# SUPERPLASTICIZERS IN CONCRETE

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## Abstract

Superplasticizers, which have been used in Europe and Japan since the mid-1960's and in the United States since the 1970's, act as high-range water-reducers in concrete.

This report describes the performance of superplasticizers and helps to understand what they are, how to use them, and advantages in using them. It also describes an experimental investigation of conventional concrete containing superplasticizers. The results show that superplasticizers are capable of either increasing the workability of concrete at equal mix proportions or reducing the unit water content at equal slump which results in higher strength.

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# Introduction

The development of water-reducing admixtures about the time of World War II was a step forward in solving the water-cement ratio problems. Water-reducing admixtures that have mainly a physical influence, giving an inexpensive, effective way to reduce water requirements up to about ten percent and improve the workability of concrete. However, when higher dosages were used to obtain greater water reduction, side effects such as excessive retardation and increased air content reached such magnitude that they could not be tolerated.

Now, a solution to that problem is available through the development of new or modified chemicals to improve the workability without substantially altering other properties of fresh and hardened concrete. These additives are known as "superplasticizers". These superplasticizers were produced and tested in Germany and in Japan for the first time in the mid-Sixties. The use of superplasticizers in concrete increased rapidly in the Seventies. More recently, their use has spread into other parts of the world, including the United States.

The purpose of this report is to understand superplasticizers better. It also describes the experiments that have been performed on concrete using superplasticizers.

## Types of Superplasticizer and Requirements

There are three types of superplasticizer currently in use; they are :

1. Sulfonated melamine-formaldehyde condensates.
2. Sulfonated naphthalene-formaldehyde condensates.
3. Modified lignosulfonates.

Most of these superplasticizers consist mainly of organic sulfonates of the type $RSO_3^-$, where R is a complex organic group (1). Physical properties of the above superplasticizers are given in Table 1 . Organic groups for sulfonated melamine and sulfonated naphthalene are given in Figure 1 .

Superplasticizers exert thier action by (2) :

a) producing a lubricating film at particle surfaces,

b) equidirectional charging of cement particles,

c) decreasing the surface tension of water.

Sulfonated melamine-formaldehyde condensates, act mainly by forming a lubricating film at the particle surfaces. Modified lignosulfonates decrease the surface tension of the water. Sulfonated naphthalene-formaldehyde condensates decrease the surface tension of water to a minor degree, but in addition they charge the surface of the cement particles equidirectionally to form a lubricating film at the particle surfaces. According to a report by the Cement and Concrete Association, London, their mode of action is best described as follows (3) :

"These admixtures are thought to be adsorbed onto cement particles, causing them to become mutually repulsive as a result of the anionic nature of superplasticizers, which causes the cement particles to become negatively charged. In principle, this adsorption and dispersing effect is similar to that found for normal anionic plasticizers."

The plasticizing action of superplasticizers must be considerably stronger than that of normal plasticizers. Their plasticizing effect is retained in concrete for a period of 30 to 60 minutes, after that time the concrete will go back to it's original slump. The amount of time that the plasticizing effect remain depends on the type of superplasticizers, the dosage used, the initial slump of concrete, the mixing time, as well as the temperature of the concrete.

Superplasticizers are available in two forms, liquid and powder. Superplasticizers in liquid form are preferred to products in powder form, because dispersing is easier and can be made more accurately (2). It is not recommended to use superplasticizers in doses less than 0.8 percent of the cement mass, in order to guarantee prompt and uniform distribution within the mixture.

The strengh of hardened concrete containing superplasticizer is normally higher than that for the same concrete without superplasticizer.

## Purpose of Using Superplasticizers in Concrete

Superplasticizers are use in concrete for two purposes :

1. to increase workability and producing flowing concrete,
2. to increase strength and producing high quality concrete at a low water-cement ratio.

At first, the only use of superplasticizers was just to modify the consistency and to produce flowing concrete. At a later time, the use of superplasticizers was extended to reduce the water content of concrete without changing its consistency. This will yield a high quality concrete at low water-cement ratio. Of course, it is possible to combine the two methods, improving workability and reducing the water content of the concrete at the same time.

If the superplasticizers are used to improve the workability of the concrete, then the normal slump concrete becomes "flowing concrete". This is concrete having a slump equal to 8 inches or more. In addition to having high workability, flowing concrete should not exhibit excessive bleeding or segregation. Flowing concrete is also referred to as self-compacting concrete.

As with conventional workability or plasticizing admixtures, one can take advantage of the enhanced workability state to make a reduction in the water content of superplasticized concrete, while maintaining workability levels, normally 2 to 3 inches slump. Concrete in this state is water reduced or high strength concrete.

Advantages and disadvantages of using superplasticizers to produce flowing concrete and high strength concrete will be discussed in more detail in the following sections.

## The Concept of Flowing Concrete

For a long time, it has been an engineering objective to be able to make self-levelling and flowing concrete while maintaining water-cement ratio levels that did not cause bleeding,segregation or strength reduction either during or after placing of the concrete. By using superplasticizers this can be achieved without having these problems.

Flowing concrete is a fresh concrete displaying good flow properties and at the same time, satisfactory cohesive properties. Concrete of this nature is obtained from initially stiff, low-slump concrete by subsequent addition of a superplasticizer. The cement and water volumes of the initial concrete remain practically unchanged in the flowing concrete, so that favorable properties of the initial stiff concrete will remain unchanged. Improved workability of the concrete will simplify its placing and reduce the compacting energy. Under equal conditions, flowing concrete will yield a more uniform product than stiff and low slump concrete.

The high workability effect imparted by superplasticizers is temporary. The flowing concrete gradually goes back to its original workability 30 to 60 minutes after being dosed with superplasticizer. It is possible by re-dosing the concrete, to regain the high workability. However, repeated admixture addition is not recommended (2), and it is best to use concrete as soon as possible after dosing.

Considerable quantities of air are released from flowing concrete. This effect is due to both the normal air release capability associated with plasticizing or water reducing admixtures and lower "viscosity" of flowing concrete which eases the release of entrapped air.

Figure 2 shows a melamine based superplasticizer used as a plasticizer where the water-cement ratio is constant (except for the water in the admixture), but the slump has increased from 3 inches to what is known as collapse (in excess of 10 inches) (4). The strengths in this example are approximately the same before and after the addition of the admixture, but workability is dramatically improved. Results typically show strengths after the addition of superplasticizer to be approximately 5 to 15 percent higher even though there has been a slight increase in the water-cement ratio.

The following benefits can be achieved by using superplasticizers, to produce flowing concrete :

1. Reduced placement labor cost.
2. Minimized drying shrinkage cracking.
3. Improved pumpability.
4. Improved consolidation with minimal vibration.
5. Highly workable concrete without segregation.

## The Concept of Water-Reduced High Strength Concrete

High Strength concrete is characterized by a high degree of strength (6000 psi and up), and is produced from a fully compacted concrete mixture having a low water-cement ratio. The low water-cement ratio will result generally in a stiff consistency; this will require intensive compaction by vibration.

Superplasticizers are used to allow a very significant water reduction resulting in high strength concrete. Much of the development for this use of superplasticized concrete has occurred in Japan (5), where superplasticizers have been used to reduce water content by as much as 20 to 33 percent, compared with 15 to 16 percent when using normal plasticizing admixtures. By reducing the water content 25 to 30 percent, an increase of 50 to 70 percent in the 24-hour strength may be obtained under normal conditions, and a normal 7-day strength is achievable at 3 days and 28-day strength at 7 days (6). This property of superplasticized concrete are shown in Tables 2 and 3, and in Figure 3.

Table 2 shows the resuts of using a melamine based superplasticizer as water reducer. Slump has been maintained at a constant $3\pm1/2$ inches with corresponding reduction in water content as the dosage rate is increased (4).

Table 3 shows the actual compressive strength as well as the percent increase over the reference batch (4). Depending on what dosage rate is used, early strength can be increased anywhere from 35 to 150 percent. Figure 3 corresponds to data of Tables 2 and 3 (4).

The requirements established for high-quality concrete may be fulfilled more easily when using superplasticizers. High-strength concrete with superplasticizer may be produced on the site as well as in precast concrete plants. The percentage of high-strength concrete with respect to the overall concrete production has increased steadily in recent years, and is expected to increase further in the future. Where superplasticizers are being adopted, high-strength concrete may even be obtained by using cements and aggregates with lower quality. As an example, by using superplasticizer in Normal Portland Cement (Type I), higher strength can be achieved than in High Early Strength Cement (Type III) without using superplasticizer (Figure 4) (4).

Concrete with superplasticizer can be placed in heavily reinforced sections without or with only light vibration. Its high initial strength allows early stripping times in the production of prefabricated concrete elements (2).

The following benefits can be achieve by using a superplasticizer, to produce water-reduced high-strength concrete :

1. High-early-strength.
2. Reduction or even elimination of the neccessity for external heat.

Slump Loss in Superplasticized Concrete

Concrete loses slump with time because some of the water reacts with the cement and some is lost through evaporation. Most of these changes occur after concrete has been placed; therefore loss of slump is not noted. Thus, "slump loss" is a term usually applied to the behavior of concrete up to the time of placement, and almost invariably to an unusually fast rate of stiffening.

When superplasticizer admixtures are used in conjuction with portland cement in concrete, a rapid rate of slump loss occurs. Some of the factors known to affect this rapid rate of slump loss are : type of admixture, dosage and time of addition to the mix, temperature, cement type, and presence of other admixtures prior to the addition of superplasticizers. Meyer and Perenchio (7), in their report, conclude that the addition of a chemical admixture can upset the balance between the soluble sulfate and tricalcium aluminate content of a portland cement. This can produce mild or severe flash setting, which causes rapid loss in workability, or slump. This phenomenon can be reversed by the addition of either gypsum ($Ca\ SO_4*2H_2O$ ), or plaster ($Ca\ CO_4*1/2H_2O$ ); however, this would be difficult on a job site and would have the potential of causing long-term expansion in the concrete.

## Factors Effecting Slump Loss in Superplasticized Concrete

As stated before, some of the factors known to effect slump loss in superplasticized concrete are : temperature, cement content and type, time of addition of the superplasticizer, and the use of other admixtures prior to the addition of superplasticizers. Mailvaganam investigated some of these factors in his report (8).

Three cement contents (237, 326, and 415 $Kg/m^3$ ) were used in his work with Type I cements. Concretes made with Type III and Type V cements were investigated at the 326 $Kg/m^3$ cement content. The influence of three mix temperatures (15.5 , 22 , and 32 $^oC$) and three times of addition (20 , 40 , and 60 minutes after initial mixing ) of the superplasticizer were studied. A lignosulfonate water reducer and a hydroxycarboxylic acid retarder were used with a sulfonated melamine formaldehyde type superplasticizer. The effects produced by the superplasticizer with a retarding ingredient were also noted.

The results of slump loss with time are plotted in Figures 5 thr 11. The graphs show the slump loss as a percentage of the slump attained immediately after the addition of the superplasticizer. Chemical composition and surface area of cements are given in Table 4 . Mix proportions are given in Table 5 . The 7 and 28 day strength values relating to these concrete mixes are presented in Table 6.

The rate of fall-off of high workability at 32 °C was quite rapid. At 22 °C, the high plasticity lasted for 15 minutes, after which a relatively rapid decrease in slump was observed. The mixes made at 15.5 °C showed a more gradual slump loss at all ages (Fig. 5 ). The mix containing the retarding superplasticizer did not revert to the original slump for a period in excess of two hours at a temperature of 32°C (Fig. 5 ). The compressive strength values (Table 6 ) show that no adverse effects resulted in hardened concrete by addition of the retarding superplasticizer.

The effect due to the variation of final slump indicates that higher rates of slump loss occurred at early ages(15 minutes) for mixes with lower final slump values (180 and 200 mm ). After 15 minutes, the pattern was reversed, with the mixes of higher slumps (220 and 250 mm ), then showing greater slump loss, and at 45 minutes all mixes had reverted to the former slumps (Fig. 6 ).

In Figure 7 , the mix made with Type V cement, which had a $C_3A$ content of 3 percent, showed a 30 minute extention of the period for reversion as compared to that observed for mixes made with Types I and III cements. The effect due to blaine surface area of cement was therefore not obvious.

It can be noted from Figure 8 that there was no meaningful difference in the slump loss shown by mixes made with the four brands of Type I cement, which had varying $C_3A$ contents.

The effects produced by the presence of conventional admixtures indicate that hydroxycarboxylic acid retarders possibly extend the workability at later ages (Fig. 9 ). The mix with the retarding superplasticizer retained the state of high workability (slump greater than 175 mm. ) for 90 minutes.

There was no clear trend in the rate of slump loss due to the addition of the superplasticizer at different concrete ages (Fig. 10 ). Reversion to the original slump occurred at 30, 45, and 35 minutes for the mixes where addition was done at 20, 40, and 60 minutes respectively.

The results shown due to the variation in cement content of the mixes indicate that the mix with medium cement content ( 326 $Kg/m^3$) had a more gradual fall-off in workability. In contrast, the mix with low cement content (237 $Kg/m^3$) showed a rapid rate of slump loss, with the mix reverting to the original slump in only 30 minutes (Fig. 11 ). These differences in the behavior of the mixes can not be attributed to a single dominant factor. It is possible that the effects are due to an interplay of a number of factors including variation in mortar content, total surface area, and viscosity of the paste.

The results indicate that lower temperatures, medium cement contents, and higher slump values enhance the retention of high workability. The presence of retarding admixtures prior to the addition of a superplasticizer reduces the rate of slump loss at later ages.

Performance of Superplasticizers For Repeated Doses

It is recognized that superplasticizers may be used for two reasons, either to produce high strength concrete or to produce flowing concrete which means increasing a normal slump from 50-75 mm to greater than 200 mm. It is also recognized that the flowing characteristic of concrete gained by the addition of a superplasticizer is normally lost in about 30 to 60 minutes, and therefore the use of the admixture is limited for routine ready-mix concrete unless the workability can be rejuvenated (9).

Addition of a second dose of the superplasticizer causes a higher slump value than that obtained with the first dose, it also causes more gradual decrease in slump and will extend the time for reversion to the original slump (8).

The addition of a second dose of the superplasticizer increases the 28-day compressive strength. Redosing of superplasticized concrete can produce a reduction of entrained air. This feature may account for some of the strength increase (9).

Experiments have shown that mixes with higher cement content and higher superplasticizer dosage maintain their slump for a longer period after redosig compared to mixes with a lower cement content and lower superplasticizer dosage (10).

## Durability of Superplasticized Concrete

Durability of concrete can not be measured directly, but exposure of concrete to repeated cycles of freezing and thawing produces measurable changes in weight, length, pulse velocity and resonant frequency of the test specimen. Measurements made on the test specimens after freezing and thawing cycles provide data that can be used to evaluate the relative frost resistance or durability. Another useful index to determine the durability of concrete exposed to freeze-thaw cycling is the bubble spacing factor, an index related to the maximum distance in inches of any point in the cement paste from the periphery of an air-void (11).

The air-void spacing factor has a great effect on the durability factor of a superplasticized concrete, at a given water-cement ratio, and if the spacing factor is of an appropriate level, it is possible to obtain frost resistance of the same degree as with ordinary air-entrained concrete. The required spacing factor tends to become higher as water-cement ratio becomes lower (12). Therefore, when using superplasticizers in concrete where durability against freezing and thawing is stressed, it is important to select the required air content at a level which will not be excessively high, carefully determining the spacing factor taking into account the water-cement ratio and the exposure condition.

For superplasticizers of both the sulfonated melamine and sulfonated naphthalene types, when used without combining with an air-entraining admixture, the air entrainment in concrete will be extremly small, and consequently the air-void spacing factor will be fairly high. However,lowering the spacing factor to the desired level can be easily achieved by increasing the air content through the combined use of an air-entraining admixture and superplasticizer (12).

According to ASTM C494, the minimum durability factor is 80 percent. By using superplasticizers, researchers have found that the durability factor was well above 80 percent (10, 13).

## Properties of Hardened Superplasticized Concrete

As stated, one of the advantages of using superplasticizers is high strengh concrete. This development depends on the initial water-cement ratio, cement and aggregates content, and superplasticizer dosages.

Figures 12 thr 16 show the effect of water-cement ratio and cement content on compressive strength for superplasticized concrete (10).

Figures 17 thr 21 show the effect of different superplasticizer dosages and cement contents on the compressive strength (10). Relationships between compressive strength and water-cement ratio are given in Figures 22 thr 26 (10).

These figures show that for the same water-cement ratio and superplasticizer dosage, concrete with a lower cement content has a higher strength. For the mixes with the same water-cement ratio and cement content, the one with the highest dosage of superplasticizer has the higher strength. For the mixes with the same dosage of superplasticizer and cement content, the one with the lower water-cement ratio has the higher strength. For the mixes with the same dosage of superplasticizer, water-cement ratio, and the cement content, the one with low percentage of fine aggregate has higher strength.

Tables 7 and 8, show mix proportions and compressive strengths for mixes in Figures 12 thr 26 (10).

The flexural strength of superplasticized concrete is the same or slightly higher than concrete without superplasticizer, depending upon the type and dosage of superplasticizer (11).

The modulus of elasticity of superplasticized concrete is going to be the same as that of concrete without superplasticizer (11, 14 ).

In concrete without superplasticizers, a decrease in water-cement ratio leads to less shrinkage, but when superplasticizers are used to produce water-reduced concrete and flowing concrete, an increase in shrinkage sometimes occurs (15, 16, 17 ).

Examples of Application of Superplasticized Concrete

As mentioned before, high strength concrete is a concrete with a high degree of strength. By lowering the water-cement ratio, high strength concrete can be achieved. Concrete mixes that have a low water-cement ratio are difficult to work with, because of their low-slump.

In working with concrete , contractors would like to have a flowing concrete; so they sometimes add more water to the concrete mix than the design calls for. Adding this water will lower the strength and overall quality of the final concrete. By using superplasticizers instead of adding more water, this problem can be solved.

Because of many advantages of superplasticized concrete, they are gaining acceptance in the construction industry. There have been numerous successful applications in the Japan, Canada, the United States , and other parts of the world. Below are some examples of using superplasticized concrete.

In Japan, many important structures have been constructed using concrete containing superplasticizers. Names and dates of construction of the structures are listed in Table 9, and information on the mix formulations are shown in Table 10 (18).

The first significant use of superplasticizers in North America was in 1976 for the precast elements of the Montreal

Stadium in Canada. The specified strength was 6000 psi at 28 days; release strength was 3000 psi at six hours. The amount of reinforcing steel dictated that the slump be not less than 6 to 7 inches, in order to have the concrete properly placed and consolidated. The placement was performed by using a melamine based superplasticizer (19).

The 58-story, 644 ft. high Trump Tower, New York, one of the tallest concrete buildings in the world, was constructed using a superplasticizer. The column concrete developed a strength of 8000 psi. , and concrete for shear walls developed a strength of 6000 psi. , both at 28 days. The concrete had a 9-inch slump and was a "flowing" mixture that required little vibration (19).

The concrete for slabs for the 16-story Green's Point Hotel in Houston, Texas, required a strength of 3000 psi. at two days to facilitate early post-tensioning. A slump of 8±1 inches was achieved by using a superplasticizer. All of the 16 floors had two 260-cubic-yard placements. The use of the superplasticizer helped in the completion of the concrete phase of the project two months ahead of schedule (19).

