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16. Abstract

Superplasticizers, or high-range water-reducing admixtures, are currently being used mostly in precast plants, and also in 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 of the many material properties of concrete affected by the addition of superplasticizer may be relevant to the concrete-reinforcing steel bond performance.

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EFFECT OF SUPERPLASTICIZERS ON THE BOND BEHAVIOR OF REINFORCING STEEL IN CONCRETE MEMBERS

by

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and J. O. Jirsa

Research Report No. 383-2F

Research Study No. 3-5-84-383

"Anchorage and Development of Reinforcement in
Concrete Made Using Superplasticizers"

Conducted for

Texas
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In Cooperation with the
U.S. Department of Transportation
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by

CENTER FOR TRANSPORTATION RESEARCH
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THE UNIVERSITY OF TEXAS AT AUSTIN

November 1985

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

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

Superplasticizers, or high-range water-reducing admixtures, are currently being used mostly in precast plants, and also in 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 hae been reported on the structural aspects of superplasticized concrete. The main objective of this research program is to determine which of the many material properties of concrete affected by the addition of superplasticizer may be relevant to the concrete-reinforcing steel bond performance.

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SUMMARY

The main objective of the work described herein is to determine if the use of superplasticizing admistures to produce high slump concrete affects the bond performance of deformed bars embedded in that concrete.

A research program was developed which would allow the study of the effect of a naphthalene-based superplasticizer on the material properties of concrete, and on the bond behavior of the reinforcement. Bond behavior was studied through development and splice tests, in which the applied load and corresponding slips at the free and loaded ends were measured. Forty-five development and 27 sphere tests of #8 Grade 60 deformed bars were run. Eighteen development tests of Grade 270 1/2 in. 7 wire tendons were conducted. Top cast bars at different heights were compared with bottom cast bars. The temperature of the concrete at casting (58° and 78°) was varied. Low-slump and high-slump (with and without the addition of superplasticizer) concrete were used. Special bleed tests were run to correlate bleed, slump, and bond performance.

The results of this study indicated that the addition of naphthalene-based superplasticizer to concrete did not detrimentally affect the bond performance of reinforcing steel embedded in that concrete. High-slump superplasticized concrete performed better in bond than high-slump water-based concrete.

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IMPLEMENTATION

The results of this study indicate that the bond strength was not adversely affected by the use of naphthalene-based superplasticizers. High-slump concrete produced using superplasticizers performed better in bond than high-slump concrete produced by introducing water only. However, the effect of superplasticizing admixtures on the material properties of concrete is highly dependent on the concrete age and temperature at the time the admixture is introduced. It may also be dependent on the placement techniques used. 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 Aims of the Research

The aim of this research is to evaluate the effects of high range water-reducing additives (superplasticizers) on the bond performance of reinforcing steel in concrete. The factors which accentuate the influence of the superplasticizer are examined; namely, temperature and casting positions. Both development and splice tests were conducted. Special attention is given to determining the role of segregation and bleed on bond performance.

1.2 Mechanics of Bond

In a reinforced concrete member, concrete usually resists compressive stresses, and steel reinforcing bars resist tensile stresses. Since reinforcing bars are cast inside the member, loading is applied on the concrete and tensile stresses are transferred internally to the steel. The force by which such stress transfer takes place is referred to as bond. The mechanism of bond can be classified by the relative displacement, or slip, between bar and surrounding concrete. In Fig. 1.1 is shown a typical local bond stress-slip relationship measured in a slip controlled test. Slip is caused partly by elastic deformations of the concrete, but, mainly (particularly at higher loads) by crushing of the concrete in front of the ribs. Up to a limited specific bond stress, no slip occurs. The force is transferred by adhesive or chemical bond. After slip occurs a very different mechanism takes over, whose nature depends on the type and characteristics of the surface irregularities of the reinforcing bar.

For deformed bars, adhesion and friction play only a minor role and bond results mainly from the bearing of the bar deformations (lugs) against the concrete. The component of the rib (lug) forces ($\tau^* \tan\alpha$ in Fig. 1.2) which acts radially with respect to the bar axis, loads the concrete with an internal pressure. The tensile hoop stresses so induced cause splitting cracks along the anchored bar. The radial stress can be considered as a uniform internal pressure acting on a thick-walled cylinder having an inner diameter equal to the bar diameter and a thickness C equal to the smaller of (1) the clear concrete cover, C_b; or (2) half the clear spacing, C_s, between the bar in consideration and an adjacent equally stressed bar (see Fig. 1.3). When the concrete tensile capacity is reached, splitting cracks will develop beginning at the bar surface. The type of

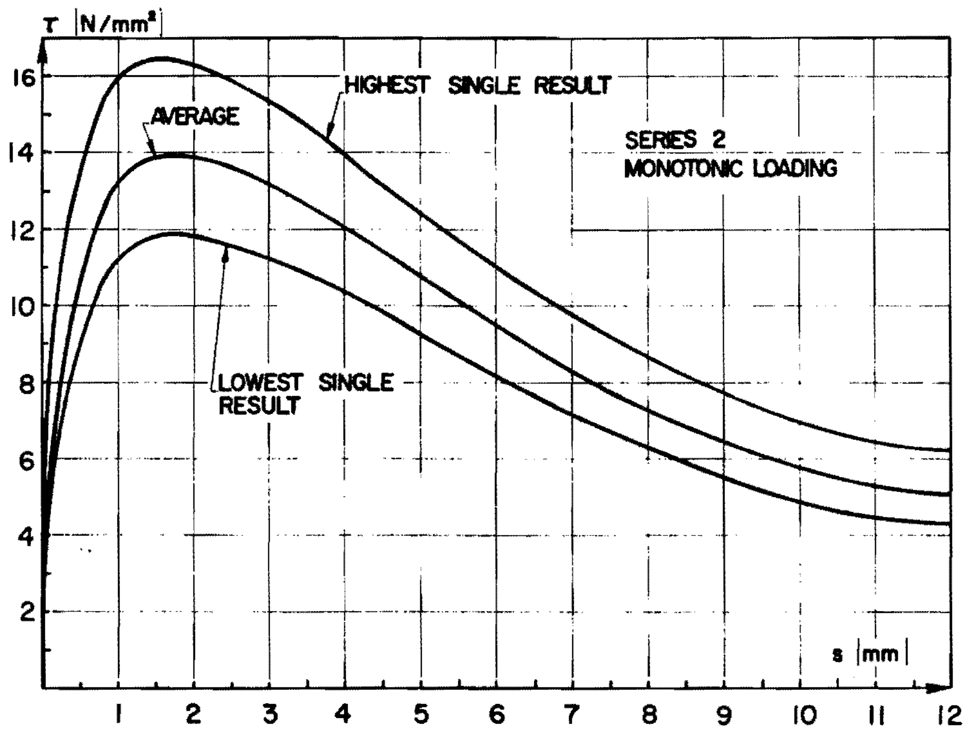


Fig. 1.1 Typical local bond stress-slip relationship measured in a slip-controlled test [16].

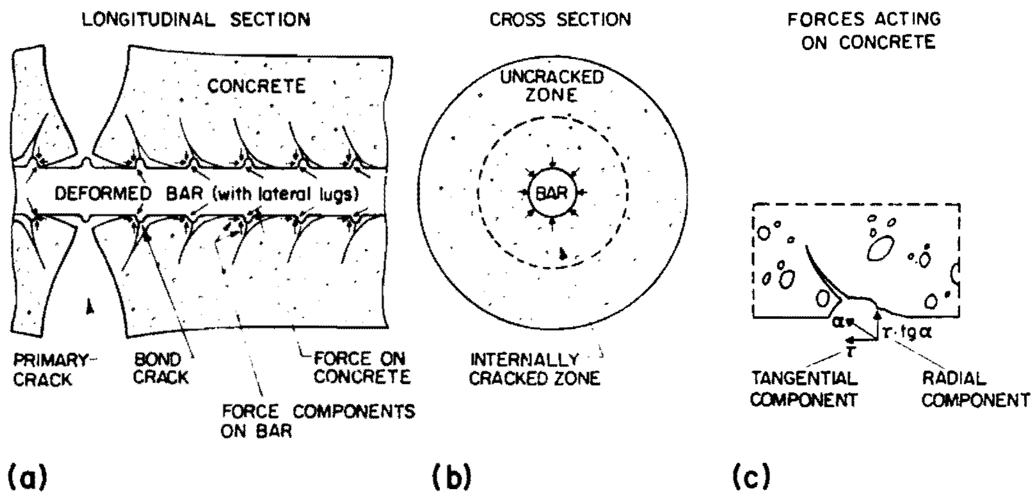


Fig. 1.2 Internal bond cracks and forces acting on concrete [20].

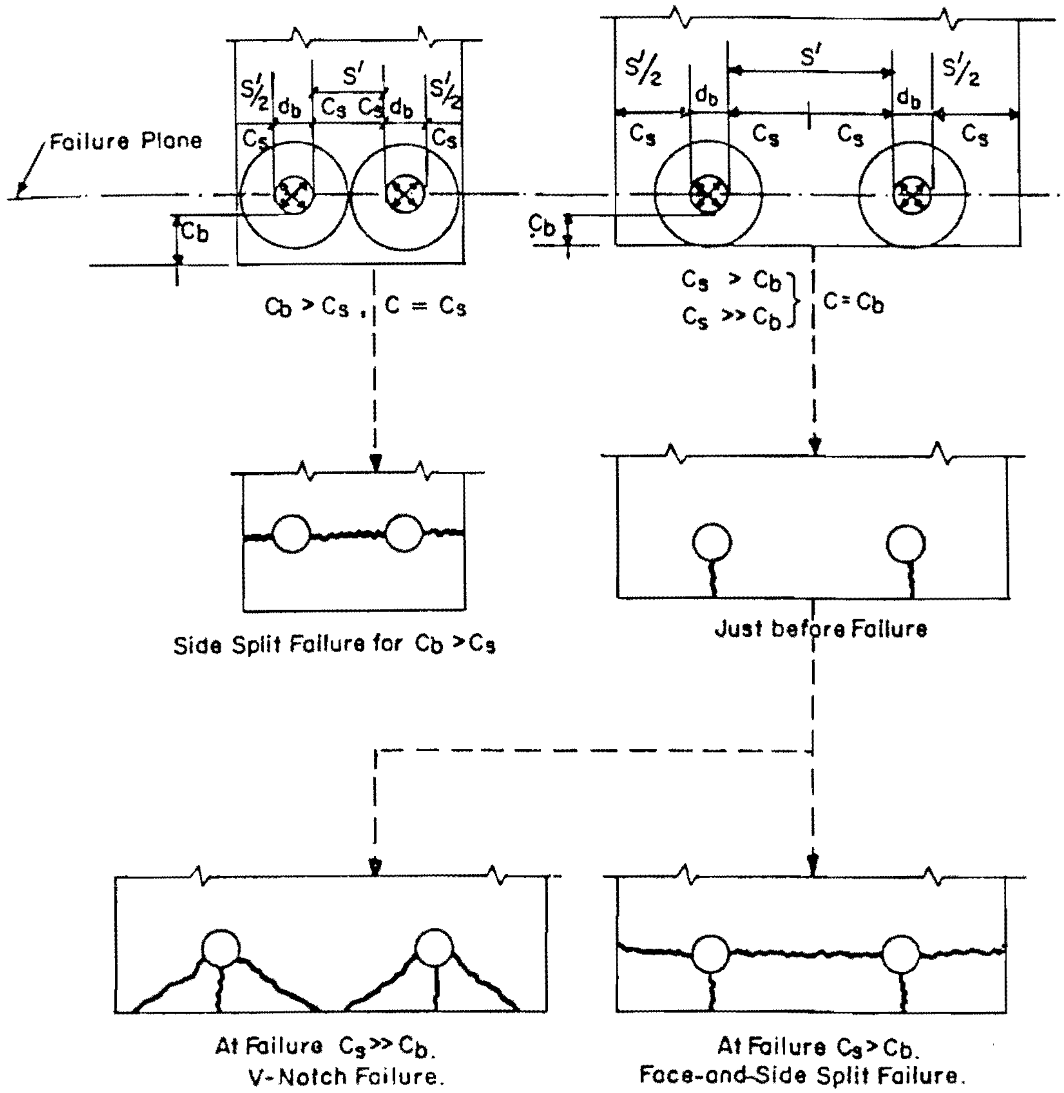


Fig. 1.3 Failure patterns of deformed bars [38].

splitting that will take place depends on the ratio of C_b to C_s (see Fig. 1.3). In a lap splice where the bars are side by side, the two cylinders for each splice interact to form an oval ring, as shown in Fig. 1.4. The failure patterns are similar to those of single bars. A more complete review of the mechanics of bond is contained in Refs. 14 and 30.

1.3 Influence of Casting Position

The influence of bar position during casting on bond behavior has been recognized since 1913 [1], and has been subsequently reported by numerous researchers [9,10,11,13,15,18,21,19,30,32,35,41]. Nonetheless, the top bar factor in the ACI Code has remained essentially the same since 1951, along with the definition of a top bar. Top bars are defined as horizontal bars so placed that more than 12 in. of concrete are cast below the bars.

Bond strength and bond stiffness are highest for bars oriented vertically during casting and loaded against the settling direction of concrete, or for bars oriented horizontally near the bottom of the specimen (Fig. 1.5). Bars oriented vertically and loaded in the settling direction of the concrete, and bars oriented horizontally well above the bottom of the formwork or the lift of concrete show an inferior bond behavior compared to the first group. This difference in bond behavior can be explained by an accumulation of porous cement paste under the lower half of the bar (when oriented horizontally) or beneath the ribs (bars oriented vertically) and also by the settling of fresh concrete, which reduces the effective projection of the concrete lugs [14,30,41] (see Fig. 1.5).

Results reported by Luke, Hamad, Jirsa and Breen [29] indicate that bond behavior is not only influenced by the absolute depth of concrete beneath the bar, but also by the slump of fresh concrete. The higher the slump, the greater was the observed reduction in bond capacity as the depth of concrete increased. The slump was adjusted using water for all specimens. Development length modification factors recommended by Luke et al. [29] for casting position and concrete slump are shown in Fig. 1.6.

1.4 Superplasticizers

Superplasticizers (high range water reducers) are natural or artificial polymers, which may be grouped by their chemical composition in several categories. Superplasticizers are used as concrete admixtures to:

a) regulate concrete consistency

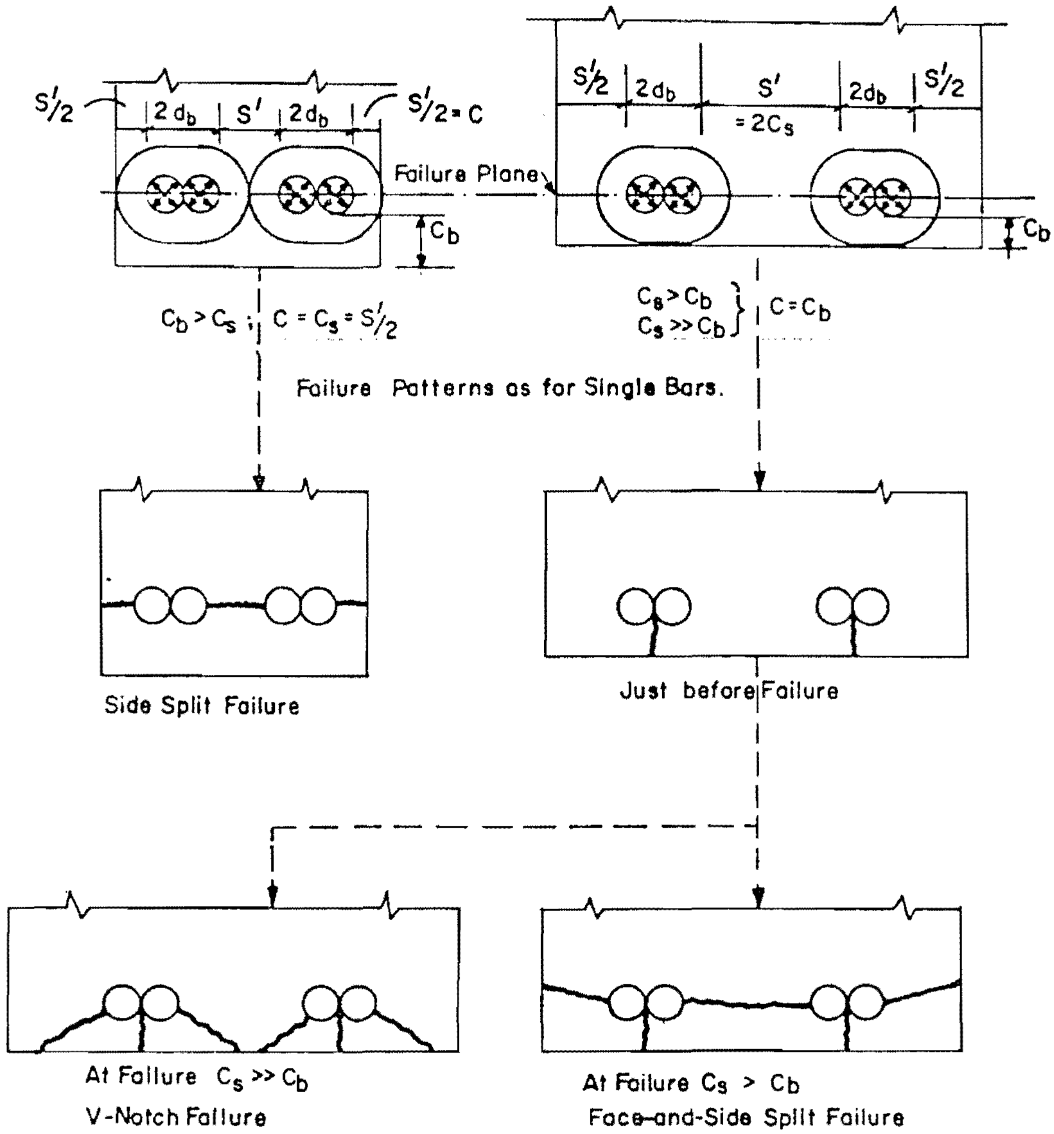


Fig. 1.4 Failure patterns of lapped splices [38].

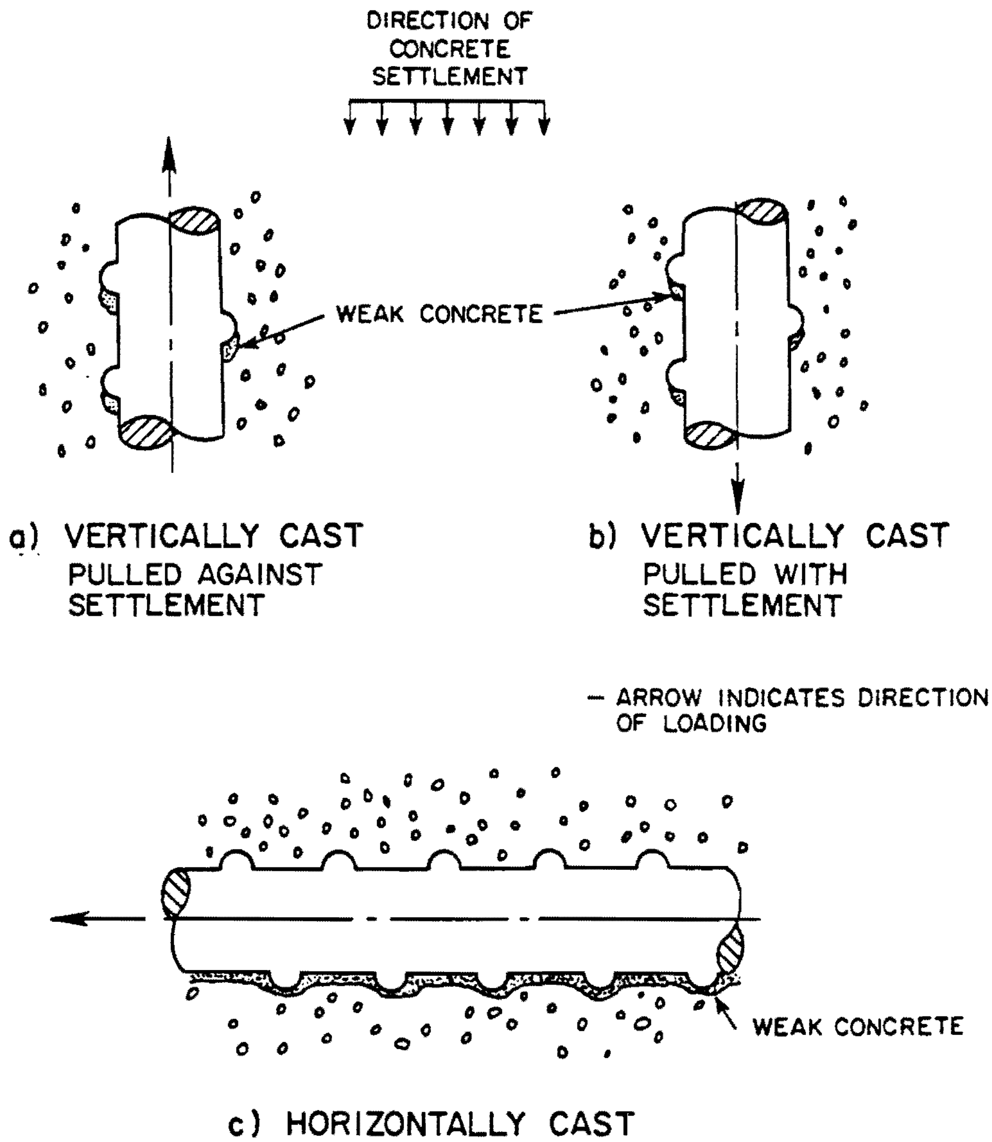


Fig. 1.5 Definition of casting position [30].

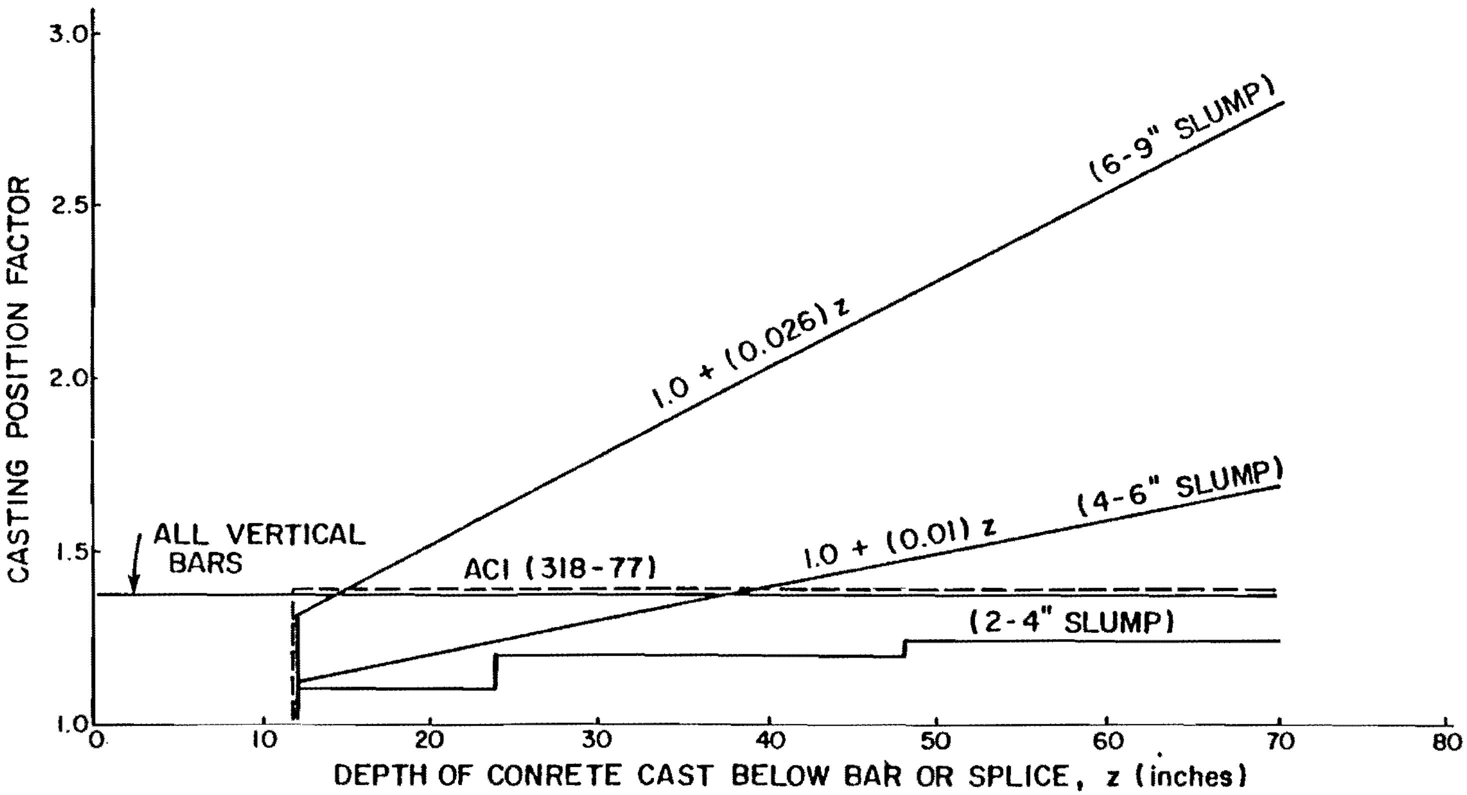


Fig. 1.6 Recommended casting position factors for all ranges of slump investigated [30].

b) produce flowing concrete; and

c) manufacture high-quality concrete having a low water-cement ratio.

Although superplasticizers have been in use in Japan since the 1960's and in Europe since the early 1970's, they were not introduced into North America until 1976. Three types of superplasticizer, all made from the salts of organic sulfonates, are currently available in North America:

1) sulfonated melamine formaldehyde condensates (melamine)

2) sulfonated naphthalene formaldehyde condensates (naphthalene)

3) modified lignosulfonates (lignin)

These superplasticizers are surface agents which are adsorbed onto the cement particles and disperse the cement agglomerates, as shown in Fig. 1.7. How this dispersive action is achieved, however, depends on 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.

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 are adsorbed onto the cement particles, the cement particles all become negatively charged and thus repel one another [33,35,36].

A review of the literature regarding the effects of superplasticizers on properties of fresh and cured concrete is contained in Refs. 35 and 36.

1.5 Bleed and Segregation

Fresh concrete consists of an unstable dispersion of coarse aggregates, sand and cement paste. The heavier coarse aggregates tend to settle, displacing the lighter water-cement paste. This process is known as segregation [7,25]. However, the coarse aggregate cannot settle freely. Bridging action of the aggregate stops the settlement (Fig. 1.8). As the water-cement paste moves upward, some of it is trapped under the coarse aggregate, forming a weak and porous zone [7] (Fig. 1.9). The rest of the water-cement paste rises to the surface as bleed water. Thus, there is some link between segregation and bleed. Before examining how segregation affects bond strength, it is worthwhile to review the factors affecting bleed.

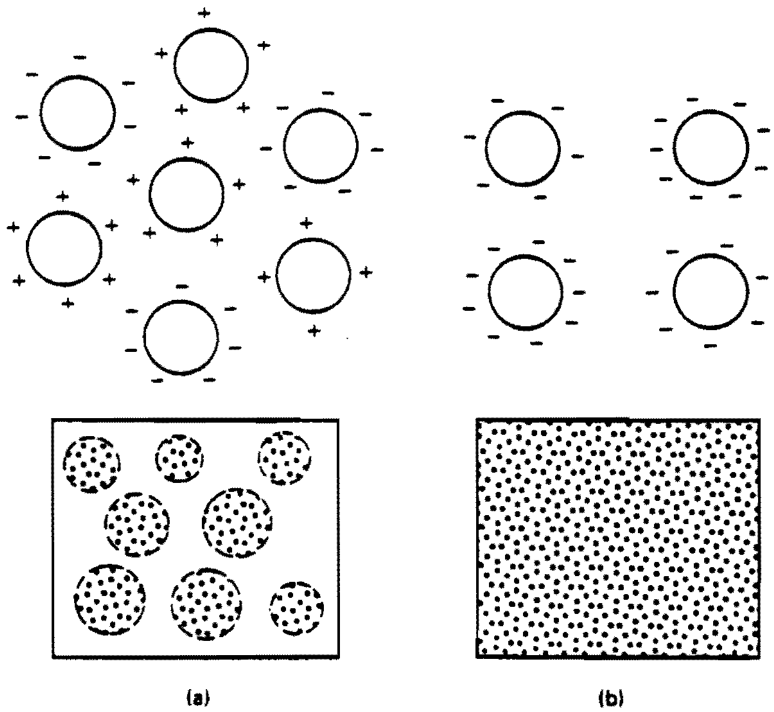


Fig. 1.7 Dispersing action of superplasticizer (schematic representation): (a) flocculated paste; (b) dispersed paste [35].

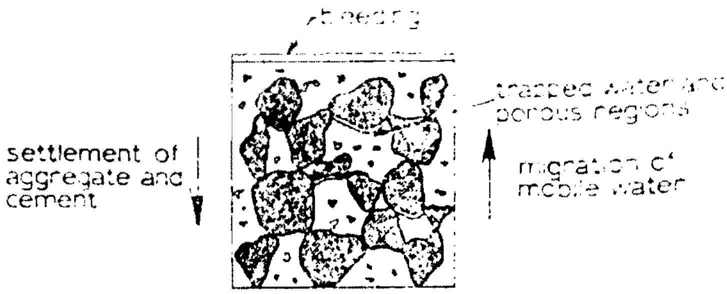


Fig. 1.8 Arching action of coarse aggregate during settlement [25]

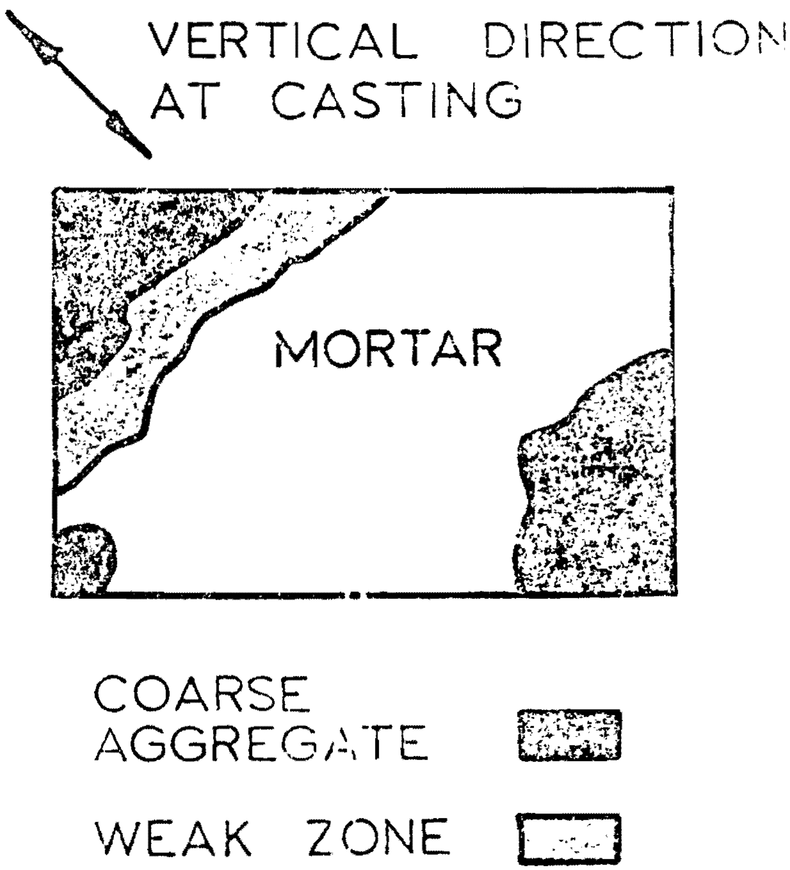


Fig. 1.9 Ground section showing weak pocket of mortar beneath a coarse aggregate particle (approx. magnification = X100) [7]

1.5.1 Factors Affecting Bleed of Concrete. Slump. The principal factor that determines bleed is the amount of free water in the mix, indicated by the slump (in the absence of admixtures) [5,9,35]. Generally, as the amount of free water increases, so does the slump, as well as the segregation and bleed.

Air-Entrainment. Entrained air has electrical charges on its outer surfaces which attract and trap the polar water molecules. Thus, bleed decreases as the percentage of air entrainment increases.

Maturity. Using standard ASTM tests, Musser [35] conducted bleed tests on concrete left in the mixer for various periods of time. At the end of each period, the concrete was dosed with superplasticizers, and bleed tests were conducted on that dosed cement. In undosed concrete, bleed decreases with concrete maturity. However, this was not necessarily so for dosed concrete. Although high bleed occurred with a time delay of 35 minutes, no decrease was observed at time delays of 60 and 95 minutes.

Superplasticizer. The effects of superplasticizers on the bleed of concrete at various ages were reported in Ref. 35. For delay periods of 30 and 55 minutes, no significant difference was observed between the bleed of dosed and undosed concrete. At a delay of 85 minutes, however, the dosed concrete bled significantly more than the undosed concrete. These results are attributed to the structure of the cement particles at the various periods of delay [35]. At 30 and 55 minutes, the hydration is still slow, whereas at 85 minutes hydration has proceeded far enough for the ettringite structure on the cement particles to trap some free water. Addition of superplasticizers at 30 and 55 minutes did not release extra free water; whereas dosage at 85 minutes did release some of the trapped water, causing increased bleed. Musser [35] also found that bleed increases with superplasticizer dosage.

Brettmann et al. [9] found that at a lower temperature (53^{o} F), superplasticized concrete bled more than non-superplasticized concrete. At higher temperatures, however, both superplasticized and non-superplasticized concrete bled almost equally. In some specimens, water was used instead of superplasticizers to achieve the high slump. In those cases, the high slump concrete bled more than low slump concrete at both high and low temperatures.

Specimen Height. Brettmann et al. [9] in measuring the bleed from the surface of the specimen found no significant differences in bleed as the height of the specimen was varied. In another test similar to that of Ref. 19, Altowaiji et al. [5] found that although bleed increased with height, the increase was insignificant.

Shima et al. [42] measured the bleed water on top of superplasticized concrete specimens 30, 60, and 90 cm in height (12, 24 and 36 in.). One of the specimens was cast in 10 cm (4 in.) rodded lifts. Another set was cast in one lift and vibrated. In both cases, bleed increased almost in proportion to the height of the specimen.

