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SUPERPLASTICIZED CONCRETE

MARCH, 1982

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16. Abstract This report presents the results of a three and one-half year study of the plastic and hardened behavior of superplasticized Portland cement concrete made with several Arkansas aggregates. The emphasis was on the effects of temperature, superplasticizer dosage, time of addition of the admixtures, agitation time before deposition, and admixture addition sequence on the plastic behavior of the concrete. Tests performed included slump at time intervals, time of set of the mortar fraction, unit weights, air contents before and after admixture additions, bleed water, freeze/thaw durability, and deicer scaling resistance. The examination of the hardened concrete focused on the effects of aggregate type, air content, superplasticizer dosage, and cement factor on the compressive strength at various ages, split cylinder strength, and abrasion resistance.

The principal findings withrespect to the plastic behavior were the following. The rate of slump loss in superplasticized concrete was significantly higher than in control mixes with the extra workability effectively lost within 30 to 60 minutes of addition of the superplasticizer. The loss rate was increased by high concrete temperature. The effectiveness of the superplasticizer was reduced by both high and low concrete temperature and by delay of superplasticizer addition. Air entrainment and adequate mixing eliminated most problems of bleed water except fcr "mortar bleed" in some mixes. Adequate freeze/thaw and deicer scaling resistance were achievable but were improved by adding the air entraining agent after the superplasticizer.

The results of the hardened specimen tests were consistent with previous work on superplasticizers. Compressive, tensile and abrasion strengths were essentially commensurate with Abrams' law.

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A STUDY OF SUPERPLASTICIZED CONCRETE MADE WITH ARKANSAS AGGREGATE

by

Larry G. Pleimann

FINAL REPORT

HIGHWAY RESEARCH PROJECT 54

conducted for

The Arkansas State Highway and Transportation Department

in cooperation with

The U.S. Department of Transportation

Federal Highway Administration

March, 1982

ABSTRACT

This report presents the results of a three and one-half year study of the plastic and hardened behavior of superplasticized Portland cement concrete made with several Arkansas aggregates. These included limestone in the plastic testing and limestone, gravel, and sandstone in the hardened concrete strength testing.

The investigative emphasis was on the effects of temperature, superplasticizer dosage, time of addition of the admixtures, agitation time before deposition after water/cement contact, and the sequence of admixture addition on the plastic behavior of the concrete. Target concrete temperatures examined included 50°, 70° and 90°F. Time of addition of the superplasticizer after water/cement contact and amount of agitation time after initial mixing included 0, 30, and 60 minute periods.

Tests performed included slump at time intervals, time of set of the mortar fraction, unit weights, air contents before and after admixture addition, measurement of bleed water, freeze/thaw durability, and deicer scaling resistance. The examination of the hardened concrete specimens focused on the effects of aggregate type, air content, superplasticizer dosage, and cement factor on the compressive strength at various ages, split cylinder strength, and abrasion resistance.

The principal findings with respect to the plastic behavior of the superplasticized concrete included the following. The rate of slump loss in the superplasticized mixes was significantly higher than in control mixes. The larger the amount of extra workability gained the faster the rate of loss. This resulted in a general rule-of-thumb that has been noted by other studies that the useful portion of the extra workability is generally lost within the first 30 to 60 minutes from the addition of the superplasticizer. The rate of slump loss is increased as the temperature of the concrete increases. The efficacy of the same amount of superplasticizer in producing a desired amount of slump seems to be a function of temperature. Surprisingly, it is not lessened simply by an increase in temperature. The efficiency of the admixture seems to be significantly reduced at lower concrete temperatures as well pointing to some optimum range of concrete temperature whose definition was outside the range of this study. The efficiency of the superplasticizer for the same dosage is also significantly reduced if the mix is agitated for some time after initial mixing before the superplasticizer is added. These last two facts point to the need of depositing the concrete as soon as possible after it is mixed and of adding the superplasticizer as close to the time of deposition as possible.

Addition of superplasticizer to a mix, especially to achieve a "flowing mode" will result in some reduction of the original air content. If this is anticipated superplasticized concrete will have enough freeze/thaw and deicer scaling resistance. In this study these resistances were improved by adding the air entraining agent after the superplasticizer.

The results of the hardened specimen tests were consistent with previous studies of superplasticized concrete. Once a reduction of water/cement ratio was achieved with the superplasticizer, the compressive and tensile strengths and the abrasion resistance were essentially commensurate with Abrams' Law.

GAINS, FINDINGS, AND CONCLUSIONS

Portland cement concrete made with Arkansas aggregates and using at leas one of the commercially-available superplasticizers with proper mix design an control will exhibit desirable strength characteristics commensurate with Abrams' Law. The superplasticizer may be used to significantly reduce the water/cement ratio of normal-workability concrete or it may be added to normal-workability concrete to produce a "flowing mode" concrete. In either use the final strength and the rate of strength gain may be important.

Difficulties associated with the use of the superplasticizer include the increased rate of slump loss over control mixes and the potential modification of the air-void structure. The higher the amount of increased workability from the superplasticizer the faster the rate of slump loss. The usable part of the increased workability is typically lost within 30 to 60 mi s of the addition of the admixture. The rate of slump loss is worsened by high concrete temperatures. The efficiency of the superplasticizer is reduced by both low and high concrete temperatures, as well as by delay in adding it after initial mixing of the cement and water.

The difficulties associated with air content can be anticipated and if care is taken in mix design and in mixing procedures an adequate air-void structure can be achieved in the concrete. Considerable agitation beyond the superplasticizer addition will harm the air-void structure although that may not be apparent from a measuring of the total air content since the air-void structure after agitation may well contain a larger fraction of large-bubble air. Air content also seems important in assuring the quality of the mix and in eliminating bleed water problems. Adding the air entraining agent after the superplasticizer seems to enhance all the qualities of the ai n-trainment except rate of slump loss.

IMPLEMENTATION STATEMENT

The results of this study and others emphasize the importance of careful mix design and construction quality control in the successful use of superplasticized concrete. Also emphasized is the potential variability of the mix with a change in Portland cement source or type, aggregate source, aggregate gradation, brand of superplasticizer, air-entraining agent, etc. In that regard attention should be paid to the minimum recommendations listed below in section 8.1 Recommendations of this report.

Despite the difficulties associated with slump loss and air-void structures that are inherent to the use of superplasticizers, their advantages far outweigh their disadvantages. They will be increasingly used in American concrete practice although their use will require more careful construction planning and inspection than is the case in much current concrete work. Their successful use will require experience.

In that regard, it is recommended that the Department begin to use superplasticized concrete in a water-reduced mode for high-early-strength in patching. As experience in the use of superplasticizers is increased, they should be tried in several bridge deck overlays and/or new construction. Both sequences of addition of superplasticizer and air-entraining agent should be tried and the durability and performance of concretes with each sequence closely monitored and compared.

Further study should be made of the performance of superplasticizers in respect to air-void structure as a function of admixture addition sequence, optimum range of temperature for superplasticizer efficiency, and the use of fly ash in conjunction with superplasticizers.

ACKNOWLEDGEMENTS

The author wishes to thank primarily Mr. Larry Lavender who kept this project going during the many adverse situations that delayed and disrupted it. As the only graduate student available during twenty of the forty-two months of the project his aid was incalculable. During the balance of the time the author had to depend on a sequence of very capable senior undergraduates who performed yoeman service: Greg Carter, Larry Cornelius, David Hill, Danny Williams, Jonathan Annable, and Barry Broadway. In addition there was the help of many other undergraduate students in batching the concrete and performing the tests, almost a score of them, too numerous to mention here.

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I. INTRODUCTION

1.1 Historical Background

Although so-called "water reducer" admixtures have been in existence and used for some time it is only in very recent years that attention has been paid to a new class of Portland cement concrete admixtures variously called in English-speaking practice "superplasticizers", "super water reducers" or "high range water reducers". The patent for the first of these materials was applied for during the mid-1930s but it has been only during the last decade and a half that their use has been large, notably in Japan [4]* and Germany [13], and more recently in England [1,7], other European countries, and the United States.

Overseas, wide application of superplasticizers has already been made. Literally millions of cubic yards of superplasticized concrete have been poured in the last decade. Japan is making routine use of flowing concrete usually placed by pumping. The Sibogrüppe, a chain of West German ready-mix suppliers who account for some 40 percent of the concrete poured in that country, use superplasticizers now as routinely as air-entraining agents. It is used throughout Canada. The Olympic stadium in Montreal could probably not have been built without flowing concrete. Its use for high-early-strength special needs has been reported worldwide.

As is inferred above, the use of these admixtures provides a spectrum of concrete qualities from normally stiff "water reduced" concrete on the one hand to "flowing" concrete on the other. In the first, the increase fluidity imparted to the cement mortar by the superplasticizer allows the

*Numbers in brackets refer to like numbered items in the List of References.

use of lowered water/cement ratio with resulting increased strength. In the second mode, the fluidity is added to an already normal-workability concrete to provide flow characteristics that approach a self-leveling character. In this latter mode, special attention must be paid to proper mix design to avoid segregation and excessive bleeding. Specifically, this can mean the possibility of either normal strength concrete at 8-inch slumps and high fluidity ("flowing concrete") or extremely low water/cement ratio concrete (0.30 to 0.35) at usual consistencies. It also means the tailoring of concrete mixes anywhere between the end points of this spectrum.

These improved qualities for Portland cement concrete could potentially give major savings in construction and maintenance. "Flowing concrete" has resulted in reductions in construction time and labor costs from ease of placement, less need for vibration or other forms of densification, ease of finishing, less forming costs because of less need for "windows" in multi-lift placement, etc. "Water reduced" concrete, on the other hand, has demonstrated savings from early form removal, less material because of higher strength, and gives promise of lessened maintenance costs because of the potentially increased abrasion resistance and impermeability to deleterious substances resulting from its increased strength.

Despite heralded successes associated with the use of these admixtures outside the United States and the potential advantages incumbent to their use, their incorporation into American concrete construction has been relatively slow and tentative. There have been a number of reasons for this. First, they are new and the normal conservative attitude of American concrete construction discouraged their use without better knowledge of their effects. In addition, little research has been done in the United States to establish and provide public access to either the control parameters for their optimum use or the predictable material properties of plastic and hardened concrete made with them. Since superplasticizers are made from a variety of chemical compounds, and since most companies were selling a product based on only one of these chemicals the usual competition meant that most of the information available about the products were in somewhat guarded proprietary reports, and many of those in Japanese or German.

The breakthrough in calling attention to American concrete practice of the use of superplasticizers came at the first International Symposium on Superplasticizers in Concrete held in Ottawa, Canada on May 29 through 31, 1978 [2]. This conference was of great importance because the some thirty papers presented there represented approximately 75 percent of the material specifically on the use of superplasticizers then available in English apart from those in-house reports of suppliers and a few reports on special uses by some state highway departments.

It was evident at the conference that despite the many problems associated with their usage, their advantages seemed to indicate that they were "here to stay". One internationally known concrete researcher remarked that with the possible exception of air-entraining agents they represent the most important development in concrete technology in the last fifty years [20].

A number of difficulties in the use of superplasticizers was noted in the pre-Ottawa literature and widely discussed at the Symposium. These difficulties seem to center on three major topics: 1) the loss of workability with time of the superplasticized concrete, 2) the effect of superplasticizers on the air-void structure of the concrete and the resulting effect on the freeze/thaw durability of the concrete, and 3) the wide variability in the plastic properties of superplasticized concrete. The variables noted with respect to this last item included type of cement, actual chemical content of the cement, type or brand of superplasticizer used, dosage used, sequence of addition of the superplasticizer in combination with other admixtures, etc.

A major area of agreement at the symposium with respect to the loss of slump problem was that we are presently lacking a test to adequately measure the consistency and fluidity of concrete, especially in the flowing concrete mode. The slump test is a static test of consistency. Even if it is combined with the German flow table (German Standard DIN 1048, 1972, Sec. 1, Clause 3.1.2) to get some measure of flow characteristics, there is still the possibility of getting the same numbers for concretes of completely different suitability.

An English researcher [21,22] has proposed a "two-point" test for the workability of concrete that measures the rheological properties of both static yield and plastic viscosity. However, the prototypes of the apparatus necessary for applying the two-point test are quite expensive and represent a measure of quality control that is not typical to much American concrete work. There is obviously the need for some more reliable and simple test for both the static and dynamic workability properties of concrete than the slump test.

This need was illustrated by the most negative report on the use of superplasticized concrete given at the symposium. The Virginia Highway Department had unsuccessful experiences using superplasticized concrete on bridge deck installations between July, 1976 and May, 1977 [19]. The properties of the concrete showed wide variability. The reference mix design had a zero slump before the addition of the superplasticizer. It was the consensus of many of the participants at the symposium that "zero slump" measurement in itself would allow a great variability in the mixes brought to the job to which the superplasticizer in appropriate dosages was added. This emphasized the need for an adequate workability test for the entire spectrum from very stiff "zero slump" mixes to the flowing concrete mode.

Since the first Ottawa conference of three years ago, there has been a small but fairly constant stream of literature about the use of superplasticizer admixtures. Some of that literature is indicated below. At the time of the writing of this report the second Ottawa conference is underway.

1.2 Recent Research and Problem Statement

Much work was reported at the Ottawa symposium that sought to isolate the problems inherent in the use of superplasticizers and to identify the parameters controlling them. The results were mixed.

1.2.1 The Problem of Slump Loss

A good bit of the discussion focused on the problem of slump loss with time and the workability characteristics of superplasticized concrete.

The attempt to use superplasticizers like other admixtures will not be successful. Careful attention must be paid to each different manufacturer's recommendations. Most admixtures, even water-reducing admixtures, are introduced into the mix water. Superplasticizers of all types are more successful if they are added after the concrete has been mixed thoroughly. This fact, combined with the phenomenon of the rapid loss o slump in the superplasticized mix, means a departure from usual ready-mix practice. The addition of the superplasticizer at the ready-mix plant will be useless unless the time from the plant site to the point of deposition is very short. Thus, most manufacturers of superplasticizers will recommend addition at the job site just before depositing the concrete. This introduces further difficulties. It is often difficult to ensure complete, uniform mixing of the admixture and good quality control is difficult to obtain. German usage seems to have encouraged the training of ready-mix truck drivers as technicians. At least one recent conversation of the author with a ready-mix company executive indicates that movement in that direction is already present in the United States.

Even with proper introduction and mixing of the admixture, the slump that has been gained initially with the use of the superplasticizer is lost rapidly. A general rule of thumb is that the beneficial effects of the superplasticizer are gone within the first 30 to 60 minutes. See Figure 1.1* for results reported at the Ottawa symposium [17]. A few researchers who did report at the symposium on the slump loss phenomenon had no agreement as to the controlling factors [3, 13, 17, 18]. And only one speaker [13] stressed the importance of temperature and the quantity of total fines as important factors to be examined. The Portland Cement Association researcher [17] indicated that with minimal care toward proper mix design, the problem of having a slump "window" (adequate period of time during which a "usable" range of slump is available) may not be as difficult as initially thought. However, the effect of temperature was not included in his study. It is interesting to note, however, that the current Australian Code governing the use of super water reduced concrete encourages the use of ice and chilled water and, in their very dry areas,

*Figures and tables follow their chapter of initial reference.

does not allow the casting of super water reduced concrete if the ambien temperature is greater than 33°C (91.4°F) [23].

The restoration of the initial slump by means of redosing either with superplasticizers or normal water reducers had been minimally examined at the symposium. See Figure 1.2 [10] for one such experience. Although the workability can be restored by a second dose of superplasticizer without harm to the concrete, this practice is wasteful of the admixture which is already quite expensive. Moreover, it seemed to be the experience of other researchers that it took more admixture to achieve the same initial slump and that more than one redosing was not at all effective. That dosing with the superplasticizer is less effective as time passes seemed to be born out by the work reported in this report. Any such attempt at retempering again required excellent quality control.

The problem of controlling slump loss is further aggravated by the wide range of parameters that seem to affect it. Included among these would be: the amount of admixture, the time of addition of the admixture, the amount of agitation time, the initial slump of the mix, the type of admixture, the superplasticizer's interaction with other admixtures, the cement factor, the cement composition, and the temperature of the concrete.

The amount of increase of slump depends directly on the dosage of the superplasticizer [7, 8, 13]. Most manufacturers recommend a range of dosage. Below the minimum of the range there is little effect on workability. Above the upper limit of the range, the effectiveness of the admixture is greatly reduced in terms of adding any extra workability. This effect is more noted in mortar pastes [17] than in concrete mixe

As was indicated above, it is more effective to add superplasticizing admixtures after the other ingredients of the concrete mix have had occation to mix thoroughly. There has not been general agreement about the effect of further agitation time on the effectiveness of the admixture. Some authors at the symposium reported a delay from mixing time to admixture addition as having little effect [8, 10, 24], while others reported that the result of sufficient delay would be to reduce the plasticising effect of the admixture [7, 17]. It was also indicated that continuous mix agitation aggrevates slump loss [6]. Some authors suggested a periodic incremental addition of the dosage [14, 25] to overcome the slump loss problem. Those who investigated the problem reported being able to restore workability by repeated doses of the superplasticizer [1, 10, 13] but at least one author advised against it [6].

The rate of loss of initial slump with time seems to depend on the magnitude of the initial slump gained by the use of the superplasticizing admixture [10, 18]. In general, that additional slump is lost within the first 30 to 60 minutes. Therefore, the greater the additional slump the more rapid the loss. At least one author, however, has noted the same phenomenon in non-admixtured concrete [26].

Mixes with higher cement factors seem to attain a higher initial slump [10], all things else being equal, but the effect on slump loss of cement factor is not yet fully investigated. Different chemical compositions of Portland cement also seem to affect the efficacy of superplasticizers. Several authors indicated the importance of the tricalcium aluminate (C_3A) content [10, 17] in that cements with a low C_3A content such as Type V cements often had less slump loss than Type I. Alkali [28] and sulfate levels [10] also seem to be important.

Different types of superplasticizers seem to have different effects on otherwise identical mixes. A number of different types or categories of superplasticizers were identified for the American reading public by the Cement Association publication of 1976 [1]. These include:

Type A - sulphonated melamine formaldehyde condensates;

Type B - sulphonated naphthalene formaldehyde condensates;

Type C - modified lignosulphonates; and

Type D - others (including mixtures of saccharates and acid amides).

Superplasticizers made with all of the above types are commercially available in the United States today but those of the first two types are the most common. Malholtra has since demonstrated the difference in behavior of different superplasticizers, particularly with respect to air content and slump loss with time [27]. In general, admixtures of the type A require higher dosages than those of type B for a given effect [7, 28]. Also, different admixtures may show different rates of slump loss, even if they are of the same type [27]. Reference 27 was unavailable at the time to guide the choice of the admixture used in the present study.

An additional possible effect on slump loss rate and other properties of fresh superplasticized concrete is the chemical composition of other admixtures used in conjunction with it. The relation of superplasticizers to air content structure changes would seem to indicate this, but no work has been found by the author that has looked carefully at this posibility. It would seem the better part of wisdom to use an air-entraining agent made by the same manufacturer as the superplasticizing agent, if possible. The addition of some retarding admixtures has been found [7, 8, 10, 17] to be helpful in delaying slump loss. There was also some private discussion among the participants at the Ottwa symposi that if the action of the superplasticizer is a physico-chemical one, then the interaction of the superplasticizer with various other admixtures not only might be important, but also the sequence of addition of the admixtures and their relative times of interaction.

Additionally, it was discussed at the Ottawa conference whether the composition, shape and overall gradation of the coarse and fine aggregates might not affect the efficacy of a superplasticizer [18]. There was no full report given on this subject at that time nor is the author aware of any systematic work that has been done in that regard since.

A final factor that should be mentioned at this point is the effect of the temperature of the concrete on slump loss. High temperature conrete hastens slump loss in plain concrete and several investigators indicated at the symposium [10, 13, 17] the same was true for superplasticized concrete.

1.2.2 The Problem of Air Void Structure Changes

The second major aspect of the use of superplasticized concrete that seems problematic is the possible change in the air-void structure when an air-entraining agent is used in conjunction with a superplasticizer. There was agreement that superplasticized concrete should be air-entrained, but a number of researchers expressed concern regarding the freeze/thaw durability of such concrete [1, 11, 12, 14, 15, 17]. A number of these reports indicated a reduction of the specific surface and an enlargement of both bubble size and spacing factor to the point that the relative durability factor was no longer acceptable. It was sometimes found that the spacing factor might exceed the recommended maximum of 0.008 in. (0.2 mm) despite the total air volume as measured by ASTM C-231 being within normal limits.

Other researchers, on the other hand, reported acceptable air-void structures and durability factors [1, 11, 14, 15, 17]. Related to the controversy was disagreement as to which procedure in ASTM Standard C-666 was proper; those studies showing poor freeze/thaw resistance had typically been done according to Procedure A with water surrounding the sample during both the freezing and thawing. Most of the successful freeze/thaw results had used Procedure B, allowing the sample to be surrounded by air during the freezing cycle. Mather [12] emphasized the use of Procedure A and critically saturated specimens. Mielenz and Sprouse [14] recommended the use of ASTM C-671, "Critical Dilation of Concrete Specimens Subjected to Freezing", for future testing of the freeze/thaw durability of superplasticized specimens.

The discussion was further complicated by the challenge of several of the superplasticizer manufacturers to the users to produce an example of freeze/thaw durability failure among the structures that have been built of superplasticized concrete in the last decade in severe climates. Thus, they emphasized that the testing procedures of ASTM C-666 are measures of relative freeze/thaw resistance rather than absolute tests. It is important to note, however, that the makers of both Mighty and Melment, the oldest and possibly the most popular of the superplasticizers, announced at the symposium the development of modified forms of their products that improve both the slump loss and air-void problems.

This problem was emphasized by some researchers as of special importance [12]. In the attempt to explain the variety of results mentioned above, Mielenz and Sprouse [14] suggested that there might be a different relationship between spacing factor and durability for superplasticized concrete than for plain concrete. It was noted by another researcher that this has been observed in concretes containing lignosulfonate-based admixture [29].

The presence of superplasticizers in the concrete can also change the dosage of air-entraining agents required for a given air content [1, 14]. The issue of when air content should realistically be measured in fresh form was also raised by some who reported greater loss of air from superplasticized concrete during placing and consolidation than with plain concrete.

1.2.3 The Problem of Variability in Plastic Behavior

As has already been noted above, there is a wide variability in the plastic properties of Portland cement concrete made with superplasticizers. Many of the contributing variables have been listed above. It was of interest in this project to constrain as many of those variables as was realistic and to control in a reasonable range those of the rest that seemed relevant to the normal use of superplasticized concrete.

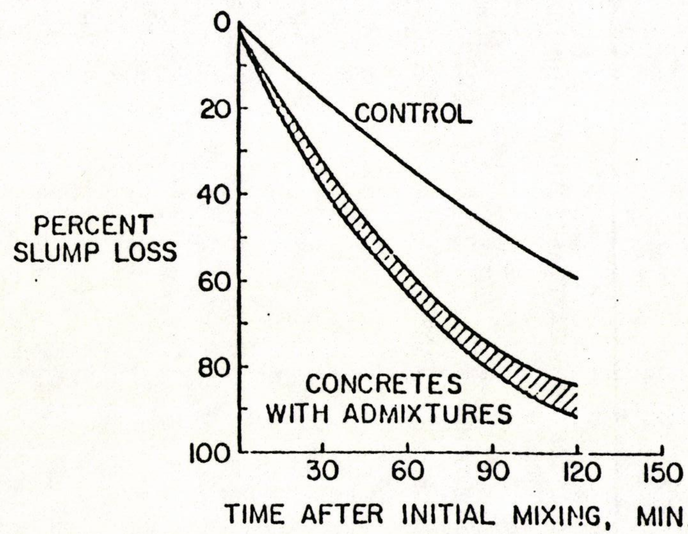
1.3 Object and Scope of this Study

The original objectives of this study included the following: 1) to identify those aspects of the operations of the Arkansas State Highway and Transportation Department that could be benefited by the use of concrete containing superplasticizers both in the "flowing concrete" and in the "water-reduced" modes; 2) to collect available data regarding the material properties and construction usage of concrete made with superplasticizers commercially available in the United States; 3) to confirm the material properties of fresh and hardened concrete made with these superplasticizers and typical Arkansas materials; and 4) to project the magnitude of economic benefits that might be realized by the use of superplasticizers in this state.

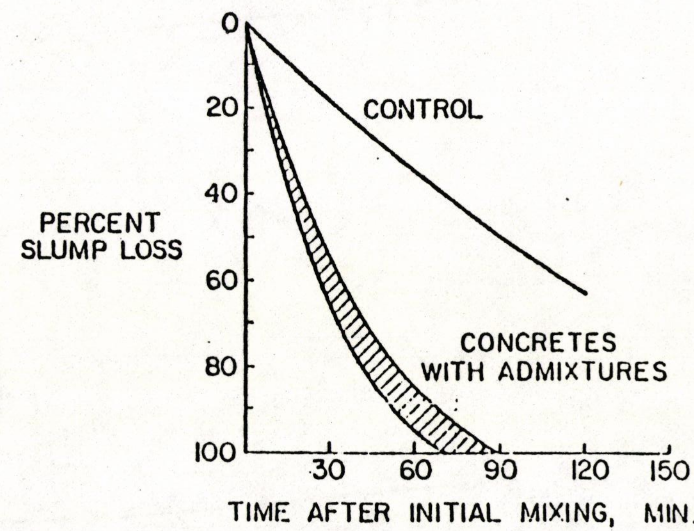
The problems of available laboratory space, equipment and availability of graduate students encountered during the conduct of this study caused sufficient delays so as to limit the realization of some of these objectives. Tests were conducted with the use of only one commercially available superplasticizer. Tests were limited to an examination of only three of the most typically used aggregates in the state of Arkansas. Portland cement was a Type I from one source. Thus, although somewhat restricted, the objectives of 2) and 3) above were essentially accomplished.

The time available, however, combined with the delays mentioned above and described in detail in previous benchmark reports has prevented this study from accomplishing objectives number 1) and 4) in any great detail. Some development is given to these two objectives in the conclusions to the report.

The scope of the project is described in greater detail in the following chapters, but can be summarized here as two-fold. First was the examination of the plastic properties of superplasticizer Type I Portland cement concrete. This included a study of slump-loss with time, air-content, etc., as the temperature, time of addition of the superplasticizer with respect to initial water/cement contact, and the period of agitation between initial water/cement contact to deposition varied. The resistance of specimens made under this range of variables to deicer scaling and freeze/thaw durability were also examined. Second was a study of the effect of cement factor, air content, and superplasticizer dosage on the compressive strength, tensile strength, and abrasion resistance of a series of specimens made with several Arkansas aggregates.



(a) Low Cement Content



(b) High Cement Content

Figure 1.1 TYPICAL LOSS OF WORKABILITY OF SUPERPLASTICIZED CONCRETE
(Taken from Reference 17)

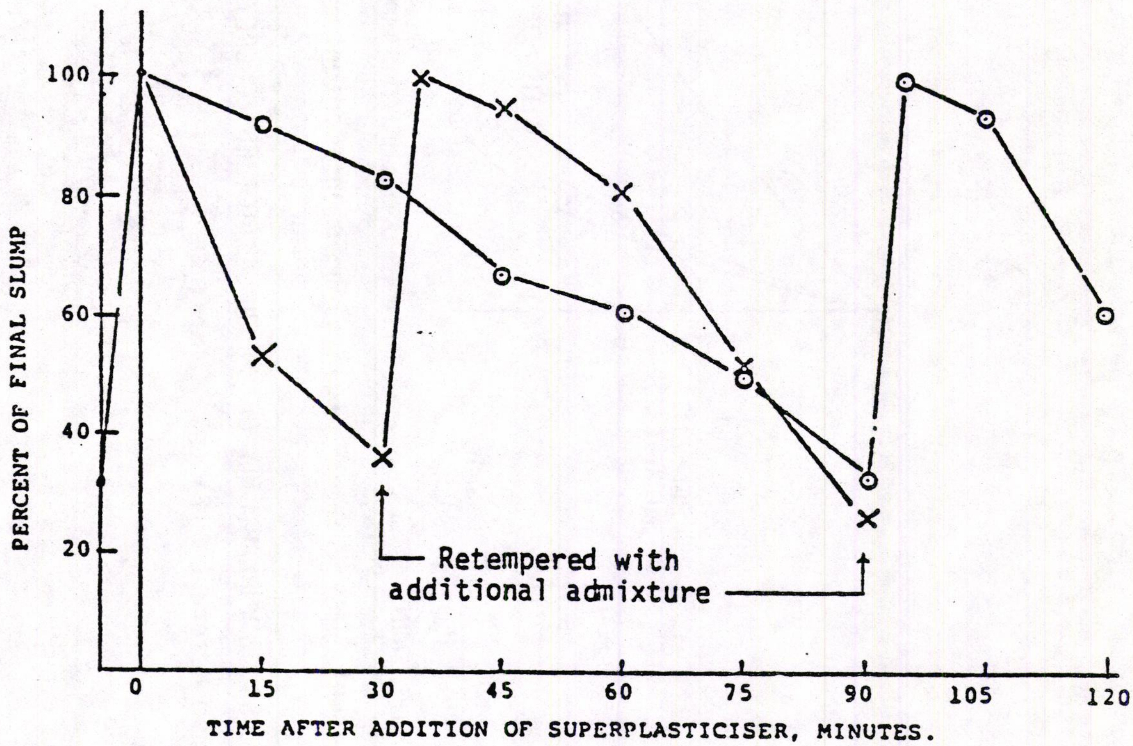


Figure 1.2 RESTORATION OF WORKABILITY BY RETEMPERING WITH ADDITIONAL SUPERPLASTICIZER (Taken from Reference 10)

II. LABORATORY STUDIES

2.1 Materials

The material to be tested in this part of the study was Portland cement concrete containing superplasticizer and an air-entraining agent. The aggregate was an Arkansas limestone. These ingredients are described in more detail below.

2.1.1 Portland Cement

The Portland cement used throughout the conduct of both parts of this study was a Type I Portland cement available in 94 pound bags manufactured by the Monarch Cement Company of Humboldt, Kansas. A chemical analysis of the major oxides in the cement was beyond the scope of the department's research facilities. However, samples were taken of each shipment and a composite sample made so that later tests may be conducted. No noticeable difference in the properties of the concrete seemed ever to be occasioned by the arrival of a new shipment.

2.1.2 Mixing Water

Mixing water used in all tests consisted of tap water supplied by the City of Fayetteville, Arkansas.

2.1.3 Aggregate

A number of aggregates were considered for inclusion in this study. These included limestone, river gravel, sandstone, and syenite, a granite base aggregate. Three of these were examined in the second part of the study regarding the properties of hardened concrete. Because of time limits, it was decided to consider only one aggregate within the scope of the plastic tests. In conference with the research liason committee of the Arkansas Highway and Transportation Department, it was decided to use a limestone aggregate exclusively in the plastic test series. This limestone was secured from the McClinton-Anchor Co. of Fayetteville, Arkansas. Near the middle of the time period of the plastic test series, the source of the limestone changed from the company's Johnson quarry and shifted to their Westfork quarry, some 10 miles south of Fayetteville. The limestone was selected because it is one of the most common aggregates in Arkansas and, therefore, widely used in concrete construction and because it was readily and economically available in the Fayetteville area. The change in site caused a temporary increase in the angularity of the aggregate for a few weeks, but did not seem to greatly affect the workability of the concrete.

The Westfork limestone quarry is located in Section 30, Township 15N, Range 30W of Washington County. It is part of the Hale formation. It has a specific gravity of 2.68 and an absorption with respect to saturated-surface-dry condition of 0.65%. Other tests on the same material done at other times have shown an L.A. Abrasion (Grade C) of 24.7, a $Na_2 SO_4$ soundness of 0.6, and a percent Insoluble Residue +#200 of 0.7 [31].

A small measure of chert was present in the Westfork limestone which caused some "pop-outs" in the freeze/thaw samples when they were tested. The delay in receiving the freeze/thaw machine meant that most of the samples were stored in a frozen condition after being cured until the machine could arrive. Thus, a major portion of the work of Part A was already accomplished before the chert made its presence known in the freeze/thaw specimens. It was decided to finish the work of Part A using the same limestone since it was from a source for much of the concrete work in this area of Arkansas and the performance would be representative of that which could be expected from that material.

It was decided to use the same limestone both as coarse and fine aggregate to serve as a base line of workability behavior. The angularity of the stone was suspected as having an influence on the workability attainable from the use of superplasticizers. The effect of the roundedness of river sand normally used for the fine aggregate with most of the angular coarse aggregates in the state could then be later observed. To assure a consistent gradation for each mix in Part A, the limestone received was separated into a number of gradation fractions so that they could be reblended in the same manner each time. This would eliminate the variable of gradation from the loss-of-slump examinations. The following is the list of ranges of gradation into which the limestone aggregate was divided and from which it was reblended for tests in Part A.

Range #	Size Range	Contributing Sieves
1	3/8" to 1-1/4"	3/8", 1/2", 3/4", 1"
2	#4 to 3/8"	#4
3	#16 to #4	#16, #8
4	#30 to #16	#30
5	#50 to #30	#50
6	finer than #50	#100, pan

The gradation targeted for both the fine and coarse aggregate is shown in Figure 2.1. They both meet the gradation requirements of ASTM C-33, although the gradations commercially available and economy forced the fine aggregate gradation to be a bit on the coarse side.

2.1.4 Superplasticizer

At the Ottawa symposium, Mather had reported successful freeze/thaw durability results with only one superplasticizer that was a modification of one of the more popular admixtures at that time [12]. It was decided to use the same admixture, Melment L10A, manufactured by the then American Admixtures Corporation of Chicago, Illinois. That decision was made before the work of Malholtra, et al. was published [27]. That paper showed a wide variation in the behavior of different superplasticizers with respect to slump-loss-rate and air-content retention. In retrospect, it might have been more advantageous to have chosen a different superplasticizer. However, at the time, the Melment, a type A sulphonated melamine formaldehyde condensate, was, and continues to be, a very popular and widely used superplasticizer. Moreover, from the variability of results reported with different plasticizers and with the problems of repeatability using superplasticizers that will be mentioned frequently throughout this report, it seems reasonable that substantial mix design and demonstration of adequate performance will be required of each contractor for each superplasticized mix that is proposed on a job. Therefore, the present work done with this currently popular superplasticizer, Melment L10A, is valuable.

2.1.5 Air Entraining Agent

The air-entraining agent used throughout the entire project was Amex 210, also manufactured by American Admixtures Corporation and, therefore, assumably compatible with the Melment L10A superplasticizing admixture.

2.2 Organization of Variables

In Part A of the total study, the study of the Plastic Concrete Behavior, it was intended that emphasis would be given to the loss-of-slump with time aspect of the superplasticized concrete's plastic behavior as well as study of the change in the air content and its effect on such properties of the hardened concrete freeze/thaw durability and resistance to deicer scaling.

The loss of slump would be measured with respect to three variables: 1) time of introduction of the admixture with respect to the initial water/cement contact, 2) duration of agitation of the mix after initial water/cement contact until time of deposition, and 3) initial temperature of the concrete mix. The time of addition of the superplasticizer from water/cement contact was to be within the range of zero to one hour in thirty minute increments. The time of additional agitation beyond initial water/cement contact was in the same range and intervals. The three targeted concrete temperatures were to be 50^{o}, 70^{o}, and 90^{o}F.

With respect to the materials described above the superplasticizer was to be used in four dosages: 1) none, for control specimens, 2) single dosage to achieve a reasonable percentage reduction in the water/cement ratio with the same workability, 3) double dosage necessary to double the previously achieved water/cement ratio reduction, and 4) sufficient dosage to achieve "flowing" concrete from a reference mix of given workability.

The air entraining agent was to be used in sufficient dosage to achieve an air content of $5 \pm 1\%$ by volume.

The combination of these variable ranges and intervals led to the following logical combinations of variables and specimen indication. Each specimen or separate "data point" was denoted by a combination of one symbol from each of the following columns:

SP Dose	AEA Dose	Conc. temp.	SP Addition	Agitation
C	N	L	0	0
$\overline{C}$	A	M	3	3
1		H	6	6
2				
F				

The first column refers to the superplasticizer dosage. The symbol "C" is for a control specimen with no superplasticizer. The "C" series was a control series with a 1.5 ± 0.5" slump for comparison with the "F" flowing concrete series. The $\overline{C}$ series had a 3-1/2 ± 1/2" slump and was used for comparison with the "1" series with single dosage of superplasticizer and with the "2" series containing a "double" dosage of superplasticizer.

The second column refers to the use of an air-entraining agent, "N" for "none", and "A" for an air-entrained mix. The "L", "M", and "H" indications of the third column refer to low (50^{o}F), medium (70^{o}F), or high (90^{o}F) concrete temperatures. The "0", "3", and "6" of the fourth column refer to intervals of zero, thirty, and sixty minutes from the time of initial water/cement contact until introduction of the superplasticizer. The same symbols in the last column refer to zero, thirty, and si minutes respectively of agitation time from initial water/cement contact until deposition of the concrete.

Thus, "$\overline{C}$AL06" on a specimen would indicate an air-entrained control mix containing no superplasticizer at a target concrete temperature of 50^{o}F, which was agitated for sixty minutes before deposition. "1AH36" would refer to a mix with the same 3 inch target slump achieved with a single dosage of superplasticizer. The mix would be air-entrained, with a target temperature of 90^{o}F. The superplasticizer was added at thirty minutes after initial water/cement contact, but the agitation was continued for another thirty minutes before deposition.

The full set of unique combinations of variables used in the study are given in Table 2.1 following. The total number of unique combinations of variables is 162. The prime series, including 1AM'00,was an additional number of data points whose combination of variables was the same as like designated data points without the prime. The difference between these data points and those like designated points without the prime was that the air-entraining agent was added after the superplasticizer.

2.3 Conduct of Tests

For each separate data point indicated in Table 2.1 by a unique set of the first two indicators, a concrete mix was designed and confirmed by trial batching. When the correct proportions had been achieved to give the desired workability, a number of batches were made to give sufficient concrete to conduct all the tests prescribed. If the change in data point combination included only a different concrete temperature, a different superplasticizer addition time or a different time of agitation, there was no need for a separate mix design.

For each separate data point, the following tests were made. Each will be discussed in more detail below:

1) slump at regular intervals after initial mixing,

2) time of setting of the concrete by penetration resistance,

3) bleed water accumulation,

4) air content at several times, and

5) casting of samples for later cyclic durability tests.

2.3.1 Slump Tests

For each data point, slump tests were conducted at intervals ranging from fifteen to twenty minutes continuously from the point of initial water/cement contact and mixing until the slump became essentially zero. The slump tests were made in accordance with ASTM C143. In the early part of the study, an attempt was made to correlate the results of the slump tests and use of the "K-slump tester". The results were found to be completely unsatisfactory and without correlation.

For the "flowing concrete" data points, the data point identifications beginning with an "F" symbol, the spread was also taken using the same modification of the German flow table specification as was described in the Cement and Concrete Association paper [1].

2.3.2 Time of Setting Tests

For each data point, time of set tests were conducted using the penetration method described in ASTM C 403. At least three batches were made from each data point. One sample of mortar was taken from each batch by sieving through a #4 standard screen. A commercially available hydraulic operated penetration tester was initially tried but proved unsatisfactor because of difficulties in calibrating the device. An alternate device was constructed using a bench stand for mounting an electric drill as a drill press. This was fitted with a small proving ring and an attachment for holding the penetration points that had been machined to size. This alternate device worked very well.

2.3.3 Bleed Water

The bleed water tests were conducted in accordance with ASTM C 232 on samples of fresh concrete properly placed in 1/2 cubic foot containers approximately 5/6 full. Bleed water was collected at the specified time intervals and accumulated until the total accumulation of water remained constant for three time intervals.

2.3.4 Air Content

For each data point, the air content of the mix was measured in accordance with ASTM C231 using a Type B pressure air meter that measures air content to the nearest 0.1 percent by volume. The air content was measured at various critical times for each separate data point depending on whether superplasticizer was used in the data point or not, the time at which it was added, and the length of agitation time. The aggregate correction factor was measured and applied for each mix design that used a different amount of aggregate per unit volume.

For each data point at the time of deposition, three separate 3" diameter by 6" high cylinders were cast and cured. These cylinders will be kept for later use in measuring the bubble size and spacing factor if that is needed or useful. The Civil Engineering Department laboratories at the University of Arkansas presently do not have the capability of performing such a linear traverse test as specified in ASTM C457, "Standard Recommended Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete".

2.3.5 Cyclic Durability Tests

For the data points indicated in Table 2.1, additional specimens were cast for testing the cyclic durability against freeze/thaw conditions and deicer scaling action for that particular data point. The freeze/thaw samples consisted of 3" x 3" x 14" specimens. The deicer scaling specimens consisted of a volume 7" x 3" x 17" ringed on the flat side by a dike 3/4" high by 1" wide at the base for enclosing a 1/4" deep quantity of brine. The surface exposed within the dike was 5" x 15". Normally, if a surface treatment or a surface texture is being tested with respect to deicer scaling resistance, the dike is added to the top of the surface to be tested. Since the object of these tests was primarily to test the mix design, the deicer scaling specimens in this study were cast as one piece using a 3-3/4" deep form with a plan view area of 7" by 17". A polished hardwood insert in the bottom of the form structured the 5" x 15" testing surface and the walls of the dike.