Formigli Cooperation of Berlin, New Jersey, a prestressed beam manufacturer, successfully employed a naphthalene based superplasticizer to ensure that the concrete for the prestressed concrete beams reached 3500 psi. in 12 hours in order to guarantee on-time tensioning. The concrete girders were designed for Harrah's Marina Hotel-Casino in Atlantic City (19).

The United States' second largest homebuilder, Fox and Jocobs( Carrollton, Texas ), is making extensive use of superplasticizers to pour the slab foundations of 4000 new homes each year. The firm uses a superplasticizer because it finds it advantageous and cost-effective to do so (20).

## Laboratory Investigation of Superplasticized Concrete at Kansas State University

This part of the report deals with the experimental work that was done at Kansas State University with concrete containing superplasticizer.

### I. Scope of Investigation

The test program consisted of an evaluation of compressive strength and slump loss on concrete containing superplasticizers.

### II. Materials Used

ASTM Type I cement was used. Quartzite stone was used as coarse aggregate, and natural sand was used as fine aggregate. Melament, which is a sulfonated melamine based superplasticizer, and Sikament, which is a sulfonated naphthalene based superplasticizer, were used as admixtures.

### III. Concrete Mixes

Two concrete mixes were used in this experiment. The first mix had a water-cement ratio of 0.35, an aggregate-cement ratio of 4, and a cement content of 27.5 $lb/ft^3$. The proportions for the second mix were the same as for the first one except that the water-cement ratio was 0.39. The mix proportions and slump values are given in Table 11. The mixing procedure for all the batches was as follow : The coarse and fine aggregate, to which the cement had been added, were placed in the mixer. The mixer was then started, and the ingredients were mixed for 1/2 minute. The mixing was continued and the water, together with the superplasticizer, was added during the next 1/2 minute. After all the ingredients were in the mixer, the mixing was done according to ASTM Standard Method of Making and Curing Concrete Test Specimens in the Laboratory(ASTM C-192-76), that is, the concrete was mixed for 3 minutes followed by 3 minutes of rest and 2 minutes of final mixing.

## IV. Preparation and Casting of Specimens

Each batch was sufficient to produce nine 3-by-6 inch cylinders. The test specimens were compacted by the standard rodding procedure. The cylinders were cast in the molds. After being molded all the specimens were covered with a plastic sheet and left in the mixing room for 24 hours. They were then unmolded and transferred to a standard moist-curing room until required for testing.

## V. Testing of Specimens

Three cylinders from each batch were removed from the moist curing room at ages of 7, 14, and 28 days, capped on both ends, and tested in compression (ASTM C 39-72, Standard Test Method for Compressive Strength of Cylinderical Concrete Specimens). The results are shown in Tables 12 and 13 .

## VI. Discussion of Test Results

The rate of slump loss versus time for batch number 4 is shown in Figure 27 . The final slump was 6.5 inches, and after 30 minutes reverted to its original slump which was 1 inch. This phenomenon of superplasticized concrete was discussed in previous sections.

Compressive strengths versus time are plotted in Figures 28 and 29. From Figure 28, one can see that two kinds of superplasticizer react in different ways in the concrete. Compressive strength at all ages for concrete with Melament were greater than those of concrete with Sikament. According to Figure 29, addition of one percent of the Sikament by weight of the cement to concrete caused increase in compressive strength at all ages.

## VII. Concluding Remarks

Superplasticizers, when used in concrete, appear to improve the workability of concrete. They will increase the compressive strength of concrete. Superplasticized concrete will lose its slump as time goes on. Different superplasticizers react in different ways in the concrete. This is mostly due to the chemical composition of the superplasticizer.

## Some Recommendations for Practical Use

Proper usage of superplasticizers should begin by gathering available information and comparing the different brands. Before using a superplasticizer, read the producer's statement about it, consider if it has a proven record of performance, and take into account if it is really economical to use.

The proper use of concrete with superplasticizers requires special skills and adequate experience. The person who is using them should be extensively instructed on the peculiarities to be considered in the application of superplasticizers, before using them. Before starting any application, it is necessary to test both the plain concrete and concrete with superplasticizer. The test conditions for both mixes should be as similar as possible to the field conditions.

The Plasticizing effect of the superplasticizers will decrease with time. The factors influencing this are type of superplasticizer, its dosage, properties of the cement, the concrete temperature, and the time during the mixing process at which the superplasticizer is added. Therefore, the person who is using a superplasticizer, should consider these factors.

## Conclusions

Superplasticizers are a new type of admixtures for concrete. They are gaining acceptance in such fields as road construction, the production of ready-mixed concrete, and the productions of prefabricated concrete elements.

Superplasticizers provide an additional option for improving concrete workability without additional water and without strength loss. They are particularly applicable where forms are easily accessible but placement is restricted by intricate reinforcing or unusual form shapes.

They increase the slump with no significant segregation. The fluidifying effect of the superplasticizer is temporary. The maximum slump of the concrete is obtained immediately after the addition of the superplasticizer, and thereafter it is reduced to its original condition in a time as short as 30 minutes. The rate of slump loss can vary depending upon cement content, initial slump, temperature, dosage of superplasticizer, and time at which superplasticizer is added to the mix.

Superplasticizers are capable of reducing the water requirement of moderate to high cement content concrete by more than 20 percent. They can increase the compressive strength of the concrete in proportion to the amount of water reduction effected.

The use of a superplasticizer in concrete can result in reduction in placement labor cost, a decrease in drying shrinkage due to reduced water content, improved consolidation with minimal vibration, and improved pumpability.

By using superplasticizers, considerable cement reduction is possible without lowering the quality of the concrete. When using normal cements with superplasticizer, the same results can be achieved as with high early strength cements without superplasticizer.

Superplasticizers are more expensive than ordinary water reducers. However, when one considers all of the advantages listed above, the in-place costs of concrete are normally reduced.

Table 1. Physical Properties of Three Types of Superplasticizer (1).

| Name | Country of Origin | Aqueous Solution (%) | Density ($lb/ft^3$) | Color | Chloride Contents (%) |
|---|---|---|---|---|---|
| Sulfonated melamine-formaldehyde condensates | Germany | 20 | 68.6 | clear to milky | 0.005 |
| Sulfonated naphthalene-formaldehyde condensates | Japan | 42 | 74.9 | dark brown | negligible |
| Modified lignosulfonates | France | 20 | 68.6 | light brown | none |

Table 2. Water-Cement Ratio and Slump for Melamine Based Superplasticizer (4).

| | Control | %1.5 Melamine | %3.0 Melamine |
|---|---|---|---|
| w/c ratio | 0.61 | 0.55 | 0.46 |
| % of control | 100 | 90 | 75 |
| slump,in. | 2.9 | 3.0 | 3.3 |
| Air % | 0.8 | 1.0 | 1.3 |

Table 3. Compressive Strengths for Melamine Based Superplasticizer (4).

| | Control (psi) | 1.5% Melamine (psi) | %Increase Over Reference | 3% Melamine (psi) | %Increase Over Reference |
|---|---|---|---|---|---|
| 16 Hr. | 330 | 515 | 56 | 845 | 156 |
| 1 Day | 1120 | 1530 | 37 | 2670 | 138 |
| 3 Days | 3400 | 4290 | 26 | 5500 | 62 |
| 7 Days | 4470 | 5685 | 27 | 6790 | 45 |
| 28 Days | 5335 | 6675 | 25 | 7795 | 46 |

Table 4. Chemical Composition and Surface Area of Four Brands of Type I, Type III, and Type V Cements, Relate to Figures 5 Thru 11 (8).

| Constituent | Type III (%) | Type V (%) | Type I (%) A | B | C | D |
|---|---|---|---|---|---|---|
| $C_3S$ | 48 | 53 | 51 | 41 | 52 | 50 |
| $C_2S$ | 23 | 26 | 20 | 29 | 20 | 25 |
| $C_3A$ | 11 | 3 | 13 | 11 | 9 | 7 |
| $C_4AF$ | 8 | 10 | 6 | 8 | 9 | 7 |
| $SO_3$ | 3.6 | 2.2 | 3.1 | 3.5 | 3.9 | 2.4 |
| Blaine Surface Area * $cm^2/g$ | 5200 | 3420 | 3580 | 3730 | 3210 | 3320 |

Note :

* 1 $cm^2/g$ = 70.31 $in^2/lb$

Table 5. Mix proportions Relating to Figures 5 Thru 11 (8).

| Ingredient | Weight (Kg/m$^3$)* A | B | C |
|---|---|---|---|
| Cement | 237 | 326 | 415 |
| Coarse Agg. (Dry) | 1102 | 1016 | 1009 |
| Fine Agg. (Dry) | 844 | 828 | 749 |
| Total W/C At 22°C For 75±10 mm Slump | 0.69 | 0.535 | 0.435 |
| | Doaage (% by Weight of Cement) | | |
| (1) Water Reducer (C L S) | 0.45 | | |
| (2) H.C. Retarder (H C R) | 0.20 | | |
| (3) Superplasticizer Retarder(M-R1) | 1.5 | | |
| Sulfonated Melamine Formaldehyde Condensate(M-L1) | 1.5 | | |

Notes :

* 1 lb/ft$^3$ = 16.02 Kg/m$^3$

(1) Lignosulfonate water reducer added with gauge water prior to addition of superplasticizer.

(2) H.c. retarder (H.C.R) Hydroxycarboxylic retarder, addition as in (1).

(3) M-R1 is the superplasticizer with retarder Ingredient.

Table 6. Compressive Strength Results at 7, and 28 Days, Related to Figures 5 Thr 11 (8).

| Slump Loss Factor Investigated | Slump-mm * Initial | Final | Dosage(% by Weight of Cement) | Mix Temp. ** °C | Compressive Strength (Mpa)*** 7 Days | 28 Days |
|---|---|---|---|---|---|---|
| Temperature | | | | | | |
| M-L1 | 75 | 230 | 1.5 | 15.5 | 33.4 | 40.0 |
| M-L1 | 75 | 220 | 1.5 | 22.0 | 32.2 | 38.0 |
| M-L1 | 75 | 230 | 1.5 | 32.0 | 29.7 | 43.3 |
| M-R1 | 75 | 250 | 1.5 | 32.0 | 33.1 | 35.5 |
| Final Slump | | | | | | |
| M-L1 | 75 | 250 | 1.75 | 22 | 33.2 | 37.2 |
| M-L1 | 70 | 220 | 1.5 | 23 | 31.6 | 38.8 |
| M-L1 | 70 | 200 | 1.25 | 22 | 31.9 | 39.1 |
| M-L1 | 75 | 180 | .90 | 22 | 30.0 | 37.5 |
| Combined Admixtures | | | | | | |
| CLS+(M-L1) | 75 | 220 | 1.5 | 23 | 36.7 | 39.5 |
| HCR+(M-L1) | 75 | 240 | 1.5 | 22 | 37.1 | 39.5 |
| M-L1 | 75 | 220 | 1.5 | 22 | 32.2 | 38.0 |
| M-R1 | 75 | 250 | 1.5 | 23 | 32.0 | 35.9 |
| Time of Addition | | | | | | |
| 20 Minutes | 65 | 200 | 1.5 | 22 | 33.5 | 37.0 |
| 40 Minutes | 50 | 200 | 1.5 | 23 | 32.7 | 36.2 |
| 60 Minutes | 50 | 180 | 1.5 | 22 | 34.0 | 37.0 |
| Cement Content $ | | | | | | |
| 237 $kg/m^3$ | 75 | 200 | 1.5 | 24 | 23.0 | 25.1 |
| 326 $kg/m^3$ | 75 | 220 | 1.5 | 22 | 32.2 | 38.0 |
| 415 $kg/m^3$ | 75 | 250 | 1.5 | 22 | 40.1 | 42.9 |

Table 6. (continued)

| Slump Loss Factor Investigated | Slump-mm * Initial | Final | Dosage(% by Weight Cement) | Mix Tem. ** °C | Compressive Strength (Mpa)*** 7 Days | 28 Days |
|---|---|---|---|---|---|---|
| ASTM Cement Type | $$ | | | | | |
| V | 75 | 230 | 1.5 | 22 | 33.2 | 39.3 |
| III | 75 | 220 | 1.5 | 24 | 35.9 | 42.5 |
| I | 75 | 220 | 1.5 | 22 | 32.2 | 38.0 |

Notes :

Initial Slump 75±10 for most mixes taken just before addition of superplasticizer.

Cylinders cast after addition of superplasticizer.

* 1 in = 25.4 mm

** $t_f = 1.8\ t_c + 32$

*** 1 Mpa = 145 psi

$ 1 lb/ft$^3$ = 16.02 kg/m$^3$

$$ Type III, and Type V cements investigated at the 326 kg/m$^3$ content.

Table 7. Mix Designation and Mix Proportions, Relate to Figures 12 Thru 26 (10).

| | Mix Proportion | | | |
|---|---|---|---|---|
| Mix Designation | Fine Aggregate (%) | Cement (sacks/y$^3$) | W/C Ratio (by Weight) | Superplasticizer Dosage (% by Weight of Cement) |
| 1 | 40 | 6.5 | 0.38 | 1.0 |
| 2 | 43 | 6.0 | 0.33 | 0.8 |
| 3 | 43 | 7.0 | 0.33 | 0.8 |
| 4 | 43 | 6.0 | 0.43 | 0.8 |
| 5 | 43 | 7.0 | 0.43 | 0.8 |
| 6 | 43 | 6.0 | 0.33 | 1.2 |
| 7 | 43 | 7.0 | 0.33 | 1.2 |
| 8 | 43 | 6.0 | 0.43 | 1.2 |
| 9 | 43 | 7.0 | 0.43 | 1.2 |
| 10 | 46 | 6.5 | 0.38 | 0.6 |
| 11 | 46 | 6.5 | 0.28 | 1.0 |
| 12 | 46 | 5.5 | 0.38 | 1.0 |
| 13 | 46 | 6.5 | 0.38 | 1.0 |
| 14 | 46 | 7.5 | 0.38 | 1.0 |
| 15 | 46 | 6.5 | 0.48 | 1.0 |
| 16 | 46 | 6.5 | 0.38 | 1.4 |
| 17 | 49 | 6.0 | 0.33 | 0.8 |
| 18 | 49 | 7.0 | 0.33 | 0.8 |
| 19 | 49 | 6.0 | 0.43 | 0.8 |
| 20 | 49 | 7.0 | 0.43 | 0.8 |
| 21 | 49 | 6.0 | 0.33 | 1.2 |
| 22 | 49 | 7.0 | 0.33 | 1.2 |
| 23 | 49 | 6.0 | 0.43 | 1.2 |
| 24 | 49 | 7.0 | 0.43 | 1.2 |
| 25 | 52 | 6.5 | 0.38 | 1.0 |

Table 8. Compressive Strength For 25 Mixes, Relate to Figures 12 Thru 26 (10).

| Mix Designation | Compressive Strength (psi) | | |
|---|---|---|---|
| | 3-Days | 7-Days | 28-Days |
| 1 | 4843 | 5183 | 5937 |
| 2 | 6180 | 6347 | 6415 |
| 3 | 5580 | 6253 | 7113 |
| 4 | 3253 | 4507 | 5470 |
| 5 | 3120 | 3917 | 5427 |
| 6 | 5190 | 7163 | 7623 |
| 7 | 4427 | 5153 | 5973 |
| 8 | 5103 | 5330 | 6217 |
| 9 | 2927 | 4000 | 4440 |
| 10 | 4220 | 4990 | 4943 |
| 11 | 4827 | 5890 | 6150 |
| 12 | 5590 | 6383 | 6813 |
| 13 | 4327 | 5557 | 6103 |
| 14 | 3780 | 4697 | 5495 |
| 15 | 2843 | 4083 | 4937 |
| 16 | 5303 | 5723 | 6083 |
| 17 | 5870 | 6730 | 7113 |
| 18 | 4833 | 6510 | 6927 |
| 19 | 3997 | 5167 | 6030 |
| 20 | 3123 | 3760 | 4727 |
| 21 | 5323 | 6923 | 7157 |
| 22 | 5143 | 6323 | 7130 |
| 23 | 3303 | 4000 | 4710 |
| 24 | 3987 | 4560 | 5403 |
| 25 | 3920 | 4647 | 5697 |

Table 9. Examples of Structures Constructed With High Strength Concrete Containing Superplasticizer in Japan (18).

| Structures No. | Name | Date of Construction | Compressive Strength at 28 Days (Mpa)* Designed | Actual |
|---|---|---|---|---|
| 1. | PC Piles | Since 1965 | 50 | 70 |
| 2. | AC Piles | Since 1970 | 85 | 90 |
| 3. | Poles | Since 1969 | 50 | 80 |
| 4. | Kohnoshima Highway Bridge | 1970 | 60 | 70 |
| 5. | Tunel Segment of JNR in Tokyo | 1973 | 55 | 70 |
| 6. | Ohtanaba Railway Bridge | 1973 | 80 | 90 |
| 7. | Iwahana Railway bridge | 1974 | 80 | 90 |
| 8. | Akkagawa Railway Bridge | 1974 | 80 | 96 |

Note :

* 1 Mpa = 145 psi

Table 10. Mix Formulations of Structures Constructed with High Strength Concrete Containing Superplasticizer in Japan (18).

| Structure* No. | Slump (mm)** | Cement Content ($kg/m^3$)*** | W/C Ratio | S/A Ratio (%Vol.) | Superplasticizer (% by Weight of Cement |
|---|---|---|---|---|---|
| 1 | 50-100 | 400 | 0.37 | 41 | 0.6 |
| 2 | 50-100 | 470 | 0.31 | 4o | 1.5 |
| 3 | 50-100 | 500 | 0.32 | 35 | 1.25 |
| 4 | 40 | 440 | 0.393 | 38.5 | 0.8 |
| 5 | 40 | 470 | 0.33 | 38 | 0.6 |
| 6 | 210 | 480 | 0.319 | 45 | 1.5 |
| 7 | 120 | 600 | 0.23 | 38.5 | 1.5 |
| 8 | 120 | 530 | 0.30 | 40 | 1.5 |

Notes :

* These numbers are equivalent to those of Table 9.

** 1 in = 25.4 mm

*** 1 $lb/ft^3$ = 16.02 $kg/m^3$

Table 11. Mix Proportions and Slumps for Concrete Made at Kansas State University by the Author.

| No. | Mix Proportions ($lb/ft^3$) | | | | W/C | Slump | Superplasticizers | |
|---|---|---|---|---|---|---|---|---|
| | Cement | Fine Agg. | Coarse Agg. | Water | | | Type | Amount (ml) |
| | | Mix I | | | | | | |
| 1. | 27.5 | 60.9 | 49.6 | 9.6 | 0.35 | 2.75 | Melament | 120 |
| 2. | 27.5 | 60.9 | 49.6 | 9.6 | 0.35 | 0.50 | Sikament | 120 |
| | | Mix II | | | | | | |
| 3. | 27.5 | 60.9 | 49.6 | 10.55 | o.39 | 1.00 | -------- | --- |
| 4. | 27.5 | 60.9 | 49.6 | 10.55 | 0.39 | 6.50 | Sikament | 140* |

Note :

* This amount was 1% by weight of cement.

