceeded relatively quickly. The concrete arrived at the laboratory 15 minutes after initial mixing, and had a 1-in. slump. The slump was increased to 5-1/2 in. with the addition of 15 gallons of water, and Specimen V5-1/2U was cast. The age and temperature of the concrete at this time were 25 minutes and 86°F.

The addition of 192 oz of superplasticizer, corresponding to a dosage rate of 7.4 fl.oz. per 100 lb of cement, increased the slump of the concrete further to 9 in., and Specimen V9N was cast. The age of the concrete was only 37 minutes after initial mixing, and the temperature of the concrete remained constant at 86°F.

6.4.6 Series VI. The concrete for Series VI arrived at the laboratory 19 minutes after initial mixing, and had a 3-in. slump. By adding 8 gallons of water, the slump was increased to 5 in., and Specimen VI5U was cast. The age and temperature of the concrete were 24 minutes and 84°F.

Superplasticizer was added to the concrete at a rate of 10.6 fl.oz. per 100 lb of cement, increasing the slump to 8-1/1 in. When Specimen VI8-1/2M was cast, the age and temperature of the concrete were 49 minutes and 85°F. Thus, the temperature of the concrete had increased by 1°F in 25 minutes.

6.4.7 Summary of Behavior of Concrete. The slump of concrete versus dosage rate of superplasticizer for Series I, II, and III is shown in Fig. 6.16. The dosage rate of superplasticizer required to increase the slump of concrete from approximately 3-1/2 in. to 9 in. increased as the age of the concrete increased.

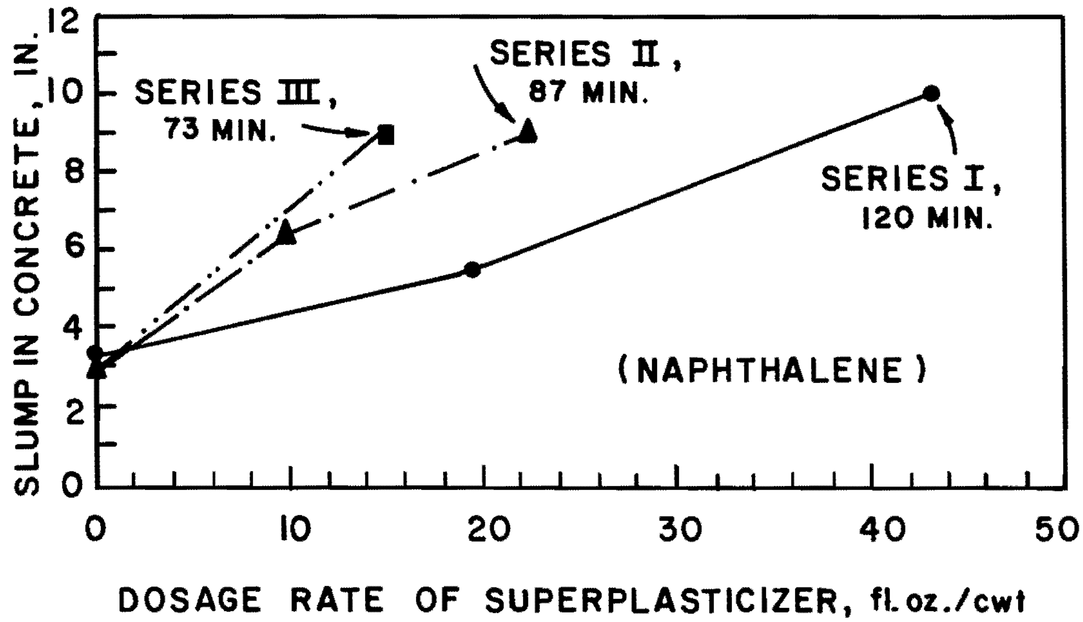



Fig. 6.16 Slump of concrete versus dosage rate of superplasticizer for Series I, II, and III

The same trend occurs in Fig. 6.17, which shows the slump of concrete versus dosage rate of superplasticizer for Series V and VI. As the age of the concrete increased, so did the dosage rate of superplasticizer required to increase the slump of the concrete.

The age and temperature of the concrete for each specimen was recorded throughout the duration of the bleed tests. This information is shown in Fig. 6.18a through 6.18f. The initial increase in temperature of the superplasticized concrete is probably due to the dispersing action of the superplasticizer and the additional mixing of the concrete in the ready-mix truck. The age and temperature of the concrete at the time each specimen was cast indicate in what stage of the hydration process the concrete is, as discussed in Sec. 6.3.1.

## 6.5 Air Content Test

The effect of dosage rate of naphthalene-based superplasticizer on the air content of concrete is shown in Fig. 6.19. In all cases, the addition of naphthalene-based superplasticizer decreased the air content of the concrete. The effect of the superplasticizer on the entrained air content was greater than on the entrapped air content.

The effect of the dosage rate of melamine-based superplasticizer on the air content of concrete is shown in Fig. 6.20. The air content of the concrete for Series V and VI remained roughly constant in spite of the addition of melamine-based superplasticizer For Series II, the air content of the concrete without superplasticizer was 5.9%. This was increased to 6.5% with the addition of 9.9 fl.oz. of superplasticizer per 100 lb of cement. When additional superplasticizer was added to increase the dosage rate of 22.5 fl.oz. per 100 lb of cement, the air content of the concrete was decreased to 5.5%. The entrapped air content of the concrete was unaffected, as shown in Fig. 6.20, for Series VI. In Series VI, the air content of the concrete before adding superplasticizer was 1.2%, and 1.1% after adding superplasticizer.

The concrete with the highest air content was used in Series IV. Specimen IV8-1/2U was cast with concrete containing no superplasticizer and having an air content of 7.4%.

## 6.6 Mix Proportions

When the mix proportions for each of the specimens were recalculated based on the measured air content of the concrete and retempering water added to the concrete, the resulting cement contents and water to cement ratios varied from specimen to specimen, as shown in Table 6.1. The range of cement contents was between 477 lb per cu.yd. for Specimen IV8-1/2U and 534 lb per cu.yd. for Specimen VI8-1/2M. Specimens VI8-1/2M and IV8-1/2U also set the limits on the range of water to cement ratios, having water to cement ratios of 0.53 and

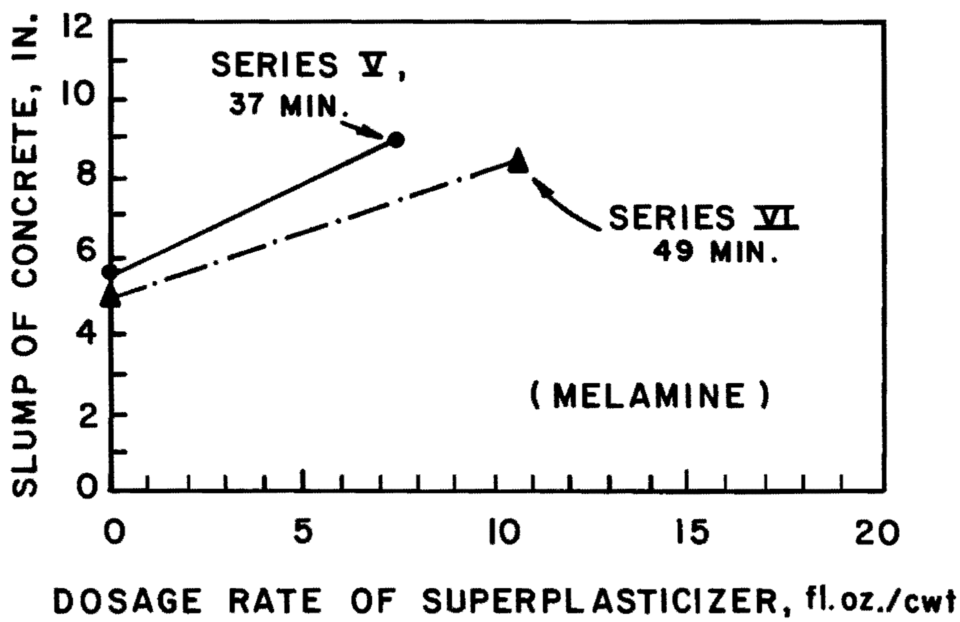



Fig. 6.17 Slump of concrete versus dosage rate of superplasticizer for Series V and VI