Temperature. The tests of Brettmann et al. [9] were carried out at temperatures of 53, 78 and 84 degrees F. The observed decrease in bleed with increased temperature was attributed to higher rates of hydration at high temperatures.

1.5.2 Effect of Specimen Height and Segregation on the Strength of Concrete. To investigate the effect of superplasticizer on the segregation of concrete, Lane and Best [28] cast standard 6 x 12 cylinders on a vibrating table and subjected them to 2, 5 and 10 sec of vibration. No noticeable segregation was observed. They reasoned that the dispersed cement in the superplasticized concrete effectively bound the available water so that bleeding and segregation were not increased, and the aggregates remained evenly distributed in the plastic concrete despite the extended vibrations.

Shima et al. [42] also studied the amount of segregation in superplasticized concrete specimens of various heights. Specimens were cast measuring 10 x 40 cm (4 x 16 in.) and having heights of 30, 60 and 90 cm (12, 24 and 36 in.) were cast. Some were cast in one lift and placed on a vibrating table for periods of 20, 30 and 40 sec. Others were cast in 10 cm (4 in.) rodded lifts. After bleeding stopped, 10 cm (4 in.) high blocks of concrete were cut from each specimen and analyzed to determine the quantity of coarse aggregate, and the amount of segregration at various heights. Figure 1.10 shows the results obtained. More coarse aggregate was observed at the bottom, and less at the top of the specimens, indicating that segregation was prominent in the superplasticized concrete. However, the most interesting observation is that the 90 cm (36 in.) specimen had a region containing a constant amount of coarse aggregate. In that region, coarse aggregate moving downward in the specimen was replaced by coarse aggregate settling from above.

Shima et al. [42] also sawed 10 cm blocks from different heights in each hardened specimen, and tested them in compression (Fig. 1.11). Due to increased segregation with height strength also decreased with height. However, for specimens 60 cm (24 in.) or taller, the strength increases again near the top of the specimen. This apparent anomaly was accounted for by examining the coarse aggregate distribution of Fig. 1.10. In the upper portions of tall specimens, the coarse aggregate remaining after segregation cannot trap as much bleed water as the greater amount of aggregate lower down in the specimen. Because less water is trapped near the top, the concrete there is stronger.

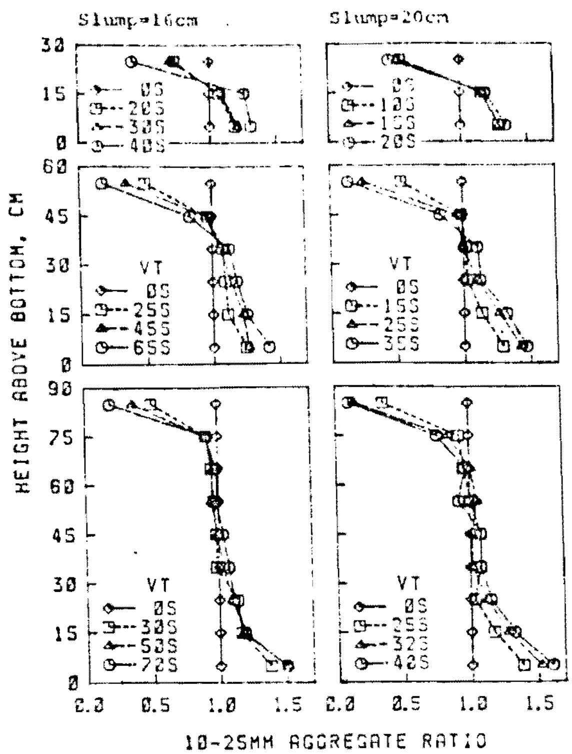


Fig. 1.10 Longitudinal distribution of 10-25mm aggregate content [42]

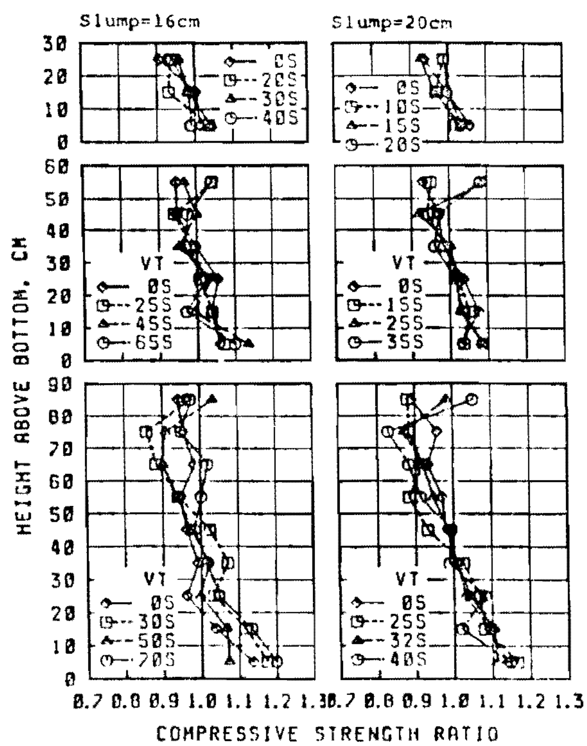


Fig. 1.11 Longitudinal distribution of compressive strength [42]

1.6 Bond Strength - Role of Superplasticizer

Numerous investigations have been reported in the areas of bond of reinforcement in non-superplasticized concrete. The material properties of superplasticized concrete were reviewed in previous sections. This section is devoted exclusively to a summary of investigations of the effect of superplasticizer on the bond behavior of reinforcing bars.

1.6.1 Collepardi and Corradi [12]. Tests of the steel-concrete bond of smooth and twisted bars were peformed as part of a broad study on the influence of superplasticizers on the strength of ordinary and lightweight concretes. Steel-concrete bond strength was measured at 7 and 28 days by determining the load necessary to pull out either smooth or twisted bars (20 mm diameter) cast in cylindrical concrete specimens.

Test results (Table 1.1) indicated substantial increase in steel-concrete bond strength by the addition of superplasticizer in both ordinary and lightweight concretes.

1.6.2 Brettmann, Darwin, and Donahey [9]. A study of the effects of superplasticizers on concrete-steel bond strength was conducted to evaluate the role of degree of consolidation, concrete slump, concrete temperature, and bar positon. Deformed reinforcing bars (#8) were used with a 2 in. cover and a 10 in. bonded length. Concrete slumps produced with both water and superplasticizer ranged from 1-3/4 in. to 9 in. Varying specimen depths were used. All specimens were modified cantilever beams (see Fig. 1.12).

The conclusions presented in the report were:

1) Vibrated, high slump concrete made with a superplasticizer has a lower bond strength than a low slump concrete of equal strength.

2) Vibrated, high slump, superplasticized concrete and its low slump, non-superplasticized base concrete appear to have approximately the same bond strength.

3) Decreased bond strength occurs when high slump concrete (superplasticized or not) is not vibrated.

4) Increased concrete slump has a negative effect on bond strength of top-cast bars.

5) When using superplasticizers, the longer the concrete remains plastic (obtained with lower concrete temperatures in this study) the lower the bond strength.

Table 1.1 Steel-concrete bond strength [12]

Caracteristics of concrete	Workability Slump (mm)	BOND STRENGTH (Kg/cm^2)			
		7 d		28 d	
		Smooth Bar	Twisted Bar	Smooth Bar	Twisted Bar
400 Kg/m^3 of cement N°I without admixture	I00	I2	I50	I3	I52
400 Kg/m^3 of cement N°I with admixture	220	35	275	40	285
500 Kg/m^3 of cement N°2 without admixture, light-weight concrete (I800 Kg/m^3)	I00	4	66	6	92
500 Kg/m^3 of cement N°2 with admixture, lightweight concrete (I800 Kg/m^3)	2I0	9	I42	2I	2I0

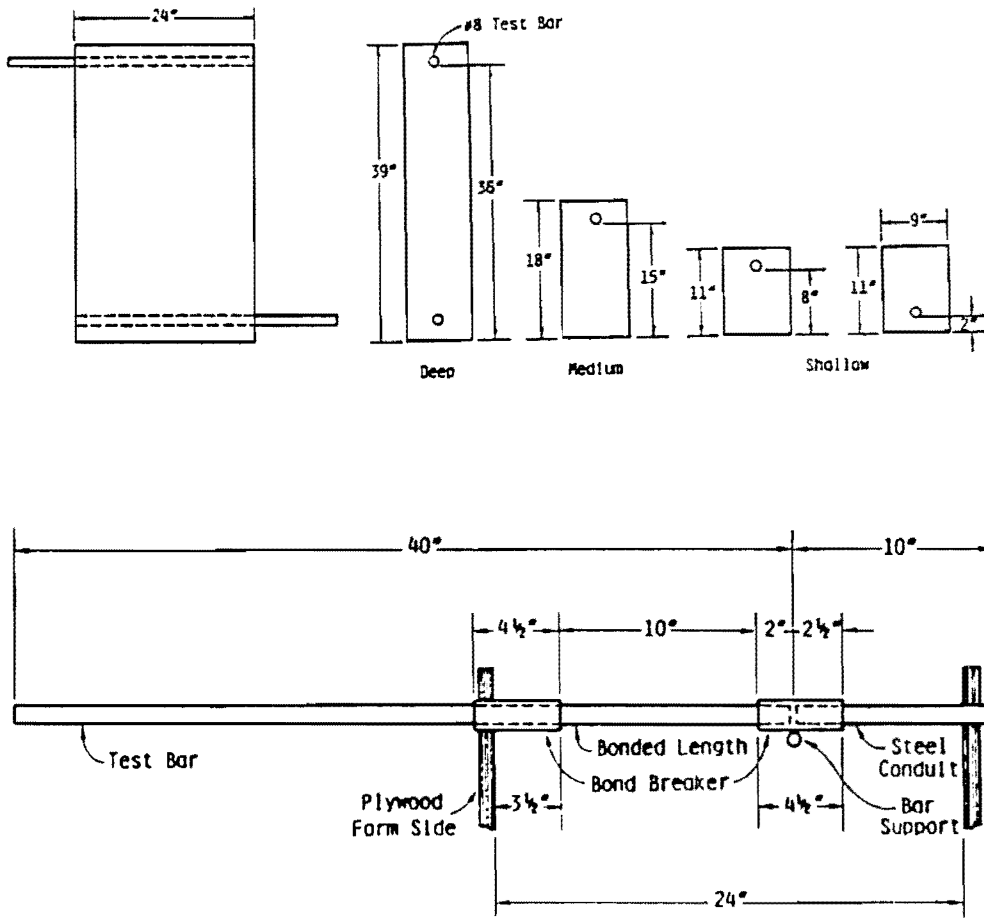


Fig. 1.12 Test specimens and test bar installation [9].

6) A sharp drop-off in bond strength between bottom and top bars strongly suggests an upper surface effect, even for relatively low amounts of concrete below the bar.

7) The bond strength of top bars decreases as the depth of concrete below a bar increases.

1.6.3 Musser [35,36]. In this investigation bond behavior was studied using pullout tests. Figure 1.13 shows the test specimen used in the investigation. The variables included in the study were:

a) slump with and without superplasticizer,

b) type of superplasticizer,

c) dosage rate of superplasticizer,

d) compressive and tensile strength of concrete,

e) bleeding of the fresh concrete,

f) casting depth, and

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

The conclusions drawn from the investigation were:

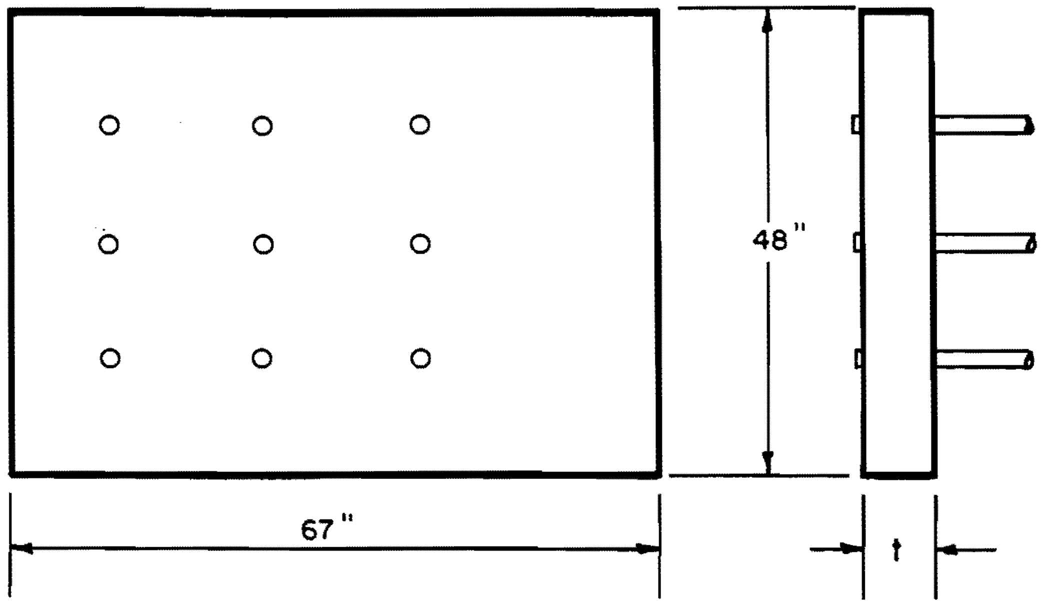
1) The bond between reinforcing steel and concrete is not decreased by the addition of either naphthalene- or melamine-based superplasticizer when these are added to concrete as workability agents.

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 maturity 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: decreased the total air content of air entrained concrete, increased bleeding of the fresh concrete, and increased the concrete compressive and splitting tensile strengths.



SERIES	t (IN.)
I	8
II	6
III	
IV	
V	
VI	

Fig. 1.13 Test specimen dimensions [35].

6) The addition of melamine-based superplasticizer did not affect the total air content of air entrained concrete, did not increase concrete bleeding; produced a smaller concrete compressive strength increase than naphthalene-based superplasticizer; and had a negligible effect on the splitting tensile strength of concrete.

1.7 Research Program

To supplement the research reported by Musser [35] on the pullout bond strength of reinforcing bars, a series of specimens was tested in which the bars were located near the edge of the cross-section to simulate the conditions in a flexural member. The bond performance of reinforcement cast in high slump superplasticized concrete, and low and high slump ordinary (non-superplasticized) concrete were compared. A naphthalene-based superplasticizer was used. Development length and lapped splice tests of Grade 270 1/2 in. strands were performed. Investigations were made of the effect of casting position on bond of horizontal top and bottom bars cast in specimens of various depths. The effect of casting temperature on bond behavior was also investigated. Control tests on the material properties of the concrete, particularly bleeding of the fresh concrete, were conducted.

CHAPTER 2

EXPERIMENTAL PROGRAM

2.1 Variables

The prime variables considered in this program were the workability of the fresh concrete (slump), the temperature of the concrete at time of casting, the casting position (top or bottom bars), and the type of test (development or splice). Table 2.1 a summarizes the test program.

2.1.1 Concrete Materials. The concrete mix used for all specimens was a standard non-air-entrained mix with a specified minimum compressive strength of 3000 psi at 28-days after casting. The concrete mix was specified to have five sacks of type I portland cement per cubic yard of concrete. The fine aggregate used was Colorado River sand. The coarse aggregate consisted of Colorado River gravel with a specified maximum size of 1 in.. All the concrete was obtained from the same commercial readymix company.

Since the aim of the study was to determine the effect of superplasticizers or bond of reinforcing steel, the consistency of the fresh concrete was a critical variable. The workability was controlled using slump. Variations in slump were obtained by changing either superplasticizer or water content. Specimens were cast using low slump (around 3 in.) concrete without superplasticizer, and high slump (around 7 in.) concrete both with and without superplasticizer (see Table 2.1).

The superplasticizer used was Pozzolith 400-N produced by Master Builders. It is a sulphonated naphthalene formaldehyde condensate. It exceeds requirements for ASTM C494 Type A (normal setting) water-reducing admixturs, and Type F water-reducing, high range admixtures. The superplasticizer was used within the manufacturer's recommended dosage of 15±5 fl oz per 100 lb of cement (see Table 2.1). The concrete strength at time of testing and at high maturity is shown in Table 2.2.

2.1.2 Temperature of Fresh Concrete. From bleed test results obtained during the first experimental portion of the study [35], there were strong indications that the temperature of the fresh concrete was an important factor affecting the workability of superplasticized concrete and also the bond behavior of reinforcing steel. Some studies suggest that superplasticizer increases bleeding in concrete [42]. Nonetheless, the bleed tests performed in the first portion of this study did not sustain such a conclusion [35]. Since

TABLE 2.1 EXPERIMENTAL PROGRAM

Series	Type of Test	Concrete Temperature at Casting (^{o}F)	Slump: Low — Slump (in.)	Low — Superplasticizer Dosage (Fl.oz/100# cement)	Low — Air Content (%)	Low — Concrete Age at Casting (Min.)	Slump: High — Slump (in.)	High — Superplasticizer Dosage (Fl.oz/100# cement)	High — Air Content (%)	High — Concrete Age at Casting (Min.)
II*	Development length of #8 bar	58	2.5	--	2.0	53	7.0	11	1.3	90
III	Development length of 1/2 in. strand	55	3.0	--	2.25	56	7.0	11	1.0	96
IV	Splices of #8 bar	53	3.0	--	2.5	57	6.5	11	1.3	91
V	Development length and splice of #8 bar	60	2.5	--	2.5	(38)	7.5	Water added	1.3	71
VI	Development length of #8 bar	78	3.0	--	2.7	58	7.5	19.5	1.3	103

*Series II duplicated Series I which was a trial series to determine proper mixing, placing, and testing procedures. Series I led to changes in subsequent series.

TABLE 2.2 CYLINDER TEST RESULTS

Series	At Time of Bond Test					High Maturity		
	Concrete Age (Days)	Low Slump		High Slump		Concrete Age (Days)	Low Slump Compressive Strength (psi)	High Slump Compressive Strength (psi)
		Compressive Strength (psi)	Tensile Strength (psi)	Compressive Strength (psi)	Tensile Strength (psi)			
II	30	5500	470	6700	510	245	5400	6300
III	30	4800	460	5000	440	238	5200	5700
IV	36	5800	500	5700	500	231	6100	6100
V	99	5200	520	4600	430	231	5300	4200
VI	35	5700	500	5900	450	146	5700	5500

these tests were conducted at high temperatures (85-90° F), it was thought that different results would be obtained at lower casting temperatures.

In order to investigate the effect of temperature, specimens were cast using concrete at low (50-60° F) and at high (around 80° F) temperatures (see Table 2.1).

2.1.3 Casting Position. The position of a reinforcing bar within a concrete member at the time of casting had been shown by numerous researchers to have a significant effect on bond behavior, see Section 1.3.

In order to investigate the effect of casting position on the bond behavior of steel in superplasticized concrete, bars were cast close to the bottom and the top surfaces of specimens of varying depths (Fig. 2.1). All bars were cast horizontally. The clear concrete cover for both the top and bottom bars was 2 in. for all specimens.

The depths of concrete cast below the top bar were 6, 12, 18, and 30 in.. The corresponding total specimen depths were 9, 15, 21, and 33 in., respectively.

2.1.4 Development and Splice Test Bars. To study bond and anchorage under typical structural conditions, tensile development tests were conducted using Grade 60 #8 deformed reinforcing bars and Grade 270 1/2 in. diameter prestressing strands. Tension lap splice tests were run on Grade 60 #8 deformed reinforcing bars.

The stress strain characteristics of the #8 bars and of the 1/2 in. strands are presented in Fig. 2.2.

2.2 Test Specimen

To accomplish the aim of this study, which was to investigate the effect of superplasticizers on the bond behavior of reinforcing bars, a specimen was designed to:

1) simulate the stress condition in the tension zone of a concrete member;

2) be relatively inexpensive to fabricate since a large number of tests were needed, and;

3) take a short time to test.

To simulate the tension zone of a member, all compressive stresses in the anchorage zone had to be eliminated. A pullout test

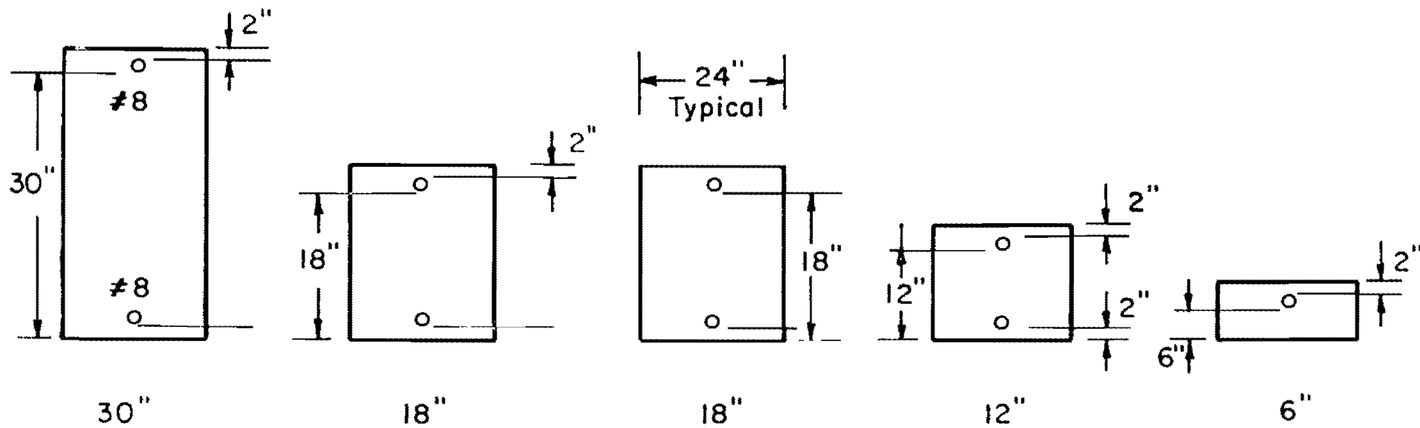


Fig. 2.1 Casting Position.

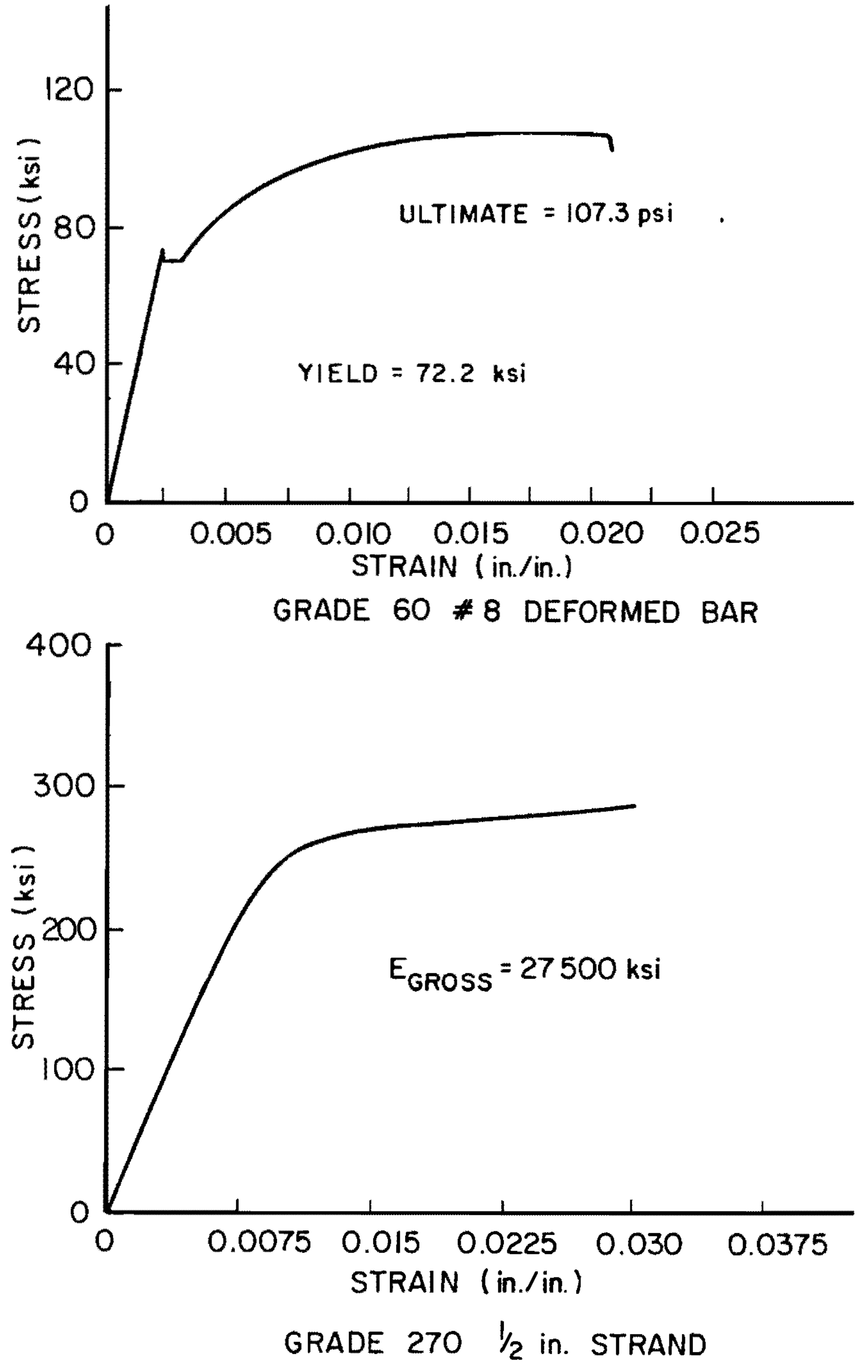


Fig. 2.2 Steel stress-strain properties.

with the loading device bearing on the concrete at the bar was not acceptable. To obtain failure by splitting of the concrete cover and to eliminate bearing against the concrete surface in the vicinity of the bar, a specimen was designed to simulate a portion of the tension zone of a member.

Figures 2.3 and 2.4 describe the test specimens selected. All relevant dimensions for development length and splice test specimens are shown.

For the development tests, additional bars were placed parallel to and in the same plane as the test bars. These bars (reaction bars) were gripped on the opposite side of the specimen and provided the reaction to the load applied on the test bar. A self equilibrating system in tension was obtained with this arrangement.

For the splice tests, two bars extended from opposite sides of the specimen permitting testing of two splices.

In order to obtain isolated behavior for the test bars and a consistent splitting failure of the anchorage, the test specimens were proportioned according to recommendations from the report by Orangun, Jirsa, and Breen [27]. Based on the test bar, confinement, and concrete properties selected, a 16 in. embedment length was provided for all specimens.

To control the type of splitting failure and to prevent cracks from propagating between top and bottom bars, transverse reinforcement was placed in the specimen. Any cracks extending between bars would have influenced the test results. Three layers of specially shaped Grade 60-#3 deformed bar stirrups were placed in each specimen. The transverse reinforcement was designed so that splitting cracks would occur only on the cover concrete. Figures 2.5 and 2.6 describe the transverse reinforcement for development length and splice test specimens. The shallow specimens were reinforced in the same way even though they did not have bottom cast bars. Figures 2.7 and 2.8 are pictures of specimens with the transverse reinforcement in place prior to casting.

2.3 Construction

2.3.1 Formwork. Formwork was built for ten specimens of four different heights. Two forms were built for 9, 15, and 33 in. high specimens, and four forms were built for 21 in. high specimens. For each series, five forms (one each at 9, 15, and 33 in. depth and two at 21 in. depth) were used for the low slump concrete and the remaining five for high slump concrete. The two 21 in. specimens permitted a check on the reproducibility of the data.

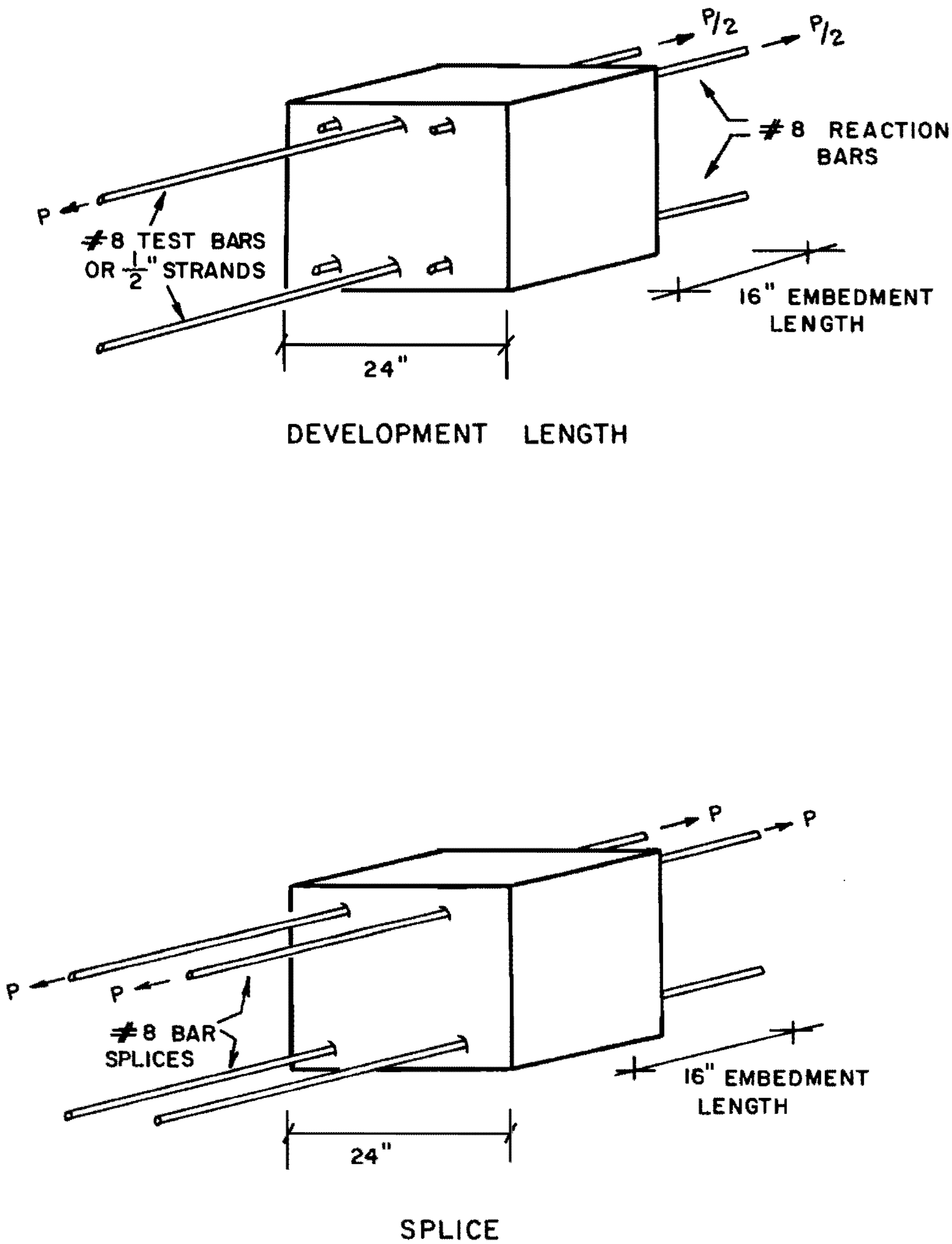
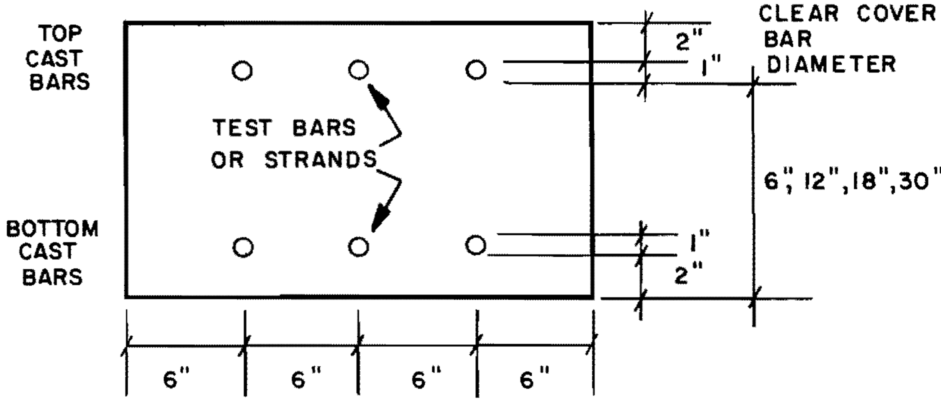
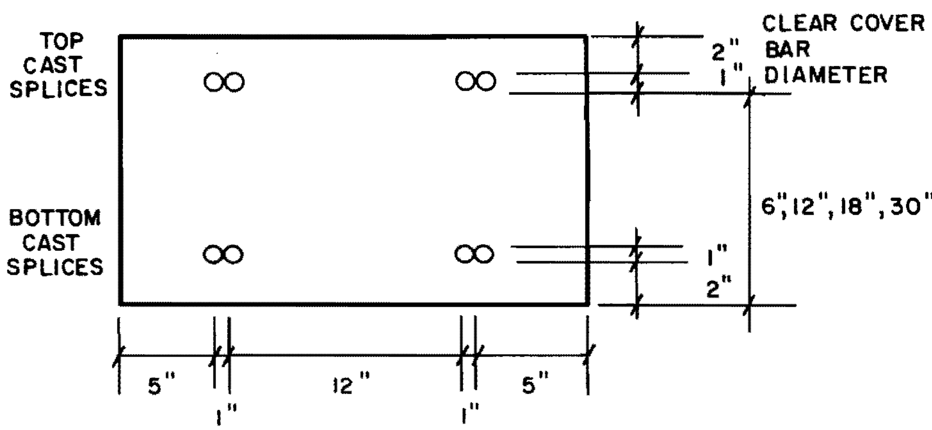


Fig. 2.3 Bond test specimens.



DEVELOPMENT LENGTH



SPLICE

Fig. 2.4 Front view of test specimens.