Table 12. Compressive Strengths for Mix I.

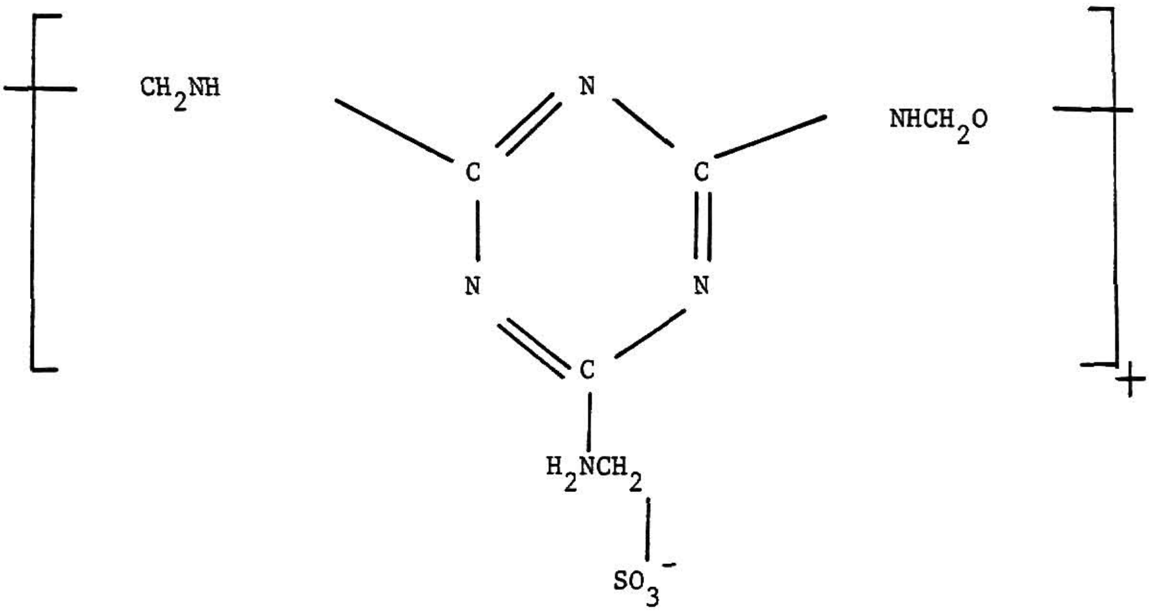
| * NO. | Type of Cement | Compressive Strength (psi) | | |
|---|---|---|---|---|
| | | 7 Days | 14 Days | 28 Days |
| 1. | Type I Cement + Melament | 7070 | 7360 | 7850 |
| | | 7210 | 7710 | 8060 |
| | | 7000 | 7570 | 8200 |
| | Average | 7090 | 7550 | 8040 |
| 2. | Type I Cement + Sikament | 5730 | 6860 | 7500 |
| | | 6080 | 6650 | 7360 |
| | | 5940 | 6580 | 7070 |
| | Average | 5920 | 6700 | 7310 |

Table 13. Compressive Strength for Mix II.

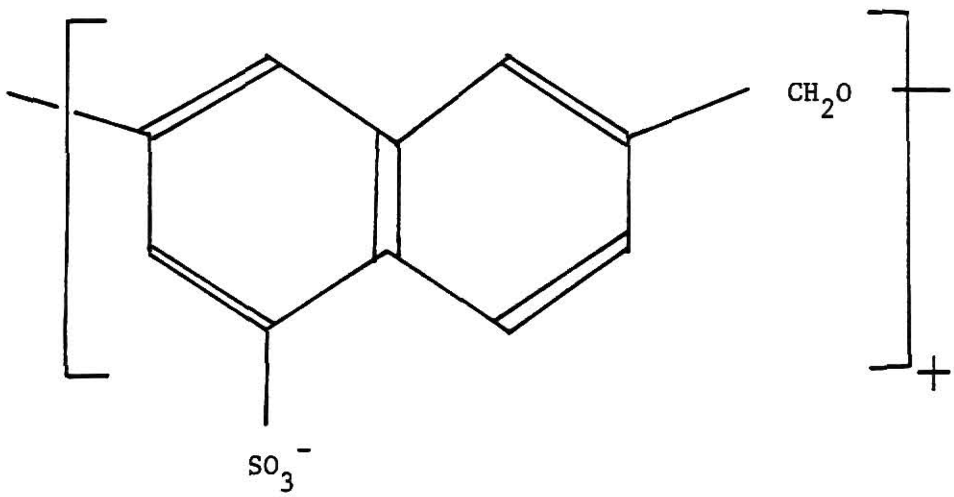
| * No. | Type of Cement | Compressive Strength (psi) | | |
|---|---|---|---|---|
| | | 7 Days | 14 Days | 28 Days |
| 3. | Type I Cement (No Superplasticizer) | 5590 | 6510 | 6860 |
| | | 5730 | 6650 | 7000 |
| | | 5370 | 6290 | 7210 |
| | Average | 5560 | 6480 | 7020 |
| 4. | Type I Cement + Sikament | 6860 | 7210 | 8130 |
| | | 6580 | 7070 | 7920 |
| | | 6510 | 7430 | 8060 |
| | Average | 6650 | 7240 | 8040 |

Note :

* These numbers are equivalent to those of Table 11.




R = Melamine - Formaldehyde




R = Naphthalene - Formaldehyde

Fig. 1. -R-Organic Group for Naphthalene Formadlehyde and Melamine Formaldehyde (1).

| | Control | 1.5% Melamine |
| --- | --- | --- |
| Water/cement ratio | 0.61 | 0.64 |
| Water content, % of control | 100 | 105 |
| Slump, inches | 3.0 | collapse |
| Air % | 0.8 | 0.5 |

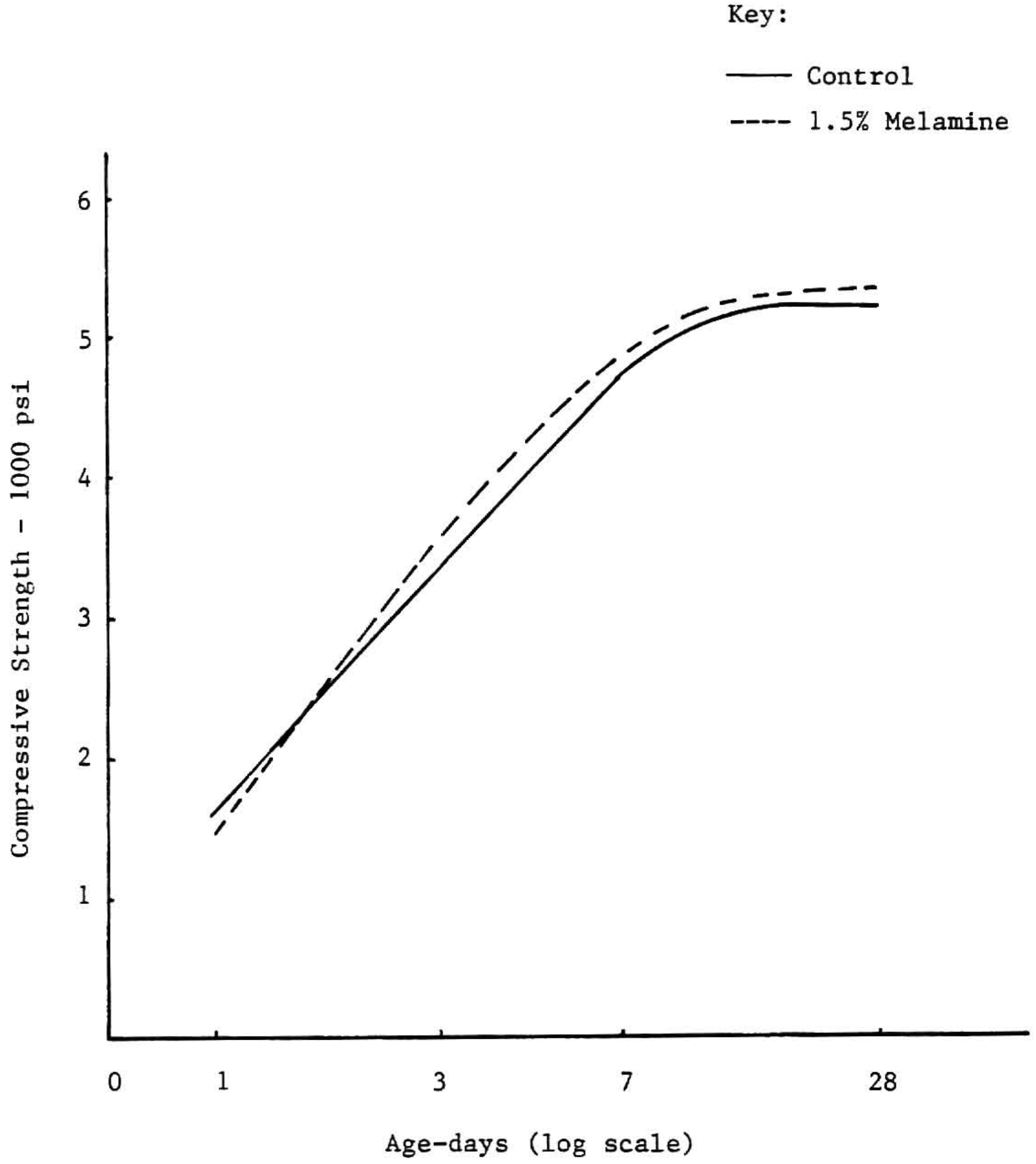



Fig. 2. Relationship Between Age and Compressive Strength for Concrete Using Melamine Based Superplasticizer (4).

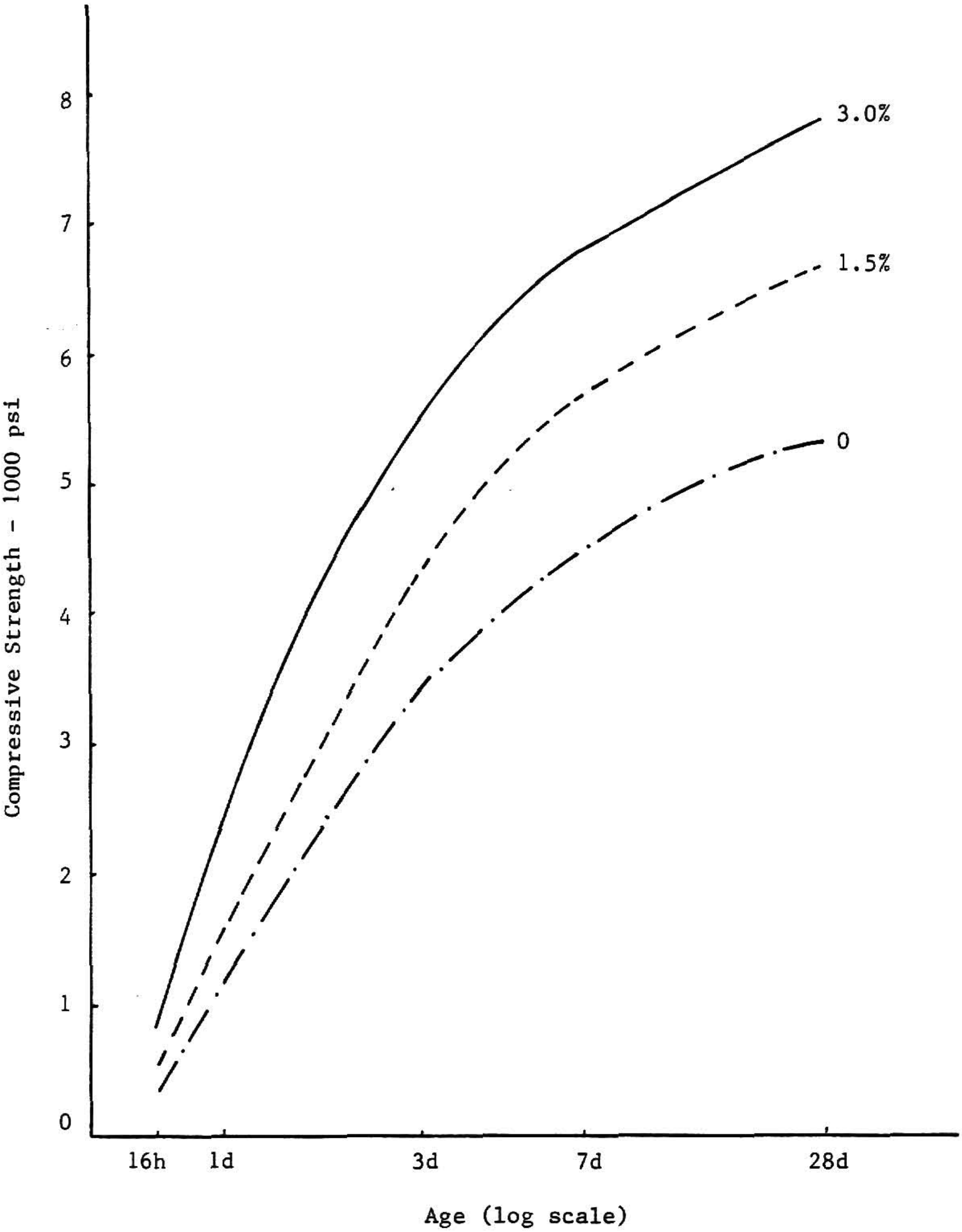



Fig. 3. Relationship Between Age and Compressive Strength for Concrete Using 0%, 1.5%, 3% Melamine Based Superplasticizer (4).

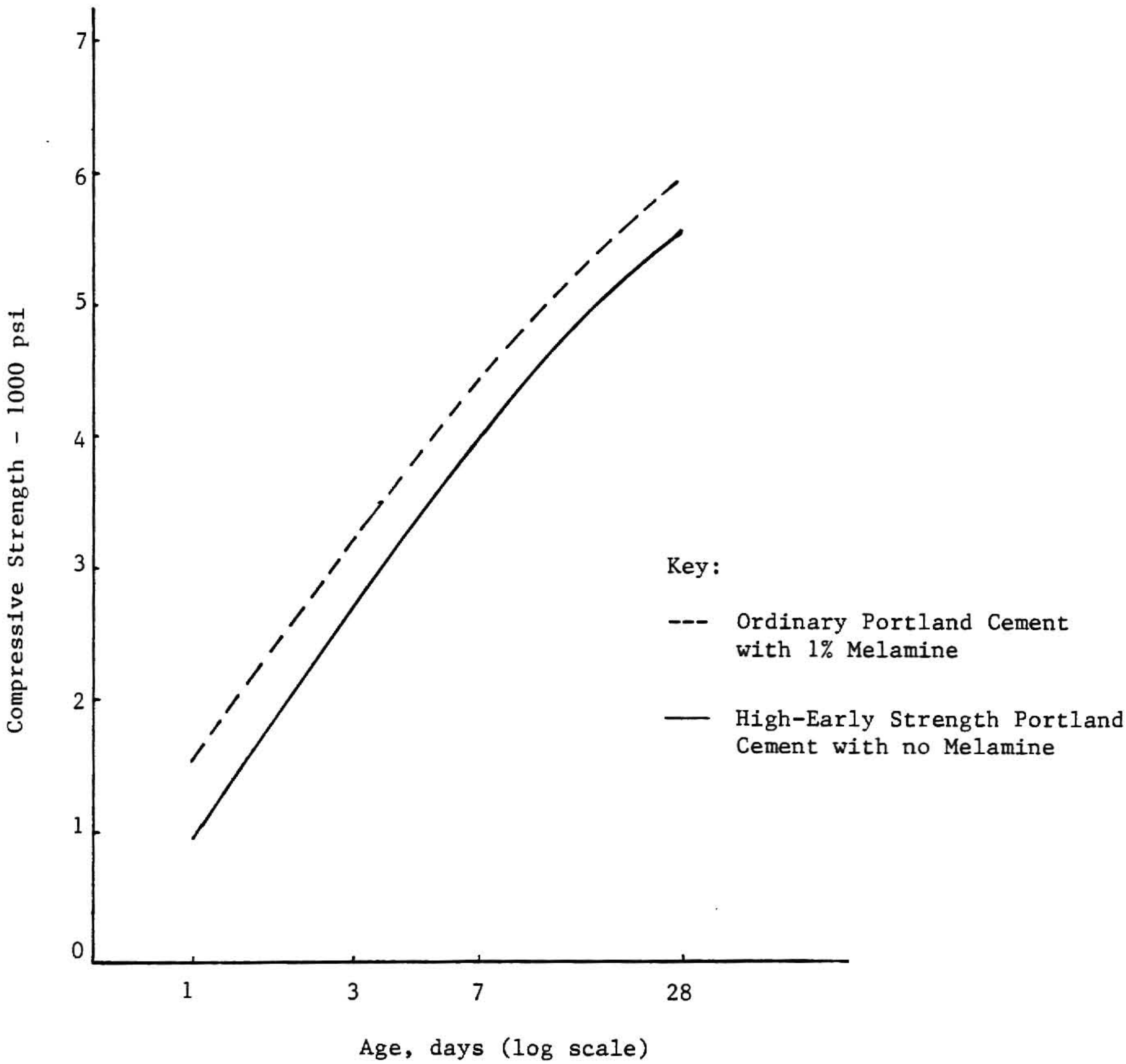



Fig. 4. Relationship Between Age and Compressive Strength for Different Types of Portland Cement (4)

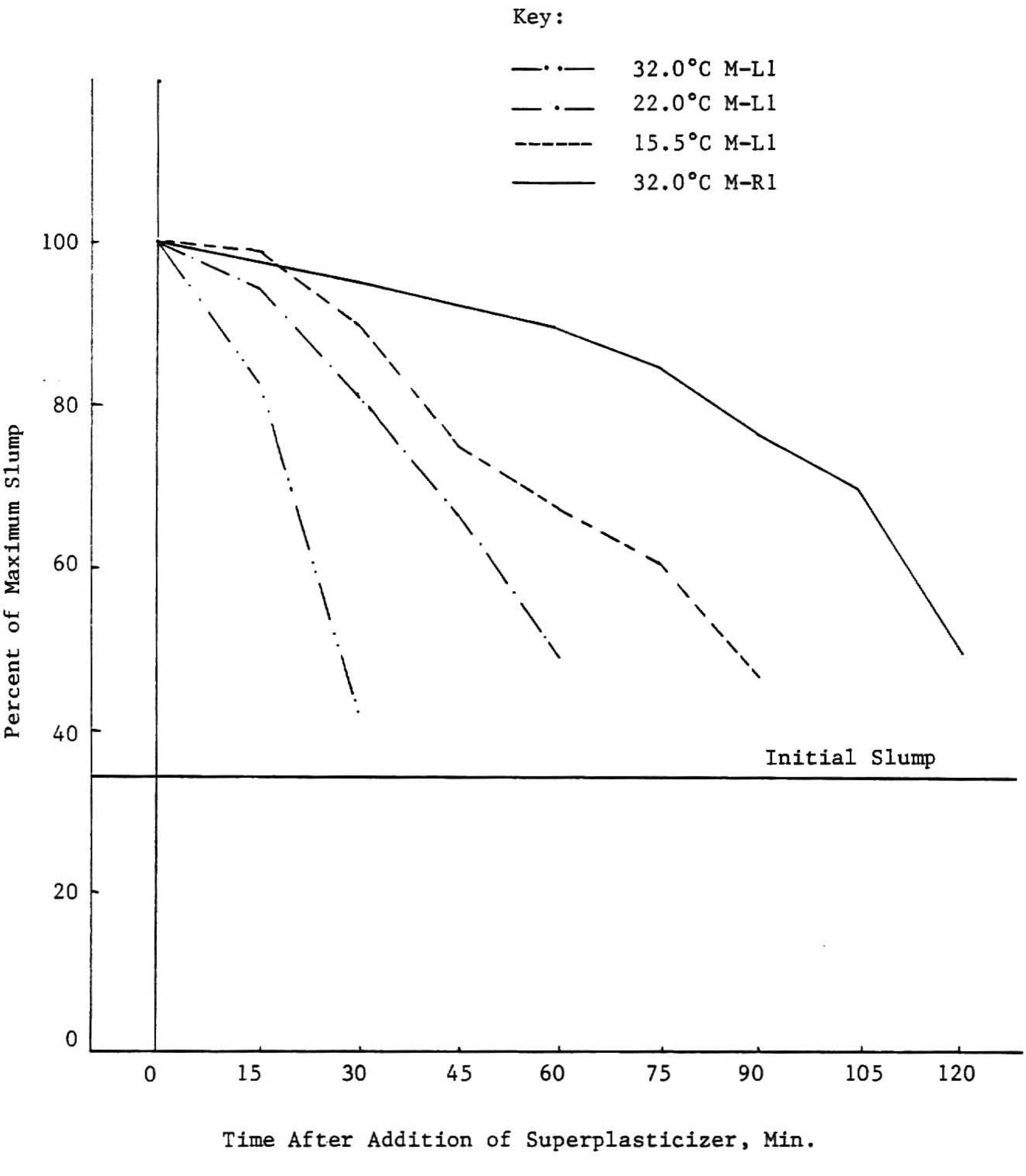



Fig. 5. Effect of Variation in Temperature on Slump Loss (8).