The freeze/thaw specimens were tested in accordance to ASTM C 666 using procedure A that requires a minimum of 1/8" of water surrounding the specimen during both the freezing and thawing parts of the cycle. The machine used was manufactured by Logan Refrigeration Co. of Logan, Utah, which uses a horizontal position for the copper cans that hold the specimen and surrounding water.

The deicer scaling specimens were tested in accordance to ASTM C 672. Two samples were tested for each data point sampled. The specimens were cycled daily from a commercially available freezer cabinet and flushed and evaluated each Friday, at the end of five cycles. The cycles were continued for each specimen until a total of fifty cycles had been completed or until the specimen had reached a surface condition corresponding to a value of 10 on the scale listed below [30]. The 0 to 10 scale used allowed more flexibility of evaluation but with the same range of surface deterioration as that measured by the usual 0 to 5 scale. The rating is based on visual observation of the extent and depth of scale. The following tabulation describes the physical significance of each numerical rating.

0 - No scale

1 - Scattered spots of very light scale

2 - Scattered spots of light scale

3 - Light scale over about one-half of the surface

4 - Light scale over most of the surface

5 - Light scale over most of the surface; few moderately deep spots

6 - Scattered spots of moderately deep scale, otherwise light scale

7 - Moderately deep scale over one-half of the surface

8 - Moderately deep scale over entire surface

9 - Scattered spots of deep scale, otherwise moderate scale

10 - Deep scale over entire surface

TABLE 2.1 MIX VARIATIONS EXAMINED AND SPECIMEN MARKS

Control Series	Single Dosage Series	Double Dosage Series	Flowing Mode Series
CNL00	1NL00	2NL00	FNL00
CNL03	1NL03	2NL03	FNL03
CNL06	1NL06	2NL06	FNL06
CNM00	1NL33	2NL33	FNL33
CNM03	1NL36	2NL36	FNL36
CNM06	1NL66	2NL66	FNL66
CNH00			
CNH03	1NM00	2NM00	FNM00
CNH06	1NM03	2NM03	FNM03
	1NM06	2NM06	FNM06
$\overline{C}$NL00	1NM33	2NM33	FNM33
$\overline{C}$NL03	1NM36	2NM36	FNM36
$\overline{C}$NL06	1NM36	2NM66	FNM66
$\overline{C}$NM00			
$\overline{C}$NM03	1NH00	2NH00	FNH00
$\overline{C}$NM06	1NH03	2NH03	FNH03
$\overline{C}$NH00	1NH06	2NH06	FNH06
$\overline{C}$NH03	1NH33	2NH33	FNH33
$\overline{C}$NH06	1NH36	2NH36	FNH36
	1NH66	2NH66	FNH66
CAL00			
CAL03	1AL00	2AL00	FAL00
CAL06	1AL03	2AL03	FAL03
CAM00	1AL06	2AL06	FAL06
CAM03	1AL33	2AL33	FAL33
CAM06	1AL36	2AL36	FAL36
CAH00	1AL66	2AL66	FAL66
CAH03			
CAH06	1AM00	2AM00	FAM00
	1AM03	2AM03	FAM03
$\overline{C}$AL00	1AM06	2AM06	FAM06
$\overline{C}$AL03	1AM33	2AM33	FAM33
$\overline{C}$AL06	1AM36	2AM36	FAM36
$\overline{C}$AM00	1AM66	2AM66	FAM66
$\overline{C}$AM03			
$\overline{C}$AM06	1AH00	2AH00	FAH00
$\overline{C}$AH00	1AH03	2AH03	FAH03
$\overline{C}$AH03	1AH06	2AH06	FAH06
$\overline{C}$AH06	1AH33	2AH33	FAH33
	1AH36	2AH36	FAH36
	1AH66	2AH66	FAH66
	1AM'00	2AM'00	FAM'00
	1AM'03	2AM'03	FAM'03
	1AM'06	2AM'06	FAM'06
	1AM'33	2AM'33	FAM'33
	1AM'36	2AM'36	FAM'36
	1AM'66	2AM'66	FAM'66

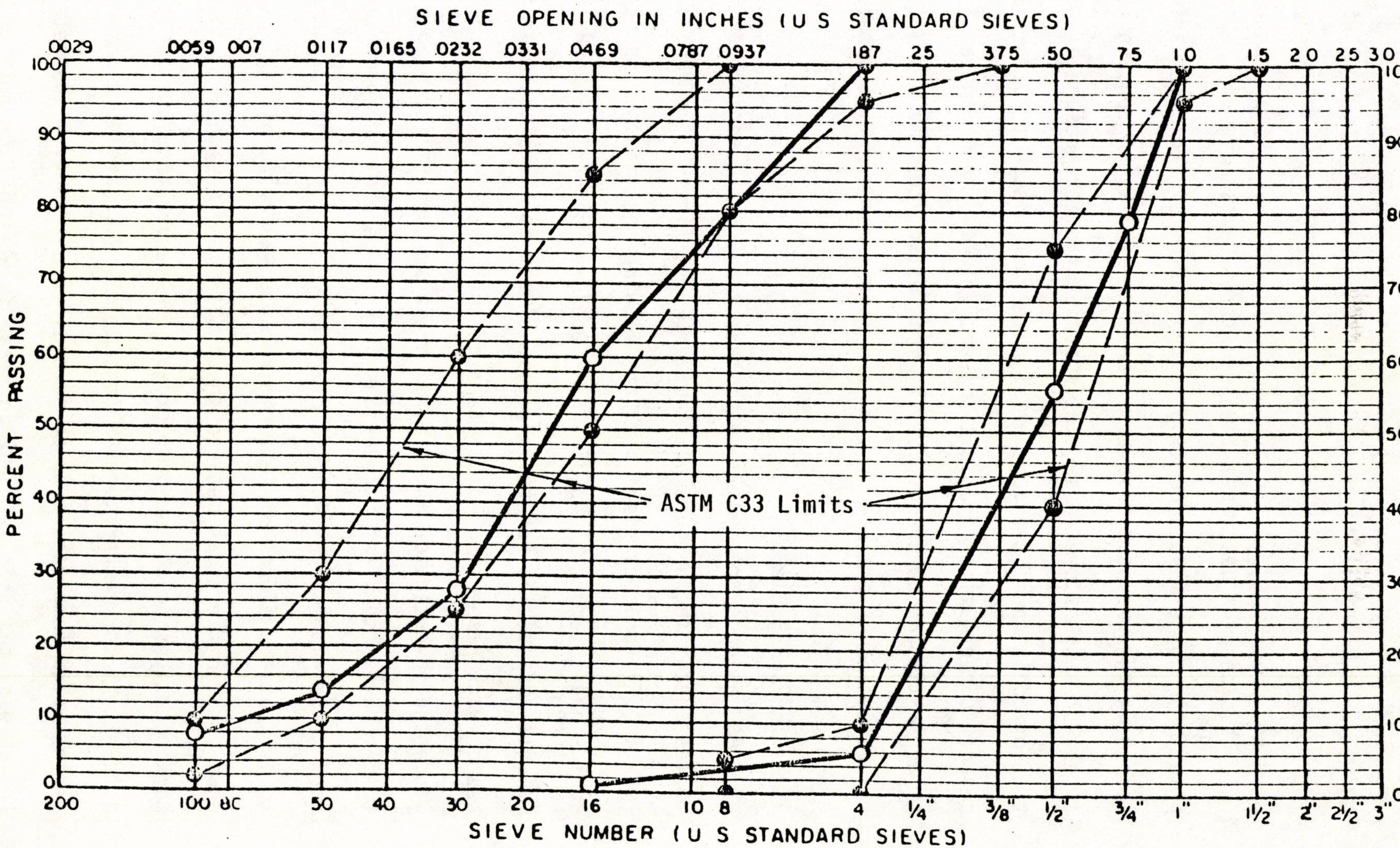


Figure 2.1 COARSE AND FINE GRADATIONS FOR LIMESTONE AGGREGATE

III. RESULTS OF TESTS

This chapter describes the results of tests made of the portions of plastic concrete made according to the system of variable variation described in the previous chapter. The emphasis was on concern for the effect of temperature, dosage of superplasticizer, dosage of air-content, time of addition of the superplasticizer with respect to initial water/cement contact, time of agitation, etc., on two major properties of the superplasticized concrete: 1) its loss of workability with time and 2) the variation of its air content and resulting durability property changes.

3.1 Slump Loss with Time

As has been previously described, the C and $\overline{C}$ series were control series containing no superplasticizer. The first had a target slump of 1.5" $\pm$ 0.5" for comparison with the flowing mode mixes, and the second series had a target slump of 3.5" $\pm$ 0.5" for comparison with the "1" (single dosage) and "2" (double dosage) series. The approach to mix design with respect to temperature of the concrete was the following. Since the investigator anticipated the best workability with a cold temperature, the first mix designs in each general group of variables were those with a low ("L", 50^{o}F) concrete temperature. In the attempt to look at the effect of temperature as a variable, all things else being equal, the differences between those data points with all other specimen mark notations being the same except for temperature are exactly the same except for temperature. The same mix was simply redone with a different water temperature to cause a different initial concrete temperatu It was expected that a steady decrease in workability would be found as the temperature of the mixes increased. Instead, the workability increased from "low" to "medium" ("M", 70°F) and then dropped again for the "high" ("H", 90°F) concrete temperature mixes. As a result, the medium mixes' workability often exceeds the initial target workability and the high temperature mixes often are lower. This result, although somewhat unexpected, is, nevertheless, consistent with the phenomenon that first led the author to be interested in the effect of temperature, namely the highly touted success with the use of superplasticizers in countries in highly temperate climates such as Japan and Germany.

Tables 3.1 through 3.6, following, indicate the data for slump with time for the C, $\overline{C}$, 1, 2, and F series respectively both with and without air-entrainment.* Plots of this same data are shown in Figures 3.1 through 3.23, following. Slump numerical values marked with an asterisk (*) are initial extrapolated values consistent with trial batches of the same mix. These extrapolated values represent data points that were on occasion missing from the lab data for a batch because of intensive activity with other tests at those initial times immediately after mixing.

Figures 3.24 through 3.38 show the same slump with time behavior but plot instead "percent of original slump" versus time to more graphically illustrate the rates of loss of slump. For a number of series, especially the control series with low slumps, problems of repeatability and difficulties associated with low slump concretes occasionally meant that the target slumps were not achieved within the desired range but the effect of temperature and the rate of slump loss could be profitably examined.

Table 3.1 contains the data for series "CN" and "CA" and Figure 3.1 plots that data. As can be seen quite graphically, the problems of re-

*"Primed" series are included in Table 3.6.

peatability were present here trying to target a slump of 1.5 inches. A the temperature of the concrete mix increased, the workability decreased, giving almost a zero slump for the same mix as the low temperature initial mix. These results illustrate the difficulties associated with setting a low initial slump as a starting reference point for a later flowing mix. In the author's opinion, it would be better to set 2.0 or 2.5 as a minimum reference slump for mixes to be converted to a flowing mode by the addition of large dosages of superplasticizer, particularly in hot weather.

Table 3.2 contains the data for slump for series "$\overline{\text{CN}}$" and "$\overline{\text{CA}}$" and Figure 3.2 plots that data. Figures 3.24 and 3.25 show the same data as percent of original slump versus time. Several interesting trends for non-superplasticized mixes should be noted. First is that for non-air-entrained mixes, the $\overline{\text{CN}}$ series, the deterioration of workability for the same mix is proportional of the concrete temperature. The workability decreases as the temperature increases. Secondly, the start of the loss of slump seems to be related to the concrete being deposited outside the mixer. As long as the concrete was kept in the mixer being agitated, the slope of the slump-vs-time lines was seemingly somewhat delayed. This behavior seemed consistent for all of the concrete temperatures. This behavior is seen even more clearly in the plot of percent slump loss with time that mollifies the effect of different starting slumps. The general rate of loss of slump with time in that portion of the typical curve with the greater slope seems to be about 4.5 inches per hour or 40.0 percent of original slump per hour for the non-air-entrained control series.

In the $\overline{\text{CA}}$, or air-entrained control series, a somewhat different behavior is noted. Now, as the concrete temperature shifts from low to to medium, the workability increases before decreasing again as the concrete temperature increases to the high target value. The "delay" in the high rate of slump loss portion of the curve is again present as the agitation of the mix continues and can again be seen even more clearly in Figure 3.25, which shows the percent of original slump with time. This behavior does seem to break down somewhat for the high temperature concrete, but this may simply be bad data.

Table 3.3 contains the data for slump for series "1N" and "1A" and Figures 3.3 through 3.8 plot that same data in slump-versus-time. Figures 3.26 through 3.30 plot the data as percent of original slump with time.

By the time the testing had proceded to this series of tests, it had been recognized that the low concrete temperature series were giving not more workability but considerably less workability than the medium and high temperature mixes. Therefore, at this state, the target workability was now used in the medium mixes and all variables were held constant except for temperature for the low and high temperature mixes. The results for all further series in the plastic testing part of this study followed this procedure.

The first significant thing to be observed in the data for these series is the severe reduction in workability in these now superplasticized mixes with low concrete temperatures. The ambient temperature of the working space for these mixes was at normal room temperature or below. Small amounts of ice were used to establish the target concrete temperatures and all of the ice was melted before the addition of the superplasticizer, but it became very difficult to achieve the target slumps at these reduced concrete temperatures. This previously noted reduction in workability for low concrete temperatures and high concrete temperatures was consistent throughout the testing of the superplasticized concrete mixes.

The rate of slump loss for the steep portion of the 1NL series was approximately 2.0 inches per hour. The percentage of original slump versus time curve for this series was not drawn because of the difficult nature of the data, although it might be estimated in the order of 200 percent per hour.

The rate of slump loss for the steep portion of the 1NM series was approximately 10 inches per hour. The rate of loss on the percentage versus time curve, Figure 3.27, was in the order of 165 percent per hour.

The rate of slump loss for the steep portion of the 1NH series was approximately 4.5 inches per hour. The percent of original slump rate of loss was approximately 450 percent per hour.

It should be noted that the variation of these rates are in line with a previous work published [17] that noted that the additional slump provided by the superplasticizing admixture is usually lost within the first thirty minutes to an hour after deposition. Thus, higher initial slumps result in larger rates of slump loss. The results from these tests fit essentially into that evaluation, but the rates of loss for any one mix, whatever its agitation and/or time of addition changes, were approximately the same for the same initial target concrete temperature.

For the air-entrained mixes with the same single dosage, the pattern of slump loss was much the same as the non-air-entrained. The low temperature mix did not allow the development of the target slump. No figure is drawn showing the percentage loss with time because of the scanty, difficult data. The rise in temperature, however, to the medium target temperature of $70^{o}F$ showed a marked improvement to the target slump. As the concrete temperature was raised to the high value of $90^{o}F$, there was some reduction in workability although not as much as in the non-air-entrained case. The rate of slump loss with time for the medium temperature was in the order of 5 inches per hour and 90 percent per hour. The rate of slump loss for the high temperature mixes was in the order of 12 inches per hour and 200 percent per hour.

A trend should also be noted at this point which will become even more noticeable as we approach larger dosages and particularly in the flowing concrete mode. As the addition of the superplasticizer is delayed until, in the case of this study, 30 minutes and 60 minutes after initial water/cement contact, the efficacy of the same dosage of super plasticizer is reduced. The slump reached at the thirty minute initial addition point is much less than that achieved if the superplasticizer is added at the initial mixing. The slump achieved at the sixty minute initial addition point is even further reduced. Just from the point of view of economy, therefore, it is again much more advantageous to deposit the concrete as soon as possible after initial water/cement contact and to add the superplasticizer as soon after initial water/cement contact as possible.

Table 3.4 contains the data for slump for series "2N" and "2A" and Figures 3.9 through 3.14 plot the same data in slump-versus-time. Figures 3.31 through 3.32 plot the data as percent of original slump with time.

The data for the 2NL series is very erratic. There is even a seeming reversal of the reduced efficiency of the superplasticizer with delay of addition and increase of agitation time before deposition. However, the scatter of the results does not warrant making this evaluation. It also does not warrant drawing the percent of original slump with time curve.

The data for the 2NM series appears nearer to the expected results. This temperature is now used for the target slump. It shows the trend of slump loss and of lessened efficiency of the superplasticizer as delay and agitation are increased. The slump loss rate for this series is in the order of 8.5 inches per hour and 180 percent of slump per hour.

The data for the 2NH series also demonstrated the same pattern as before except that now the reduction in workability with temperature is even more pronounced. The starting slumps are less than half what they are in the 2NM series. The slump loss rate for this series is in the order of only 4 inches per hour and the percent loss is in the order of 270 percent per hour. Both slump reduction rates essentially changed because of the small value of the starting slump.

For the air-entrained mixes with the same double dosage, the pattern of slump loss was much the same as the non-air-entrained. The low temperature concrete workability was reduced to very low values and after extended agitation was essentially zero before the concrete could be deposited. The percent of original slump versus time was not plotted for this particular series.

The data for the 2AM series seems much more normal. The loss of efficacy of the superplasticizer with delay in addition is seemingly a smooth curve. The slump loss rate for this series is in the order of 6.5 inches per hour, less than that of the non-air-entrained corresponding series. This same advantageous effect of air-entrainment on the rate of slump loss seems to be common throughout most of the superplasticized mixes.

The 2AH series shows a quite pronounced loss of workability due to the raised temperature. With increased agitation and delay of addition of the superplasticizer, the loss is sufficient to destroy the usability of the mix before the appointed time of deposition. The slump loss rate for this series is in the order of 4 inches per hour. The percent loss of original slump versus time curves were not drawn for the 2A series since they were of no immediate help.

Tables 3.5 contain the data for slump for series "FN" and "FA" and Figures 3.15 through 3.20 plot the same data in slump versus time. Figures 3.33 through 3.38 plot the data as percent of original slump with time.

The data for these series with their large original slumps provide more graphic display of the slump loss tendencies of superplasticized concretes with time. The slumps attainable in the FNL series are substantially less than the target initial slumps of 8" ±0.5" reached in the FNM and FNH series. The rate of slump loss in the steeper immediate portions of the curves are larger than those in the 1NM series, 10, 9, and 12, respectively, inches per hour for the FNL, FNM, and FNH series. The FNL series, however, seemed to "level off" and maintain its lesser slump values for a longer time than either the FNM or FNH series. The reduction in the efficiency of the superplasticizer with delay and agitation time was there in all three series although much more pronounced in the FNL series and somewhat more pronounced in the FNH in comparison with the FNM. The FNH36 data point seems to be an anomaly in this regard and should probably not be considered representative at least in its initial achievement of slump.

When air-entrainment is included in the series, it seems to soften the rate of slump loss in the low concrete temperature series, FAL, but seems to allow for an increase in the rate of slump loss in the other two series, FAM and FAH. The steep rates of slump loss with time are 5, 13, and 13 inches per hour in the FAL, FAM, and FAH series, respectively.

In addition to the series noted previously in this section, three additional series were completed to observe the effect of a difference in the sequence of admixture addition on the slump loss phenomenon and other properties of the plastic concrete. In all the previous series, the air-entraining agent had been added with the mix water and the superplasticizer as specified in the variable list. However, because of some questions at the Ottawa conference, it was decided to hold the addition of the air-entraining agent until after the addition of the superplasticizer. This was accomplished by holding out approximately 100 ml of the total mix water and adding the air-entraining agent to it. After the superplasticizer had been added to the mix and had become effective, the air-entraining agent was added slowly and the mixing continued for another two minutes to ensure full mixing of both admixtures.

Table 3.6 contains the data for slump for series "1AM'", 2AM'", and "FAM'". Figures 3.21 through 3.23 plot their slump with time. These mix series were exactly the same as the 1AM, 2AM, and FAM series except in that the sequence of admixture addition as described above was in effect. In comparing the effect of the admixture sequence reversal on slump loss, it would appear that the slump available or the initial effectiveness of the superplasticizer was increased. The rate of slump loss is about the same, 7, 22, and 12 inches per hour, respectively, for 1AM', 2AM', and FAM' series. The large increase in the 2AM' series versus 2AM is difficult to explain but seemed consistent throughout all the data points of the series. Although these rates of slump loss were interesting in their lack of pattern, as will be reported later, there was a definite advantage in the freeze/thaw resistance of these "primed" series with the admixture sequence reversal.

3.2 Time of Set

Tables 3.7 through 3.11 contain the data for the time of set tests for the control, single dosage ("1" series), double dosage ("2" series), flowing mode ("F" series), and prime series, respectively. The same times of set for all data points are represented graphically in Figures 3.41 through 3.51. Figure 3.39 gives a typical plot of penetration strength versus time. The time of initial set is recorded when the penetration resistance crosses the 500 psi penetration resistance line, and the time of final set is recorded when the penetration resistance crosses the 4000 psi level. Figure 3.40 gives the same plot on semi-logarithmic paper.

The data in Tables 3.7 through 3.11 show a great deal of scatter. Some of this was probably occasioned by the problems encountered with repeatability in the trial batches; part of it may be due to the varying differentials of temperature between the initial concrete temperature and the ambient environment in that the laboratory space used was not air-conditioned. In Table 3.7 for the control mixes, it may be possible to recognize the following pattern although there are anomalies throughout the data that seem to deny the pattern. When the water/cement ratio is lower the time of the initial set is sooner but the period of set between initial and final set is somewhat longer. As the temperature increases and as the time of agitation before deposition is lengthened within any one series, the time of initial set is shortened and the period of set is shortened. This trend is typically less striking between the medium to high temperatures as it is between the low to medium. Moreover, the trend is also less striking between 30 to 60 minutes agitation times as it is between 0 to 30 minute agitation times. All of these trends among the control mixes are softened by the presence of air-entrainment. Most of the anomalies are among the low temperature mixes with little agitation.

Table 3.12 is offered as a comparison among the various series. It gives the mean value of initial set, mean value of final set and mean value of period of set for all six data point series as well as the control series. Again, there is much scatter among the data but the following general trends may be observed. As one shifts from a control mix through a single dosage mix to a double dosage mix for the same temperature, the time of initial set is reached increasingly sooner. Also, the period of set is shortened from twenty to fifty minutes, the period of set being very nearly the same for the single and double dosage mixes for the same temperature. Again, the effect of air-entrainment is to regularize these changes, making them less severe between mix series of different temperatures and between mix series of the control mixes by comparison with the superplasticized mixes.

The same general trends hold in comparison between the control mixes ("C") and the flowing mode ("F") mode mixes if not air-entrained. However, in comparing the air entrained C control mixes with their flowing mode counterparts, a delay of from 30 to 80 minutes is noted. The answers to these phenomena will probably be found at the level of work of the physical chemist rather than at the level of macroscopic observations as in this study.

3.3 Bleed Water

Tables 3.13 give the results of the bleed water measurements for all data points. The tables show for each data point which showed any bleed water at all the actual amount of accumulated water in milliliters, the volume of water per exposed surface area in milliliters per square centimeter, and the percent of available mix water that was collected as bleed water. Figure 3.52 gives a representative view of the accumulation of bleed water versus time for one series that had non-zero bleed water data for essentially all of its data points, series FNH.

General trends are observable from the data. More bleed water will be available in larger slump concrete than in concrete with a smaller slump. This is true even if the large slump results from adding superplasticizer to a small slump non-admixtured concrete. If no additional agitation follows the mixing or if the bleed water is measured in a mix after the addition of superplasticizer following some previous agitation, the longer the agitation of the mix before the superplasticizer is added the less the bleed water immediately after its addition. In general, all things else being equal, the use of air-entrainment and sufficient fines will render the bleed water problem insignificant. The presence of air-entraining agent and superplasticizer were more effective in limiting bleed water than just the presence of air-entraining agent in control mixes. There seemed little difference between the bleeding in superplasticized mixes and the corresponding control mixes. There were several anomalies in the data marked by an asterisk (*), especially 2AM00 and FAM00, for which the author has no explanation apart from the possibility that adequate mixing had somehow not taken place before the bleed water sample was taken.

It should be noted at this point, however, that in many cases in the superplasticized concrete where the dosage was large and/or the concrete was in a flowing mode, the notion of "bleeding" may need redefinition. In those types of mixes, one often experienced what might be called "mortar bleed". The water was still intimately related to the cement paste but the cement paste was highly fluid and did rise to the surface in a manner that prohibited the bleed water separating from it. However, the texture and "stickiness" of the paste was such as to inhibit easy finishing. It would present no problem to filling a form, but would be a potential difficulty in finishing.

3.4 Air Content

As was described above, all of the data series described below, except for three, were mixed in the procedure where the air-entraining agent was added to the mix water before contact with the cement. Then the superplasticizer was added at the appropriate time. In three of the series, however, the initial mixing was completed, the superplasticizer added at the appropriate time, and then the air-entraining agent was added after having been mixed with approximately 100 ml of the original amount of mix water. These series include the 1AM', 2AM', and FAM' series. The purpose of conducting these additional series was to discover any beneficial effect, especially with respect to the air-void structure and the accompanying durability, from such a reversal of admixture addition.

The data for the air content of the mixes in question is graphically presented in Figures 3.55 through 3.77. There is a good bit of scatter the results, the general problem of repeatability was present during the conduct of these tests. Some problems developed with the air-content meter being used. When some of the tests were later duplicated, it was in a different ambient temperature and humidity because the laboratory space was not environmentally controllable. However, some trends did demonstrate themselves which are consistent with the results of the freeze/thaw tests to be reported below.

Figures 3.53 and 3.54 show the results for the CN and CA series respectively. Points plotted represent actual air contents modified by the appropriate aggregate correction factor. The air contents for the CN series seem high for a non-air-entrained mix. It is supposed that this stiff mix held more entrapped air by virtue of being more difficult to consolidate in the air-meter. That same phenomenon will appear later in the superplasticized results. The air-entrained low-slump mixes showed high initial air-contents also that included possibly excess entrapped air that was difficult to remove from the air-content sample. A higher temperature allowed less air-entrainment typically. Continued agitation of the air-entrained mix resulted in a drop in air content that was mirrored in the freeze/thaw results except in the CAL series.

Figures 3.55 and 3.56 show the results for the $\overline{CN}$ and $\overline{CA}$ series respectively. Now with a larger slump and more fluidity in the mortar the mix is easier to density in the air-meter and the $\overline{CN}$ results are reasonable. The drop in air content from 30 minutes of extra agitation is more pronounced but the second 30 minutes means a gain in total air content plus sufficient loss of slump so as to gain more entrapped air and make it harder to eliminate it in the air-meter before taking the test. Except for the $\overline{CAL}$ series the freeze/thaw results to be seen later show consistency between the 00 and 06 specimens indicating little change in the small-bubble air despite the noted changes in total air content.

Figures 3.57 through 3.63 show the results for the single dosage series where the initial slump after the superplasticizer was added is 3 to 4 inches. The inequality symbols (< and >) on the figures help to indicate "before" (<) and "after" (>) superplasticizer addition. Almost all the figures indicate roughly a 2% drop in air content with the addition of the superplasticizer. In the case of the non-air-entrained mixes this is down to reasonable values. The drops are typically large for the non-air-entrained mixes without agitation before addition of the superplasticizer, i.e., the 00 mixes. The drops here can be explained again in terms of the loss of large-bubble entrapped air as more fluidity is given to a stiff mix. As the stiffness of the mix (measured by a reduction in slump) increases because of increased agitation time or temperature the drop will decrease and the total air somewhat increase indicating the retention of more large bubble air.

It is apparent even at this stage of the description of the results that it is only possible to get really representative evaluations of the important small-bubble entrained air-void system by job site methods only after the addition of the superplasticizer. The possible interchange between small-bubble and large-bubble air in the mortar of superplasticized mixes needs a great deal more investigation. It is also apparent that a simple, immediate method of distinguishing quantitatively between them in a fresh sample of plastic concrete would be very valuable indeed.

In the air-entrained sing dosage mixes of Figures 3.60 through 3.62 the same initial drops are there but explainable by the same reasoning as before. Now as agitation continues there is loss of quite possibly some small-bubble air also and after even further agitation there is more often than not a general increase in the total air. Here again that is probably a further decrease in the small-bubble air but a significant increase in the large-bubble air as the mix becomes stiffer. This supposition is reinforced by the general trend of the freeze/thaw results to be discussed below wherein the durability factor is optimum if the agitation time is kept small but it is also somewhat reduced if the addition of the superplasticizer is delayed and the mix is stiffer.

Figures 3.63 through 3.68 show the air content results for the double dosage series. In the first three with no entrainment the initial drop for the 00 data point is much greater than before ranging between 3.5 to 5.5%. Now, without air entrainment and depending upon a larger dosage of superplasticizer the mixes are even stiffer before the admixture addition and the possibility of an even larger portion of entrapped air is greatly increased. The fluidity imparted by the superplasticizer makes the elimination of this entrapped air from the air-meter container easier and more reasonable values are obtained. Now as the addition of the superplasticizer is delayed the mix becomes stiffer, the superplasticizer becomes less effective, and the drops in air content after superplasticizer addition grow smaller leaving more entrapped air to be measured in the total air content. Again these suppositions are reinforced by the freeze/thaw results although it must be admitted that there was more difficulty in achieving adequate effective air content in the double dosage mixes than in any others.

The supposition regarding the interplay of small and large-bubble are further reinforced in Figures 3.69 through 3.74 which plot air content for the flowing mode series. Considering the first three figures for the non-air-entrained series first, the initial drop in air content is now minimized. This means that the fluidity imparted by the high initial slump before addition of the superplasticizer allows a more accurate evaluation of the mortar air content so that the extra fluidity given by the superplasticizer changes the evaluation very little. Note that this is especially true for the FNM series where the superplasticizer is more effective than at the other two temperatures. Unfortunately, problems were experienced with the air-meter during the conduct of the FNH tests so some of the data points are missing. However, those that are present seem consistent with the analysis presented.

In Figures 3.72 through 3.74 the air-entrained flowing mode concretes also exhibit an initial percentage drop, but that drop is now more probably a loss in small-bubble air due to the increased fluidity of the mortar. Further agitation gives scattered results. Some data indicates a continued loss of small-bubble air; others show an almost constant total air content and the FAM00 → 03 → 06 line indicates an increase in total air with further agitation. This increase is again probably large bubble air since the freeze/thaw results of the FAL and FAM series showed a consistent pattern similar to that described above.

Figures 3.75 through 3.77 gives the air content variations for the "primed" series. Now the air entraining agent is added after the superplasticizer and air contents were no longer taken before the superplasticizer was added. A new symbol is now added to the figures, "<a" or ">a" indicating "before air added" and "after air added" respectively. The most striking change in these figures as compared to the previous ones is the movement upward in air content rather than a drop for the 00, 33, and 66 data points. The initial readings for the 00, 33, and 66 points now more closely represent the actual "non-air-entrained" condition due to the high fluidity of the superplasticized mortars and the increase in air contents ">a" represent essentially a true increase of entrained air. If the mix is subjected to continued agitation the increased stiffness of the mix will entrap some air before the air-entraining-agent is added so that the initial 33 readings are usually higher than the "<a" 00 readings. Also the increase in air from "<a" to ">a" for the 33 readings is smaller than the 00 and the 66 increment is smaller still. In these cases it would be difficult to interpret or project the interaction of entrapped versus entrained air in the total. The general decrease of total content from left to right in the figures coupled with the freeze/thaw results does seem to indicate a loss of entrained air with continued agitation.

Another interesting phenomenon emerging from these three figures is the converging of the 06, 36, and 66 points. The author is not confident that he can properly interpret this. It would seem clear, however, that unless the initial slump of a mix is large enough to ensure ease of eliminating entrapped air from the sample in taking an air content reading before adding the superplasticizer the reading may not be very reliable as a quality control technique. This would certainly discourage the use of a "zero" slump concrete as a mix to be brought to a job site at some significant time interval after mixing and before the addition of superplasticizer to use as a reference before such addition. Quality control of such a mix especially in regard to air content would present a number of problems. Addition of the air-entraining-agent after addition of the superplasticizer, however, would give a satisfactory reference with respect to air content.

3.5 Freeze/Thaw Resistance

Freeze/thaw testing of the specimens cast was done according to ASTM C666 Procedure A on a machine that averaged approximately 7 cycles per day, including down time, to take readings. At that pace, six weeks is required to test a specimen if it lasts 300 cycles before deteriorating below a 60% durability factor. Because of the time involved, the freeze/thaw specimens made in Part B of this study for those mixes used to evaluate the hardened strength of superplasticized concrete have not been tested but are being stored at $0^{o}F$ according to ASTM C 666 for later testing.

The data resulting from the freeze/thaw tests made on specimens cast from the mixes used in Part A of the study regarding the plastic behavior of the concrete is shown in Table 3.14. Figure 3.78 shows the durability factor in percent versus number of freeze/thaw cycles for two specimens. One, 2AM'00, demonstrated a durability factor greater than 60% at 300 cycles and the other specimen, 2AM'36, deteriorated to a 60% durability factor before reaching 300 cycles.

In ASTM C494, the governing comparison between a specimen containing some admixture under test versus a specimen not containing the admixture is a required relative durability factor of 80 for all types of admixtures including superplasticizers. In Table 3.14, the durability factor received for each data point by averaging the results of three specimens is shown. In parentheses for the superplasticized specimens is shown the relative durability factor in comparison to the 00 non-plasticized specimen for the same temperature. This allows comparison with that specimen for dosage, time of addition of the superplasticizer, duration of agitation both before and after the addition of superplasticizer and temperature.

The first information to be noted among the superplasticized specimens is a general tendency among almost all the series. As the agitation is continued, sufficient air content seems to be lost, producing a much lowered durability factor. If the addition of the superplasticizer is delayed, then completed, followed by some additional agitation, the durability factor is lowered but not as much. Finally, if the addition of the superplasticizer is greatly delayed, then added, and the specimen made without further agitation, there is essentially little reduction below the durability factor of the 00 superplasticized specimen.

Between the control specimen 00 samples and the superplasticized air-entrained specimens, the following trends may be noticed although there was some scatter in the results and some anomalies. For the single dosage series ("1") and flowing mode series ("F"), the performance of the superplasticized concretes not only met the 80% relative durability factor requirement but more often than not were near or above the 100% relative durability factor in comparison with the control mixes for all times of addition and durations of agitation. In the case of the "primed" series, 1AM' and FAM', this was certainly true, demonstrating a definite freeze/thaw advantage in the sequence of admixture addition that has the air-entraining agent added after the superplasticizer. This seeming advantage should, however, be tempered by observing that all of the low temperature air-entrained control mixtures showed a lower durability factor for the 00 data point than the 06 data point, indicating some difficulty in the air-entraining agent being able to build the proper air-void structure at this low temperature, possibility indicating the need for a modified and more adequate mixing procedure at this low temperature. Therefore, the superplasticized comparisons at low temperature are possibly improperly exaggerated.

Another trend to be noticed is that for superplasticized concrete at larger dosages and higher temperatures, the performance is not at all successful. However, if the "primed" sequence of admixture addition is followed and the concrete is deposited quickly without additional agitation, the superior freeze/thaw performance of the "primed" procedure is still evident.

3.6 Deicer Scaling Resistance

Table 3.15 contains the data received from the deicer scaling tests. Each specimen is cycled once a day for five days then flushed, evaluated, and re-filled. The maximum number of cycles completed is 50, so the test may take as long as ten weeks to complete. In the interest of time and because of the lack of sufficient freezer volume in which to store and from which to cycle the specimens, only the 00 data points for each series were cast with the exception of 06 data points for the control specimens. The 06 specimens were done to see the effect of extended agitation on the control specimens. Figure 3.79 shows the actual change in scale value with number of cycles for a specimen showing large deterioration. Figure 3.80 represents a plot of some values on a final scale value versus number of cycles curve. All points should normally lie on the scale = 10 line or the number of cycles = 50 line. Any point within the square formed by these lines and the axes represent specimens that "failed" prematurely by virtue of their moats deteriorating beyond repair. These specimens are marked with an "X" in Table 3.15.

In general, most of the air-entrained control specimens and essentially all of the air-entrained superplasticized specimens performed very well in these tests. FAH00 is an exception. The non-air-entrained specimens, both control and superplasticized, performed very poorly, as was expected. In general, except for a few of the $\overline{\text{CN}}$ specimens, extended agitation substantially lowered the deicer scaling resistance of the mix.

Table 3.1 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- CN and CA SERIES

Series Mark	00 Δt Min	00 Slump Ins.	00 Percent	03 Δt Min	03 Slump Ins.	03 Percent	06 Δt Min	06 Slump Ins.	06 Percent
CNL	0 9 24	0.75 0.75 0.5	100 100 68	0	0.75	100	0 81 92 107	1.5 1.5 0.75 0.25	100 100 50 17
CNM	0 8	0.25 0.25	100 100	0 36 56	0.75 0.5 0.25	100 68 33	0 60 71	1.0 0.5 0.25	100 50 25
CNH	0 16	0.25 0.25	100 100	0 38	0.25 0.25	100 100	0 67	0.0 0.0	"100" 100
CAL	0 10	0.75 0.75	100 100	0 45	0.25 0.25	100 100	0 65	0.25 0.0	100 0
CAM	0 10	0.0 0.0	"100" 100	0 50	0.0 0.0	"100" 100	0 100	0.25 0.0	100 0
CAH	0 22	0.0 0.0	"100" 100	0 5	0.0 0.0	"100" 100	0 6	0.0 0.0	"100" 100

Table 3.2 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- $\overline{C}$N and $\overline{C}$A SERIES

	00			03			06		
Series Mark	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent
$\overline{C}$NL	0	4.0	100	0	3.5	100	0	4.0	100
	9	3.75	94	36	3.0	86	70	2.25	56
	24	1.5	38	51	1.5	43	85	1.5	38
	44	1.0	25	66	1.0	29	100	1.0	25
	59	0.75	21	81	0.5	14	115	0.25	6
				96	0.0	0			
$\overline{C}$NM	0	3.0	100	0	3.25	100	0	2.5	100
	23	1.75	58	43	3.0	92	12	2.5	100
	38	1.0	33	59	1.75	54	77	1.75	70
	53	0.5	17	74	1.5	46	92	1.25	50
	68	0.25	8	89	0.75	23	107	1.0	40
				104	0.5	15	122	0.5	20
				119	0.0	0	137	0.25	10
$\overline{C}$NH	0	2.75	100	0	2.5	100	0	1.75	100
	10	2.75	100	10	2.5	100	9	1.75	100
	25	1.5	55	40	1.75	70	74	0.5	29
	40	0.75	27	55	1.5	60	91	0.25	14
	55	0.25	9	70	0.25	10			
$\overline{C}$AL	0	4.0	100	0	4.0	100	0	4.0	100
	10	4.0	100	10	4.0	100	10	4.0	100
	25	3.0	75	35	3.5	88	75	1.75	45
	40	2.0	50	50	2.5	63	90	1.25	31
	55	1.25	31	65	1.5	38	105	1.0	25
	70	0.75	19	75	0.75	19	120	0.0	0
	85	0.25	6	90	0.5	13			
				105	0.25	6			
$\overline{C}$AM	0	4.75	100	0	3.5	100	0	4.5	100
	13	4.75	100	8	3.5	100			
	38	4.0	84	38	3.0	86	71	2.0	44
	68	2.25	47	55	2.25	64	86	1.75	39
	83	1.25	26	70	1.25	36	101	0.5	11
	113	0.5	11	85	1.25	36	116	0.5	11
	143	0.0	0	100	0.24	7	131	0.25	6
$\overline{C}$AH	0	3.5	100	0	3.0	100	0	4.0	100
	10	3.5	100						
	25	2.0	57	35	2.0	67	68	2.0	50
	40	0.75	21	50	1.25	42	85	1.5	38
	55	0.25	7	65	0.75	25	100	0.75	19
				85	0.25	8	115	0.25	6

Table 3.3 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- 1N and 1A SERIES

Series Mark	00 Δt Min	00 Slump Ins.	00 Per-cent	03 Δt Min	03 Slump Ins.	03 Per-cent	06 Δt Min	06 Slump Ins.	06 Per-cent	33 Δt Min	33 Slump Ins.	33 Per-cent	36 Δt Min	36 Slump Ins.	36 Per-cent	66 Δt Min	66 Slump Ins.	66 Per-cent
1NL	0	2.0	100	0	3.0	100	0	2.5	100	35	2.0	100	37	2.25	100	65	1.0	100
	11	2.0	100	11	3.0	100	9	2.5	100	55	0.75	38	49	0.75	33	87	0.25	25
	29	1.25	63	21	1.5	50	22	0.75	30	85	0.25	13	67	0.25	11			
	49	0.75	25	34	0.75	25	36	0.25	10									
	64	0.0	0	56	0.25	8	50	0.0	0									
1NM	0	3.75	100	0	4.5	100	0	1.25	100	38	5.25	100	37	5.25	100	62	5.25	100
	8	3.75	100	7	4.5	100	5	1.25	100	50	5.25	100	67	1.75	33	77	3.5	56
	23	1.0	27	35	1.5	33	70	0.0	0	70	0.75	14	82	0.75	14	97	0.75	12
	38	0.5	13	55	0.25	6				85	0.0	0				117	0.25	4
1NH	0	3.25	100	0	2.5	100	0	2.25	100	36	0.5	100	35	2.5	100	67	0.5	100
	9	3.25	100	11	2.5	100	9	2.25	100	51	0.25	50	65	0.0	0	82	0.0	0
	28	1.75	54	38	0.0	0	71	0.0	0									
	43	0.75	23															
1AL	0	2.0	100	0	1.0	100	0	1.0	100	36	0.25	100	37	0.5	100	66	0.0	"100"
	9	2.0	100	10	1.0	100	10	1.0	100				68	0.25	50			
	27	1.5	75	26	0.0	0	25	0.25	25									
	44	0.75	38															
	59	0.25	13															
1AM	0	3.5	100	0	4.0	100	0	5.5	100	30	3.5*[1]	100	30	3.25*	100	60	1.5*	100
	9	3.5	100	11	4.0	100	11	5.5	100	41	3.0	86	34	3.0	92	70	1.0	67
	24	2.25	64	41	1.0	25	71	0.0	0	56	1.5	43	69	0.75	23	85	0.0	0
	39	1.5	43	56	0.25	6							84	0.5	15			
	54	0.0	0										99	0.0	0			
1AH	0	3.5	100	0	3.75	100	0	6.0	100	30	2.5*	100	30	3.5*	100	60	1.25*	100
	10	3.5	100	12	3.75	100	10	6.0	100	37	1.5	60	36	2.5	71	68	0.75	60
	25	1.75	50	39	0.75	20	65	0.0	0	52	0.5	20	65	0.5	14	90	0.0	0
	40	0.75	21	54	0.0	0				67	0.0	0						

[1]Values followed by an asterisk indicate assumed values when data was missed but which seem appropriate to the shape of the slump versus time curve.