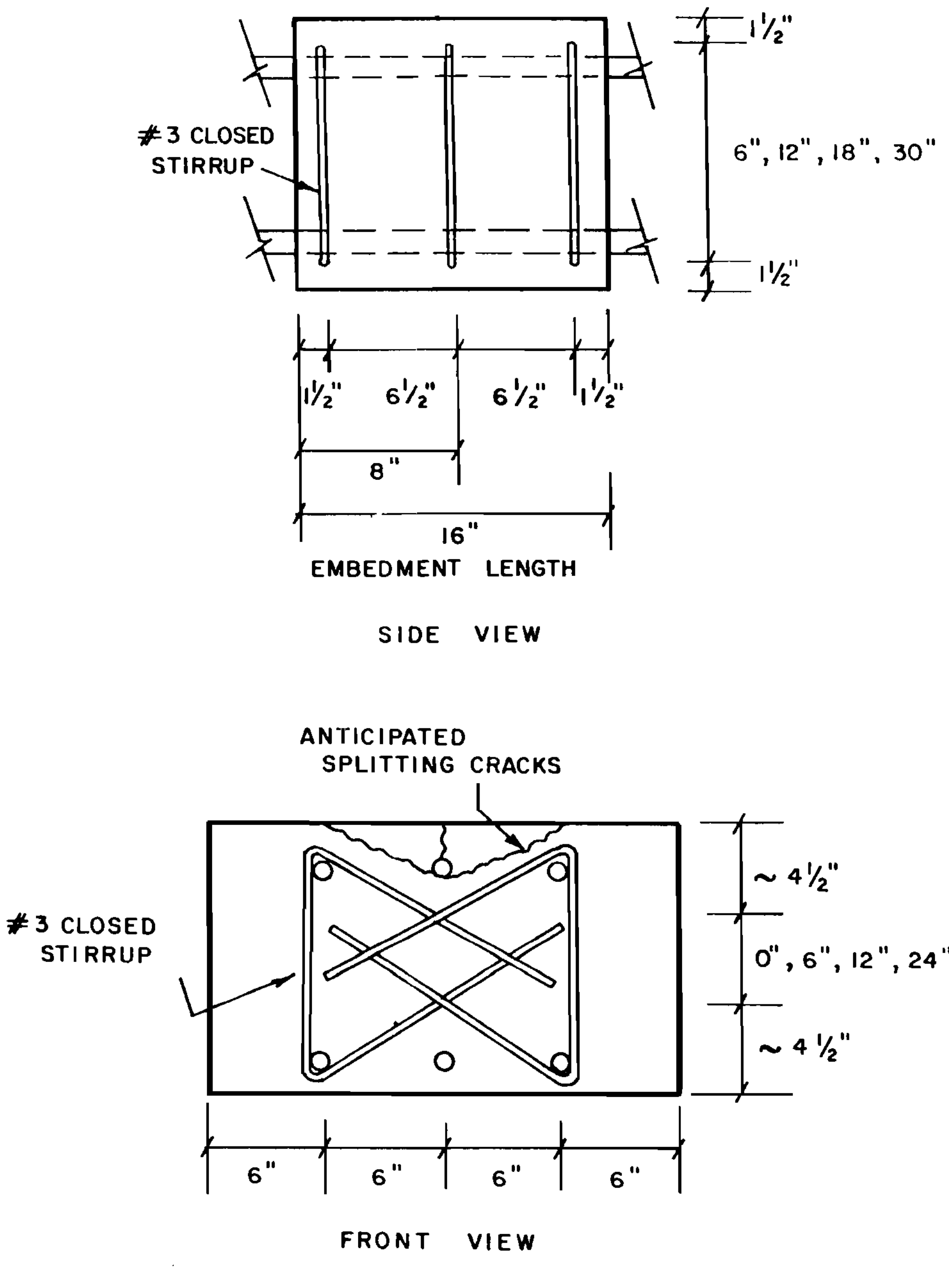


Fig. 2.5 Transverse reinforcement - development length test specimen.

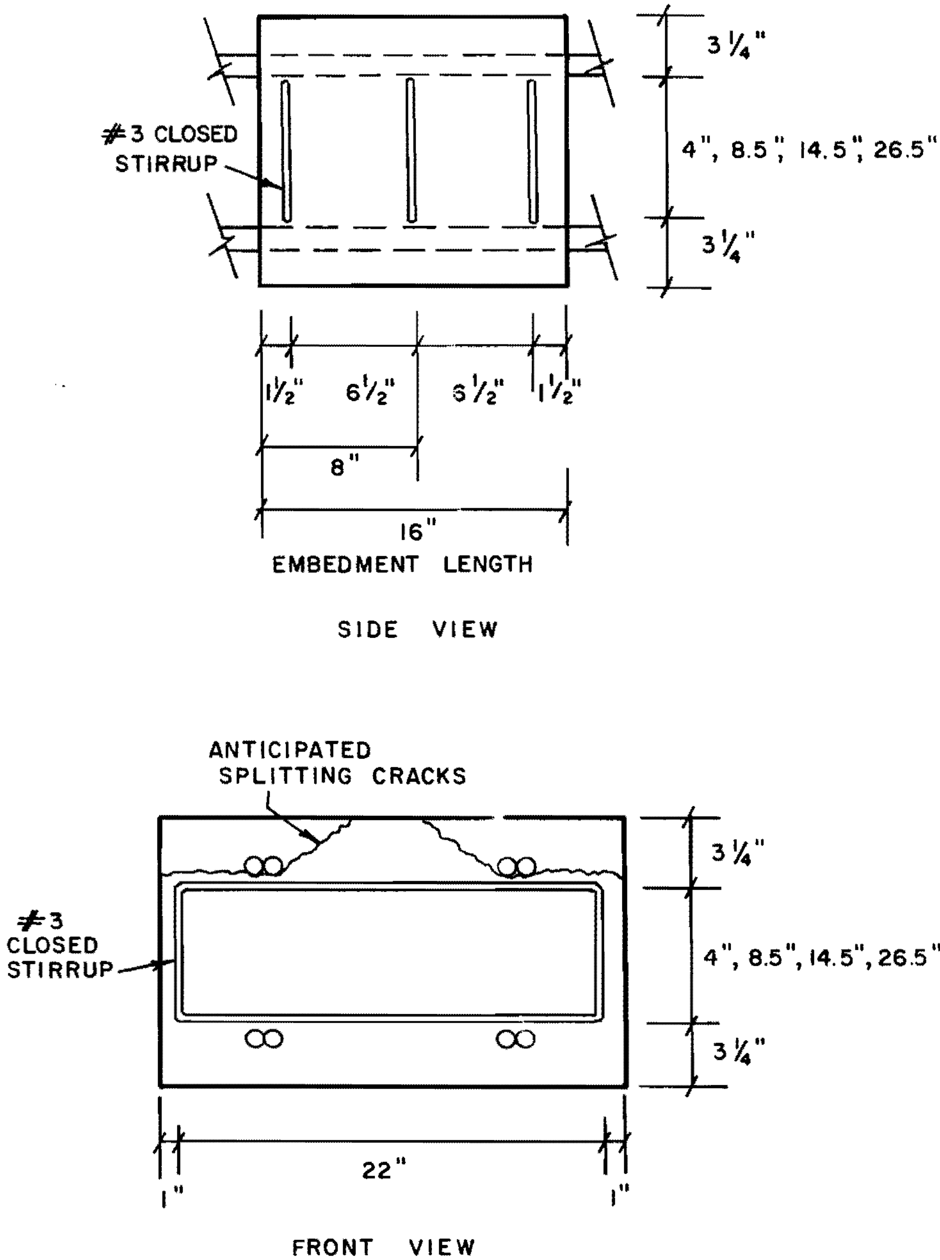
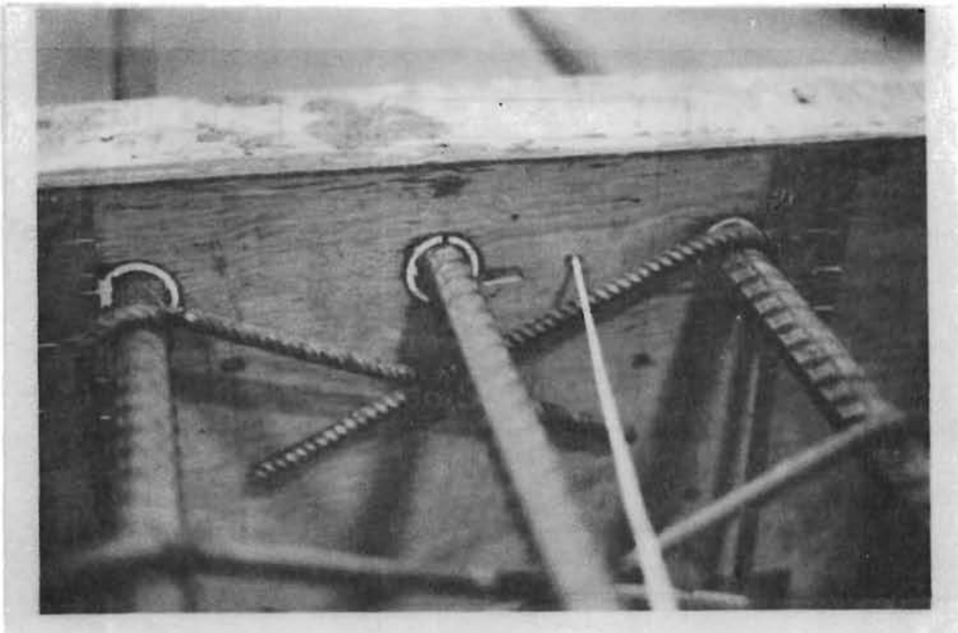
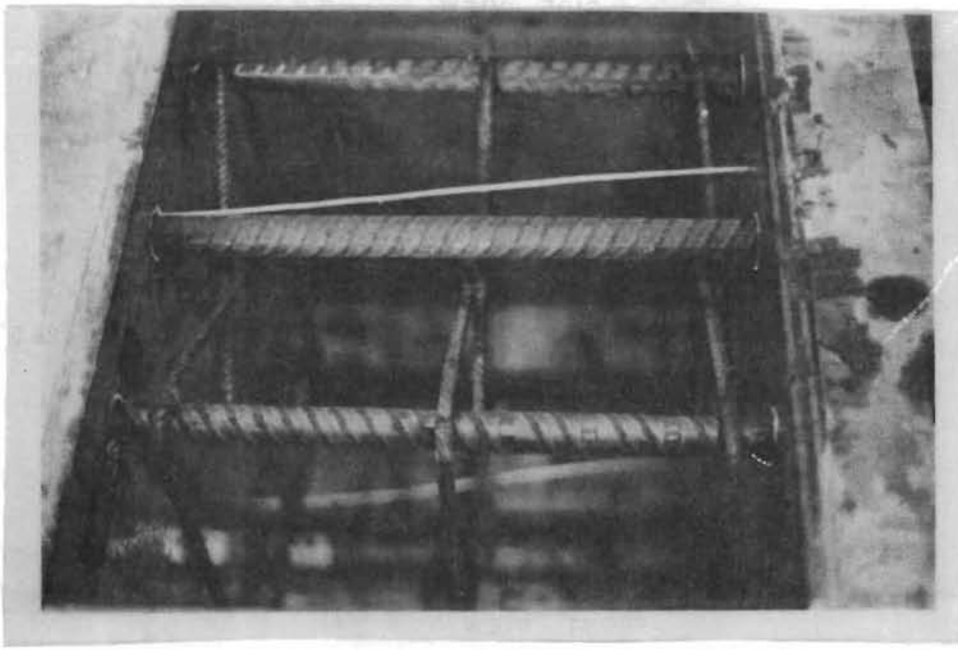


Fig. 2.6 Transverse reinforcement - splice test specimen.



Transverse reinforcement in place prior to casting.



Distribution of reinforcement along the bar's embedment length.

Fig. 2.7 Transverse reinforcement - development length test specimen.

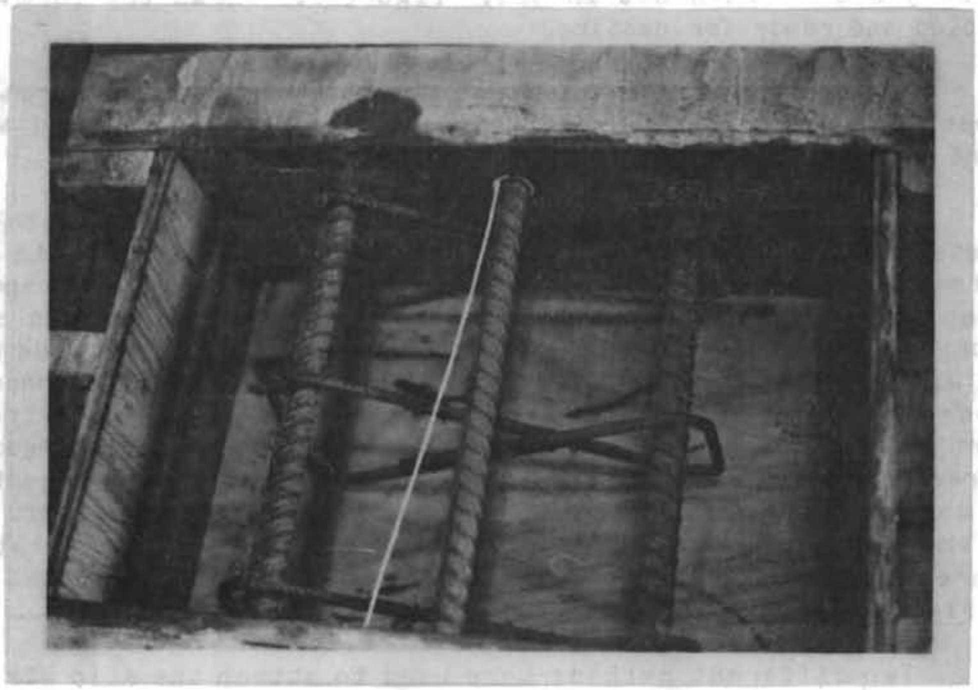


Fig. 2.8 Transverse reinforcement - 9 in. deep specimen without bottom bars.

The inside faces of the forms were lacquered. Immediately prior to placing the steel in the forms, a coating of oil was applied to these faces. Care was taken that no oil from the formwork contaminated the test bars. The same formwork was used for both types of tests; splices and development. Openings to accommodate bars were carefully sealed when not in use. Figure 2.9 shows the formwork assembled and ready for casting.

2.3.2 Bar Placement. Steel was placed after the formwork had been coated with oil. Test bars were carefully cleaned with acetone prior to placement.

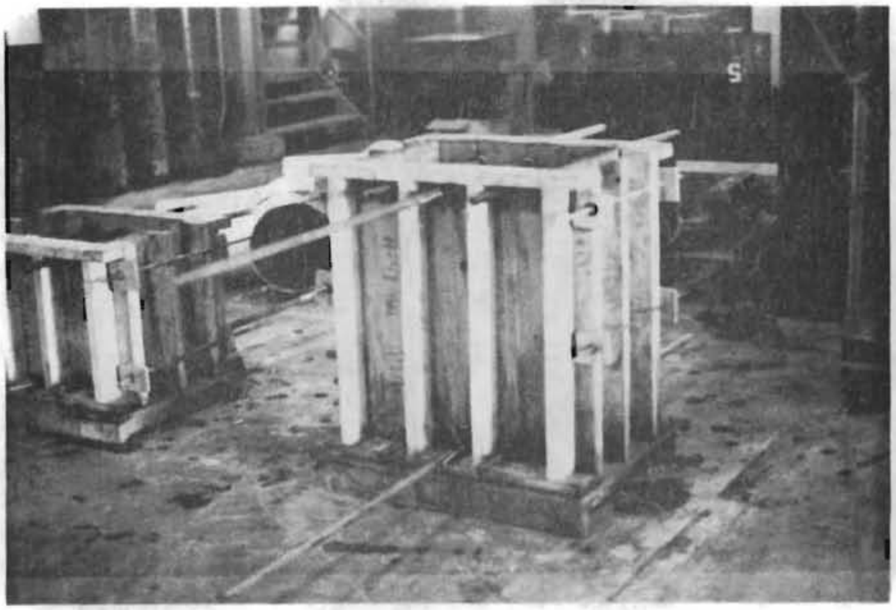
2.3.3 Instrumentation. Slip of the test bar relative to the concrete was measured at both the loaded and the free ends of the bar. The free end slip measurements were taken directly between the exposed free end of the test bar and the concrete. For the loaded end slip measurement a slip wire arrangement was used. This consisted of a piano wire firmly attached to the test bar at the loaded end concrete surface of the specimen. A plastic tube was placed over he wire to prevent bonding of the wire to the concrete. The slip wire emerged on the free end surface of the specimen (see Fig. 2.10). Measurement of wire movement was recorded using a 2 in. linear potentiometer. At both the point of attachment on the loaded end and the point of measurement, the slip was parallel to the main axis of the test bar (see Fig. 2.10).

Two different methods were used to attach the slip wire to the test bar. One consisted of epoxying the tip of a slip wire in a small hole drilled in the test bar. This end of the wire was then covered by a rubber sealant and cast inside the specimen near the loaded end surface (see Fig. 2.11). The point of attachment was within an in. of the concrete surface.

A different method was used for most of the specimens. It was simpler because it did not involve drilling or epoxying. It consisted of attaching the slip wire to the test bar by gripping it with a metalic hose clamp. This was done just before testing. The point of attachment was outside the concrete within an inch of the loaded end surface (see Fig. 2.11).

2.3.4 Casting Procedure. A truck containing 6 cu yd of concrete was ordered for casting each series. Upon the truck's arrival at the laboratory, water was added to produce a slump of about 3 in.. When the desired slump was obtained, five of the ten specimens were cast. The concrete was discharged from the truck into a 1/3 cu yd bucket and placed into the formwork using an overhead crane (see Fig. 2.12).

All specimens were cast in 7 to 9 in. high lifts. This corresponds to 1, 2, 3, and 4 lifts for the 9, 15, 21, and 33 in. high



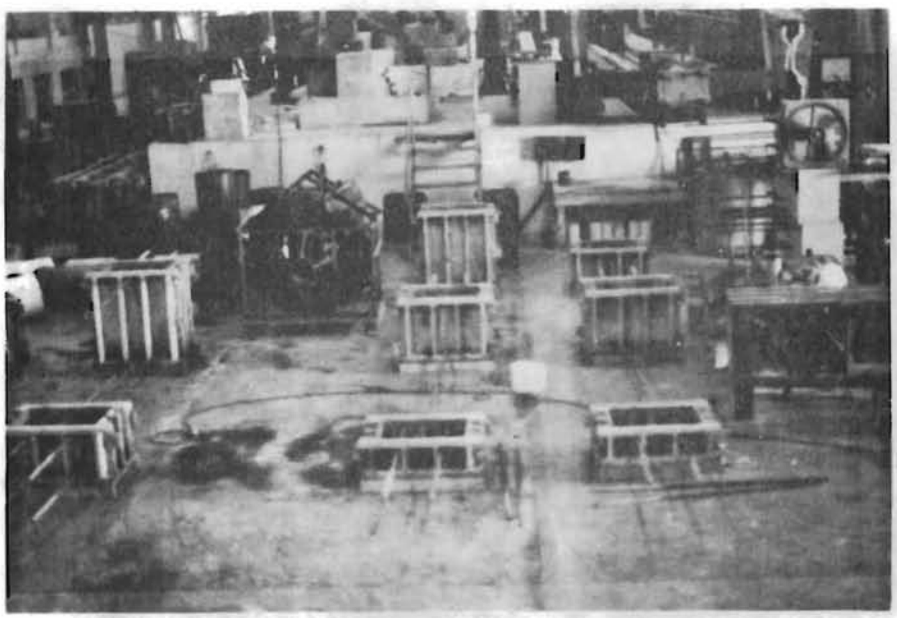
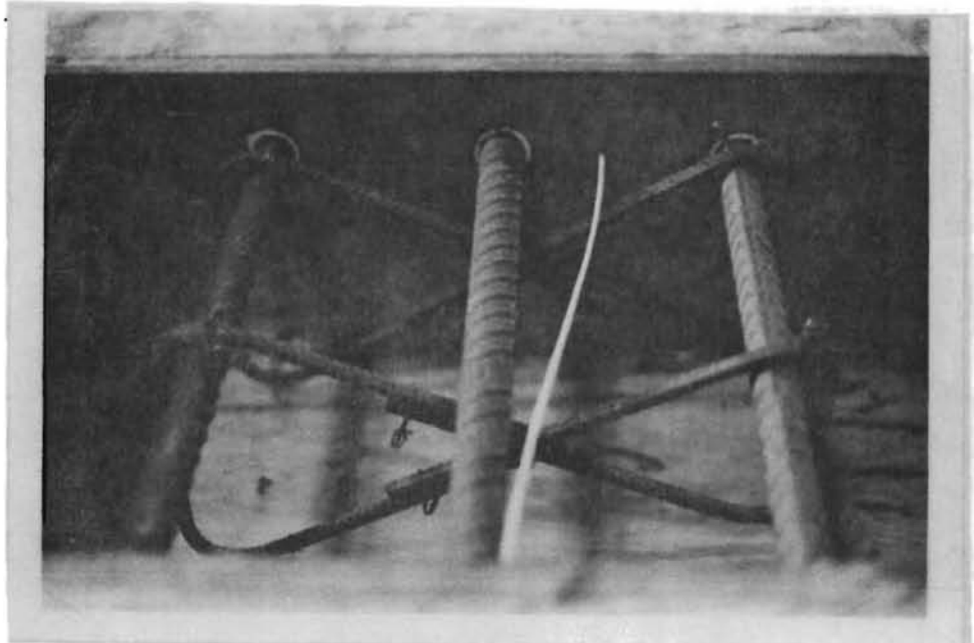


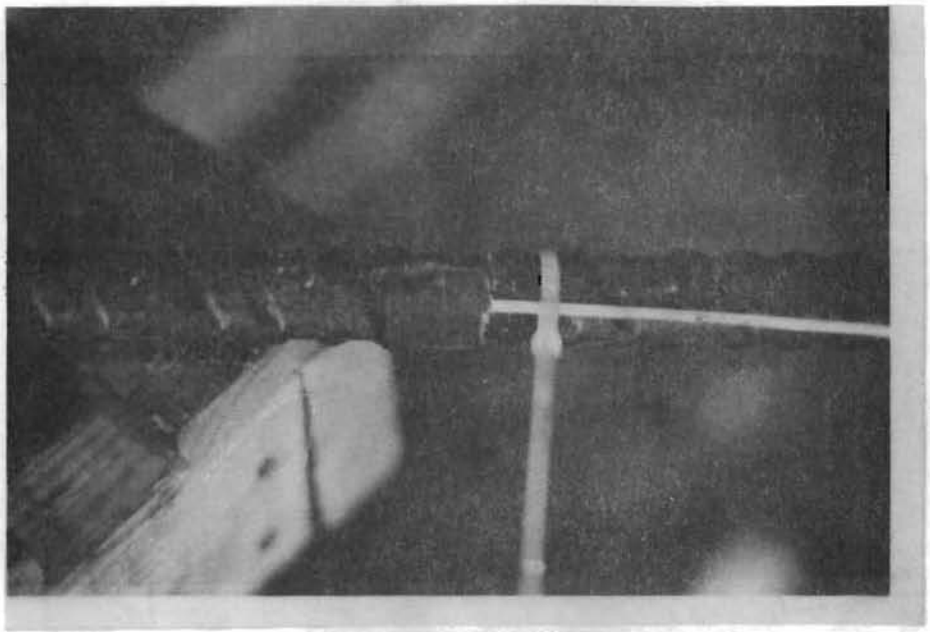
Fig. 2.9 Formwork ready for casting.



Inside the specimen.

Free end extension.

Fig. 2.10 Slip wire placed in the formwork.



Attachment of slip wire using epoxy cement

Hose clamp gripping the slip wire.

Fig. 2.11 Attachment of slip wire to test bar.

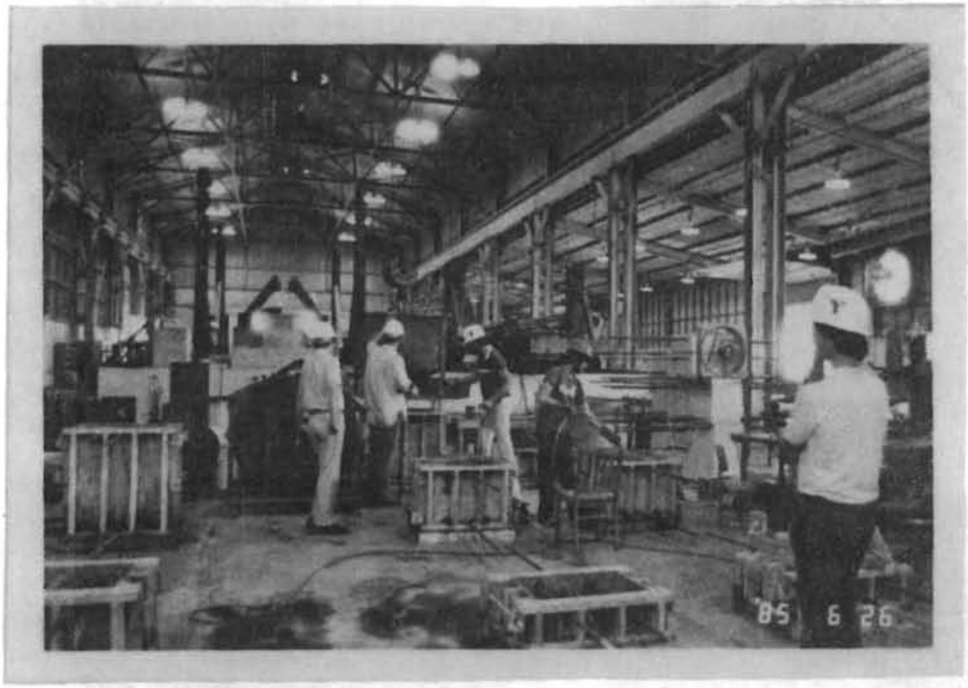


Fig. 2.12 Casting operation - concrete being cast and vibrated.

specimens, respectively. The average casting time per lift was 70 seconds.

All lifts were vibrated using a 3/4 in. diameter internal vibrator. Vibration was applied by inserting and extracting the vibrator slowly at an angle for periods of about 5 seconds 6 times for each lift. One lift was vibrated at a time without revibration of previous lifts. The same operator vibrated all the specimens using the same machine for consistency of results (see Fig. 2.12).

When the first five specimens had been cast, the slump of the remaining concrete was adjusted to about 7 in. using superplasticizer. The superplasticizer was applied directly to the concrete in the truck using a funnel and a 10 ft long PVC pipe. The pipe was used to insure that the additive was placed in the front of the drum. Unless this was done, distribution of the superplasticizer throughout the concrete could not be assured. This procedure was developed after problems were encountered with series I in which a non-homogeneous mix was produced when the admixture was placed directly into the hopper of the ready-mix truck.

After the concrete had been mixed properly and the desired slump obtained, it was cast in the remaining five specimens. The casting procedure was identical to that used for the first five specimens.

The only exception to the casting sequence described occurred in series V. The ten specimens in Series V were cast using high slump concrete produced by adding water to the concrete. Five of the specimens in this series were development length tests and five were splice tests.

When the casting operation was completed, the specimens were carefully screeded and covered with plastic. All specimens were stripped two days after casting and stored in the laboratory with no further curing until the test date. Control cylinders were cured in a similar manner.

2.3.5 Bleed Test. Fourteen containers of various heights were used to monitor the bleed behavior of the fresh concrete in each series. Five containers were used for the low slump concrete and nine for the high slump concrete. The depths of concrete in the containers were related to the depth of concrete cast below the top bars in the test specimens. These depths were 6, 10, 18, and 30 in. (Fig. 2.13).

Three containers for each depth were fabricated using 12 in. diameter PVC pipe. The other two containers were ASTM standard aluminum buckets, in which concrete was placed to a depth of 10 in.. One aluminum bucket and one PVC container of each concrete depth were used for low slump concrete. For high slump concrete, one aluminum

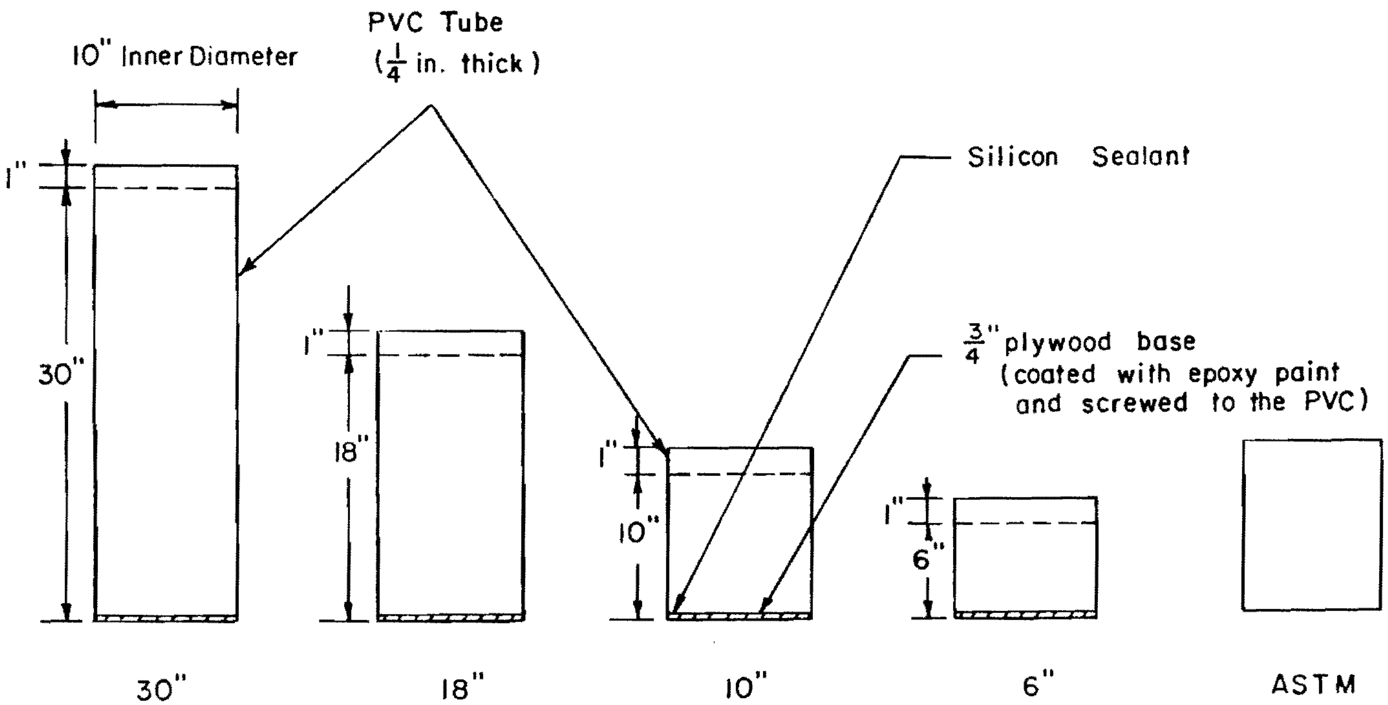


Fig. 2.13 Bleed test containers.

bucket and two PVC containers of each depth were used. Figure 2.14 shows all the bleed containers arranged for testing.

The tests performed using the aluminum buckets met the ASTM C232-71 standard test method for bleeding of concrete except that the concrete for all blood tests was placed at ambient temperature rather than the specified 65 to 75° F. Concrete was placed in three layers to a height of 10 in.. Each layer was rodded 25 times.

The tests performed using the PVC buckets followed a procedure identical to that of the ASTM standard test, except for the type of bucket and the concrete placing procedure. The concrete was placed to heights of 6, 10, 18, and 30 in. in 1, 2, 3, and 4 lifts in a manner similar to that used placing concrete in the formwork. Each lift was vibrated once for five seconds using a 3/4 in. diameter internal vibrator. Bleed tests began simultaneously with the casting of the bond specimens, and continued until the concrete stopped bleeding.

Bleed water was measured every 10 minutes for 40 minutes, after which it was measured every 30 minutes until bleeding stopped. Two minutes before each measurement, the bleed buckets were tilted by placing a short piece of wood under one side of the base. This permitted collection of the bleed water at one side of the bucket. To measure the bleed water, a pipette was used to transfer the water into a measuring cylinder. The time, temperature, initial amount and final amount of water in the cylinders were read and recorded.

2.3.6 Air Content Test. The air content was measured for the low and high slump concrete in each series. The tests were performed according to the volumetric method as described in ASTM C173-78. The air content test results are summarized in Table 2.1.

2.4 Test Set-Up

2.4.1 Test Frame. The test frame was manufactured using structural steel sections. Two channel sections, welded together at the ends with a 4 in. gap between them, spanned across the specimen with the bars inserted through the gap. The channel sections were supported on the corners of the frame by columns. The columns were welded together in pairs parallel to the test bars.

The test frame was free-standing on the floor and acted as a self equilibrating system (see Fig. 2.15). The channel sections could be placed on or removed from the frame, allowing the necessary modifications between development length and splice tests. This feature also allowed easy placement and removal of specimens. Channels on opposite sides of the specimen were tied together using steel rods to restrain movement at failure of the specimen. Three sets

Fig. 2.14 Bleed containers arranged for testing.