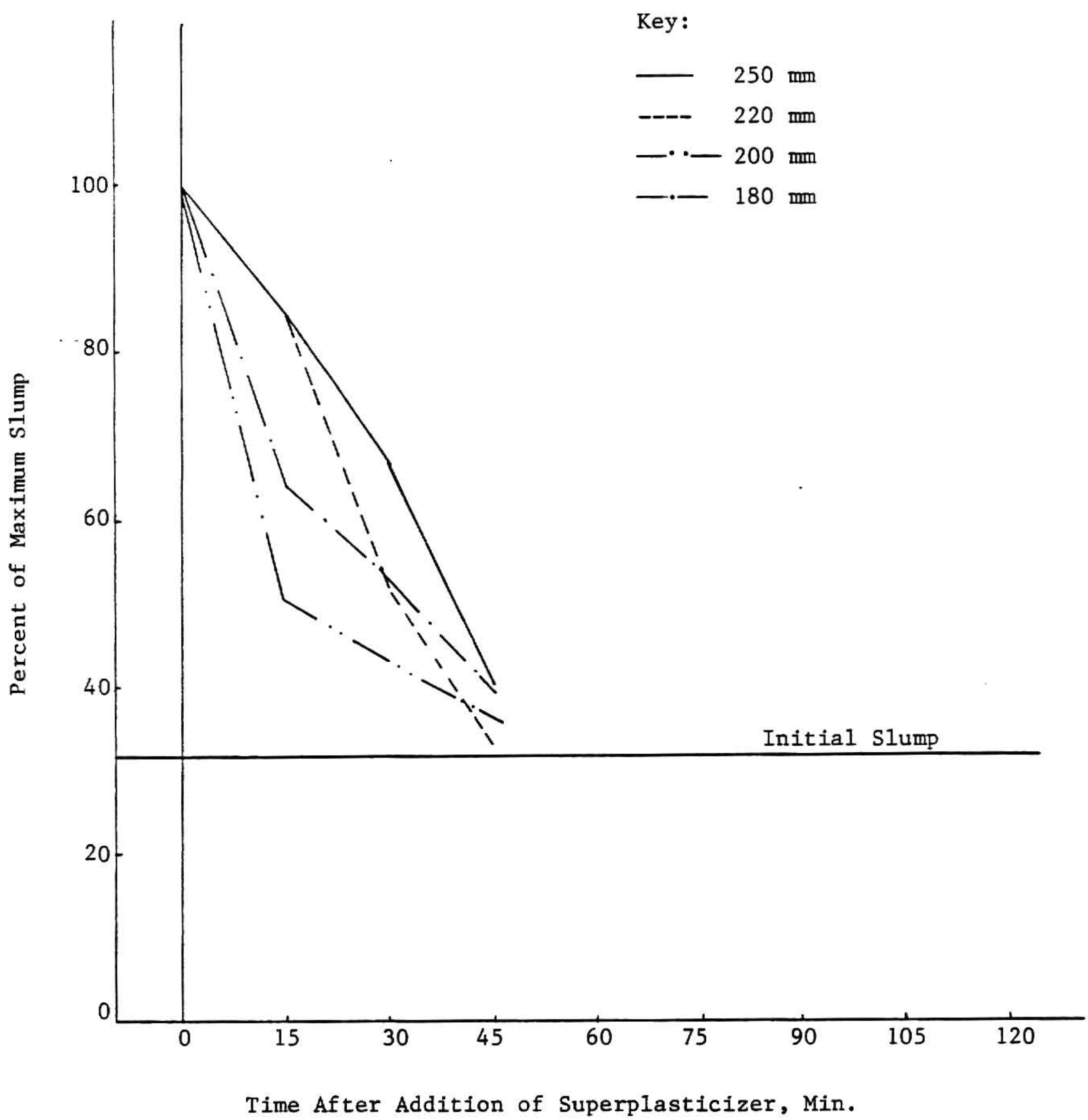



Fig. 6. Effect of Variation in Final Slump on Slump Loss (8).

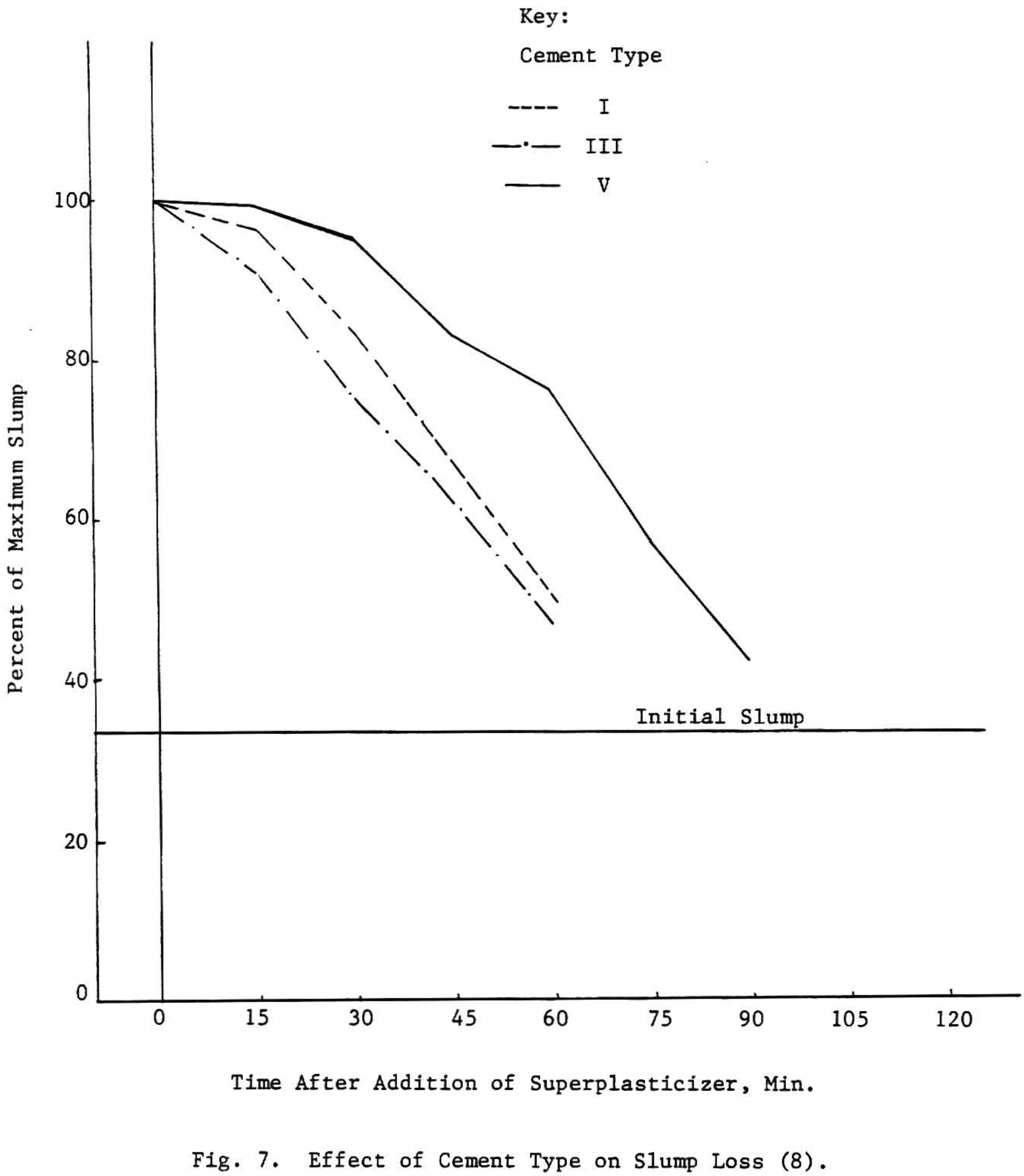



Fig. 7. Effect of Cement Type on Slump Loss (8).

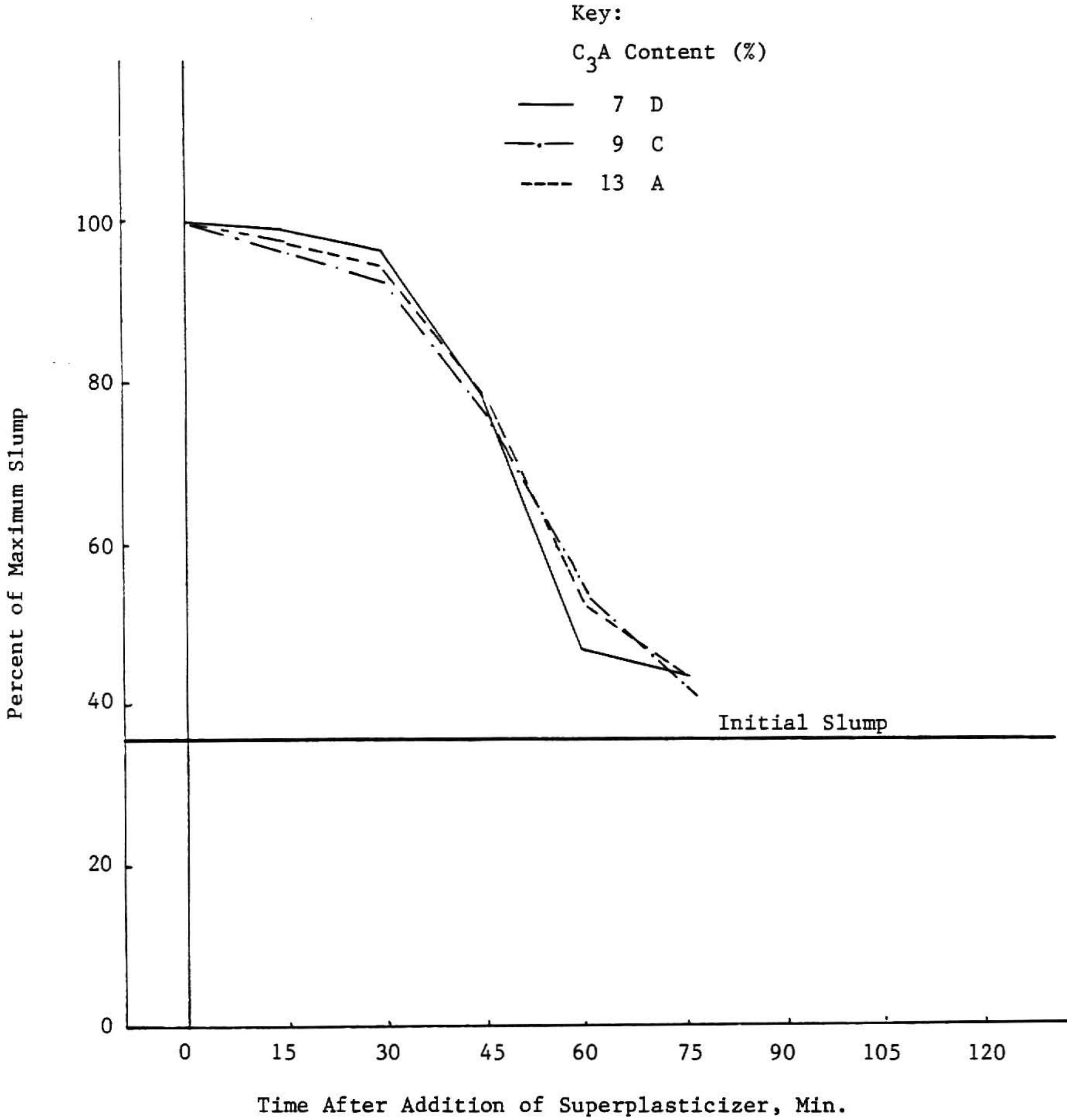



Fig. 8. Effect of Variation in $C_3A$ Content (Type I Cement) on Slump Loss (8).

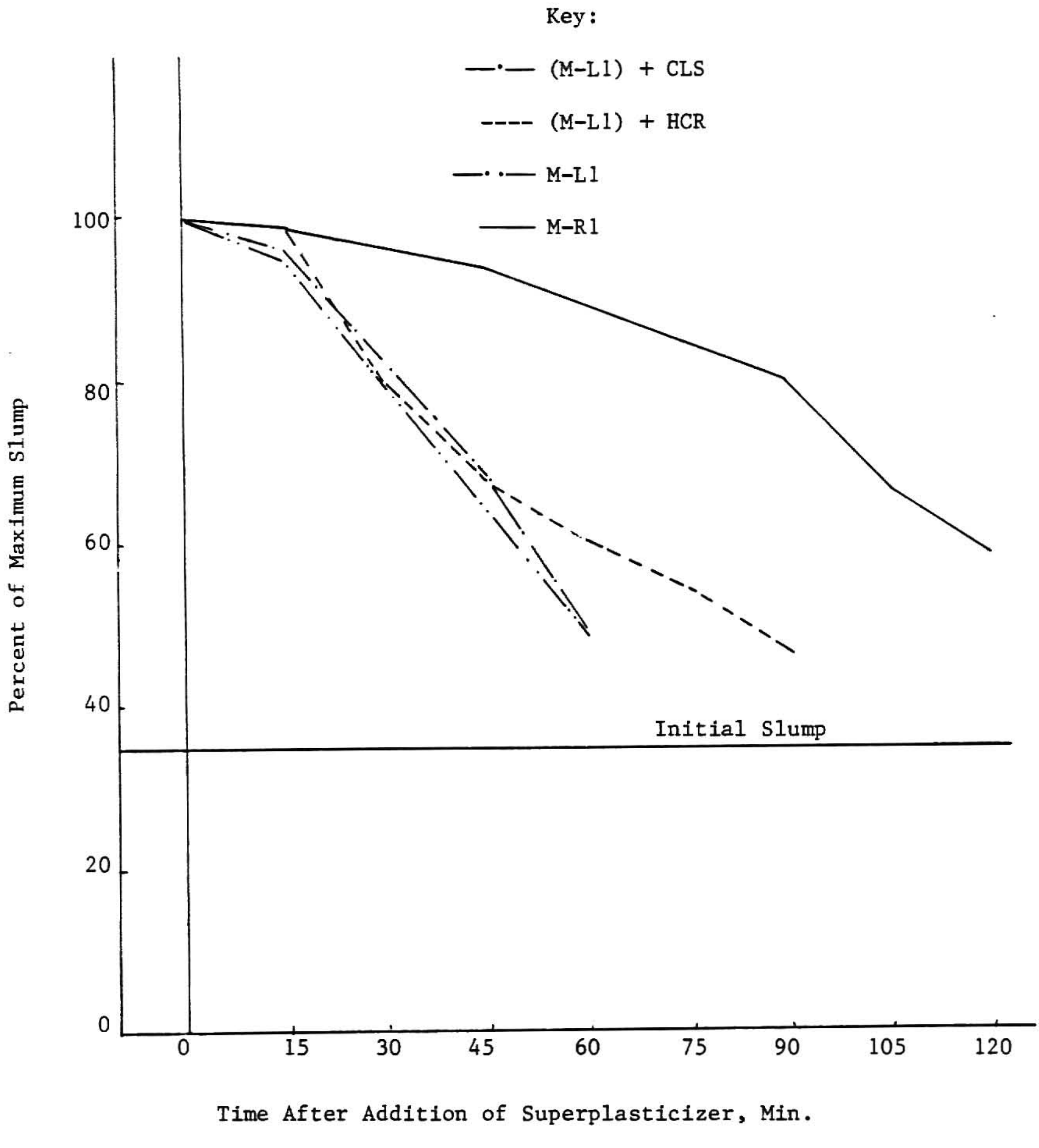



Fig. 9. Effect of Combined Admixtures on Slump Loss (8).