Table 3.4 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- 2N and 2A SERIES

	00			03			06			33			36			66		
Series Mark	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent
2NL	11	1.25	100	8	1.0	100	11	2.0	100	36	0.0	"100"	37	2.5	100	67	0.0	"100"
	24	0.5	40	20	0.0	0	20	0.75	38				55	0.5	20			
	39	0.25	20				35	0.0	0				65	0.0	0			
2NM	0	4.0	100	0	4.0	100	0	3.5	100	-[1]	4.0	100	-	3.75	100	72	0.0	"100"
	15	4.0	100	15	4.0	100	12	3.5	100	30	2.0*[2]	50	30	1.75*	47			
	30	2.25	56	40	1.24	31	27	1.0	29	39	1.25	31	36	1.25	33			
	45	1.25	31	47	0.25	6	47	0.0	0	54	0.25	6	53	0.25	7			
	60	0.25	6							69	0.0	0						
2NH	0	1.5	100	0	1.25	100	0	1.5	100	30	1.5*	100	30	1.5*	100	65	0.0	"100"
	13	1.5	100	13	1.25	100	12	1.5	100	33	1.5	100	37	1.0	67			
	26	0.0	0	33	0.0	0	25	1.5	100	46	0.25	13	50	0.5	33			
							45	0.0	0				70	0.0	0			
2AL	12	0.5	100	12	1.0	100	11	1.5	100	33	0.25	100	35	0.25	100	68	0.0	"100"
	24	0.25	50	28	0.25	25	62	0.0	0									
2AM	0	3.5	100				0	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100
	10	3.5	100				32	3.0	86	30	3.0*	86	30	3.25*	93	64	1.5	43
	25	0.75	21				89	0.25	7	36	2.5	71	35	3.0	86	79	0.0	0
	40	0.0	0							56	0.25	7	62	0.25	7			
2AH	0	2.5	100	0	2.0	100	75	0.0	"100"	-	3.5	100	37	0.25	100	65	0.0	"100"
	13	2.5	100	8	1.75	86				30	1.25*	36						
	28	1.0	40	38	0.0	0				38	0.75	21						
	43	0.25	10							54	0.0	0						

[1] Values following a "-" in the "Δt" column indicate assumed "100%" slump values commensurate with 00 initial slump.
[2] Values followed by an asterisk indicate assumed values when data was missed but which seem appropriate to the shape of the slump versus time curve.

Table 3.5.1 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- FN SERIES

Series Mark	00 Δt Min	00 Slump Ins.	00 Per-cent	03 Δt Min	03 Slump Ins.	03 Per-cent	06 Δt Min	06 Slump Ins.	06 Per-cent	33 Δt Min	33 Slump Ins.	33 Per-cent	36 Δt Min	36 Slump Ins.	36 Per-cent	66 Δt Min	66 Slump Ins.	66 Per-cent
FNL	-	6.5	100	0	0.5	8	0	0.25	4	-[1]	6.5	100	-	6.5	100	-	6.5	100
	14	6.5	100	4	0.5	8	5	0.25	4	5	0.25	4	5	0.75	12	5	1.0	15
	35	4.5	69	15	6.5	100	14	6.5	100	25	0.25	4	28	0.5	8	58	0.25	4
	55	2.5	39	27	3.25	50	29	2.75	42	35	3.0	46	37	5.5	85	68	2.5	39
	70	2.0	31	35	2.5	39	44	1.75	27	52	2.5	39	53	2.75	42	88	1.5	23
	95	1.25	19	55	2.0	31	67	0.75	12	72	1.5	23	66	2.25	35	103	1.5	23
	110	0.75	12	77	1.25	19	89	0.5	8	87	1.0	15	88	1.5	23	123	1.0	15
	130	0.5	8	110	0.5	8	109	0.5	8	102	0.5	8	103	1.0	15	143	0.25	4
	145	0.25	4	127	0.25	4	124	0.25	4	117	0.25	4	118	0.5	8			
	160	0.0	0										133	0.25	4			
FNM	-	7.5	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100
	7	1.25	17	18	8.0	100	16	8.0	100	39	6.5	81	35	7.5	94	53	0.75	9
	15	7.5	100	36	6.5	81	33	6.5	81	54	5.5	69	68	3.5	44	64	6.5	81
	31	5.75	77	58	3.25	41	48	4.0	50	74	2.75	34	85	1.5	19	86	3.0	38
	46	3.25	43	78	2.0	25	63	2.5	31	89	1.75	22	100	0.25	3	101	2.0	25
	61	2.0	27	93	1.0	13	78	1.0	13	104	0.75	9				116	1.0	13
	76	1.25	17	108	0.75	9	93	0.25	3	124	0.5	6				131	0.75	9
	91	0.75	10	123	0.25	3				144	0.0	0				146	0.0	0
	106	0.0	0															
FNH	-	7.5	100	-	7.5	100	-	7.5	100	-	7.5	100	-	7.5	100	-	7.5	100
	4	0.25	3	15	7.5	100	5	0.25	3	4	0.25	3	2	0.25	3	5	0.25	3
	14	7.0	93	25	6.75	90	15	7.5	100	39	6.0	80	27	0.25	3	66	4.25	57
	34	4.0	53	37	5.5	73	37	4.0	53	59	2.0	27	37	8.0	107	81	1.75	23
	49	1.5	20	57	1.5	20	50	2.25	30	89	0.75	10	52	3.75	50	101	0.5	7
	64	0.75	10	77	0.75	10	63	1.25	17	109	0.5	7	64	1.75	23	116	0.25	3
	79	0.5	7	92	0.5	7	80	0.5	7	124	0.25	3	82	1.0	13			
	99	0.25	3	107	0.25	3	95	0.25	3				97	0.25	3			

[1]Values following a "-" in the "Δt" column indicate assumed "100%" slump values commensurate with 00 initial slump.

Table 3.5.2 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- FA SERIES

Series Mark	00 Δt Min	00 Slump Ins.	00 Per-cent	03 Δt Min	03 Slump Ins.	03 Per-cent	06 Δt Min	06 Slump Ins.	06 Per-cent	33 Δt Min	33 Slump Ins.	33 Per-cent	36 Δt Min	36 Slump Ins.	36 Per-cent	66 Δt Min	66 Slump Ins.	66 Per-cent
FAL	-	7.0	100	-[1]	7.0	100	-	7.0	100	-	7.0	100	-	7.0	100	-	7.0	100
	3	0.25	4	5	0.0	0	5	0.75	11	3	0.25	4	5	0.5	7	5	0.5	7
	15	6.5	93	15	6.75	96	15	6.5	93	25	0.25	4	39	5.25	75	57	0.25	4
	30	4.0	57	25	2.75	39	34	3.0	43	36	6.25	89	51	3.0	43	67	4.75	68
	45	2.25	32	38	1.5	21	49	1.75	25	58	4.5	64	64	2.25	32	87	3.5	50
	90	1.25	18	65	1.0	14	67	0.5	7	73	2.75	39	76	1.75	25	102	2.25	32
	110	0.75	11	90	0.75	11	84	0.24	4	88	1.25	18	96	0.75	11	117	1.5	21
	135	0.25	4	120	0.24	4				108	0.75	11	111	0.25	4	132	1.0	14
										138	0.25	4				147	0.75	11
																162	0.25	4
FAM	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100
	3	0.25	3	6	0.25	3	4	0.25	3	7	0.5	6	5	0.25	3	3	0.5	6
	16	8.0	100	15	7.0	88	15	7.0	88	26	0.5	6	25	0.25	3	58	0.5	6
	28	5.25	66	23	6.75	84	28	6.5	81	37	6.25	78	37	8.25	103	68	4.5	56
	43	4.75	59	35	3.5	44	43	5.25	66	57	3.25	41	52	5.25	66	88	2.25	28
	61	2.5	31	49	1.75	22	66	2.0	25	72	1.5	19	68	3.0	38	103	1.5	19
	76	0.75	9	67	0.75	9	93	0.5	6	117	0.5	6	85	1.0	13	118	0.5	6
	98	0.25	3	82	0.25	3	108	0.25	3	137	0.25	3	110	0.25	3	128	0.25	3
FAH	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100
	5	0.25	3	3	0.25	3	8	0.25	3	4	0.25	3	3	0.0	0	3	0.0	0
	16	8.5	106	15	7.25	91	12	7.0	88	29	0.25	3	37	8.0	100	67	3.0	38
	35	5.5	69	33	3.5	44	29	2.25	28	37	6.5	81	55	2.25	28	84	1.25	16
	55	1.5	19	50	1.5	19	49	0.5	6	59	1.75	22	70	0.5	6	104	0.25	3
	75	0.75	9	65	0.75	9	67	0.0	0	74	0.5	6	90	0.0	0			
	90	0.25	3	80	0.25	3				89	0.25	3						

[1]Values following a "-" in the "Δt" column indicate assumed "100%" slump values commensurate with 00 initial slump.

Table 3.6 DATA FOR SLUMP AND PERCENT SLUMP VERSUS TIME -- 1AM', 2AM', FAM' SERIES

	00			03			06			33			36			66		
Series Mark	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent	Δt Min	Slump Ins.	Per-cent
1AM'	-[1]	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100
	9	5.25	150	9	4.5	129	10	4.0	114	35	3.0	86	37	2.25	64	64	2.25	64
	21	4.5	129	22	2.25	64	28	1.5	43	50	2.25	64	53	0.75	21	81	1.25	36
	36	3.0	86	34	1.0	29	43	0.5	14	72	1.25	36	65	0.5	14	96	0.75	21
	51	1.75	50	51	0.25	7	56	0.25	7	90	0.5	14	77	0.25	7	111	0.25	7
	68	1.0	29							105	0.25	7						
	81	0.5	14															
	96	0.25	7															
2AM'	-	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100	-	3.5	100
	10	5.0	143	10	6.5	186	9	8.0	229	32	3.5	100	36	2.5	71	63	1.25	36
	27	2.5	71	25	1.25	36	24	1.25	36	49	2.0	57	49	0.5	14	78	0.5	14
	49	1.25	36	35	0.25	7	43	0.0	0	67	1.0	29	67	0.0	0	93	0.25	7
	64	0.75	21							85	0.75	21						
	81	0.25	7							100	0.25	7						
FAM'	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100	-	8.0	100
	10	9.5	119	9	9.0	113	8	9.25	116	35	8.5	106	35	8.5	106	65	7.5	94
	32	8.0	100	23	6.0	75	25	5.5	69	52	6.5	81	49	6.0	75	82	5.0	63
	47	6.5	81	36	3.0	38	41	2.5	31	73	4.0	50	66	3.0	38	97	2.75	34
	62	3.75	47	51	2.5	31	53	1.25	16	87	3.25	41	84	1.75	22	118	2.0	25
	77	2.75	34	76	1.75	22	62	0.75	9	117	1.5	19	99	0.75	9	132	1.5	19
	92	2.0	25	106	1.25	16	74	0.5	6	132	1.0	13	114	0.25	3	147	0.75	9
	107	1.25	16	122	0.75	9	89	0.25	3	162	0.5	6				165	0.25	3
	122	0.75	9	137	0.5	6				177	0.25	3						
	137	0.5	6	152	0.25	3												
	152	0.25	3															

[1]Values following a "-" in the "Δt" column indicate assumed "100%" slump values commensurate with and for comparison with initial slump values for 00 points of the corresponding "unprimed" series.

TABLE 3.7. TIME OF SET RESULTS - CONTROL MIXES

Specimen Mark	Initial Set h:m	Final Set h:m	Setting Increment h:m	Group Average	Initial Set h:m	Final Set h:m	Setting Increment h:m
CNL00	4:19	6:23	2:04				
CNL03	4:37	7:06	2:29	CNL	4:30	6:47	2:17
CNL06	4:35	6:51	2:16				
CNM00	4:55	8:46	3:51				
CNM03	4:22	6:44	2:22	CNM	4:35	7:19	2:44
CNM06	4:28	6:28	2:00				
CNH00	3:57	6:24	2:27				
CNH03	4:00	5:55	1:55	CNH	3:53	5:57	1:64
CNH06	3:42	5:31	1:49				
Average	4:19	6:41	2:21				
CAL00	3:28	5:35	2:07				
CAL03	3:15	4:47	1:32	CAL	3:27	5:07	1:40
CAL06	3:38	5:00	1:22				
CAM00	4:06	5:57	1:51				
CAM03	3:39	5:19	1:40	CAM	3:49	5:24	1:35
CAM06	3:43	4:56	1:13				
CAH00	2:43	4:06	1:23				
CAH03	3:07	4:13	1:06	CAH	2:58	4:09	1:11
CAH06	3:03	4:07	1:04				
Average	3:25	4:53	1:29				
$\overline{C}$NL00	5:34	8:12	2:28				
$\overline{C}$NL03	4:10	6:09	1:59	$\overline{C}$NL	4:43	6:39	1:53
$\overline{C}$NL06	4:26	5:37	1:11				
$\overline{C}$NM00	3:56	5:51	1:55				
$\overline{C}$NM03	4:54	7:00	2:06	$\overline{C}$NM	4:27	6:18	1:51
$\overline{C}$NM06	4:32	6:04	1:32				
$\overline{C}$NH00	3:44	5:30	1:46				
$\overline{C}$NH03	4:05	5:17	1:12	$\overline{C}$NH	3:50	5:12	1:22
$\overline{C}$NH06	3:40	4:49	1:09				
Average	4:20	6:03	1:42				
$\overline{C}$AL00	4:24	6:52	2:28				
$\overline{C}$AL03	4:01	5:16	1:15	$\overline{C}$AL	4:05	5:52	1:47
$\overline{C}$AL06	3:49	5:27	1:38				
$\overline{C}$AM00	4:28	6:50	2:22				
$\overline{C}$AM03	4:29	6:20	1:51	$\overline{C}$AM	4:19	6:17	1:57
$\overline{C}$AM06	4:01	5:40	1:39				
$\overline{C}$AH00	3:29	5:25	1:56				
$\overline{C}$AH03	3:29	5:23	1:54	$\overline{C}$AH	3:31	5:17	1:45
$\overline{C}$AH06	3:36	5:02	1:26				
Average	3:58	5:48	1:50				

TABLE 3.8. TIME OF SET RESULTS - SINGLE DOSAGE MIXES

Specimen Mark	Initial Set h:m	Final Set h:m	Setting Increment h:m
INL00	4:03	5:41	1:38
INL03	3:38	5:13	1:35
INL06	4:06	5:17	1:21
INL33	3:50	5:15	1:25
INL36	3:42	4:55	1:13
INL66	4:17	5:41	1:24
Average	3:56	5:20	1:26
INM00	3:08	4:24	1:16
INM03	2:57	4:09	1:12
INM06	3:09	4:11	1:02
INM33	3:29	4:42	1:13
INM36	3:19	4:22	1:03
INM66	3:38	4:43	1:05
Average	3:17	4:25	1:09
INH00	3:24	4:49	1:25
INH03	3:18	4:26	1:08
INH06			
INH33	3:03	4:56	1:53
INH36	3:20	4:10	0:50
INH66	3:17	4:26	1:09
Average	3:16	4:33	1:17
1AL00	4:01	5:44	1:43
1AL03	3:25	4:45	1:20
1AL06	3:45	5:08	1:23
1AL33	3:21	4:51	1:30
1AL36	3:16	4:26	1:10
1AL66	3:19	4:51	1:32
Average	3:31	4:58	1:26
1AM00	2:55	4:12	1:17
1AM03	2:39	3:50	1:11
1AM06	3:03	3:59	0.56
1AM33	2:50	3:57	1:07
1AM36	2:56	4:00	1:04
1AM66	3:03	4:05	1:03
Average	2:54	4:00	1:06
1AH00	2:44	4:00	1:16
1AH03	2:54	4:03	1:09
1AH06	2:50	3:49	0.59
1AH33	2:57	4:06	1:09
1AH36	2:56	3:53	0.57
1AH66	2:53	3:48	0.55
Average	2:52	3:56	1:04

TABLE 3.9. TIME OF SET RESULTS - DOUBLE DOSAGE MIXES

Specimen Mark	Initial Set h:m	Final Set h:m	Setting Increment h:m
2NL00	3:44	5:17	1:33
2NL03	2:50	4:27	1:37
2NL06	2:59	4:20	1:21
2NL33	2:37	4:11	1:34
2NL36	3:02	4:21	1:19
2NL66	3:03	4:50	1:47
Average	3:03	4:34	1:32
2NM00	3:42	4:52	1:10
2NM03	3:09	4:08	0.59
2NM06	3:26	4:21	0.55
2NM33	3:18	4:20	1:02
2NM36	3:09	4:11	1:02
2NM66	3:15	3:51	0.36
Average	3:20	4:17	0.57
2NH00	3:16	4:23	1:07
2NH03	2:52	3:53	1:01
2NH06	3:06	4:24	1:18
2NH33	2:58	3:56	0.58
2NH36	2:45	3:59	1:14
2NH66	2:40	3:39	0.59
Average	2:56	4:04	1:06
2AL00	3:28	5:19	1:51
2AL03	2:59	4:37	1:38
2AL06	3:11	4:36	1:25
2AL33	3:11	4:43	1:32
2AL36	3:11	4:40	1:29
2AL66	3:30	5:13	1:43
Average	3:15	4:51	1:36
2AM00	3:31	4:58	1:27
2AM03	3:02	4:20	1:18
2AM06	3:02	3:58	0.56
2AM33	3:21	4:22	1:01
2AM36	2:54	3:52	0.58
2AM66	3:15	4:20	1:05
Average	3:11	4:18	1:08
2AH00	3:17	4:32	1:15
2AH03	2:25	3:42	1:17
2AH06	2:55	4:03	1:08
2AH33	2:45	3:42	0.57
2AH36	2:48	3:51	1:03
2AH66	2:50	3:48	0.58
Average	2:50	3:56	1:06

TABLE 3.10. TIME OF SET RESULTS - FLOWING MODE MIXES

Specimen Mark	Initial Set h:m	Final Set h:m	Setting Increment h:m
FNL00	5:05	7:32	2:27
FNL03	4:30	6:41	2:11
FNL06	4:40	7:02	2:22
FNL33	4:32	6:24	1:52
FNL36	4:39	6:40	2:01
FNL66	4:34	6:27	1:53
Average	4:40	6:48	2:08
FNM00	3:57	5:23	1:26
FNM03	3:53	5:10	1:17
FNM06	3:28	4:19	0.51
FNM33	3:17	4:15	0.58
FNM36	3:24	4:12	0.48
FNM66	3:55	5:10	1:15
Average	3:39	4:45	1:06
FNH00	3:53	5:43	1:50
FNH03	3:27	4:38	1:11
FNH06	3:27	4:37	1:10
FNH33	3:33	4:59	1:26
FNH36	4:04	5:24	1:20
FNH66	3:19	4:17	0.58
Average	3:37	4:56	1:19
FAL00	4:45	6:40	1:55
FAL03	4:58	7:00	1:02
FAL06	4:18	5:57	1:39
FAL33	4:53	6:32	1:39
FAL36	4:54	6:29	1:35
FAL66	4:51	6:40	1:49
Average	4:47	6:33	1:37
FAM00	4:28	5:56	1:28
FAM03	4:58	6:49	1:51
FAM06	3:44	5:01	1:17
FAM33	4:00	5:22	1:22
FAM36	3:43	5:22	1:39
FAM66	4:50	6:34	1:44
Average	4:17	5:51	1:34
FAH00	4:43	6:35	1:52
FAH03	4:30	5:57	1:27
FAH06	4:38	6:43	2:05
FAH33	4:02	5:22	1:20
FAH36	3:50	5:47	1:57
FAH66	4:14	5:27	1:13
Average	4:20	5:59	1:39

TABLE 3.11. TIME OF SET RESULTS - "PRIMED" MIXES

Specimen Mark	Initial Set h:m	Final Set h:m	Setting Increment h:m
1AM'00	3:50	5:25	1:35
1AM'03	4:01	5:48	1:47
1AM'06	3:45	5:39	1:54
1AM'33	3:40	5:12	1:32
1AM'36	3:24	4:56	1:32
1AM'66	3:50	5:20	1:30
Average	3:45	5:23	1:38
2AM'00	3:25	4:59	1:24
2AM'03	3:26	4:55	1:21
2AM'06	3:33	5:10	1:37
2AM'33	3:24	4:48	1:24
2AM'36	3:43	5:06	1:23
2AM'66	3:02	4:35	1:33
Average	3:26	4:56	1:27
FAM'00	5:16	7:14	1:58
FAM'03	4:39	6:01	1:22
FAM'06	4:06	5:38	1:32
FAM'33	4:50	6:27	1:37
FAM'36	4:25	5:38	1:13
FAM'66	4:36	6:04	1:28
Average	4:39	6:10	1:32

TABLE 3.12. COMPARISON OF AVERAGE TIME OF SET VALUES FOR ALL SERIES

Specimen Mark	CNL	FNL		$\overline{C}$NL	1NL	2 NL		
Initial Set, h:m	4:30	4:40(+10)		4:43	3:56(-47)	3:03(-53)		
Final Set, h:m	6:47	6:48		6:39	5:20	4:34		
Set Increment, h:m	2:17	2:08		1:53	1:26	1:32		
Specimen Mark	CNM	FNM		$\overline{C}$NM	1NM	2NM		
Initial Set, h:m	4:35	3:39(-56)		4:27	3:17(-70)	3:20(+3)		
Final Set, h:m	7:19	4:45		6:18	4:25	4:17		
Set Increment, h:m	2:44	1:06		1:51	1:09	0.57		
Specimen Mark	CNH	FNH		$\overline{C}$NH	1NH	2NH		
Initial Set, h:m	3:53	3:37(-16)		3:50	3:16(-34)	2:56(-20)		
Final Set, h:m	5:57	4:56		5:12	4:58	4:04		
Set Increment, h:m	1:64	1:19		1:22	1:26	1:06		
Specimen Mark	CAL	FAL		$\overline{C}$AL	1AL	2AL		
Initial Set, h:m	3:27	4:47(+80)		4:05	3:31(-34)	3:15(-16)		
Final Set, h:m	5:07	6:33		5:52	4:58	4:51		
Set Increment, h:m	1:40	1:37		1:47	1:26	1:36		
Specimen Mark	CAM	FAM	FAM'	$\overline{C}$AM	1AM	2AM	1AM'	2AM'
Initial Set, h:m	3:49	4:17(+28)	4:39(+50)	4:19	2:54(-85)	3:11(+17)	3:45(-34)	3:26(-19)
Final Set, h:m	5:24	5:51	6:10	6:17	4:00	4:18	5:23	4:56
Set Increment, h:m	1:35	1:34	1:32	1:57	1:06	1:08	1:38	1:27
Specimen Mark	CAH	FAH		$\overline{C}$AH	1AH	2AH		
Initial Set, h:m	2:58	4:20(+82)		3:31	2:52(-39)	2:50(-2)		
Final Set, h:m	4:09	5:59		5:17	3:56	3:56		
Set Increment, h:m	1:11	1:39		1:45	1:04	1:06		

* Numbers in parentheses indicate difference in minutes from control time immediately to the left.

TABLE 3.13.1. BLEED WATER RESULTS - CONTROL MIXES

Specimen Mark	Accumulated Water/ml	Un.Wt. pcf	Cement Factor	W/C Factor w/o SP	W/C Factor w/SP	Vol/Area ml/cm^3	Perc Available Mix Water
CNL00	0						
CNL03	6.5	145	4.84	0.571		0.0132	0.357
CNL06	0						
CNM00	0						
CNM03	5.0	144	4.81	0.571		0.0101	0.276
CNM06	1.0	144	4.81	0.571		0.0020	0.055
CNH00	5.5	143	4.77	0.571		0.0111	0.307
CNH03	0						
CNH06	0						
CAL00	5.0	137	4.54	0.479		0.0101	0.349
CAL03	0						
CAL06	0						
CAM00	0						
CAM03	0						
CAM06	0						
CAH00	0						
CAH03	0						
CAH06	0						
C̄NL00	69.5	145	5.13	0.606		0.1407	3.[illegible]
C̄NL03	19.0	144	5.10	0.606		0.0385	0.[illegible]
C̄NL06	5.5	145	5.10	0.606		0.0111	0.270
C̄NM00	75.0	143	5.06	0.606		0.1518	3.717
C̄NM03	8.0	144	5.10	0.606		0.0162	0.393
C̄NM06	21.0	145	5.13	0.606		0.0425	1.027
C̄NH00	44.5	144	5.10	0.606		0.0901	2.188
C̄NH03	10.0	145	5.13	0.606		0.0202	0.489
C̄NH06	3.0	143	5.06	0.606		0.0061	0.149
C̄AL00	12.0	136	5.28	0.541		0.243	0.638
C̄AL03	7.5	141	5.48	0.541		0.0152	0.384
C̄AL06	1.5	141	5.48	0.541		0.0030	0.007
C̄AM00	37.5	136	5.28	0.541		0.0759	1.995
C̄AM03	2.0	139	5.40	0.541		0.0040	0.104
C̄AM06	16.5	140	5.44	0.541		0.0333	0.852
C̄AH00	30.5	136	5.28	0.541		0.0617	1.623
C̄AH03	9.0	141	5.48	0.541		0.0182	0.461
C̄AH06	1.0	140	5.44	0.541		0.0020	0.052

TABLE 3.13.2. BLEED WATER RESULTS - SINGLE DOSAGE MIXES

Specimen Mark	Accumulated Water/ml	Un.Wt. pcf	Cement Factor	W/C Factor w/o SP	W/C Factor w/SP	Vol/Area ml/cm³	Percent Available Mix Water
1NL00	8.0	145	5.19	0.489	(.506)	0.0162	0.463
1NL03	0						
1NL06	0						
1NL33	1.5	147	5.26	0.489	(.506)	0.0030	0.0086
1NL36	0						
1NL66	0						
1NM00	31.0	144	5.17	0.490	(.510)	0.0627	1.787
1NM03	0						
1NM06	0						
1NM33	13.0	147	5.28	0.490	(.510)	0.0263	0.734
1NM36	12.5	148	5.32	0.490	(.510)	0.0253	0.700
1NM66	9.5	146	5.25	0.490	(.510)	0.0192	0.539
1NH00	41.0	144	5.15	0.489	(.506)	0.0830	2.391
1NH03	9.5	146	5.22	0.489	(.506)	0.0192	0.547
1NH06	0						
1NH33	0						
1NH36	0						
1NH66	0						
1AL00	0						
1AL03	0						
1AL06	0						
1AL33	0						
1AL36	0						
1AL66	0						
1AM00	13.0	143	5.71	0.443	(.454)	0.0263	0.762
1AM03	0						
1AM06	0						
1AM33	4.0	143	5.83	0.443	(.454)	0.0081	0.230
1AM36	0						
1AM66	0						
1AH00	12.0	146	5.75	0.443	(.454)	0.0243	0.699
1AH03	0						
1AH06	0						
1AH33	0						
1AH36	0						
1AH66	1.5	147	5.71	0.443	(.454)	0.0030	0.088
1AM'00	1.0	146	5.75	0.446	(.457)	0.0020	0.058
1AM'03	0						
1AM'06	0						
1AM'33	0						
1AM'36	0						
1AM'66	0						

TABLE 3.13.3. BLEED WATER RESULTS - DOUBLE DOSAGE MIXES

Specimen Mark	Accumulated Water/ml	Un.Wt. pcf	Cement Factor	W/C Factor w/o SP	W/C Factor w/SP	Vol/Area ml/cm^3	Percent Available Mix Water
2NL00	0						
2NL30	0						
2NL06	0						
2NL33	0						
2NL36	0						
2NL66	0						
2NM00	8.0	150	5.91	0.339	(.369)	0.0162	0.558
2NM03	0						
2NM06	0						
2NM33	4.0	148	5.84	0.339	(.369)	0.0081	0.282
2NM36	0						
2NM66	0						
2NH00	3.0	151	5.95	0.339	(.369)	0.0061	0.208
2NH03	0						
2NH06	0						
2NH33	1.0	151	5.95	0.339	(.369)	0.0020	0.069
2NH36	0						
2NH66	0						
2AL00	0						
2AL03	0						
2AL06	0						
2AL33	0						
2AL36	0						
2AL66	0						
2AM00	247.0*	149	6.15	0.357	(0.381)	0.4999	16.021
2AM03	0.5	149	6.15	0.357	(0.381)	0.0010	0.032
2AM06	0						
2AM33	0						
2AM36	0						
2AM66	0						
2AH00	0.5	148	7.64	0.340	(0.364)	0.0010	0.027
2AH03	0						
2AH06	0						
2AH33	0						
2AH36	0						
2AH66	0						
2AM'00	0						
2AM'03	0						
2AM'06	0						
2AM'33	0						
2AM'36	0						
2AM'66	0						

TABLE 3.13.4. BLEED WATER RESULTS - FLOWING MODE MIXES

Specimen Mark	Accumulated Water/ml	Un.Wt. pcf	Cement Factor	W/C Factor w/o SP	W/C Factor w/SP	Vol/Area ml/cm^3	Percent Available Mix Water
FNL00	6.0	145	4.85	0.562	(.587)	0.0121	0.320
FNL03	0						
FNL06	0						
FNL33	0						
FNL36	0						
FNL66	0						
FNM00	79.0	146	4.88	0.562	(.587)	0.1599	4.191
FNM03	16.0	146	4.89	0.562	"	0.0324	0.847
FNM06	6.0	147	4.91	0.562	"	0.0121	0.316
FNM33	21.0	148	4.94	0.562	"	0.0425	1.101
FNM36	6.0	148	4.94	0.562	"	0.0121	0.314
FNM66	8.5	148	4.94	0.562	"	0.0172	0.445
FNH00	2.5	147	4.91	0.562	(.587)	0.0051	0.132
FNH03	11.5	145	4.84	0.562	"	0.0233	0.615
FNH06	0						
FNH33	19.5	145	4.84	0.562	"	0.0395	1.043
FNH36	20.0	146	4.88	0.562	"	0.0405	1.061
FNH66	7.5	147	4.91	0.562	"	0.0152	0.395
FAL00	8.0	143	5.18	0.479	(.504)	0.152	0.466
FAL03	0						
FAL06	0						
FAL33	0						
FAL36	0						
FAL66	0						
FAM00	371.0*	143	5.15	0.479	(.504)	0.7508	21.723
FAM03	3.5	145	5.23	0.479	"	0.0071	0.202
FAM06	0						
FAM33	10.0	143	5.15	0.479	"	0.0202	0.586
FAM36	1.0	146	5.26	0.479	"	0.0020	0.057
FAM66	2.0	144	5.20	0.479	"	0.0040	0.116
FAH00	8.5	147	5.30	0.479	(.504)	0.0172	0.484
FAH03	0						
FAH06	0						
FAH33	0.5	145	5.23	0.479	"	0.0010	0.029
FAH36	0						
FAH00	0						
FAM'00	3.5	145	5.24	0.479	(.504)	0.0071	0.201
FAM'03	0						
FAM'06	0						
FAM'33	1.5	146	5.26	0.479	(.504)	0.0030	0.086
FAM'36	0						
FAM'66	0						

TABLE 3.14. FREEZE/THAW DURABILITY FACTOR RESULTS

Specimen Mark	D.F. %	Specimen Mark	D.F. %	Specimen Mark	D.F. %	Specimen Mark	Durability Factor, %	Specimen Mark	Durability Factor, %
C̄NL00	3.1	C̄AL00	26.4	1NL00	11.4	1AL00	45.0(170.5)		
C̄NL06	3.5	C̄AL06	46.4	1NL06	12.8	1AL06	34.8(131.7)		
				1NL36	13.8	1AL36	64.1(242.8)		
				1NL66	30.2	1AL66	39.0(147.7)		
C̄NM00	2.3	C̄AM00	58.8	1NM00	5.2	1AM00	60.5(102.9)	1AM'00	88.2(150.0)
C̄NM06	8.1	C̄AM06	55.0	1NM06	2.5	1AM06	46.7(79.4)	1AM'06	59.6(101.4)
				1NM36	3.4	1AM36	53.2(90.5)	1AM'36	61.5(104.6)
				1NM66	4.2	1AM66	58.4(99.3)	1AM'66	84.3(143.4)
C̄NH00	7.6	C̄AH00	50.2	1NH00	2.6	1AH00	65.7(130.9)		
C̄NH06	5.8	C̄AH06	47.4						
C̄NL00	3.1	C̄AL00	26.4	2NL00	9.3	2AL00	27.2(103.0)		
C̄NL06	3.5	C̄AL06	46.4	2NL06	5.6	2AL06	13.2(50.0)		
				2NL36	6.4	2AL36	50.4(190.9)		
				2NL66	8.1	2AL66	23.0(87.1)		
C̄NM00	2.3	C̄AM00	58.8	2NM00	13.6	2AM00	24.3(41.3)	2AM'00	84.5(143.7)
C̄NM06	8.1	C̄AM06	55.0	2NM06	7.2	2AM06	15.6(26.5)	2AM'06	20.0(34.0)
				2NM36	9.7	2AM36	19.8(33.7)	2AM'36	30.0(51.0)
				2NM66	11.4	2AM66	25.8(43.9)	2AM'66	83.5(142.0)
C̄NH00	7.6	C̄AH00	50.2	2NH00	9.6	2AH00	24.3(48.4)		
C̄NH06	5.8	C̄AH06	47.4						
CNL00	2.6	CAL00	17.2	FNL00	5.7	FAL00	80.3(466.9)		
CNL06	3.1	CAL06	28.1	FNL06	3.0	FAL06	59.4(345.3)		
				FNL36	4.1	FAL36	78.5(456.4)		
				FNL66	4.8	FAL66	69.6(404.7)		
CNM00	2.0	CAM00	48.5	FNM00	3.4	FAM00	57.8(119.2)	FAM'00	73.1(150.7)
CNM06	5.9	CAM06	14.2	FNM06	2.0	FAM06	23.0(47.4)	FAM'06	65.5(135.1)
				FNM36	2.5	FAM36	42.1(86.8)	FAM'36	75.2(155.1)
				FNM66	2.9	FAM66	54.9(113.2)	FAM'66	59.4(122.5)
CNH00	5.5	CAH00	44.7	FNH00	2.6	FAH00	5.6(12.5)		
CNH06	4.9	CAH06	37.0						

TABLE 3.15. DEICER SCALING RESULTS, 0 → 10 SCALE

Specimen Mark	N/M**	Specimen Mark	N/M	Specimen Mark	N/M
$\overline{C}$NL00	10/20	INL00	7/12.5*	2NL00	10/20
$\overline{C}$NL06	10/22.5				
$\overline{C}$NM00	5/15*	INM00	6.5/20*	2NM00	10/27.5
$\overline{C}$NM06	10/5				
$\overline{C}$NH00	10/5	INH00	6.5/17.5*	2NH00	10/7
$\overline{C}$NH06	10/10				
$\overline{C}$AL00	5/50	IAL00	1.5/50	2AL00	2.5/50
$\overline{C}$AL06	10/50				
$\overline{C}$AM00	1.5/50	IAM00	1/50	2AM00	0/50
$\overline{C}$AM06	4/50	1AM'00	0.5/50	2AM'00	0/50
$\overline{C}$AH00	1/50	1AH00	1/50	2AH00	1/50
$\overline{C}$AH06	2.5/45*				
CNL00	10/40	FNL00	10/10		
CNL06	9/25*				
CNM00	6/50	FNM00	10/10		
CNM06	10/30				
CNH00	10/30	FNH00	10/10		
CNH06	10/20				
CAL	1.5/50	FAL00	0/50		
CAL	8/50				
CAM	3/50	FAM00	1/50		
CAM	9.5/50	FAM'00	1/50		
CAH	3.5/50	FAH00	6.5/50		
CAH	10/45				

* Indicates testing stopped when dike became irrepairable.