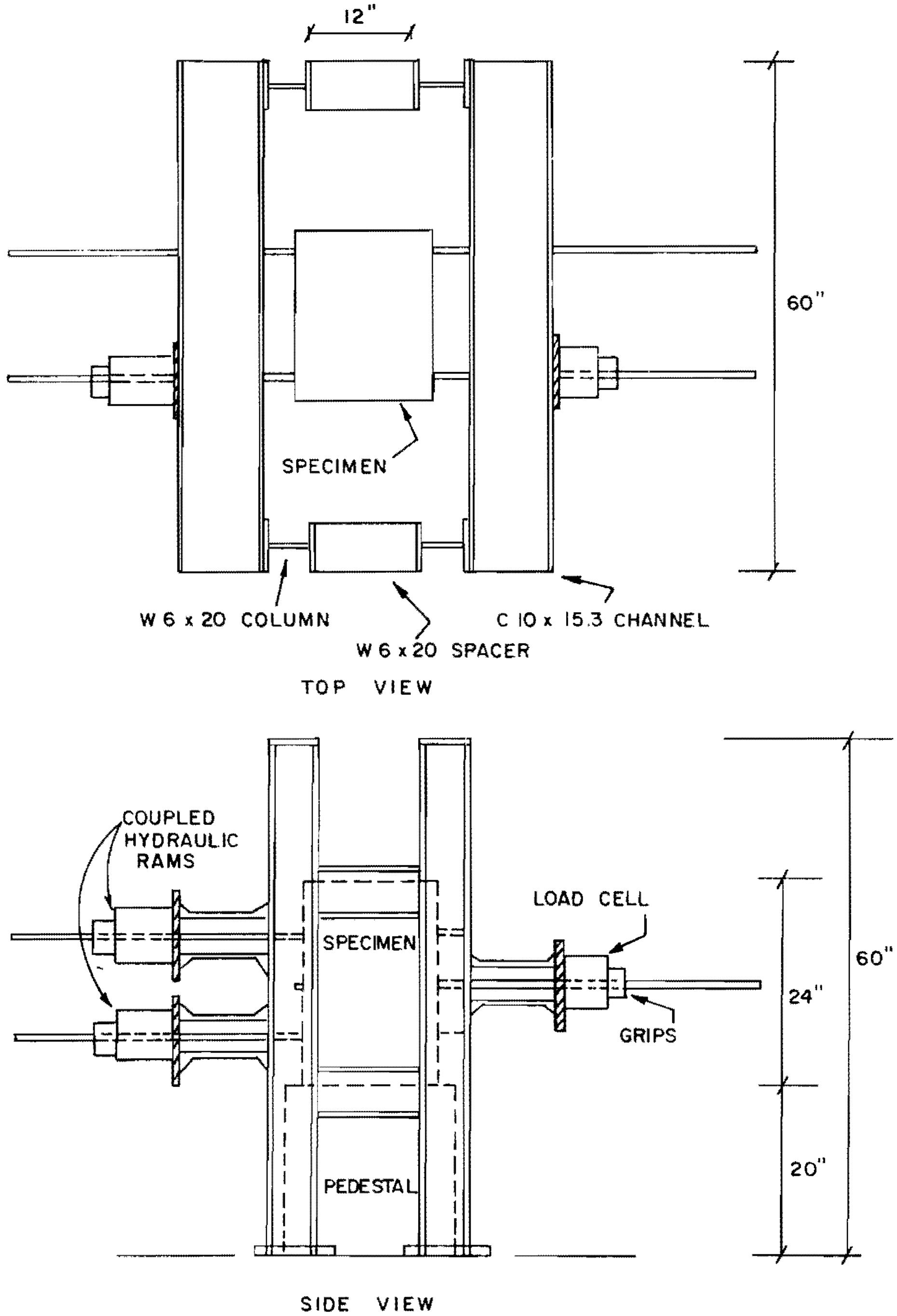


Fig. 2.15 Test frame (schematic)

of channels were used for development length tests and four sets for splice tests.

The specimens were placed on a concrete pedestal for testing. All the specimens were placed in the test frame such that the bars were always at the same height. Figure 2.16 shows the test frame with a specimen in position.

2.4.2 Loading System. The loading system consisted of two 30 ton capacity center hole rams connected in parallel to a common hydraulic hand pump. The rams were coupled to apply an identical load to the two bars being loaded. The bars were gripped using an anchor plate and chuck arrangement (see Fig. 2.17).

For development length tests, the two reaction bars were loaded and a 100 kip calibrated load cell was placed on the test bar. The two splices cast at the top or the bottom surfaces were tested simultaneously. Therefore, a pair of 60 ton capacity center hole rams were coupled for loading. A second set of coupled rams in a closed loop was placed on the reaction bars to ensure equal load to each bar and to allow the differences in movement of the grips during seating to be accommodated by ram deformations. A 100 kip calibrated load cell was placed on each of the splice test bars (see Fig. 2.18).

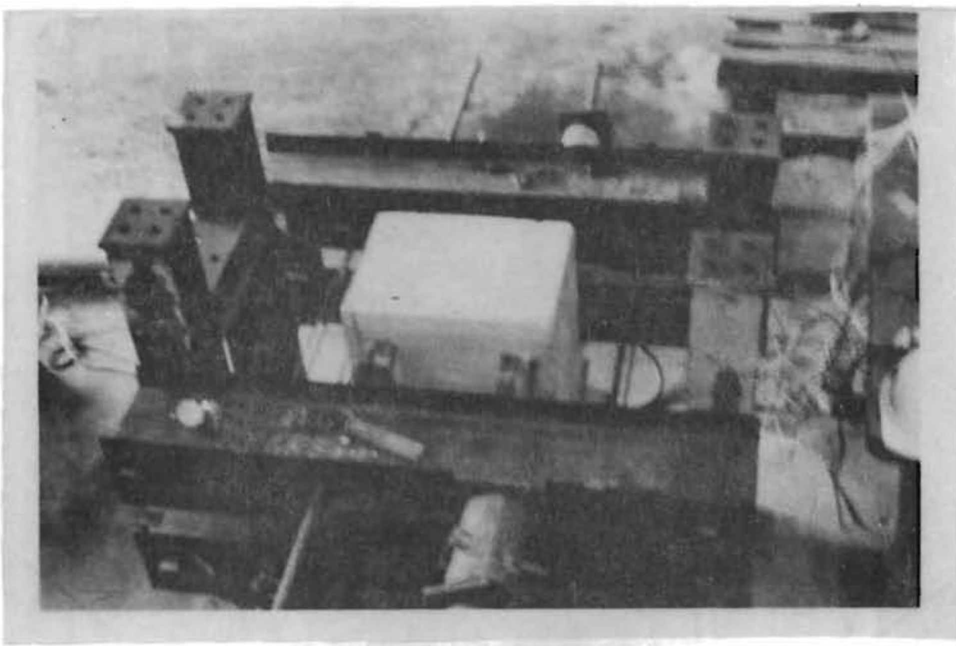
2.5 Instrumentation

2.5.1 Slip Measurement. A small aluminum frame was attached with epoxy to the concrete surface near the free end extension of each test bar before the specimen was placed in the test frame. The aluminum frames supported 2 in. linear potentiometers used to measure slip. Since the potentiometers were firmly attached to the frames, and the frames were fixed to the concrete, any slip wire or bar movement measured corresponded to bar slip relative to the concrete.

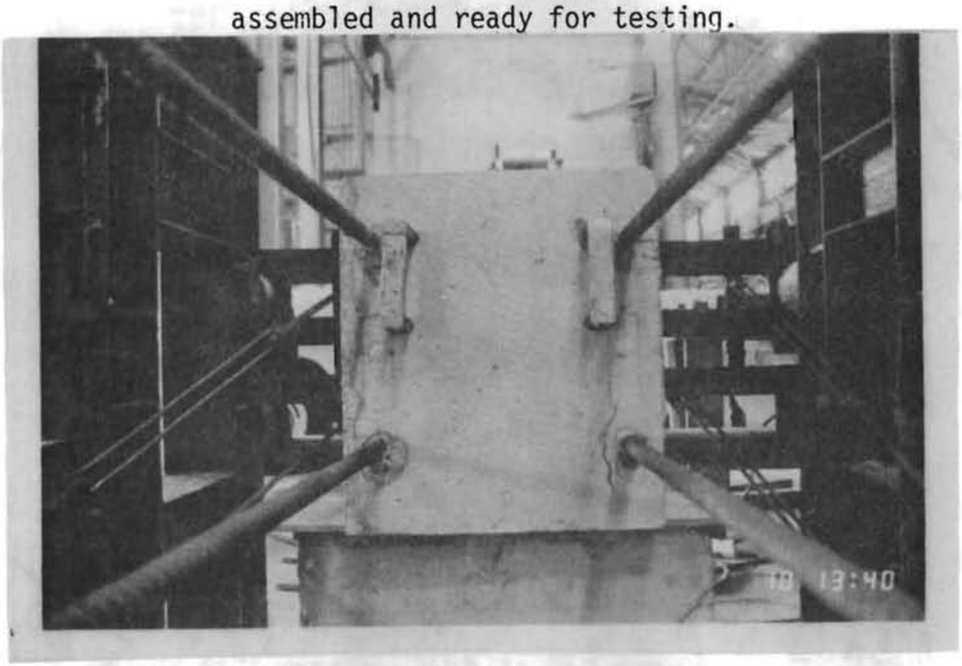
The potentiometer shaft rested directly against the exposed flat free end of the test bar for free end slip measurements. For loaded end slip measurements, a slip wire arrangement was installed, as described in Section 2.3.3. In order to provide a flat surface to support the potentiometer shaft, a small aluminum block was attached to the slip wire (see Fig. 2.19).

Two inch linear potentiometers were used for all slip measurements except for a few tests in which free end slip measurements were taken using a 1 in. dial gage. Figure 2.20 shows the slip measurement arrangement installed.

2.5.2 Test Procedure. All specimens were tested after the concrete had cured at least 28 days.



assembled and ready for testing.



specimen inside the test frame.

Fig. 2.16 Test frame.

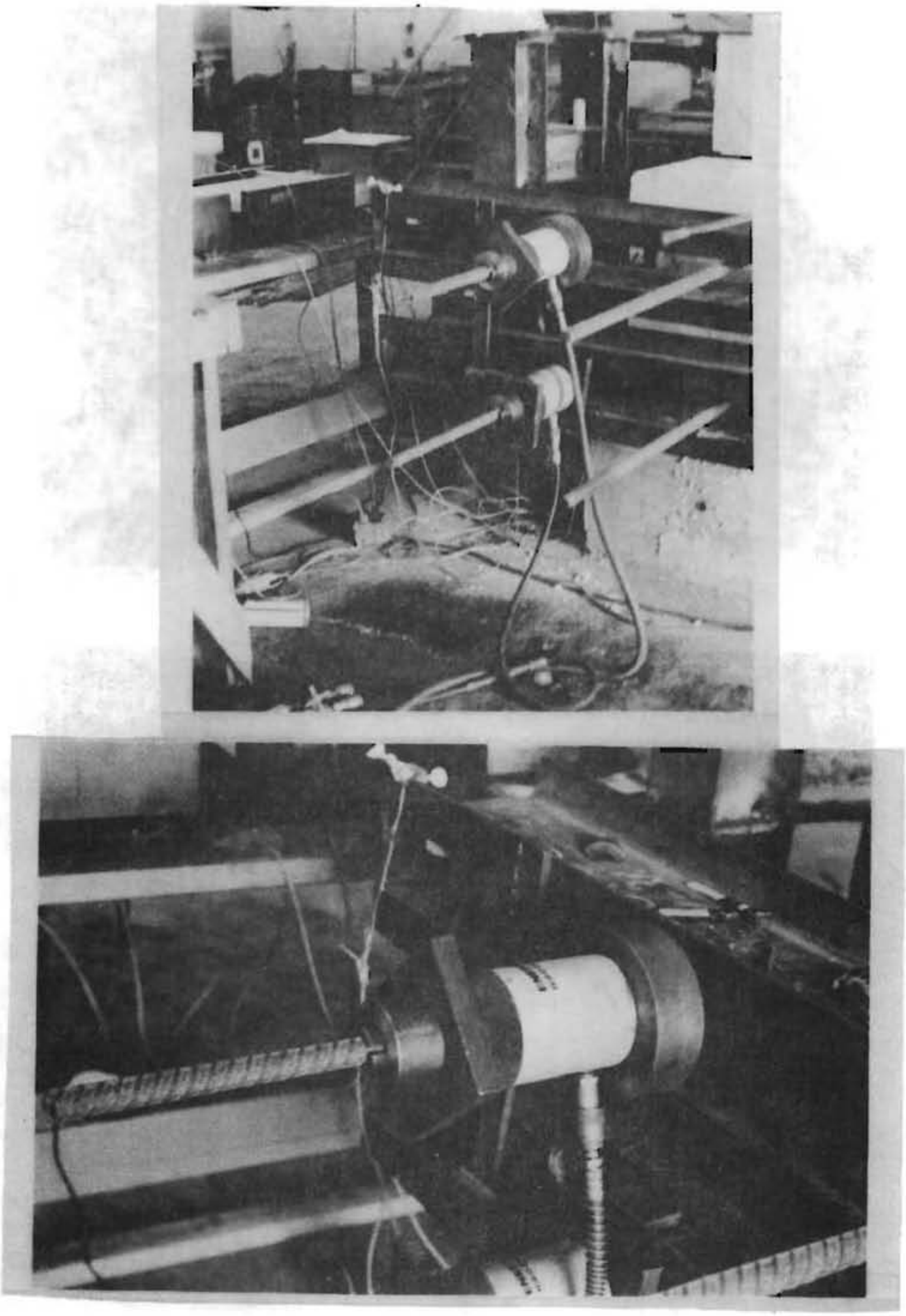


Fig. 2.17 Loading system ready for testing. 30 ton rams and chucks assembled.

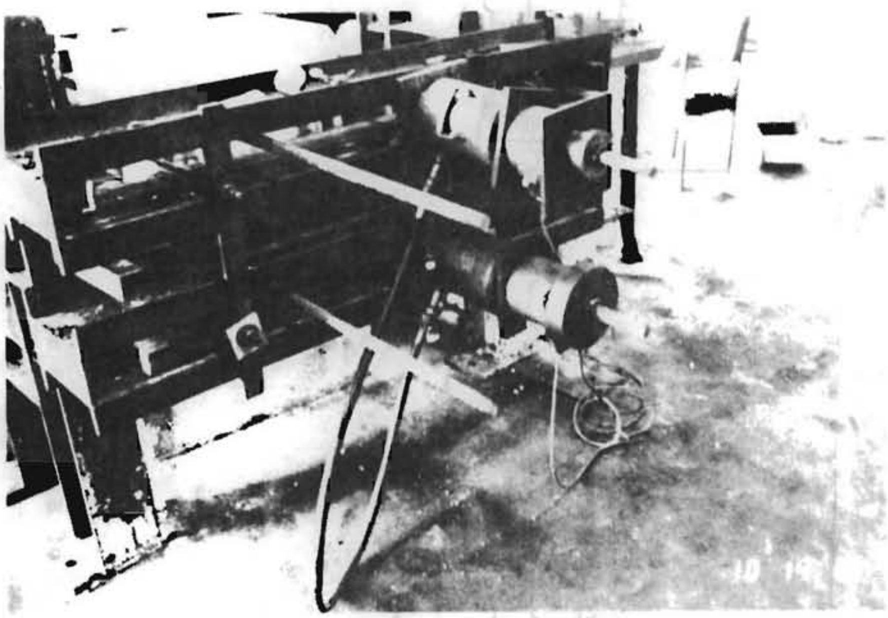


Fig. 2.18 Load distribution and load cell arrangement for the reaction side of splice tests.

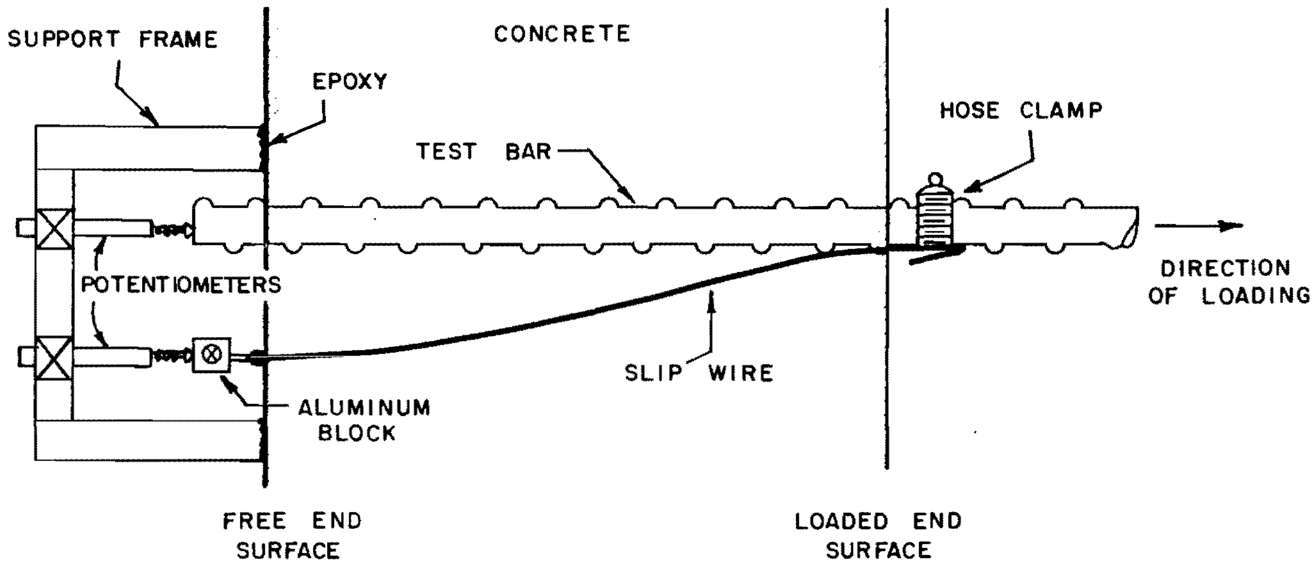


Fig. 2.19 Top view of slip wire arrangement.

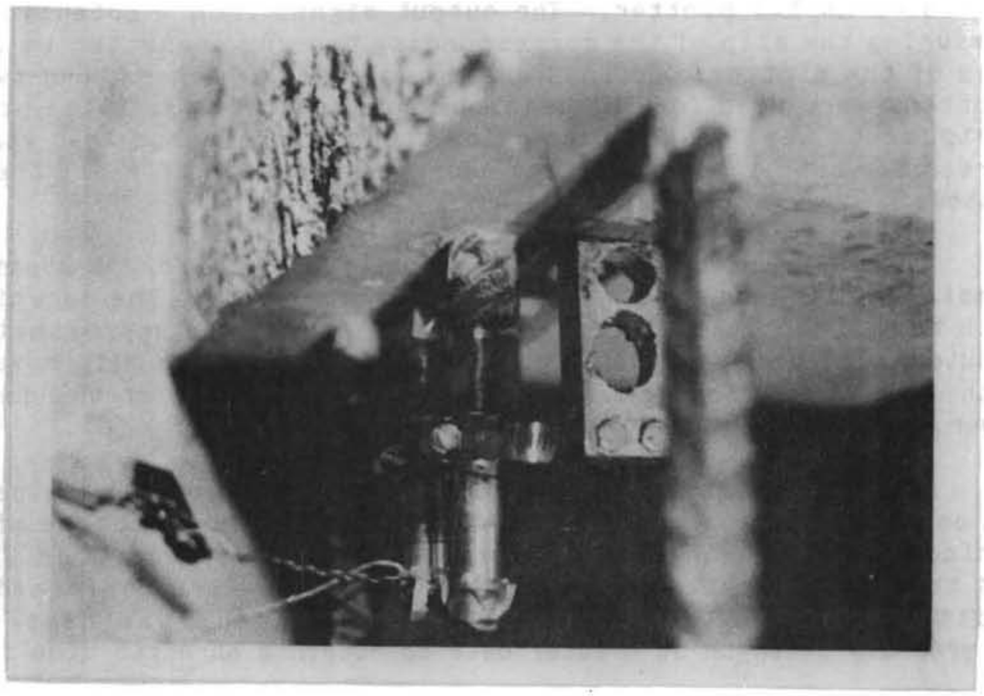


Fig. 2.20 Linear potentiometers ready for testing.

After the test frame was assembled around the specimen, the hydraulic rams and load cells were placed over the bars and the chucks attached. The linear potentiometers were then mounted.

The output signal from the load cell was connected to the Y-axis of an X-Y plotter. The output signal from a potentiometer measuring the slip of the corresponding bar was connected to the X-axis of the plotter. One load cell, two potentiometers, and two X-Y plotters were used for the development length tests. Twice as many instruments were needed for splice tests. Continuous load vs. slip curves for both loaded and free ends were obtained for all the bars tested.

Loading was applied monotonically to failure. A steady and consistent loading rate was applied for all tests. The duration of each test, from initial loading until failure, was approximately 2 minutes. Failure was usually sudden and involved large slip movements with loss of all load carrying capacity and fracture of the concrete cover.

At the time of testing of the bond specimens, the nine 6x12 in. control cylinders cast with high and low slump concrete of each series were tested. Three compressive strength tests (ASTM C39-81) and three split cylinder tests (ASTM C496-71) were performed. An additional group of three 6x12 in. cylinders was tested for compressive strength at a later date to obtain a strength time curve.

CHAPTER 3

BOND TESTS

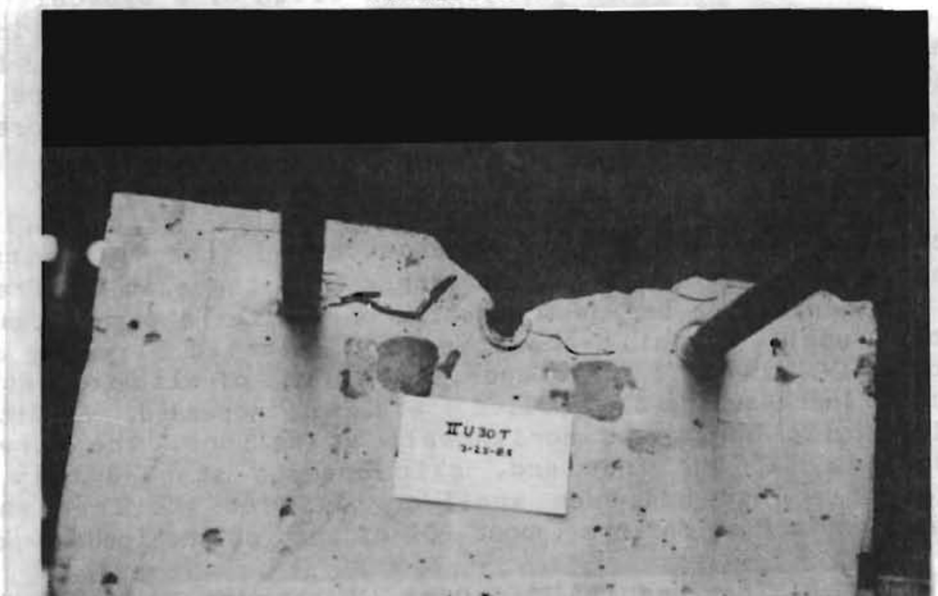
3.1 Development Length Tests of #8 Bars

3.1.1 Failure Pattern. All #8 bar development length test specimens exhibited a V-notch splitting failure. A very small crack extended from the test bar to the concrete face over the bars just before the ultimate load was attained. When the failure load was reached, the concrete cover split suddenly. Cracking on the surface near the loaded end extended from the test bar towards the corners of the specimen (see Fig. 3.1). Cracking on the surface near the free end was much steeper, extending only a few inches away from the test bar. Figure 3.2 shows the decrease in width of a typical failure surface from the loaded end to the free end. This reduction in width of the failure surface towards the free end probably occurred because of the variation in stress between the loaded end and the free end of the test bar. A study of the stress distribution along anchored bars is presented in Ref. 17.

3.1.2 General Load vs. Slip Behavior. Figure 3.3 shows typical load vs. slip curves for loaded and free end slips. As expected, loaded-end slips were larger than those at the free end. Also, free-end slips became noticeable only after a significant load had been applied, while the loaded end started slipping almost immediately. In the early stages, the amount of slip for each load increment increased as the applied load level increased. At ultimate, the load slip curve was horizontal; at failure, the curve was descending. At the free end, slip usually started only after considerable load had been applied. Slip at the free end was relatively small at failure (about 20% of that at the loaded end).

3.1.3 Test Results. Figures 3.4 through 3.6 show the test results for Series II, V, and VI. These results are presented as stresses for the various specimen heights. Results for top and bottom cast bars in low and high slump concrete are included within each specimen height. As mentioned in Chapter 2, the 6 in. specimens had only top cast bars, and Series V had only high slump concrete without superplasticizer. For a general description of the various series, refer to Table 2.1. Figures 3.4, 3.5, and 3.6 show the ultimate stresses, stresses at 0.01 in. loaded-end slip, and stresses at 0.001 in. free-end slip for all specimen heights of series II, V, and VI, respectively.

loaded end



free end

Fig. 3.1 Crack pattern - #8 bar development length test specimens.

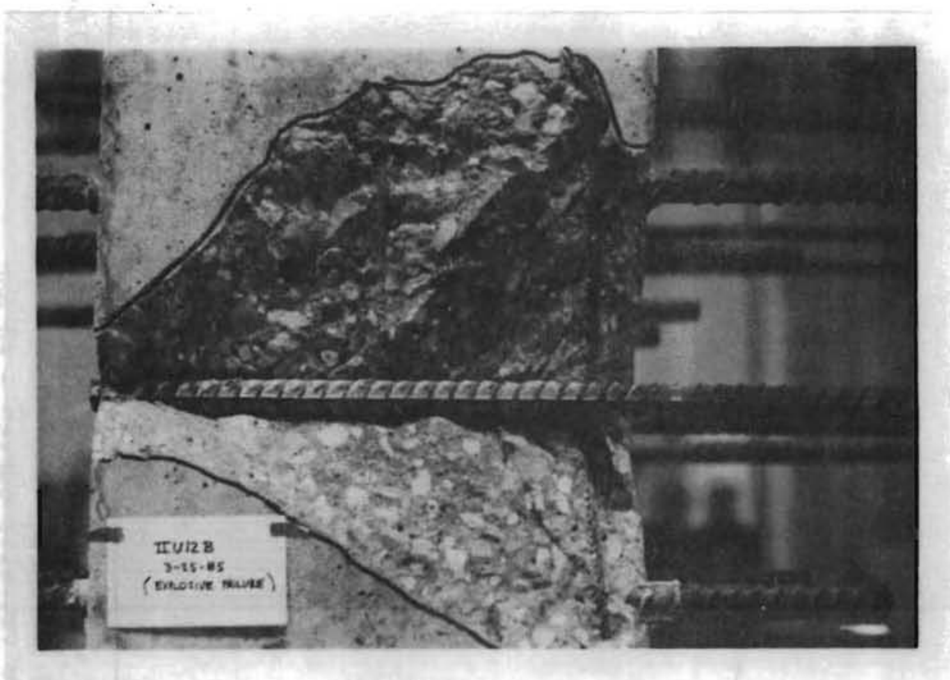


Fig. 3.2 Failure surface - #8 bar development length test spicimen.

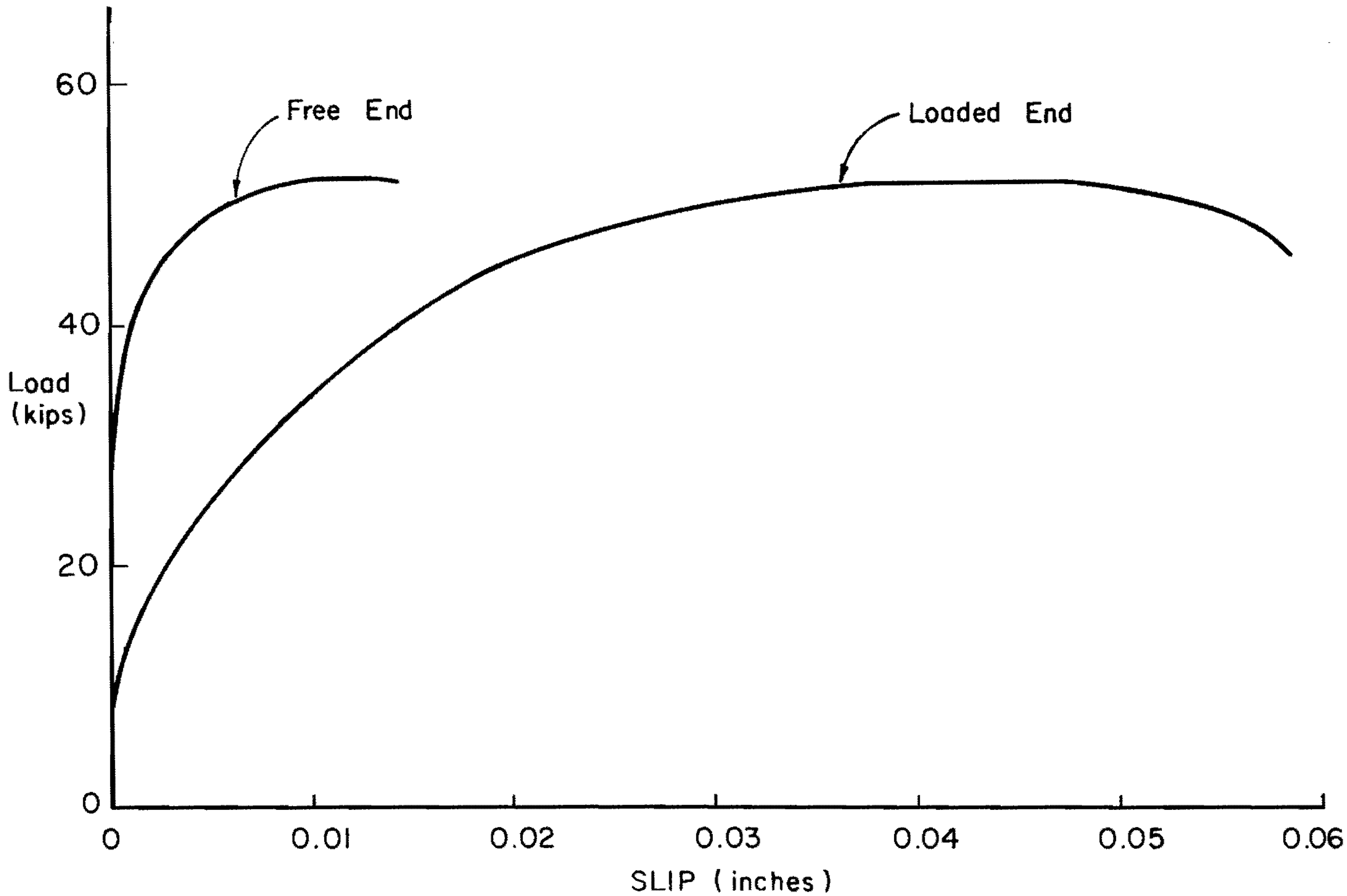


Fig. 3.3 Typical load vs. slip curves - #8 bar development length test.

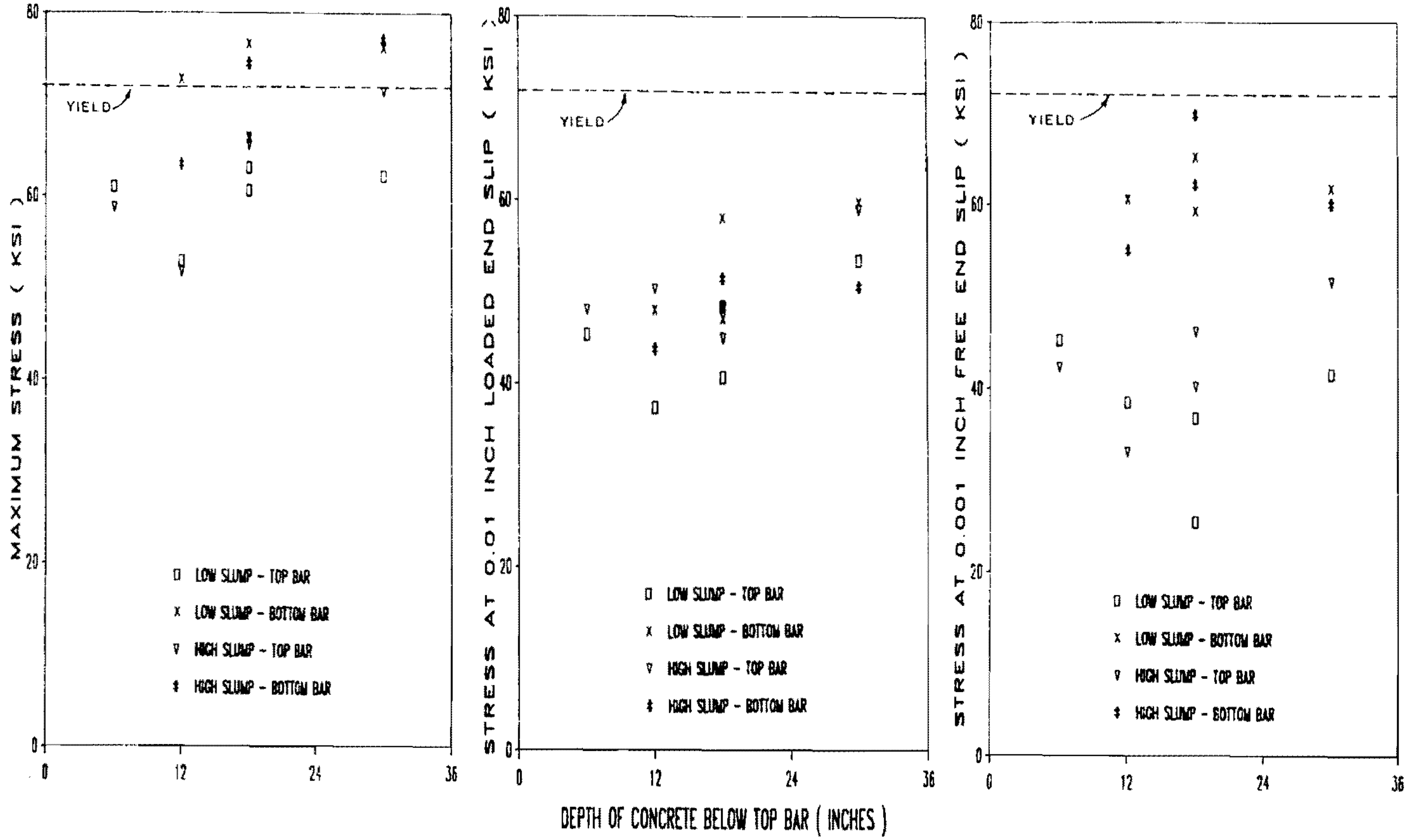


Fig. 3.4 Stress vs. specimen height. #8 development test - low temperature (Series II).