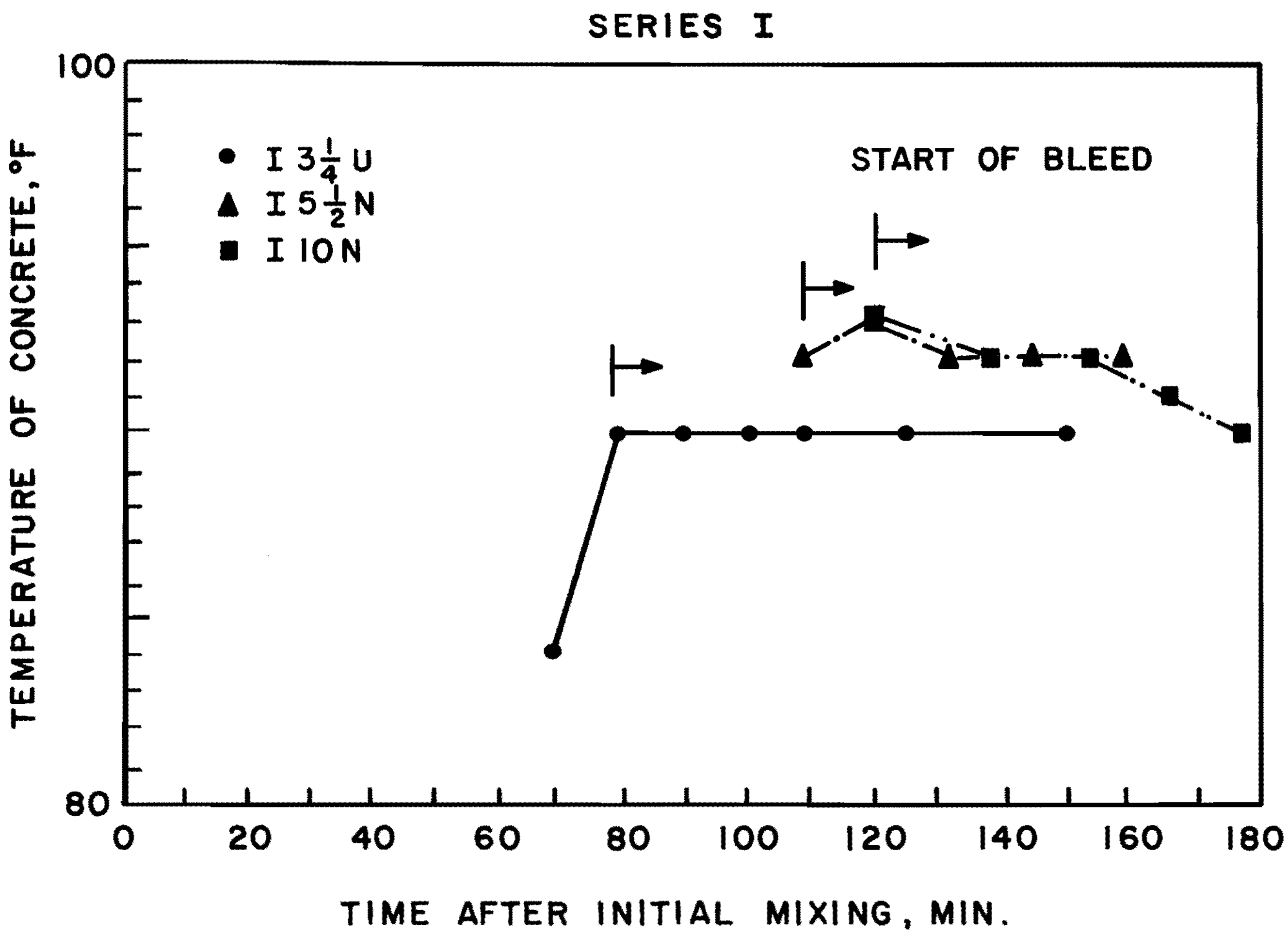



Fig. 6.18a Temperature of concrete with time during bleed tests for Series I

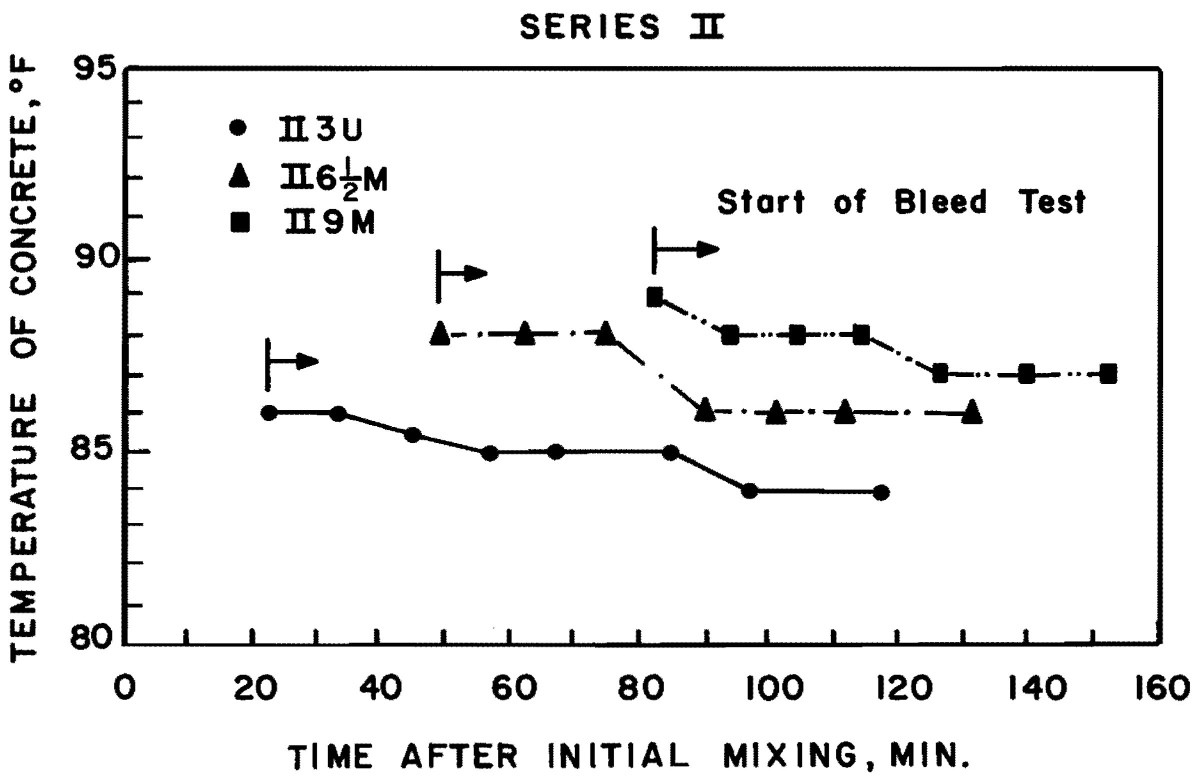



Fig. 6.18b Temperature of concrete with time during bleed tests for Series II

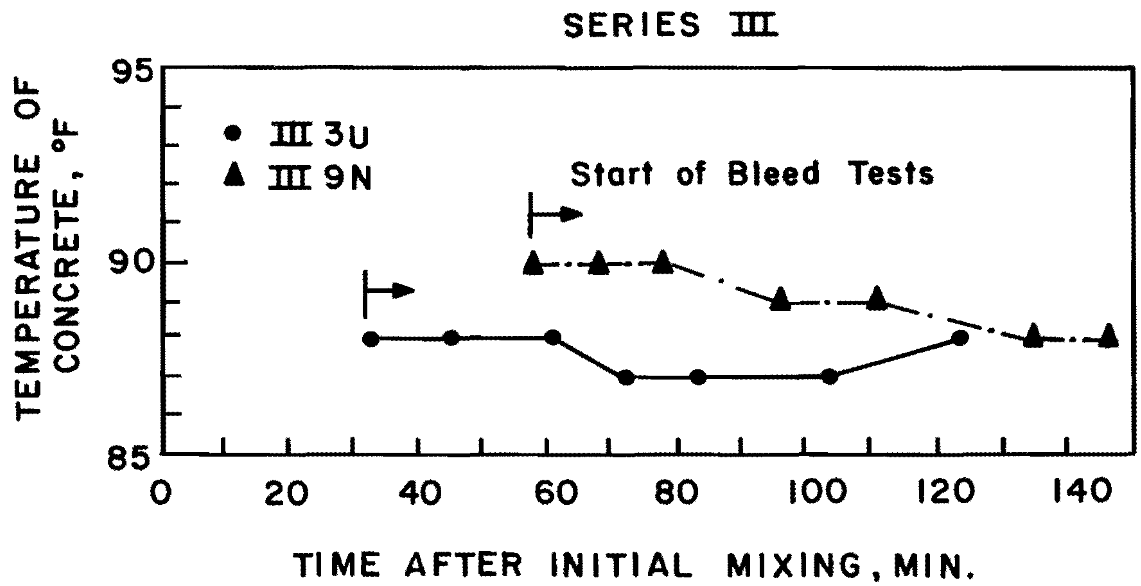



Fig. 6.18c Temperature of concrete with time during bleed tests for Series III

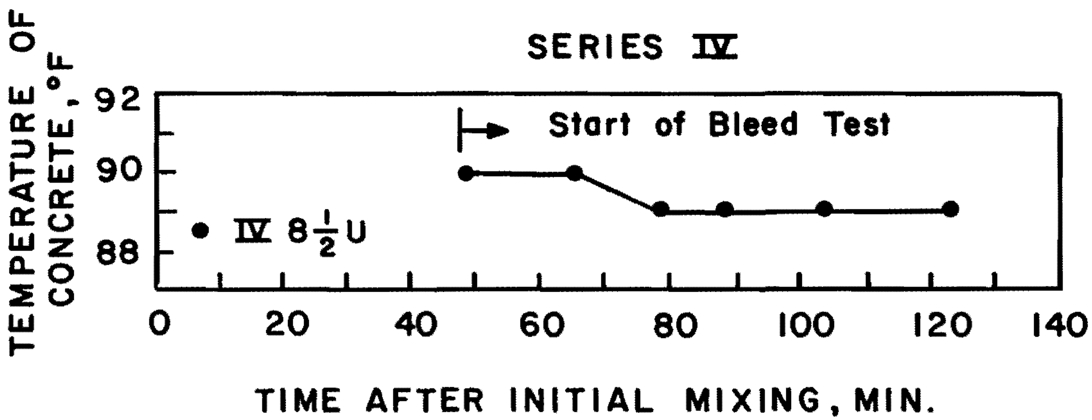



Fig. 6.18d Temperature of concrete with time during bleed tests for Series IV

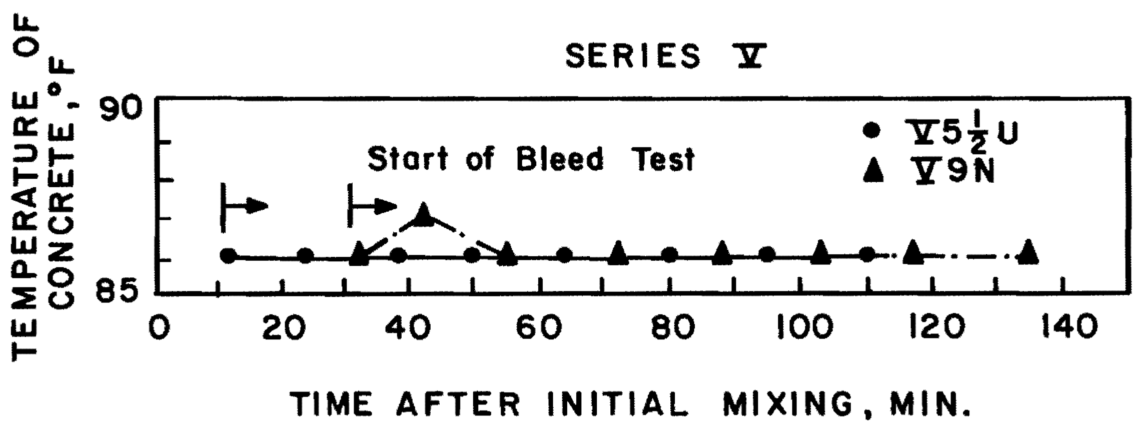



Fig. 6.18e Temperature of concrete with time during bleed tests for Series V

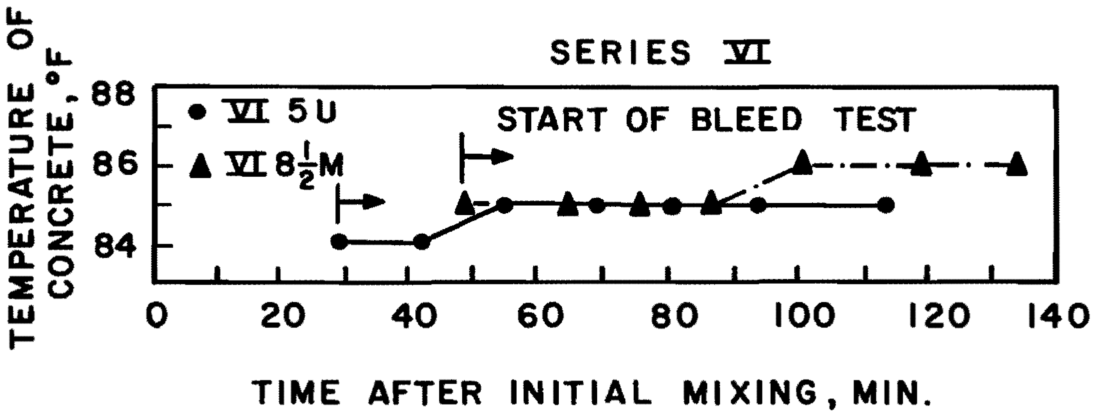



Fig. 6.18f Temperature of concrete with time during bleed tests for Series VI

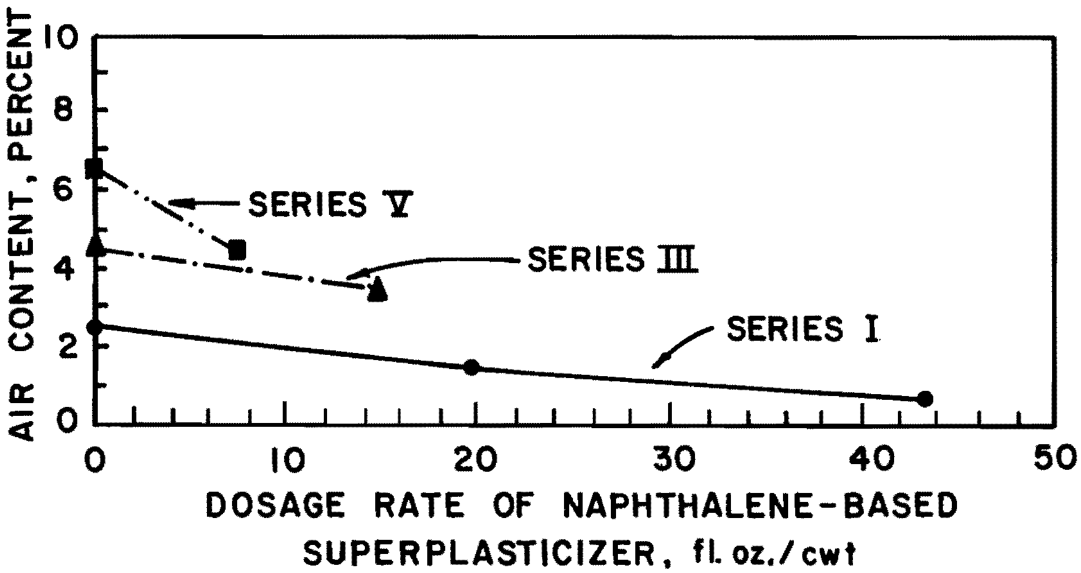



Fig. 6.19 Effect of naphthalene-based superplasticizer on air content of concrete

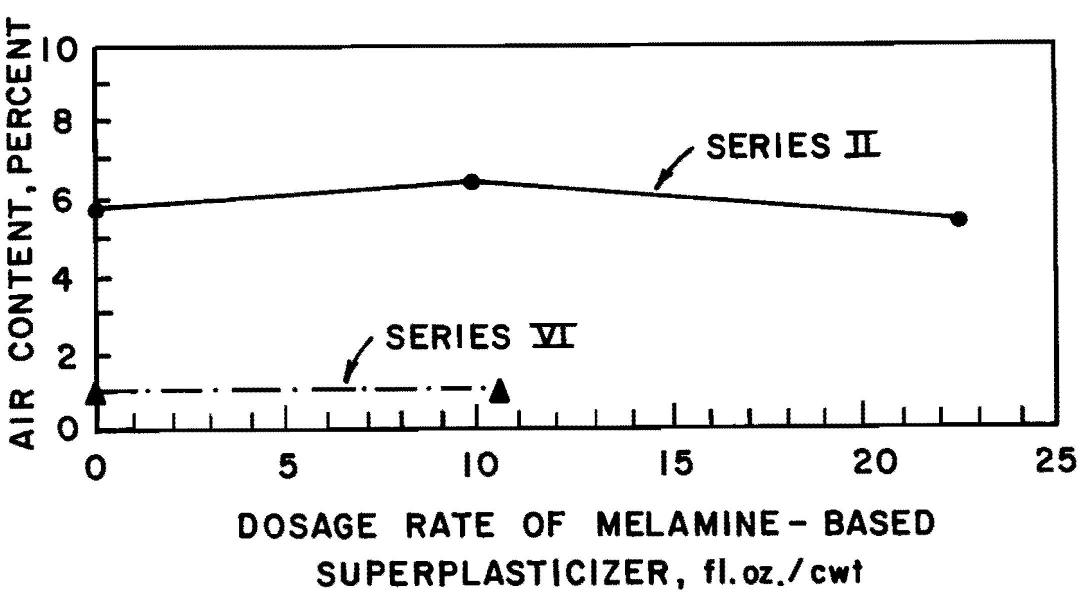



Fig. 6.20 Effect of melamine-based superplasticizer on air content of concrete

TABLE 6.1 Cement Content Per Cubic Yard and Water to Cement Ratio for Each Specimen

| Series | Specimen | Cement Content, lbs | W/C Ratio, by weight |
|---|---|---|---|
| I | I3-1/4U | 521 | 0.57 |
| | I5-1/2N | 527 | |
| | I10N | 530 | |
| II | II3U | 505 | 0.56 |
| | II6-1/2M | 502 | |
| | II9M | 507 | |
| III | III3U | 508 | 0.59 |
| | III9N | 513 | |
| IV | IV8-1/2U | 477 | 0.71 |
| V | V5-1/2U | 502 | 0.55 |
| | V9N | 513 | |
| VI | VI5U | 533 | 0.53 |
| | VI8-1/2M | 534 | |

0.71 respectively. Details of the revised mix proportions were given in Table 4.10.

## 6.7 Bleed Test

In this section, the bleed test results from the six series of specimens cast will be discussed. The possible effects of factors such as time of addition of superplasticizer and air content of concrete will be examined.

Figure 6.21 shows the total bleed of the concrete versus dosage rate of naphthalene-based superplasticizer for Series I, III and V. The open data points for Series I indicate that the bleeding of the concrete had not stopped when the last readings for those bleed tests were taken. Therefore, the total bleed at those points would actually be greater than shown. In spite of this, the bleeding of the concrete was increased by the addition of naphthalene-based superplasticizer in all cases.

Total bleed of concrete versus dosage rate of melamine-based superplasticizer for Series II and VI is shown in Fig. 6.22. In all cases, the bleeding of the concrete was decreased with the addition of melamine based superplasticizer.

It is likely that the differing effects on bleeding of the two types of superplasticizer are due to two factors: 1) the mode of action of each of the superplasticizers, and 2) their effect on the air content of the concrete.

When added to concrete, naphthalene-based superplasticizer imparts a negative surface charge to the cement particles. It slows the hydration rate of the cement particles and frees water molecules which had been trapped in the ettringite structure, as discussed in Section 6.3. Melamine-based superplasticizer, on the other hand, forms a lubricating film on the cement particles, but imparts no surface charge to these. When added to concrete, the molecules of this type of superplasticizer have no net charge, and do not repel the polar water molecules. Therefore, water molecules trapped within the ettringite structure are not expelled. Instead, the melamine-based superplasticizer forms a lubricating film around the cement particle, ettringite and entrapped water included. Hydration is delayed, but no water is freed. Thus, the bleeding of the superplasticized concrete in Series II and VI is less than that of the control concrete because the superplasticized concrete was older, and more water was bound to or entrapped within the cement particles, as was discussed in Section 6.3.

The bleeding of concrete is also affected by the entrained air content. Adding naphthalene-based superplasticizer to concrete decreases the air content, thereby increasing the bleeding of that

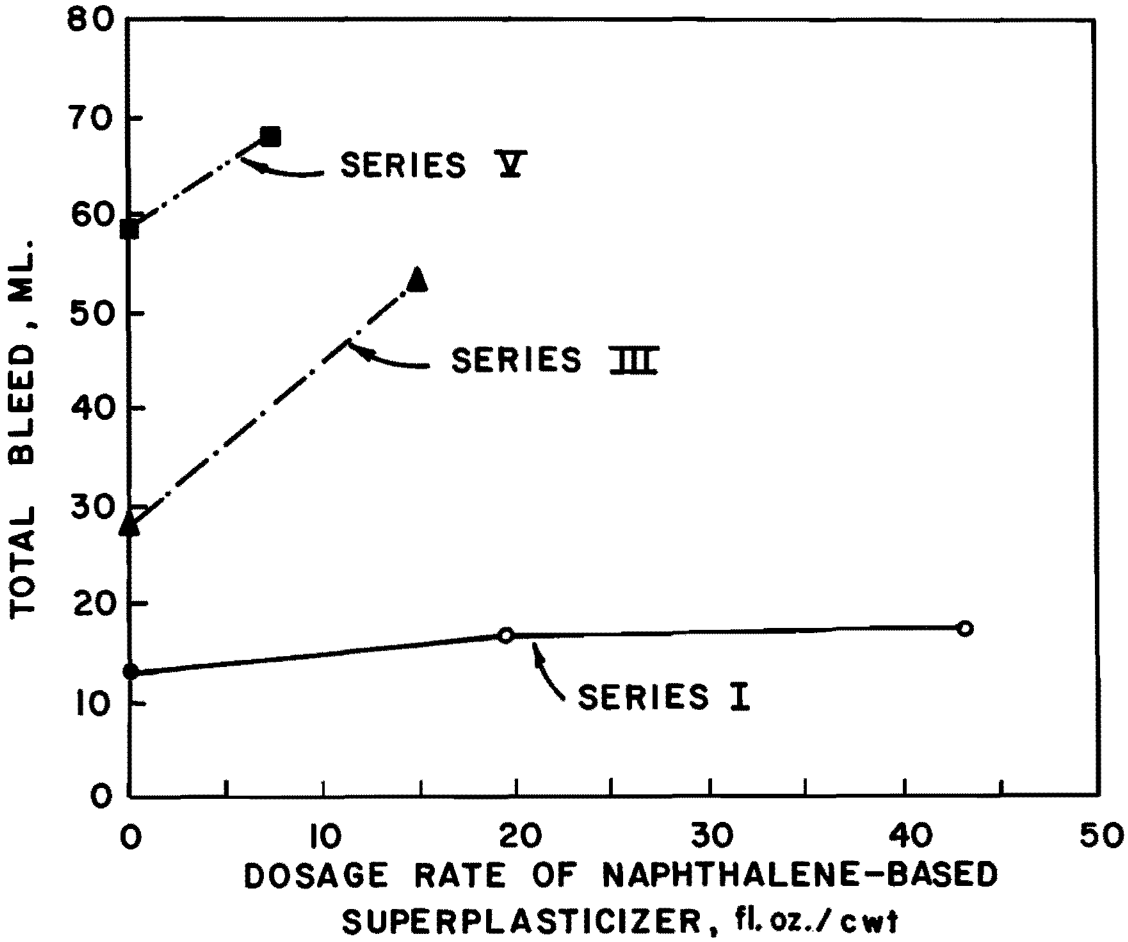



Fig. 6.21 Effect of naphthalene-based superplasticizer on the bleeding of concrete

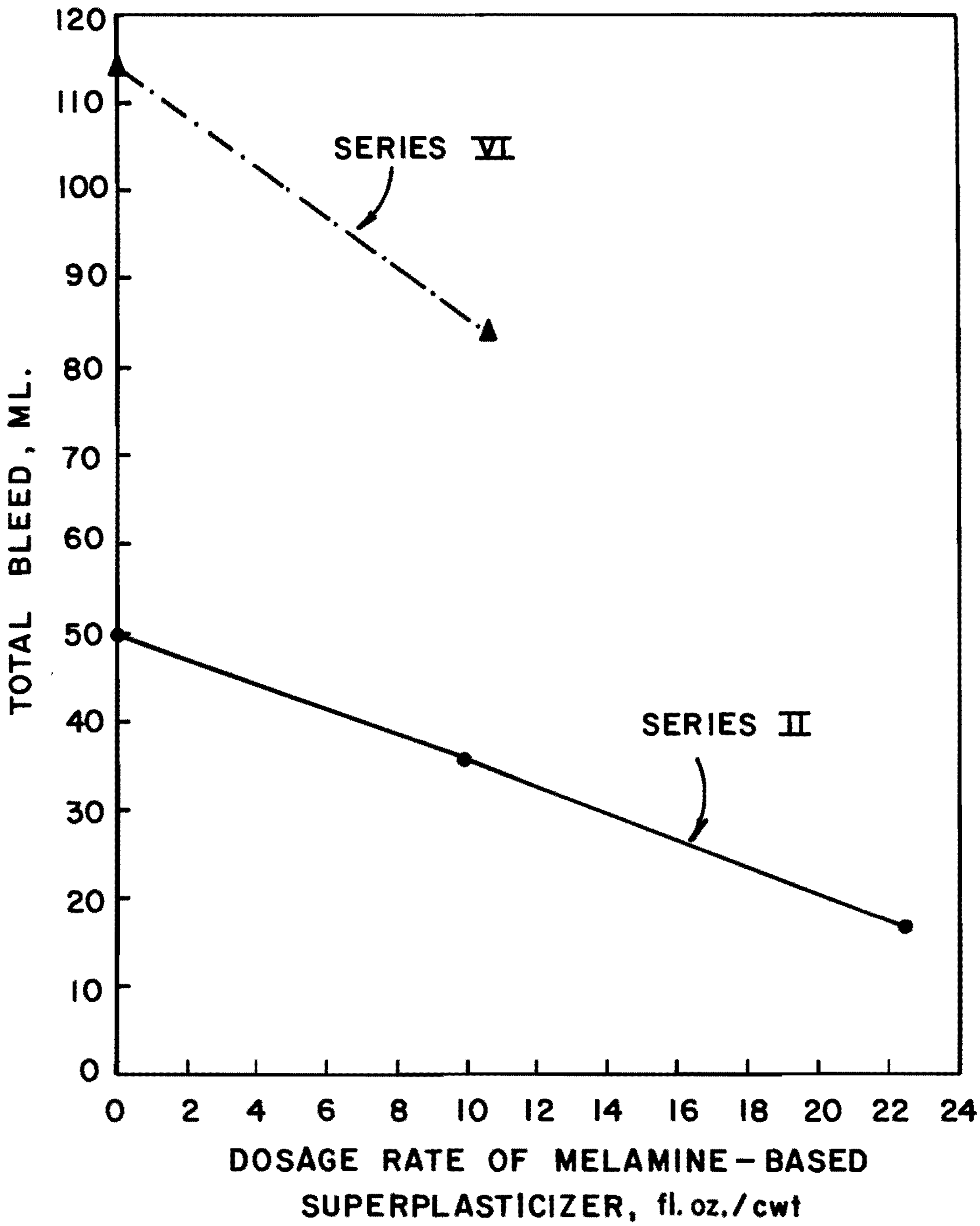



Fig. 6.22 Effect of melamine-based superplasticizer on the bleeding of concrete

concrete. The effects of melamine-based superplasticizer on the entrained air content of concrete, however, were negligible.

## 6.8 Compressive Strength Test

The results of the compressive strength tests will be discussed in this section, including the results from the 6 in. x 12 in. molded cylinders, and the 3 in. x 6 in. drilled cores taken from the specimens in Series IV and V.