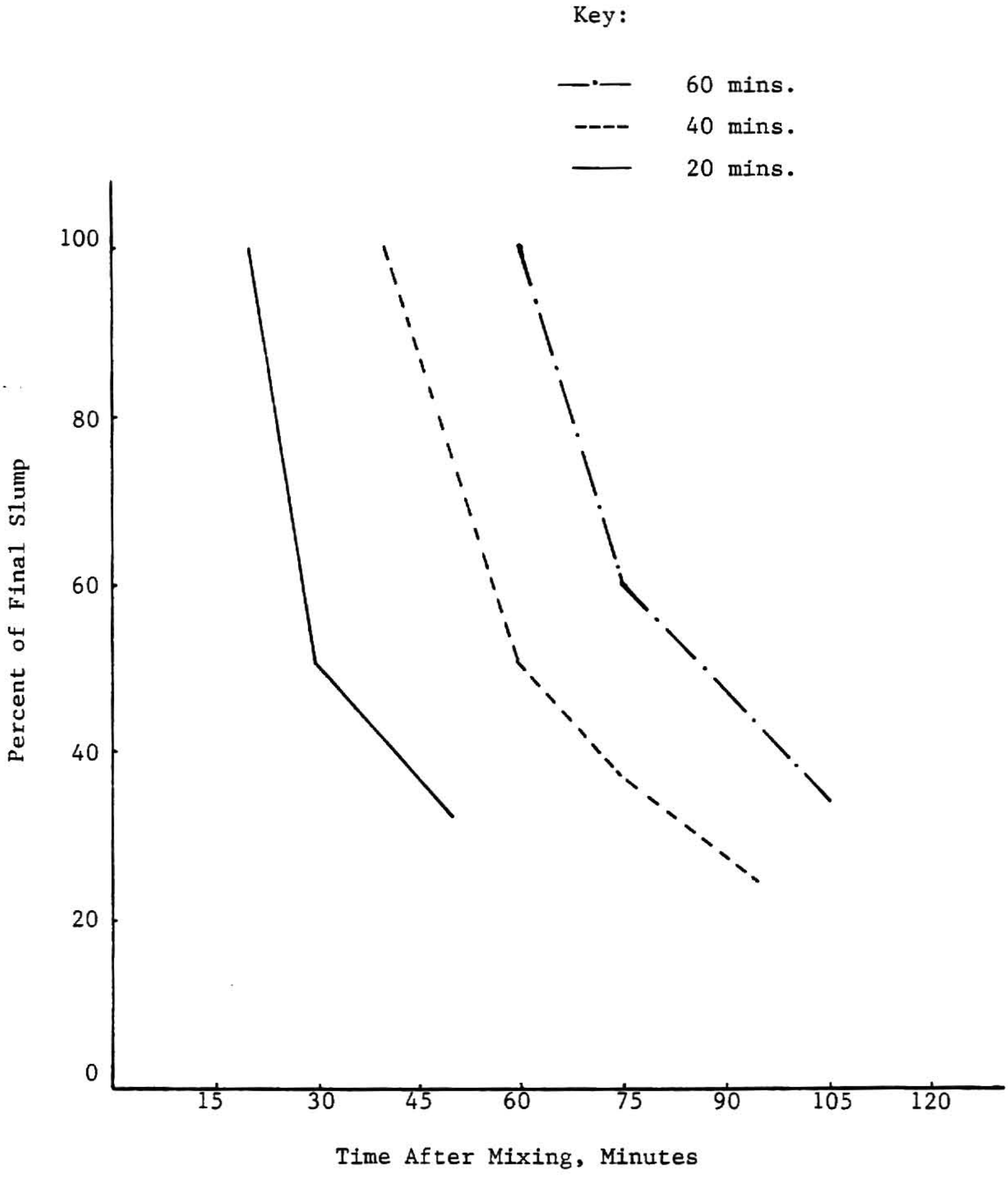



Fig. 10. Effect of Concrete Age on Slump Loss (8).

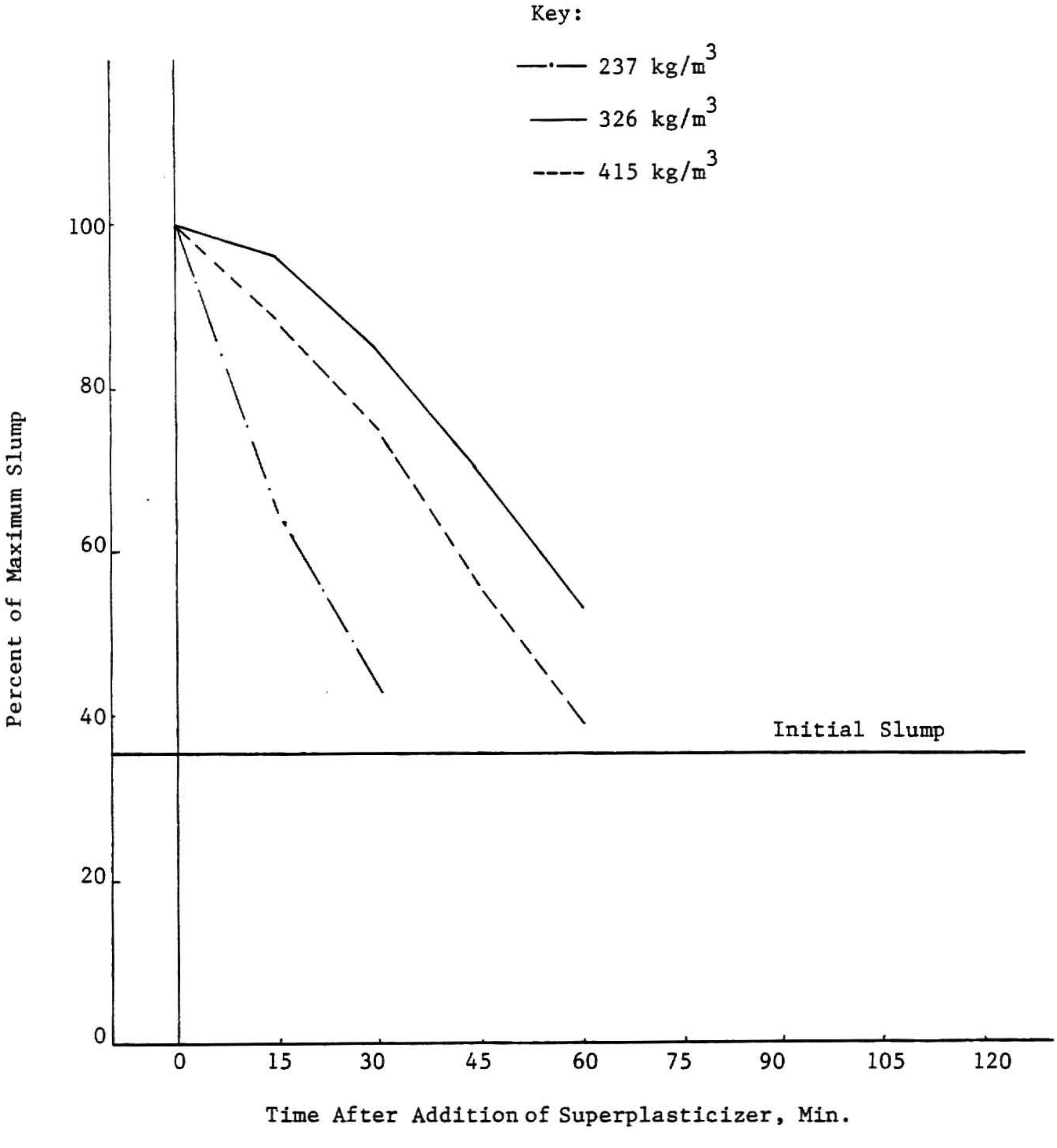



Fig. 11. Effect of Cement Content on Slump Loss (8).

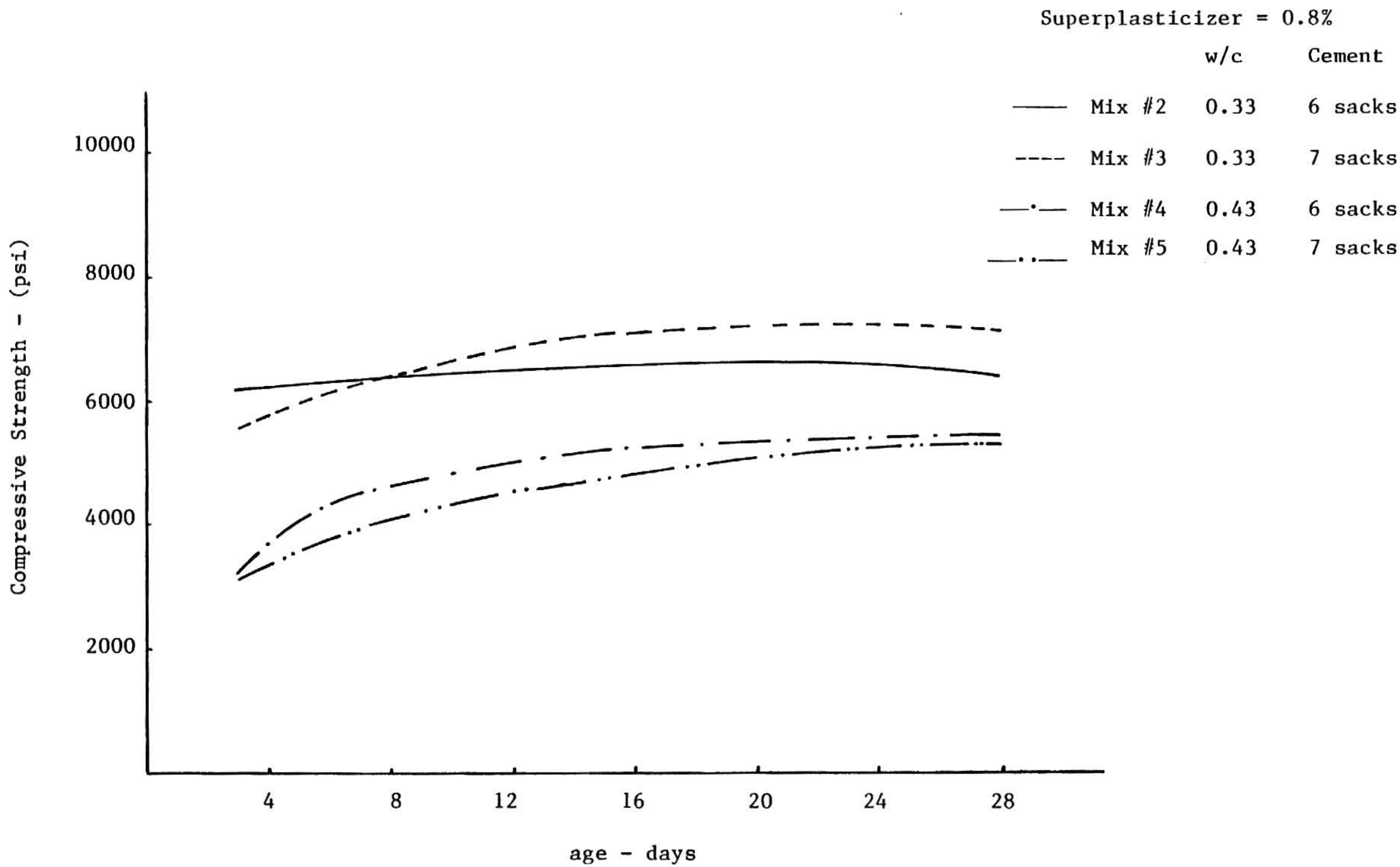



Fig. 12. Relation Between Strength and Age for Mixes 2, 3, 4, 5 (10).

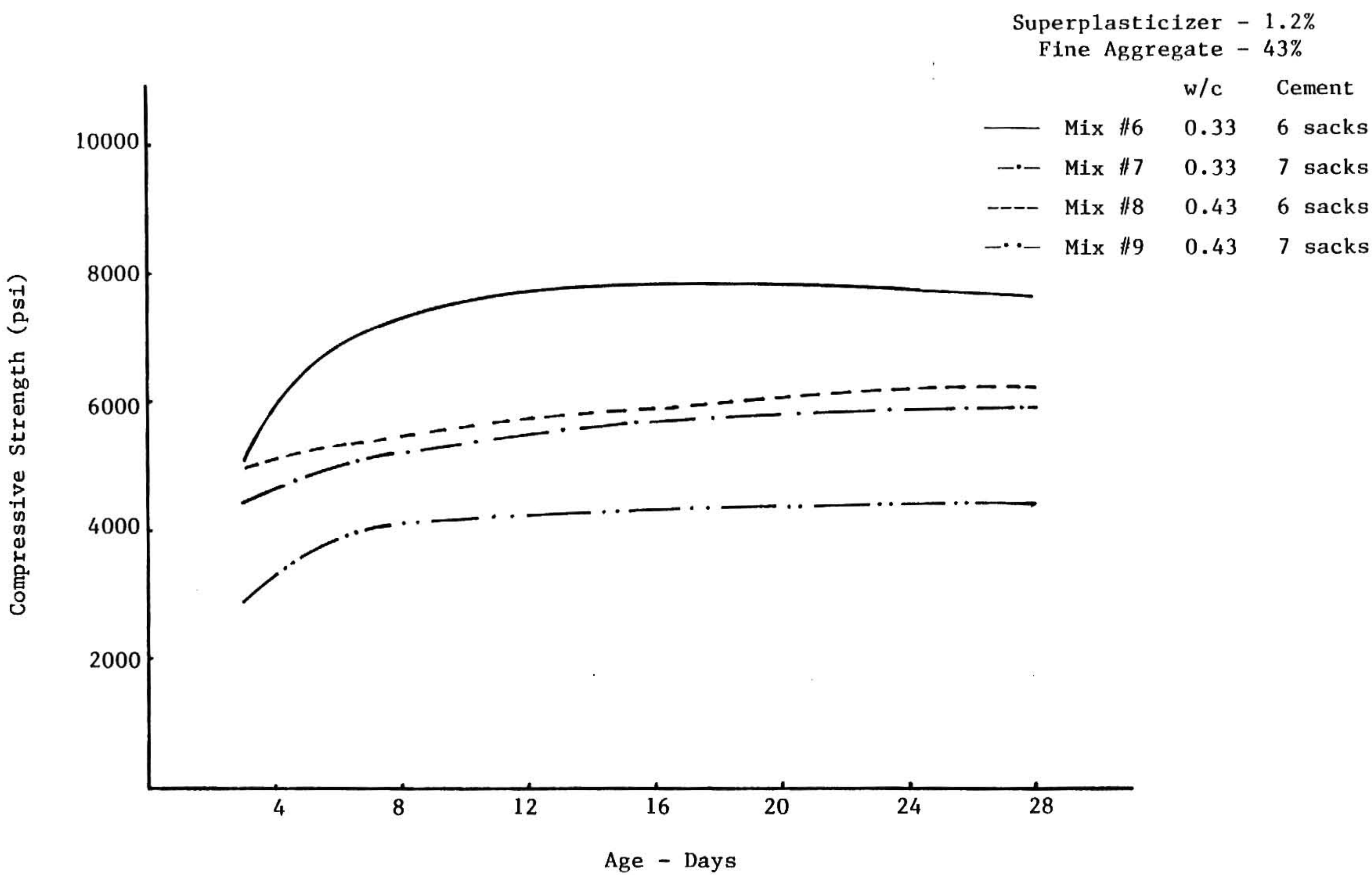



Fig. 13. Relation Between Strength and Age for Mixes 6, 7, 8, and 9 (10).

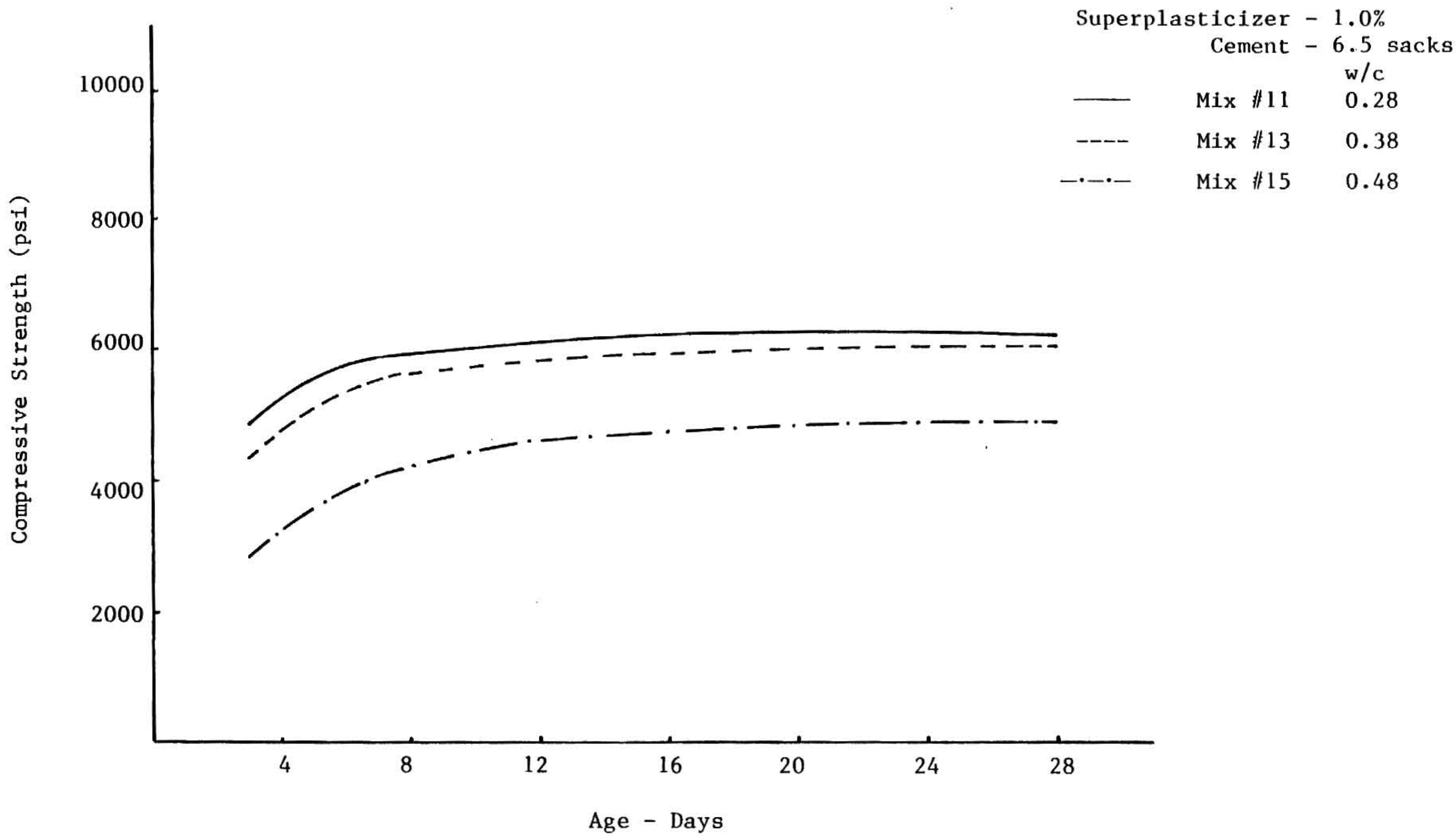



Fig. 14. Relation Between Strength and Age for Mixes 11, 13 and 15 (10).