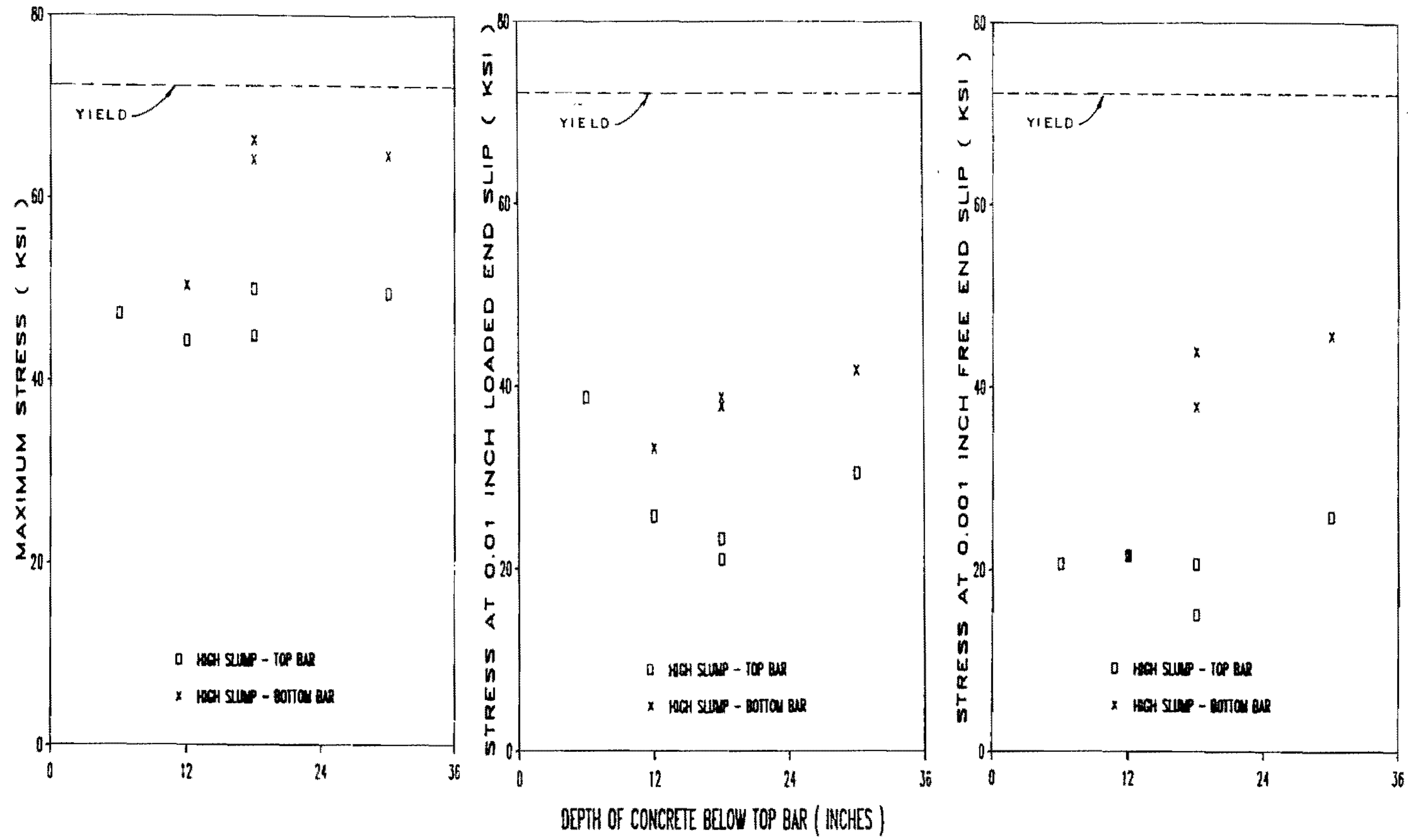


Fig. 3.5 Stress vs. specimen height. #8 development test - high slump concrete, no superplasticizer (Series V).

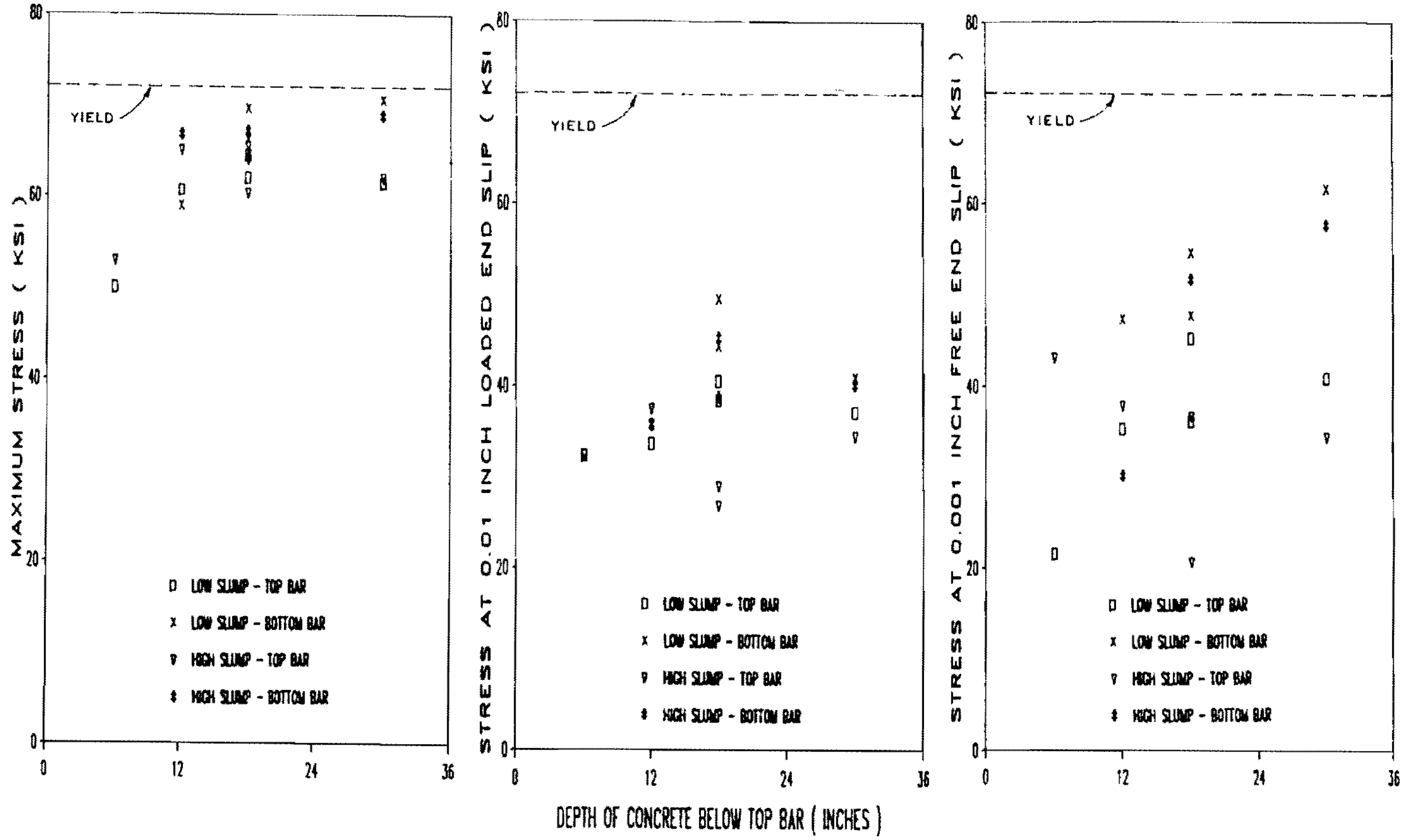


Fig. 3.6 Stress vs. specimen height. #8 development test - high temperature (Series VI).

3.2 Splice Tests of #8 Bars

3.2.1 Failure Pattern. The failure pattern for splice tests typically consisted of a V-notch with concrete splitting extending to the side of the specimen (see Fig. 3.7). Since a spliced bar was pulled from each side of the specimen, both sides exhibited similar crack patterns.

Splices failed as the two test bars were pulled simultaneously from opposite sides of the specimen. The face cover concrete was cracked over the splice due to radial stresses from the bars. This crack appeared over the loaded end of each bar, shifting from one bar to the other approximately at the center of the specimen.

As with the development-length tests, the width of the failure surface decreased from the loaded end to the free end. But since both sides of the specimen were loaded, this width was approximately constant, decreasing slightly towards the center of the specimen (see Fig. 3.8). Cracking was hardly noticeable prior to failure, and splitting of the concrete cover was sudden.

3.2.2 General Load vs. Slip Behavior. Figure 3.9 shows typical load vs. slip curves for loaded and free end slip of spliced bars. Spliced bars usually slipped less than development length test bars before failure, especially at the loaded end. A reason for this difference may be that splices, are not as able as single bars to redistribute the load along the bar to lower-stressed concrete. Since the concrete on both ends of the splice is at high stress, the concrete at the free end of the bar cannot provide additional load carrying capacity when the cover at the loaded end fails.

Figure 3.9 also shows that in splices, the difference between loaded-and free-end slip is not as large as that observed in development-length tests. This may also be due to the higher stress level in the concrete at the free end of spliced bars. Since cracks may develop in the concrete at the free end of a spliced bar due to stresses induced by the bar adjacent to it, free end slip is greater.

3.2.3 Test Results. Figures 3.10 and 3.11 show the test results for Series IV and V. As in Section 3.4.3 for single bar tests, the stresses for the various specimen heights are presented. Results for top and bottom cast splices in low and high slump concrete are included within each specimen height. Refer to Table 2.1 for a description of the series involved.

Figures 3.10 and 3.11 show the ultimate stresses, stresses at 0.01 in. loaded-end slip, and stresses at 0.001 in. free-end slip for all specimen heights of series IV and V, respectively.

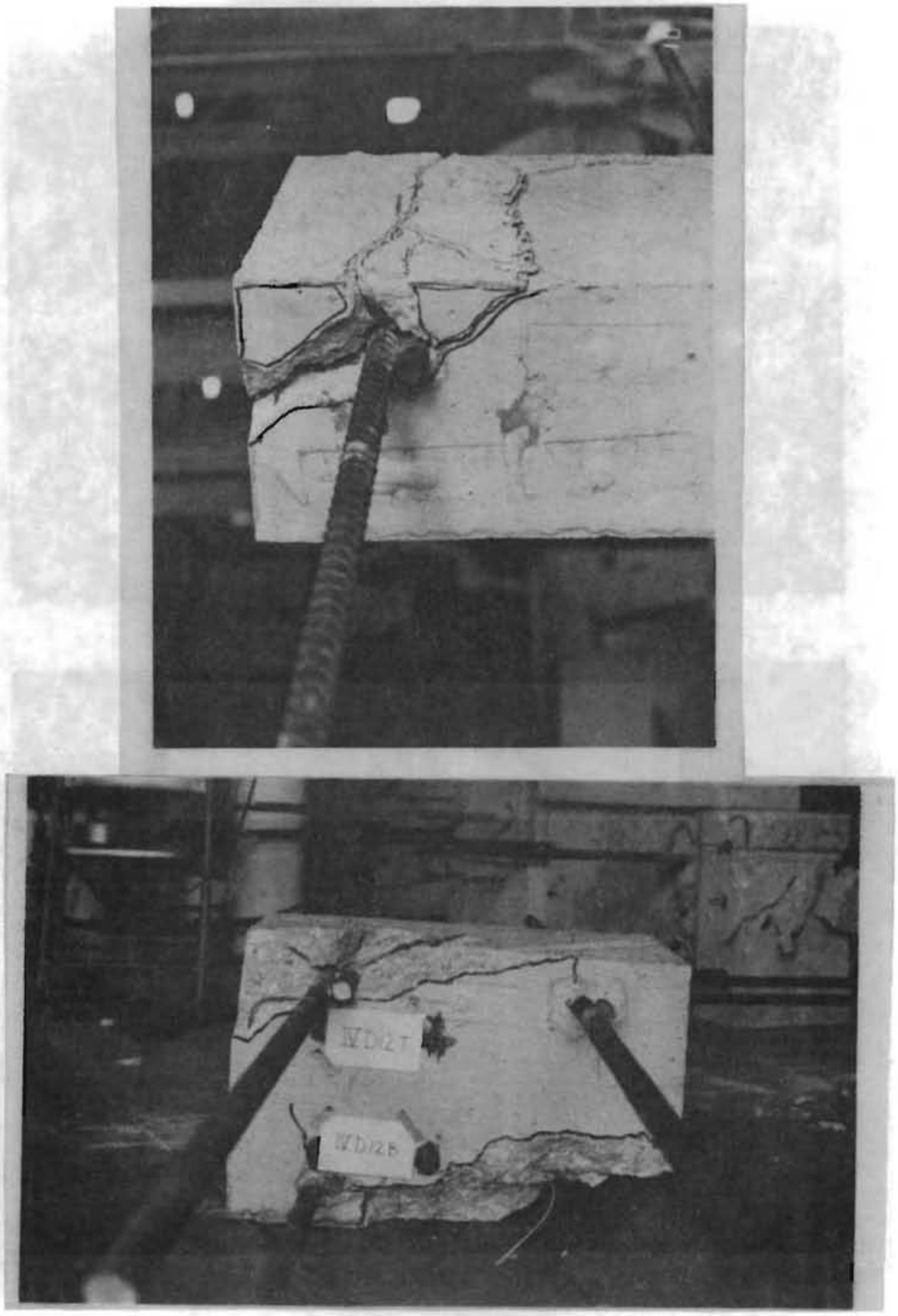


Fig. 3.7 Crack Pattern - #8 splice specimens.

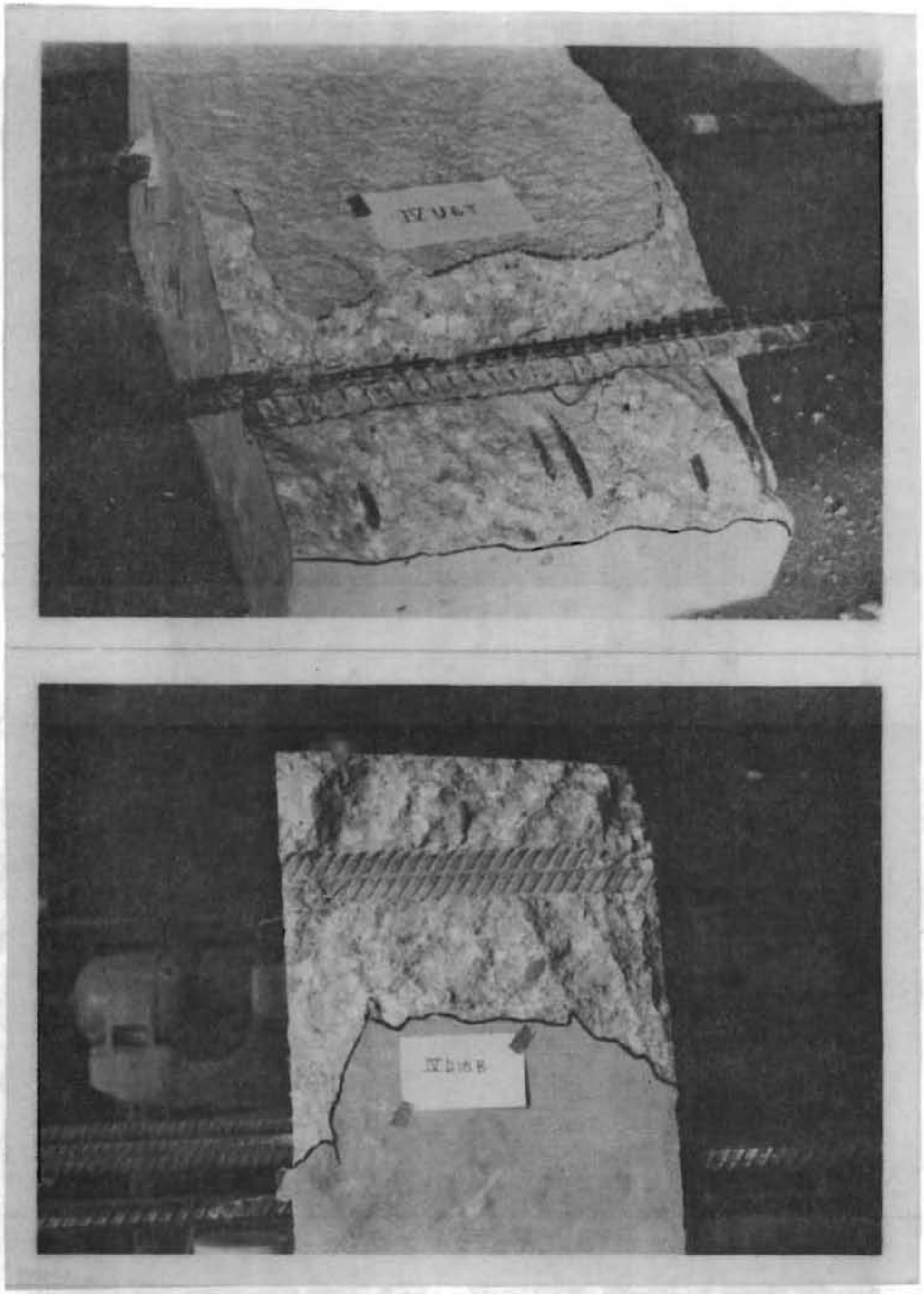


Fig. 3.8 Failure surface - #8 splice specimens.

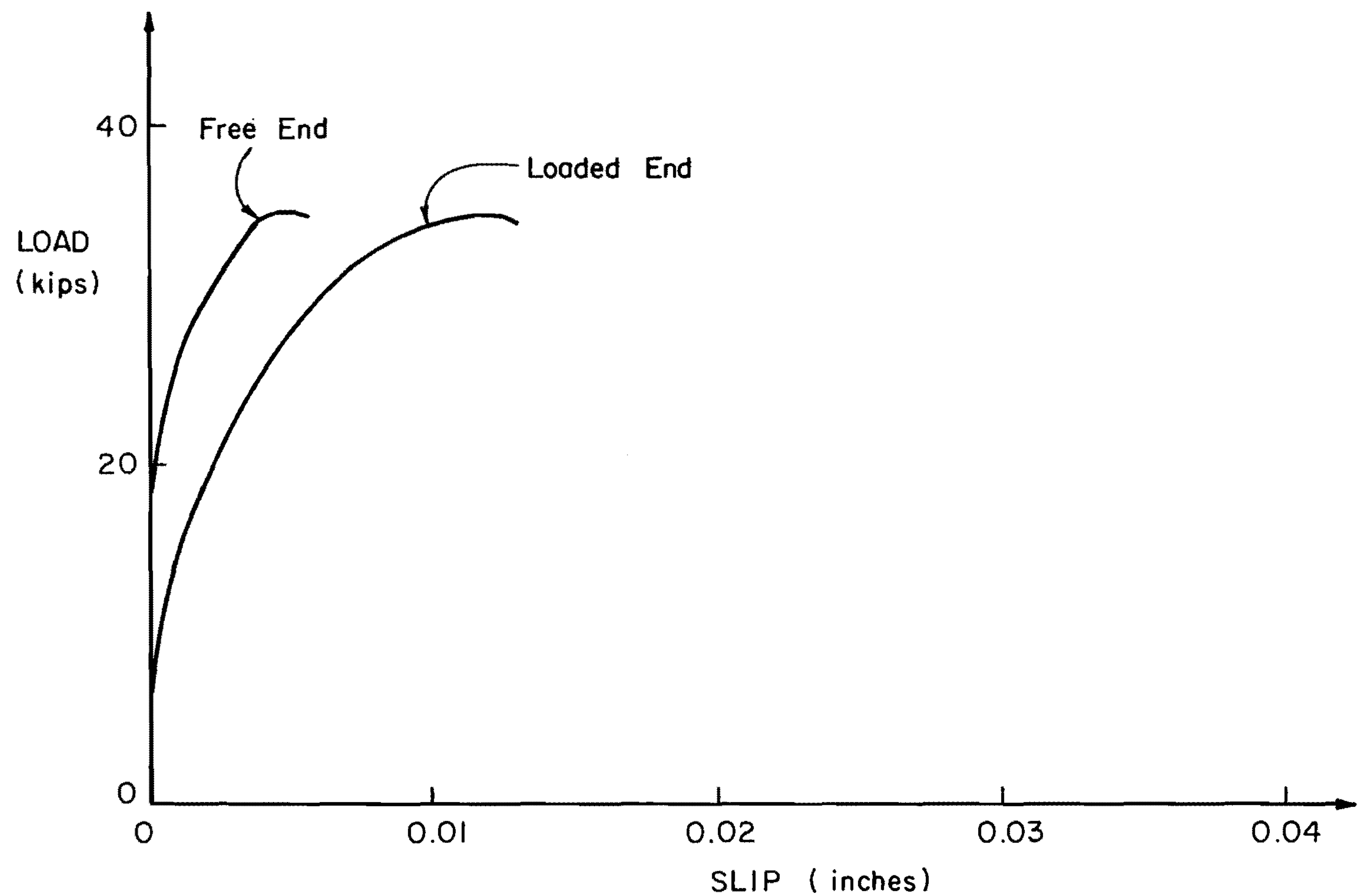


Fig. 3.9 Typical load vs. slip curves - #8 splice test.

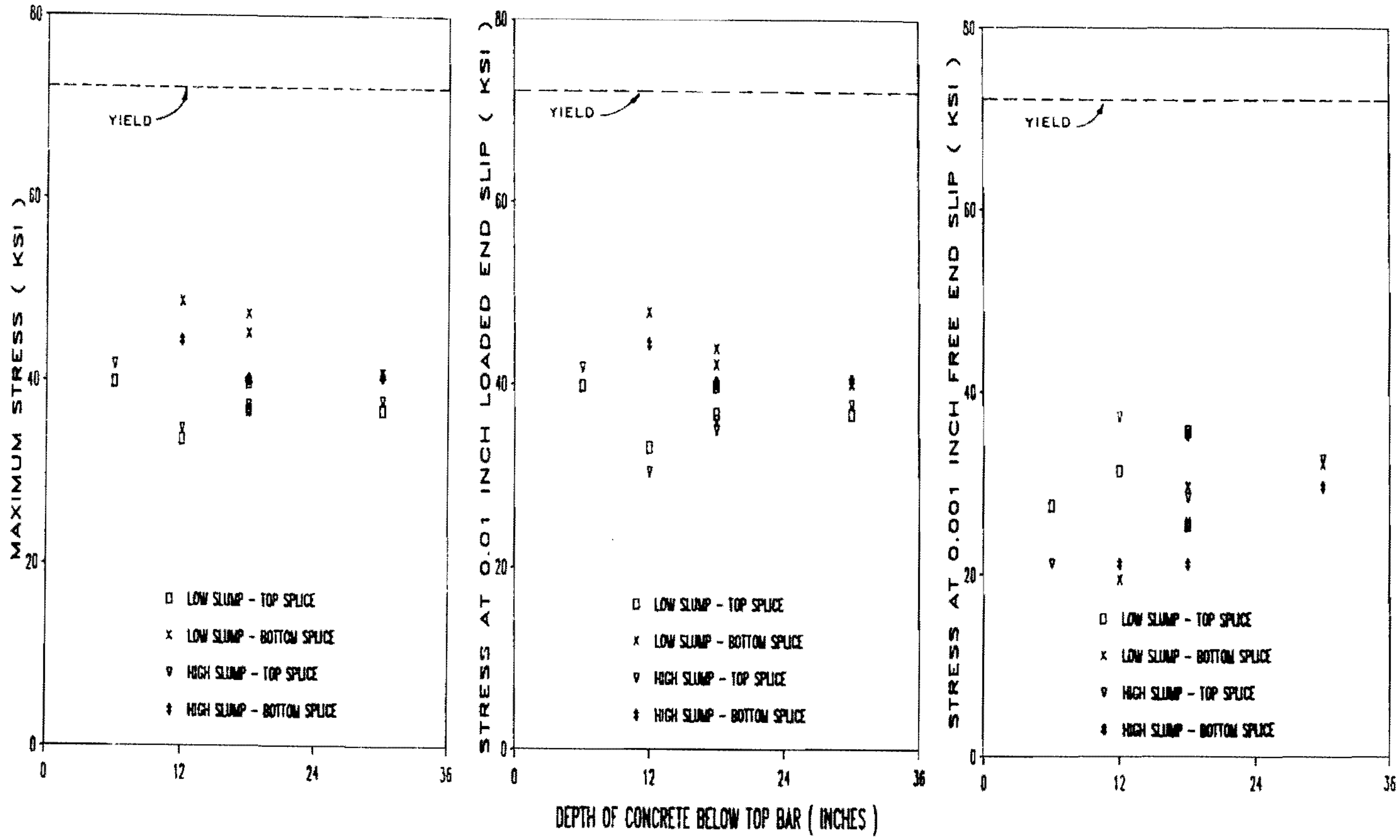


Fig. 3.10 Stress vs. specimen height. #8 splice test
(Series IV).

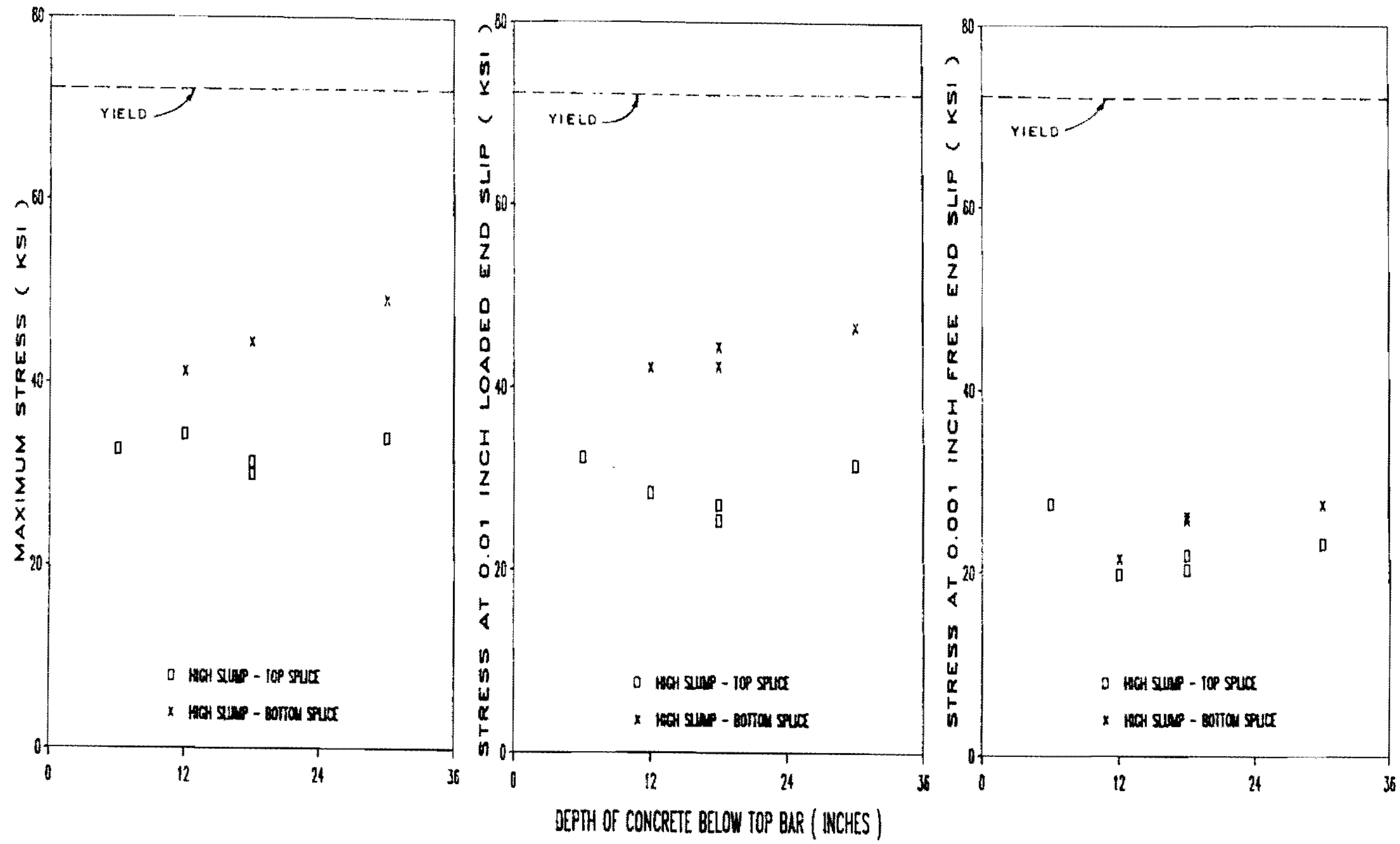


Fig. 3.11 Stress vs. specimen height. #8 splice test-
high slump concrete, no superplasticizer (Series V).

3.3 Development Length Tests of Strand

3.3.1 Failure Pattern. The 1/2 in. 7-wire strand development length test specimens failed with no apparent distress to the concrete. The strands were pulled through the specimen with no visible cracking or shearing of the concrete.

Since the tests of prestressing strands were added after the specimens and test frame had been designed, the strand specimens were constructed in the same manner as those for #8 bars. Therefore, the strands were not prestressed, and did not have the benefit of transverse expansion at their free end due to the Poisson effect. It was noted that the tendons appeared to "twist" or unwind out of the concrete as load was applied. Such a phenomenon would not be possible in an actual member. Therefore, the strand tests cannot be considered indicative of behavior in a concrete member.

3.3.2 General Load vs. Slip Behavior. Figure 3.12 shows typical load vs. slip curves for loaded and free end slips of 1/2 in. strands. Loaded-end slip increased very rapidly under loading until the maximum load level was reached. At the peak load, free-end slip began, and both the loaded and free ends slipped with no change in the applied load.

3.3.3 Test Results. Figure 3.13 shows the test results for Series III. It shows the maximum stress, stress at 0.01 in. loaded end slip, and stress at 0.001 in. free-end slip for the various specimen heights. The stresses for top and bottom cast strands in low and high slump are included within each specimen height.

3.4 Analysis of Bond Test Results

Bar stresses at ultimate were used to determine the effect of superplasticizers on bond for the variables included in the study. Results of development tests were not compared to those of splice tests because they exhibited different failure patterns. Test results were not normalized to account for concrete strength variations. The largest adjustments would have been about +/-2.5% based on the square root of f'_c values. Adjustments in about the same range would have been obtained based on splitting tensile strength, but these adjustments were in the opposite sense for some series. Therefore, no normalization of test results was considered justified considering the small magnitude of the necessary adjustments.

3.4.1 High Slump Superplasticized Concrete vs. Low Slump Ordinary Concrete. The bond performance of bars in high slump superplasticized concrete is compared with that of bars in low slump ordinary concrete in Figs. 3.14, 3.15, and 3.16. The ratios of bar stress for high slump superplasticized concrete over that for low

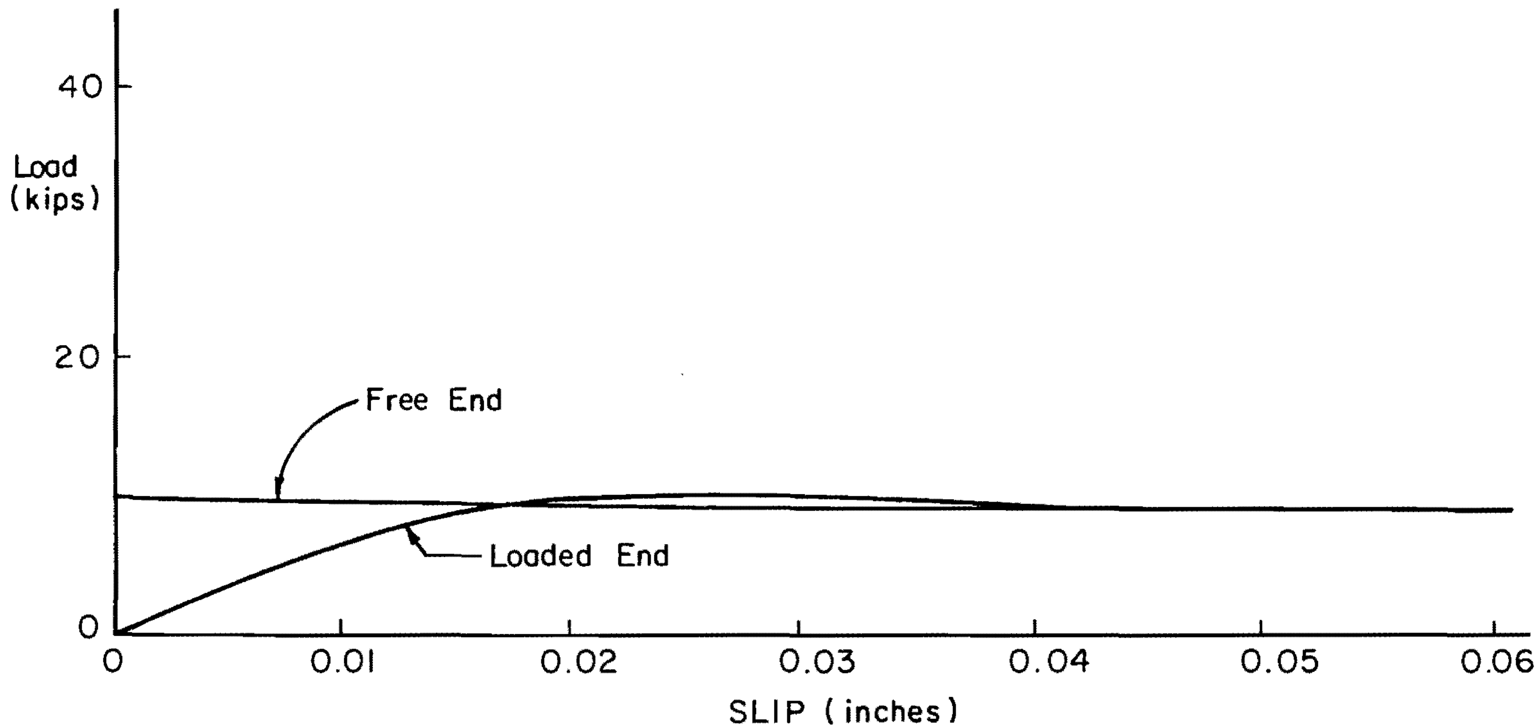


Fig. 3.12 Typical load vs. slip curves - 1/2 in. strand development length test.