** N/M = (Scale Value)/(Number of Cycles).

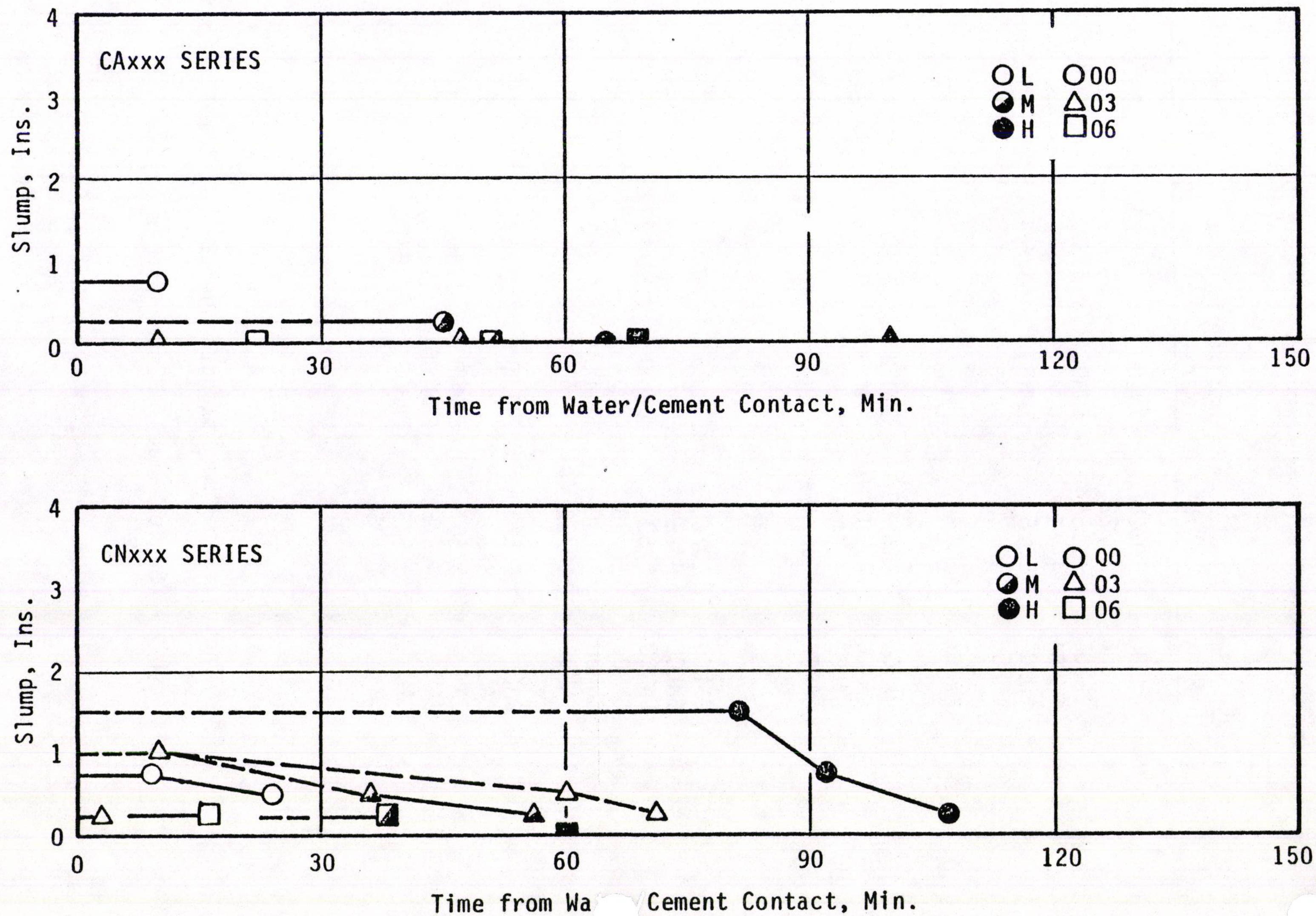
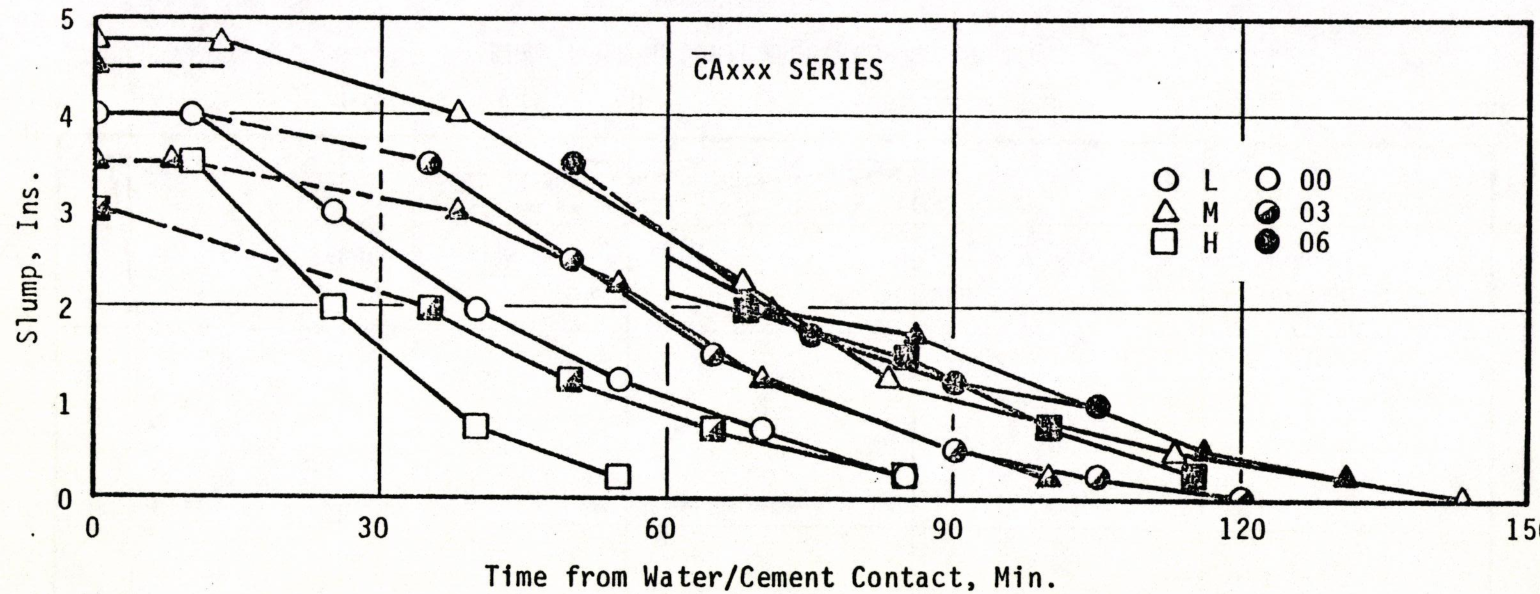