6.8.1 Molded Cylinders. The results of the compressive strength tests for the concrete of each series are shown in Figs. 6.23 through 6.27. In all cases, the addition of superplasticizer increased the compressive strength of the concrete. The increase in compressive strength of the concrete induced by the addition of superplasticizer is shown as a percentage of the strength of the control concrete in Table 6.2. As shown in this table, there was no correlation between dosage rate of superplasticizer and percent increase in compressive strength. However, addition of melamine-based superplasticizer resulted in a smaller percentage increase in strength than did the addition of naphthalene-based superplasticizer.

The difference in strength increase caused by the two types of superplasticizer is probably due to their mode of action. The compressive strength of concrete is increased slightly due to the increased compactibility of concrete with higher slump. Thus, the addition of either type of superplasticizer will result in concrete with slightly higher strength due to the higher slump induced by the superplasticizer. The addition of naphthalene-based superplasticizer to concrete, however, causes further increase in the compressive strength of concrete due to the dispersion of the cement particles, whereas the addition of melamine-based superplasticizer does not. Thus, the percent strength increase resulting from the addition of naphthalene-based superplasticizer is greater than that of melamine-based superplasticizer.

6.8.2 Drilled Cores. Three cores were drilled at each casting depth from Specimens IV8-1/2U, V5-1/2U, and V9N. The average compressive strengths of these cores are plotted versus casting depth for each specimen in Fig. 6.28.

For all three specimens, the compressive strength of the cores taken at a casting depth of 36 in. were the lowest. This could be attributed to the accumulation of water at higher casting depths due to bleeding and segregation of the concrete in the forms, thus increasing the water to cement ratio of that concrete, as well as creating discontinuities in the hardened concrete, as shown in Fig. 6.29.

For Specimen V9N, the core compressive strength decreased as the casting depth increased. However, the cores drilled from Specimens

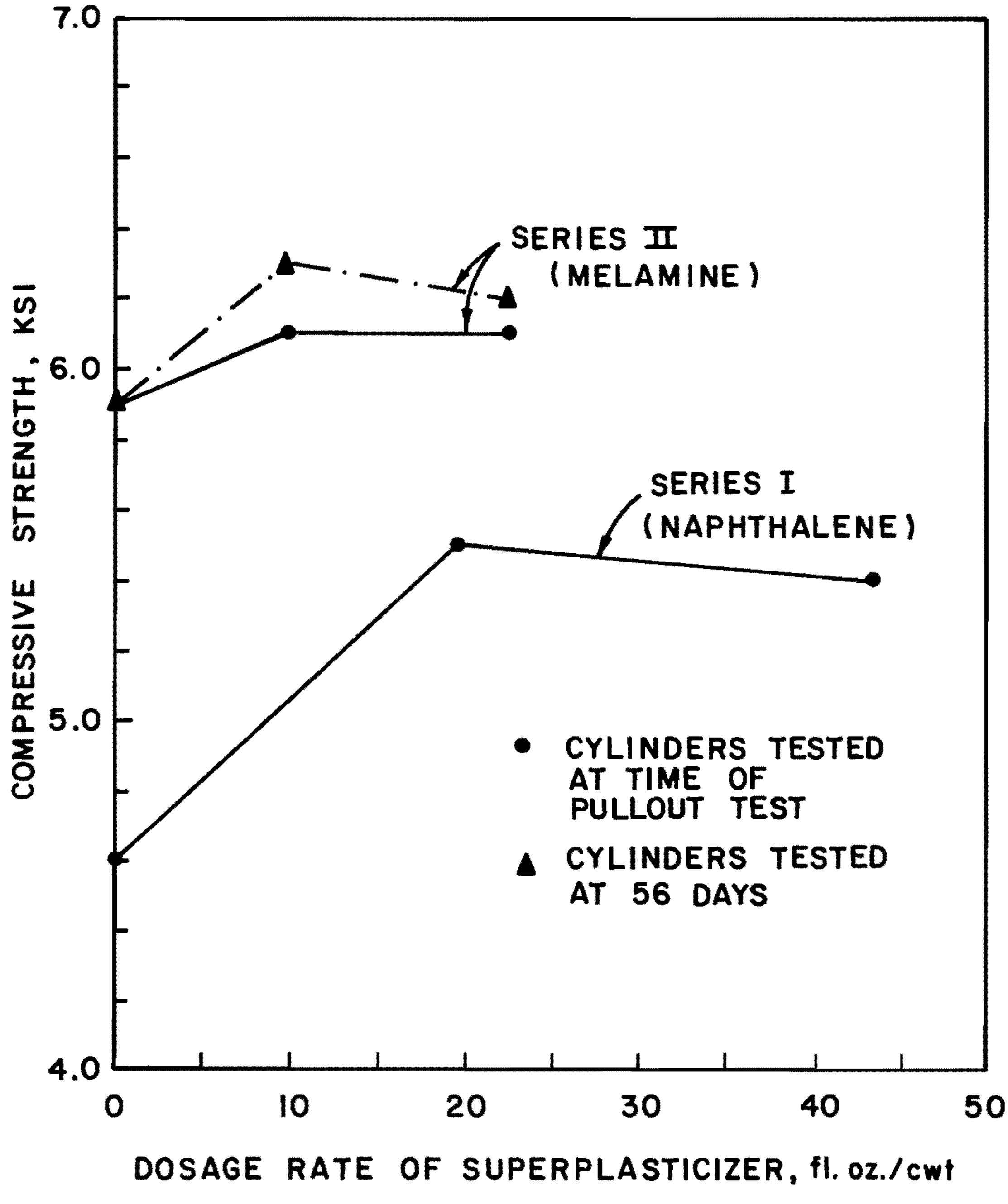



Fig. 6.23 Effect of addition of superplasticizer on compressive strength of concrete for Series I and II

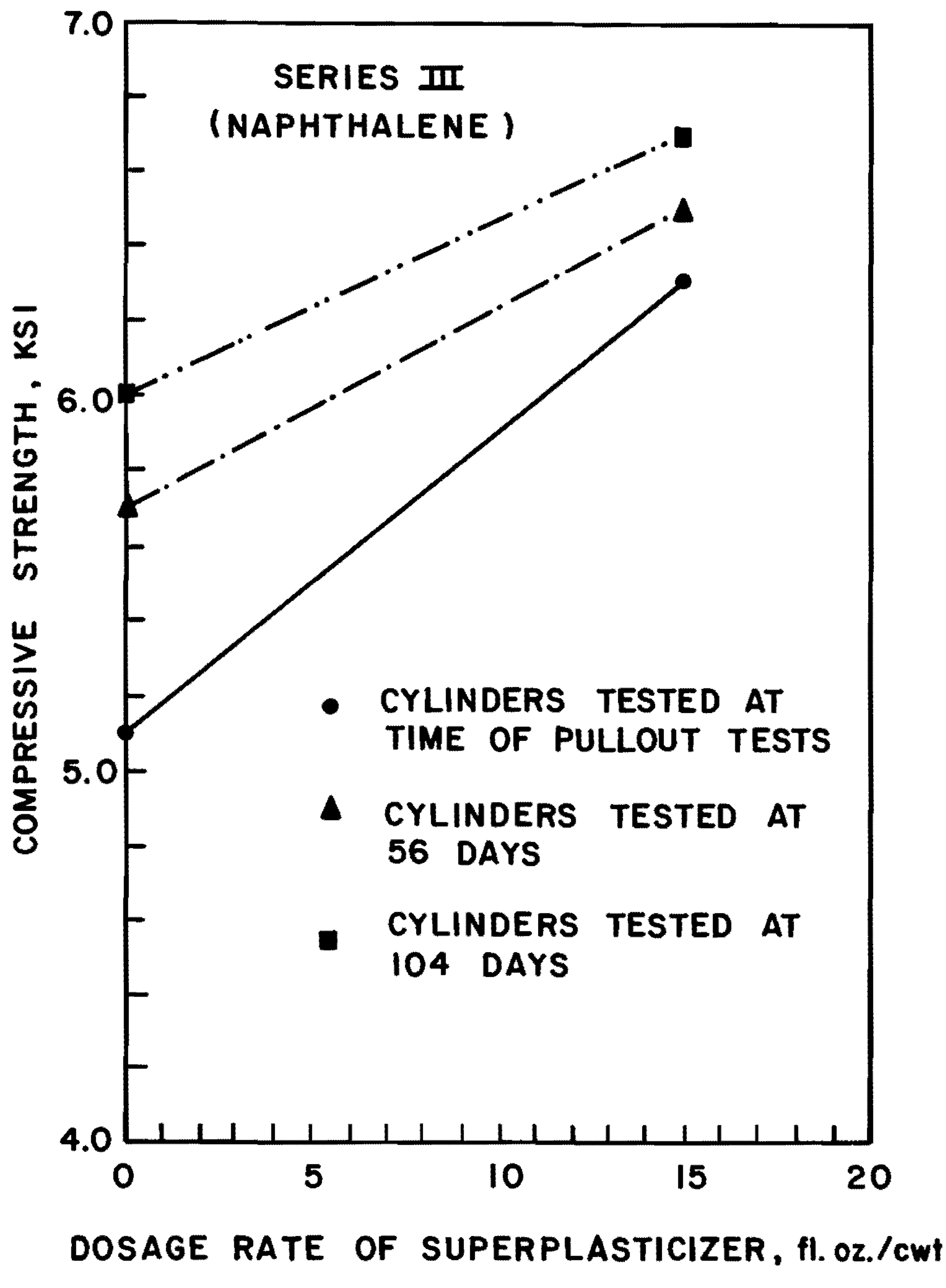



Fig. 6.24 Effect of addition of superplasticizer on compressive strength of concrete for Series III

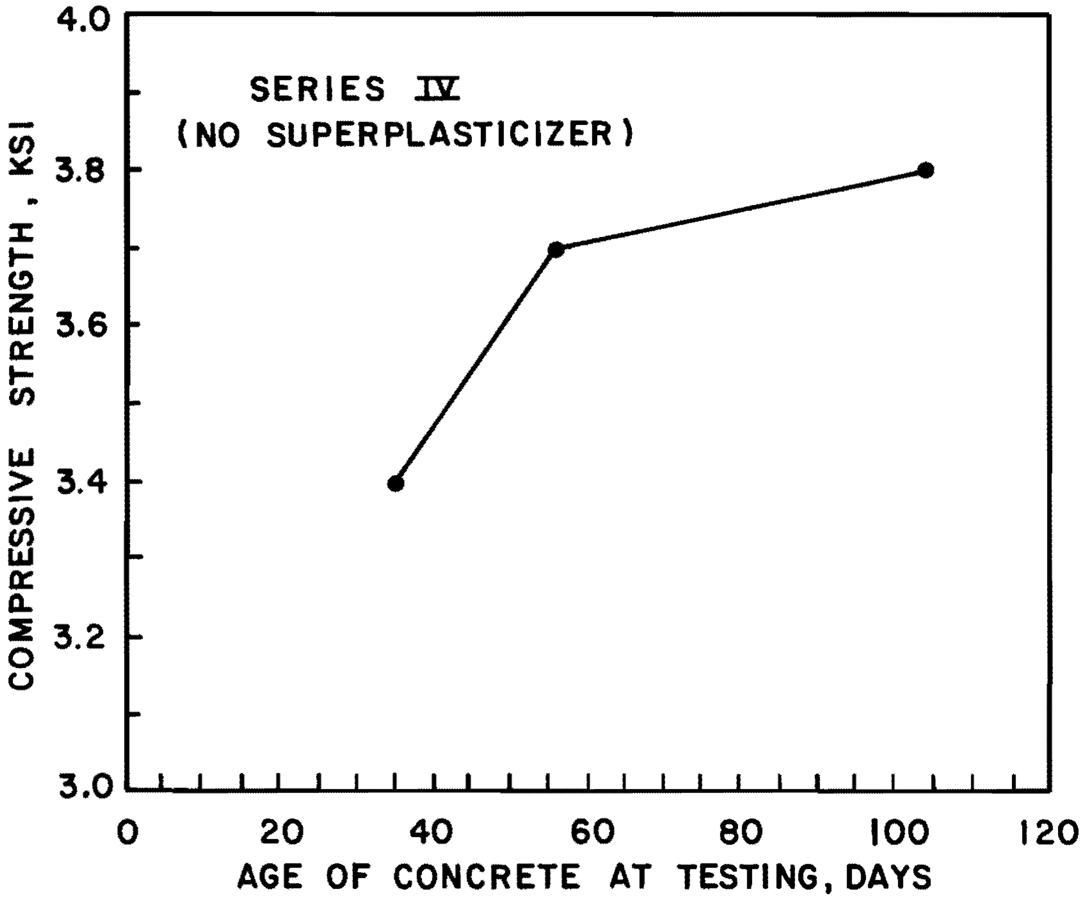



Fig. 6.25 Compressive strengths of cylinders from Series IV

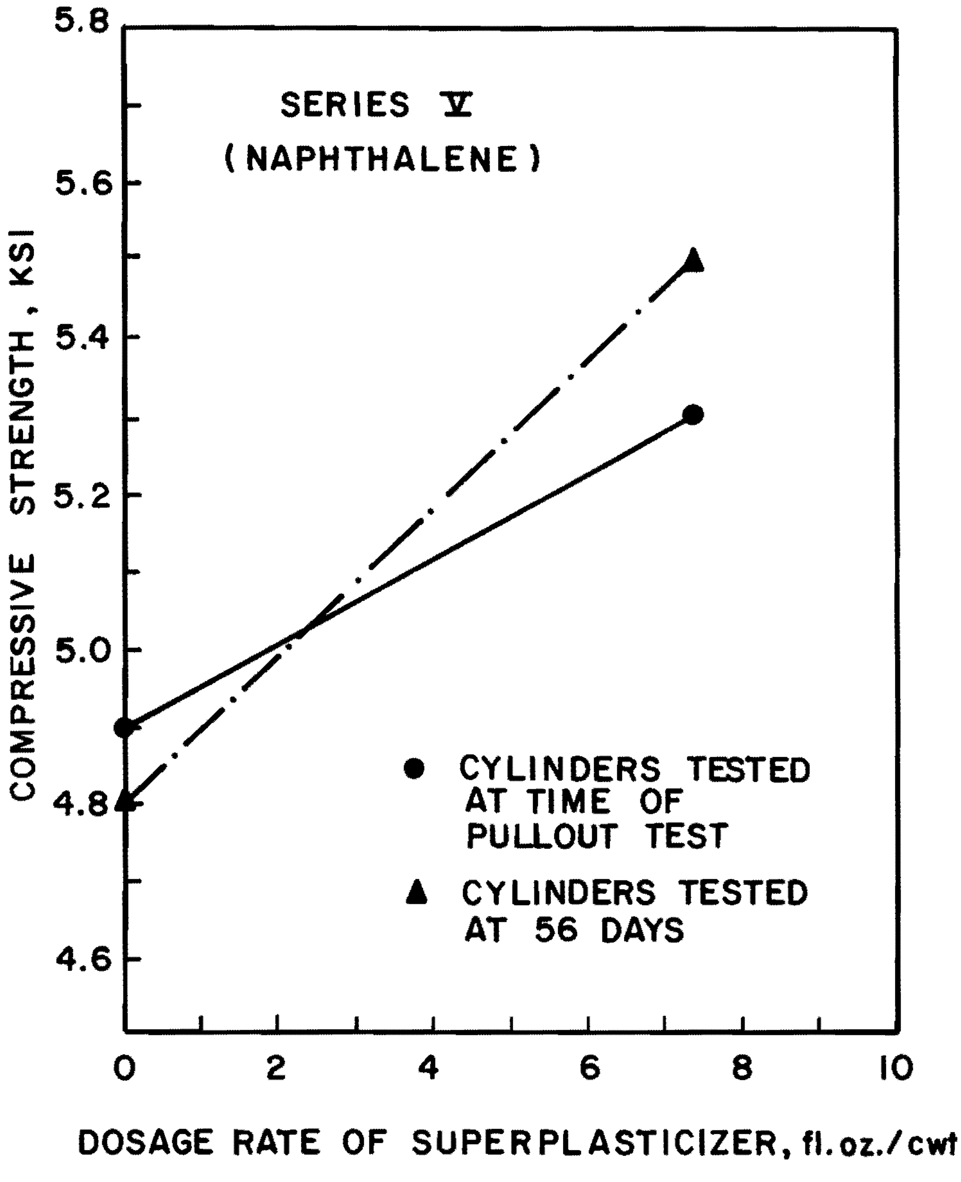



Fig. 6.26 Effect of addition of superplasticizer on compressive strength of concrete for Series V

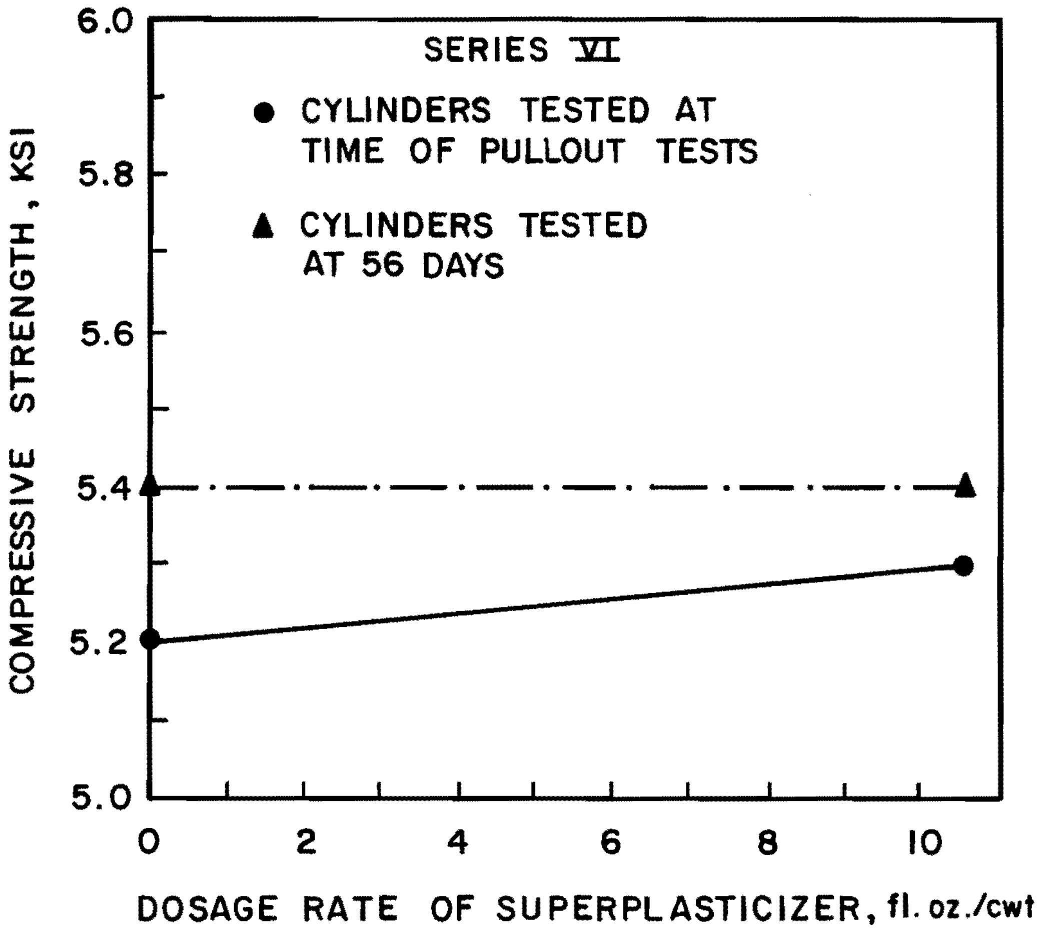



Fig. 6.27 Effect of addition of superplasticizer on compressive strength of concrete for Series VI