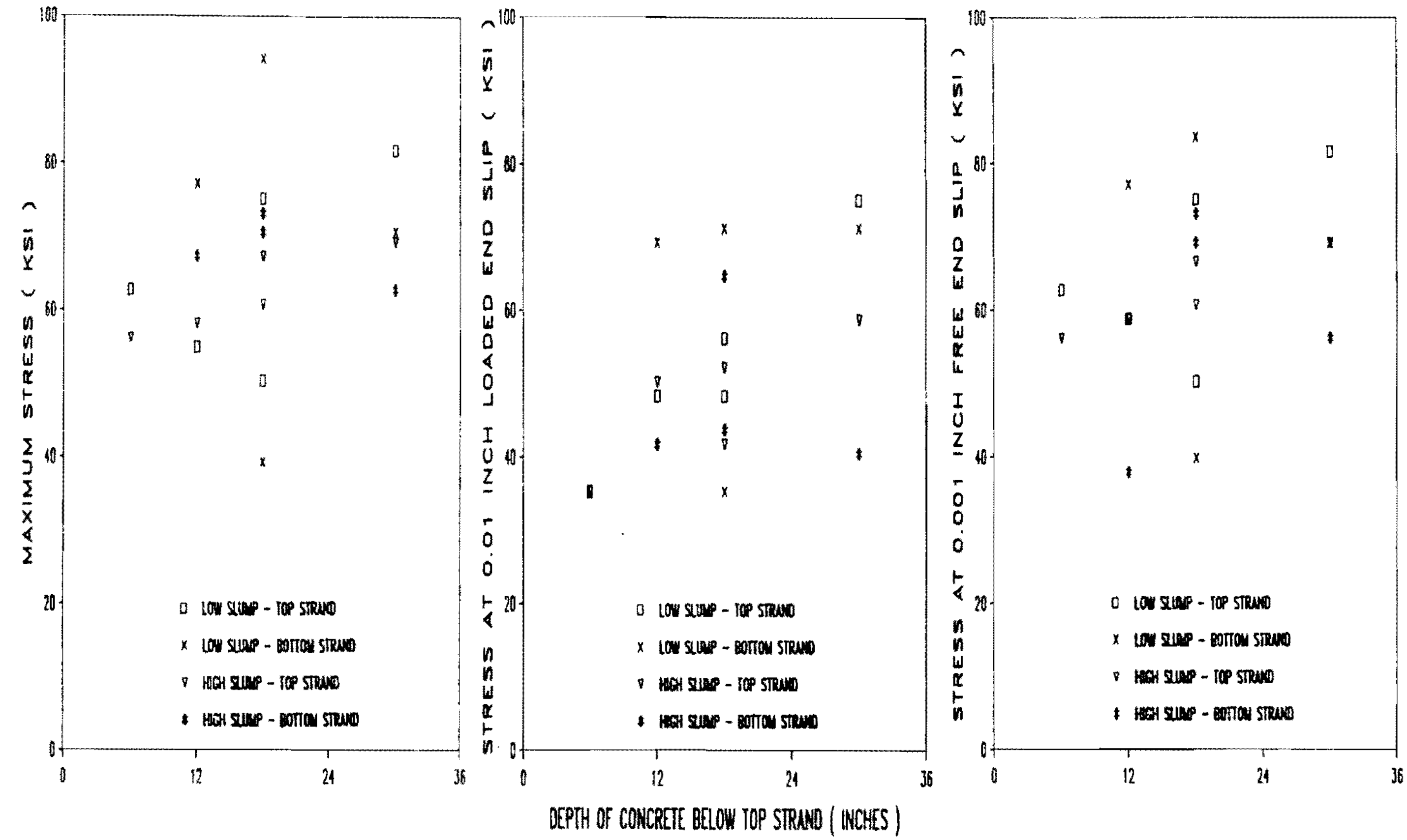


Fig. 3.13 Stress vs. specimen height. 1/2 in. strand development length test.

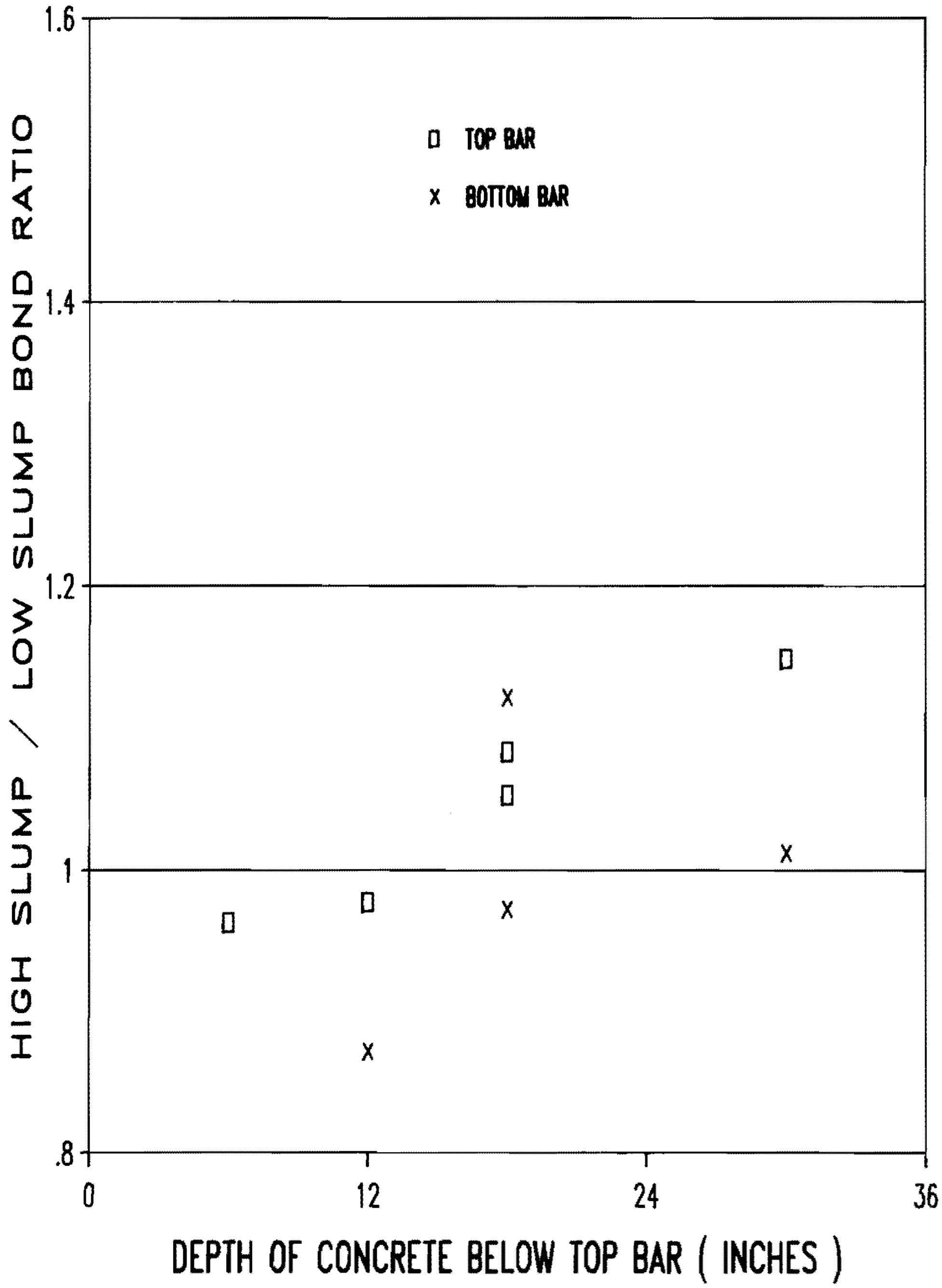


Fig. 3.14 Ratio of bond strength in high (7 in.) slump superplasticized concrete and low (2.5 in.) slump ordinary concrete. development test - low temperature (Series II).

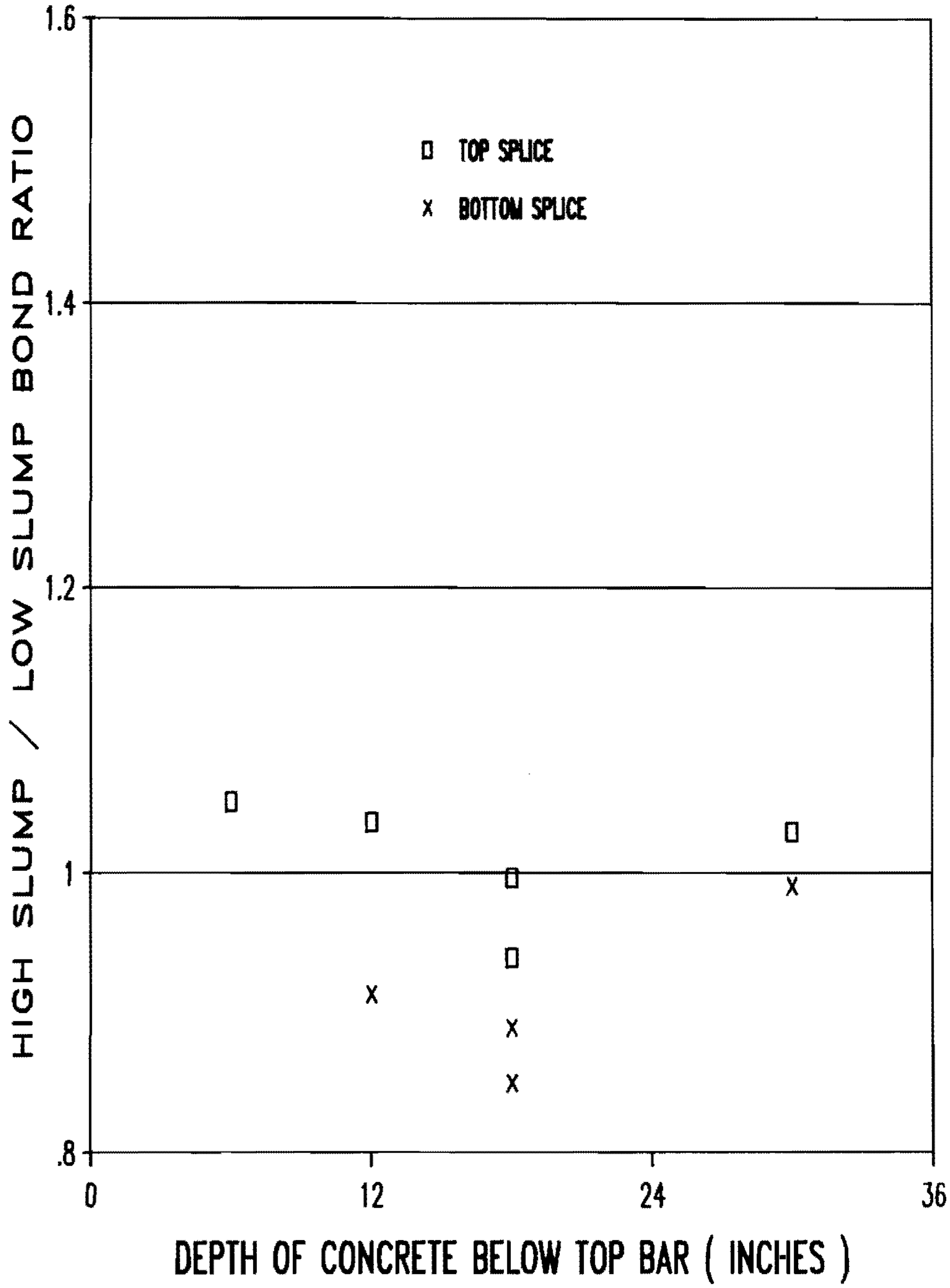


Fig. 3.15 Ratio of bond strength in high (6.5 in.) slump superplasticized concrete and low (3 in.) slump ordinary concrete. Splice test (Series IV).

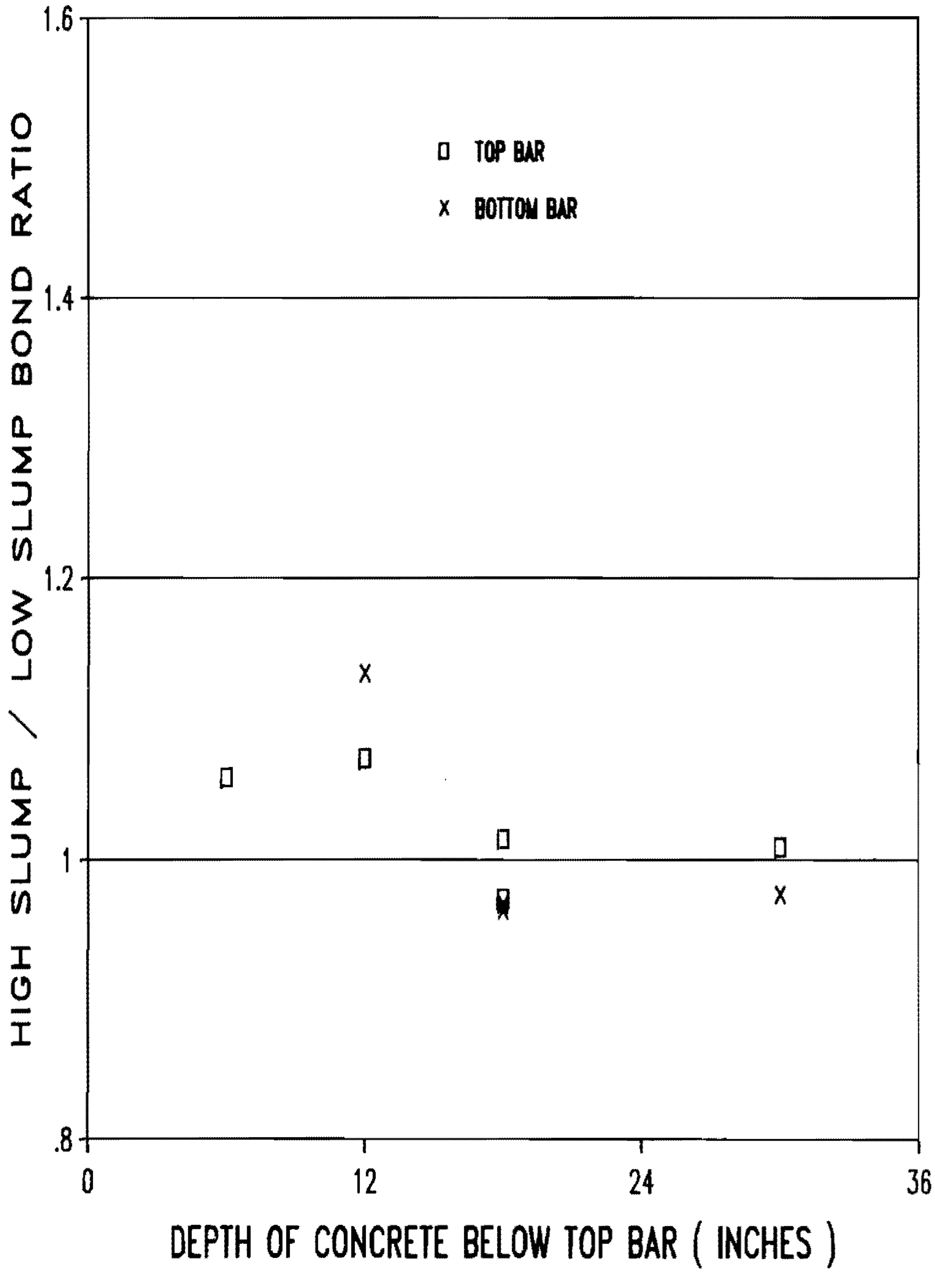


Fig. 3.16 Ratio of bond strength in high (7.5 in.) slump superplasticized concrete and low (3 in.) slump ordinary concrete. Development test - high temperature (Series VI).

slump ordinary concrete are presented for Series II, IV, and VI. These ratios were determined for bars of corresponding casting position and specimen depth for the two concrete types. A ratio higher than one indicates a better bond performance for superplasticized concrete than for low slump ordinary concrete.

The values in Figs. 3.14 through 3.16 are close to unity, with a slight tendency to be higher than unity except for the bottom splices of Series IV. Therefore, no variation in the anchorage capacity of deformed reinforcement was obtained by increasing the concrete slump using superplasticizer. There appears to be no need to modify required development lengths for the effect of superplasticizer.

3.4.2 High Slump Superplasticized Concrete vs. High Slump Ordinary Concrete. The bond capacities of deformed reinforcement cast in superplasticized high slump concrete and ordinary (non-superplasticized) high slump concrete are shown in Figs. 3.17 and 3.19. The comparison is presented in the form of ratios of bar stress values for bars and splices cast in superplasticized high slump concrete to those for bars and splices cast in the corresponding positions in ordinary high slump concrete. The average of all ratios was greater than 1.1, indicating that high slump concrete made with superplasticizer consistently gave better bond performance than did concrete whose slump had been increased by adding water.

The development bond capacity increased an average of about 20% for bottom bars, and about 35% for top bars. An increase of about 20% was obtained for top splices, while the average capacity ratio of bottom splices was abut 0.95. However, the overall trend is clear - the use of superplasticizer provides a concrete with greater bond capacity than does a high slump concrete obtained by using water in proportioning the mix.

3.4.3 Effect of Temperature on Superplasticized Concrete. In planning the test program, the initial hypothesis was that bleeding of concrete would decrease with increasing temperature. A reduction in amount of bleed was expected to improve the bond capacity of reinforcing bars. From the limited data shown in Fig. 3.19, however, the role of temperature is not clear.

In Fig. 3.19 are shown the ratios of bond strength for bars cast in similar positions during hot (78^{o}) and cold (58^{o}) casting temperatures. Most ratios fall in a narrow band between 0.9 and 1.0. No distinction between top or bottom bars or between bars in concrete with low slump (no superplasticizer) or high slump (superplasticizer added) is evident. To define the effects of temperature on the bond capacity of deformed bars, a greater number of tests would be needed with a wider range of variables considered.

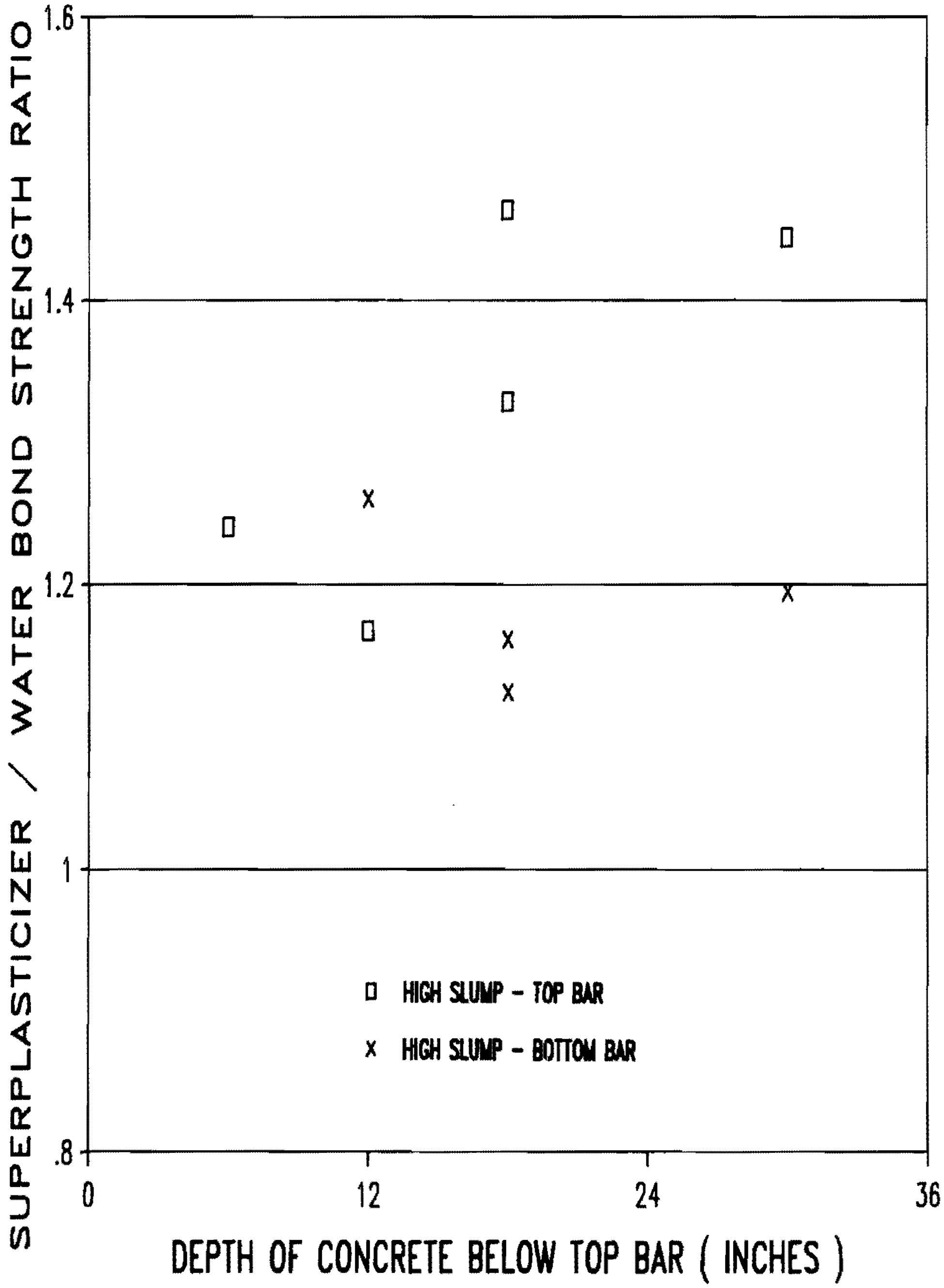


Fig. 3.17 High (7 in.) slump superplasticized concrete vs. high (7.5 in.) slump ordinary concrete - development tests.

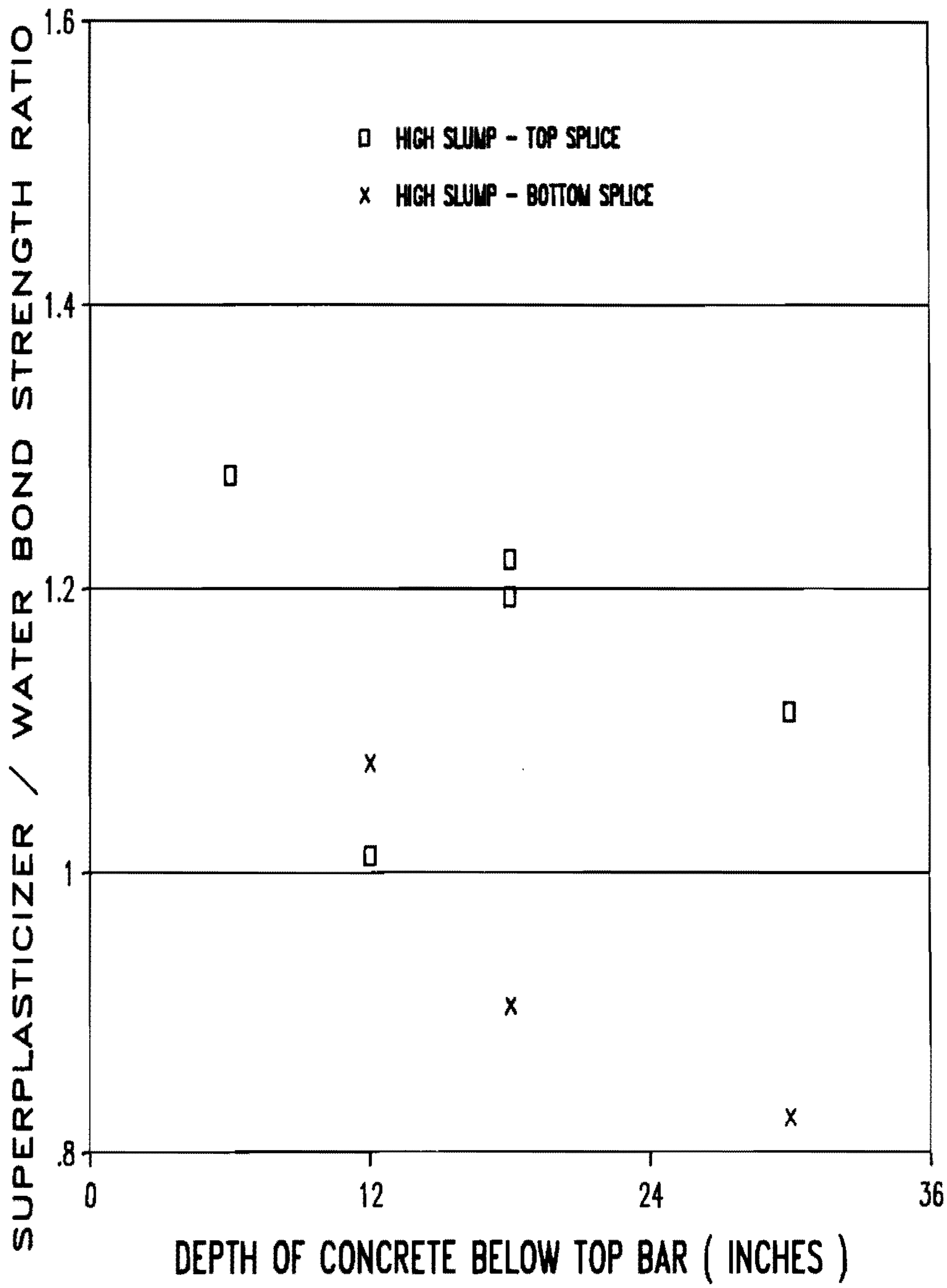


Fig. 3.18 High (6.5 in.) slump superplasticized concrete vs. high (7.5 in.) slump ordinary concrete - splice tests.

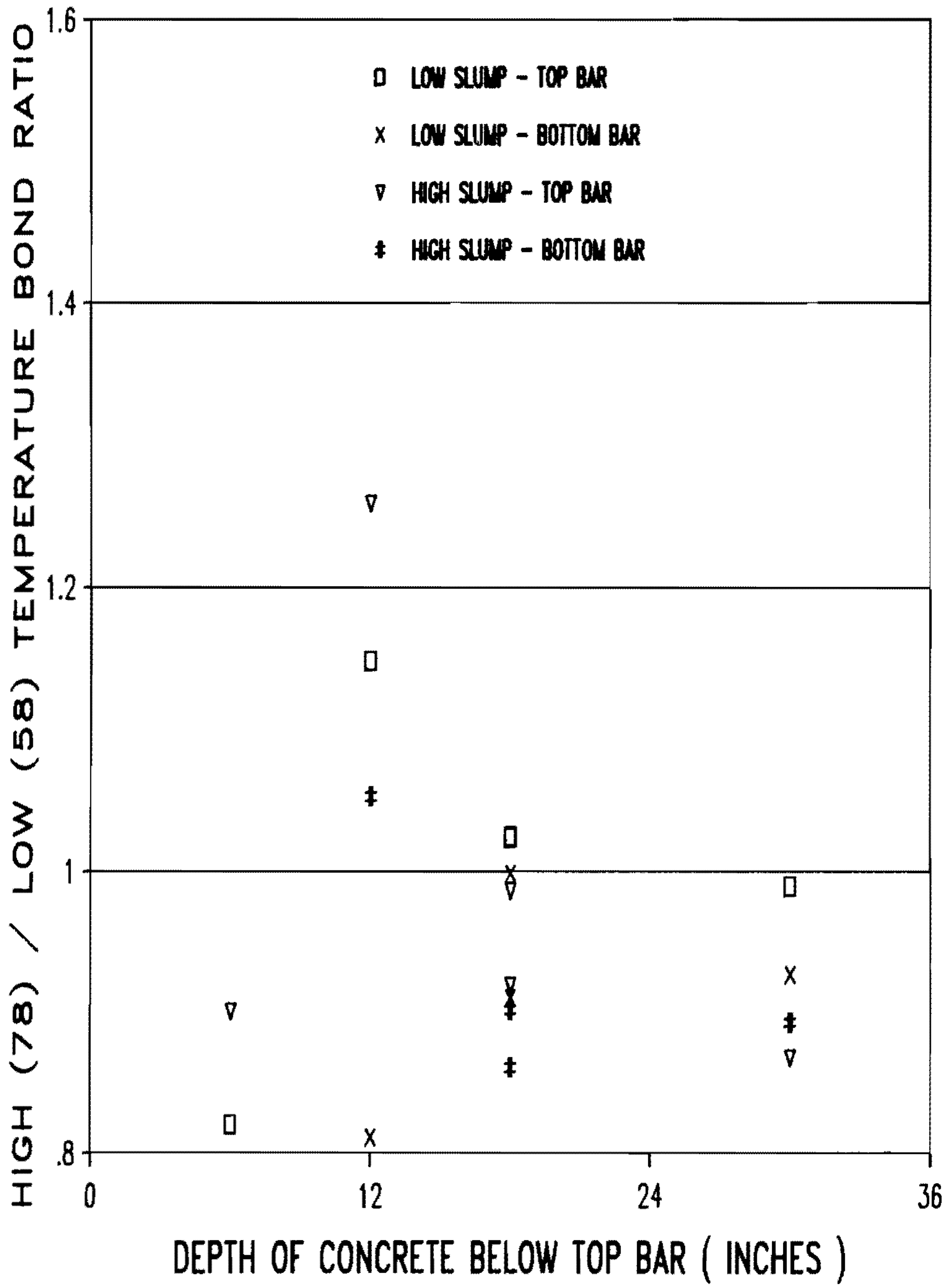


Fig. 3.19 Effect of casting temperature on bond capacity - development tests.

3.5 Effect of Superplasticizers on Casting Position Bond Factor

Figures 3.20 through 3.23 show the top bar factor for Series II, IV, V, and VI. The top bar development length factor for each concrete mix was obtained by dividing the average value for the bottom bar strengths in that mix, by the top bar strength. An average value was used for the bottom bar to give results which represent a reference value for each series. Regardless of the depth of concrete above the bottom bar, the placement procedure for all bottom bars were the same. The concrete was placed in 7-8 in. lifts and vibrated. Therefore the consolidation procedure and the age of the fresh concrete at the time the bottom bars were cast was nearly identical for all the bars in a given series.

Ratios of bottom bar to top bar results were used to represent a development length factor for top bars compared to the development length required for bottom bars. This factor is analogous to the one specified in the AASHTO and ACI codes for horizontal bars with more than 12 in. of concrete cast below the bar. Such bars are called top reinforcement and a 1.4 modification factor is specified for their development length. Since development length is inversely proportional to bond efficiency, this 40% increase in required development length corresponds to a 30% decrease in bond efficiency for top bars compared to bottom bars.

The results obtained indicate that the development length factor for top bars and splices is smaller for high slump superplasticized concrete than for low slump ordinary concrete (Series II, IV, VI). The difference is greatest when comparing the top bar factors obtained for superplasticized concrete, with the top bar factors for high slump ordinary concrete (Series V). The factors obtained for bars and splices cast in cold temperature are similar; about 1.1 for superplasticized concrete, 1.2 for low slump ordinary concrete, and 1.35 for high slump ordinary concrete.

The effect of temperature on bond of bars cast in both superplasticized and low slump ordinary concrete can be seen by comparing Figs. 3.20 and 3.23. For low temperature concrete, the top bar factors (Fig. 3.20) average about 1.2 while for high temperature concrete, the factor is about 1.05. Also, the scatter is less for the high temperature concrete.

These casting position factors appeared to be independent of variations in the depth of the specimen. In general, top bars had the same bond capacity whether 6, 12, 18, or 30 in. of concrete was cast below the bar. The greatest deviation from this pattern occurred for the 6 in. high specimens in Series VI. Even though the top bars in these specimens would be classified as bottom bars by the ACI code, they exhibited the greatest top bar factor. Since these shallow

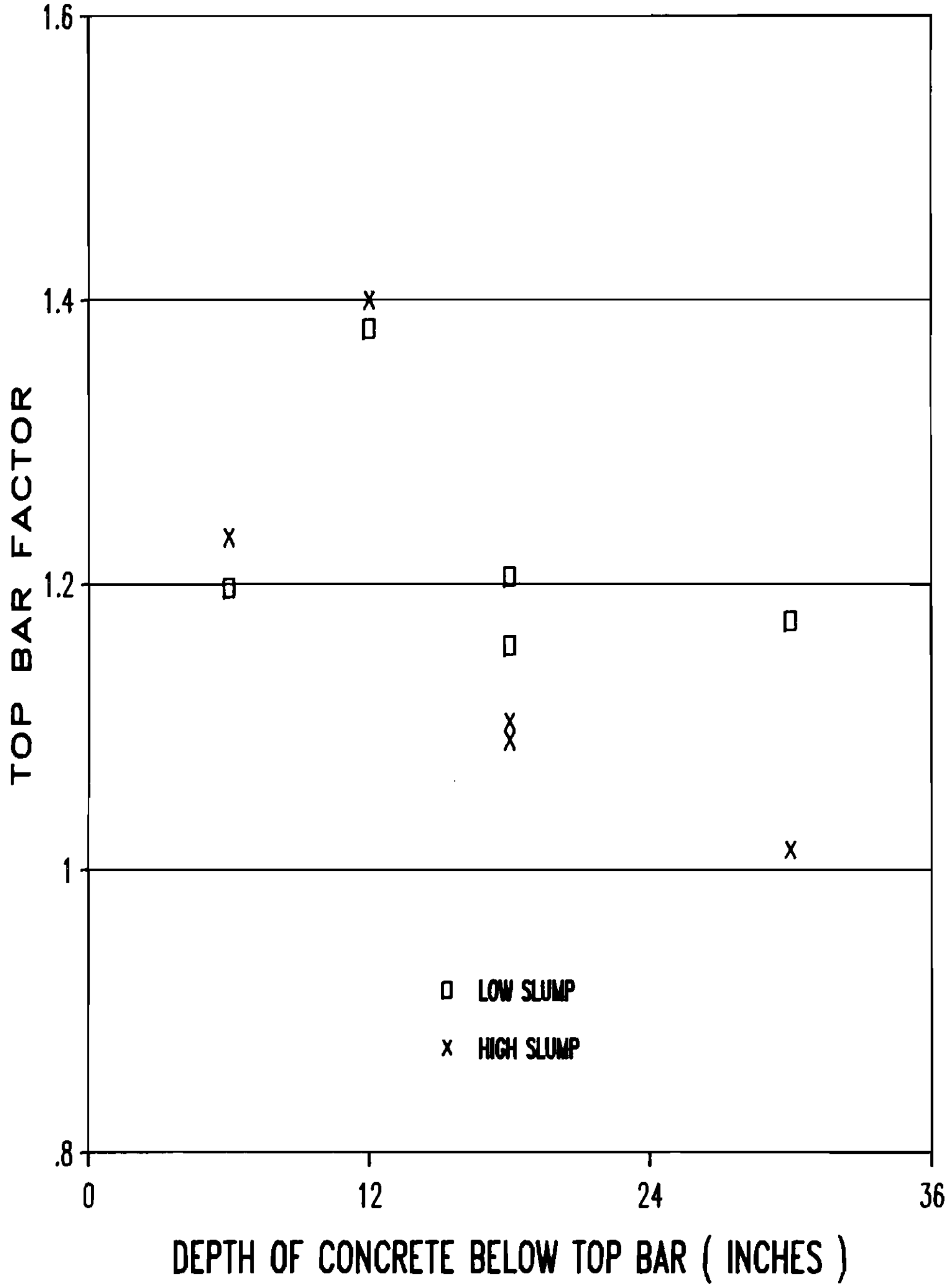


Fig. 3.20 Top bar development length factor. Series II (low temperature).