Figure 3.1 SLUMP VS. TIME, Cxxxx SERIES



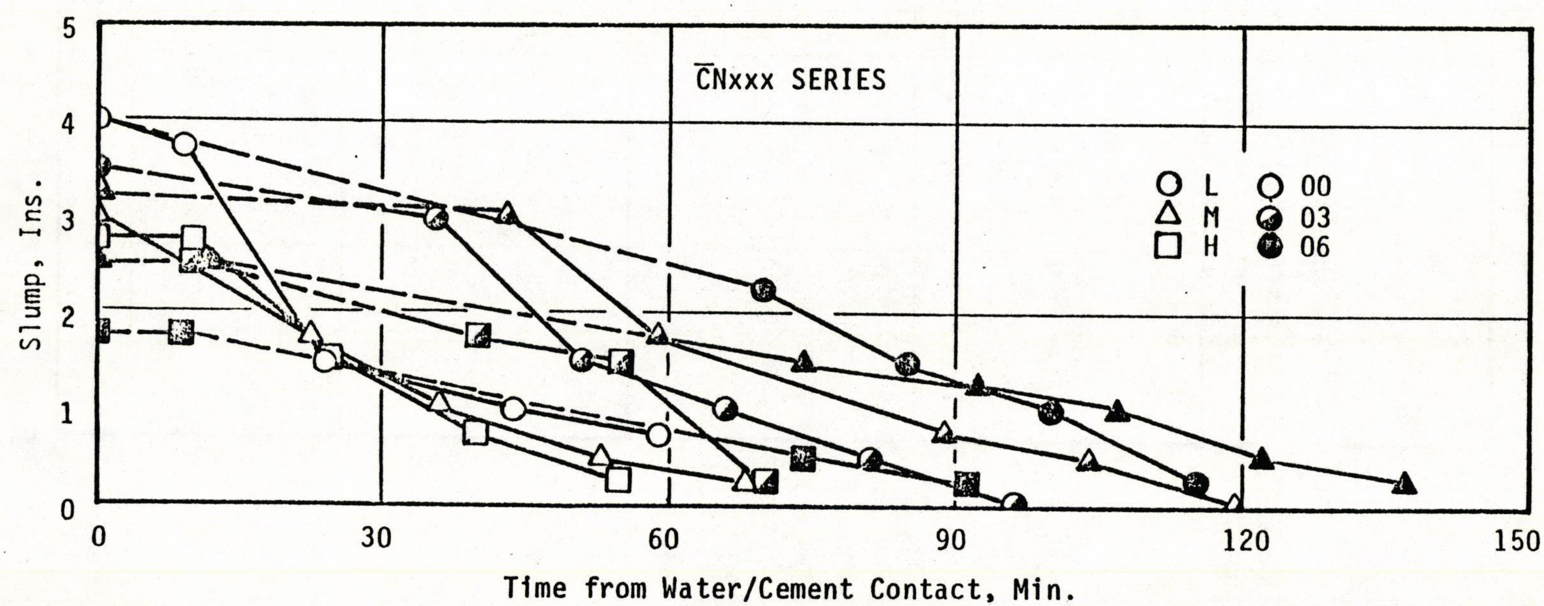


Figure 3.2 SLUMP VS. TIME, $\overline{C}$xxxx SERIES

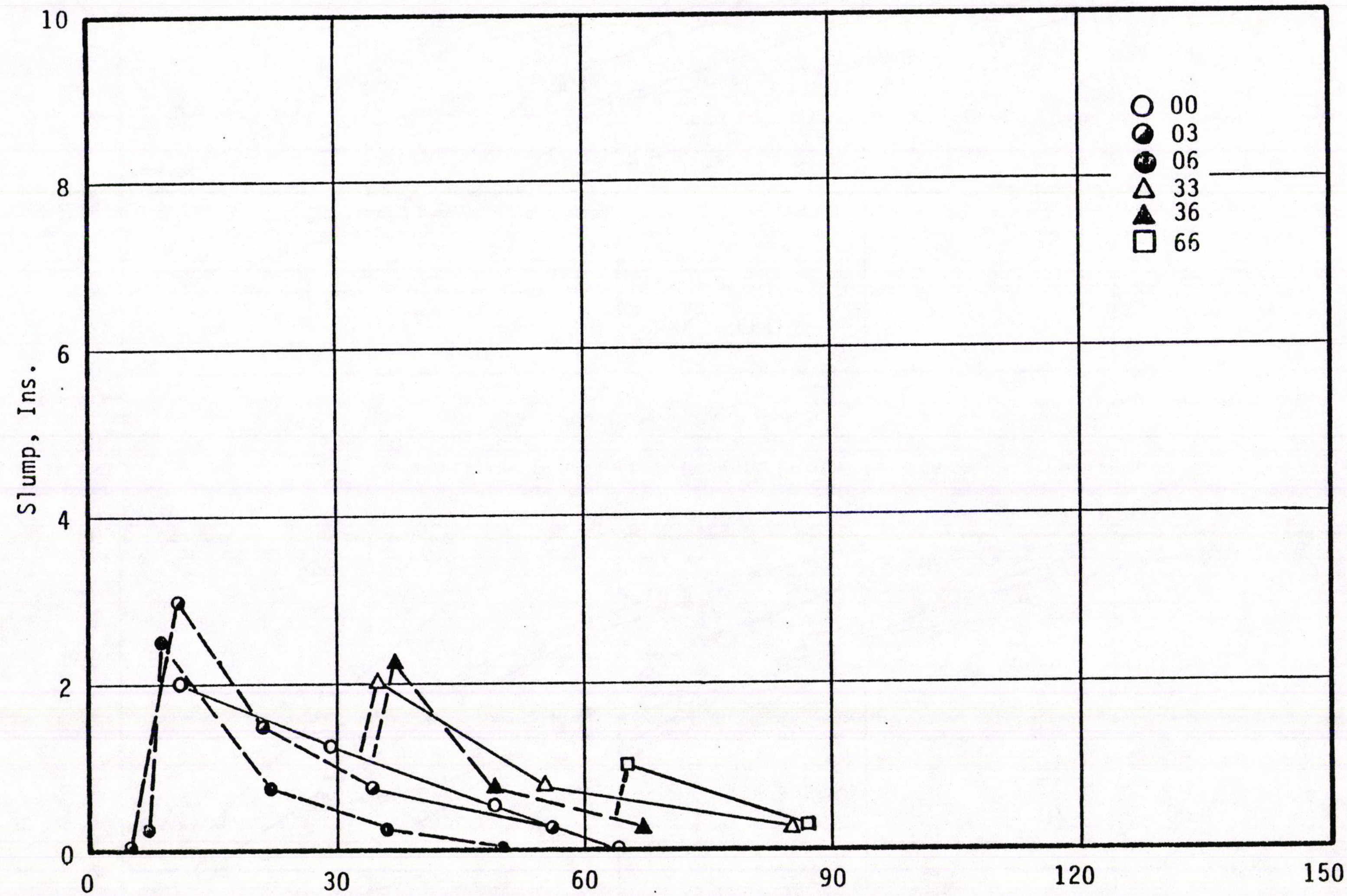


Figure 3.3 SLUMP VS. TIME, 1NLxx SERIES

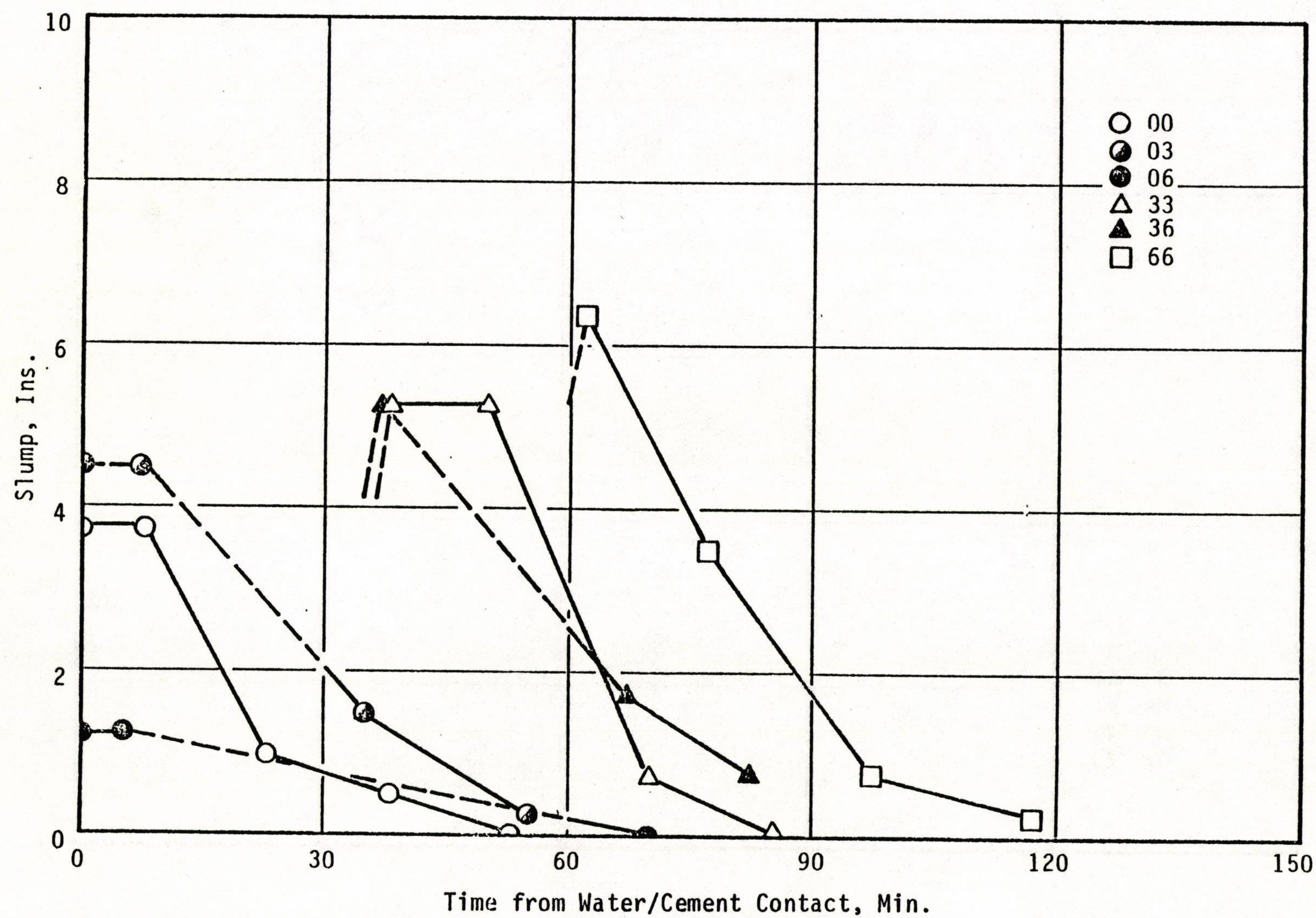


Figure 3.4 SLUMP VS. TIME, 1NMxx SERIES

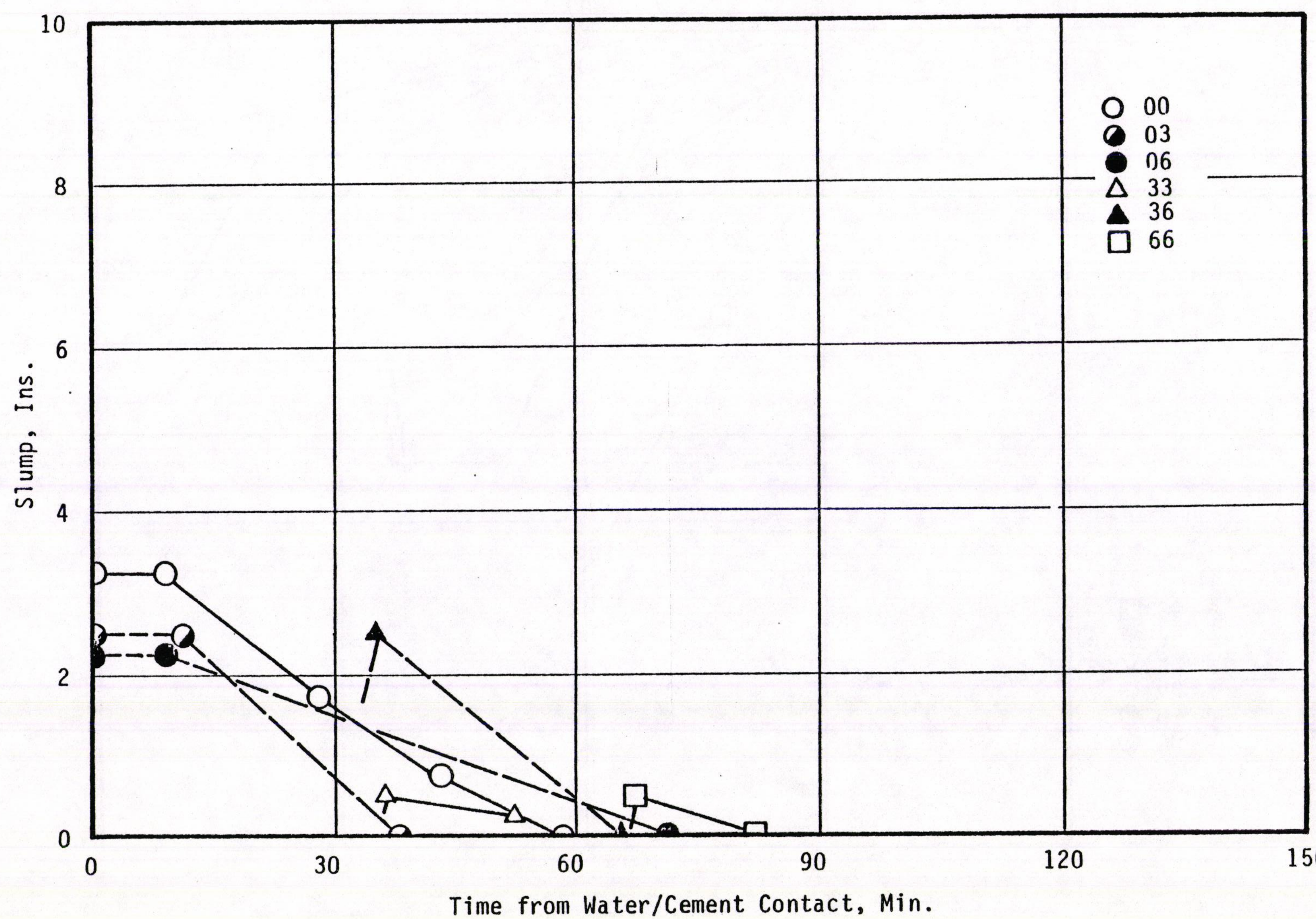


Figure 3.5 SLUMP VS. TIME, 1NHxx SERIES

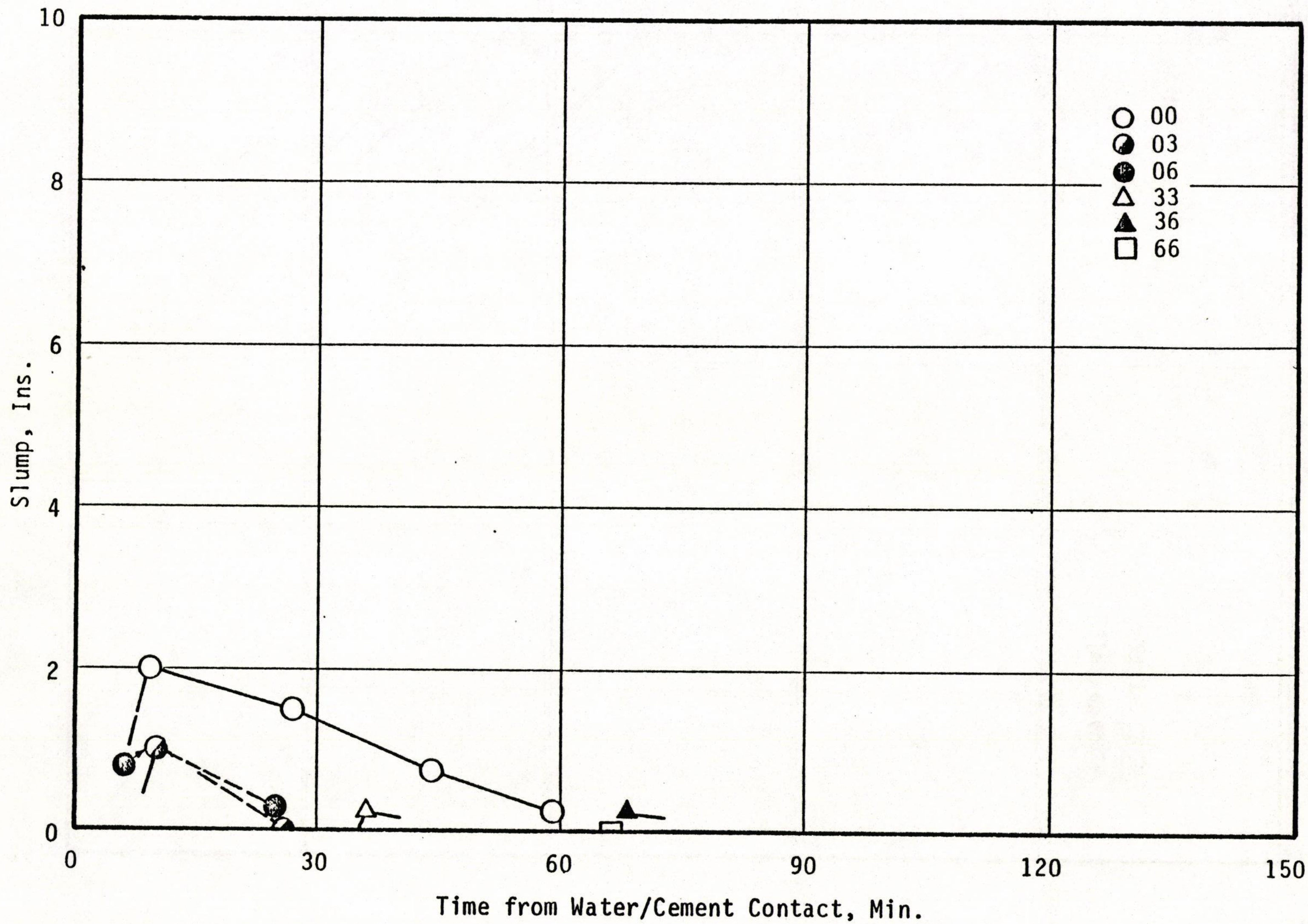


Figure 3.6 SLUMP VS. TIME, 1ALxx SERIES

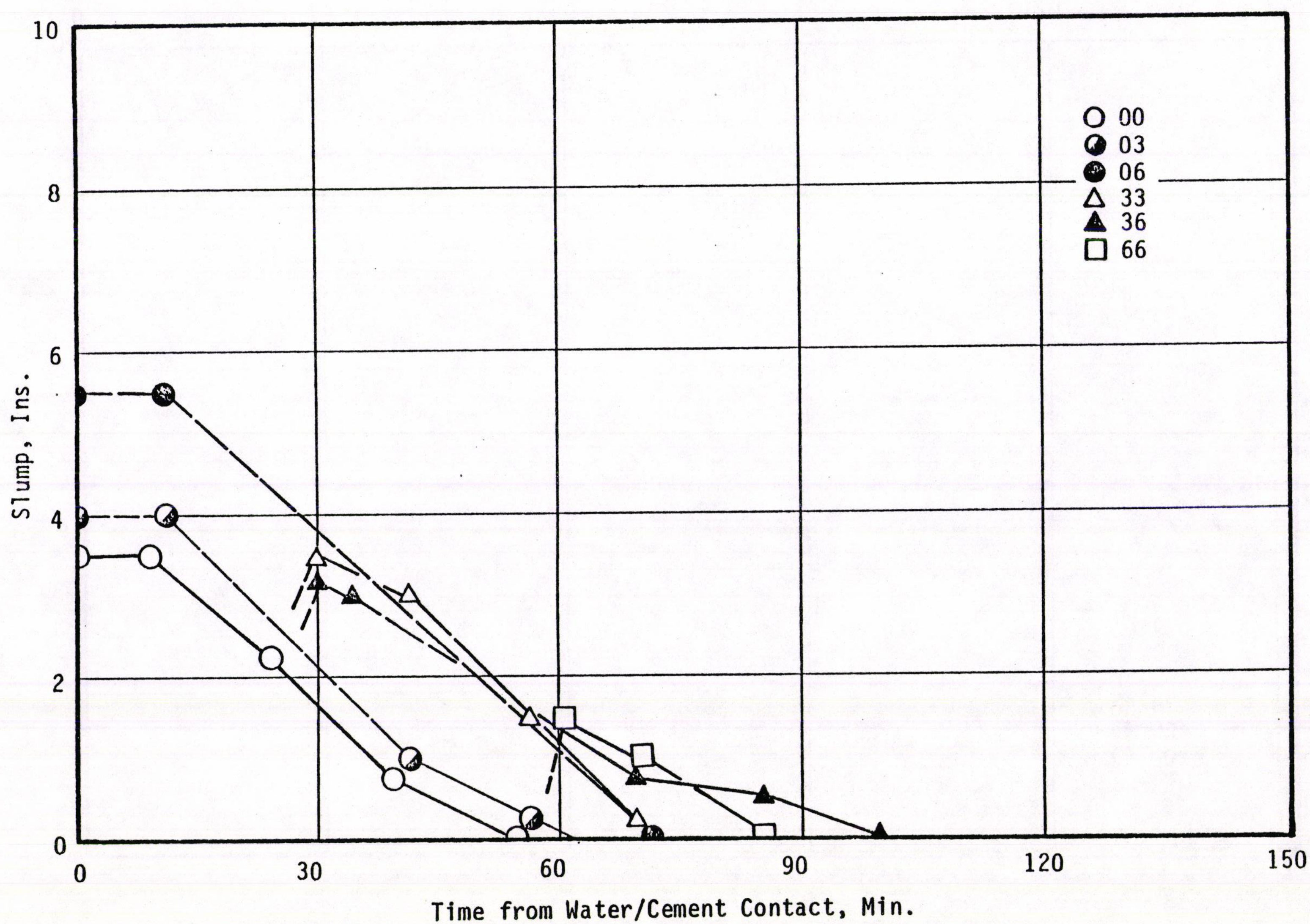


Figure 3.7 SLUMP VS. TIME, 1AMxx SERIES

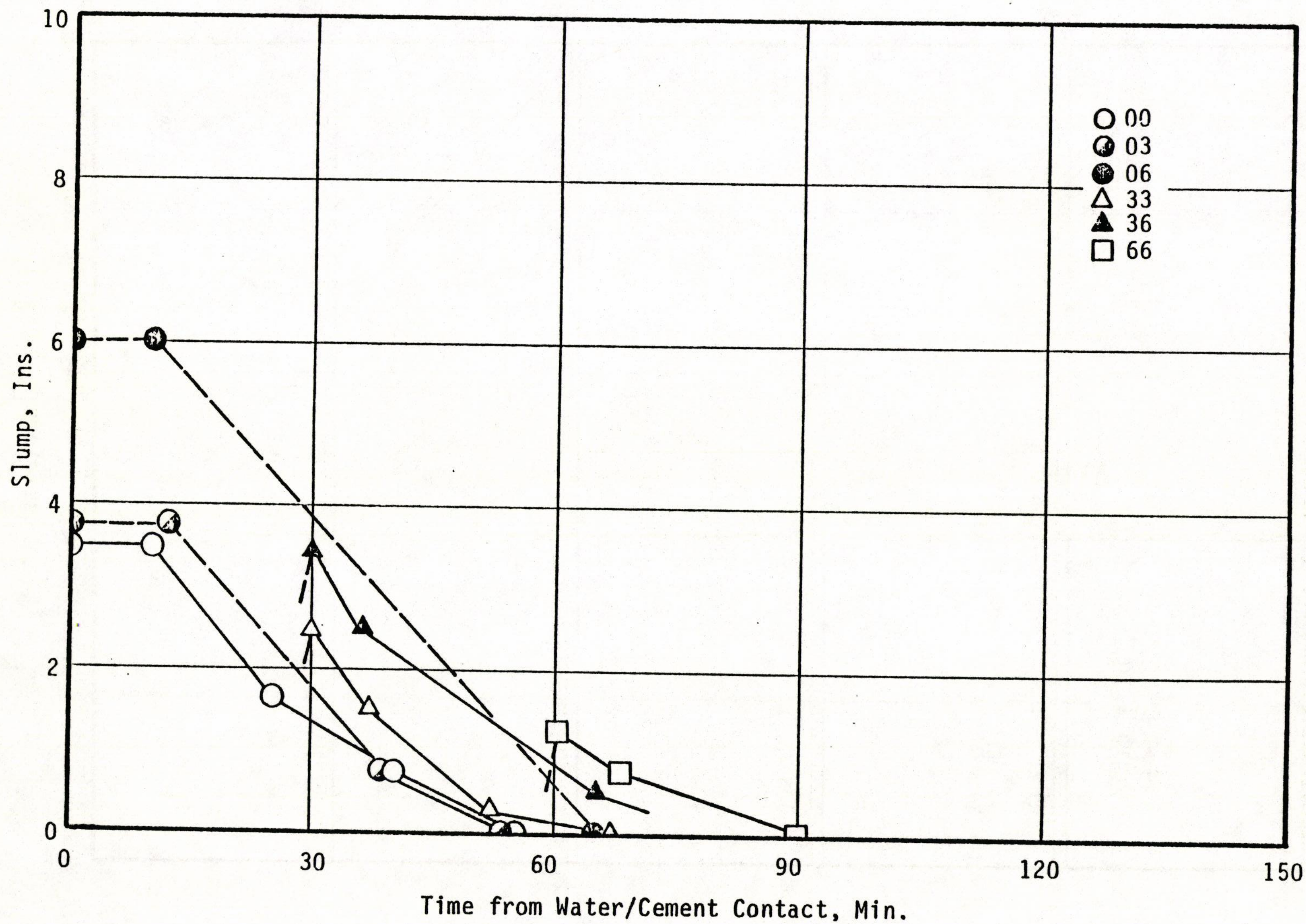


Figure 3.8 SLUMP VS. TIME, 1AHxx SERIES

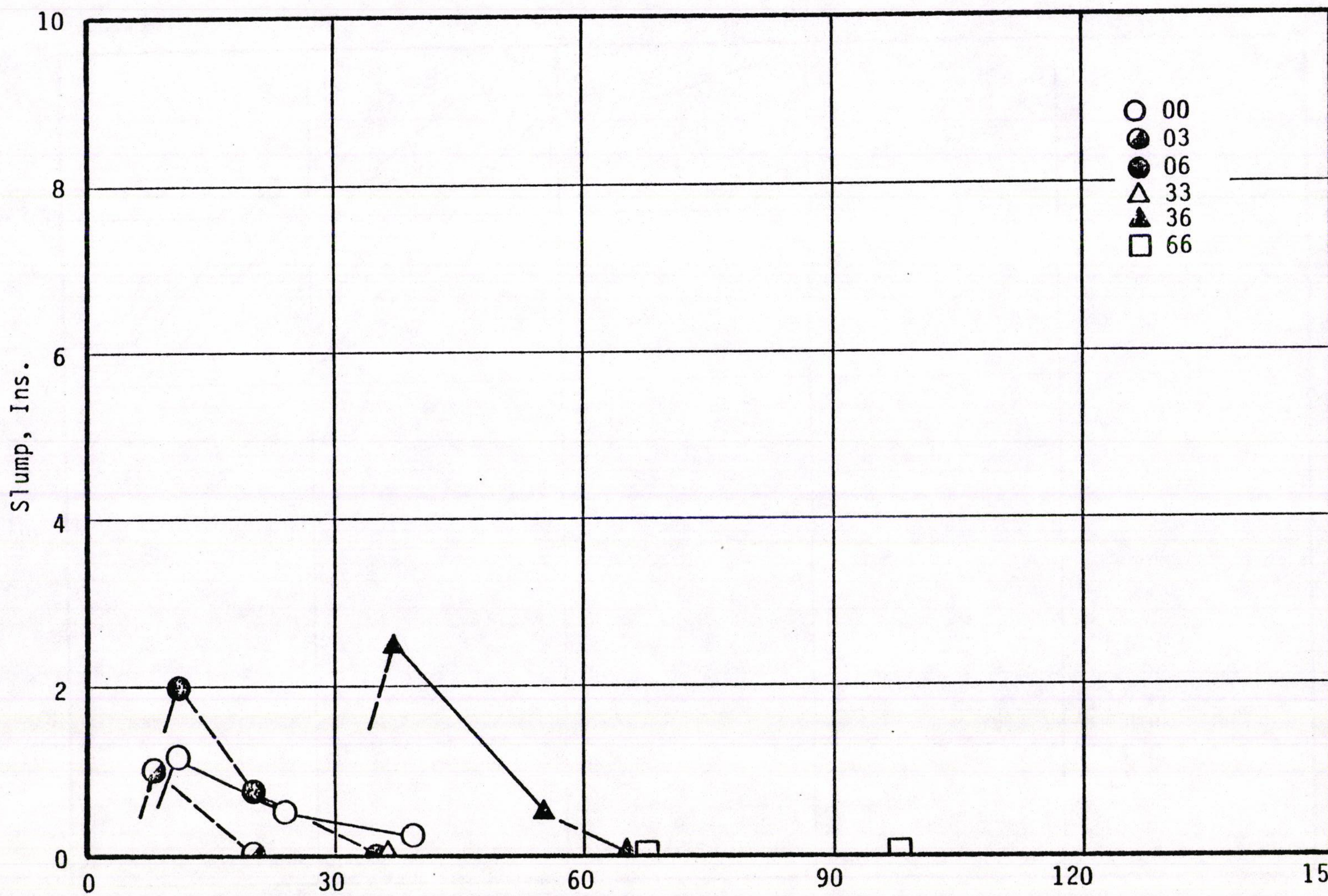


Figure 3.9 SLUMP VS. TIME, 2NLxx SERIES

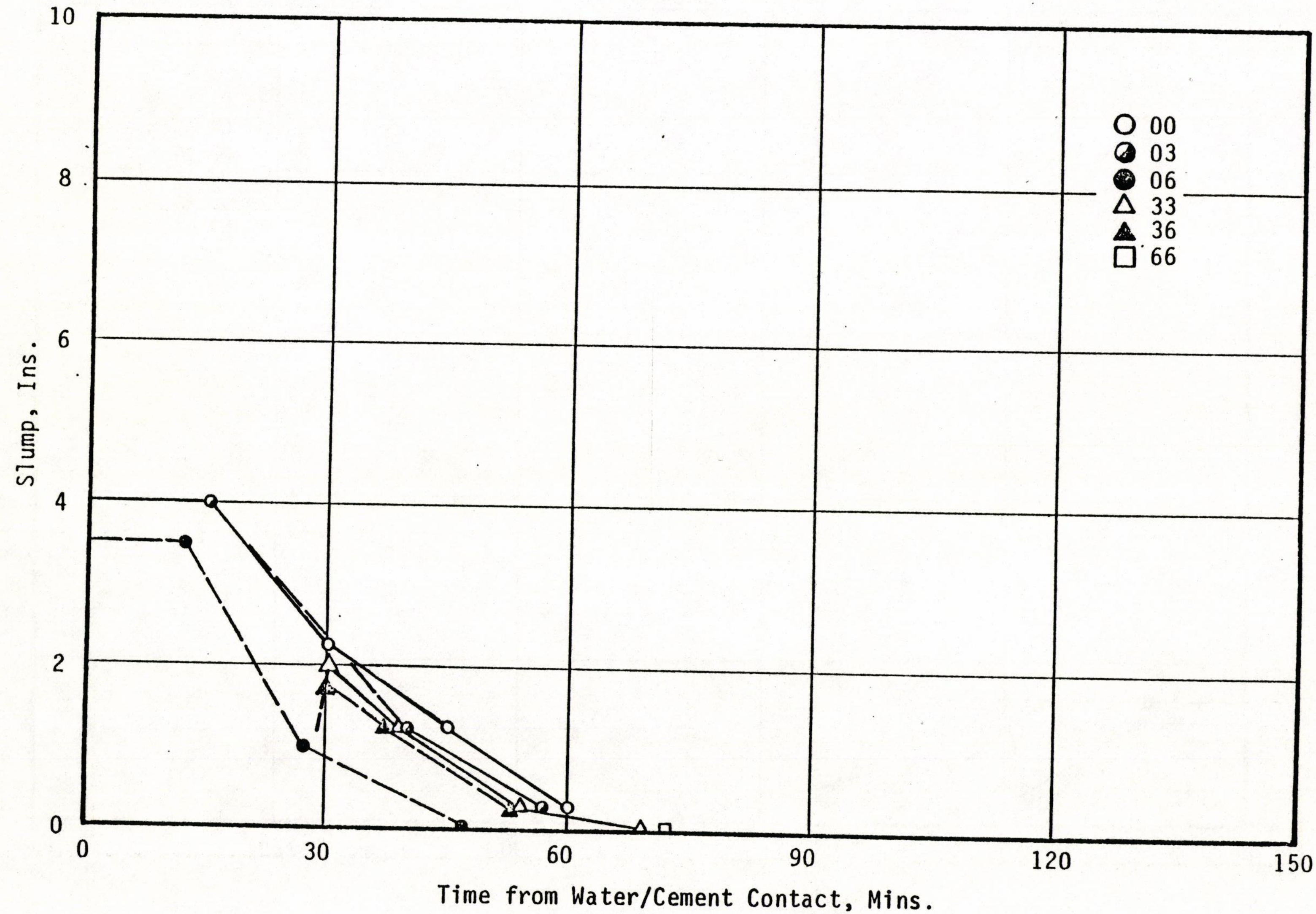


Figure 3.10 SLUMP VS. TIME, 2NMxx SERIES

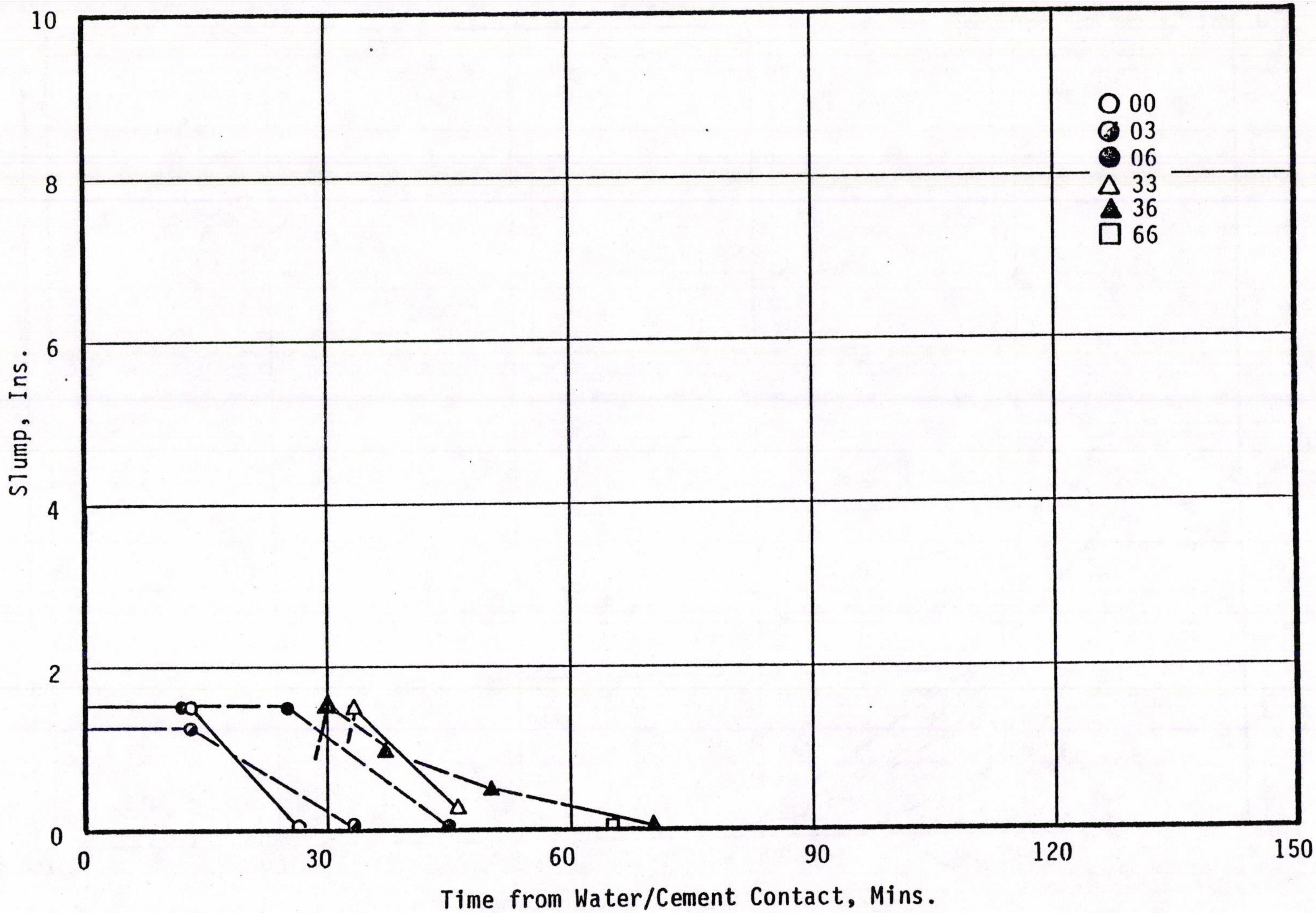


Figure 3.11 SLUMP VS. TIME, 2NHxx SERIES

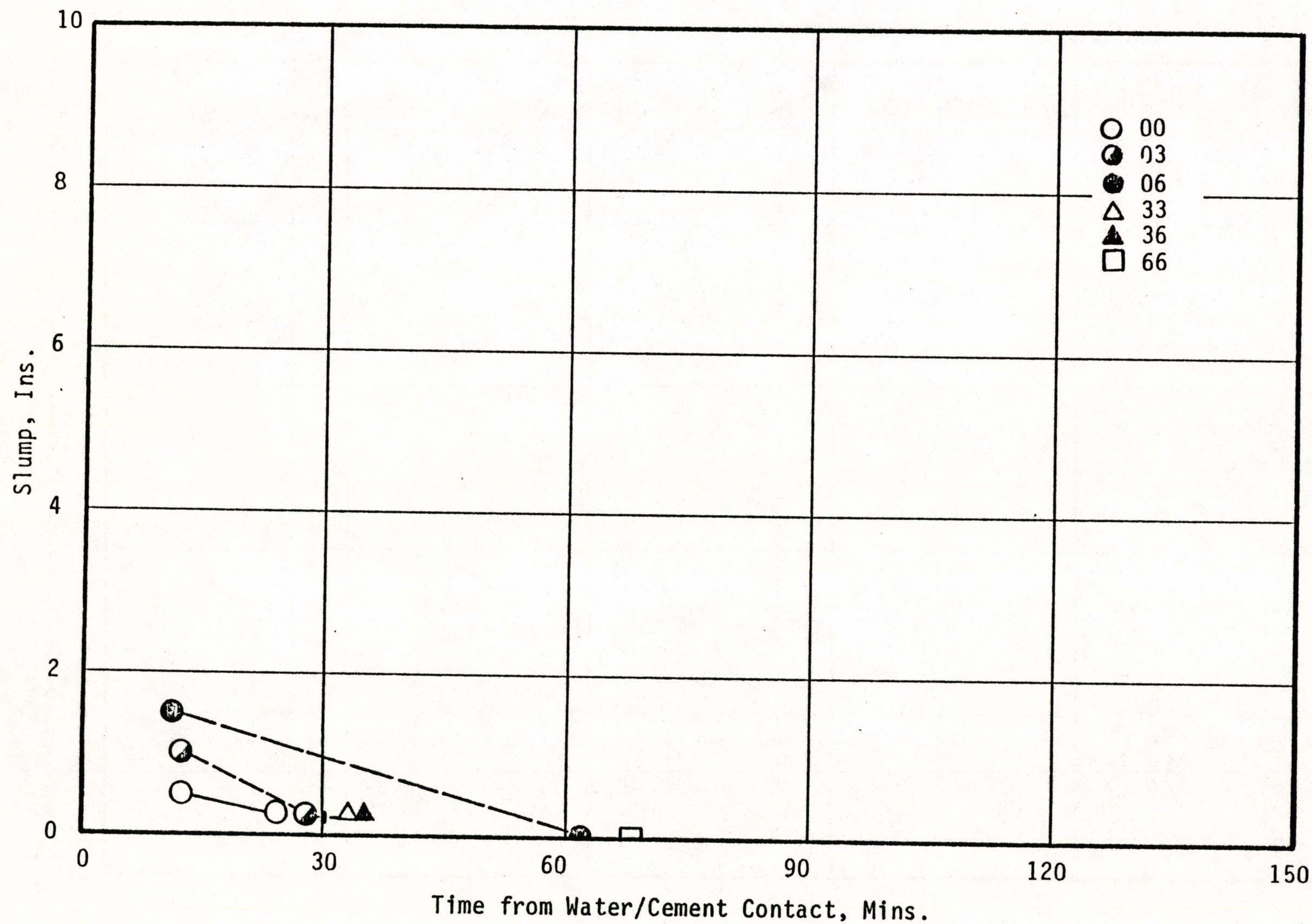


Figure 3.12 SLUMP VS. TIME, 2ALxx SERIES

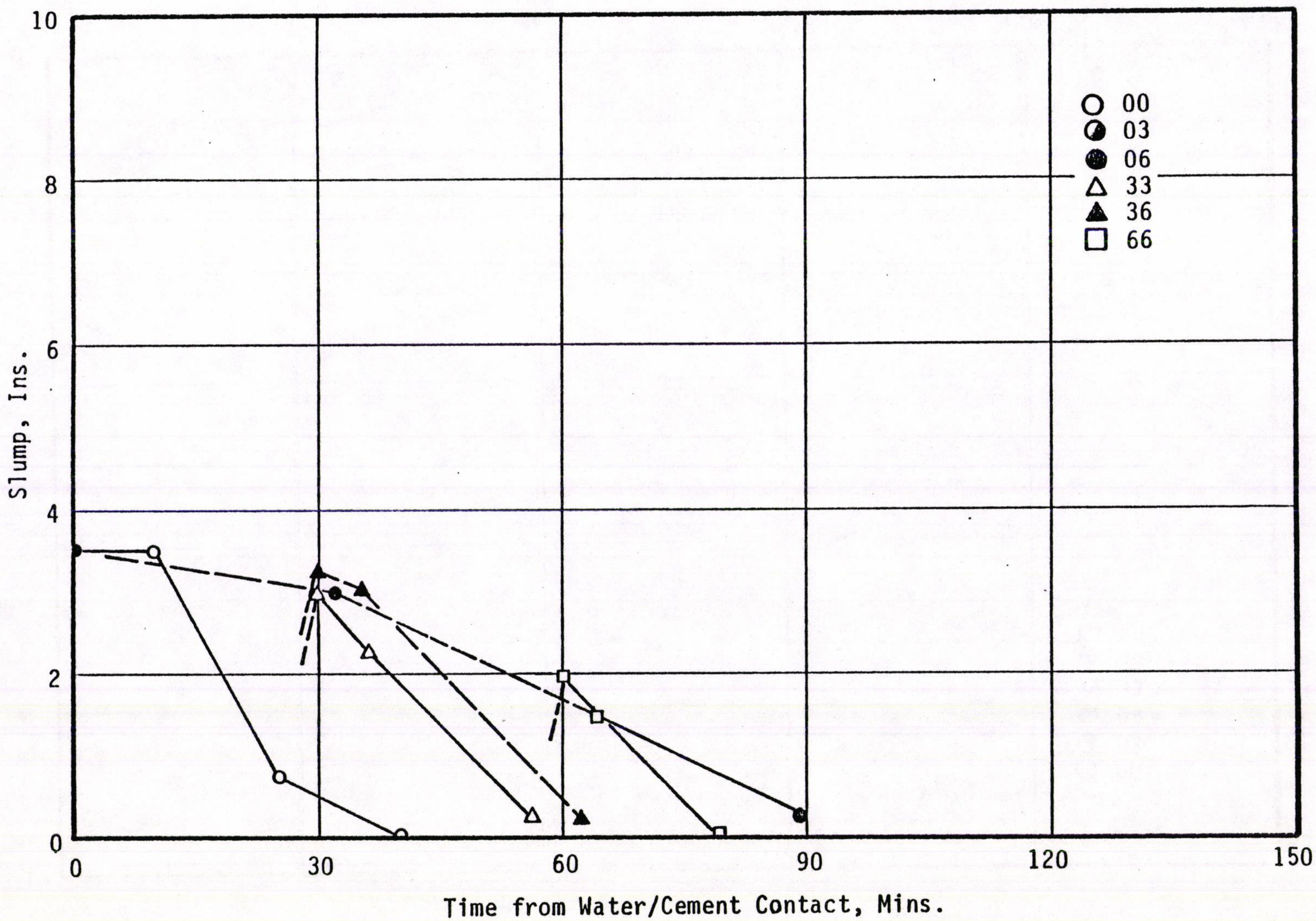


Figure 3.13 SLUMP VS. TIME, 2AMxx SERIES

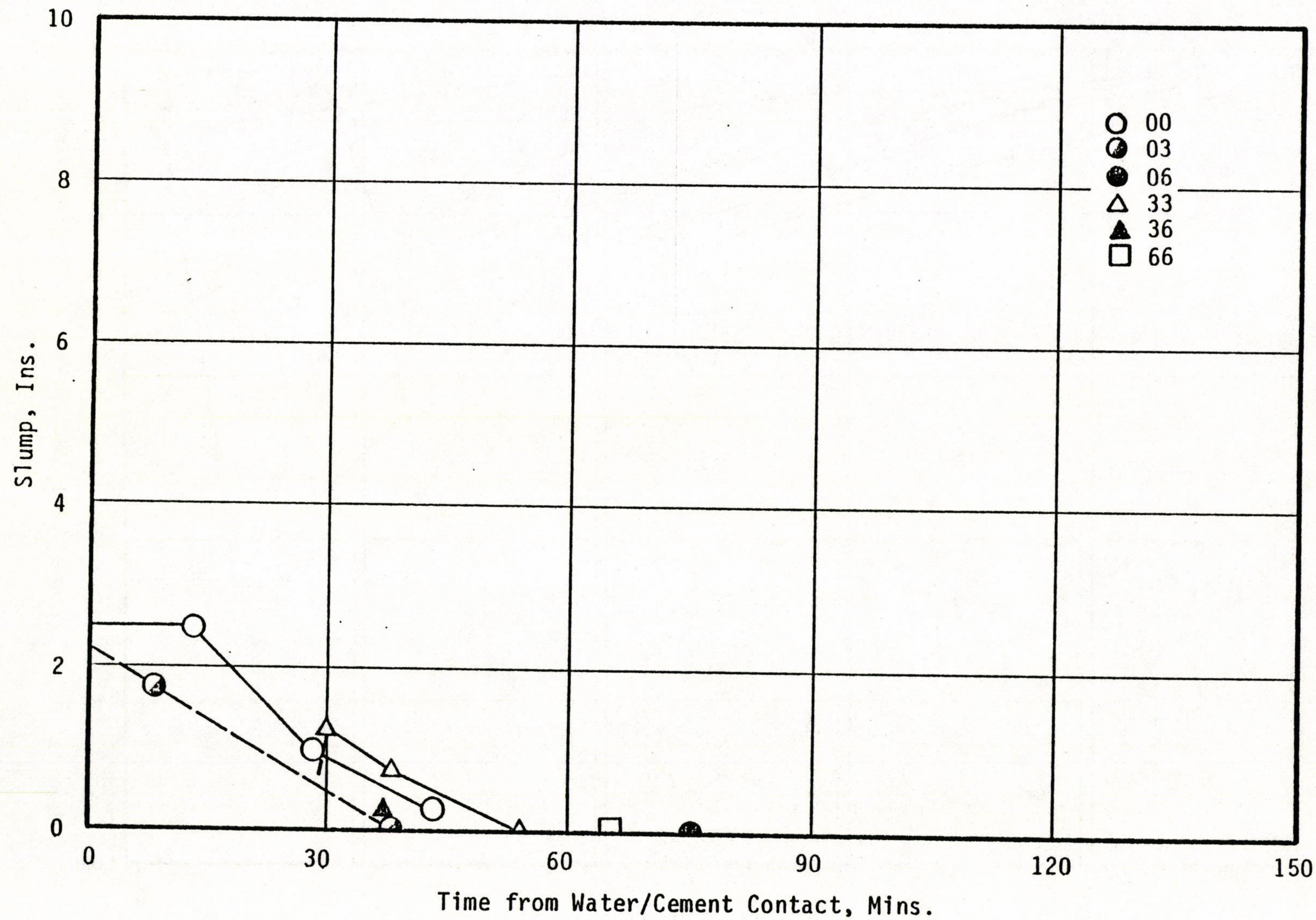


Figure 3.14 SLUMP VS. TIME, 2AHxx SERIES

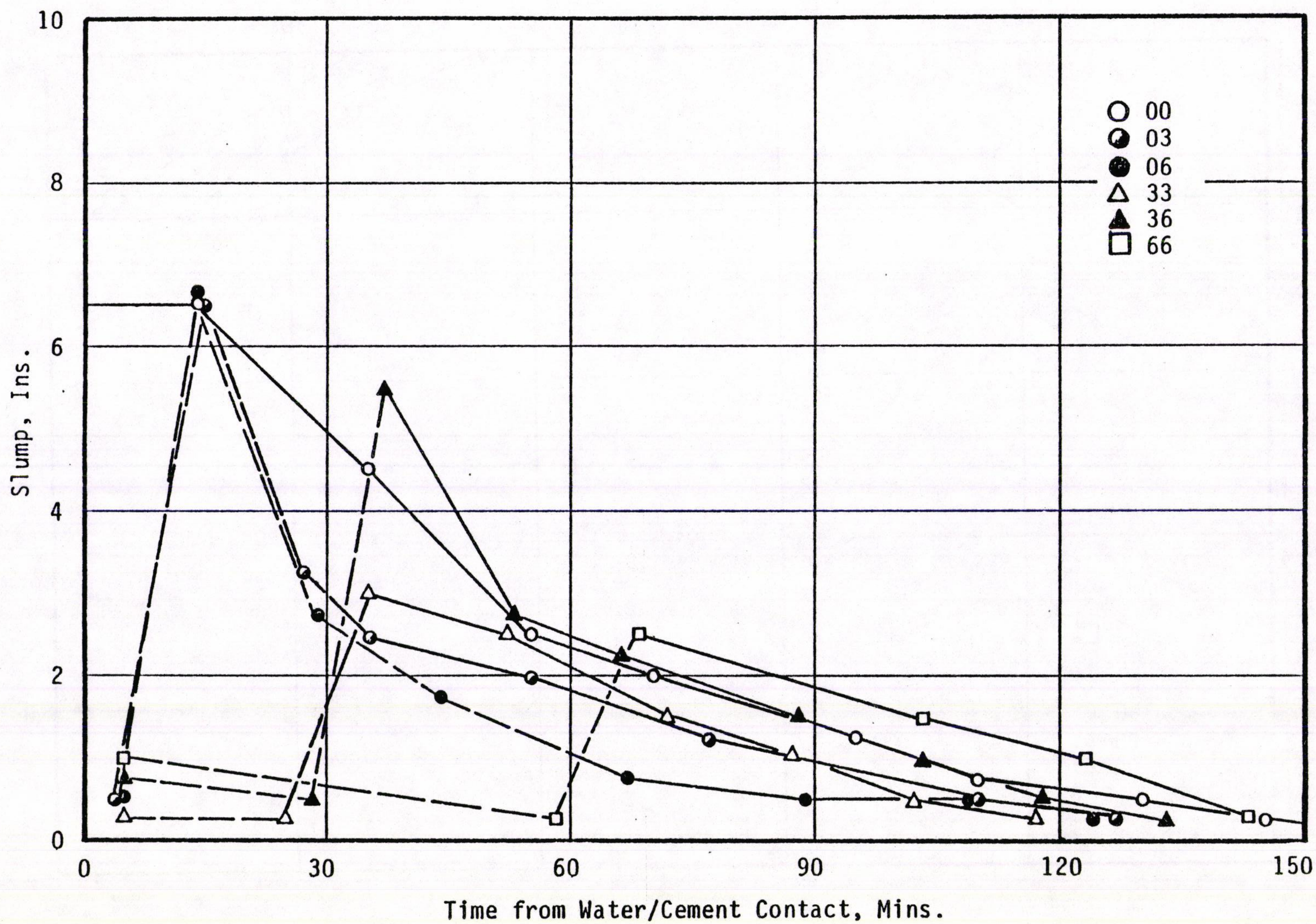


Figure 3.15 SLUMP VS. TIME, FNLxx SERIES

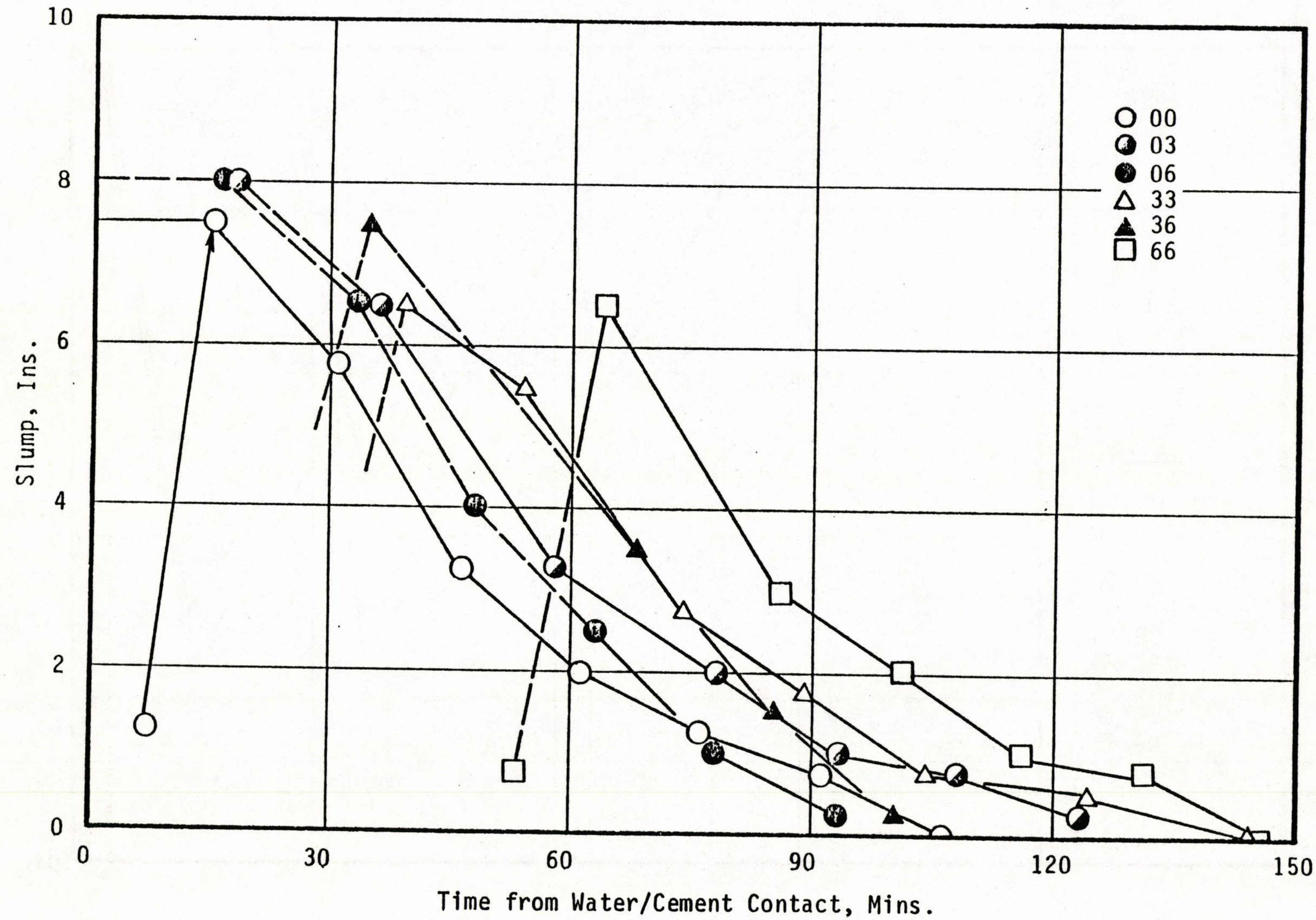