TABLE 6.2 Increase in Compressive Strength of Concrete Due to Addition of Superplasticizer

| Specimen | Dosage Rate of Superplasticizer, fl.oz./cwt | Strength Increase,[a] % |
|---|---|---|
| I3-1/4U | 0.0 | ---- |
| I5-1/2N | 19.6 | 19.6 |
| I10N | 43.2 | 17.4 |
| II3U | 0.0 | ---- |
| II6-1/2M | 9.9 | 3.4 |
| II9M | 22.5 | 3.4 |
| III3U | 0.0 | ---- |
| III9N | 15.0 | 23.5 |
| IV8-1/2U | 0.0 | ---- |
| V5-1/2U | 0.0 | ---- |
| V9N | 7.4 | 8.2 |
| VI5U | 0.0 | ---- |
| VI8-1/2M | 10.6 | 1.9 |

[a] Expressed as a percentage of the strength of the control mix containing no superplasticizer

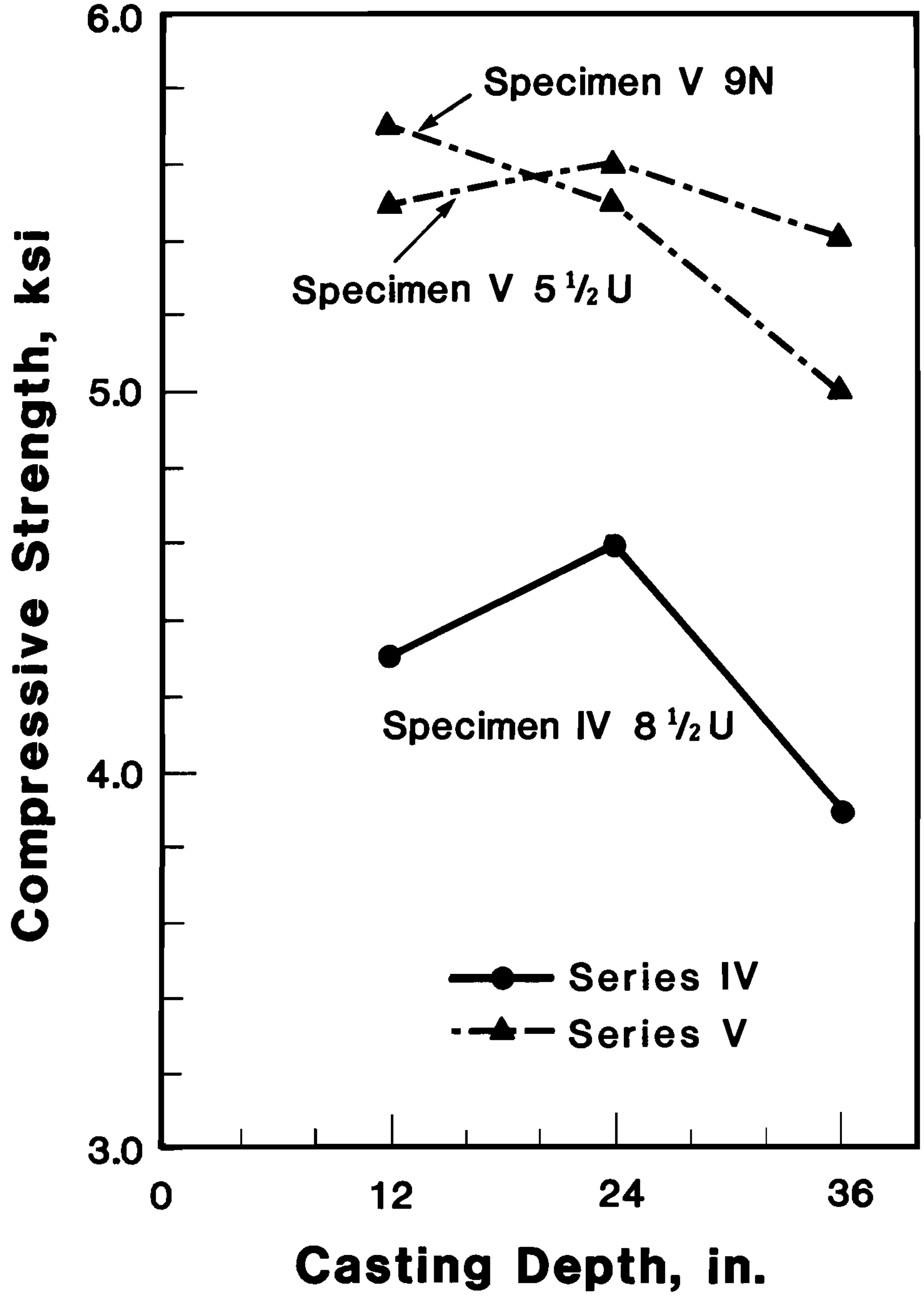



Fig. 6.28 Core compressive strength as a function of casting depth

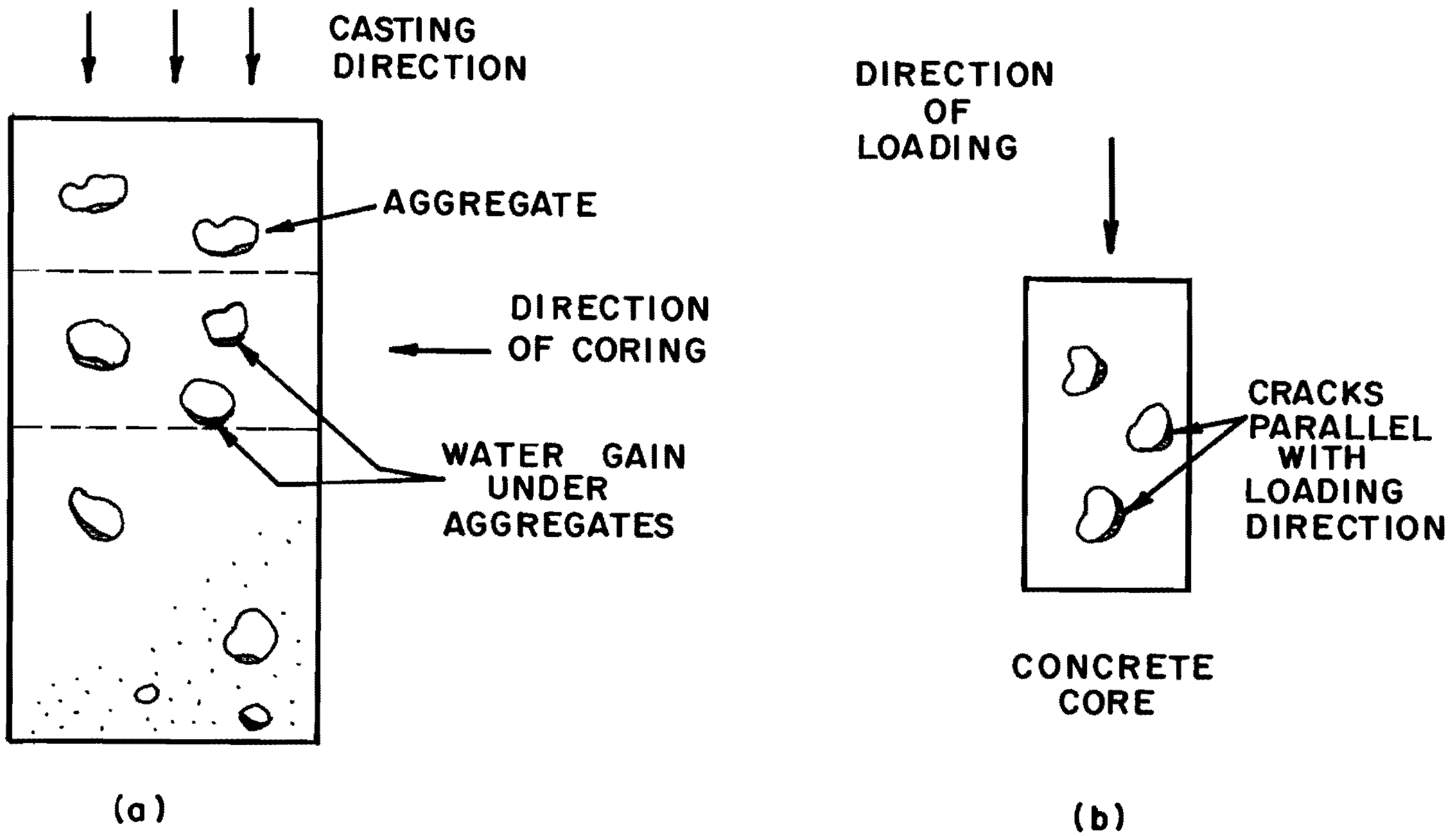



Fig. 6.29 Discontinuities in concrete caused by bleeding of concrete: (a) core drilled perpendicular to casting direction; and (b) cracks caused by water gain around aggregates running parallel with loading direction

IV8-1/2U and V5-1/2U at a casting depth of 24 in. had the highest compressive strength. This could have been caused by better compaction of the concrete at mid-depth of the forms than at the bottom. The forms were 4 ft deep and only 6 in. wide, and heavily congested with steel. For this reason, adequate compaction of the concrete at the bottom of the forms was difficult.

The highest core strength, tested at 104 days, from Specimens V-5-1/2U and V9N were 5600 psi and 5700 psi respectively. The corresponding molded cylinder strengths tested at 56 days for Specimens V5-1/2U and V9N were 4800 psi and 5500 psi, respectively. However, the compressive strength of the cores taken from Specimen IV8-1/2U were significantly greater than the molded cylinder strength for that specimen tested at 104 days. The highest core strength was 4600 psi, whereas the molded cylinder strength was only 3800 psi. Thus, although the drilled cores and molded cylinders were tested at the same age, the compressive strength of the drilled cores was significantly higher.

## 6.9 Splitting Tensile Strength Test

The effect of addition of naphthalene-based superplasticizer on the splitting tensile strength of concrete is shown in Fig. 6.30. In general, the splitting tensile strength of the concrete increased upon addition of naphthalene-based superplasticizer.

The effect of melamine-based superplasticizer on the splitting tensile strength of concrete is shown in Fig. 6.31. In general, for concrete containing melamine-based superplasticizer, the tensile splitting strength was similar to that of the control mix containing no superplasticizer.

The percent increase in splitting tensile strength of concrete induced by the addition of superplasticizer is shown in Table 6.3. As shown in this table, the percent increase in splitting tensile strength of concrete induced by the addition of naphthalene-based superplasticizer is much higher than that induced by the addition of melamine-based superplasticizer, except for Specimen I5-1/2N. The differing behavior of this specimen is probably due to the older age of the concrete. For Specimen I10N, the high dosage rate of superplasticizer overrode the effects of concrete age.

The greater increase in splitting tensile strength induced by the addition of naphthalene-based superplasticizer can be attributed to the dispersion of the cement particles caused by this admixture. Well dispersed, the cement particles coat the aggregates better, thereby improving the bond between the aggregates and mortar. This, in turn, increases the splitting tensile strength of the concrete. Addition of melamine-based superplasticizer, on the other hand, does not result in dispersion of the cement particles, and therefore has a negligible effect on the splitting tensile strength of the concrete.

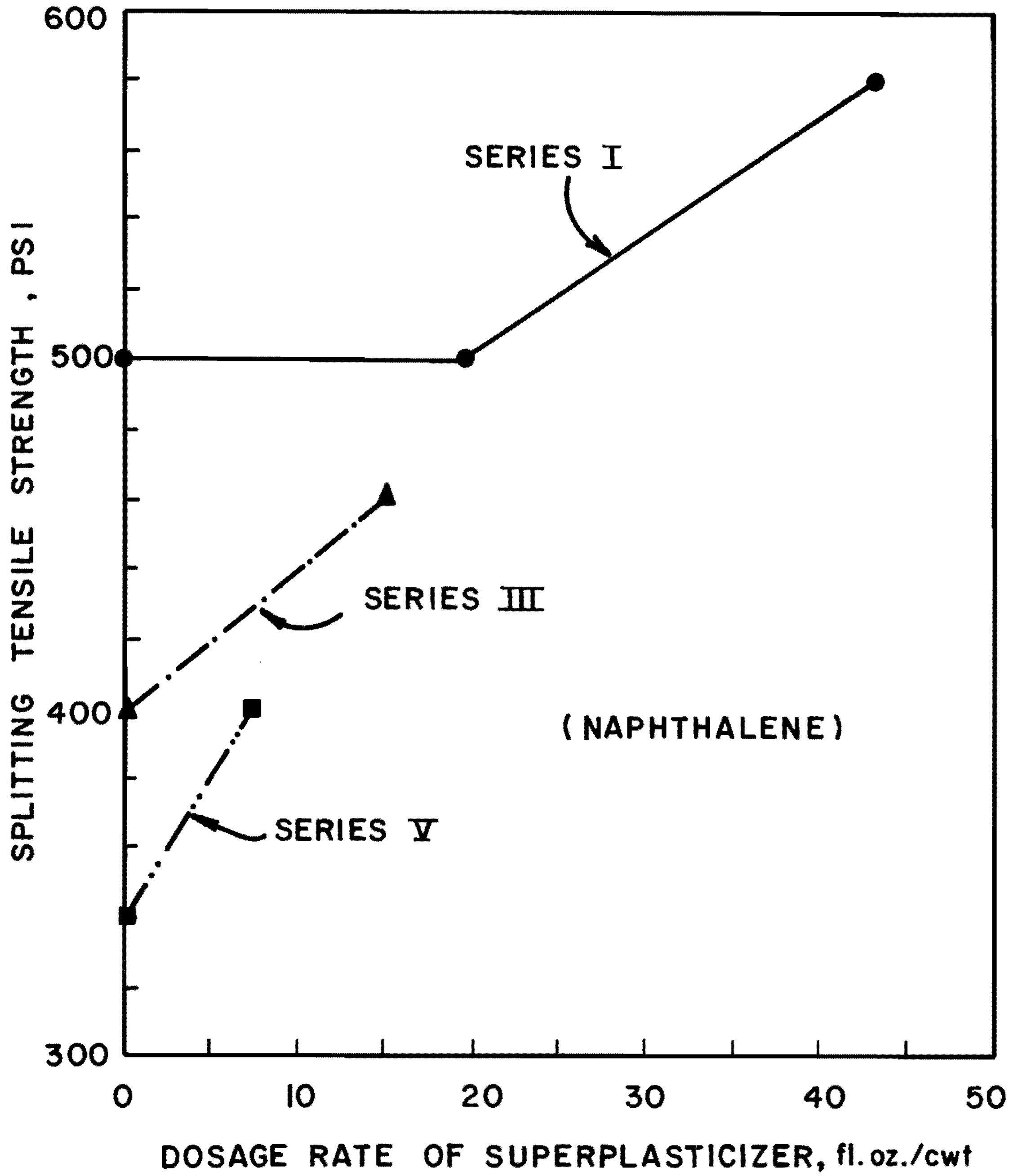



Fig. 6.30 Effect of dosage rate of naphthalene-based superplasticizer on splitting tensile strength of concrete

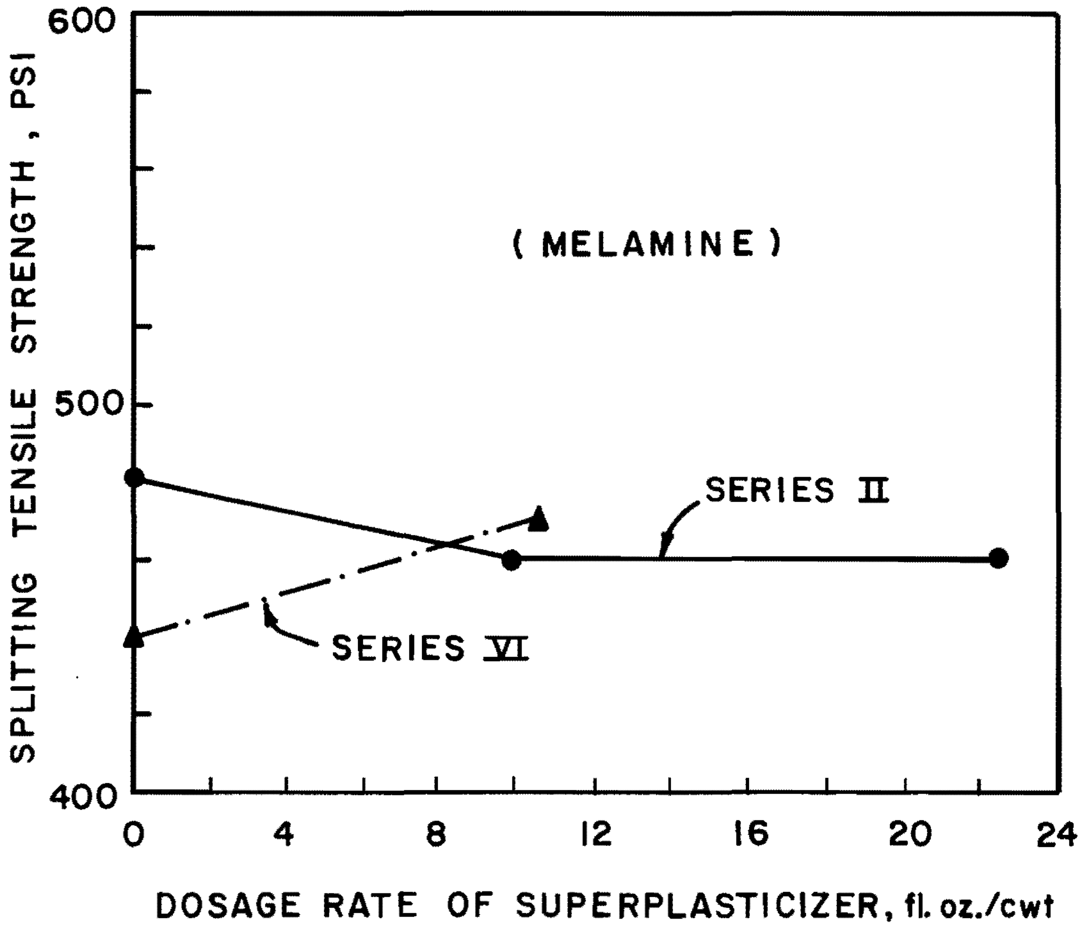



Fig. 6.31 Effect of dosage rate of melamine-based superplasticizer on splitting tensile strength of concrete

TABLE 6.3 Increase in Splitting Tensile Strength of Concrete Due to Addition of Superplasticizer

| Specimen | Dosage Rate of Super-plasticizer, fl.oz./cwt | Strength Increase,[a] % |
|---|---|---|
| I3-1/4U | 0.0 | ---- |
| I5-1/2N | 19.6 | 0.0 |
| I10N | 43.2 | 16.0 |
| II3U | 0.0 | ---- |
| II6-1/2M | 9.9 | (-4.2) |
| II9M | 22.5 | (-4.2) |
| III3U | 0.0 | ---- |
| III9N | 15.0 | 15.0 |
| IV8-1/2U | 0.0 | ---- |
| V5-1/2U | 0.0 | ---- |
| V9N | 7.4 | 17.6 |
| VI5U | 0.0 | ---- |
| VI8-1/2M | 10.6 | 6.8 |

[a] Expressed as a percentage of the strength of the control mix containing no superplasticizer

## 6.10 Pullout Test

The results of the pullout tests conducted in this research program will not be discussed in this section. Since the embedded length of each pullout bar in this study was considerably shorter than that corresponding to full development length, the effect of superplasticizer on the pullout behavior will be discussed based on the maximum pullout load achieved during each test.