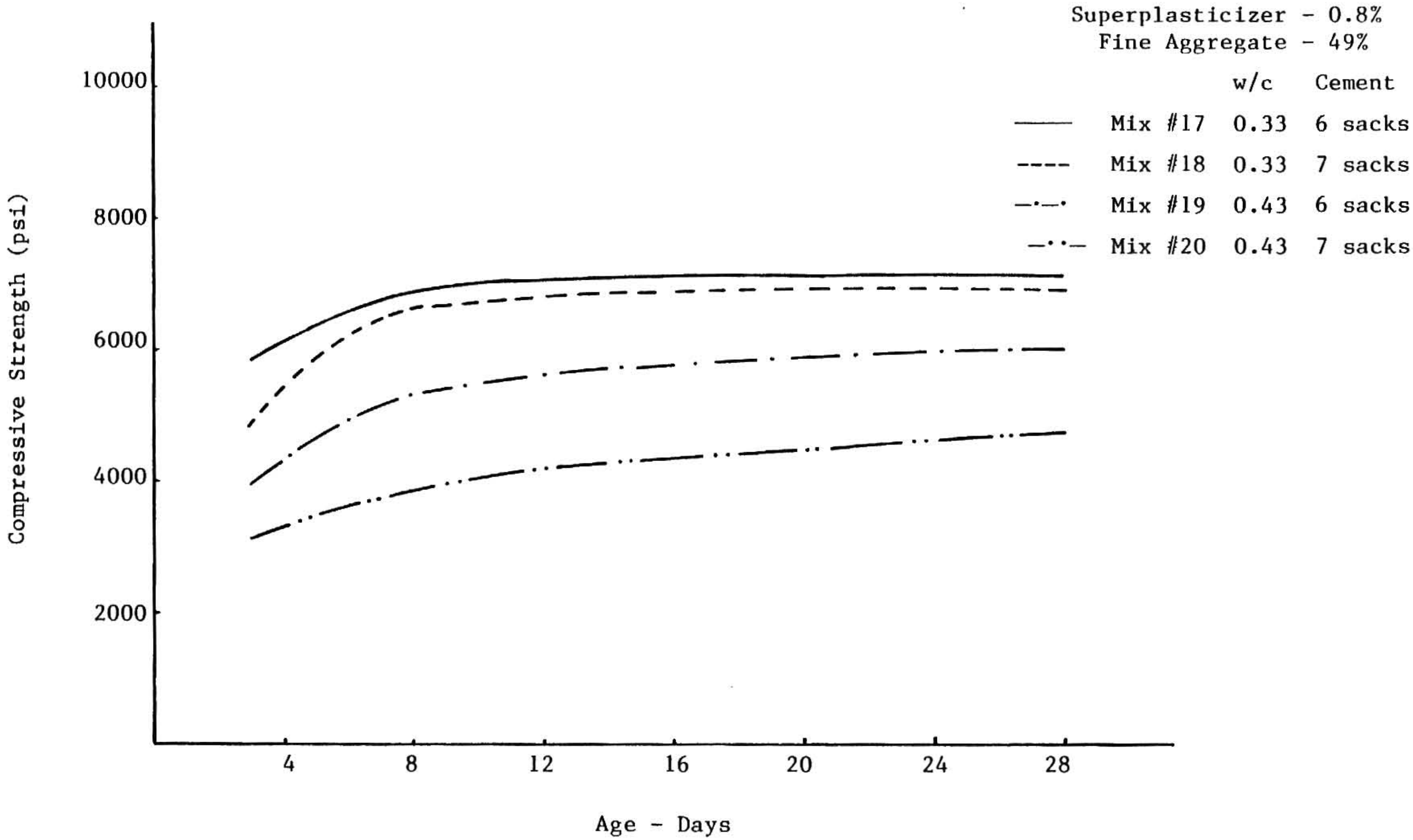



Fig. 15. Relation Between Strength and Age for Mixes 17, 18, 19, and 20 (10).

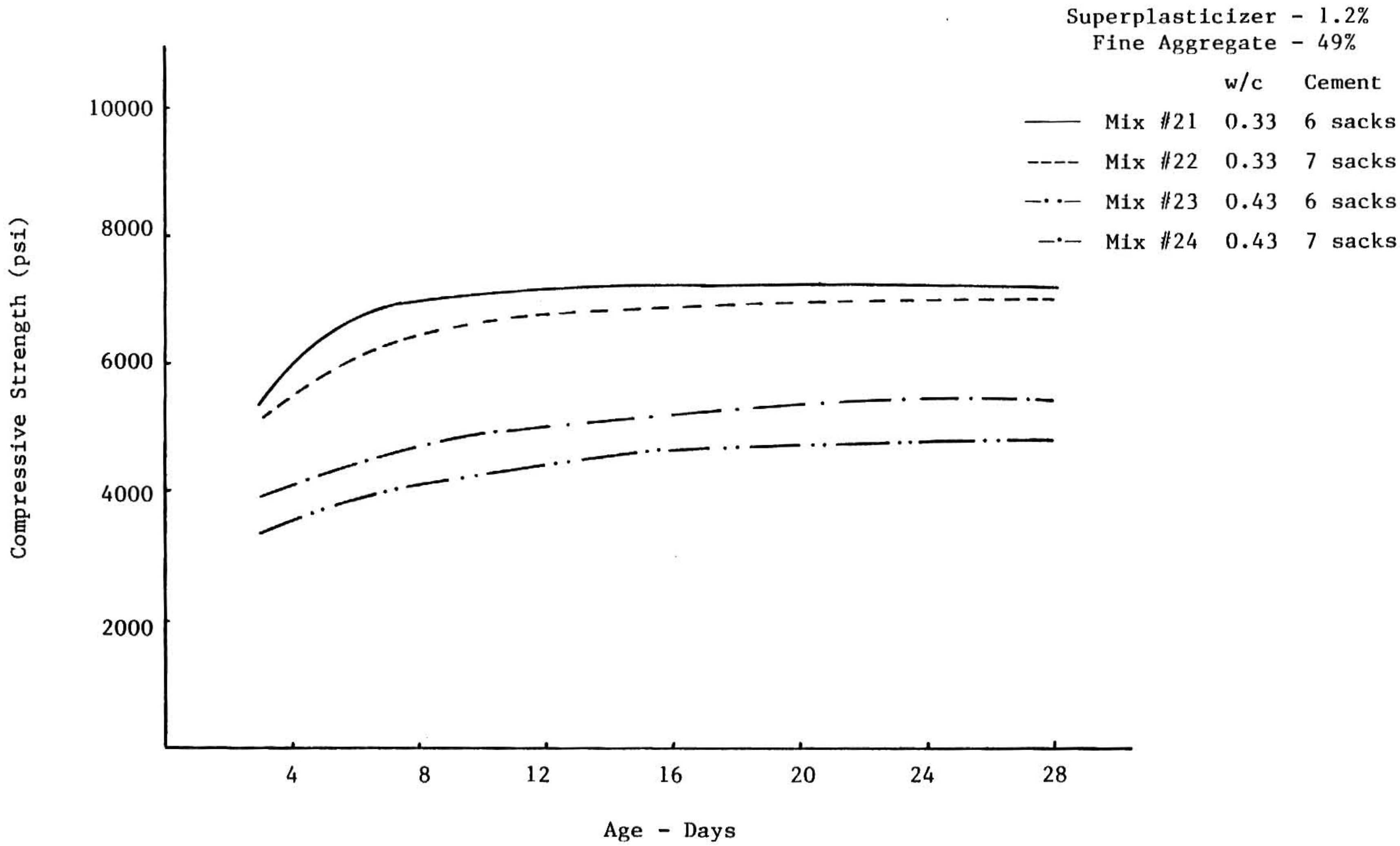



Fig. 16. Relation Between Strength and Age for Mixes 21, 22, 23, and 24 (10).

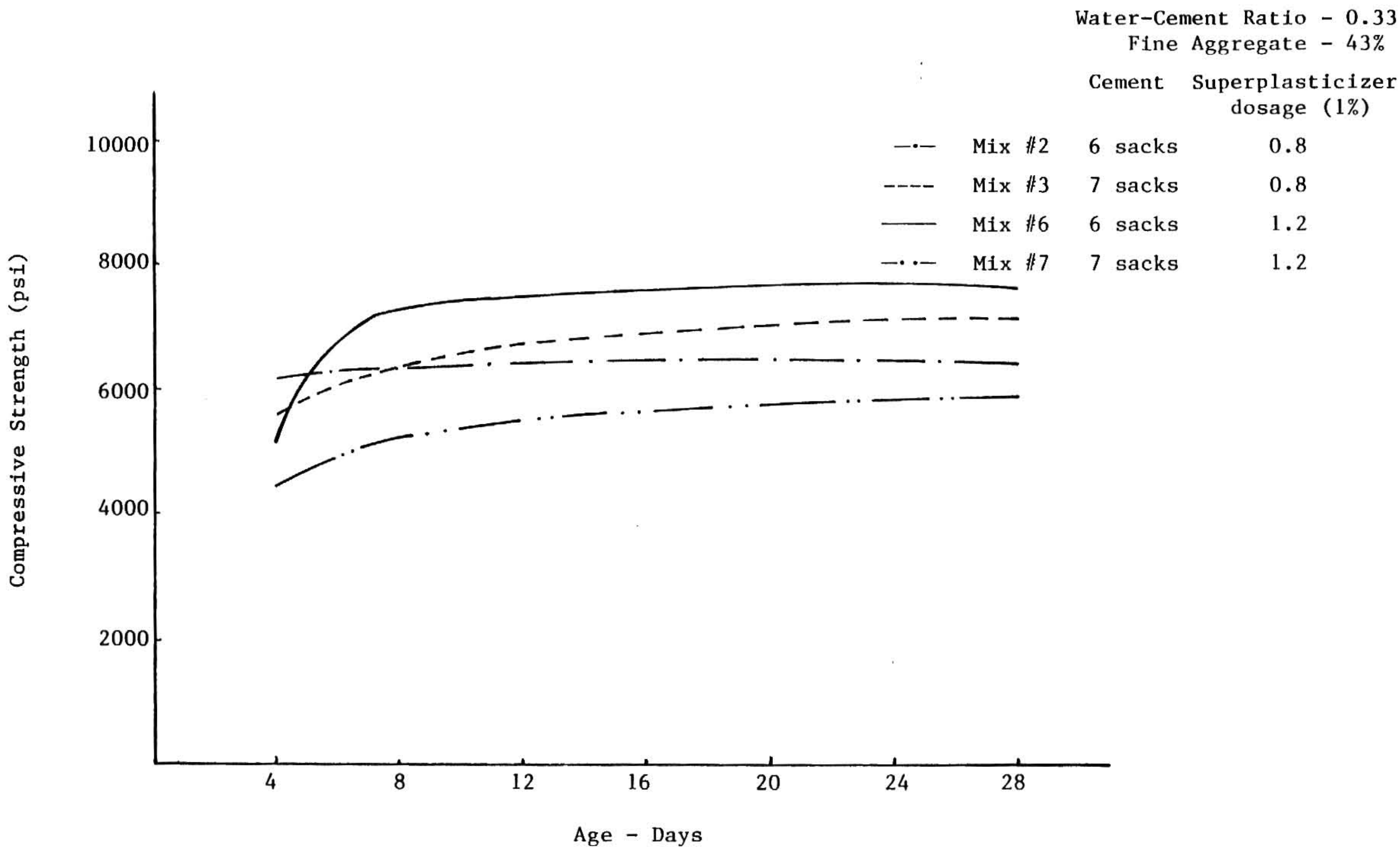



Fig. 17. Relation Between Strength and Age for Mixes 2, 3, 6, and 7 (10).

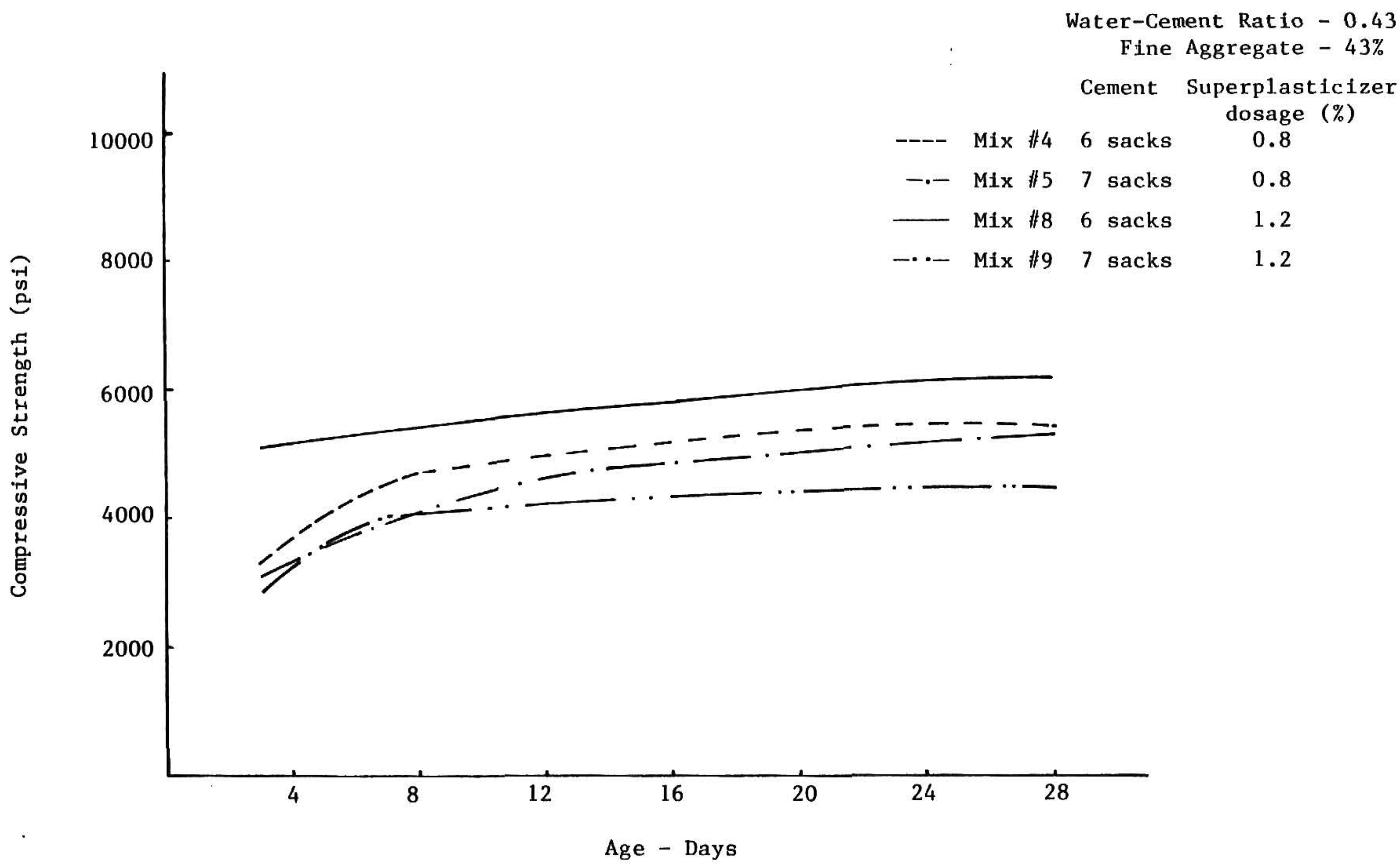



Fig. 18. Relation Between Strength and Age for Mixes 4, 5, 8, and 9 (10).

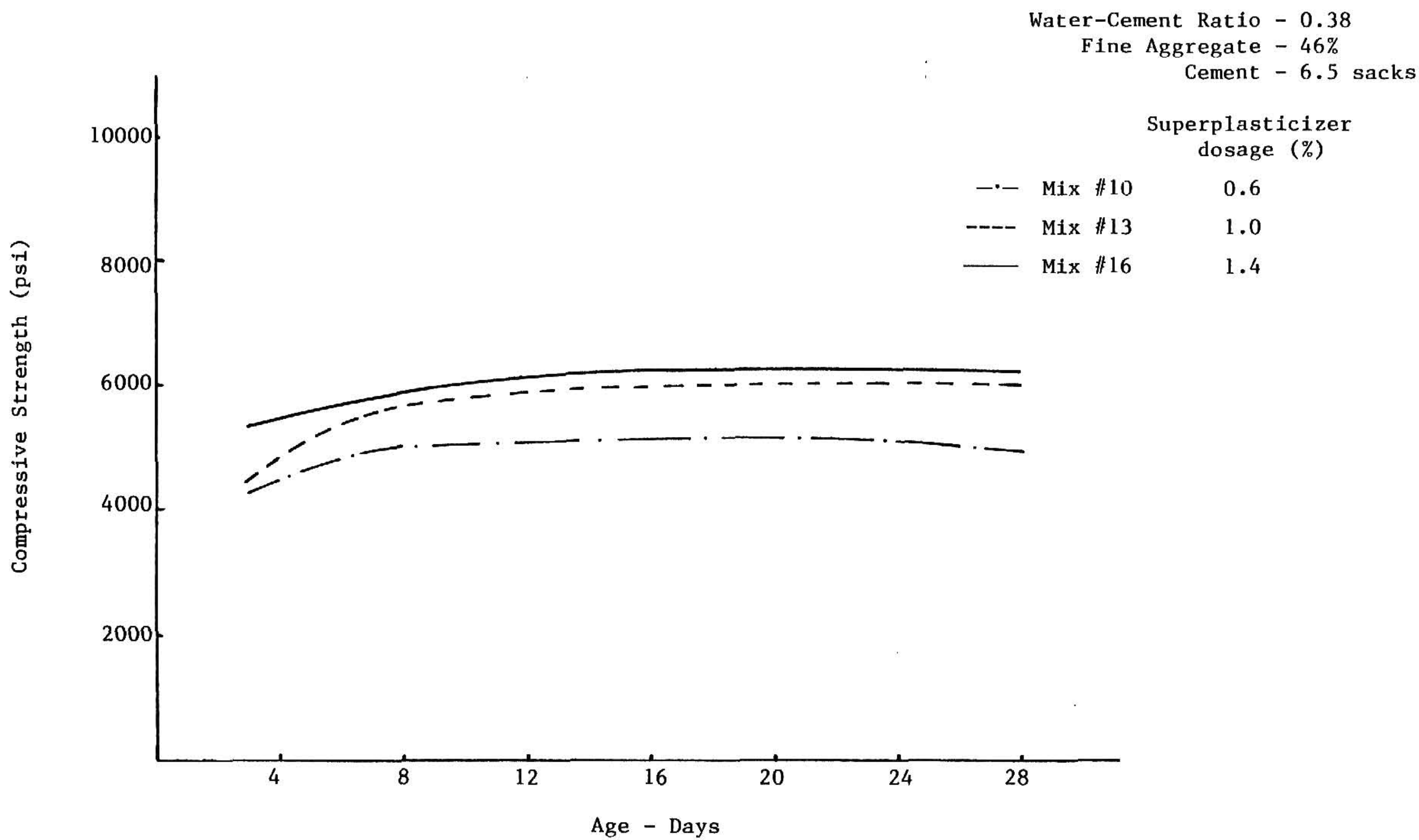



Fig. 19. Relation Between Strength and Age for Mixes 10, 13, and 16 (10).