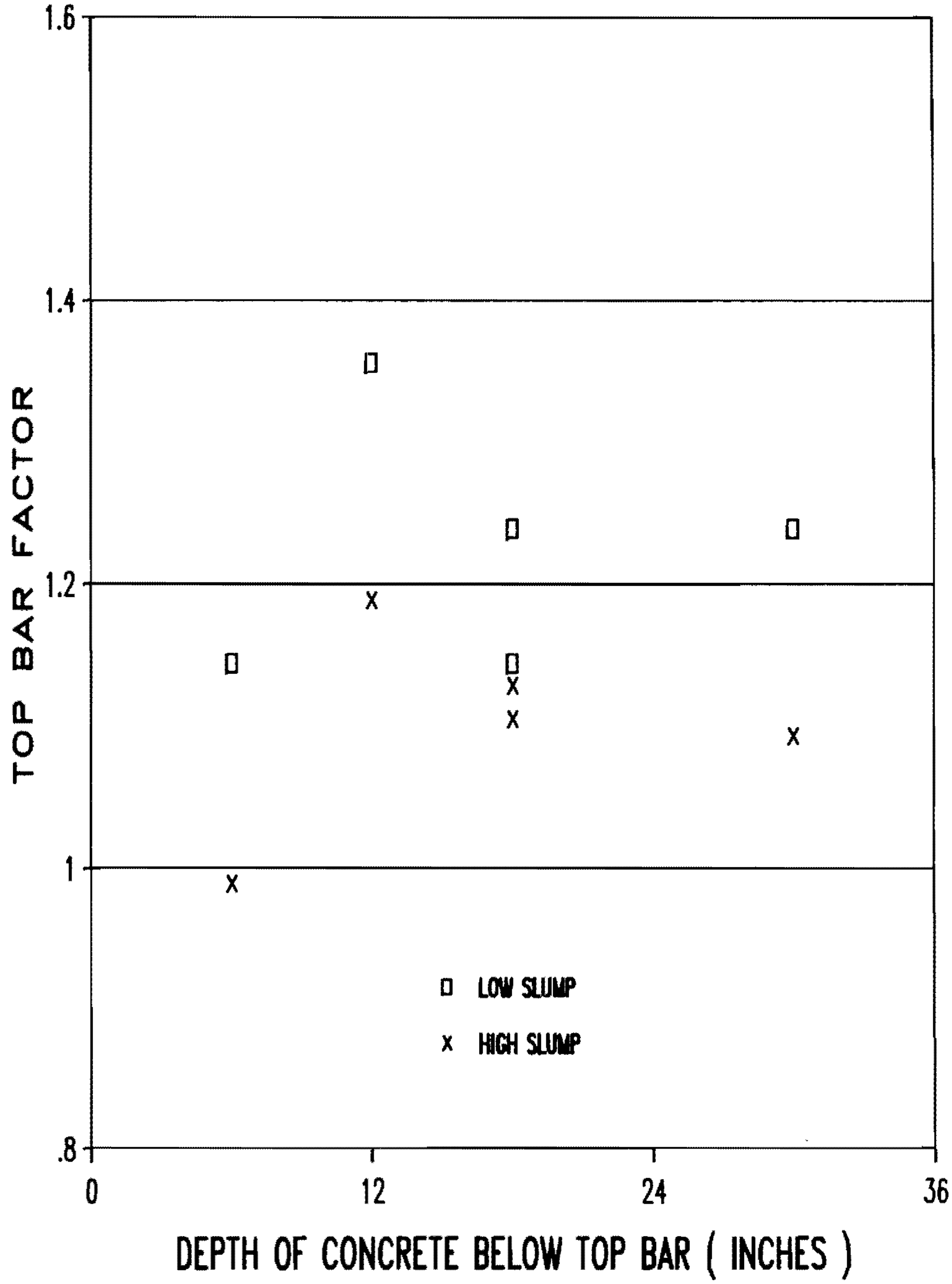


Fig. 3.21 Top splice development length factor. Series IV (low temperature).

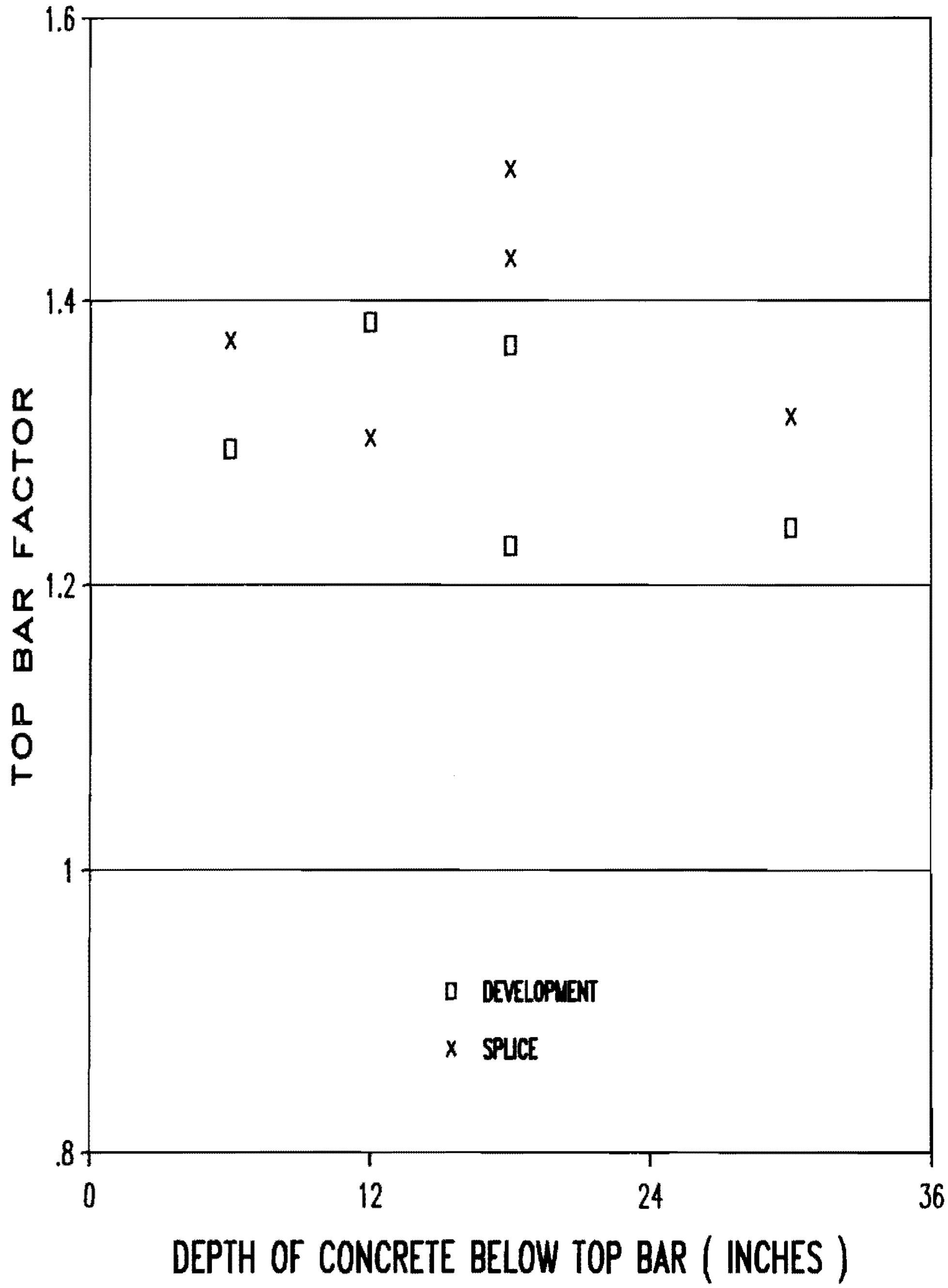


Fig. 3.22 Top bar and splice development length factor.
Series V - high slump - no superplasticizer.

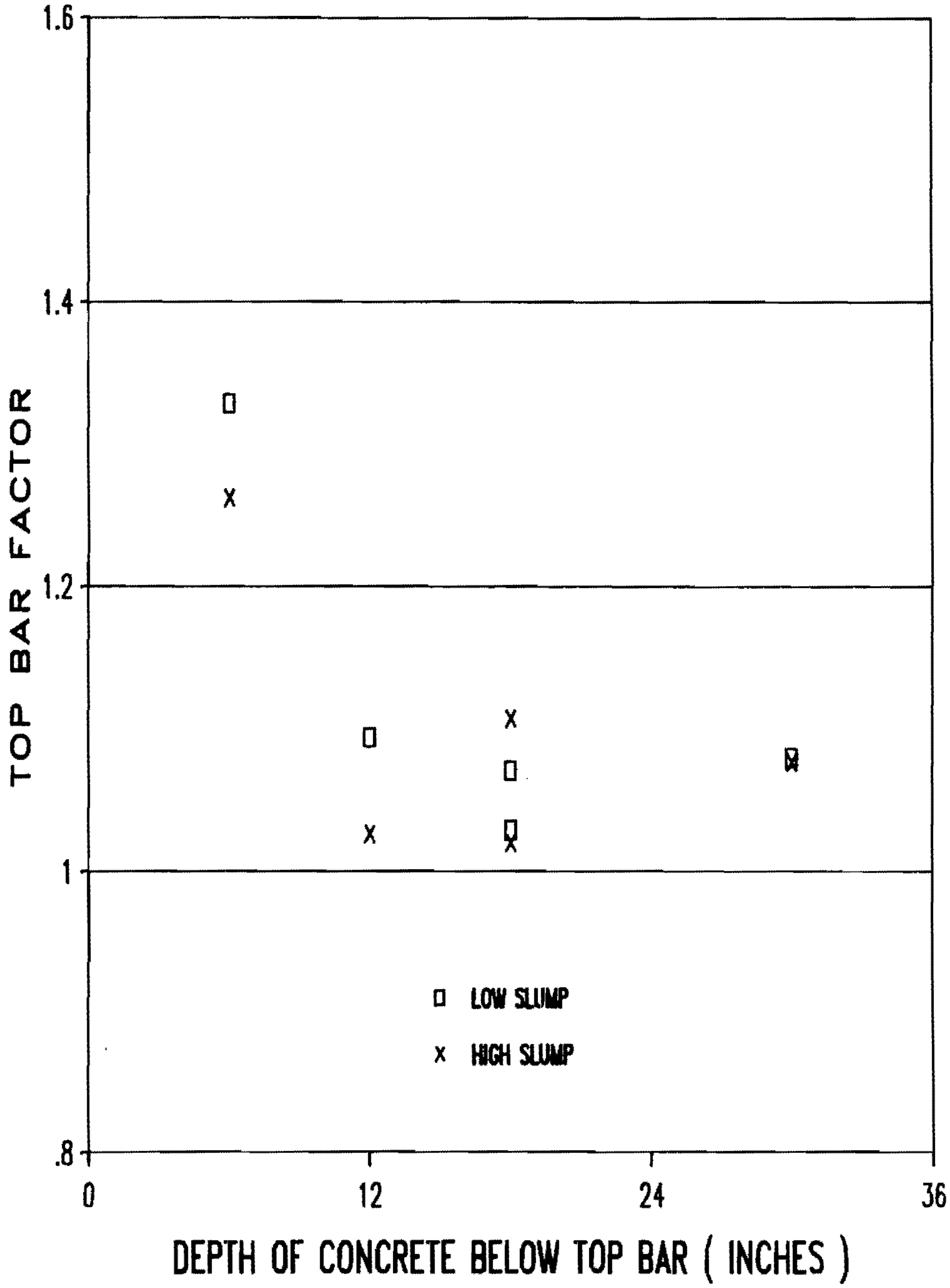


Fig. 3.23 Top bar development length factor. Series VI (high temperature).

specimens did not include bottom bars, and similar behavior was obtained for low and high slump concrete, it is uncertain whether this deviation should be considered as scatter or as the result of some factor not considered herein. One such factor could be the interaction between flexural stresses produced during testing, and the stresses produced by drying shrinkage cracking due to the high surface to volume ratio of these shallow specimens cast at high temperature.

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CHAPTER 4

BLEED TESTS

4.1 Cumulative Bleed

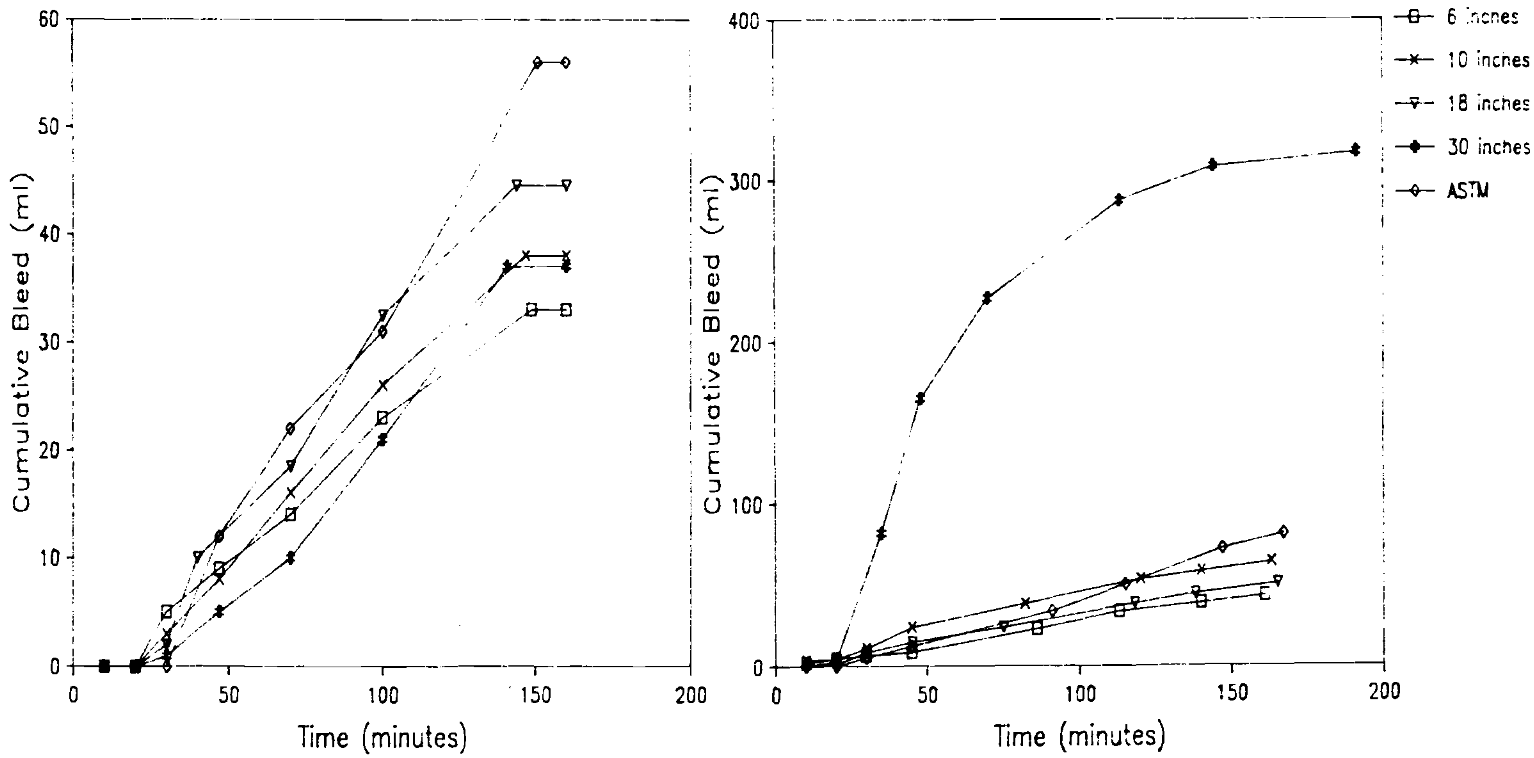
Cumulative bleed versus time curves for each series are depicted in Figs. 4.1 through 4.5. The curves for the dosed concrete are based on the average of two bleed tests. For the undosed concrete and for the ASTM test, only one bleed test was conducted. Time is measured from when the concrete was placed in the bleed containers.

For the dosed and undosed concrete of Series II, III and IV, cast at low temperature, bleed generally increased as specimen height increased. Note that the bleed for Series III was three to four times that observed in the other similar low temperature mixes (II,IV). Since Series III involved only bond of 7-wire strands, it is not possible to determine the influence of such high bleed values on bond strength of bars. In Series VI, the high termperature concrete, bleed was too small to show any significant trend. In all the series, the ASTM bleed tests showed higher bleed than that observed using a PVC bleed bucket of the same 10 in. height. Moreover, as shown in Figs. 4.6 and 4.7, the amount of bleed varies for the same specimen height from series to series. In these figures, bleed data for Series III has been omitted since its role on bond strength can not be determined.

From these results, it is evident that increasing the heights of the specimens did not result in a proportional increase in bleed. This implies that the bleed water did not come from the entire height of the specimen, but possibly only from the the top section.

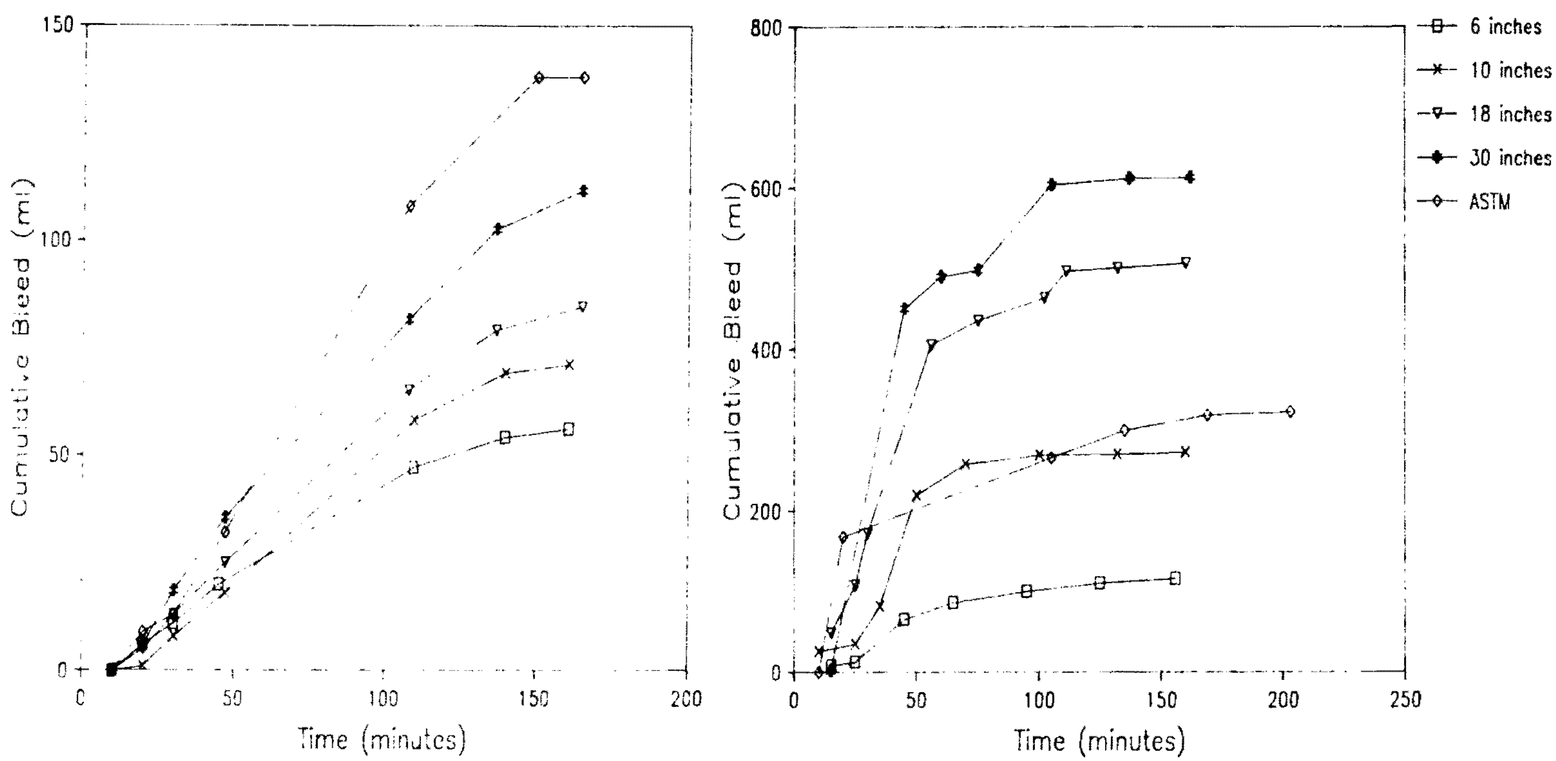
4.2 Bleed Segregation Phenomena

Bleed is considered to be an indication of segregation. Segregation probably occurs in two phases: 1) a rapid phase, which takes place as the concrete is vibrated; and 2) a slow phase, that takes place in the undisturbed plastic concrete after vibration. Recall that in the casting procedure of these tests, the heights of the lifts used and the vibration in each lift were relatively constant. This means that the entire depth of the specimens received equal compactive effort. The resulting segregation due to vibration (the quick phase) and the slow phase would be similar throughout the entire depth of the specimens. Segregation, however does not proceed freely. Settling of the coarse aggregate develops bridging action which stops further settlement [45]. Since segregation occurs throughout the entire specimen depth, bleed water is displaced



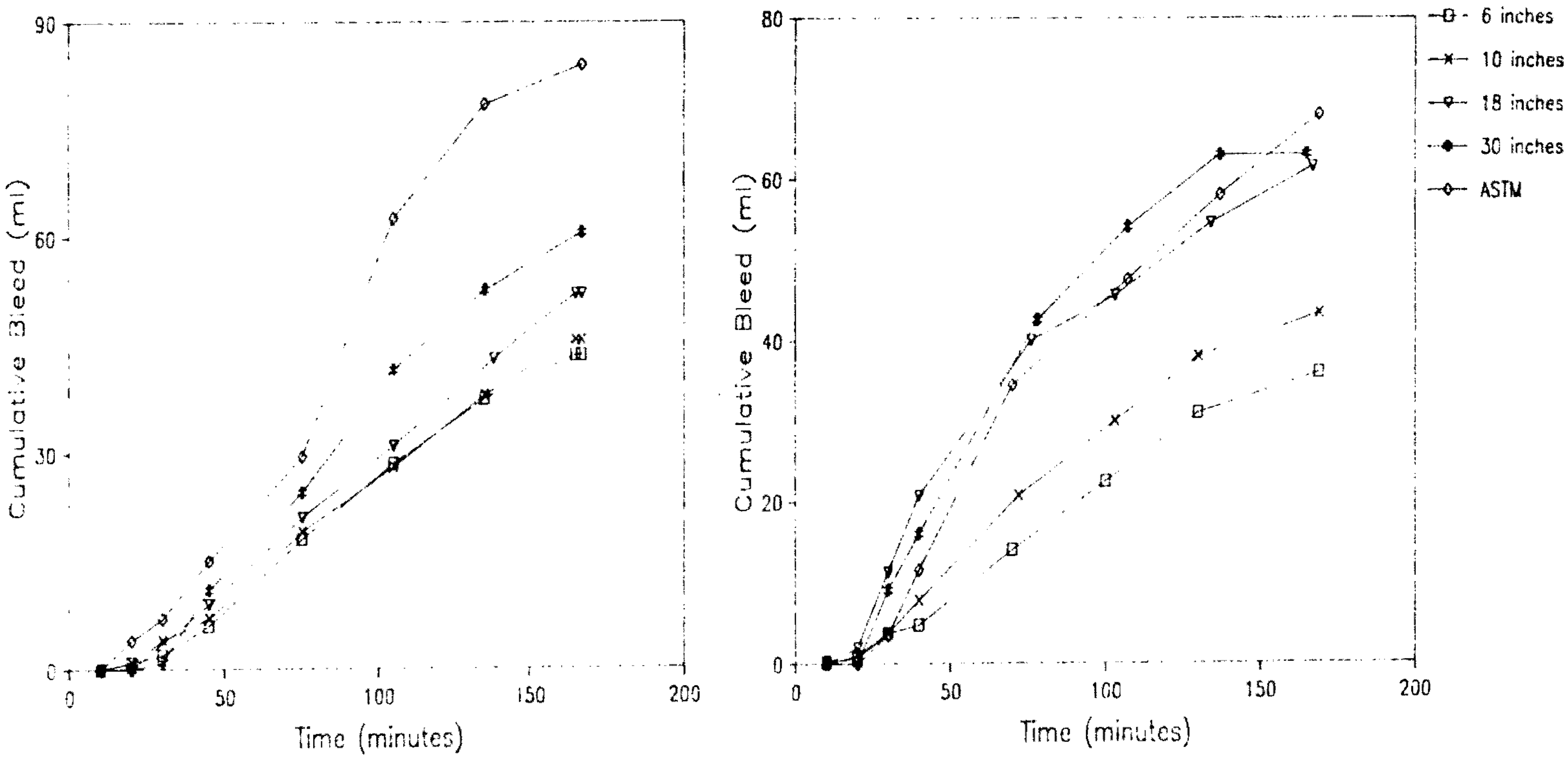
(a) Undosed (b) Dosed

Fig. 4.1 Cumulative bleed vs. time, Series II



(a) Undosed (b) Dosed

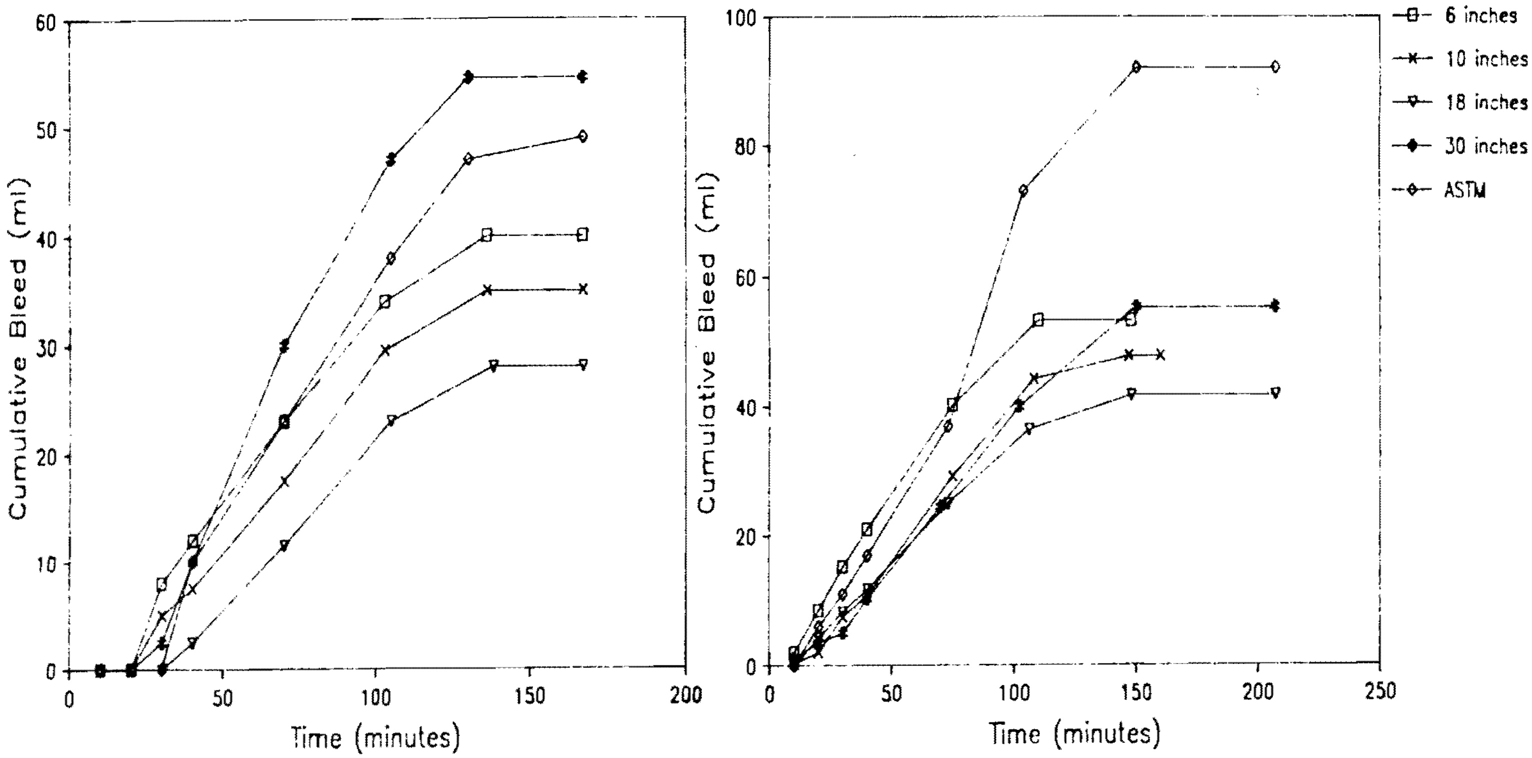
Fig. 4.2 Cumulative bleed vs. time, Series III



(a) Undosed

(b) Dosed

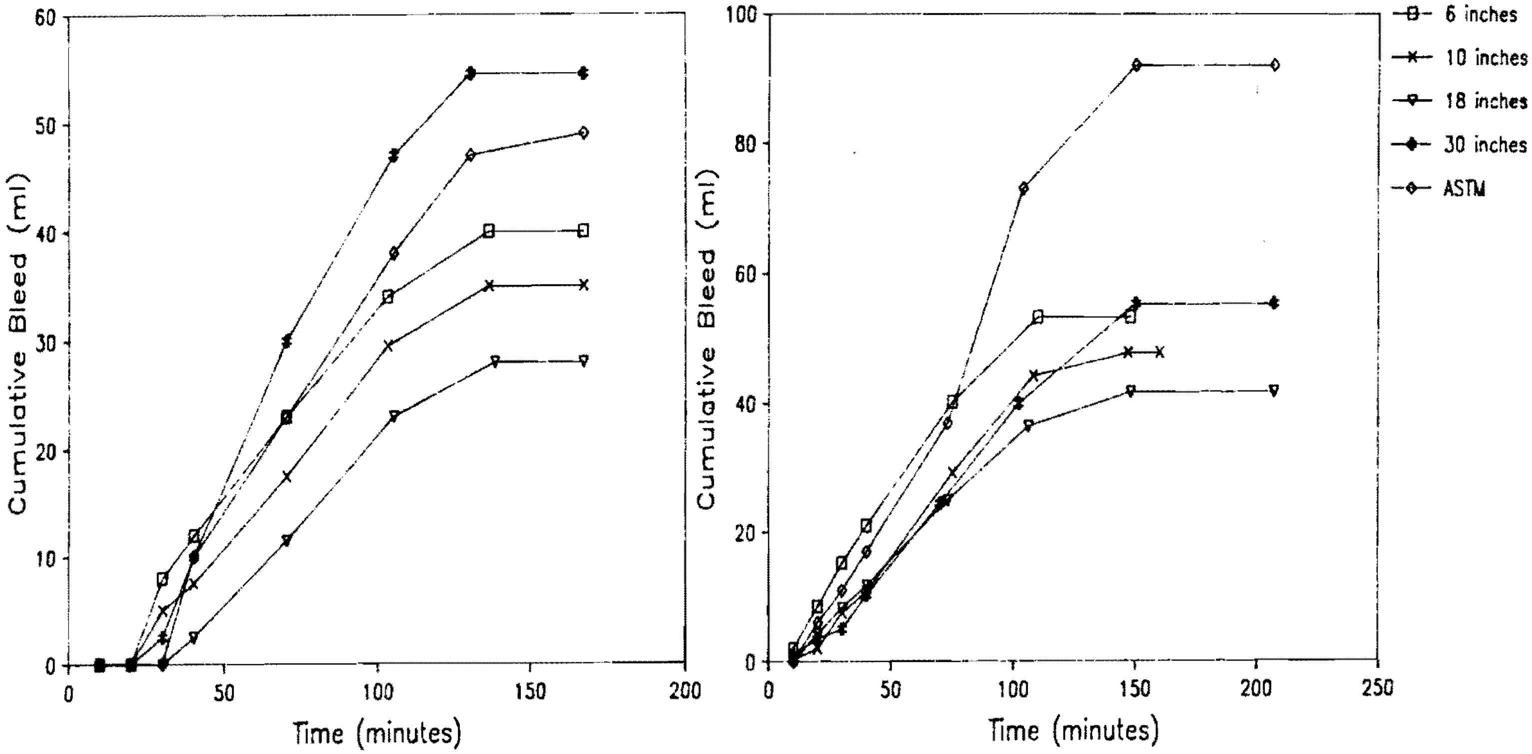
Fig. 4.3 Cumulative bleed vs. time, Series IV



(a) Undosed

(b) Dosed

Fig. 4.4 Cumulative bleed vs. time, Series V



(a) Undosed (b) Dosed

Fig. 4.5 Cumulative bleed vs. time, Series VI

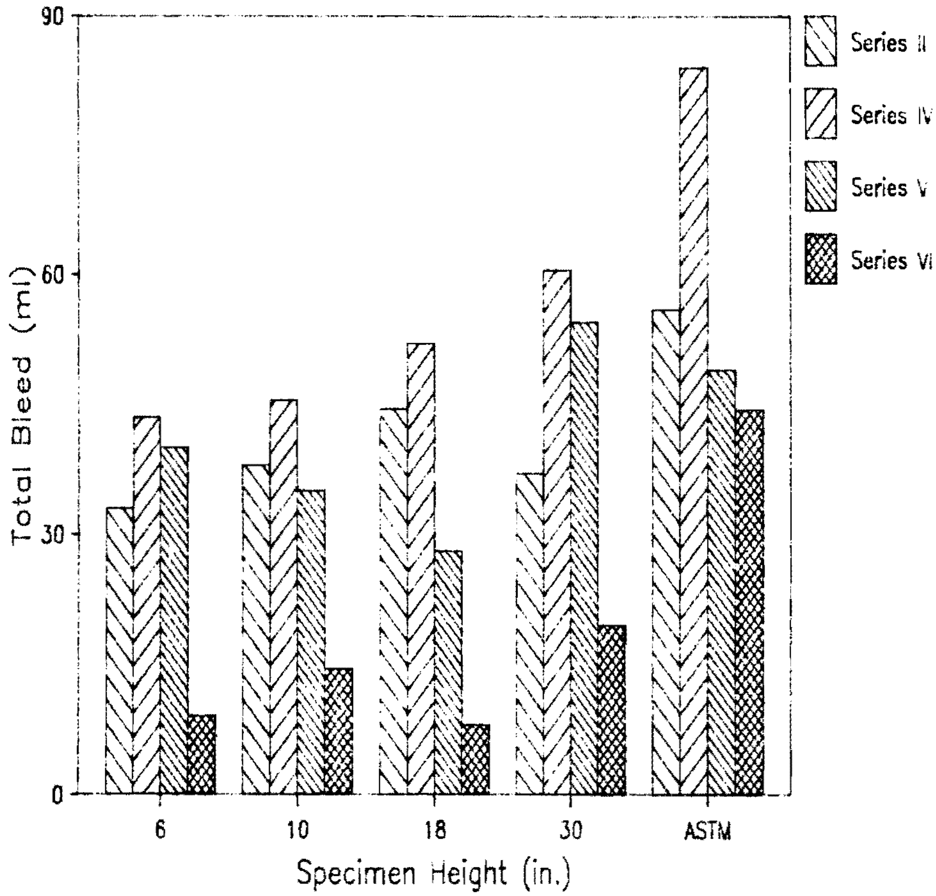


Fig. 4.6 Bleed vs. height--low slump

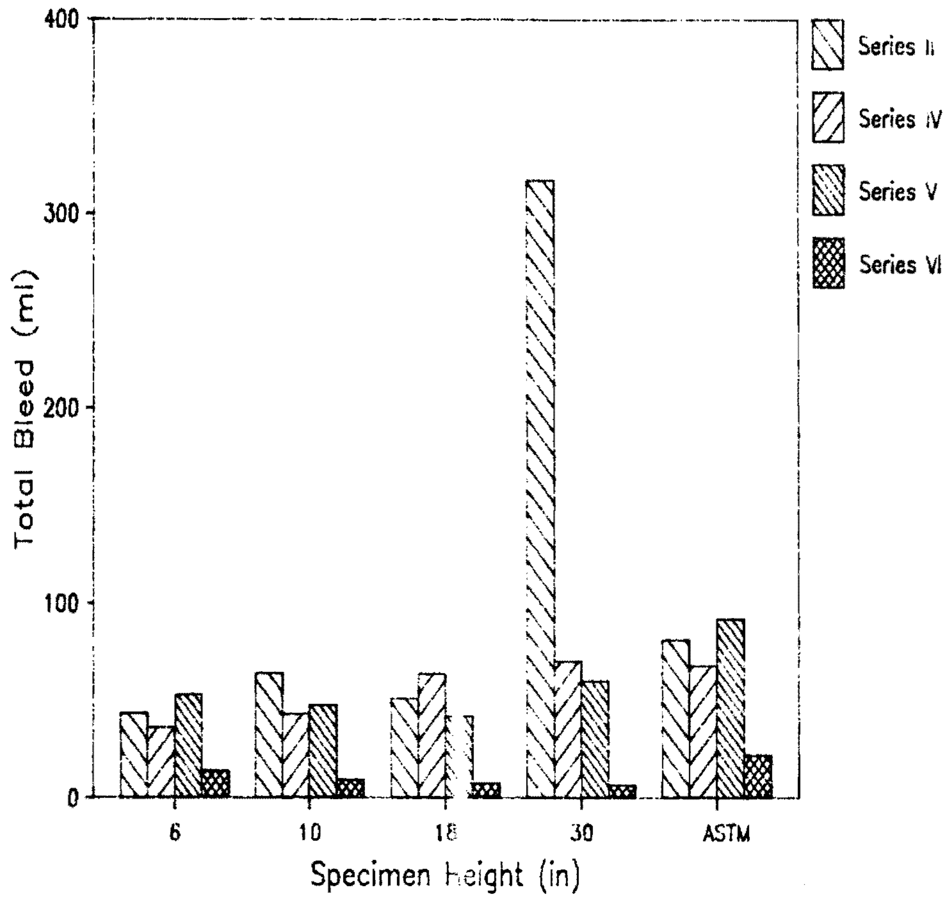


Fig. 4.7 Bleed vs. height--high slump

throughout the entire depth too. However, most of the bleed water is trapped by the coarse aggregates. In this model, depicted schematically in Fig. 4.8 it is hypothesized that the entire height of the concrete settles and produces bleed, but that only the bleed water from the top section rises to the surface.