The study of the effect of superplasticizer on the bond behavior of reinforcing steel embedded in concrete will include two aspects. One of these is the overall effect of superplasticizer, including its effects on concrete tensile strength, slump, and bleeding, on the bond between concrete and reinforcing steel. The other aspect studied is the effect of superplasticizer on the bleeding of concrete, and, in turn, how that bleeding affected the bond performance of the concrete and reinforcing steel.

6.10.1 Overall Effect of Superplasticizer. The overall effect of superplasticizer on the bond pullout performance of reinforcing steel and concrete will be investigated on the basis of maximum pullout load. Thus, the combined effect of superplasticizer on bleeding and splitting tensile strength of concrete, and the interaction of these factors in determining bond behavior, can be discussed.

In Fig. 6.32, the maximum pullout load for each bar tested from Series I is shown versus casting depth, in addition to the average maximum pullout load for each casting depth. Values for bars which failed by yielding are not shown. In all cases, the maximum pullout loads for bars embedded in concrete containing naphthalene-based superplasticizer were greater than those for bars embedded in the control concrete. Thus, the increased tensile capacity of the concrete outweighed the effect of increased bleeding induced by the superplasticizer.

For Specimens I3-1/4U and I5-1/2N, no significant difference was observed in maximum pullout load as a function of casting depth referring to the depth of fresh concrete cast below each bar. Due to yielding of the pullout bars, there is insufficient data for determining the effect of casting depth on pullout performance for Specimen I10N.

The maximum pullout load for each bar tested from Series II is plotted versus casting depth in Fig. 6.33. In general, the maximum pullout loads for reinforcing steel embedded in concrete containing melamine-based superplasticizer are equal to or greater than those for reinforcing steel embedded in concrete containing no superplasticizer. However, the effect of casting depth on pullout bond behavior is much more pronounced in the higher slump specimens than in the control

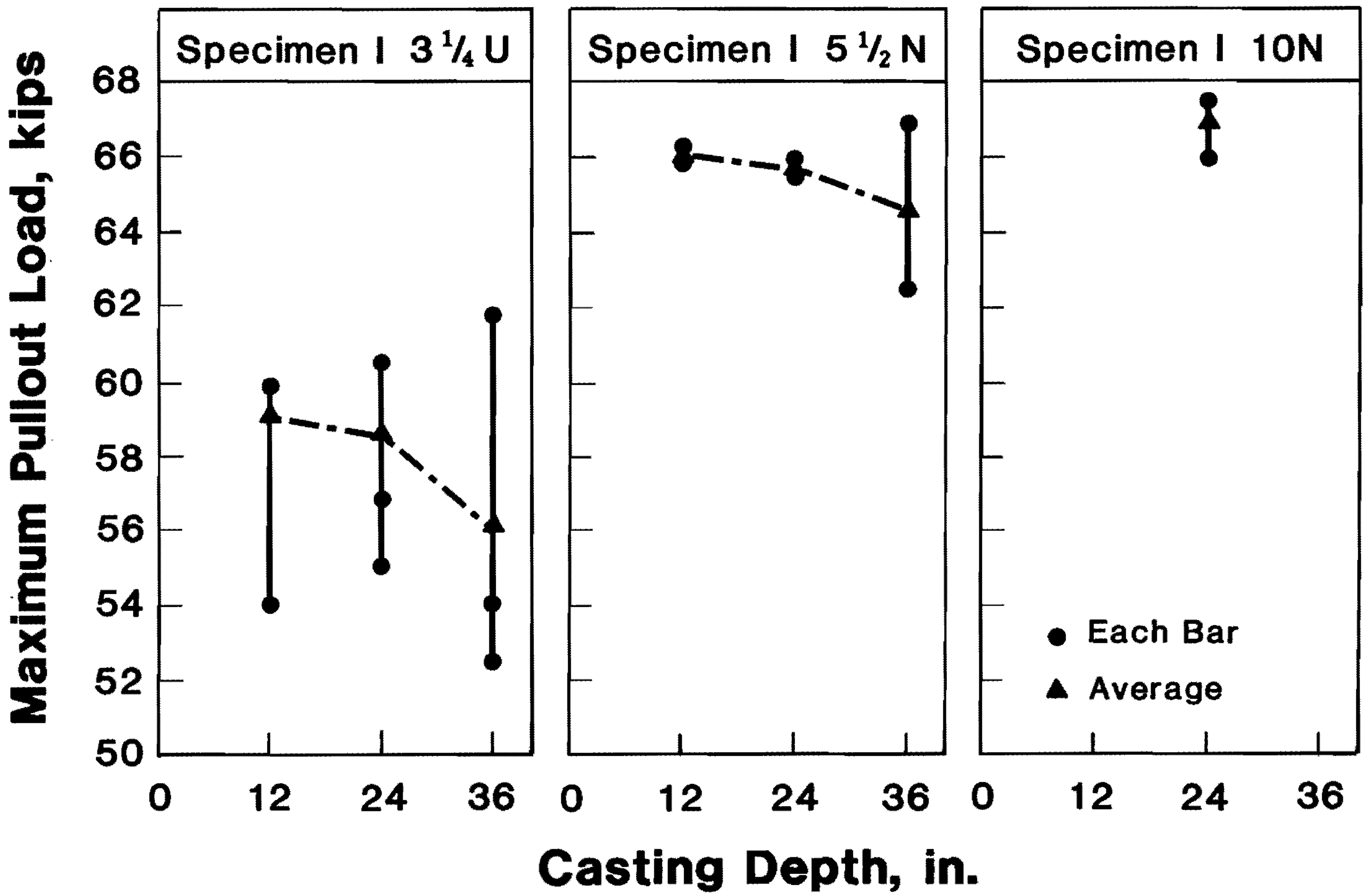



Fig. 6.32 Maximum pullout load versus casting depth for bars from Series I

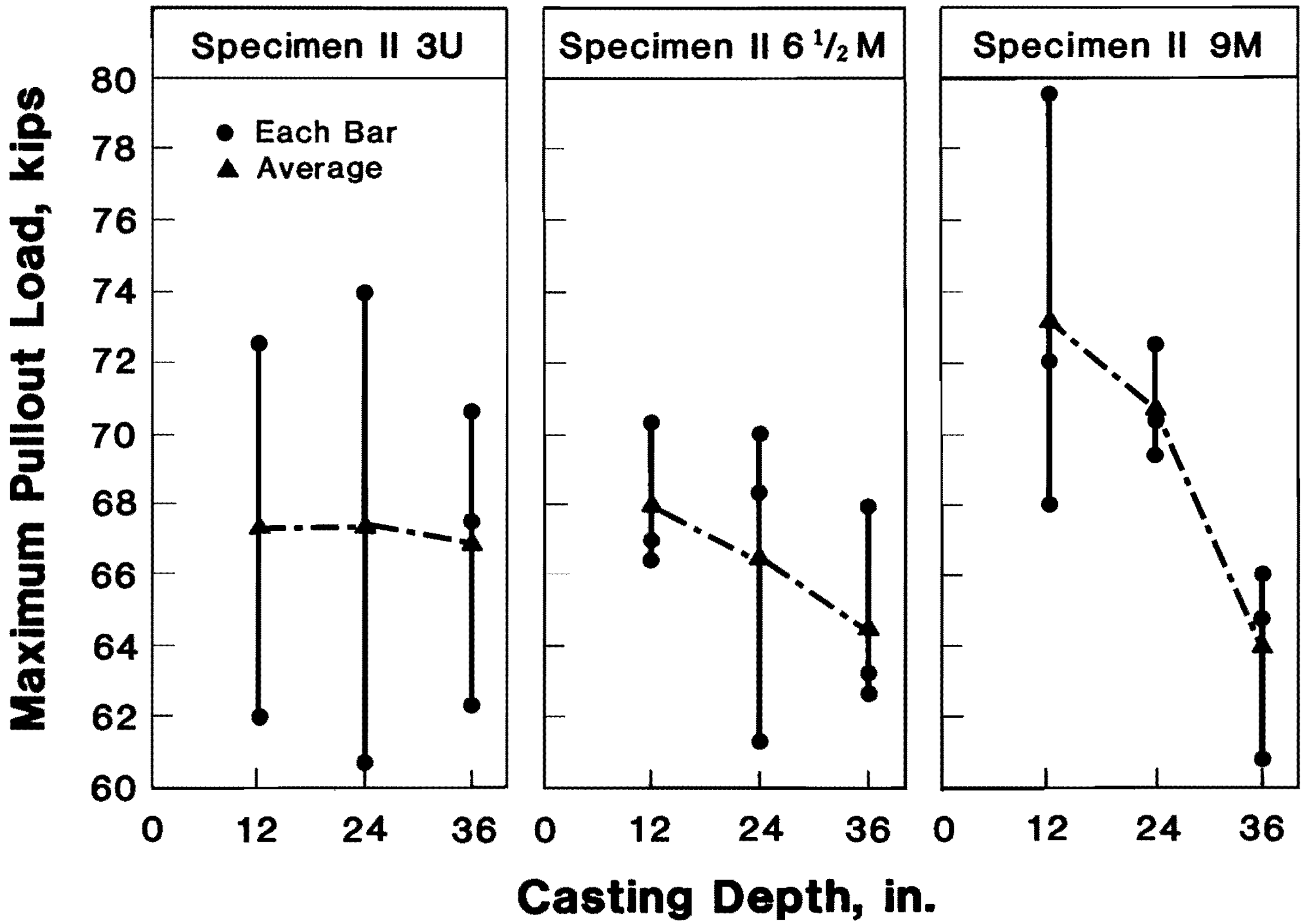



Fig. 6.33 Maximum pullout load versus casting depth for bars from Series II

concrete. In Specimen II6-1/2M, the maximum pullout load decreased with increasing casting depth. The decrease in maximum load capacity with increasing casting depth was even greater for Specimen II9M. This can be attributed to the greater compaction of the concrete at the lower casting depth of the higher slump specimen due to the effect of the superplasticizer in reducing the friction among the cement particles, and not to a reduction in maximum pullout load at greater casting depths due to bleeding of the concrete.

The maximum pullout loads versus casting depth for the bars of Series III are shown in Fig. 6.34. For a given casting depth, the pullout loads for the bars embedded in concrete containing superplasticizer are greater than or equal to the pullout loads for the bars embedded in the control concrete. However, the increase in maximum pullout load induced by the use of naphthalene-based superplasticizer in the specimens of Series III is much less than the increase seen in Series I, the reason for this difference being the increased bleeding of the concrete containing superplasticizer in Series III as compared to that in Series I.

In Specimen III3U, the maximum pullout load increased with casting depth, perhaps due to poor compaction of the concrete in the lower half of the form.

Figure 6.35 shows the maximum pullout load versus casting depth for Specimen IV8-1/2U, as well as the average value at each casting depth. The maximum pullout loads for each casting depth were similar, regardless of the high slump of the concrete containing no superplasticizer.

The maximum pullout load versus casting depth for the bars from Series V is shown in Fig. 6.36. The bond performance of reinforcement embedded in the concrete containing naphthalene-based superplasticizer is the same as the bond performance of reinforcement embedded in the control concrete. Contrary to the effect observed in Series I and III, the addition of naphthalene-based superplasticizer to the concrete of Series V did not increase the maximum pullout load. This can be attributed to the similar bleed of Specimens V5-1/2U and V9N, and to the much smaller dosage of superplasticizer required to increase the slump of the concrete.

Figure 6.37 shows the maximum pullout load versus casting depth for the bars from Series VI. The addition of melamine-based superplasticizer did not have a significant effect on the maximum pullout load. In addition, the maximum pullout load was independent of casting depth.

In general, the bond between reinforcing steel and concrete was not adversely affected by the addition of either naphthalene- or melamine-based superplasticizer to the concrete, independent of the