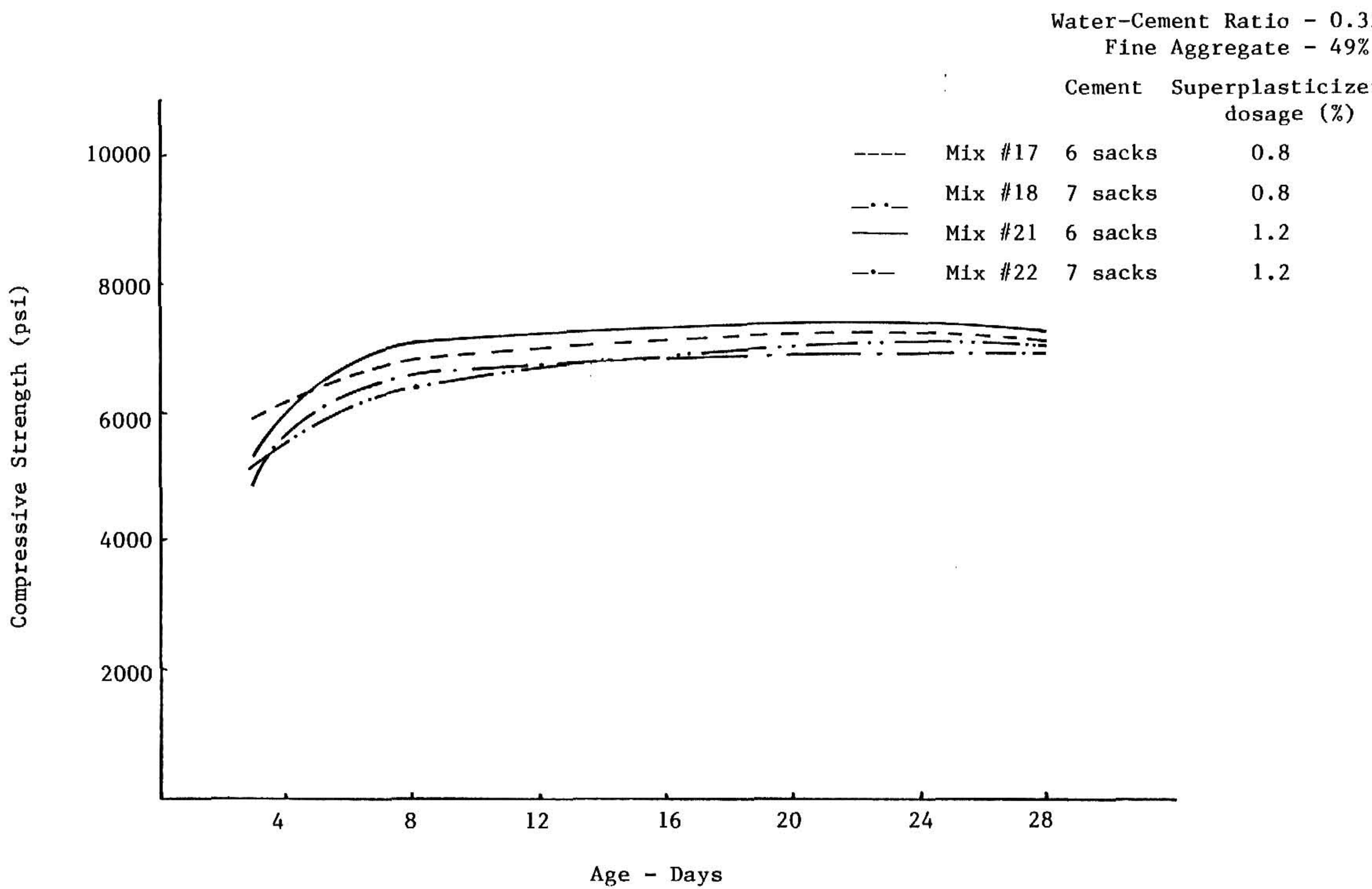



Fig. 20. Relation Between Strength and Age for Mixes 17, 18, 21, and 22 (10).

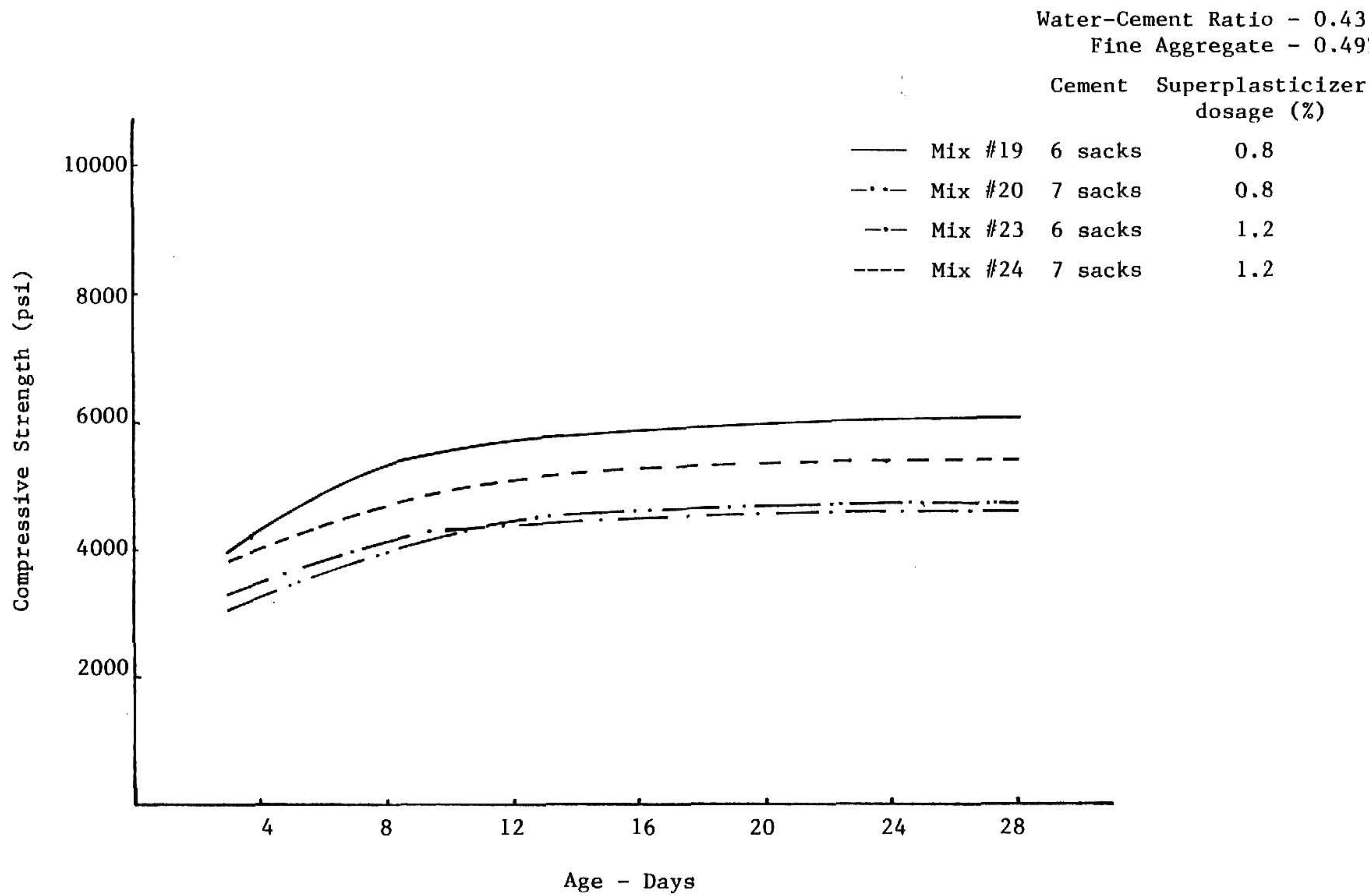



Fig. 21. Relation Between Strength and Age for Mixes 19, 20, 23, and 24 (10).

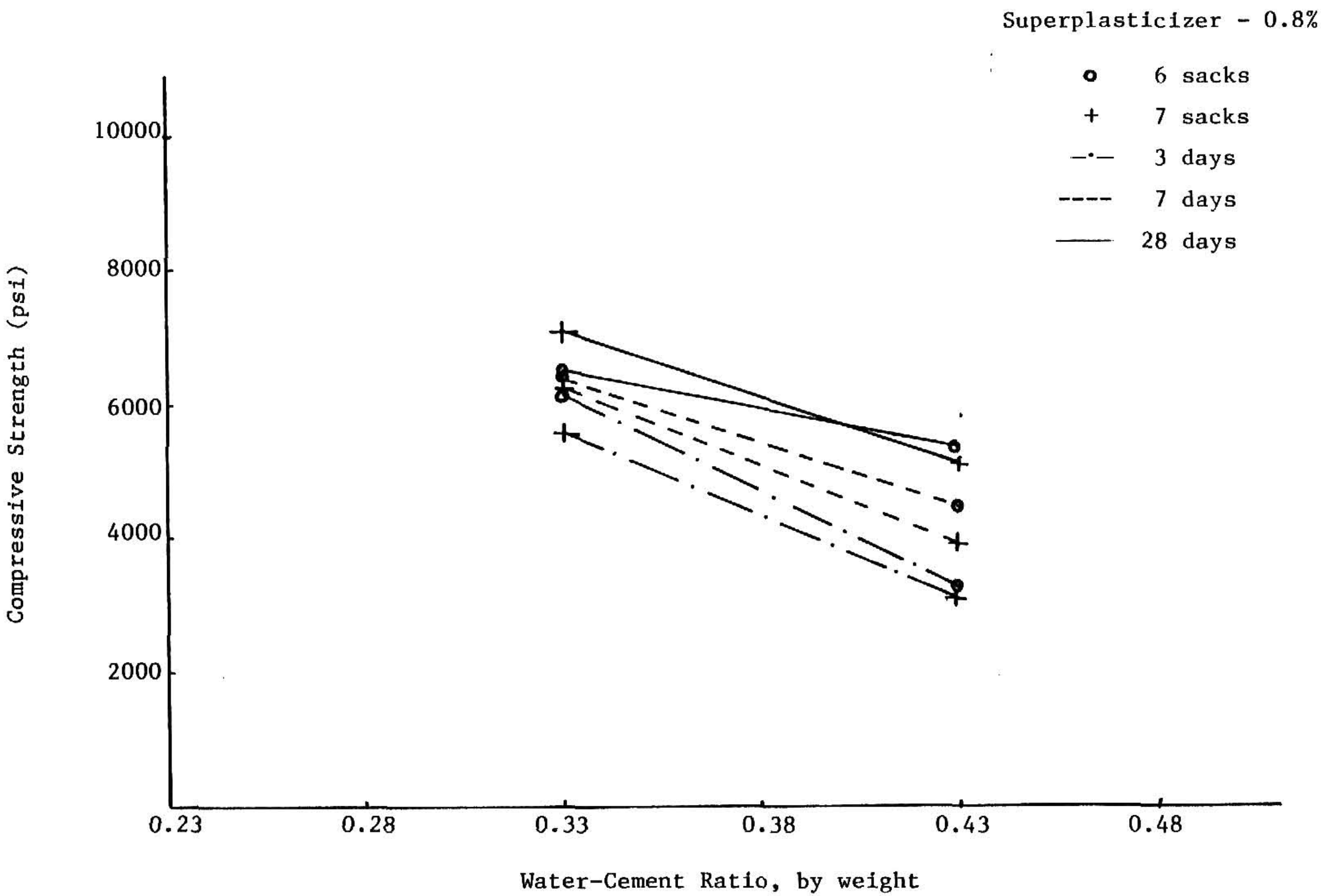



Fig. 22. Effect of W/C Ratio on Compressive Strength for Mixes 2, 3, 4, and 5 (10).

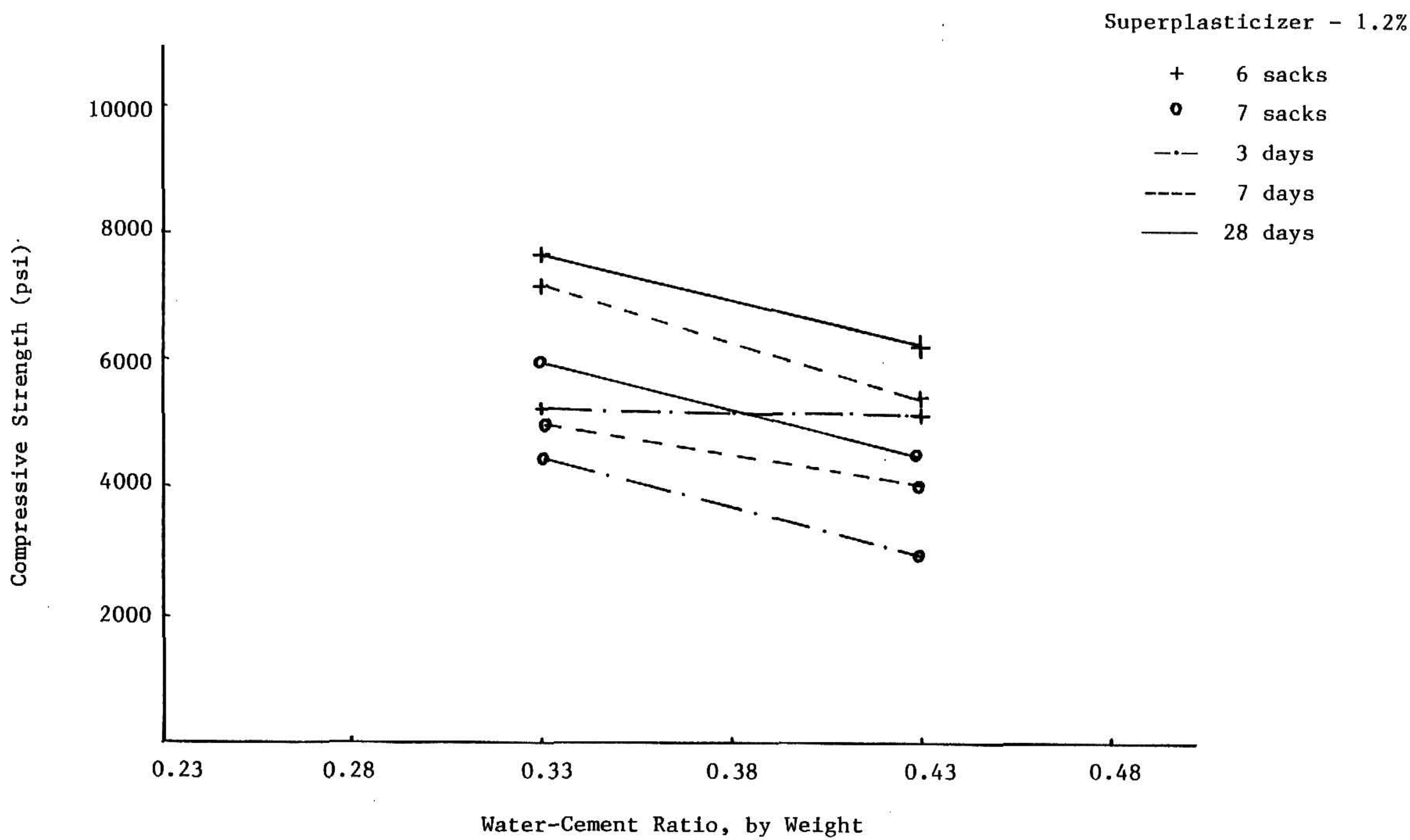



Fig. 23. Effect of W/C Ratio on Compressive Strength for Mixes 6, 7, 8, and 9 (10).

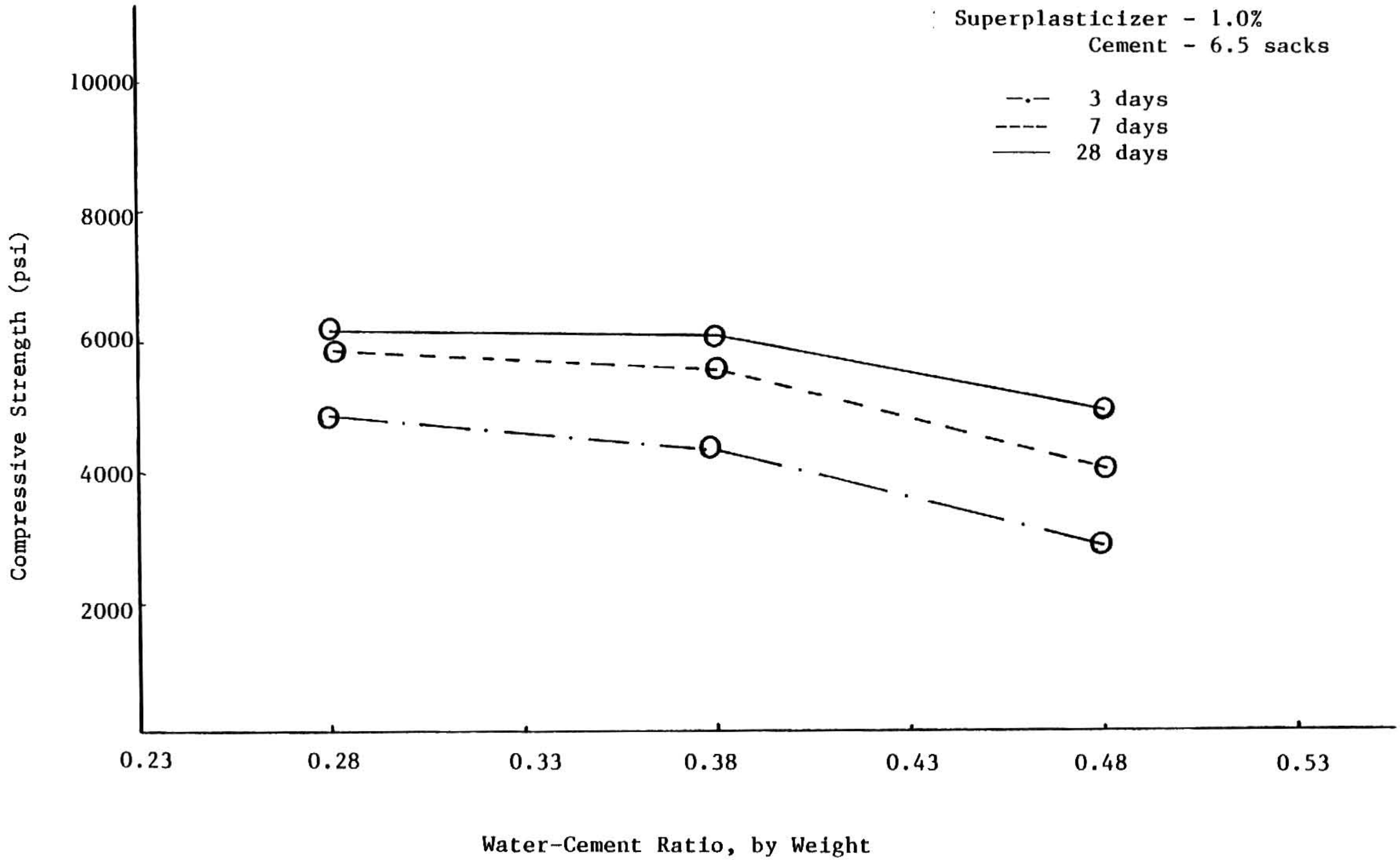



Fig. 24. Effect of W/C Ratio on Compressive Strength for Mixes 11, 13, and 15 (10).