Figure 3.16 SLUMP VS. TIME, FNMxx SERIES

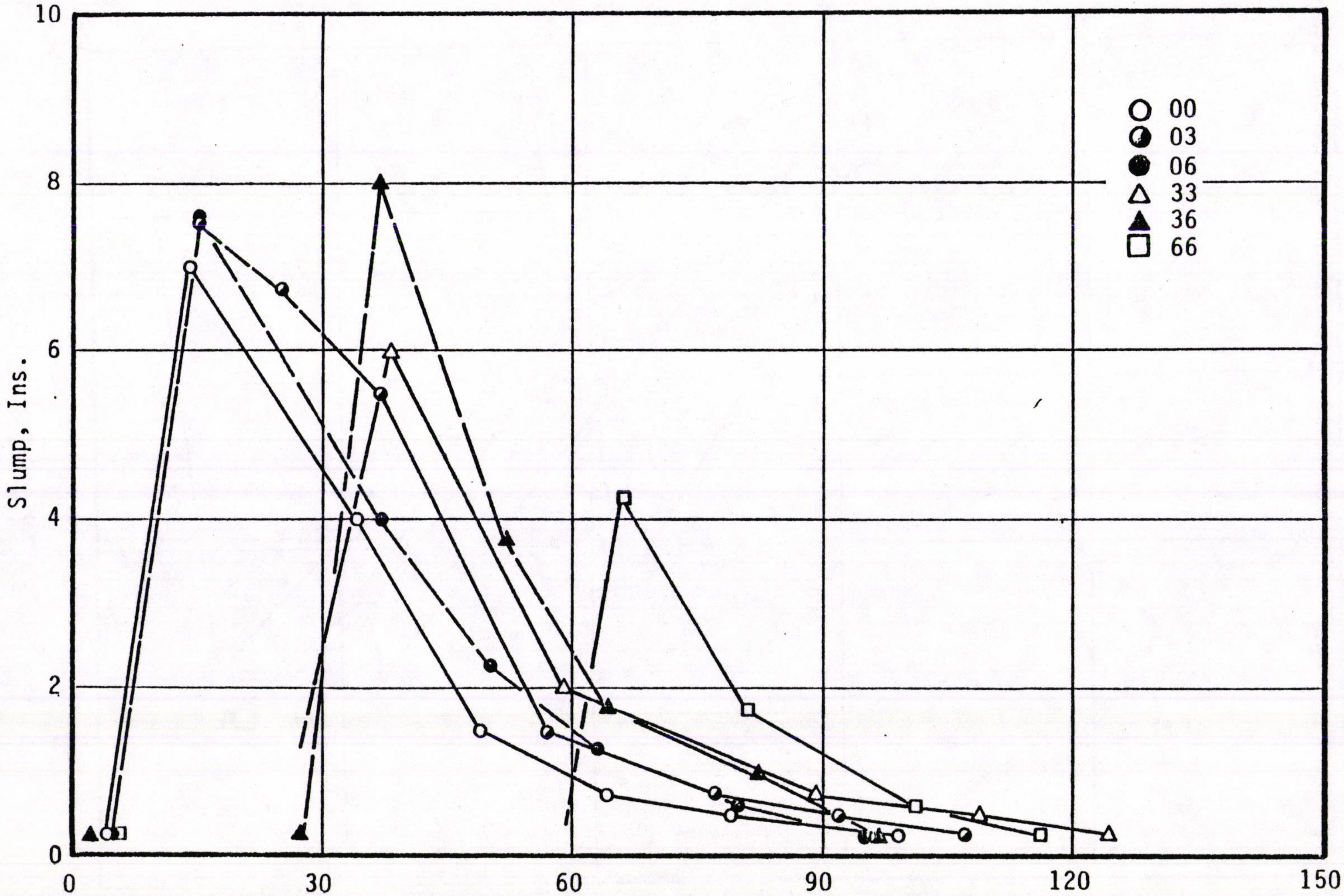


Figure 3.17 SLUMP VS. TIME, FNHxx SERIES

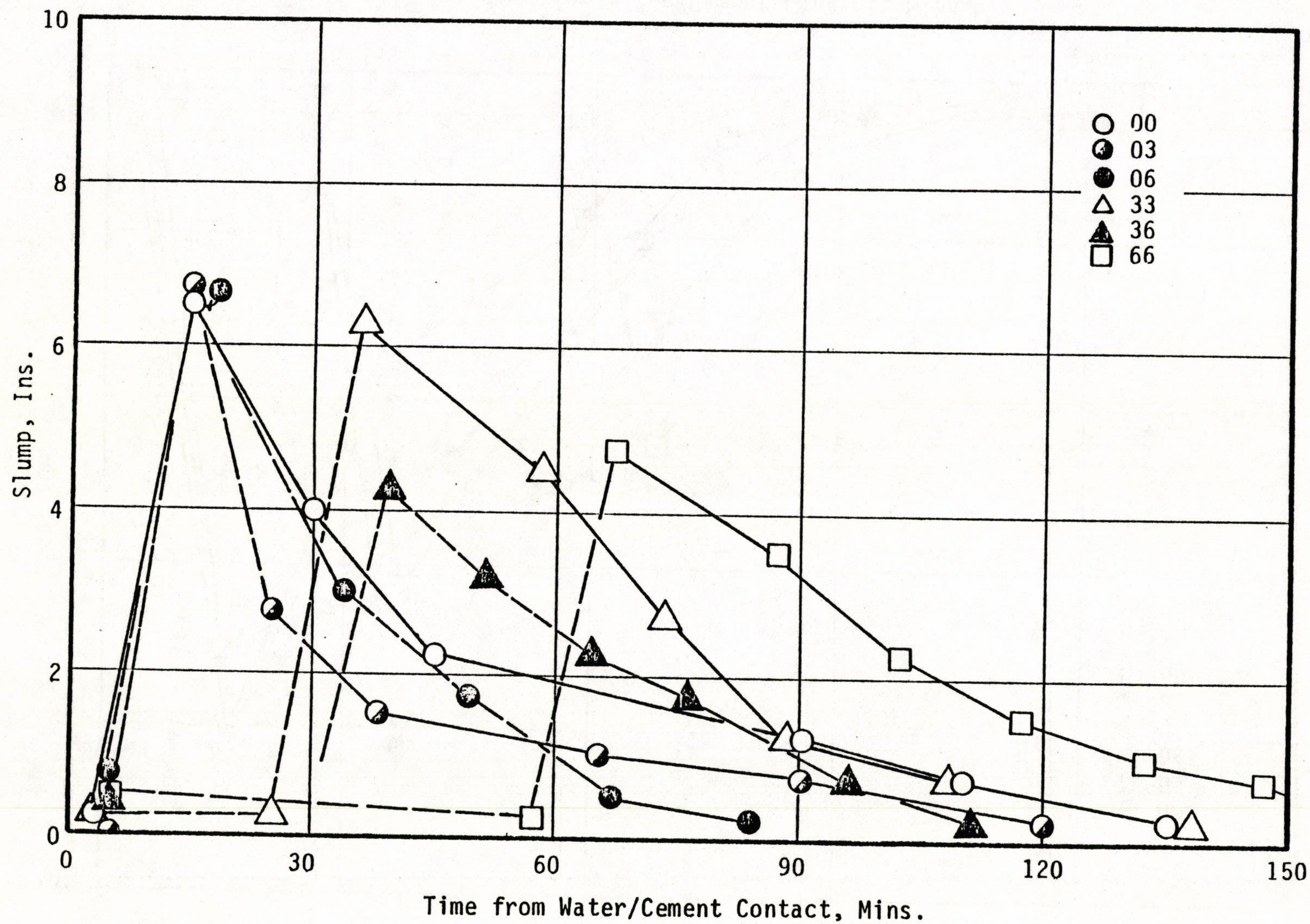


Figure 3.18 SLUMP VS. TIME, FALxx SERIES

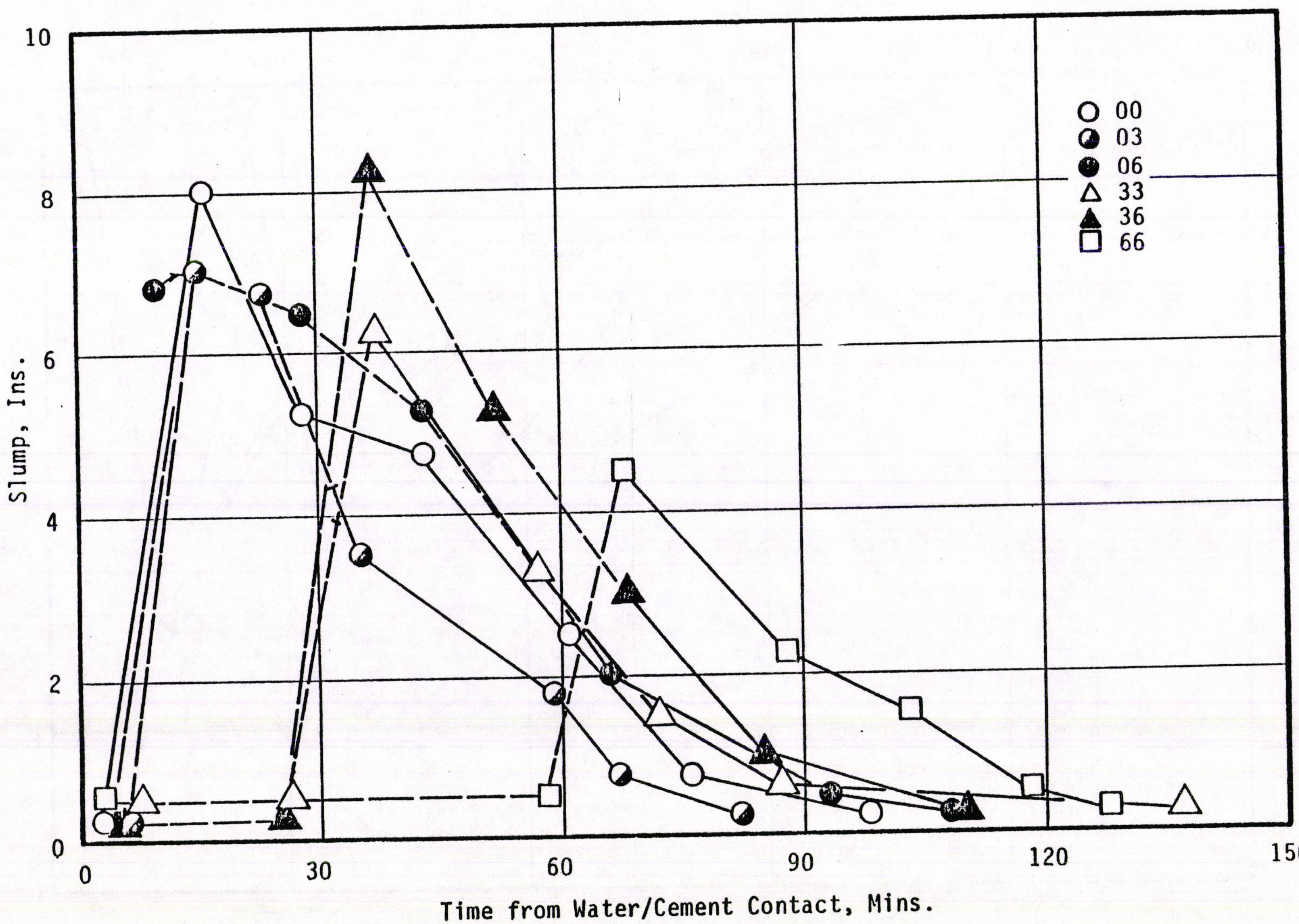


Figure 3.19 SLUMP VS. TIME, FAMxx SERIES

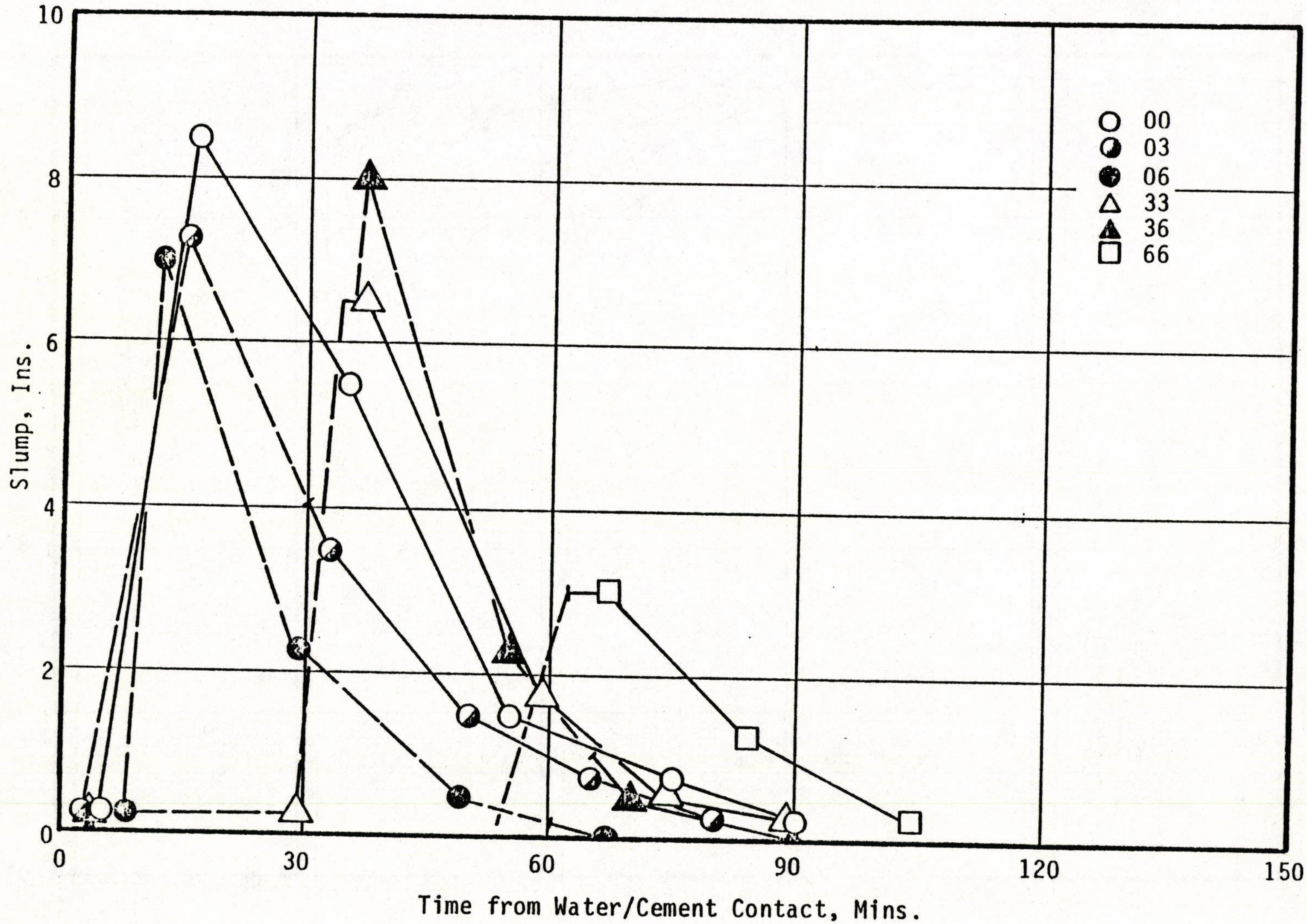


Figure 3.20 SLUMP VS. TIME, FAHxx SERIES

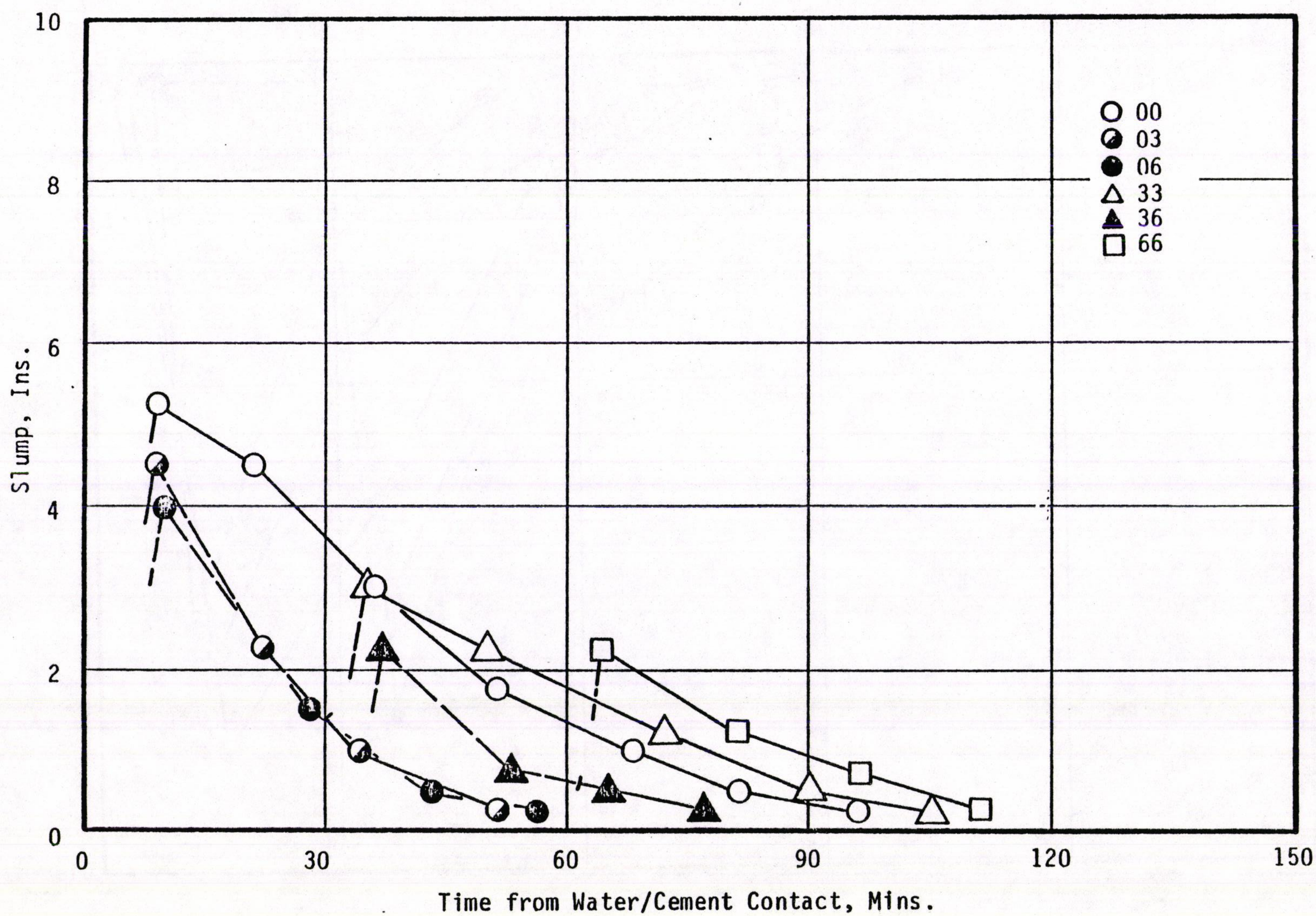


Figure 3.21 SLUMP VS. TIME, 1AM'xx SERIES

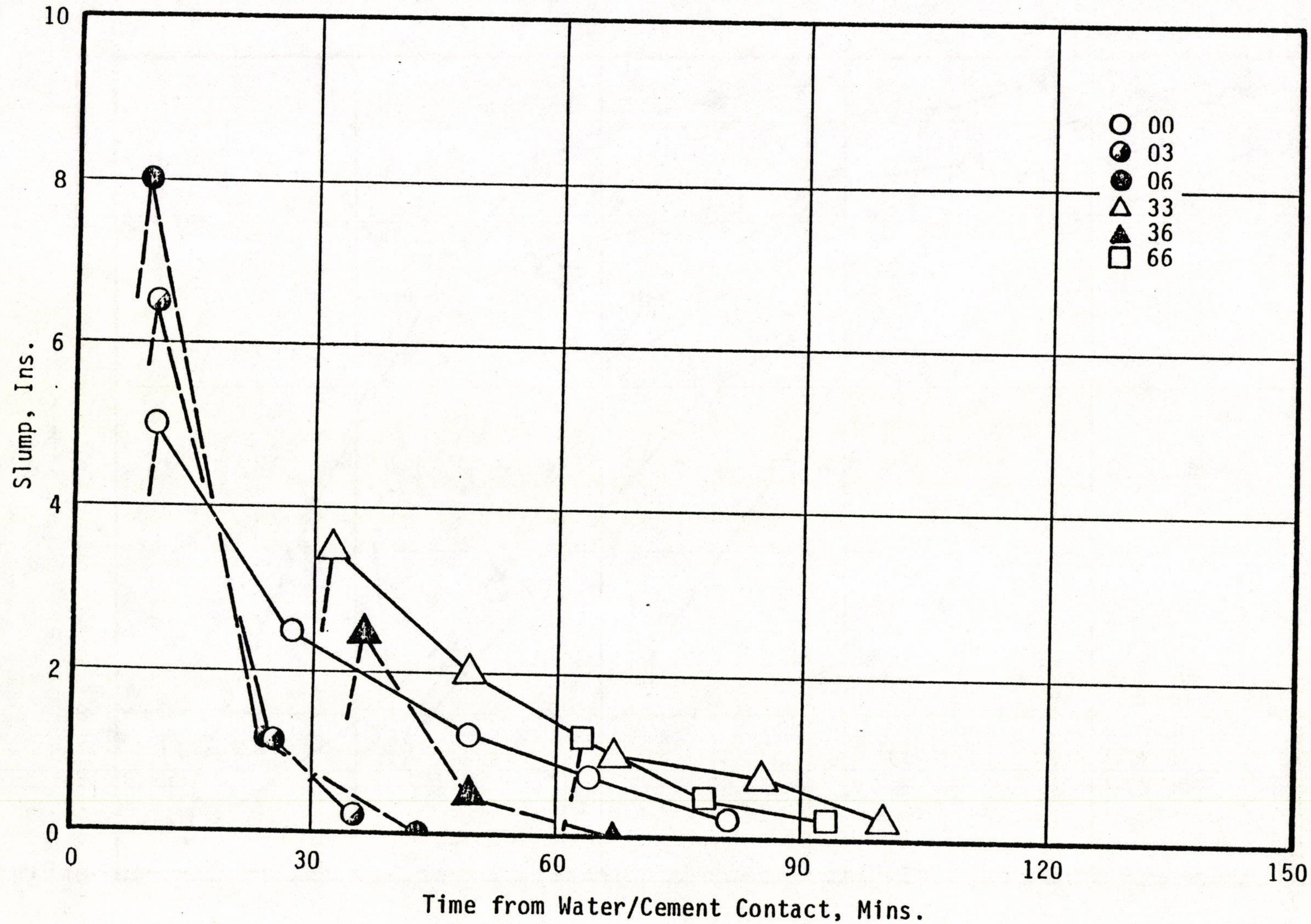


Figure 3.22 SLUMP VS. TIME, 2AM′xx SERIES

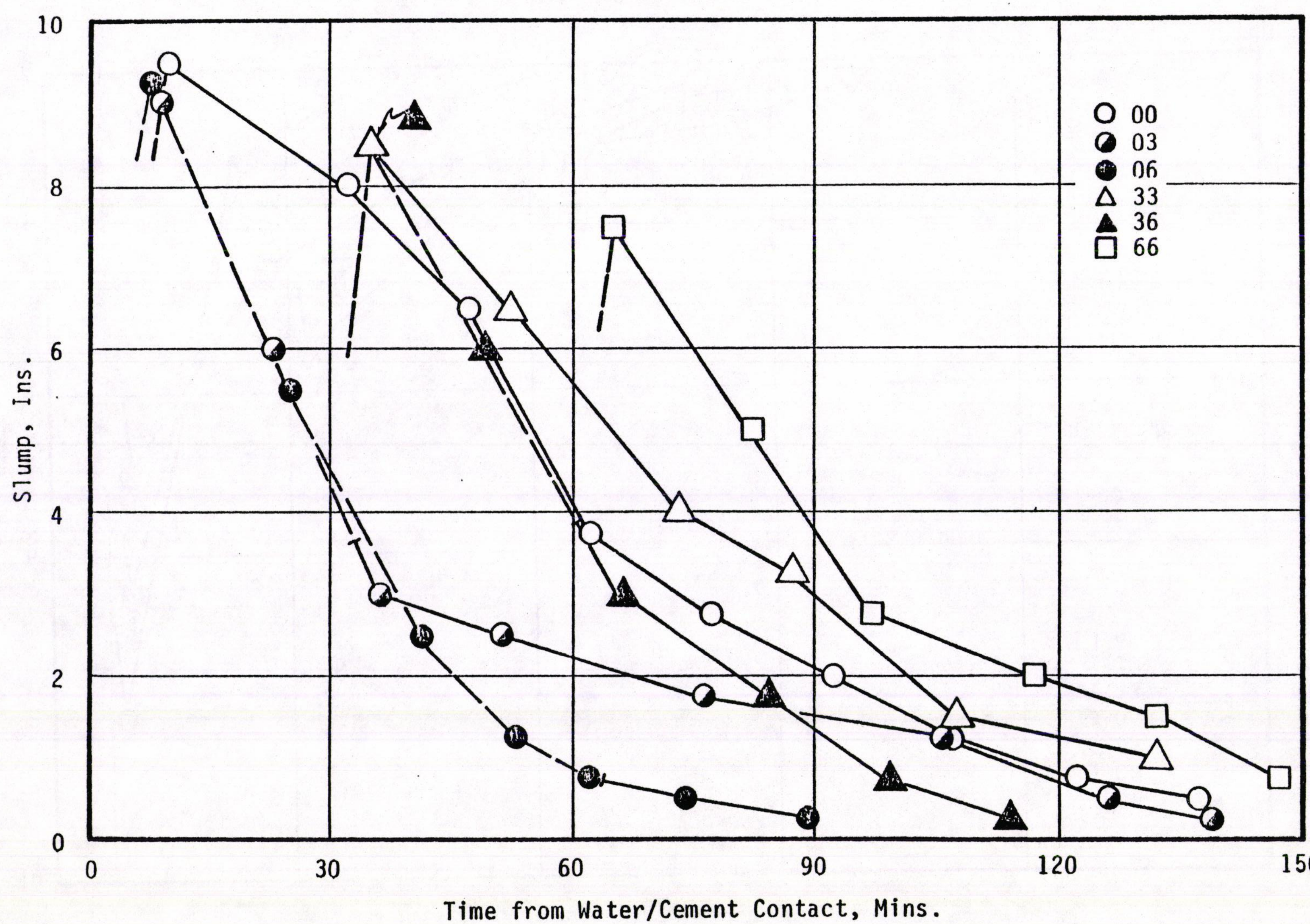


Figure 3.23 SLUMP VS. TIME, FAM′xx SERIES

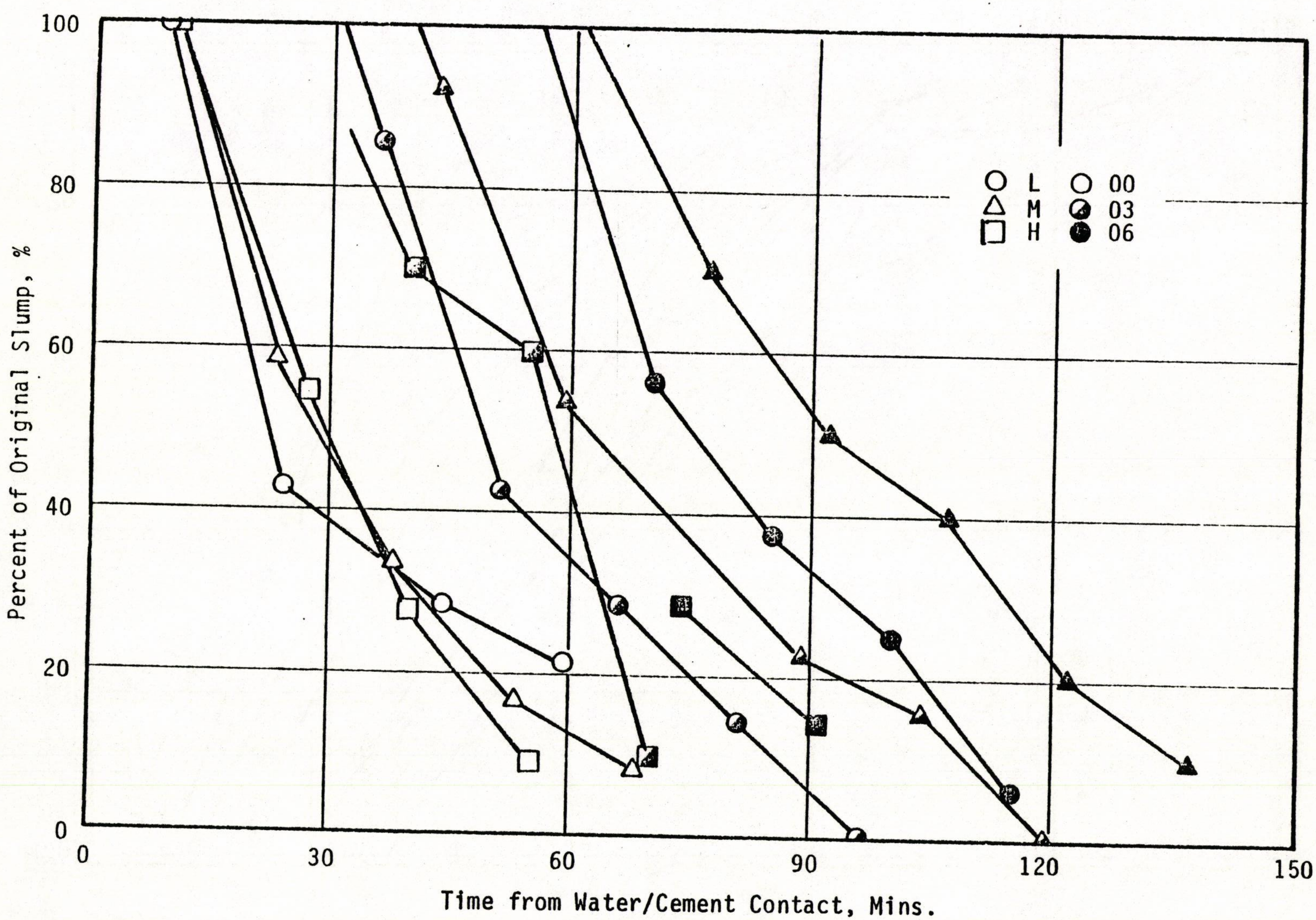


Figure 3.24 PERCENT OF ORIGINAL SLUMP VS. TIME, $\overline{C}$Nxxx SERIES

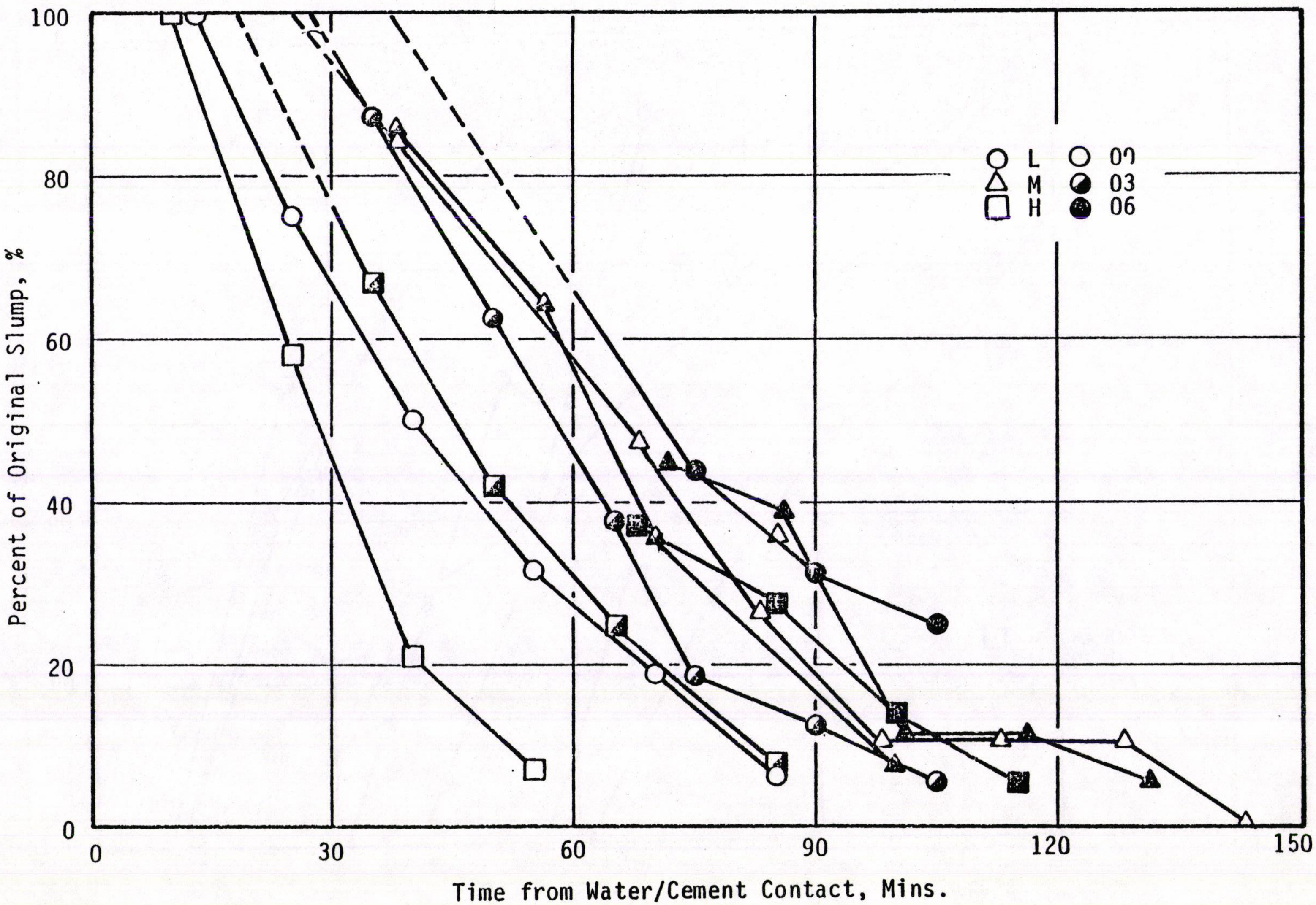


Figure 3.25 PERCENT OF ORIGINAL SLUMP VS. TIME, $\overline{C}$Axxx SERIES

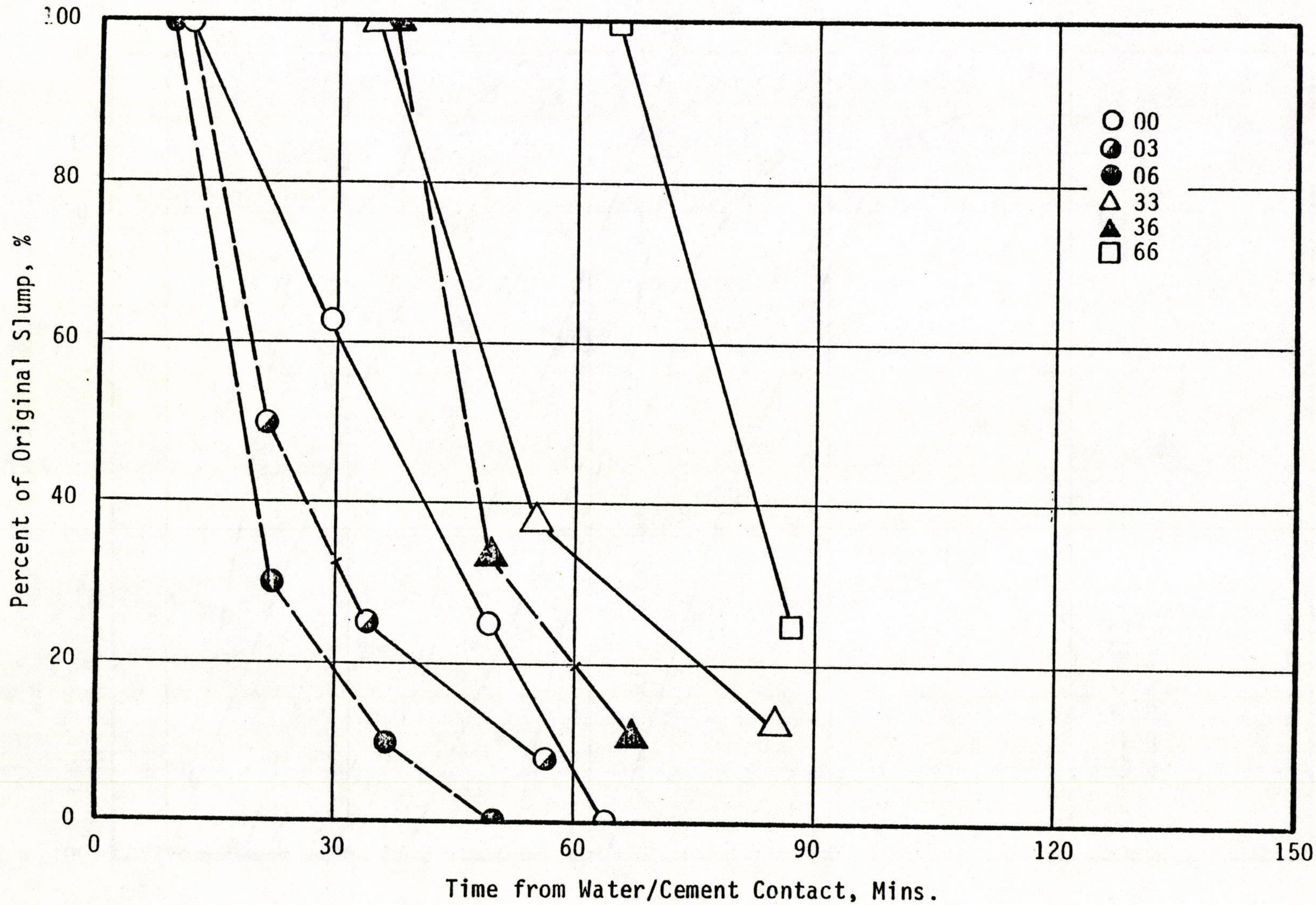


Figure 3.26 PERCENT OF ORIGINAL SLUMP VS. TIME, 1NLxx SERIES

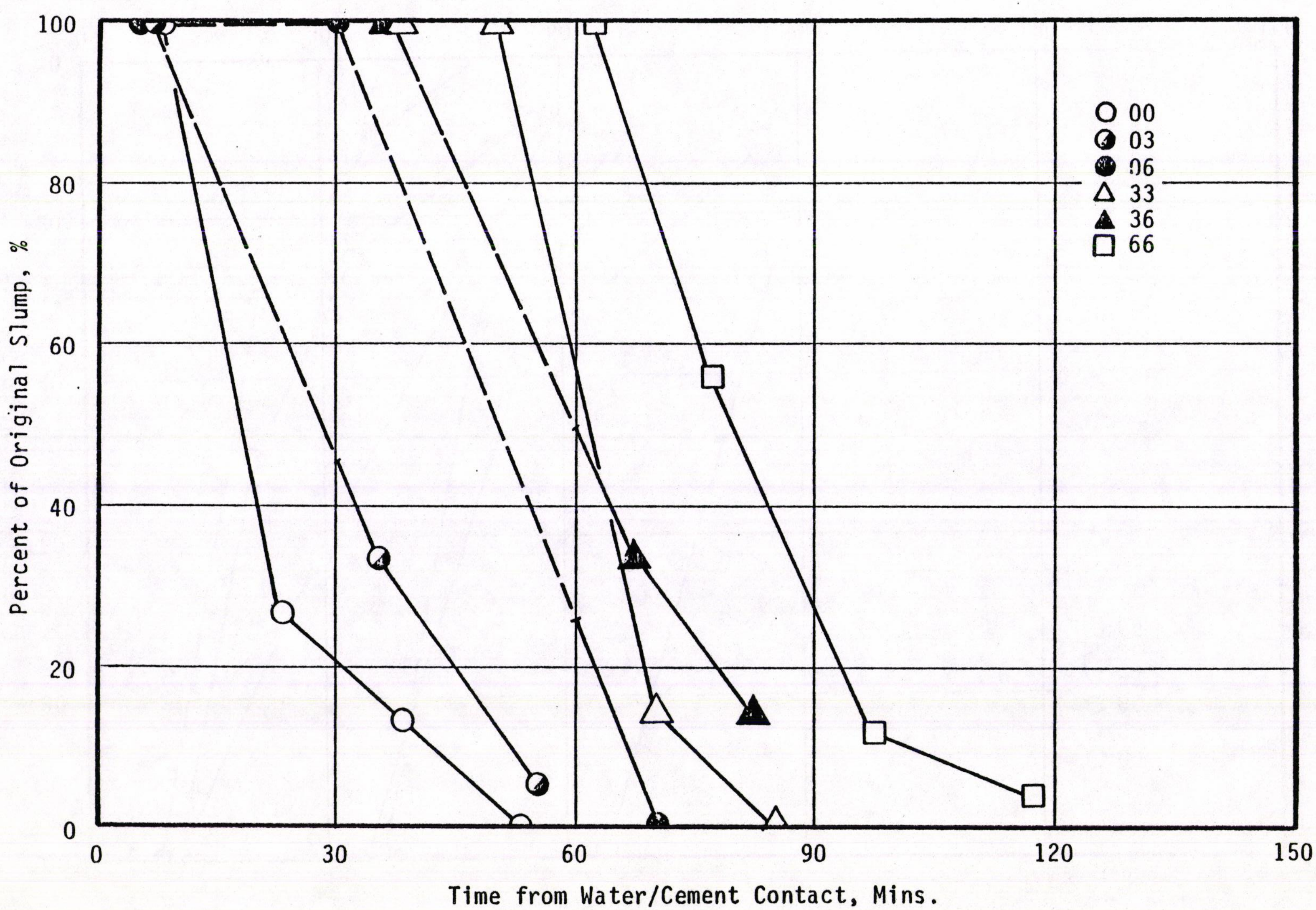


Figure 3.27 PERCENT OF ORIGINAL SLUMP VS. TIME, 1NMxx SERIES

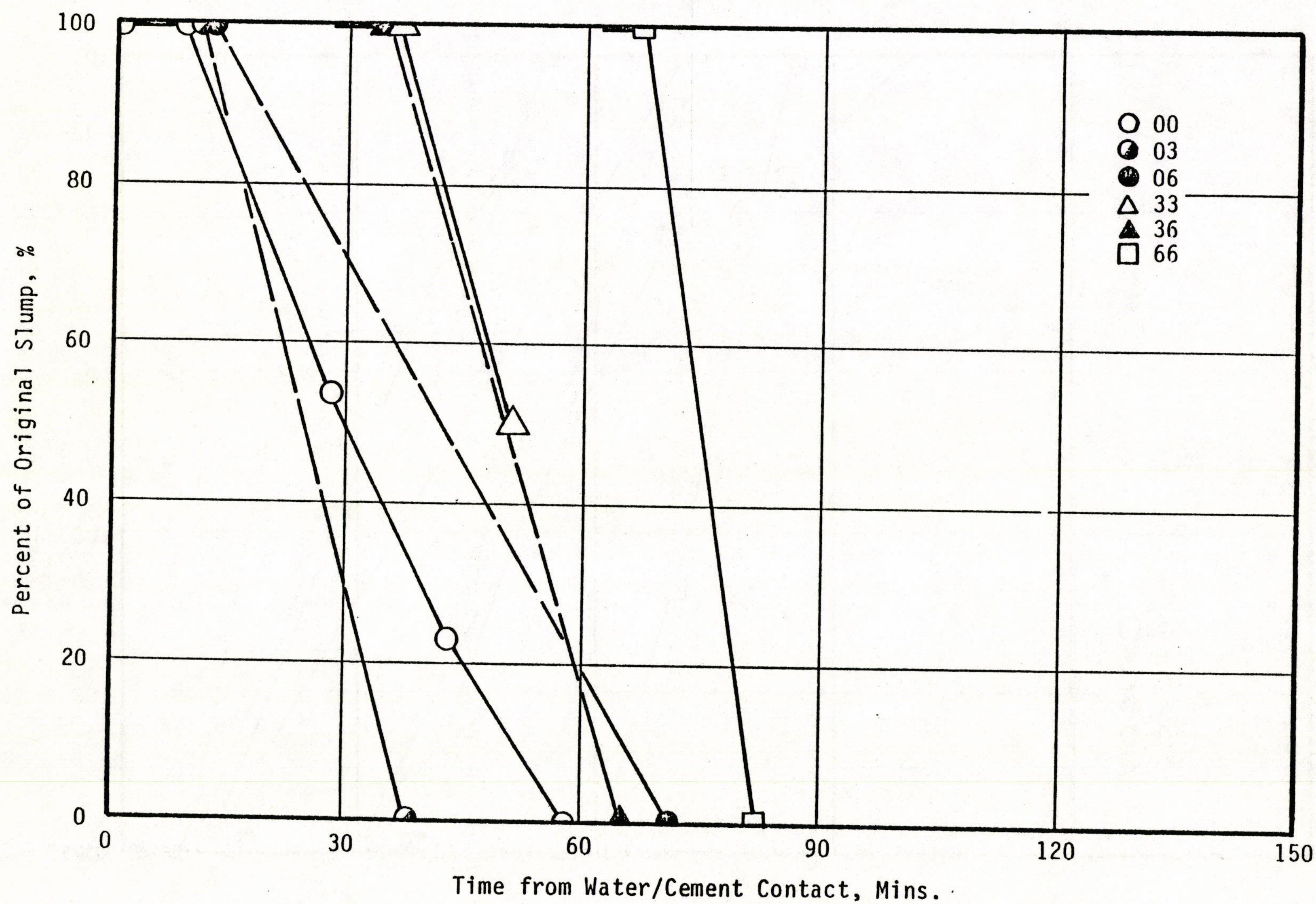


Figure 3.28 PERCENT OF ORIGINAL SLUMP VS. TIME, 1NHxx SERIES

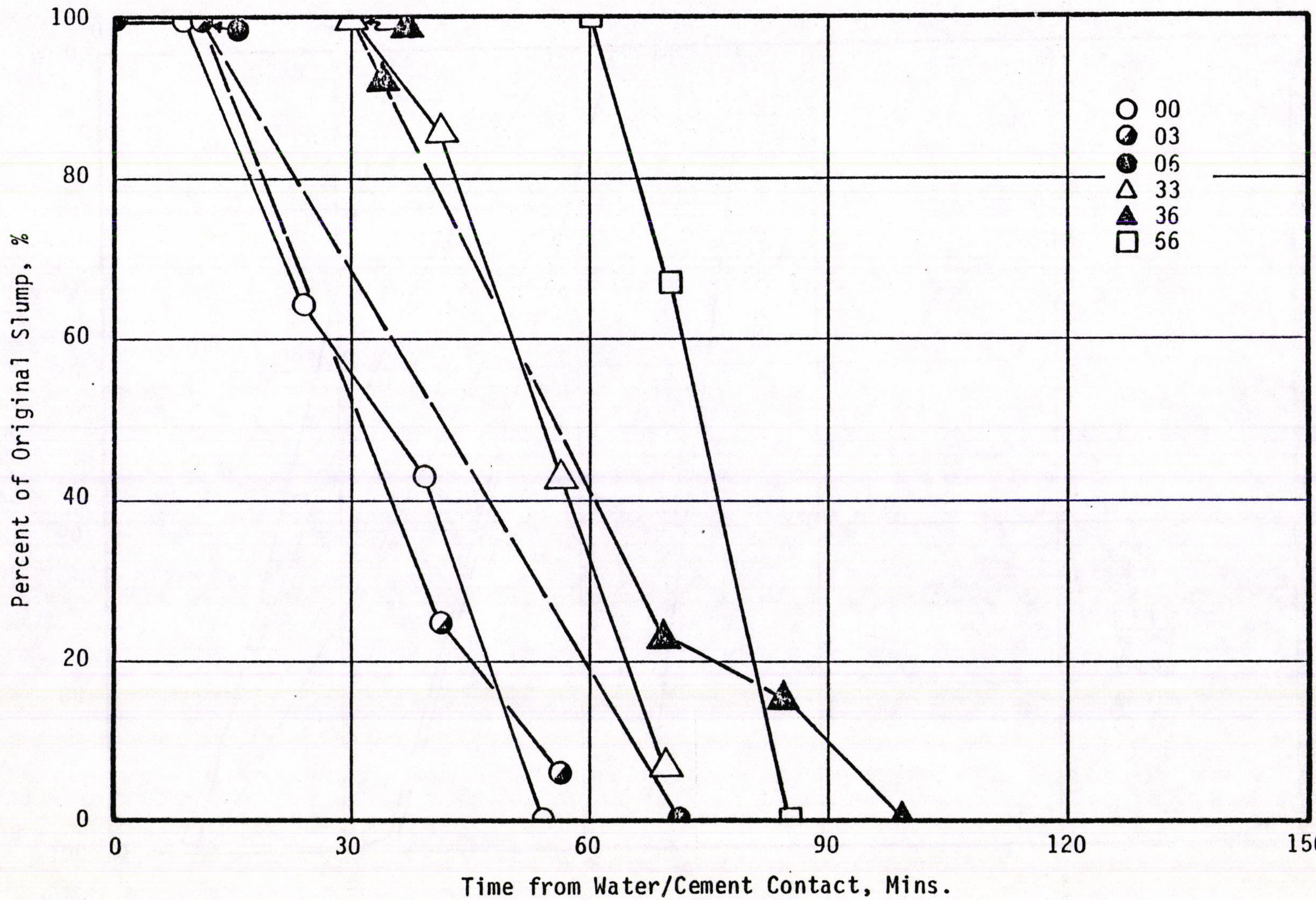


Figure 3.29 PERCENT OF ORIGINAL SLUMP VS. TIME, 1AMxx SERIES