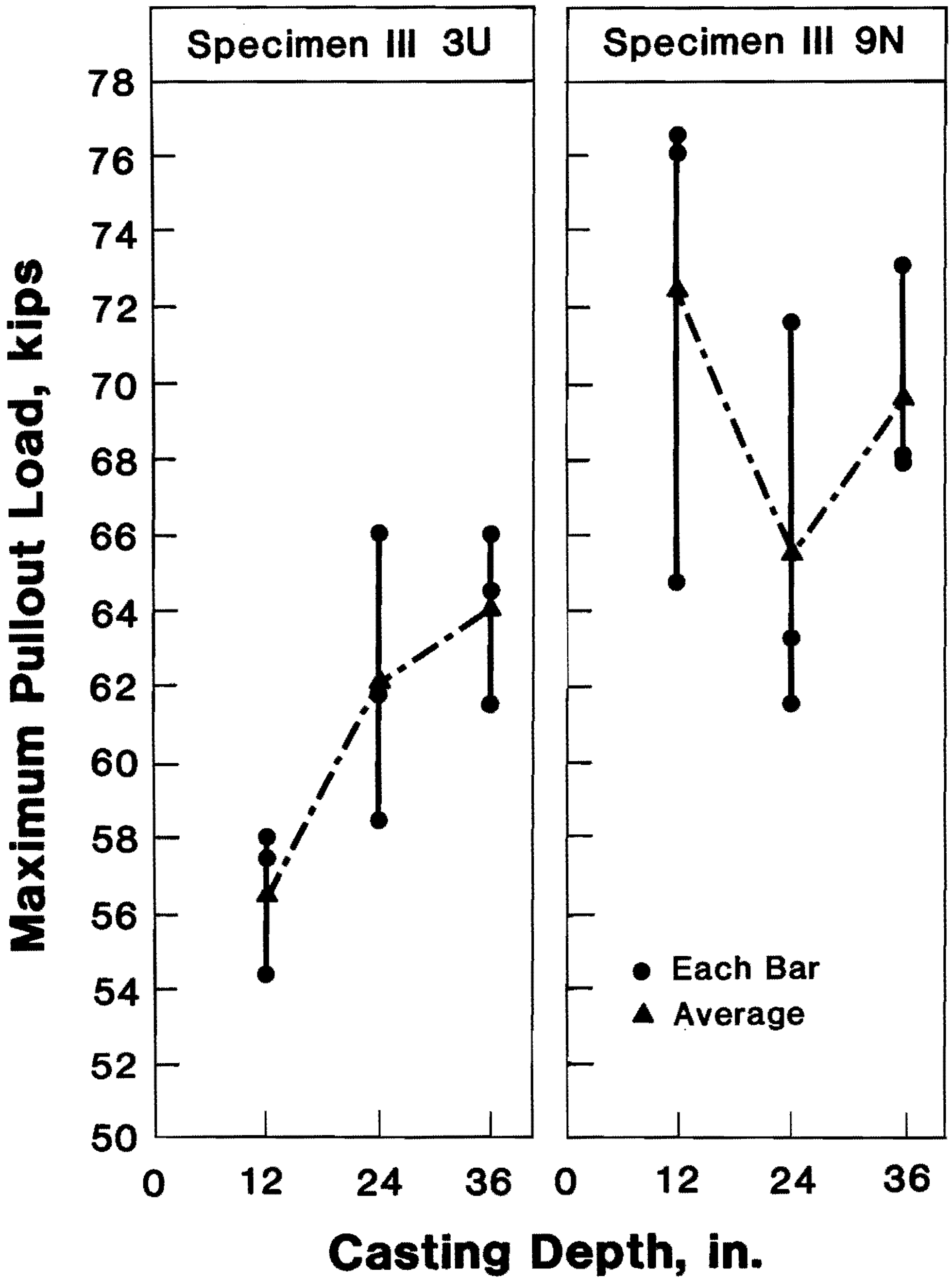



Fig. 6.34 Maximum pullout load versus casting depth for bars from Series III

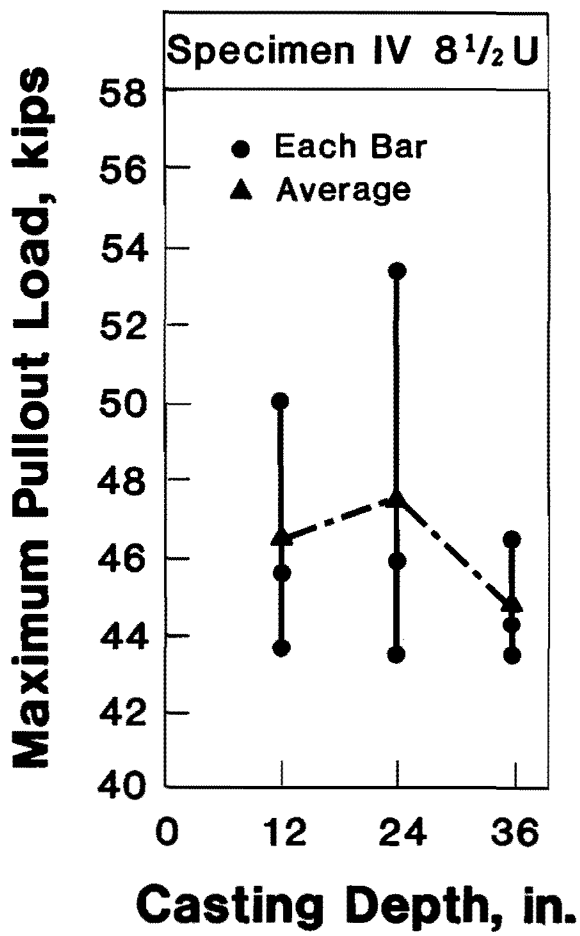



Fig. 6.35 Maximum pullout load versus casting depth for bars from Series IV

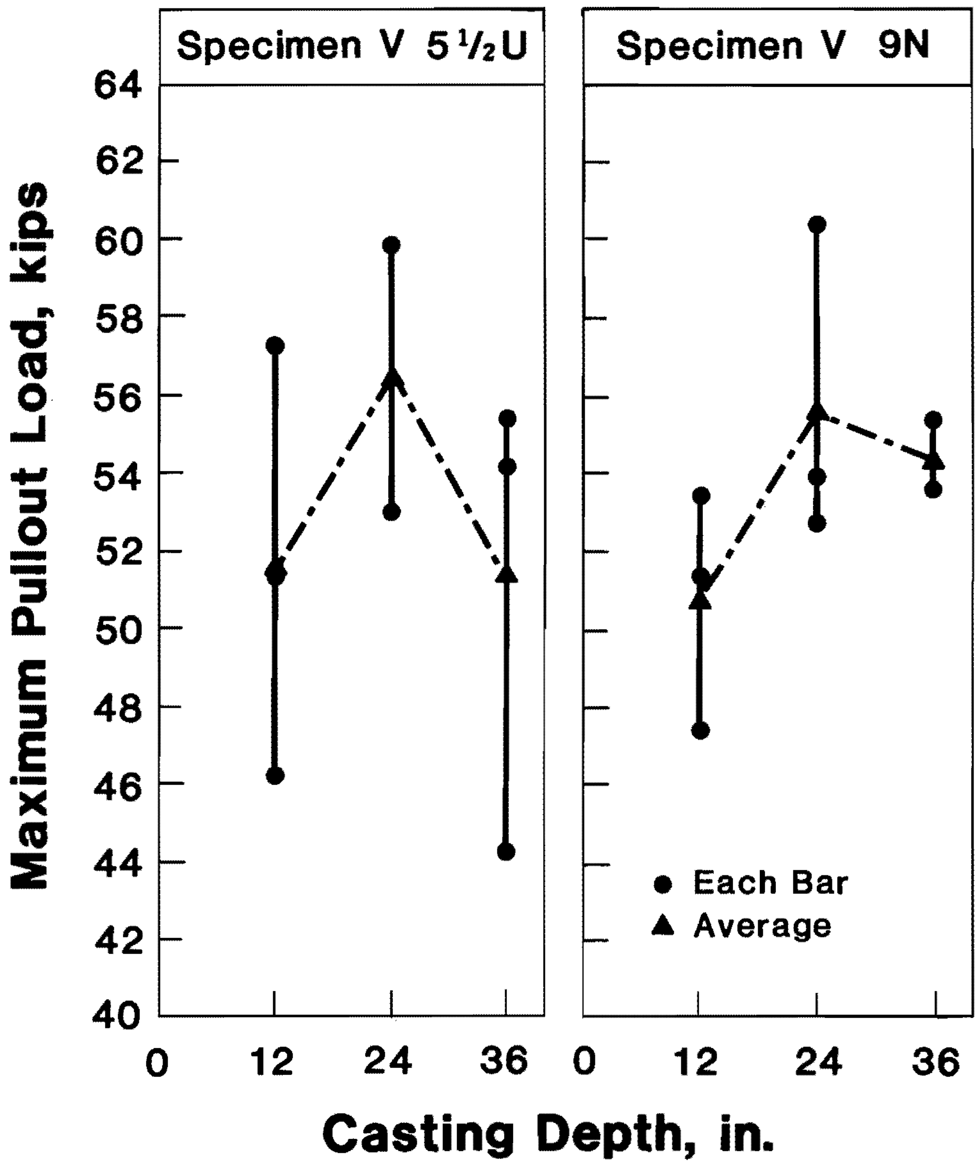



Fig. 6.36 Maximum pullout load versus casting depth for bars from Series V

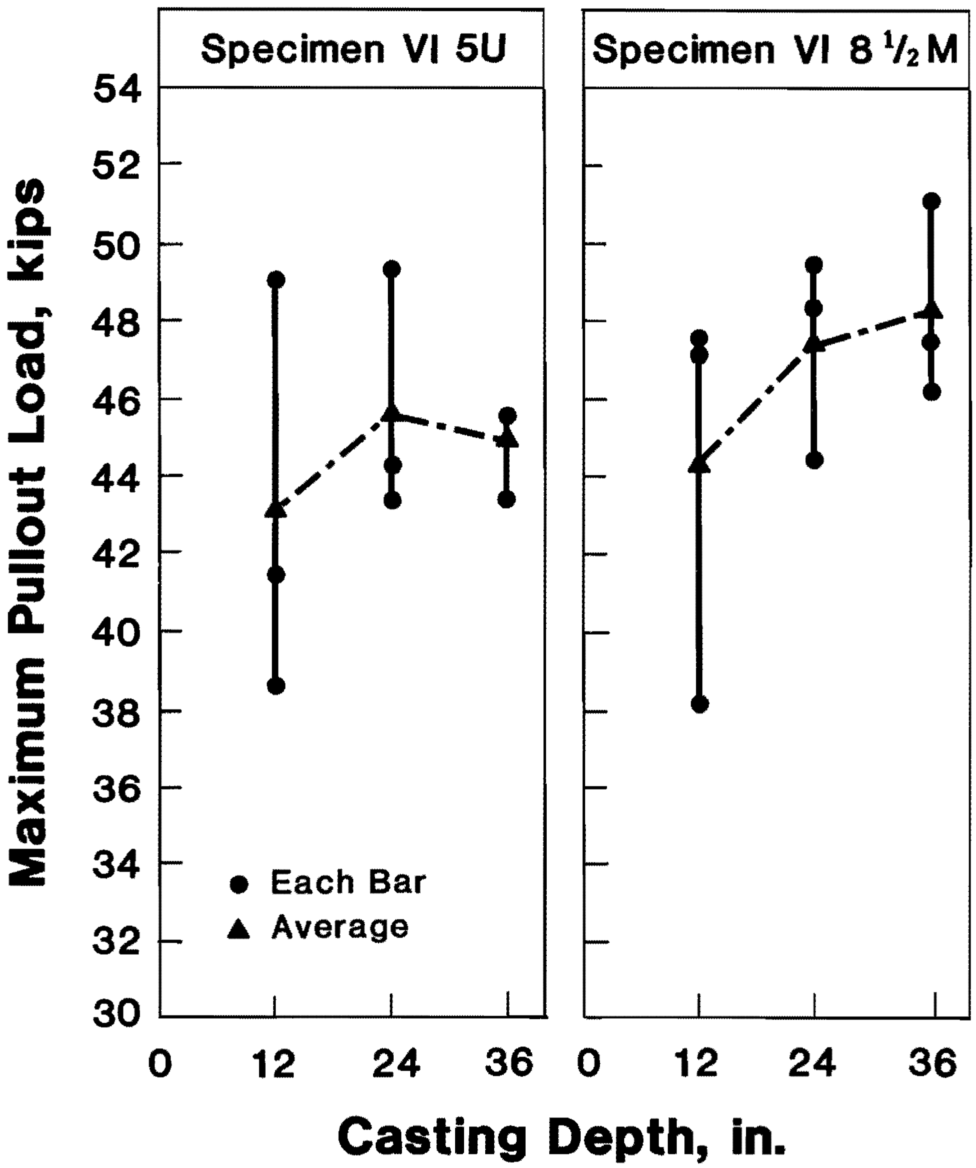



Fig. 6.37 Maximum pullout load versus casting depth for bars from Series VI

slump of the concrete before adding the superplasticizer. For a given slump, the maximum pullout load for bars embedded in concrete containing superplasticizer was higher than that for bars embedded in concrete containing no superplasticizer.

6.10.2 Effect of Bleeding of Concrete. The effect of bleeding of concrete on the bond pullout performance of reinforcing steel and concrete will be investigated through the use of maximum pullout loads normalized to account for variations in the tensile strength of concrete. The normalization of the loads was done based on the results of the split cylinder tests conducted for this research program.

In Series I, II, and III, the normalized maximum pullout loads for specimens containing superplasticizer were not lower than those for the control specimen in each series, as shown in Figs. 6.38 through 6.40. This was due to the relatively low bleed of all concretes, resulting from the older age and low slump of the control concrete. As discussed in Section 6.10.1, the increase in normalized maximum pullout load observed in Specimen II9M at a casting depth of 12 in. was attributed to better compaction of the concrete, and not to the effect of bleed.

The normalized maximum pullout loads versus casting depth for the bars from Series V are shown in Fig. 6.41. In this series of specimens, the slump of the control concrete was increased from 5-1/2 in. to 9 in. using naphthalene-based superplasticizer. The total bleeding of the concrete for specimens V5-1/2U and V9N, measured during the bleed tests, was 59 ml and 68 ml, respectively. Although no conclusions can be drawn concerning the effect of casting depth on the pullout behavior of either specimen, it is clear from the figure that the increased bleeding caused by the addition of naphthalene-based superplasticizer resulted in a reduction in the normalized maximum pullout loads of Specimen V9N.

Figure 6.42 shows the normalized pullout test results versus casting depth for the bars from Series VI, in which the slump of the control concrete was increased from 5 in. to 8-1/2 in. with the addition of melamine-based superplasticizer. Although the bleeding of the concrete decreased with the addition of the superplasticizer, being 114 ml and 84 ml for Specimens VI5U and VI8-1/2M, respectively, it was the highest observed in all specimens tested. As a result of the high bleed in both the control concrete and the concrete containing superplasticizer, there was no significant different in the normalized maximum pullout load between specimens. However, in comparing the normalized test results from Series VI to those of the other series, including Series IV shown in Fig. 6.43, the normalized maximum pullout loads in Series VI were the lowest, due to the high bleed of the concrete.

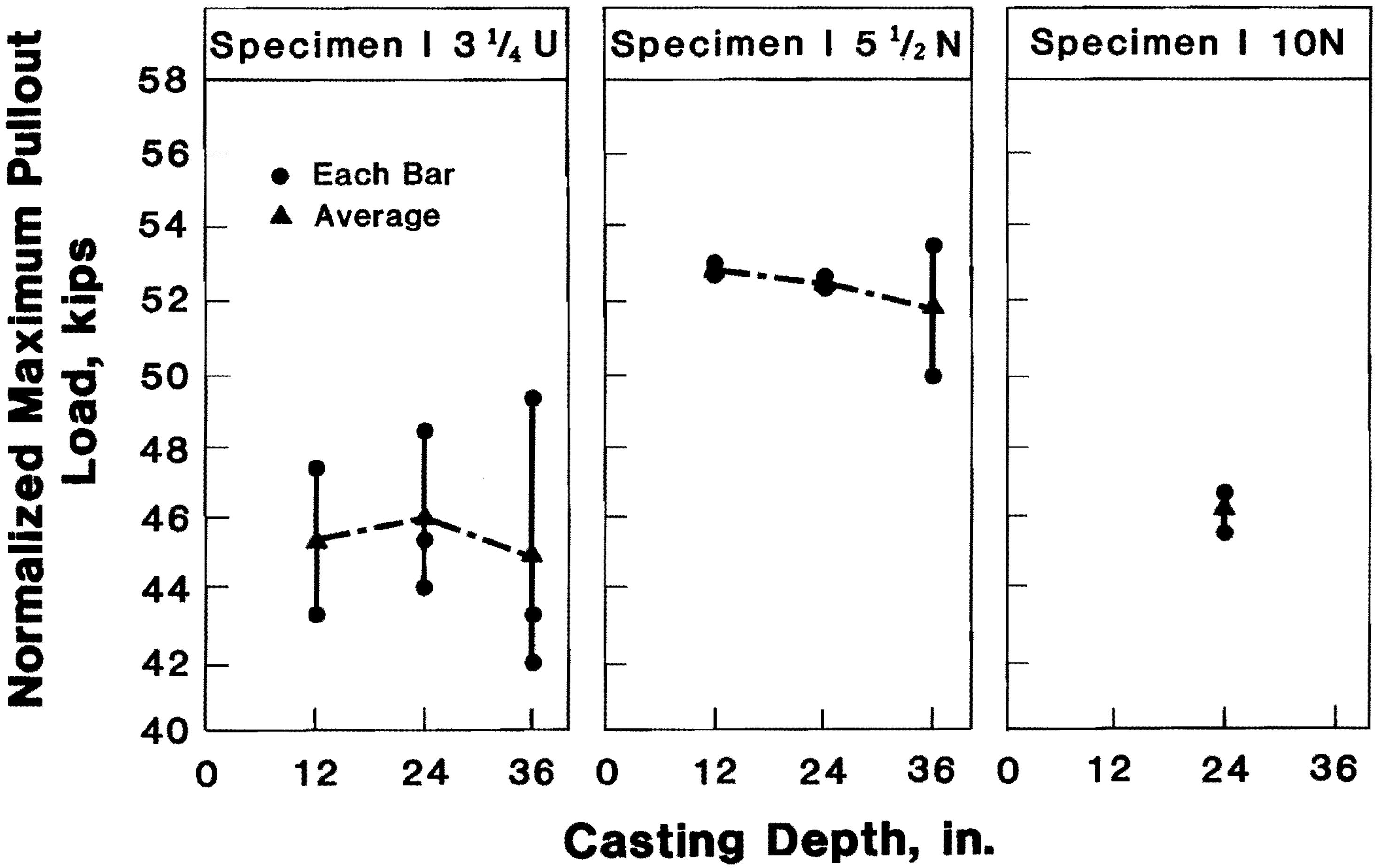



Fig. 6.38 Normalized maximum pullout load versus casting depth for bars from Series I

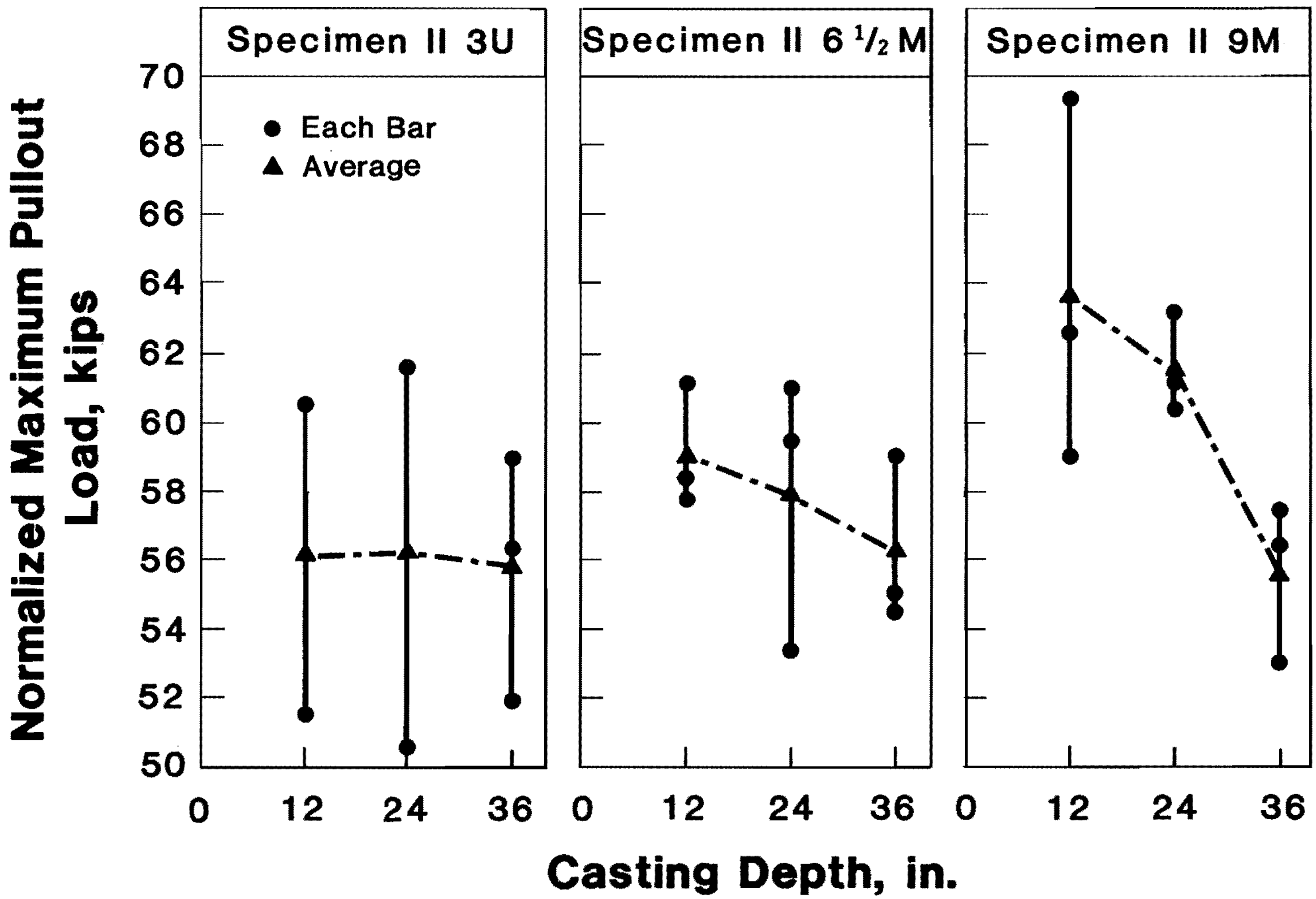



Fig. 6.39 Normalized maximum pullout load versus casting depth for bars from Series II