Due to segregation, the distribution of coarse aggregate in the specimen profile will differ. In particular, there will be a zone with more coarse aggregate concrete at the bottom of the specimen, a zone of concrete with constant coarse aggregate content in the middle section of the specimen where aggregates settling are replaced by aggregates settling from above, and finally, a zone of concrete with a reduced amount of coarse aggregate at the top section. It has been shown that the middle zone is present only in taller specimens [42]. In shorter specimens, only the bottom and the top zones are present. Moreover, the reduction of the coarse aggregate content in the top zone is more pronounced for the taller specimen. The proposed profile in the specimen is shown in Fig. 4.9.

The top zone of the profile affects bleeding the most since most of the bleed water comes from that section. If a deep lift bleeds more, it is because of increased segregation near the top and of the inability of the top section to trap the bleed water because the coarse aggregate content is reduced.

4.2.1 Effect of Superplasticizer on Bleed. In Figs. 4.1 through 4.5, it was seen that superplasticizer increased bleed for all the cold-weather series. Moreover, dosed concrete generally showed the same trends as undosed with respect to bleed versus specimens height. The increase in bleed due to superplasticizer can be explained as follows: naphthalene-based superplasticizer imparts a negative charge to the cement particles and disperses them. This has four effects on bleed: 1) it stops the cement particles from using up more water because the hydration between the cement and water is slowed by the charged layer. Thus, some of this water is able to migrate to the surface as bleed; 2) in the process of dispersion, the water trapped (but not yet used for hydration) by the cement particles is released [35]. Again, more water is available to bleed; 3) the resulting high slump results in more segregation and consequently more bleed; and, 4) superplasticizer decreases air content and allows the bleed water to flow more easily.

4.2.2 Slump as an Indicator of Bleed. As seen in Figs. 4.6 and 4.7, high-slump concrete bleeds more than low slump concrete, irrespective of whether the high slump is obtained by adding superplasticizer or adding water. Superplasticizer can increase the amount of water available to bleed. Clearly, adding more mixing water has the same effect. Slump is therefore an indicator of potential bleed whether the concrete is dosed or undosed.

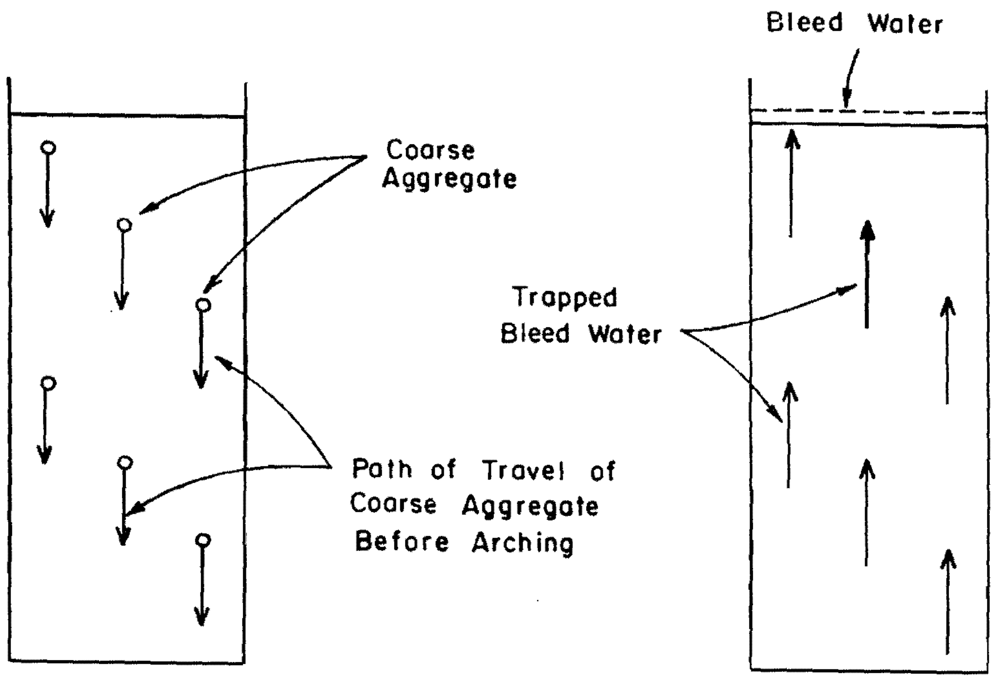


Fig. 4.8 Schematic model for bleed-settlement of coarse aggregate phenomena

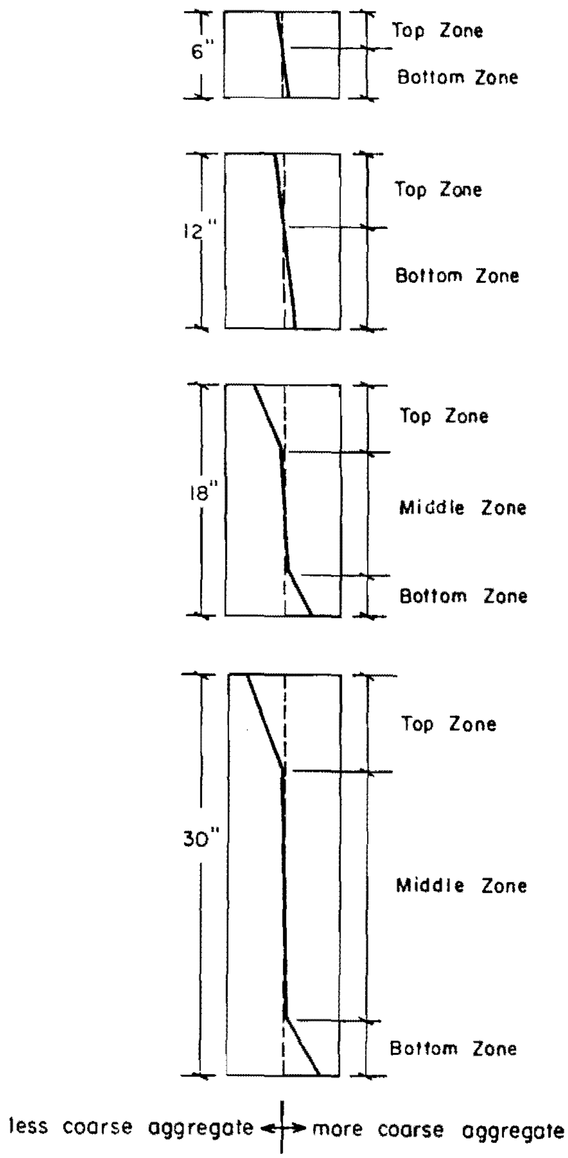


Fig. 4.9 Segregation of coarse aggregate [42]

4.2.3 Relationship between Bleed, Slump, and Temperature. As temperature increases, bleed decreases. This is clearly shown by the results of Series VI (hot weather concrete) in (Fig. 4.5 which showed substantially lower bleed than the other series. The effect of temperature can be studied rationally by investigating the concrete maturity, defined as the area under the temperature vs time graph. This gives an indication of the degree of hydration that has taken place in the cement particles. Clearly, more mature concrete would have less water available for bleed.

To investigate the relationship between bleed, slump and temperature, graphs of bleed vs slump normalized by temperature and age were plotted in Fig. 4.10. For low-slump concrete, a fairly linear trend is obtained. For high-slump concrete, more scatter is observed. The results from Series III have been omitted. From the above graphs, bleed is seen to be nearly directly related to slump if other factors are held constant.

Finally, to further test the hypothesis, bleed results from Ref. 35 were plotted in Fig. 4.11 and the same trends are evident. Only ASTM bleed tests in hot weather were done in this series.

4.3 Effect of Bleed on Bond Strength

4.3.1 Low-Temperature Concrete. Figures 3.20 through 3.23 show top bar factors for the tests of Series II, IV, V, and VI. The top bar factors for both development length and splices in Series II and IV are greatest at a 12 in. casting depth, and drop as height increases. Examining the bleed results of Figs. 4.1 and 4.4, it is clear that bleed increases indicating more segregation with increasing specimen height. Yet for both the development length and splice tests, bond strength does not decrease in a systematic manner with casting heights. This behavior at first seems contrary to the relationship between bleed, segregation and bond strength. In order to account for this seemingly contradictory behavior, it is necessary to look more closely at the effect of bleed and segregation on the strength of the concrete specimen.

As discussed previously, a zone of reduced coarse aggregate content forms on the top section of the concrete specimen due to segregaton. This zone is larger in the 18 and 30 in. specimens as compared to the 12 in. specimen. It has been shown (Ref. 42) that zones of reduced coarse aggregate content have higher compressive strength. It is reasonable to assume that the concrete in such zones will also have improved tensile and splitting characteristics. Therefore, the 18 and 30 in. top-cast bars may have been surrounded by concrete of higher strength compared to the 12 in. top-cast bar. These bars did not exhibit as much bond reduction as the 12 in. top cast bars.

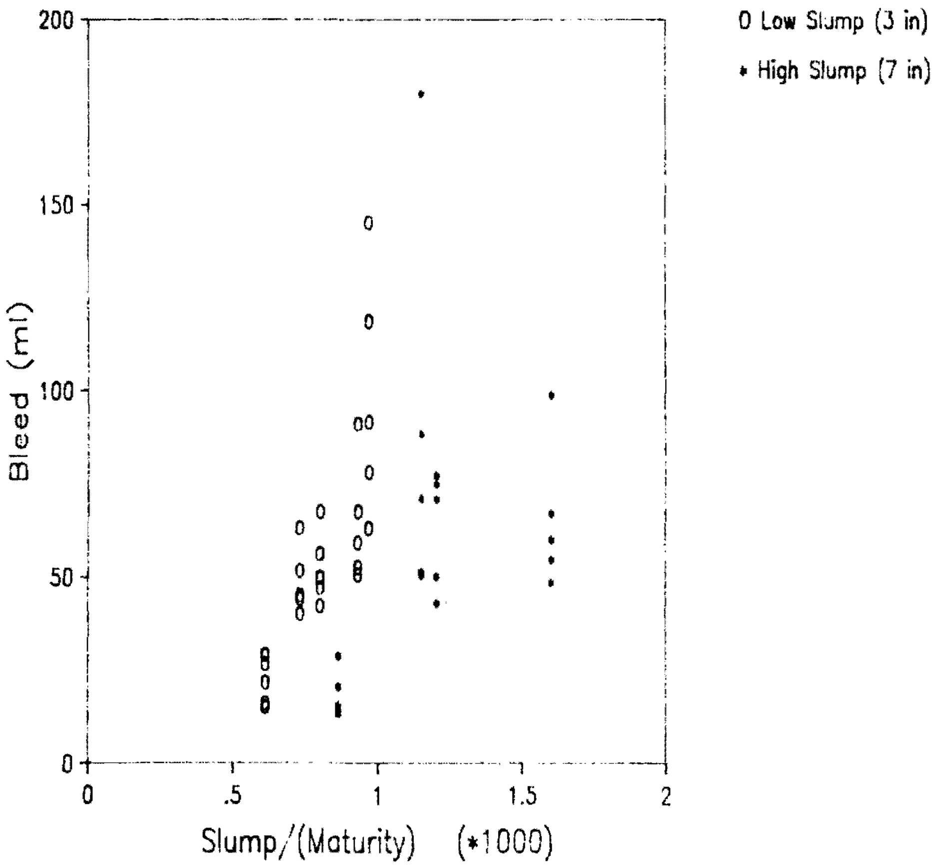


Fig. 4.10 Bleed vs. slump--maturity ratio

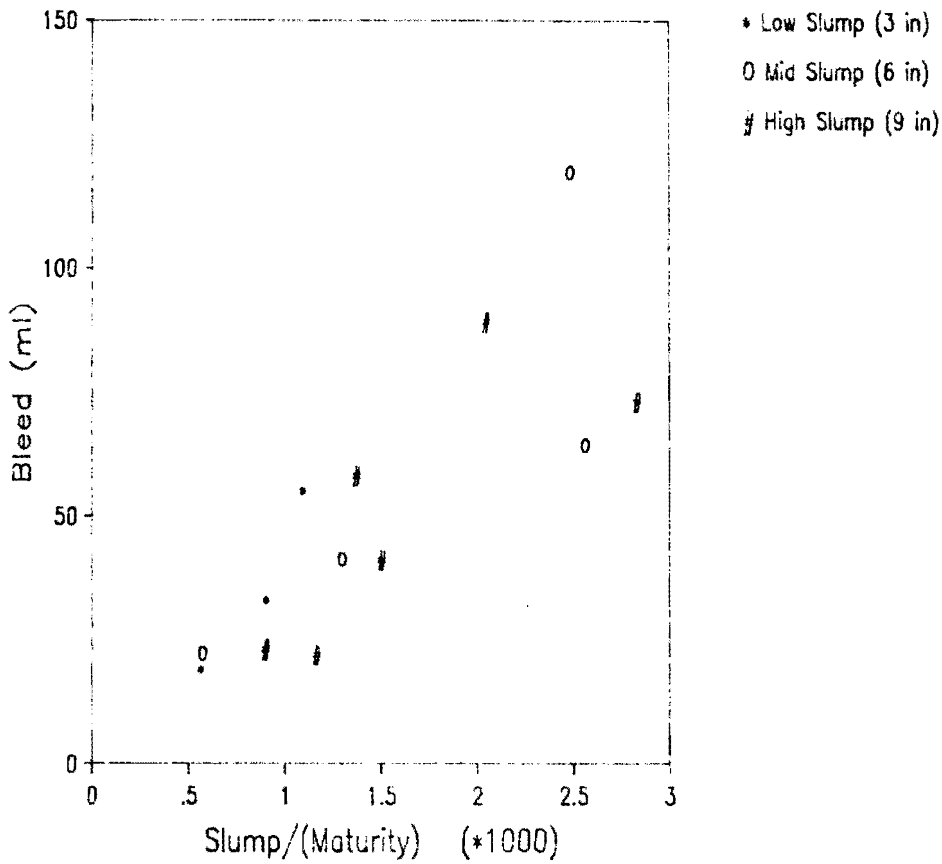


Fig. 4.11 Bleed vs. slump--maturity ratio [35]

The bleed for 6 in. specimens was less than for the 12 in. specimens. Less water may have been trapped beneath the bars and the aggregate leading to improved bond and a low top bar factor at 6 in. in Series II and IV.

It is interesting to note that while both dosed and undosed specimen behave similarly, the dosed concrete has a lower top bar factor than the undosed concrete at most casting heights.

As shown in Chapter 3, the bond strength of high slump water-dosed concrete is lower than the bond strength of high slump superplasticized or low slump non-superplasticized concrete. However, like the dosed and undosed concrete in Series II and IV, the top bar factor for water-dosed concrete did not change with height, as shown in Fig. 3.22. For the development length tests, the 12 in. top-cast bar has the highest top bar factor, whereas for the splice test, the 18 in. top-cast bar has the highest top bar factor. However, the top bar factor in Series V at all heights was higher than the factors for Series II and IV.

Interestingly, bleed decreased with height for Series V, except for the 30 in. specimen (Fig. 4.5). This may indicate that segregation was not as pronounced as in Series II or Series IV, where bleed increased with height. A large quantity of coarse aggregate may have remained in the top section of the 12 or 18 in. specimens to trap bleed water, resulting in a higher top bar factor for these bars.

4.3.2 High-Temperature Concrete. A totally different behavior was observed in the top bar effect in Series VI, the high temperature concrete. As shown in Fig. 3.23 the top bar factor was low and relatively constant for all casting depths except the 6 in. specimen. At high temperatures the concrete matured rapidly and may not have allowed the coarse aggregate to segregate thereby rendering the model in Fig. 4.9 inapplicable. Since the bleed is low in rapidly maturing concrete, the top bar effect is expected to be small and constant as shown in Ref. 35. Temperature therefore has no apparent effect on the bond strength, but only reduced the top bar effect.

The large top bar factor for the 6 in. specimen may not be related to bleed and maturity. This small specimen has the highest ratio of surface area to volume, and may suffer shrinkage cracking in hot weather, which would tend to reduce bond strength.

4.4 Supplementary Bleed Tests

In the bleed tests, it was observed that the ASTM bleed test seemed to give results consistently higher than those obtained using a PVC bleed bucket of the same height. It was thought that perhaps the different compaction methods used in the ASTM bucket and the PVC bleed buckets might account for the discrepancy.

Also, all the PVC bleed buckets were cast in lifts similar in height to those used in casting the bond test specimens. It was not clear if different bleed results would be produced if the bleed containers were cast in one lift instead of multiple lifts. If bleed were different, segregation in the specimens might be different than if they had been cast in one lift. On the job site, there is little control over the number of lifts used by the contractor, and it is important to find out if the results obtained previously would need to be modified to account for the worst case.

Two modified ASTM bleed tests were carried out. In the first one, the bucket was cast in one lift and rodded 75 times. In the other, the bucket was also cast in one lift, but was vibrated for about 10 seconds instead. Two 10-in. PVC bleed buckets were cast. The first one was cast in 3 lifts and rodded 25 times for each lift. The other was cast in one lift, and was vibrated for about 10 seconds. Two 18-in. PVC bleed buckets were cast. One was cast in 3 lifts, and each lift was vibrated for about 6 seconds. The other was cast in only one lift, but was vibrated for about 18 seconds. The procedure is summarized in Table 4.1. The casting procedures allowed a comparison of:

1. ASTM bucket vs. 10-in. PVC bucket,

2. rodding vs. vibration, and

3. single vs. multiple lifts.

The concrete mix design was as shown below:

Coarse Aggregate	298 lbs
Fine Aggregate	211.5 lbs
Cement	70 lbs
Water	33.7 lbs

The slump obtained from this mix was 6.5 in. It was noted that the fine aggregate used was very damp because of exposure to rain the night before the test. Consequently, the mix contained more water than is recorded above. However, the desired slump was achieved. The slump was purposely kept high to ensure sufficient bleed to permit a reasonable comparison.

The results of the supplementary bleed tests are shown in Table 4.1. Very little difference in bleed was observed among the

TABLE 4.1 Summary of Supplementary Bleed Tests

Bleed Bucket	Number of Lifts Used	Method of Compaction	Bleed (ml)
ASTM	1	rodded	62.5
ASTM	1	vibrated	59.5
10-in. PVC	1	vibrated	63.0
10-in. PVC	3	rodded	67.0
18-in. PVC	1	vibrated	64.0
18-in. PVC	3	vibrated	54.0

different types of bleed tests. The small differences observed were probably due to experimental variations. Rodded specimens bled just as much as vibrated ones. Specimens cast in 3 lifts bled as much as a single lift. ASTM buckets and 10-in. PVC buckets gave equal bleed. Finally, the short specimens bled as much as the tall ones. This implies that the bleed water probably came from the top layers of the specimens. However, it is clear that additional work would need to be carried out to determine the relationships between concrete placement procedures, bleed test results, and bond strength.

C H A P T E R 5

SUMMARY AND CONCLUSIONS

5.1 Summary

Forty-five development length and twenty-seven lapped splice tests were performed on Grade 60 #8 deformed bars, and eighteen development length tests, on Grade 270 1/2 in. 7-wire strands. Bond performances of reinforcement cast in high slump superplasticized (naphthalene base) concrete was compared with that of low and high slump ordinary (non-superplasticized) concrete. Top and bottom bars cast in specimens of various depths were tested in order to examine the effect of casting position on bond performance in each concrete mix. An analysis of the effect of temperature on bond capacity was performed by comparing the test results of specimens cast under low (58°) and high (78°) temperatures. Special bleed tests were fun in an attempt to correlate bleed, slump, and bond performance.

5.2 Conclusions

From the bond test results, the following conclusions can be made:

1) The use of superplasticizers as workability admixtures for concrete caused no detrimental effect on the anchorage capacity of deformed reinforcing bars. High slump superplasticized concrete exhibited bond strengths comparable to that of low slump ordinary concrete.

2) The reduction in anchorage capacity of top bars compared to bottom bars was diminished by the use of superplasticizers. The casting position effect (top bar factor) was greater for low slump ordinary concrete than for high slump superplasticized concrete. The top bar factor increased with slump using ordinary concrete. The top bar factor appeared to be independent of the depth of concrete cast below the top bar for the range of depths and concrete mixes included in this study.

3) The detrimental effect of casting position on the anchorage capacity of top bars was diminished at high casting temperatures for both superplasticized and ordinary concretes.

4) Development and splices were affected similarly.

Based on the bleed test results of this study, the following conclusions can be drawn:

1. For superplasticized concrete cast in cold weather, bleed increased with specimen height, but was not directly proportional to height.

2. Bleed increased with slump and decreased with temperature.

3. Concrete dosed with the naphthalene-based superplasticizer bled more than undosed concrete from the same mix.

4. For specimens of the same height, having small variation in slump and air content, bleed was proportional to slump normalized by the product of temperature and age (maturity).

5.3 A Model for Segregation and Bleed

It is hypothesized that although segregation occurred throughout the height of the specimens, most of the coarse aggregate settled only a few inches. Most of the resulting bleed water was trapped and only the bleed water from the top section of the specimens rose to the surface. The model can be used to help explain the phenomena observed. For concrete at 57°F, where bleed increases with height, segregation may result in a zone of reduced coarse aggregate contents at the top of the specimen. For the taller specimens, these zones were large, and did not trap much bleed water. Consequently, the bond strength of the top cast bars in these specimens was reduced only slightly. In concrete cast at 78°F, very little bleed was observed. The rapidly maturing concrete might have prevented segregation and reduced bleed. As a result, there was very little bond deterioration. Additional research on the relationships between bleed and segregation would help explain the role of bleed water, placement techniques, and segregation on bond performance.

5.4 Recommendations

A clear distinction must be made between ordinary and superplasticized high slump concrete. Required lengths for development and splices cast in superplasticized concrete may be considered similar (top bar factor = 1.0) to those for bars and splices cast in low slump ordinary concrete for the mixes used in this study.

Superplasticizers should be mixed carefully with the concrete, and proper placing procedures should be used in order to achieve homogeneous superplasticizing action and desired structural performance.

REFERENCES

1. Abrams, D.A., "Tests of Bond Between Concrete and Steel," Bulletin 71, Engineering Experiment Station, University of Illinois, 1913.

2. ACI Committee 318, Building Code Requirements for Reinforced Concrete (ACI 318-83), American Concrete Institute, Detroit, 1983.

3. ACI Committee 318, Commentary on Building Code Requirements for Reinforced Concrete, American Concrete Institute, Detroit, 1983.

4. ACI Committee 408, "Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension," Concrete International, July 1979, pp. 44-46.

5. Altowaiji, W.A.k., Darwin, D., Donahey, R.C., "Preliminary Study of the Effect of Revibration on Concrete-Steel Bond Strength," S L Report 84-2, The University of Kansas Transportation Center, November 1984.

6. American Concrete Institute, Developments in the Use of Superplasticizers, Publication SP-68, 1981.

7. Ash, J.E., "Bleeding in Concrete - A Microscopic Study," Journal of the American Concrete Institute, April 1972, pp. 209-210.

8. American Concrete Institute, Superplasticizers in Concrete, Publication SP-62, 1979.

9. Brettmann, B.B., Darwin, D., Donahey, R.C., "Effect of Superplasticizers on Concrete-Steel Bond Strength," SL Report 84-1, The University of Kansas Transportation Center, April 1984.

10. Clark, A.P., "Bond of Concrete Reinforcing Bars," Journal of the American Concrete Institute, Proc. V. 46, No. 3, November 1949.

11. Clark, A.P., "Comparative Bond Efficiency of Deformed Concrete Reinforcement Bars," Journal of the American Concrete Institute, Proc. V. 43, No. 4, December 1946.

12. Collepardi, M., Corradi, M., "Influence of Naphthalene - Sulfonated Polymer Based Superplasticizers on the Strength of Ordinary and Lightweight Concretes," Special Publication SP - 62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 315-336.

13. Collier, S.T., "Bond Characteristics of Commercial and Prepared Reinforcing Bars," Journal of the American Concrete Institute, Proc. V. 43, June 1947.

14. Comite Euro-International du Beton, "Bond Action and Bond Behavior of Reinforcement - State of the Art Report," Bulletin D'Information No. 151, December 1981.

15. Davis, R.E., Brown, E.H., Kelly, J.W., "Some Factors Influencing the Bond Between Concrete and Reinforcing Steel," Proceedings ASTM, Vol. 38-11, 1938, pp. 394-409.

16. Eligehausen, R., Popov, E.P., Bertero, V.V., "Local Bond Stress-Slip Relationships of Deformed Bars Under Generalized Excitations," Report No. UCB/EERC - 83/23, Earthquake Engineering Research Center, University of California, Berkeley, October 1983.

17. Ferguson, P.M., Reinforced Concrete Fundamentals, Fourth Edition, 1979, John Wiley and Sons.

18. Ferguson, P.M., Thompson, J.N., "Development Length of Large High Strength Reinforcing Bars," Journal of the American Concrete Institute, Proc. V. 62, No. 1, January 1965.

19. Goto, Y., "Cracks Formed in Concrete Around Deformed Tension Bars." Journal of the American Concrete Institute, 1971. pp. 244-251.

20. Goto, Y., Otsuka, K., "Experimental Studies on Cracks Formed in Concrete Around Deformed Tension Bars." The Technology Reports of the Tohoku University. Vol. 44 (1979) No. 1, June. pp. 49-83.

21. Hamad, B.S., "Effect of Casting Position on Development of Anchored Reinforcement," Master's Thesis, The University of Texas at Austin, May 1979.

22. Hattori, K., "Experiences with Mighty Superplasticizer in Japan," Special Publication SP-62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 37-66.

23. Hewlett, P.C., "The Concept of Superplasticized Concrete," Special Publication SP-62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 1-11.

24. "How Super are Superplasticizers?" Concrete Construction, May 1982, Vol. 27, November 5, pp. 409-415.

25. Hughes, B.P., Ash, J.E., "Water Gain and its Effect on Concrete," Concrete, December 1969, Vol. 3, No. 12, pp. 494-496.

26. Jirsa, J.O., Breen, J.E., "The Influence of Casting Position and Shear on Development and Splice Length - Design Recommendations," Research Report 242-3F, Project 3-5-78-242, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, November 1981.

27. Jirsa, J.O., Lutz, L.A., Gergely, P., "Rationale for Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension," Concrete International, July 1979, pp. 47-61.

28. Lane, R.O., Best, J.F., "Laboratory Studies on the Effects of Superplasticizers on the Engineering Properties of Plain and Fly Ash Concrete," Special Publication SP-62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 193-207.

29. Luke, J.J., Hamad, B.S., Jirsa, J.O., Breen, J.E., "The Influence of Casting Position on Development and Splice Length of Reinforcing Bars," Research Report 242-1, Center for Transportation Research, The University of Texas at Austin, June 1981.

30. Luke, J.J., "The Effect of Casting Position on Development and Lapped Splice Length Requirements for Deformed Reinforcement," Master's Thesis, The University of Texas at Austin, December 1979.

32. Menzel, C.A., "Some Factors Influencing Results of Pull-Out Bond Tests," Journal of the American Concrete Institute, Proc. V. 35, June 1939.

33. Meyer, A., "Experiences in the Use of Superplasticizers in Germany," Special Publication SP-62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 21-36.

34. Mindess, S., and Young, F. Concrete, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981, 671 p.

35. Musser, P.L., "Bond Performance of Reinforcing Steel Embedded in Concrete Made Using Superplasticizer," Master's Thesis, The University of Texas at Austin, May 1985.

36. Musser, P.L., Carrasquillo, R.L., Jirsa, J.O., and Klingner, R.E., "Anchorage and Development of Reinforcement in Concrete Mode Using Superplasticizers," Research Report 383-1, Center for Transportation Research, The University of Texas at Austin, Sept. 1985.

37. Orangun, C.O., Jirsa, J.O., Breen, J.E., "A Reevaluation of Test Data on Development Length and Splices," Journal of the American Concrete Institute, March 1977, pp. 114-122.

38. Orangun, C.O., Jirsa, J.O., Breen, J.E., "The Strength of Anchored Bars: A Reevaluation of Test Data on Development Length and Splices," Research Report 154-3F, Center for Highway Research, The University of Texas at Austin, January 1975.

39. Perenchio, W.F., Whiting, D.A., Kantro, D.L., "Water Reduction, Slump Loss and Entrained Air-Void Systems as Influenced by Superplasticizers," Special Publication SP-62, Superplasticizers in Concrete, American Concrete Institute, 1979, pp. 137-155.

40. Rehm, G., Eligehausen, R., Neubert, B. "Rationalisierung der Bewehrungstechnik im Stahlbetonbau (Rationalization of Reinforcement in Concrete Construction)," Report of the Lehrstuhl Fur Werkstoffe im Bauwesen, Universitat Stuttgart from October 1979.

41. Rehm, G., "Uber die Grundlagen des Verbundes Zwischen Stahl und Beton (The Fundamentals of Bond Between Steel Reinforcement and Concrete), "Deutscher Ausschuss Fur Stahlbeton, Heft 138, p.59, 1961.

42. Shima, H., Mizuguchi, H., Wada, T., Kohno, K., "Properties of Hardened Concrete Affected by Segregation of Superplasticized Concrete," Transactions of the Japan Concrete Institute Vol 6, pp. 1-8, 1984.

43. Sooi, T.K., "Effect of Bleed and Temperature on the Bond Behavior of Superplasticized and Non-Superplasticized Reinforced Concrete", Master's Thesis, The University of Texas at Austin, December 1985.

44. Soshiroda, T., "Segregation Characteristic of Concrete Containing a High-Range Water-Reducing Admixture," Special Publication SP-68, Developments in the Use of Superplasticizers, American Concrete Institute, 1981, pp. 121-129.

45. Welch, G.B., Patten, J.F., "Bond Strength of Reinforcement Affected by Concrete Sedimentation," Journal of the American Concrete Institute, February 1965, pp. 251-263.

46. Zekany, A.J., Neumann, S., Jirsa, J.O., Breen, J.E., "The Influence of Shear on Lapped Splices in Reinforced Concrete," Research Report 242-2, Project 3-5-78-242, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, July 1981.

47. Zilveti, A., "Effect of Superplasticizers on the Bond Behavior of Reinforcing Steel in Concrete Members,"M.S. Thesis, The University of Texas at Austin, December 1985.