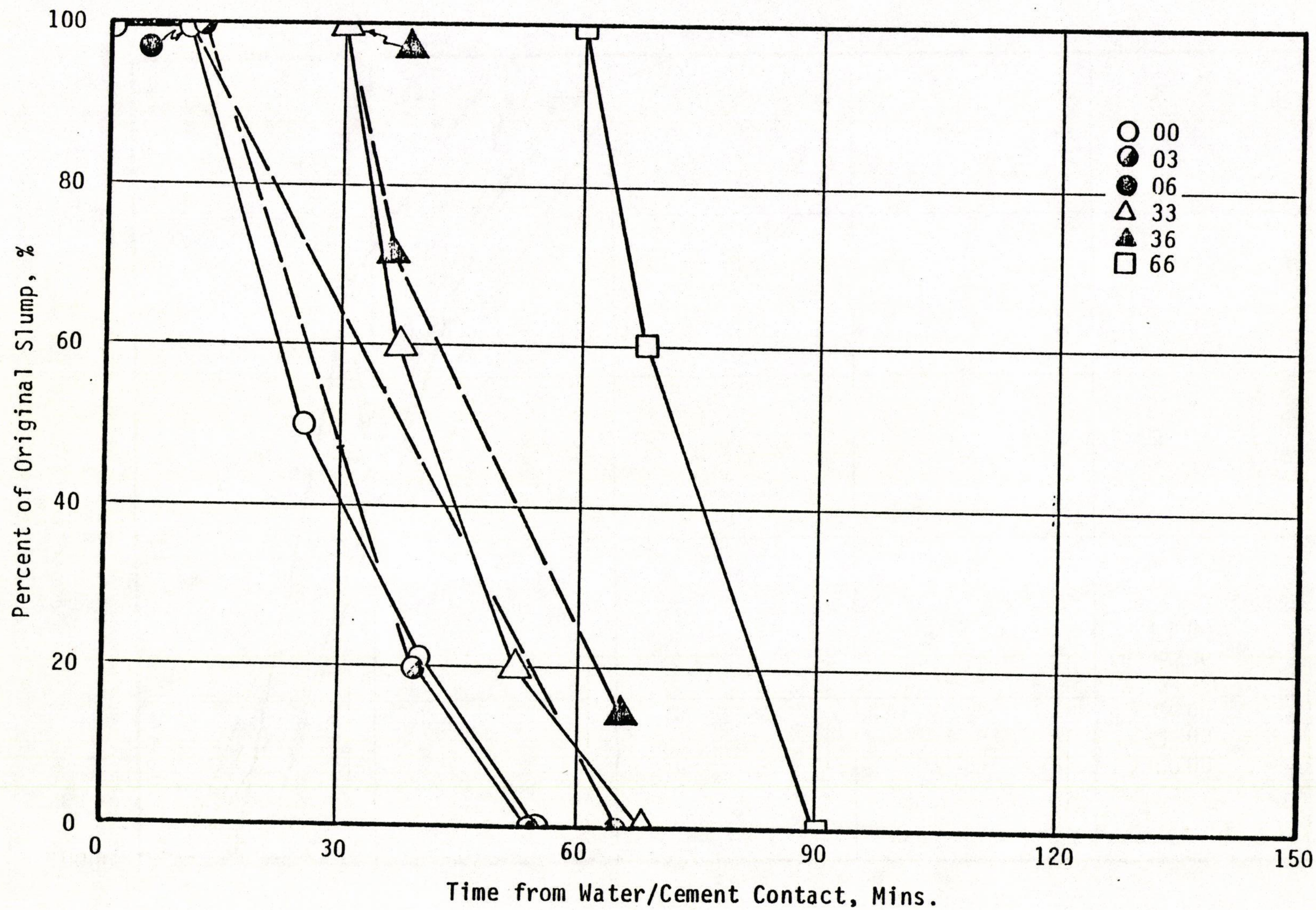


Figure 3.30 PERCENT OF ORIGINAL SLUMP VS. TIME, 1AHxx SERIES

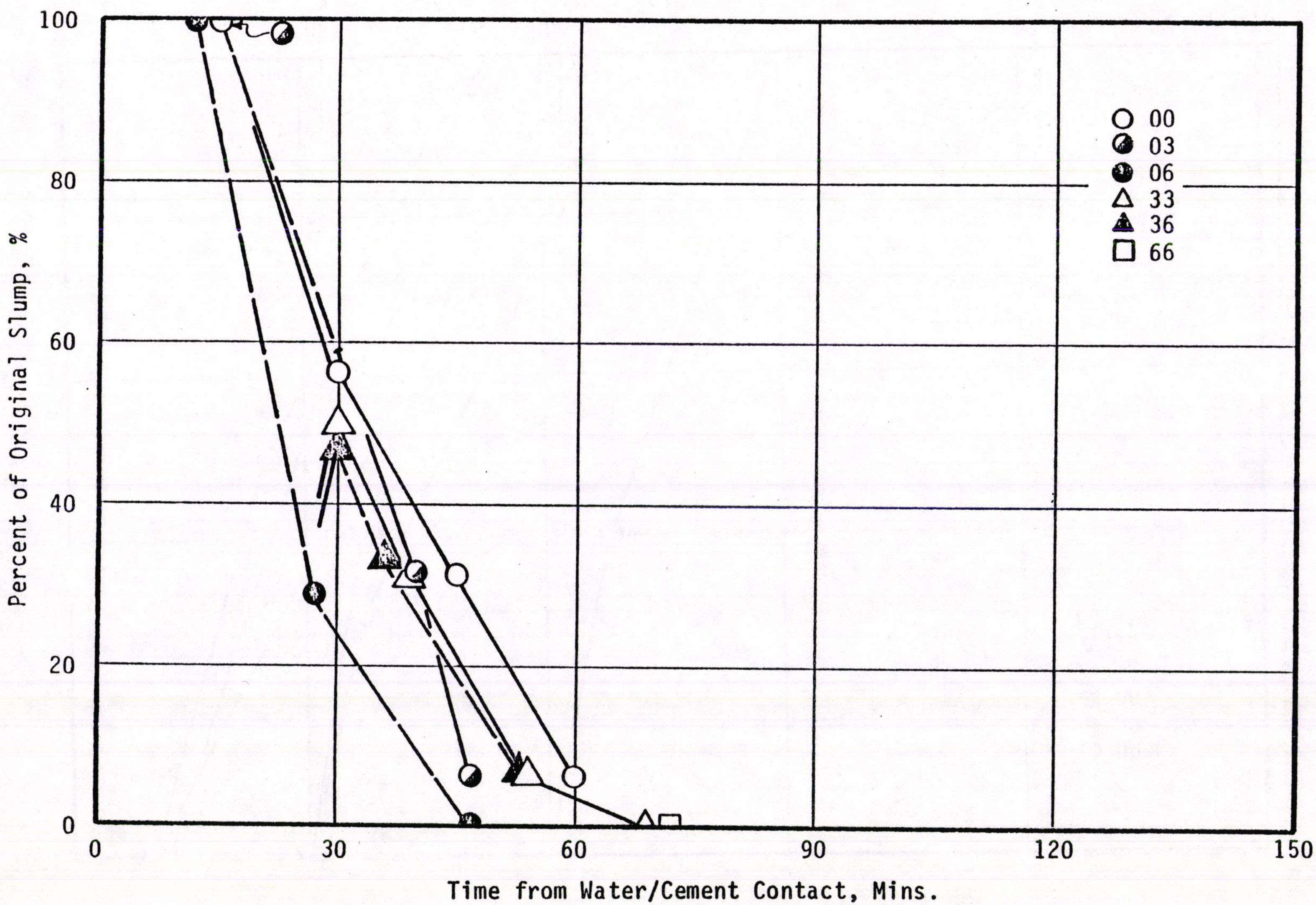


Figure 3.31 PERCENT OF ORIGINAL SLUMP VS. TIME, 2NMxx SERIES

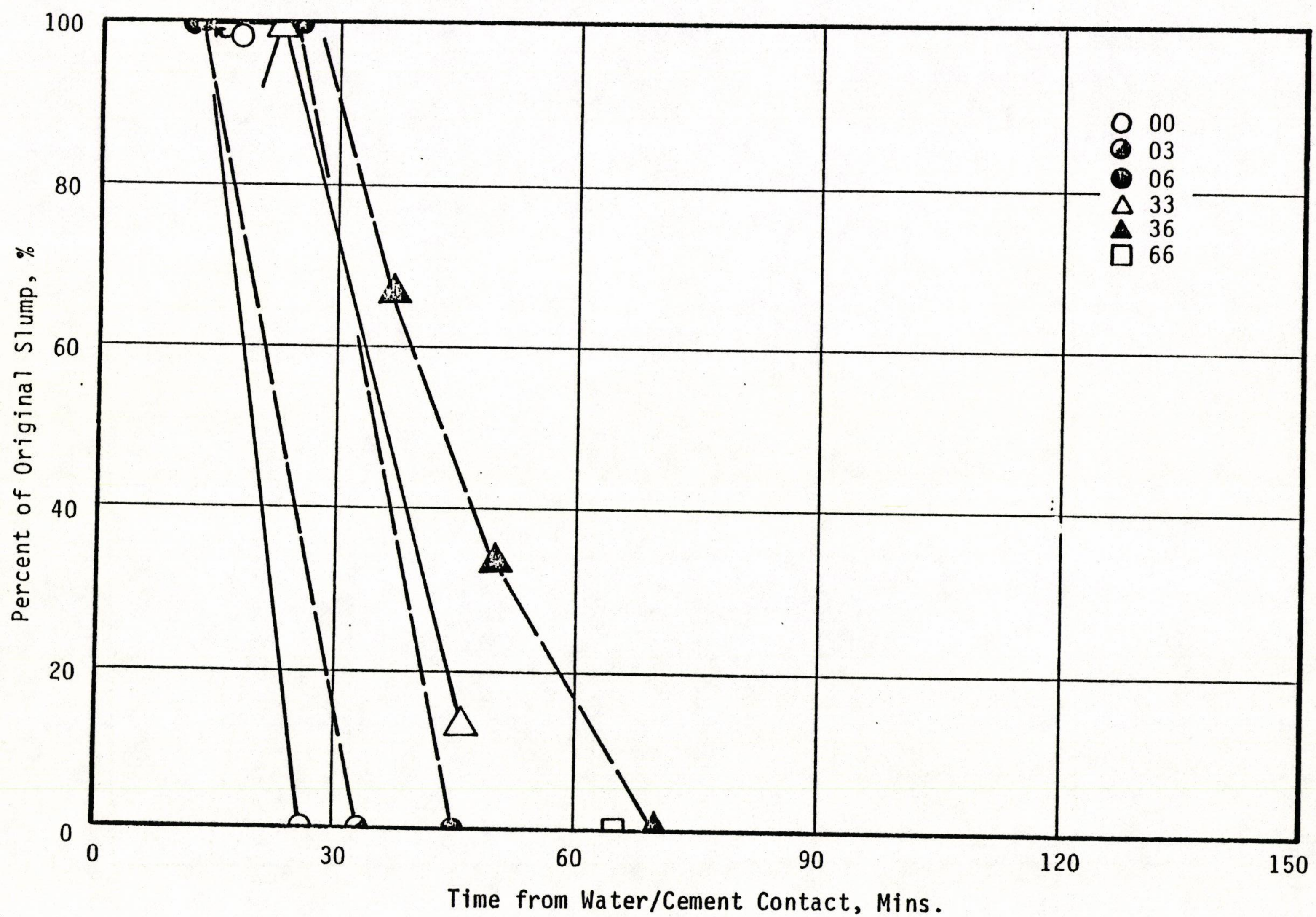


Figure 3.32 PERCENT OF ORIGINAL SLUMP VS. TIME, 2NHxx SERIES

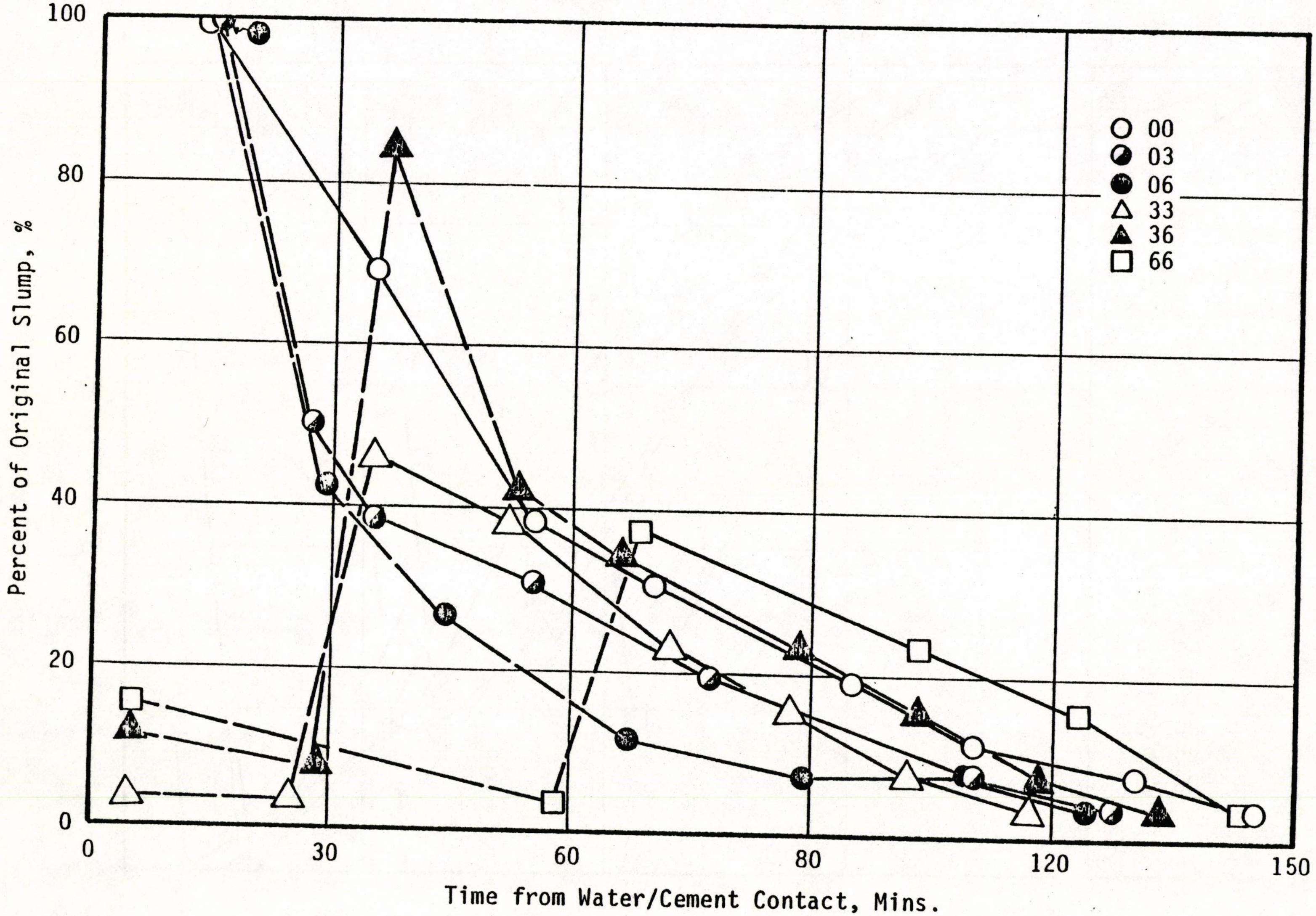


Figure 3.33 PERCENT OF ORIGINAL SLUMP VS. TIME, FNLxx SERIES

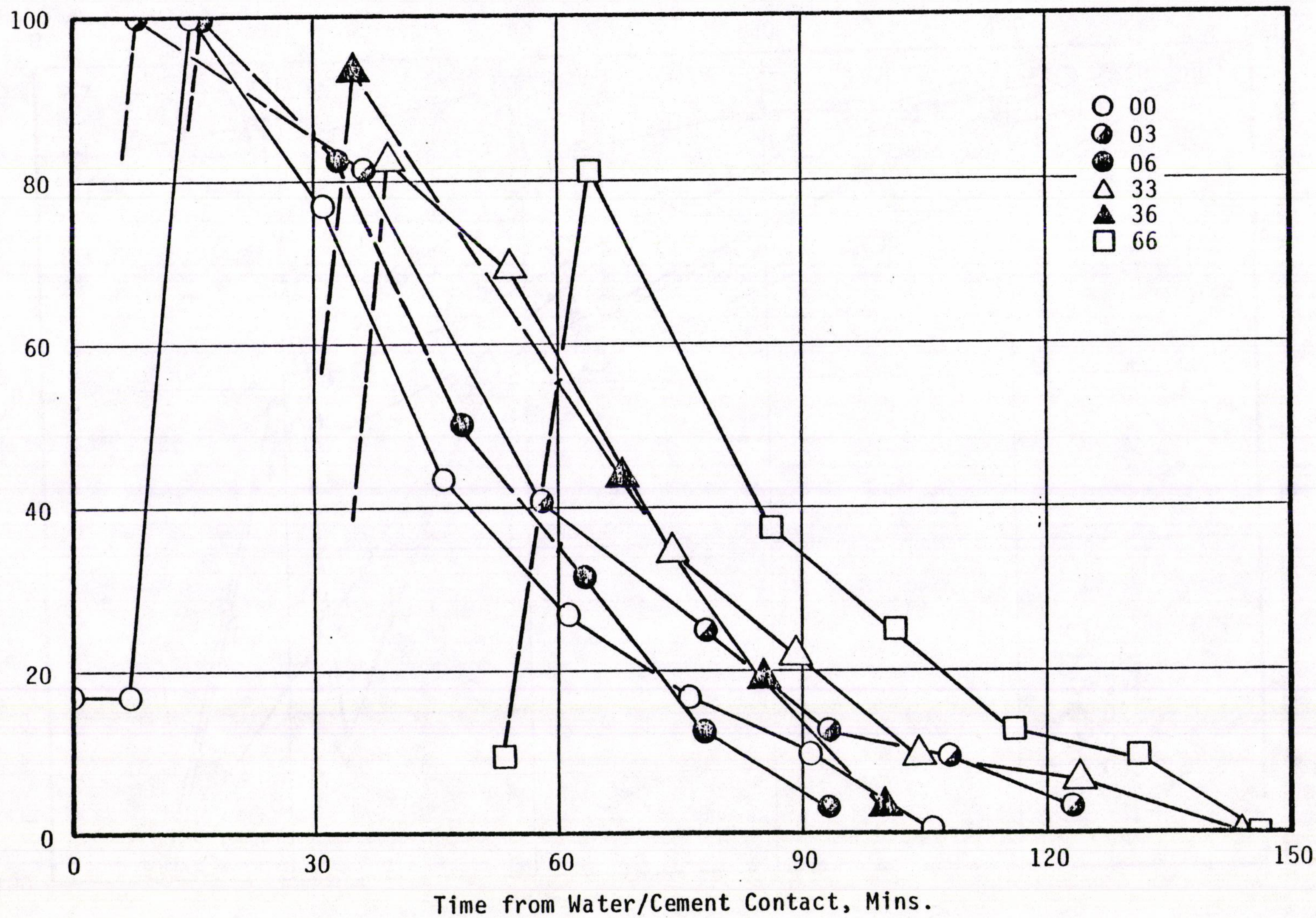


Figure 3.34 PERCENT OF ORIGINAL SLUMP VS. TIME, FNMxx SERIES

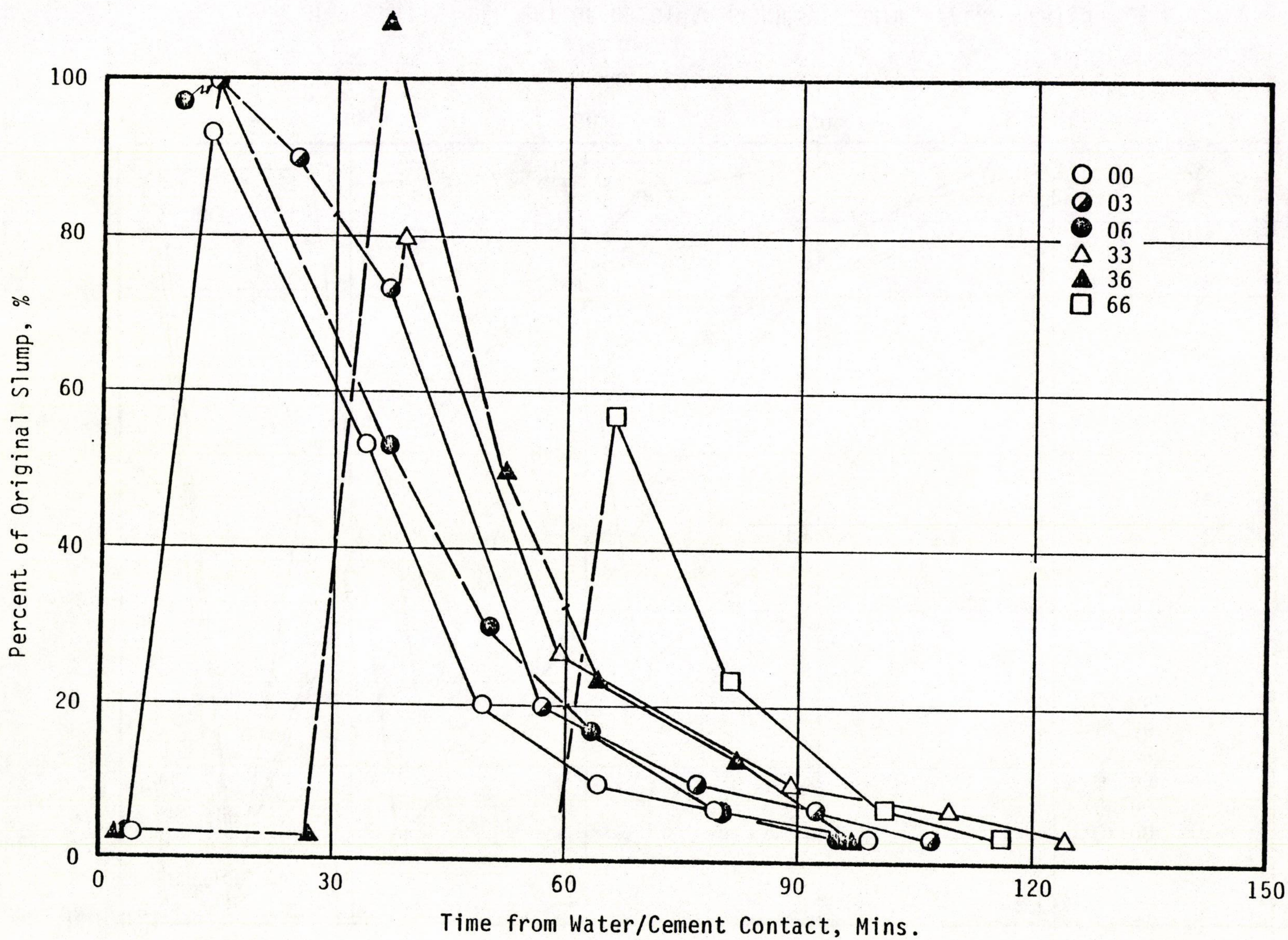


Figure 3.35 PERCENT OF ORIGINAL SLUMP VS. TIME, FNHxx SERIES

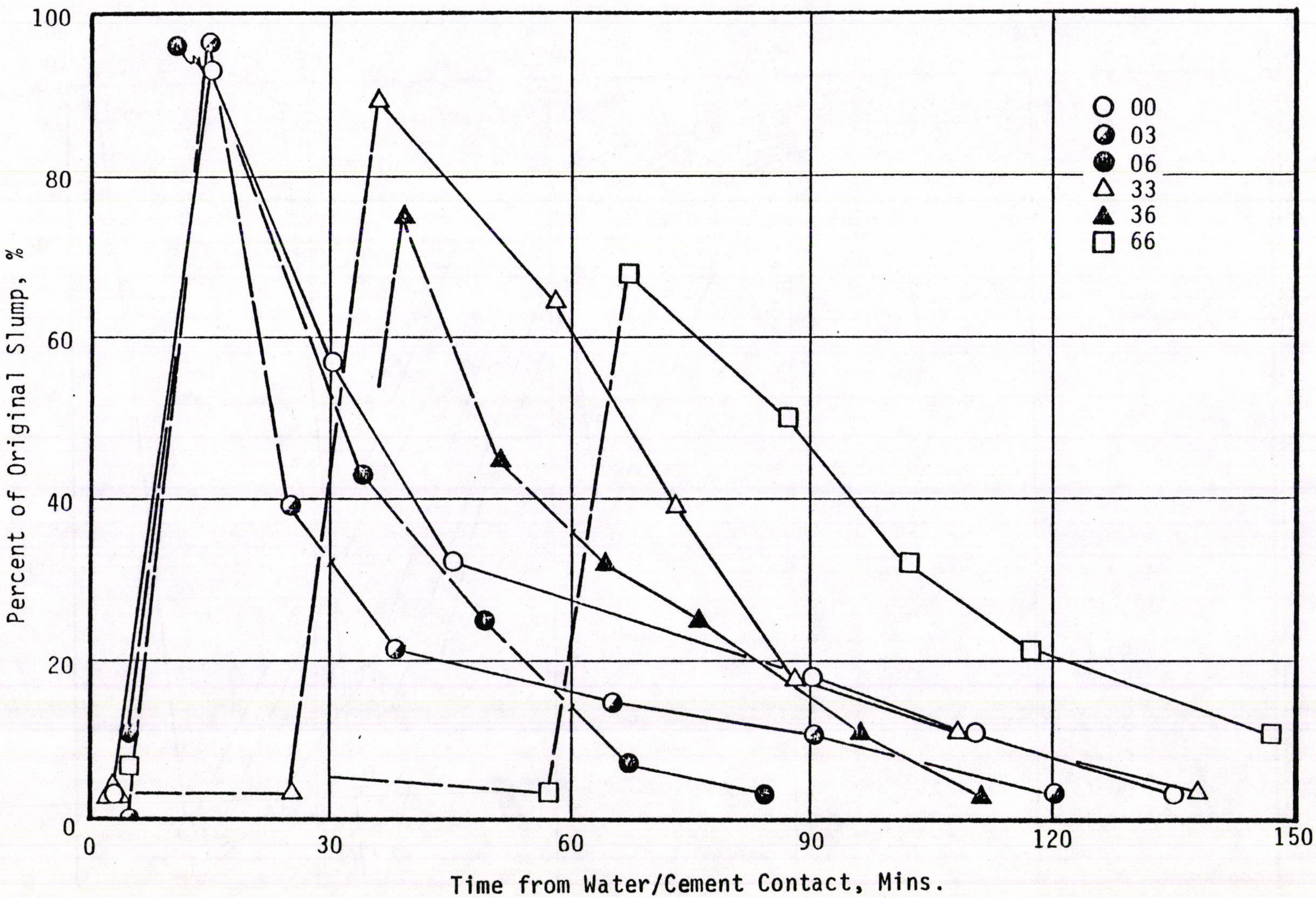


Figure 3.36 PERCENT OF ORIGINAL SLUMP VS. TIME, FALxx SERIES

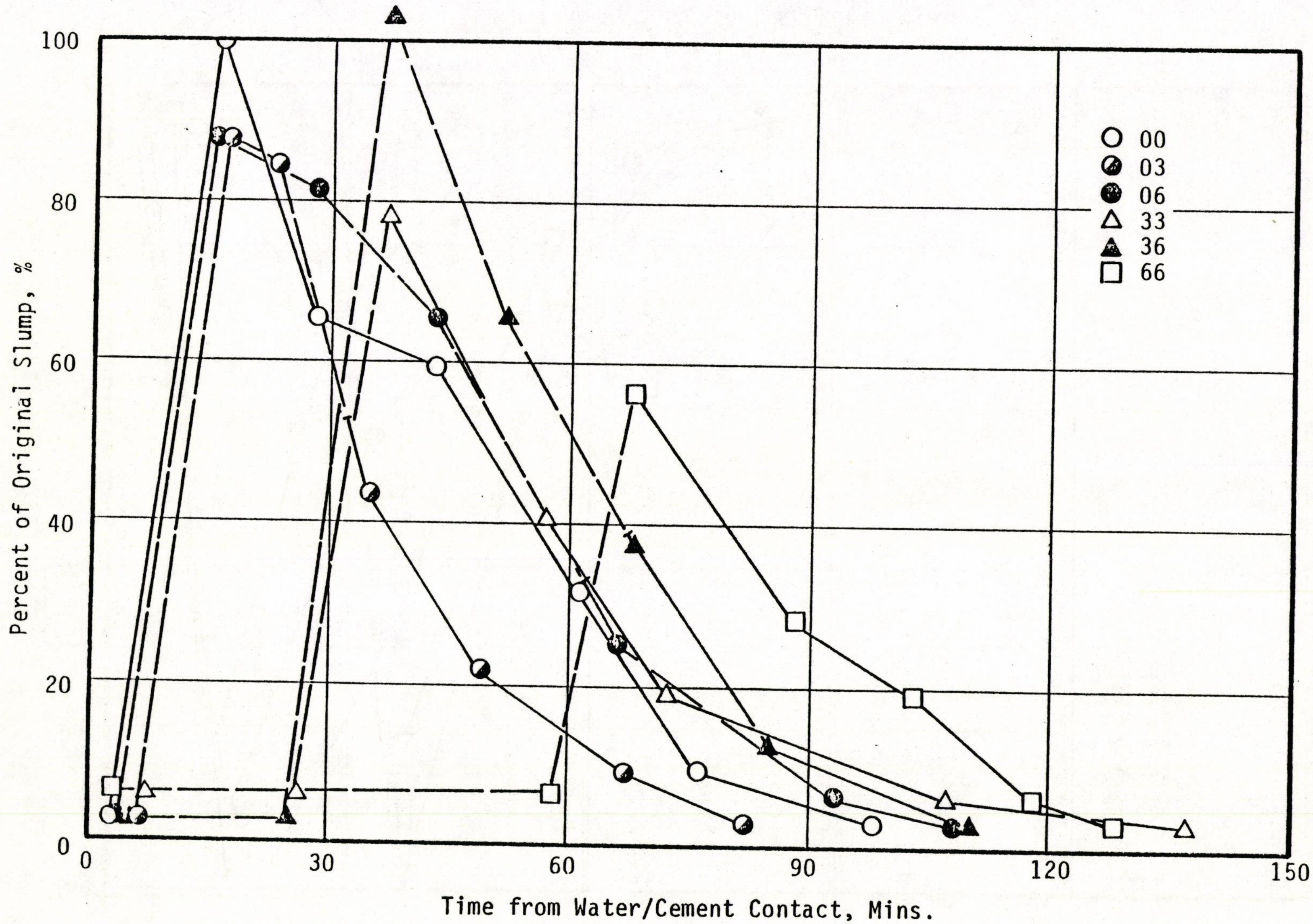


Figure 3.37 PERCENT OF ORIGINAL SLUMP VS. TIME, FAMxx SERIES

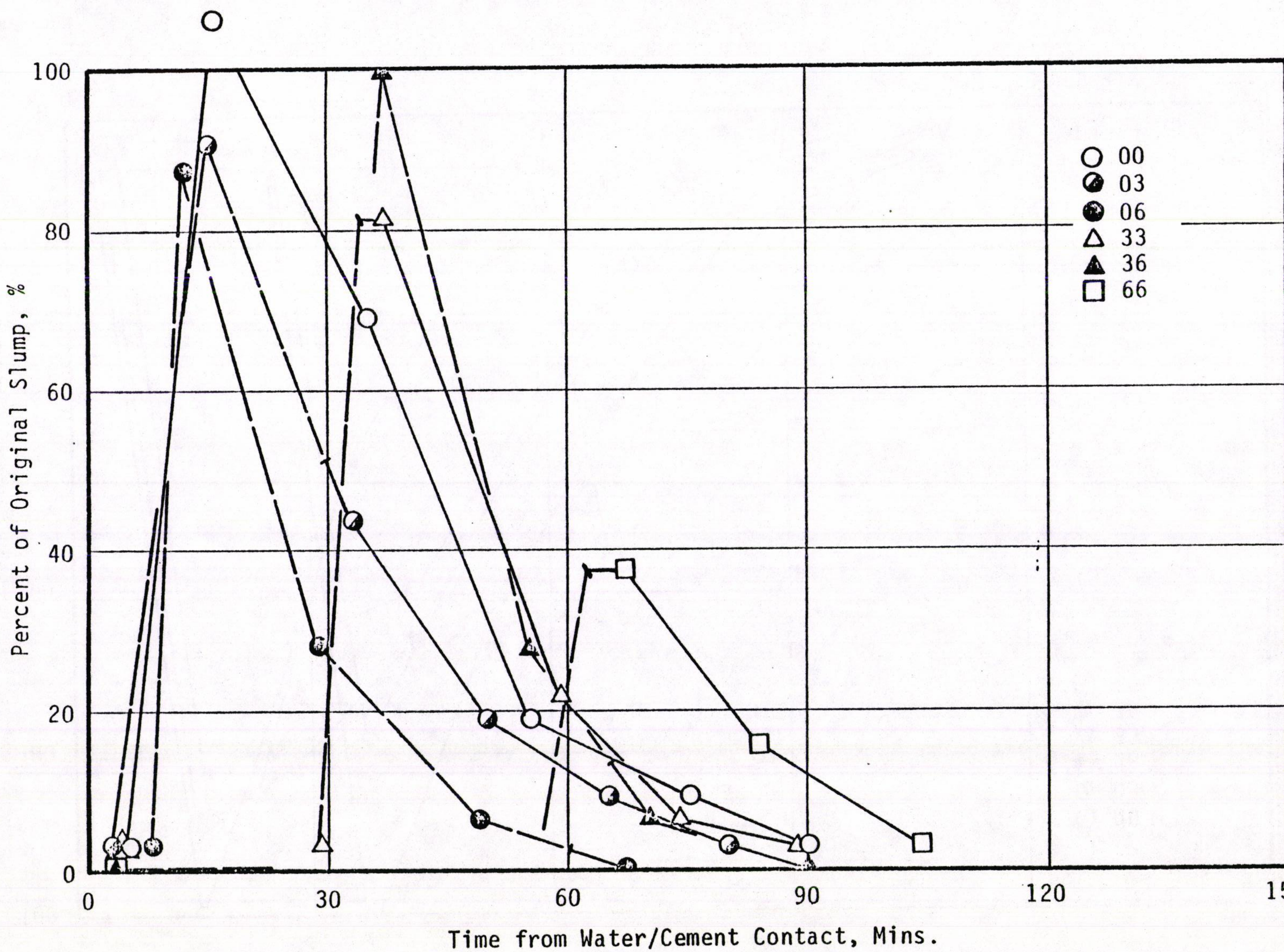


Figure 3.38 PERCENT OF ORIGINAL SLUMP VS. TIME, FAHxx SERIES

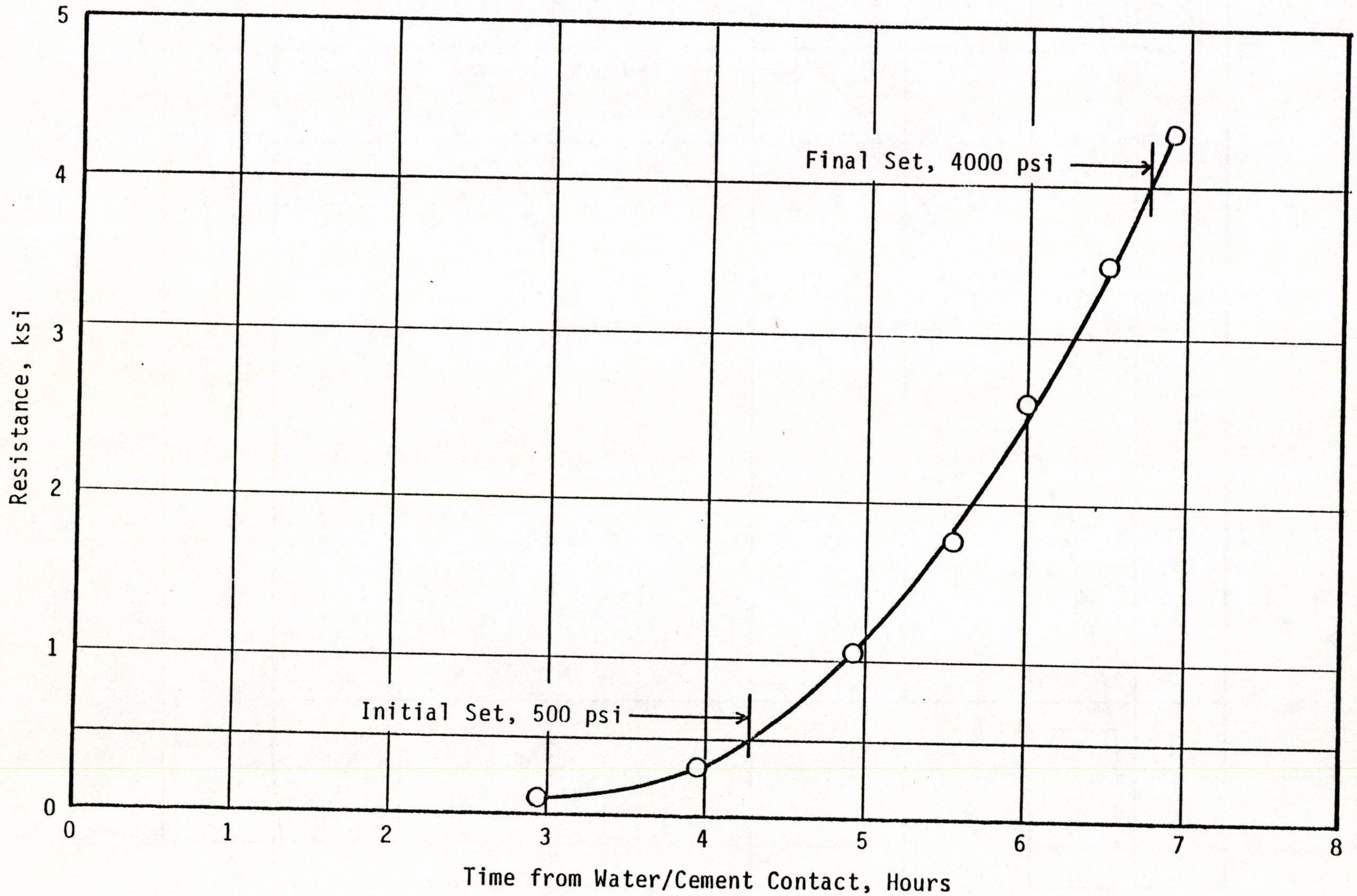


Figure 3.39 TYPICAL TIME OF SET CURVE, CNM03 SPECIMEN

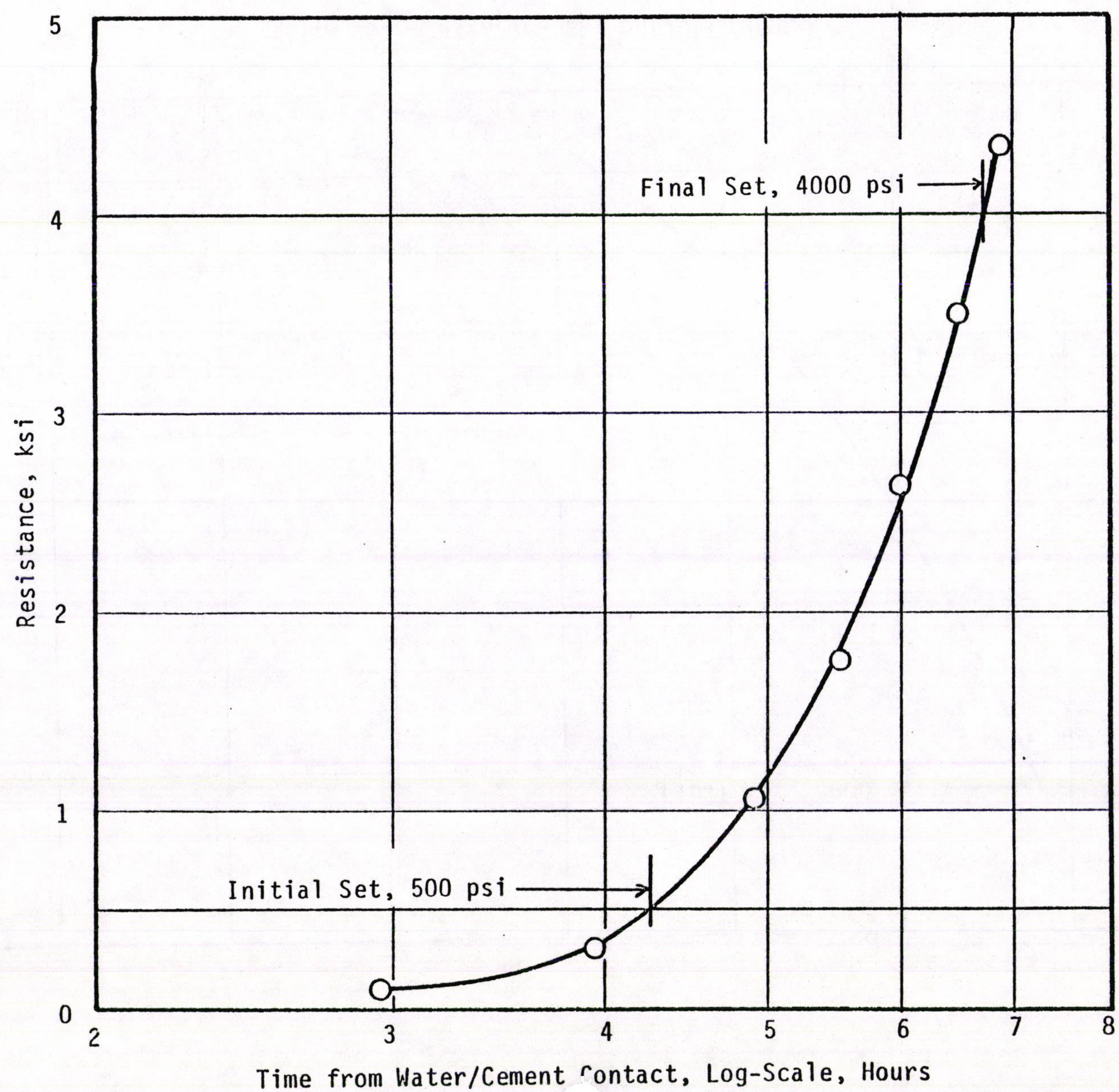


Figure 3.40 TYPICAL TIME OF SET CURVE, LOG-SCALE, CNM03 SPECIMEN

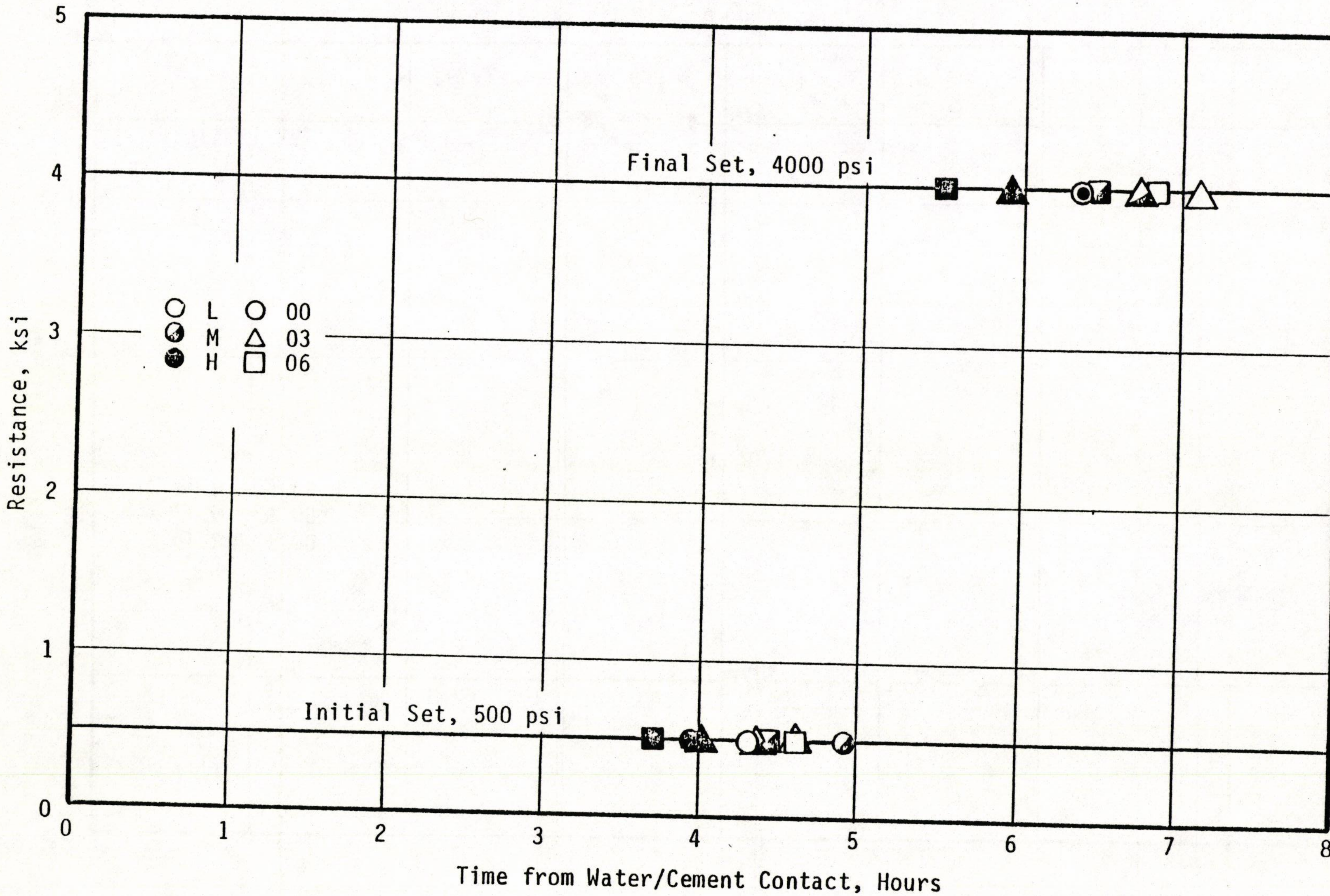


Figure 3.41 TIME OF SET RESULTS, CNxxx SERIES