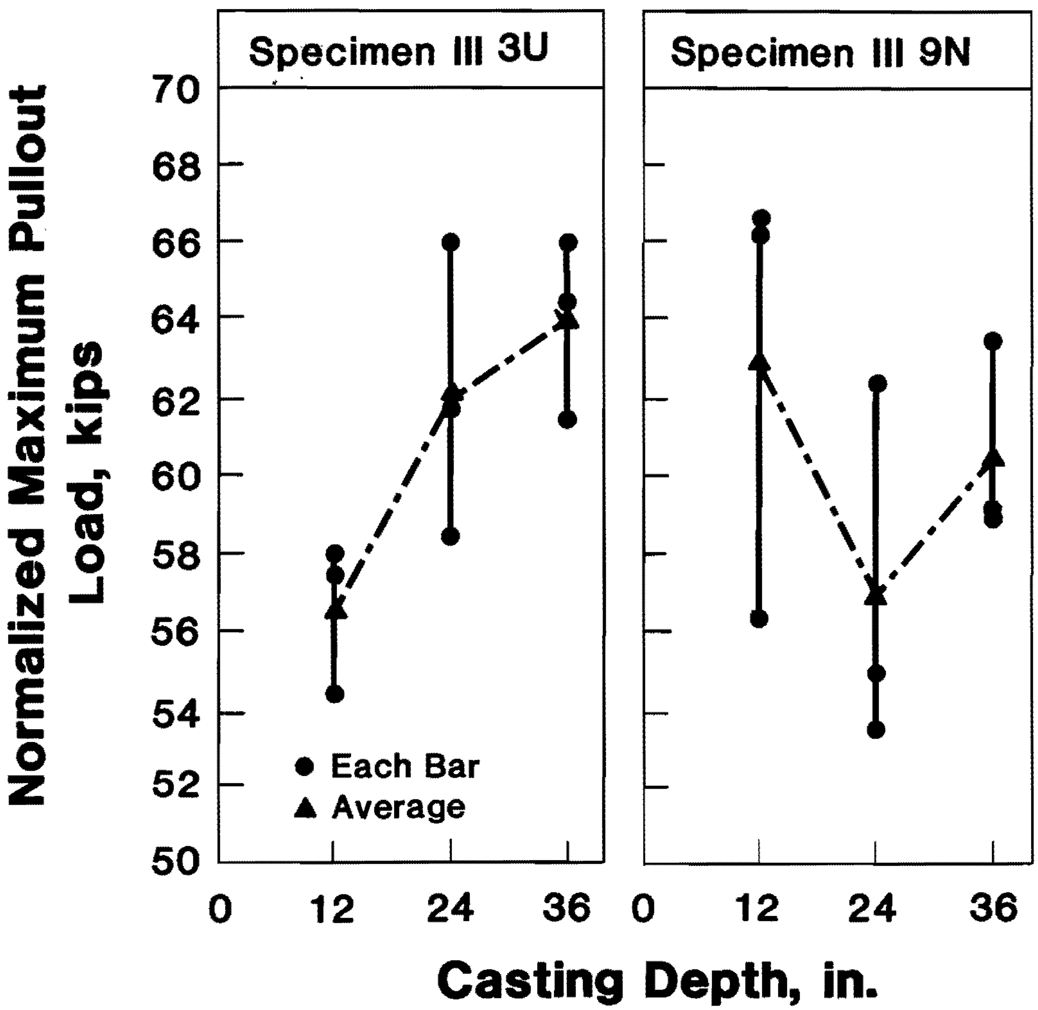



Fig. 6.40 Normalized maximum pullout load versus casting depth for bars from Series III

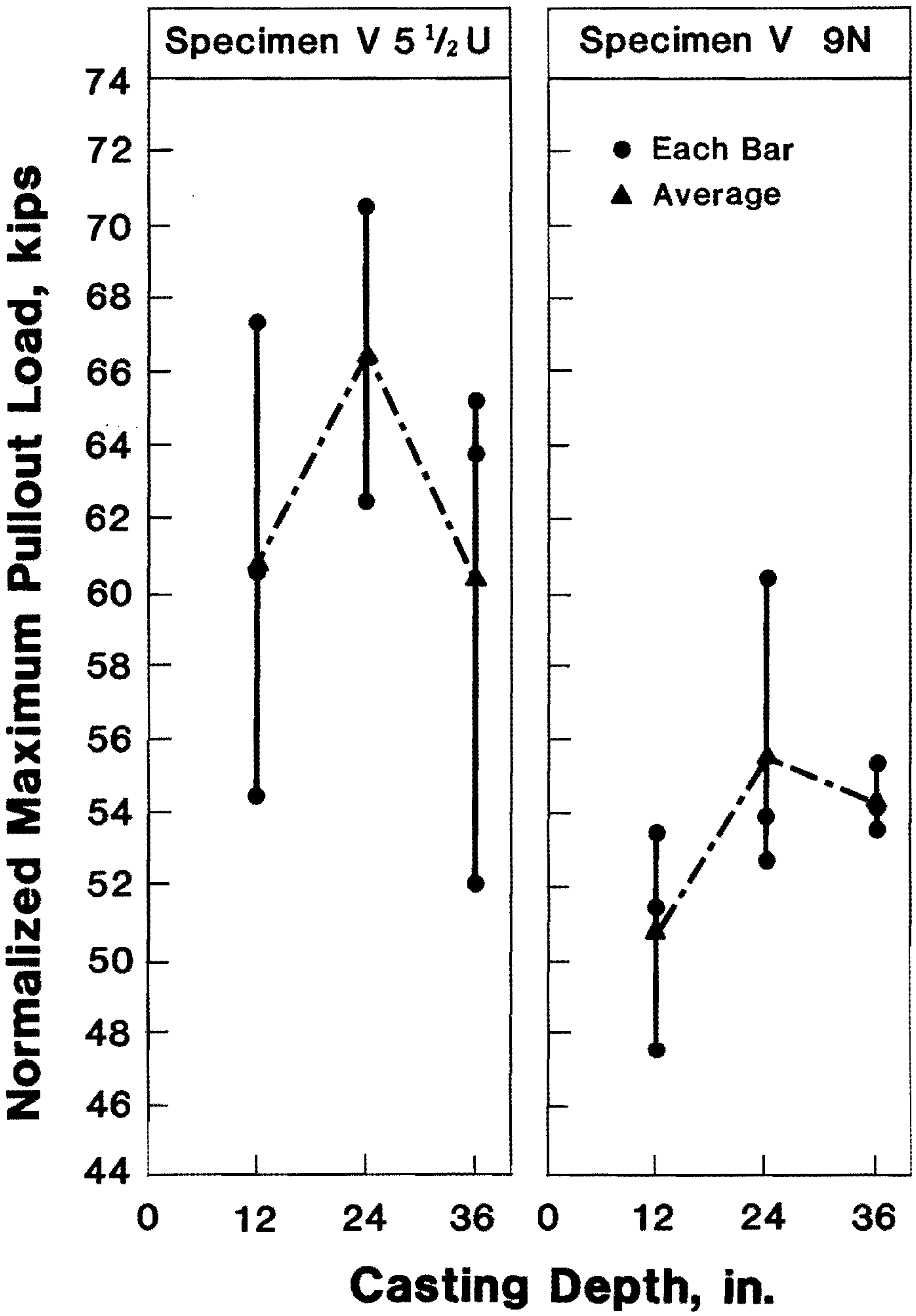



Fig. 6.41 Normalized maximum pullout load versus casting depth for bars from Series V

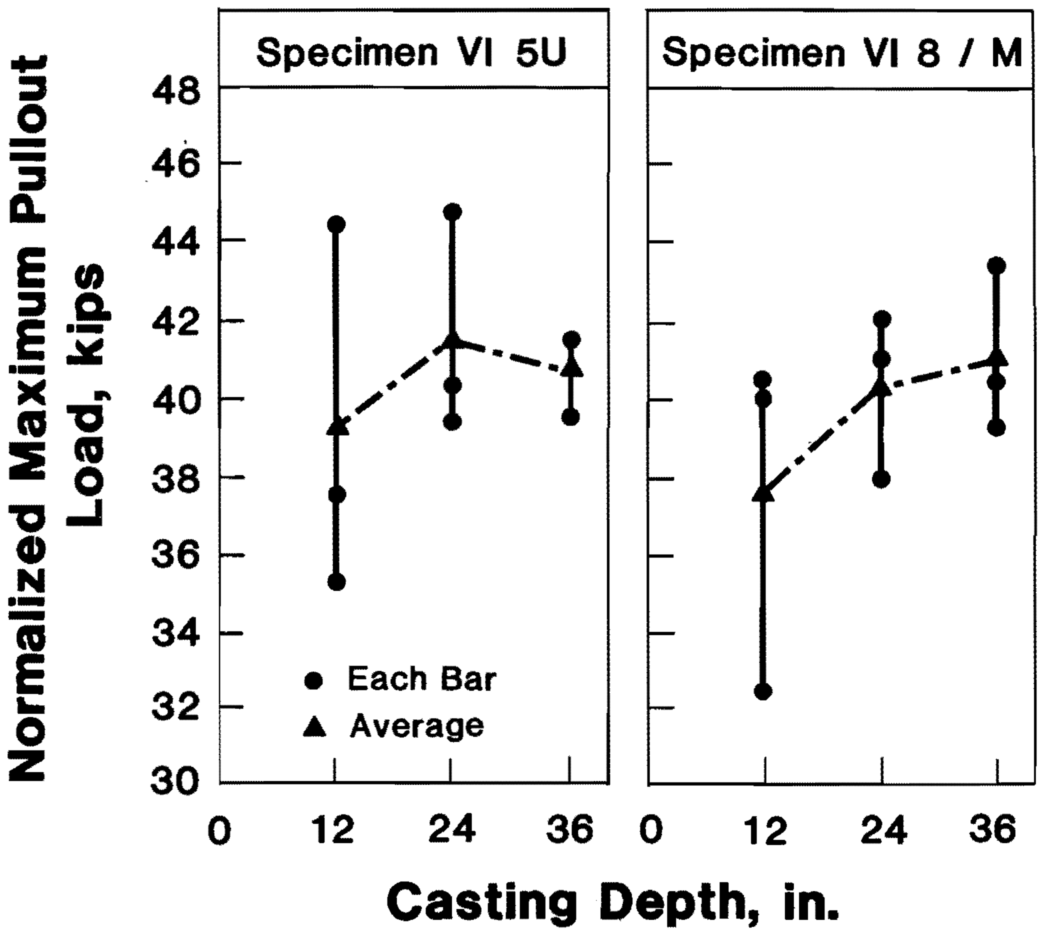



Fig. 6.42 Normalized maximum pullout load versus casting depth for bars from Series VI

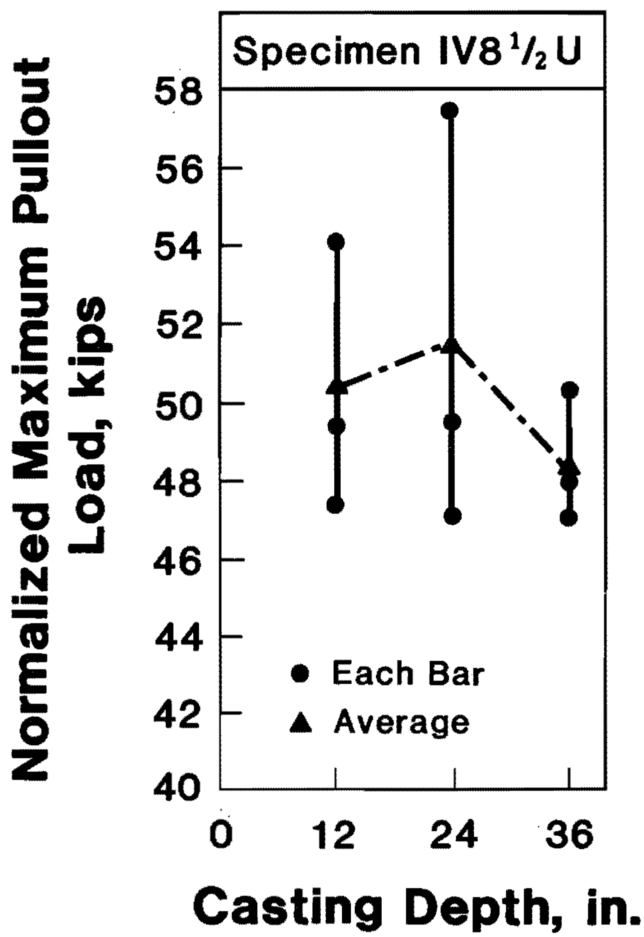



Fig. 6.43 Normalized maximum pullout load versus casting depth for bars from Series IV

# CHAPTER 7

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDY

### 7.1 Summary

The main objective of this investigation was to determine if the use of superplasticizer to produce high slump concrete affects the bond performance of deformed bars embedded in concrete. Pullout tests were conducted on 13 specimens, each with 9 pullout bars, to investigate the effect of superplasticizer on the bond between the concrete and reinforcement. The variables studied included:

a) slump of concrete before adding superplasticizer;

b) slump increase induced using superplasticizer;

c) type of superplasticizer;

d) dosage rate of superplasticizer;

e) compressive strength of the concrete with and without superplasticizer;

f) tensile strength of the concrete with and without superplasticizer;

g) bleed characteristics of the concrete with and without superplasticizer;

h) casting depth; and

i) compressive strength of the concrete as a function of casting depth.

### 7.2 Conclusions

Based on the results obtained from the present investigation, the following conclusions can be drawn:

1. The bond between reinforcing steel and concrete is not decreased by the addition of either naphthalene- or melamine-based superplasticizer when added to concrete as workability agents.

2. For a given slump, the maximum pullout load for bars embedded in concrete containing superplasticizer is higher than that for bars embedded in concrete containing no superplasticizer.

3. The dosage of superplasticizer required to increase the slump of concrete to a given value increases as the age of the concrete at the time of addition increases.

4. The total bleed of the concrete decreases as the age of the concrete at the start of the bleed test increases.

5. The addition of naphthalene-based superplasticizer to air entrained concrete resulted in a decrease in total air content.

6. The addition of melamine-based superplasticizer to air entrained concrete did not affect the total air content.

7. The addition of naphthalene-based superplasticizer to concrete increased the bleeding of that concrete.

8. The addition of melamine-based superplasticizer to concrete did not increase the bleeding of that concrete.

9. The addition of either naphthalene- or melamine-based superplasticizer to concrete increased the compressive strength of that concrete. However, the strength increase resulting from the addition of naphthalene-based superplasticizer is much greater than that due to the addition of melamine-based superplasticizer.

10. The addition of naphthalene-based superplasticizer to concrete increases the splitting tensile strength of that concrete.

11. The addition of melamine-based superplasticizer to concrete had a negligible effect on the splitting tensile strength of that concrete.

## 7.3 Recommendations for Further Research

Based on the findings of the study presented herein, the following directions for further investigation are suggested:

1. Study the potential use of superplasticizer for decreasing the required development length of reinforcing steel in concrete, especially in heavily reinforced areas where superplasticizer is added to facilitate placement and consolidation of the concrete.

2. Study the effect on the bond pullout behavior of steel in concrete when superplasticizer is added within 5 minutes after initial mixing.

3. Study the effect on the bond pullout behavior of steel in concrete when superplasticizer is used to produce a concrete of given strength having a lower cement content.

# APPENDIX A

## DETERMINATION OF REQUIRED EMBEDMENT LENGTH OF PULLOUT BARS

## A.1 Explanation of Governing Equations

Three equations were used to describe the behavior of the test specimens, one equation for each possible failure mode. These equations are discussed in the following sections.

A.1.1 Yielding of Pullout Bar. The minimum load at which yielding of the pullout bar will occur is given by:

$$P_y = A_s \cdot f_y \tag{A.1}$$

where: $P_y$ = minimum load required to produce yielding of bar,

$A_s$ = nominal cross-sectional area of bar, and

$f_y$ = nominal yield strength of bar.

A.1.2 Conical Failure of Surrounding Concrete. The load at which conical failure of the surrounding concrete will occur is given by:

$$P_c = \Pi \cdot f_t \cdot [\ell_e/\tan\alpha] \cdot [\ell_e/\tan\alpha + d_b] \tag{A.2}$$

where: $P_c$ = load required to produce conical failure of the surrounding concrete,

$f_t$ = tensile strength of the concrete,

$\ell_e$ = embedment length of bar,

$\alpha$ = angle of inclination of conical failure surface, and

$d_b$ = nominal diameter of bar.

A schematic representation of the conical failure surface is given in Fig. A.1.