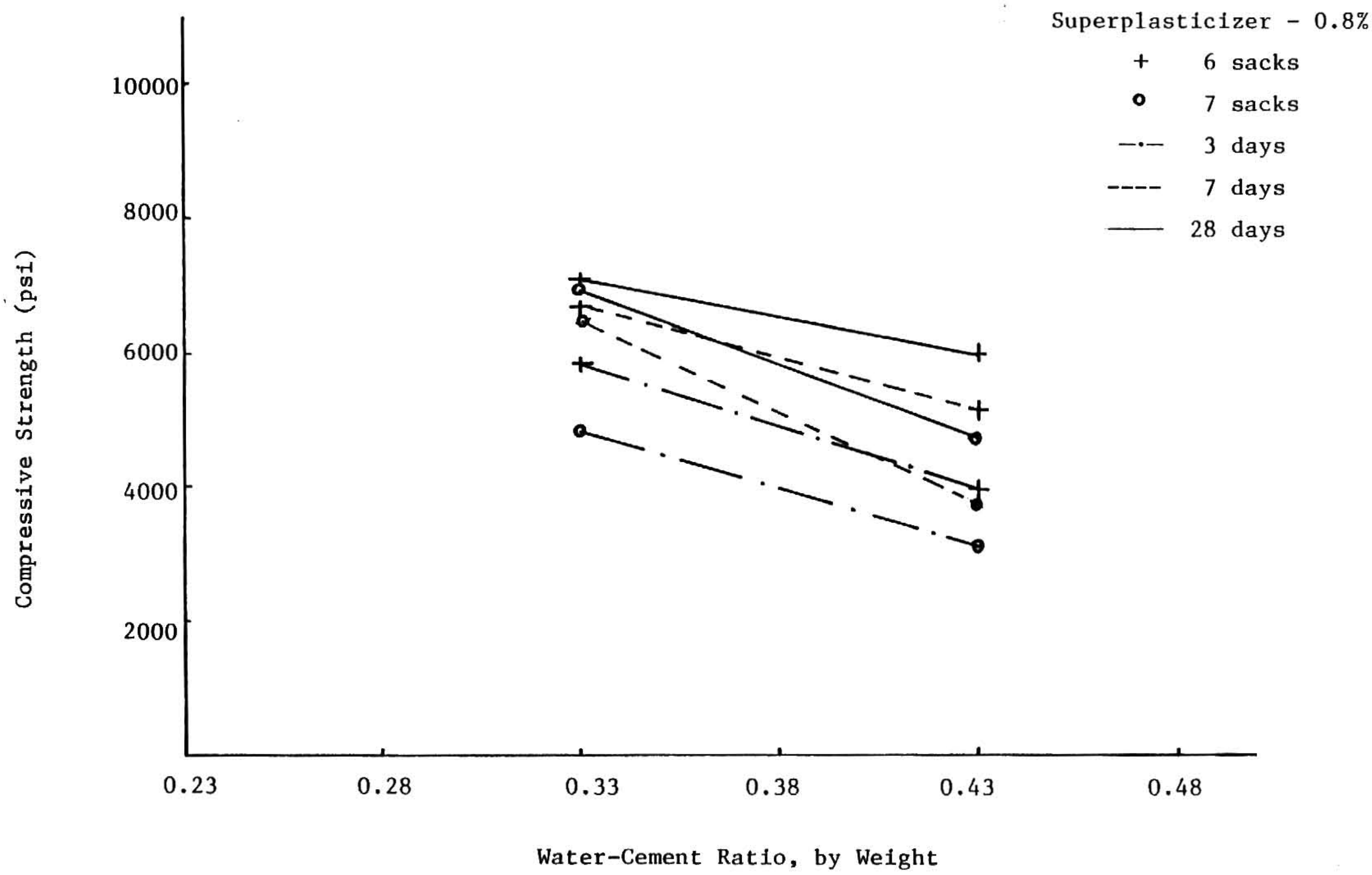



Fig. 25. Effect of W/C Ratio on Compressive Strength for Mixes 17, 18, 19, and 20 (10).

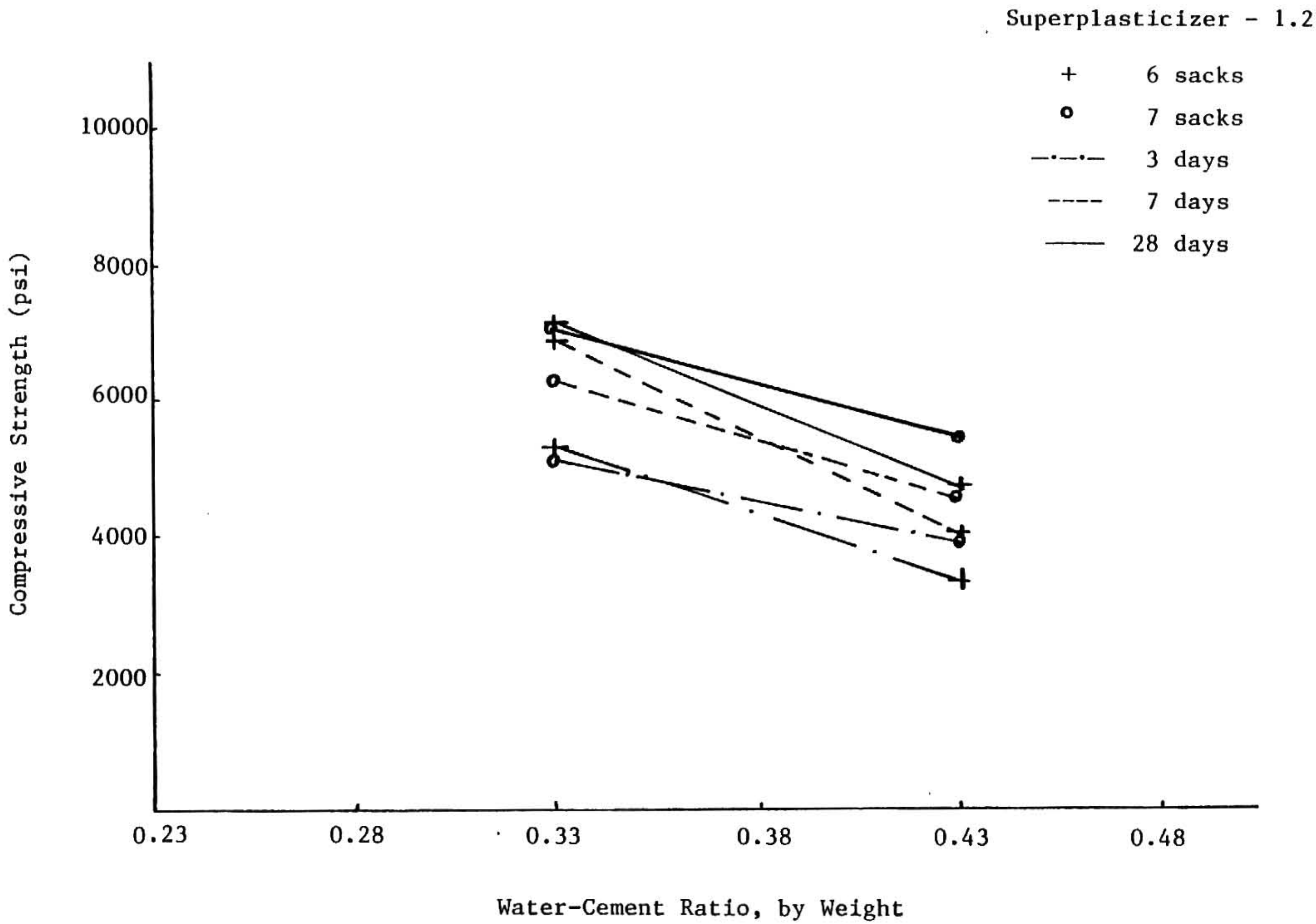



Fig. 26. Effect of W/C Ratio on Compressive Strength for Mixes 21, 22, 23, and 24 (10).

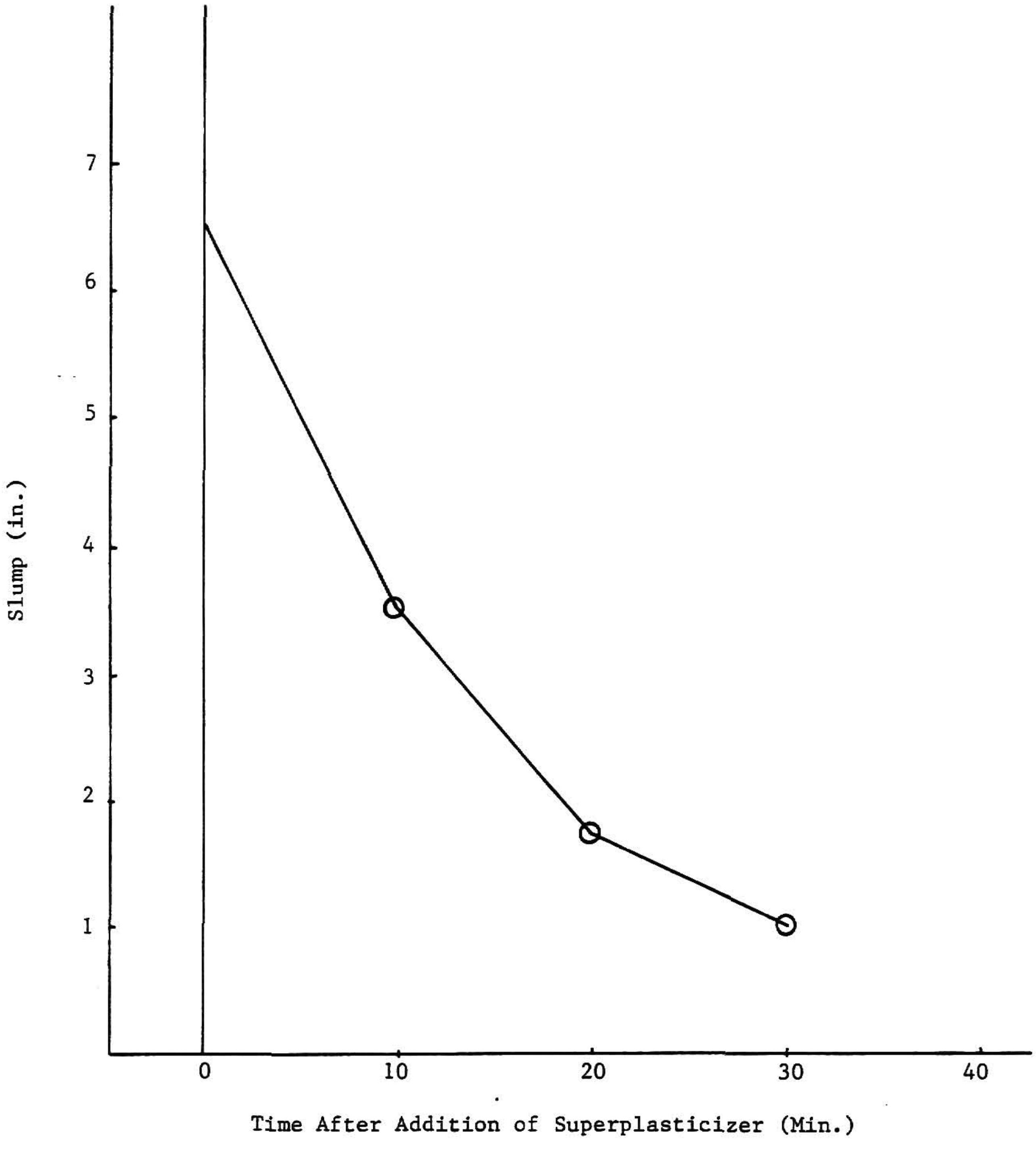



Fig. 27. Slump Loss Time for Batch No. 4 of Mix II.

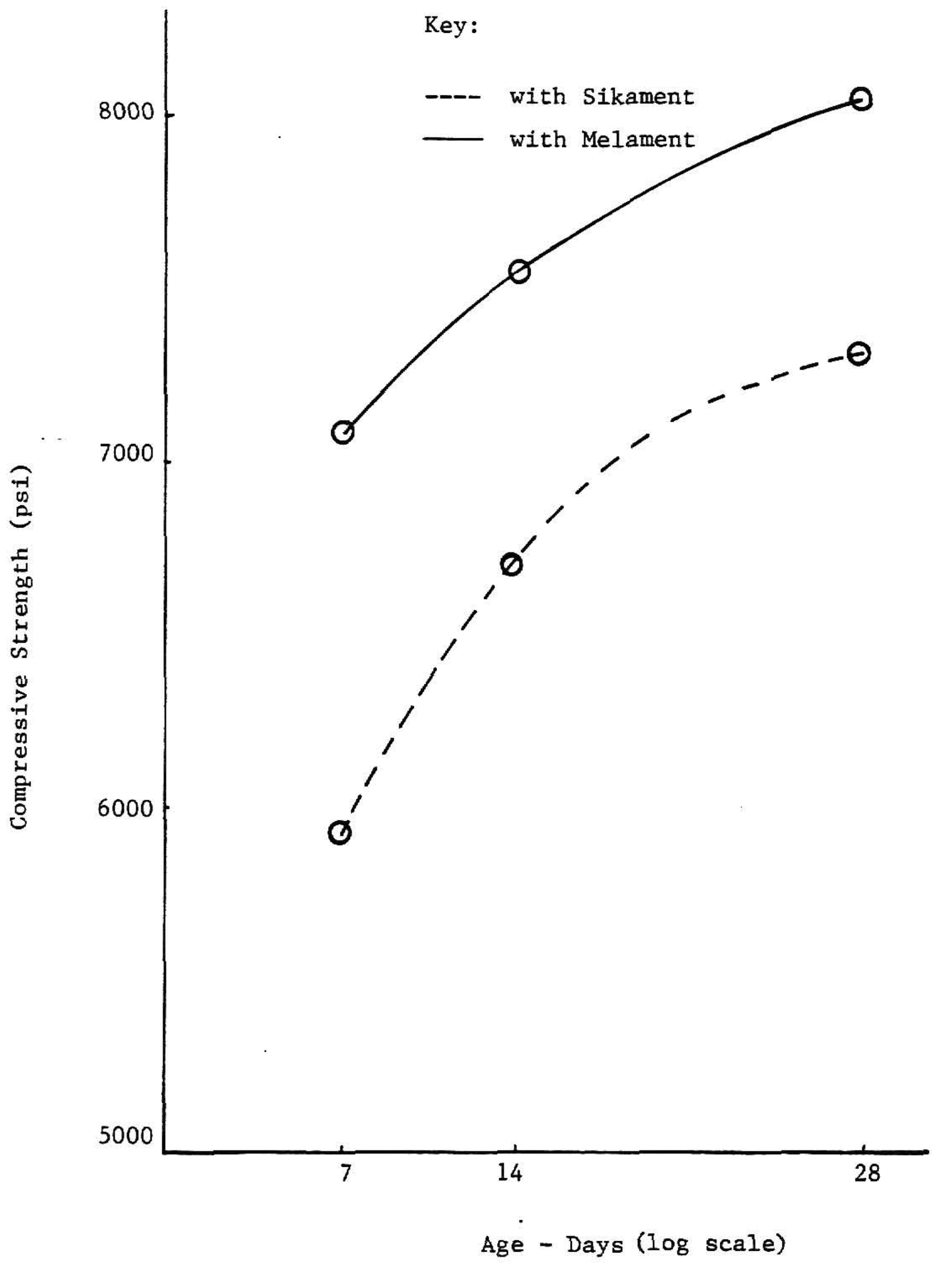



Fig. 28. Compressive Strength vs. Time for Mix I.

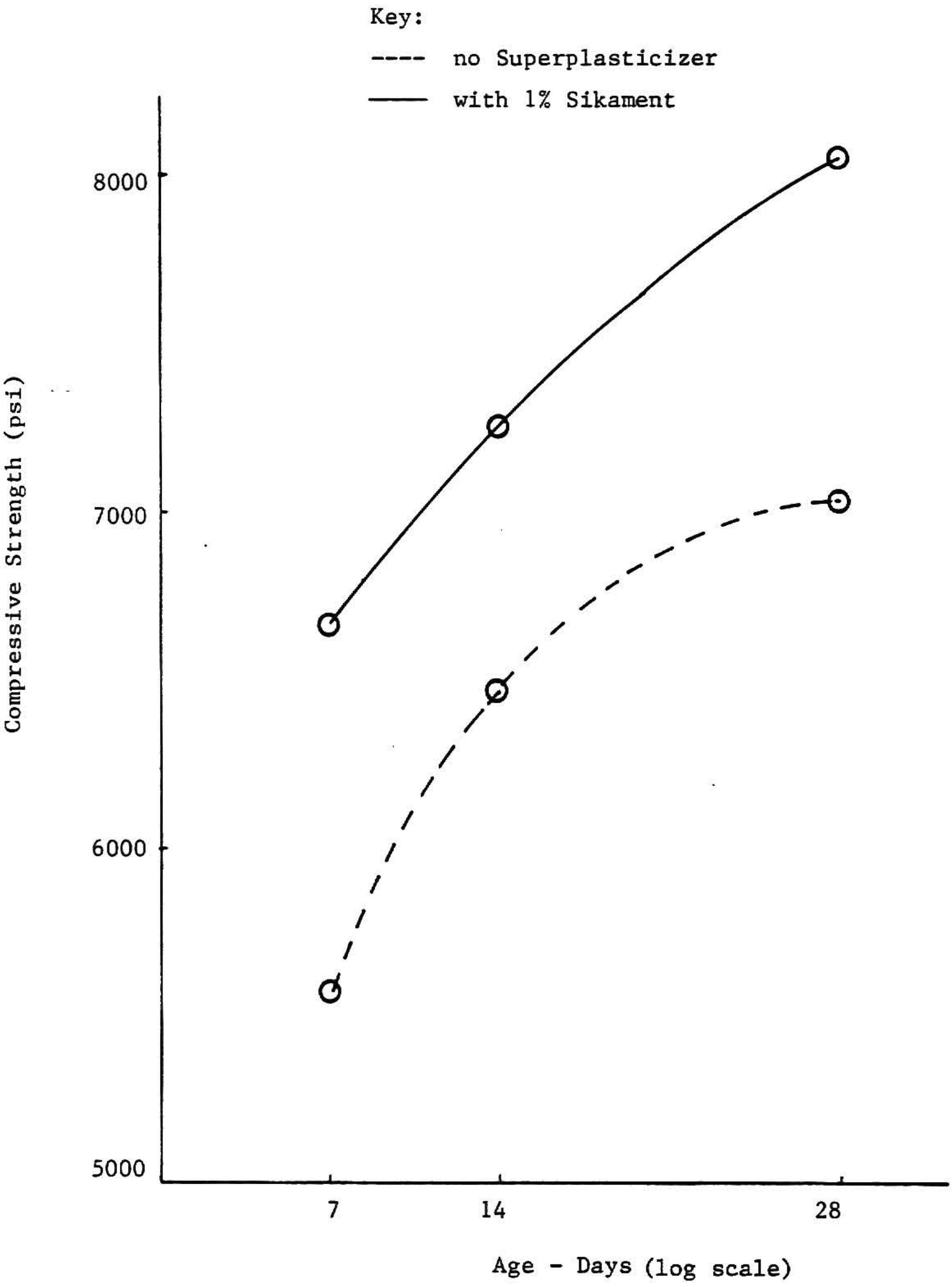



Fig. 29. Compressive Strength vs. Time for Mix II.

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SUPERPLASTICIZERS

IN CONCRETE

by

MEHRDAD KAPANPOUR

B.S. Kansas State University, 1979

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AN ABSTRACT OF A MASTER'S REPORT

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MASTER OF SCIENCE

Department of Civil Engineering

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## Abstract

Superplasticizers, which have been used in Europe and Japan since the mid-1960's and in the United States since the 1970's, act as high-range water-reducers in concrete.

This report describes the performance of superplasticizers and helps to understand what they are, how to use them, and advantages in using them. It also describes an experimental investigation of conventional concrete containing superplasticizers. The results show that superplasticizers are capable of either increasing the workability of concrete at equal mix proportions or reducing the unit water content at equal slump which results in higher strength.