A.1.3 Shear Bond Failure. The load at which shear bond failure will occur is given by:

$$P_{SH} = \ell_e \cdot \pi \cdot d_b \cdot u \tag{A.3}$$

where: $P_{SH}$ = load at occurrence of shear bond failure,

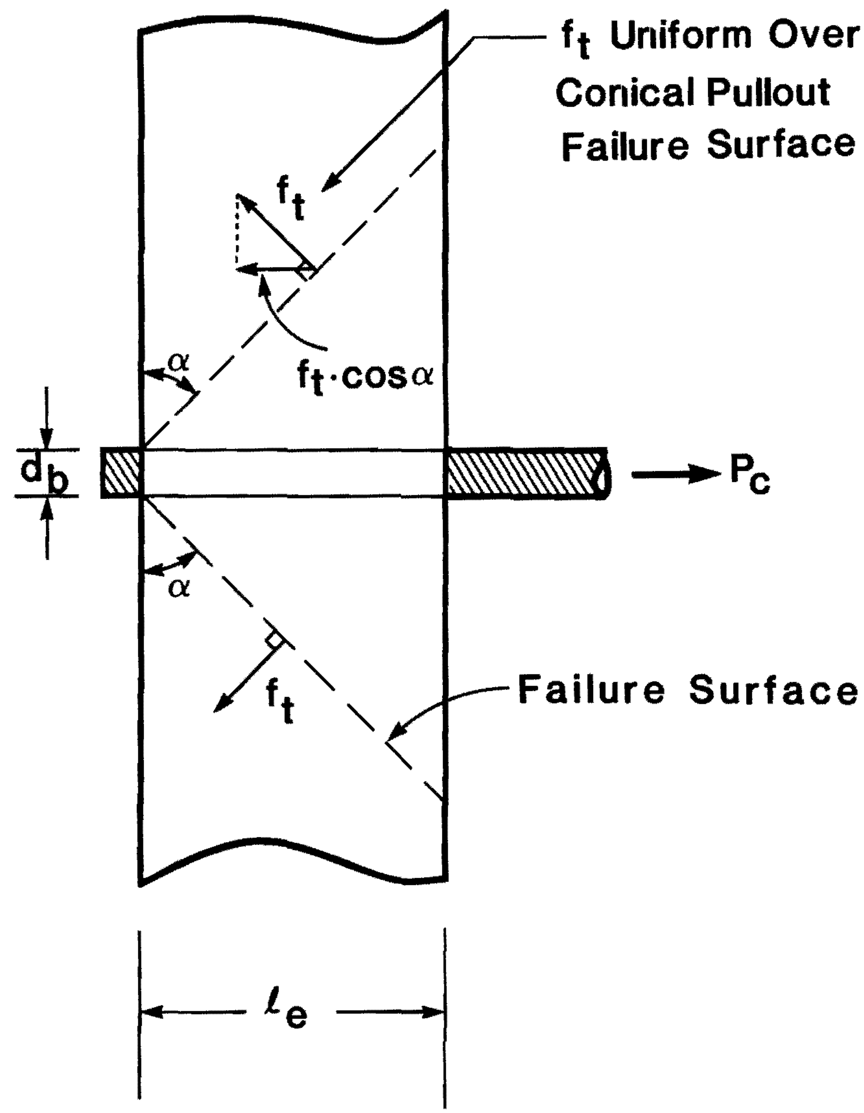



Fig. A.1 Schematic representation of conical pullout failure surface

$\ell_e$ = embedment length of bar,

$d_b$ = nominal diameter of bar, and

u = uniform nominal shear bond strength along embedment length of bar.

A schematic representative of shear bond failure is given in Fig. A.2.

## A.2 Calculation of Embedment Length

In order for the pullout tests to result in shear bond failure, the embedment length was calculated so that the bond failure load would lie between the yielding load and the conical failure load reduced by a capacity reduction factor $\phi$. To set these limits, Eq. A.3 was combined with both Eq. A.1 and Eq. A.2, resulting in the following two equations:

$$\ell_e \cdot \pi \cdot d_b \cdot u \leq A_s \cdot f_y \qquad \text{(A.4)}$$

and

$$\ell_e \cdot \pi \cdot d_b \cdot u \leq \phi \cdot \pi \cdot f_t \cdot [\ell_e/\tan\alpha] \cdot [\ell_e/\tan\alpha + d_b] \qquad \text{(A.5)}$$

where $\phi$ = capacity reduction factor.

Rearranging Eqs. A.4 and A.5 gives:

$$\ell_e \leq [A_s \cdot f_y]/[\pi \cdot d_b \cdot u] \qquad \text{(A.6)}$$

and

$$\ell_e \leq \tan\alpha \cdot d_b \cdot [(u \cdot \tan\alpha)/(\phi \cdot f_t) - 1] \qquad \text{(A.7)}$$

The values of the other terms in the equations were taken as follows:

$A_s$ = 1.00 in.$^2$ (#9 bar)

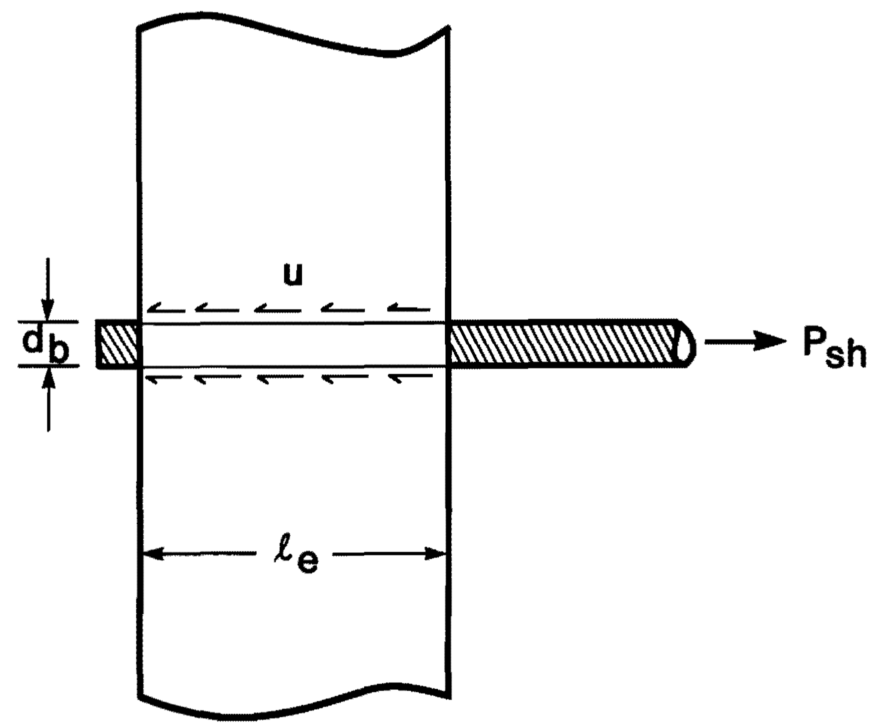



Fig. A.2 Shear-bond failure

$f_y$ = 60.0 ksi

$d_b$ = 1.128 in. (#9 bar)

$\alpha$ = $45^o$ [29]

$f_t = 4\sqrt{f'_c}$, psi

$u = 15\sqrt{f'_c}$, psi

Choose $f'_c$ = 6000 psi.

Substituting the above values into Eqs. A.6 and A.7 results in the following limits for the embedment length:

$$[4.23 \text{ in.}/\phi] - 1.128 \leq \ell_e \leq 14.6 \qquad \text{(A.8)}$$

An embedment length of 8 in. was consistent with a capacity reduction factor, $\phi$, of 0.5. Thus, an embedment length of 8 in. was found to satisfy the equations governing the pullout test behavior.

# APPENDIX B

# CORRECTION PROCEDURE FOR APPLIED LOAD VERSUS LOADED END SLIP CURVES

The curve shown in Fig. B.1 is that of applied load versus loaded-end slip, before correction. The correction is applied by passing a line through the point at which slip commenced and extending it in a smooth curve to a point of zero load, as shown by the dotted line in Fig. B.2. This locates a new origin, and results in the corrected curve shown in Fig. B.3.

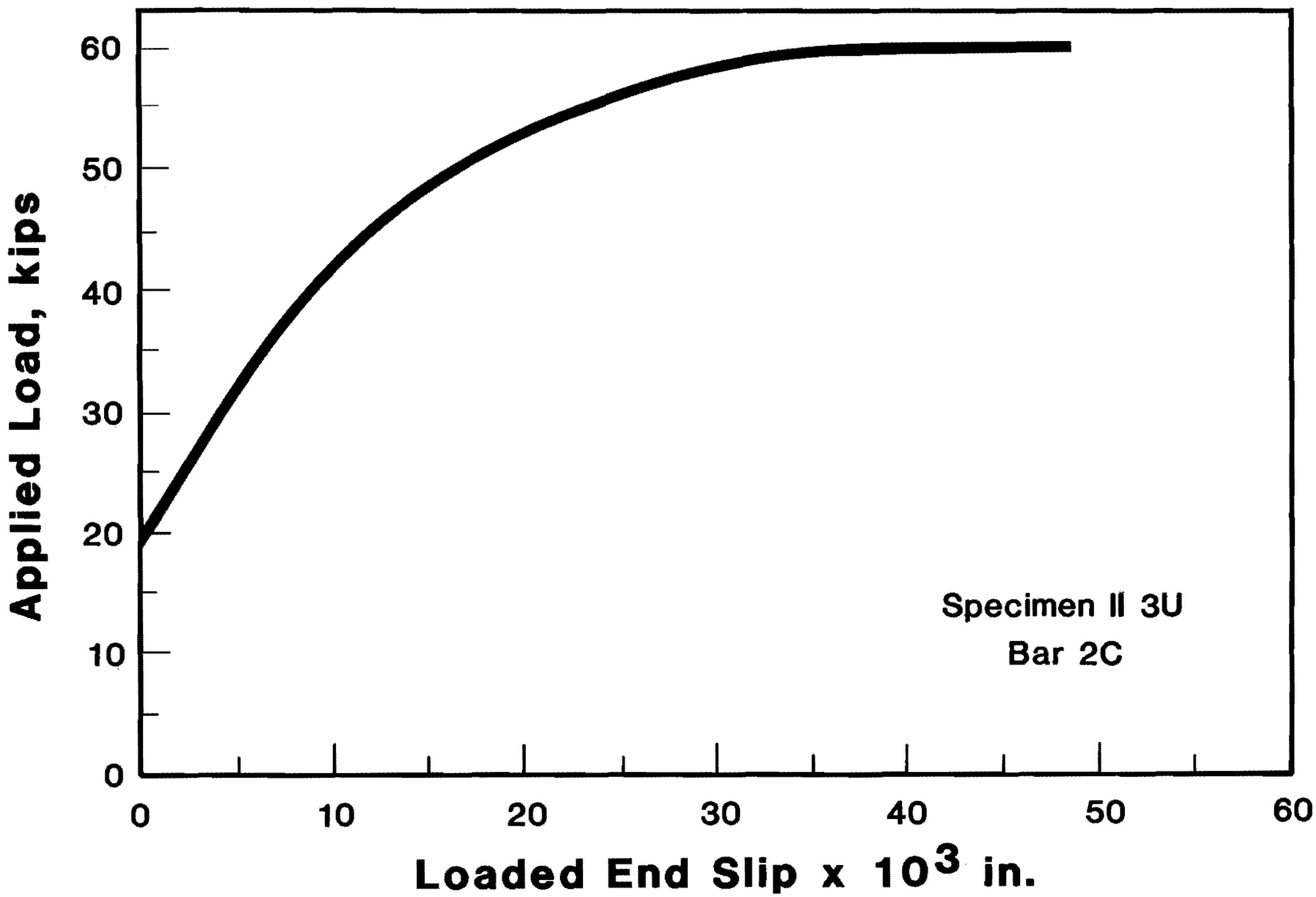



Fig. B.1 Loaded end slip curve before correction

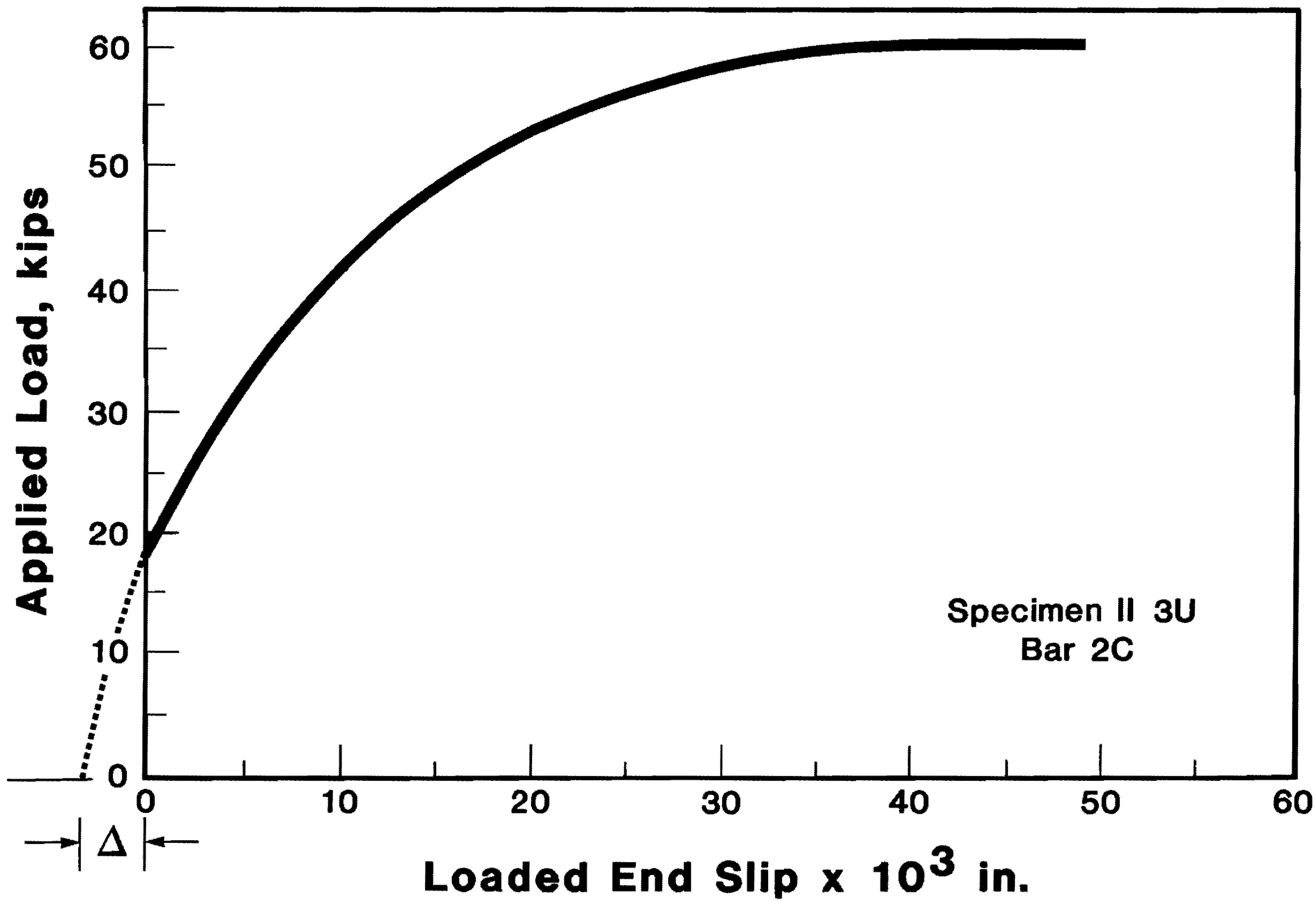



Fig. B.2 Correction to loaded end slip curve

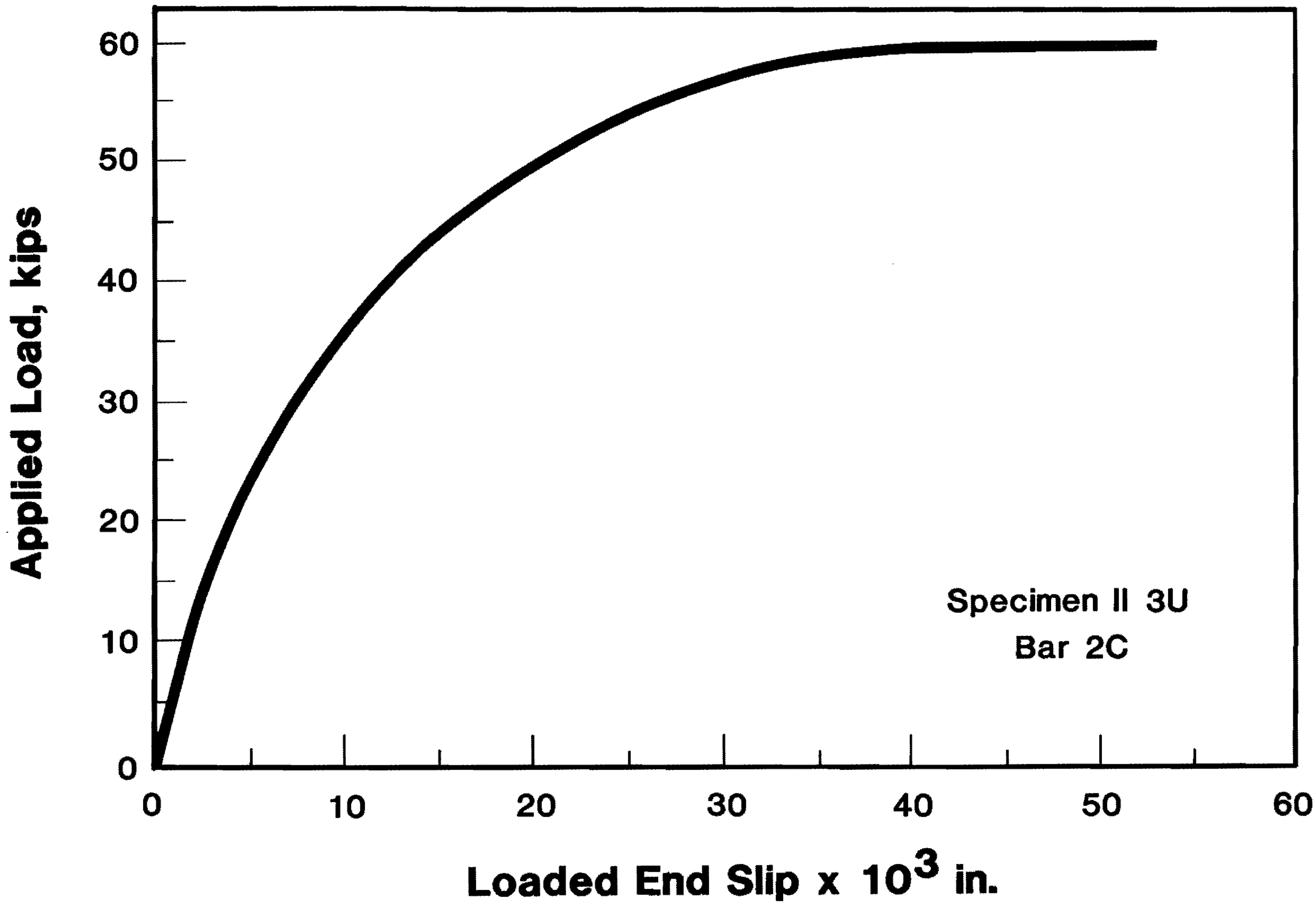



Fig. B.3 Corrected loaded end slip curve

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