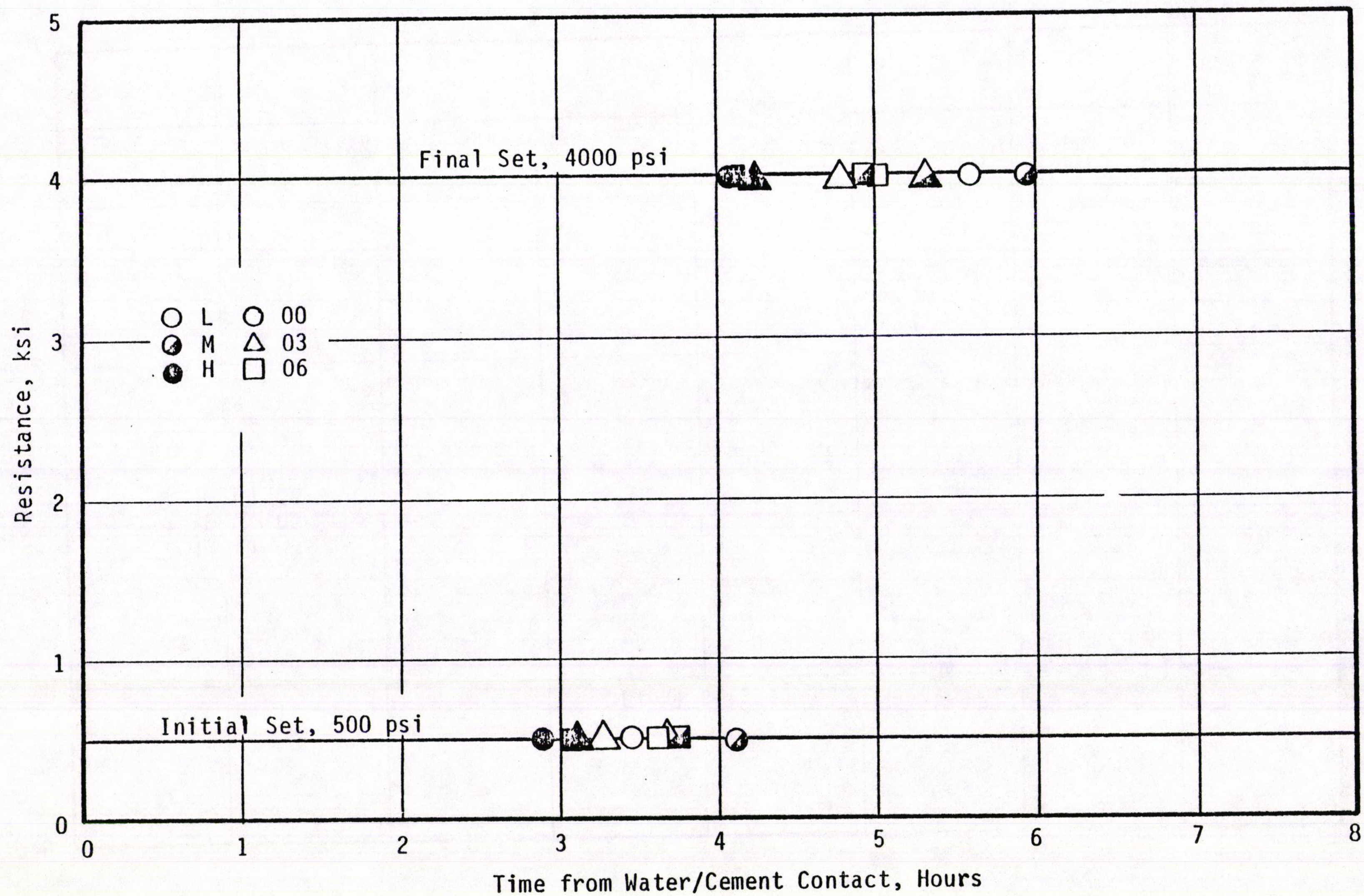


Figure 3.42 TIME OF SET RESULTS, CAxxx SERIES

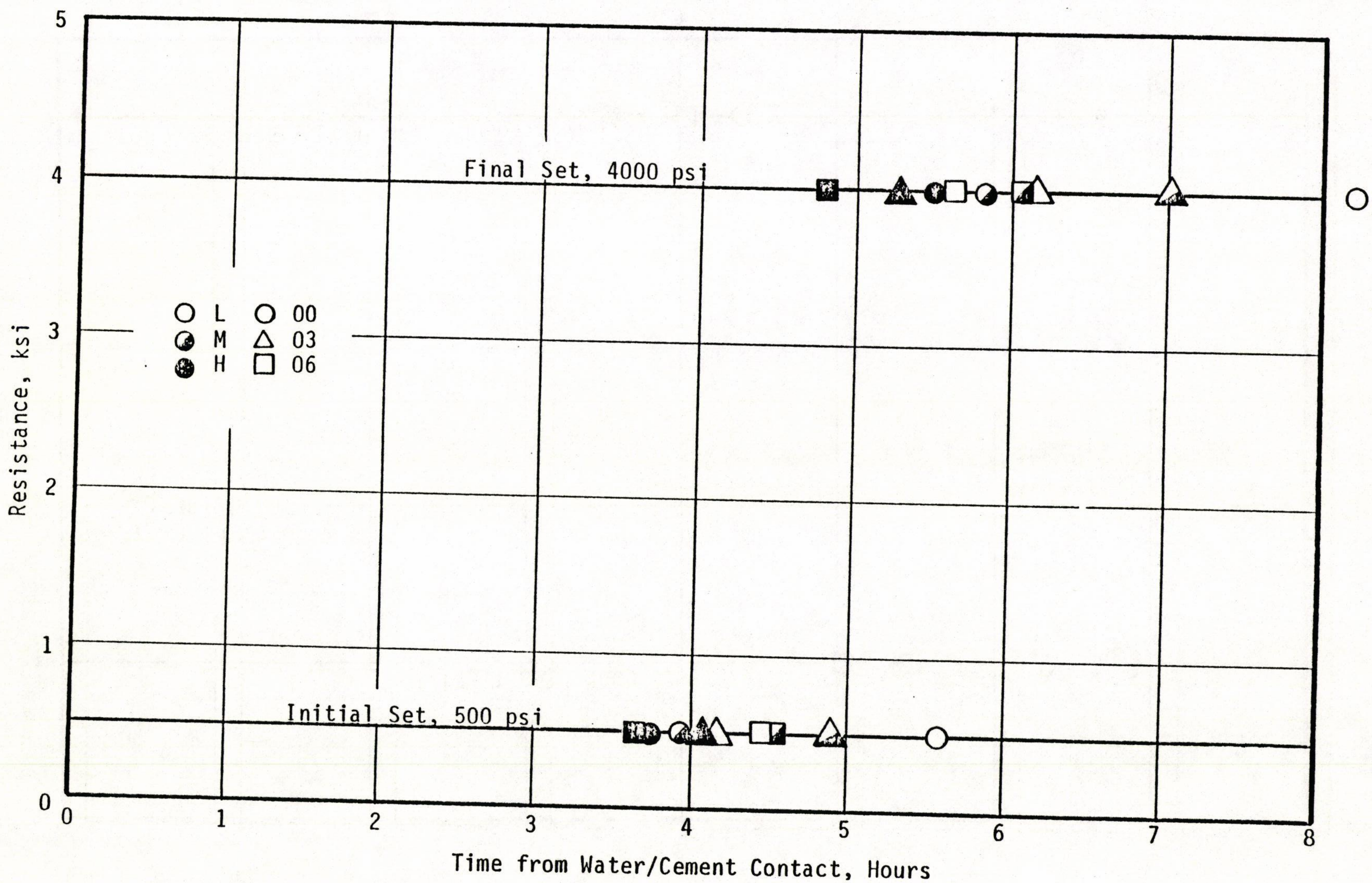


Figure 3.43 TIME OF SET RESULTS, $\overline{C}$Nxxx SERIES

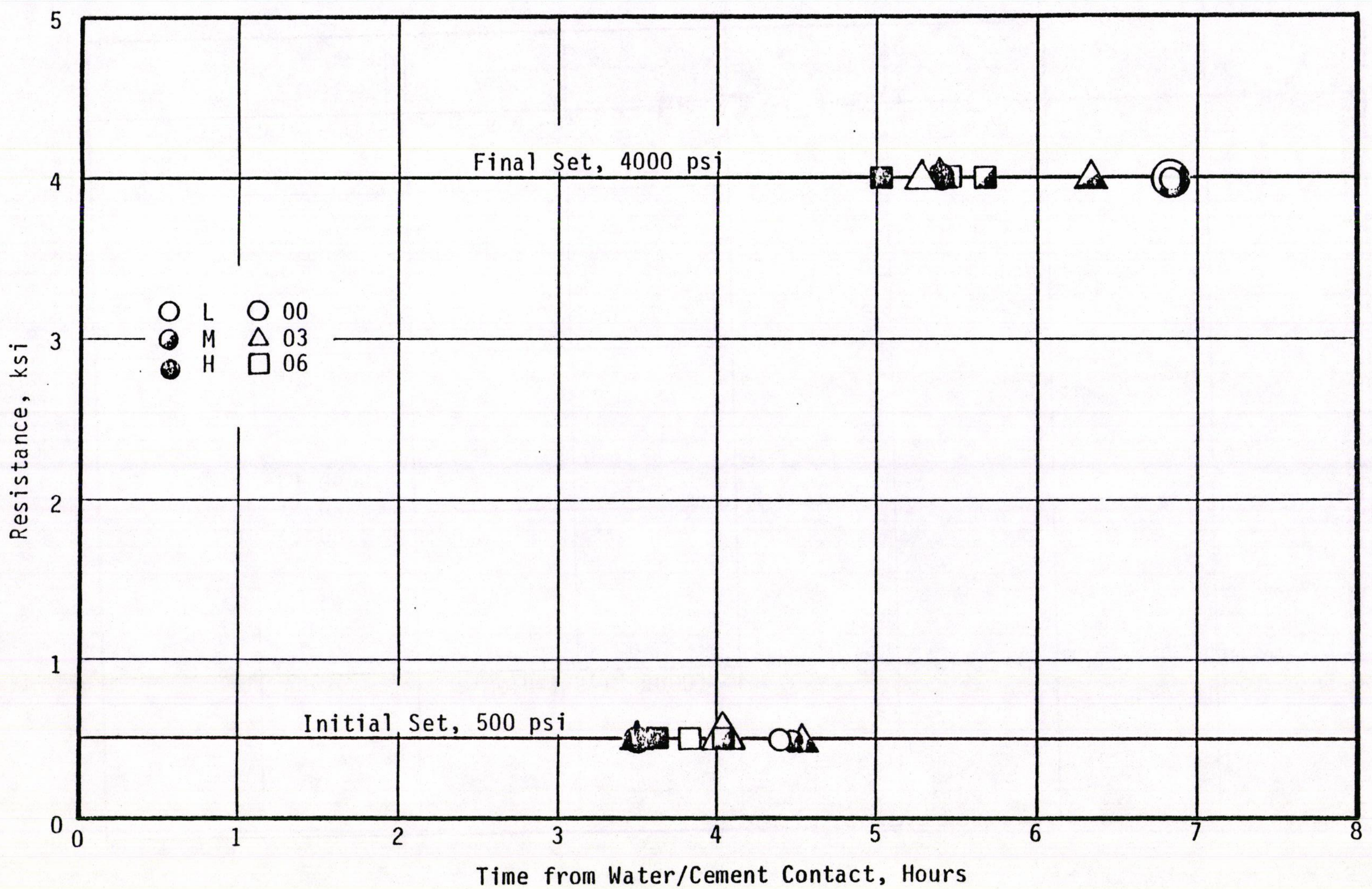


Figure 3.44 TIME OF SET RESULTS, CAxxx SERIES

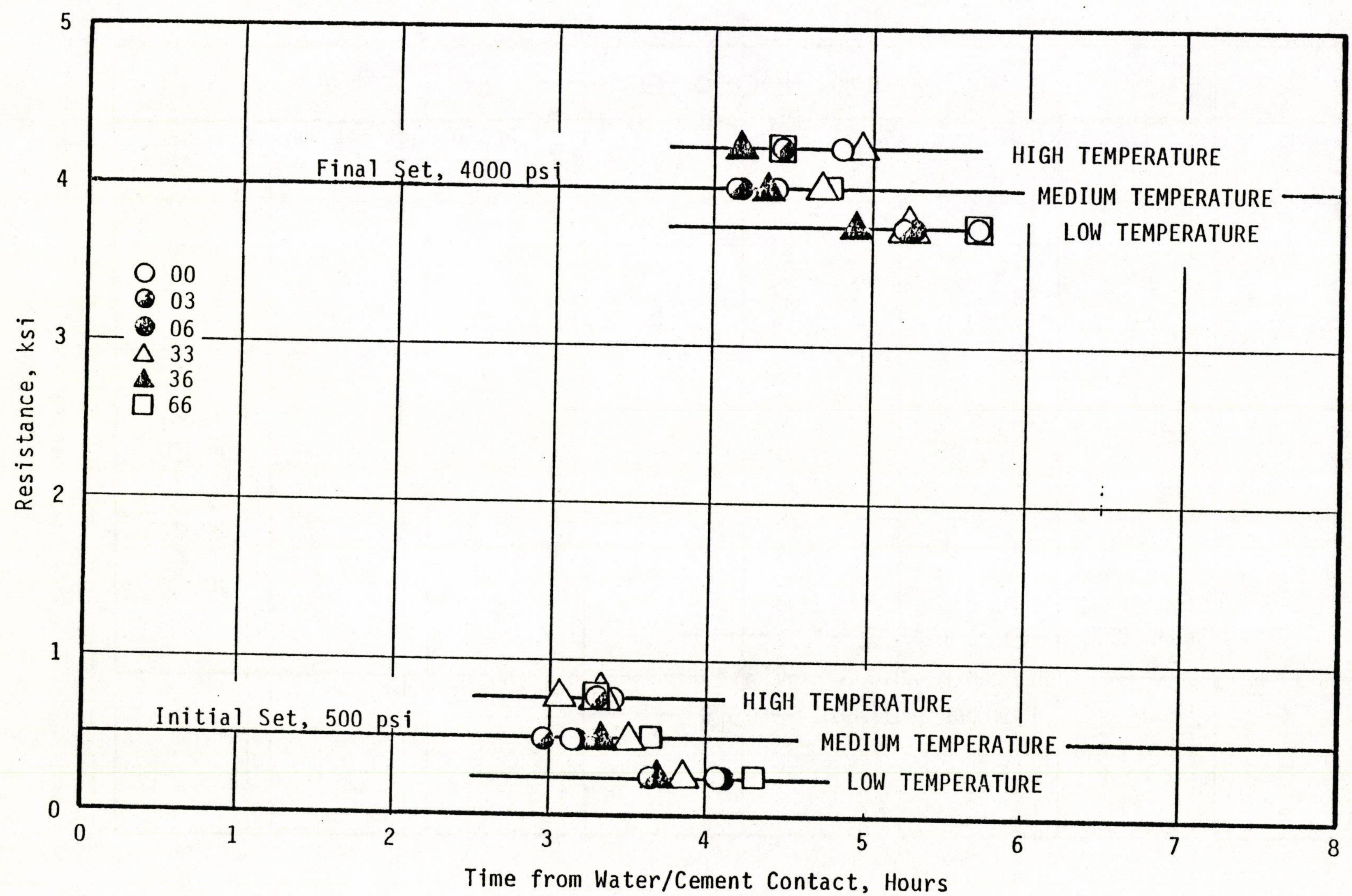


Figure 3.45 TIME OF SET RESULTS, 1Nxxx SERIES

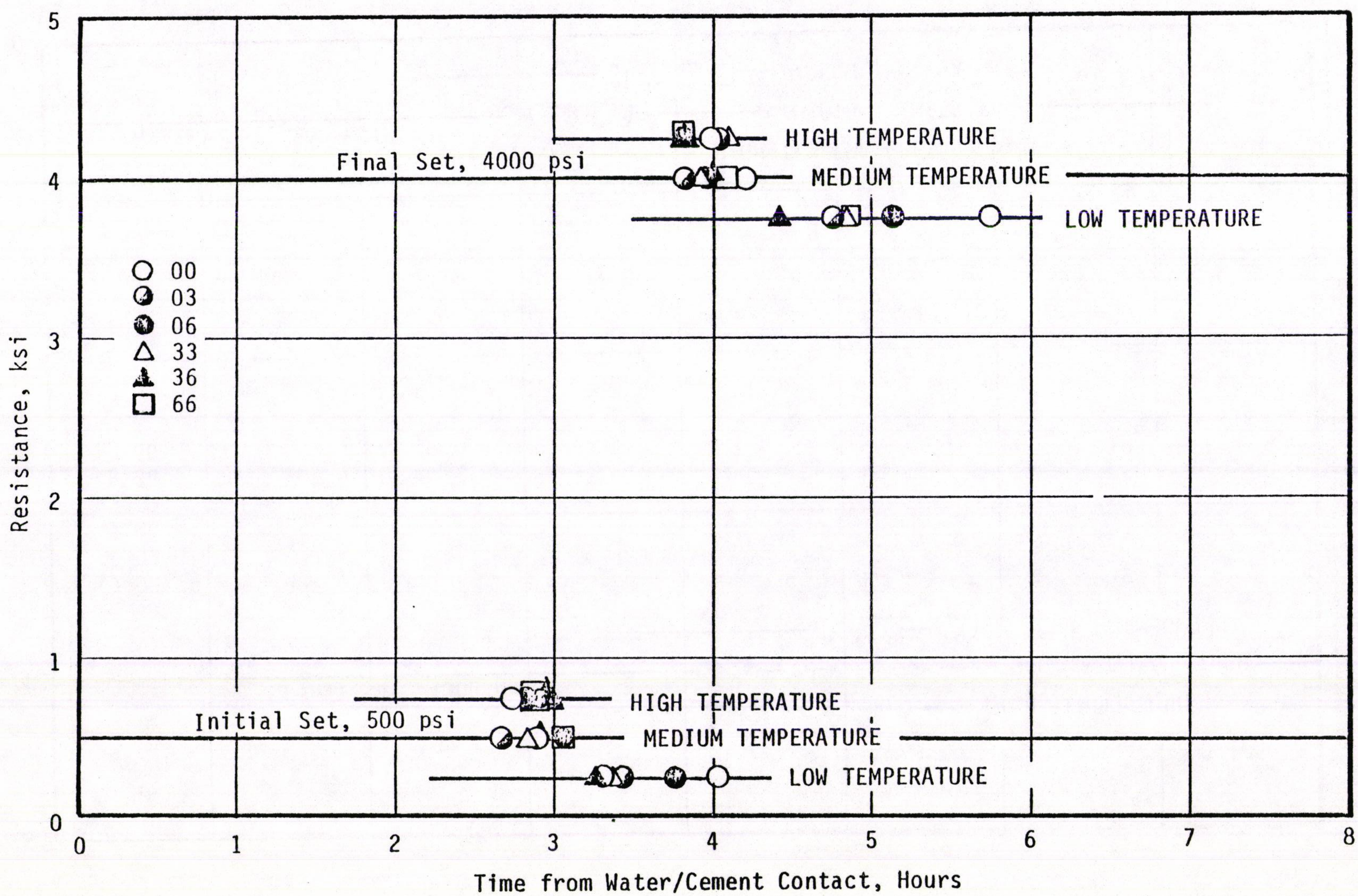


Figure 3.46 TIME OF SET RESULTS, 1Axxx SERIES

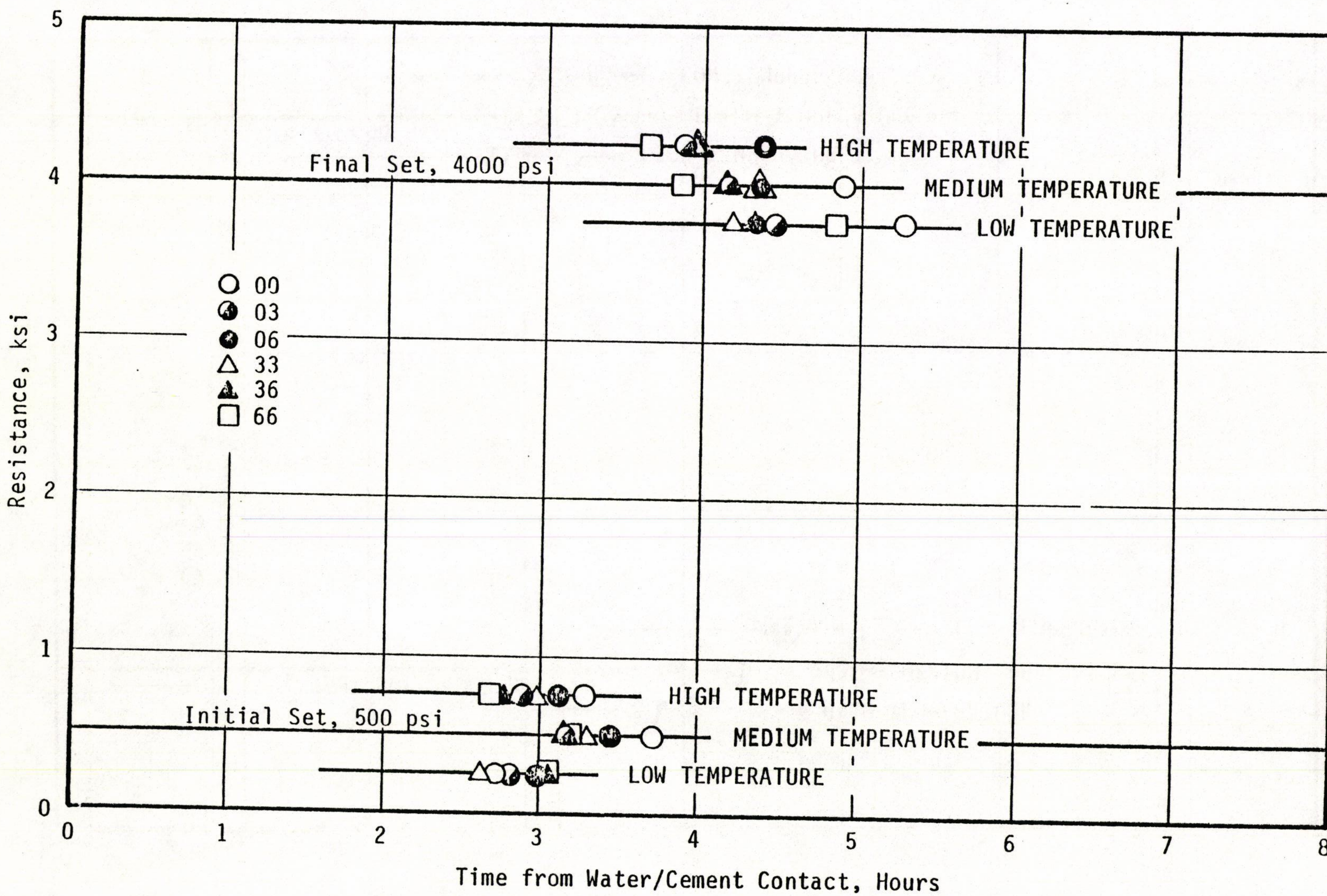


Figure 3.47 TIME OF SET RESULTS, 2Nxxx SERIES

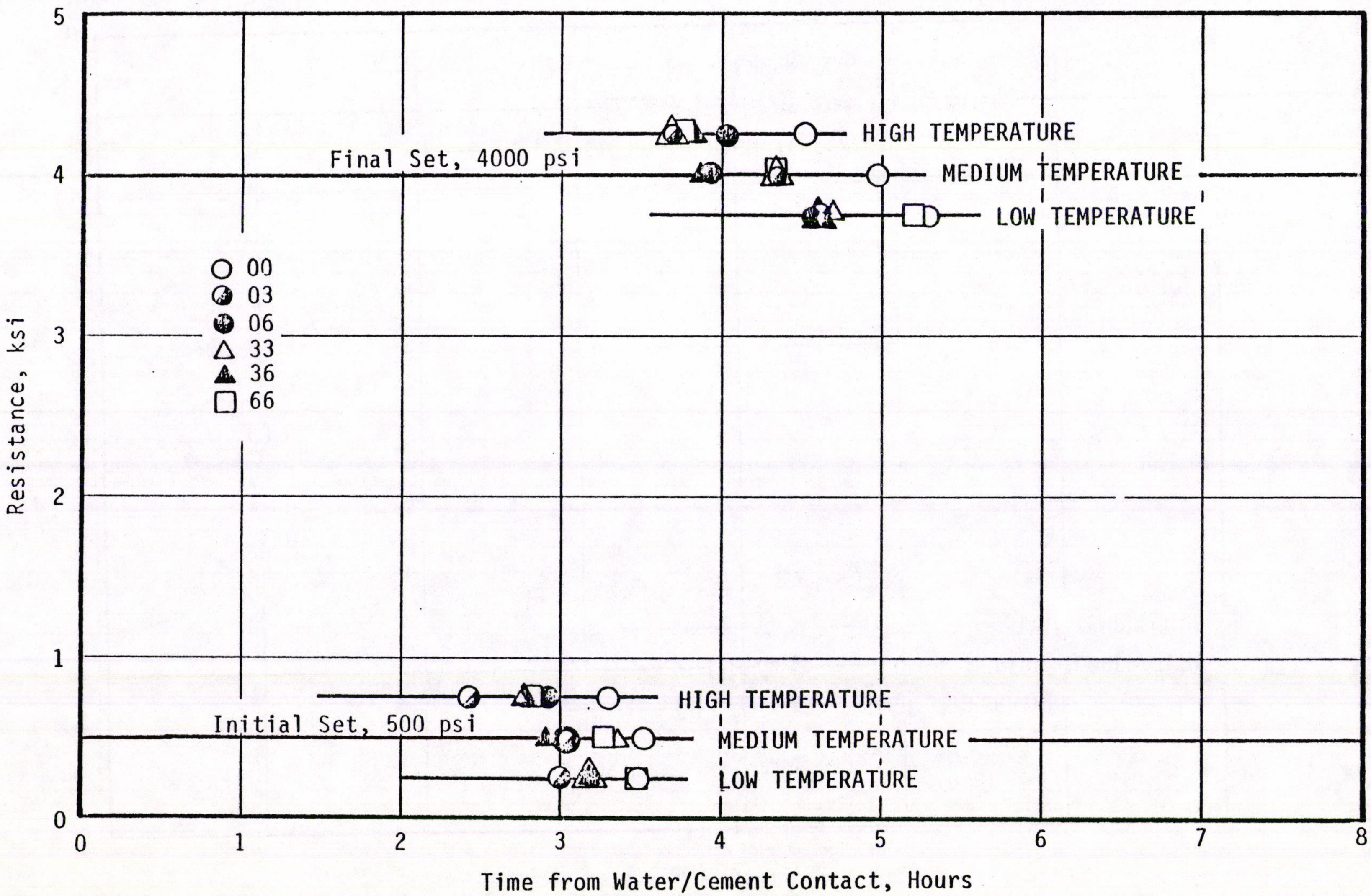


Figure 3.48 TIME OF SET RESULTS, 2Axxx SERIES

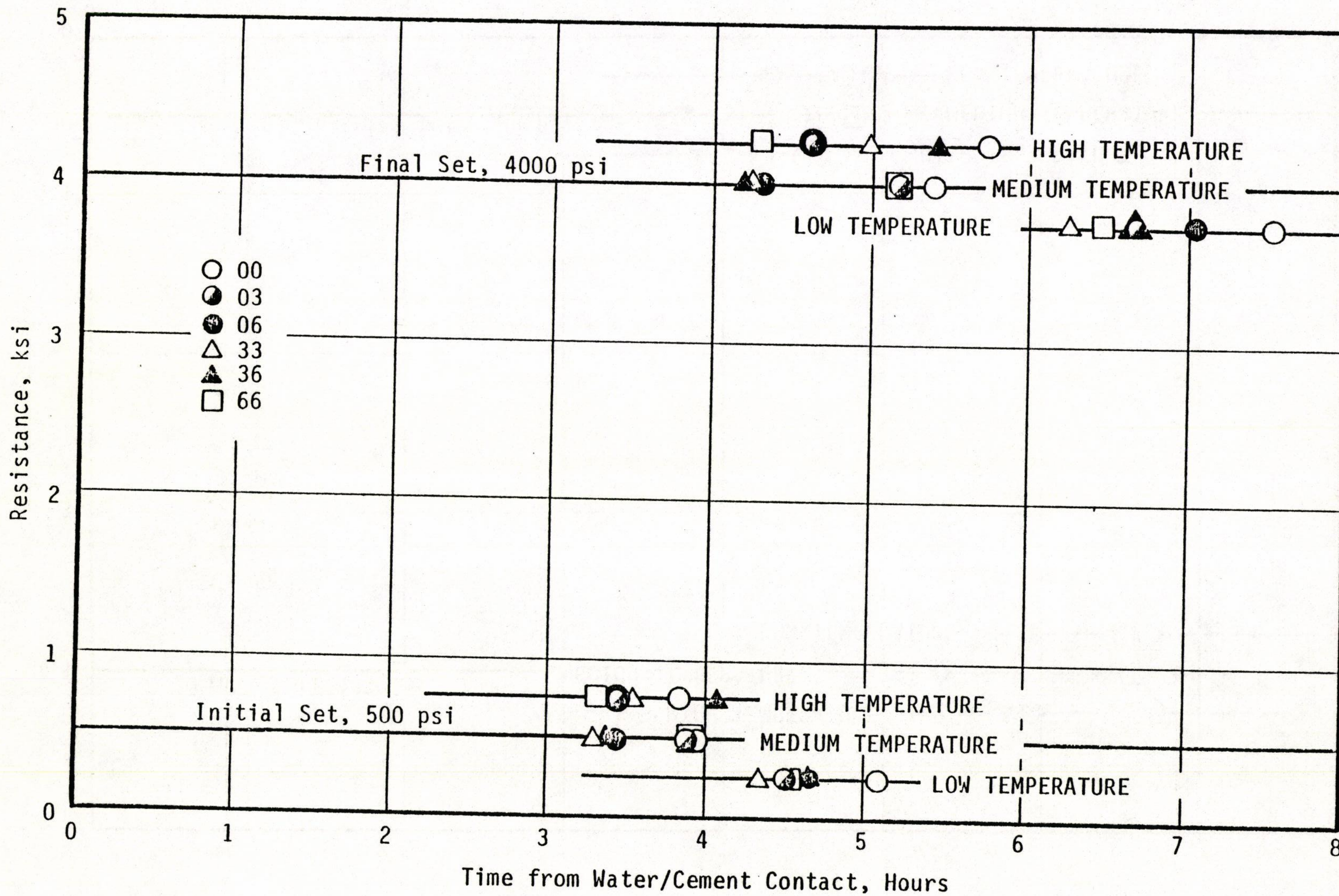


Figure 3.49 TIME OF SET RESULTS, FNxxx SERIES

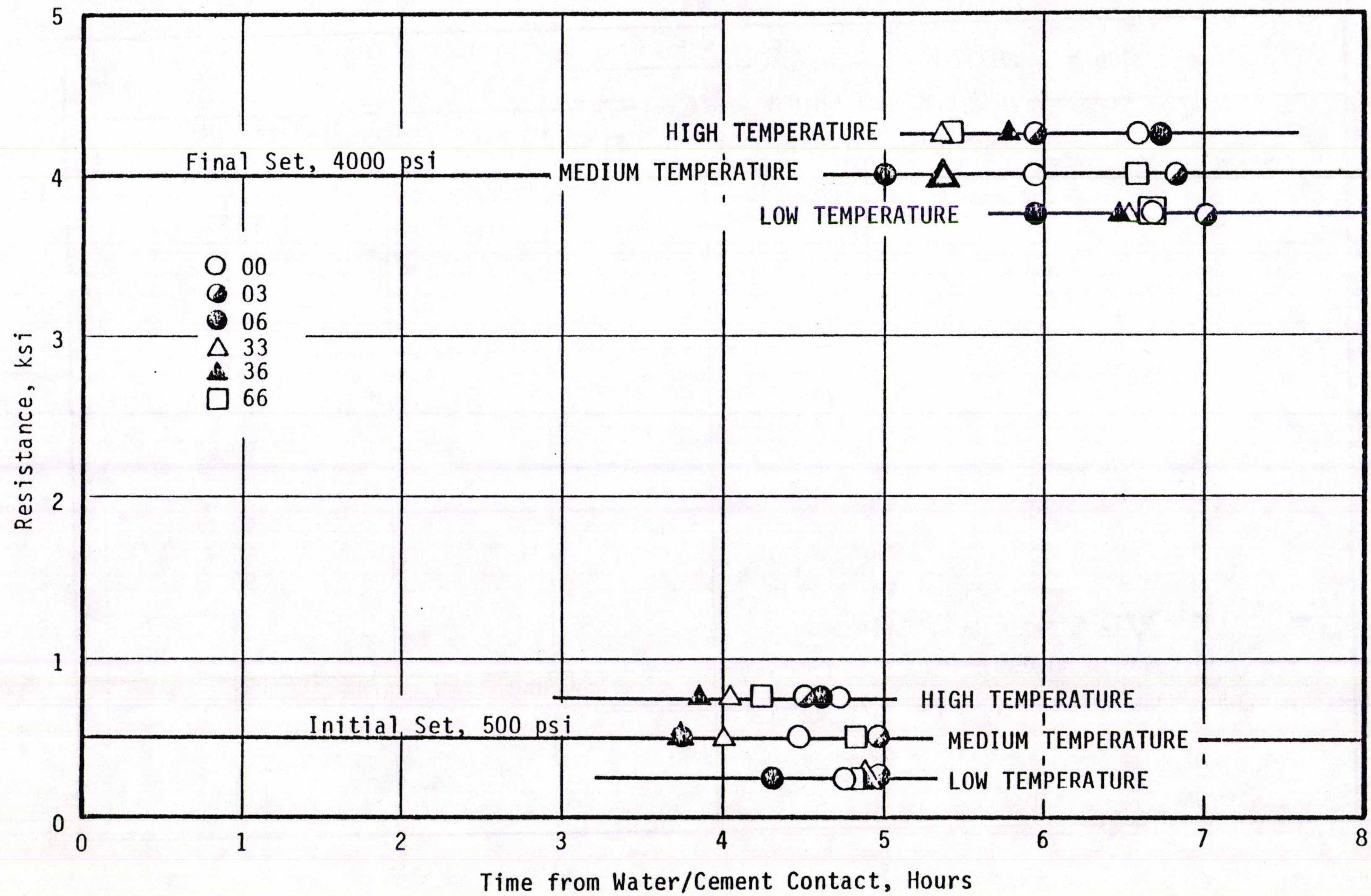


Figure 3.50 TIME OF SET RESULTS, FAxxx SERIES

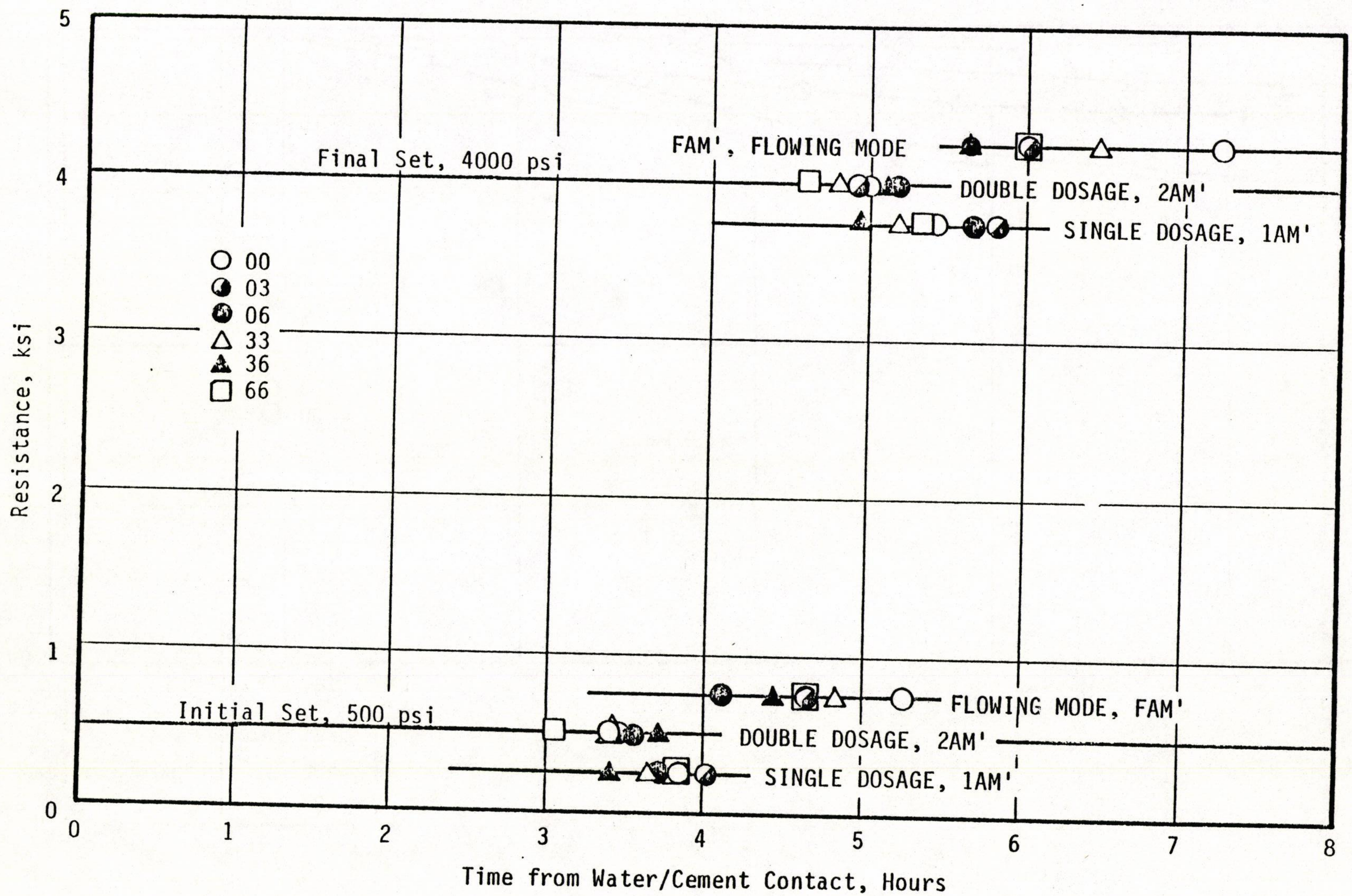


Figure 3.51 TIME OF SET RESULTS, xAM'xx SERIES

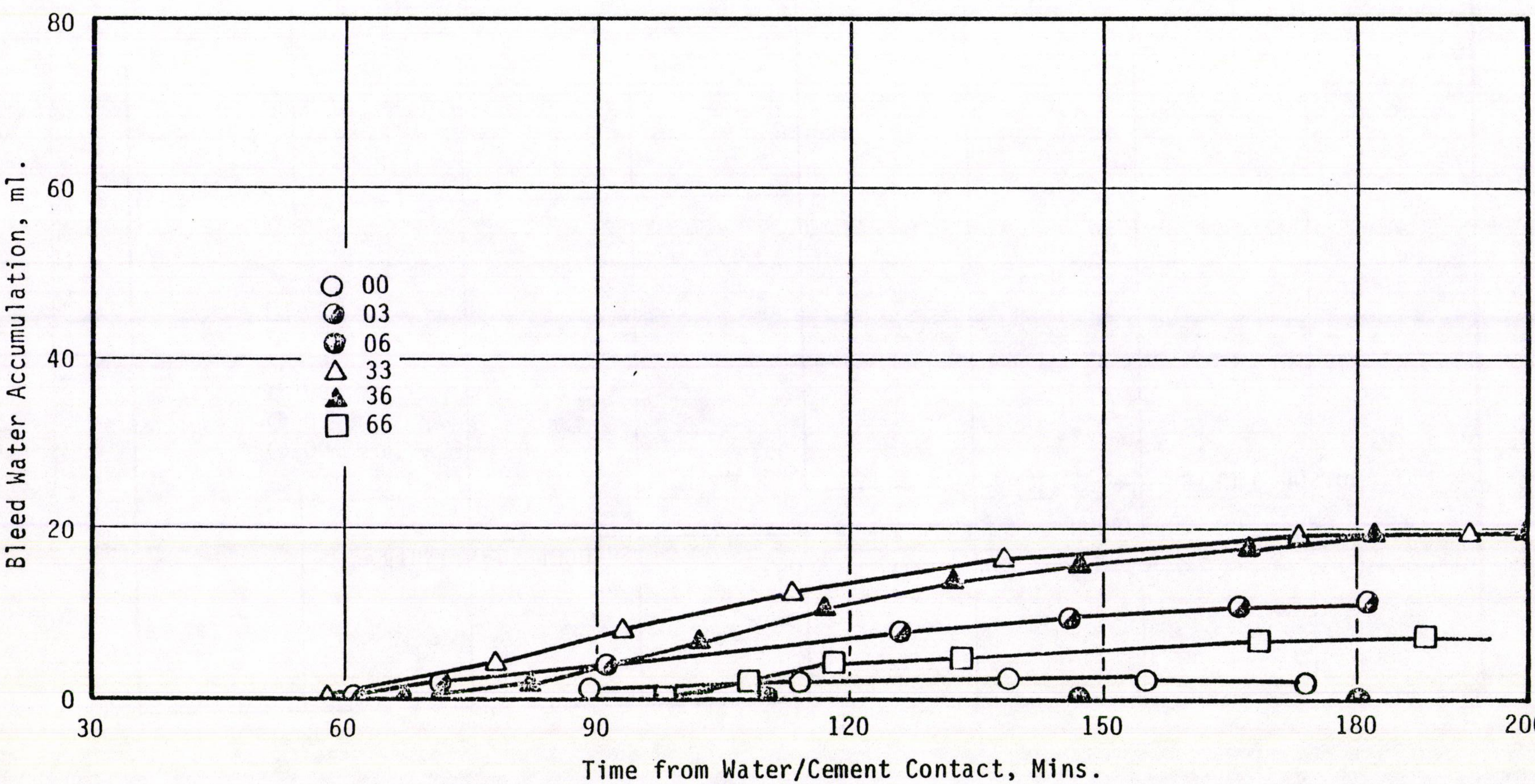


Figure 3.52 SAMPLE BLEED WATER CURVE, FNMxx SERIES

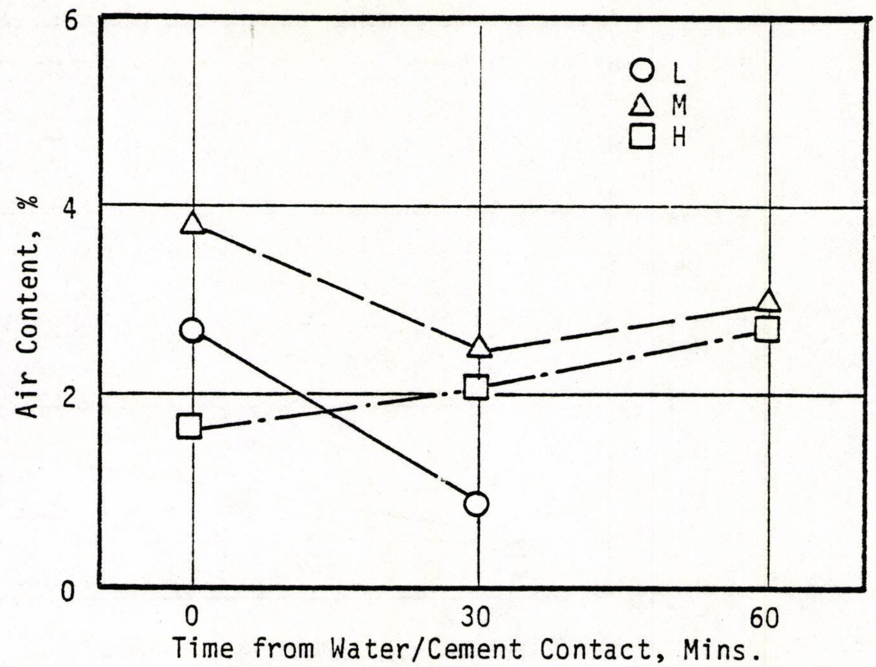


Figure 3.53 AIR CONTENT VARIATION, CNxxx SERIES

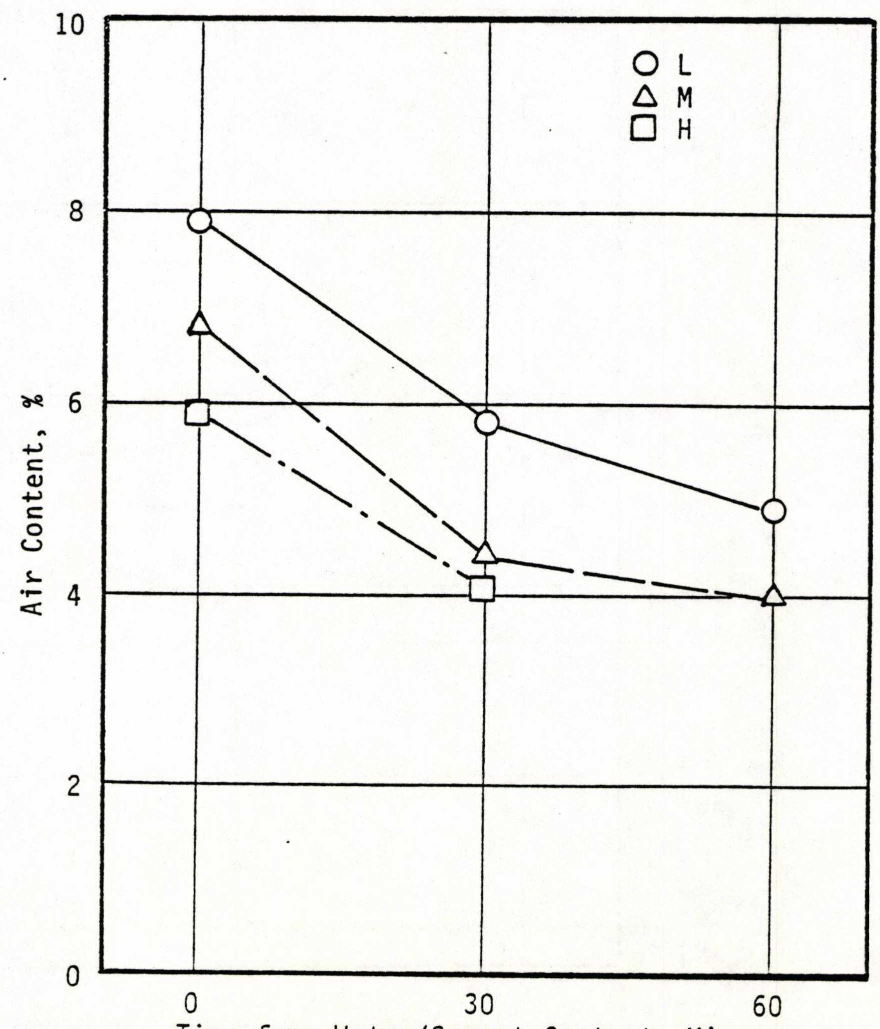


Figure 3.54 AIR CONTENT VARIATION, CAxxx SERIES

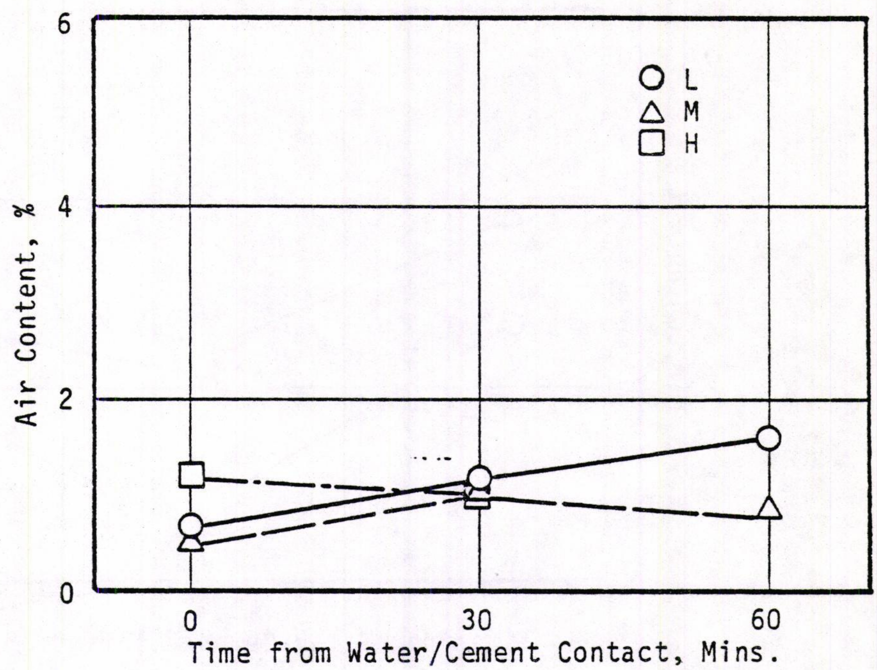


Figure 3.55 AIR CONTENT VARIATION, $\overline{C}$Nxxx SERIES

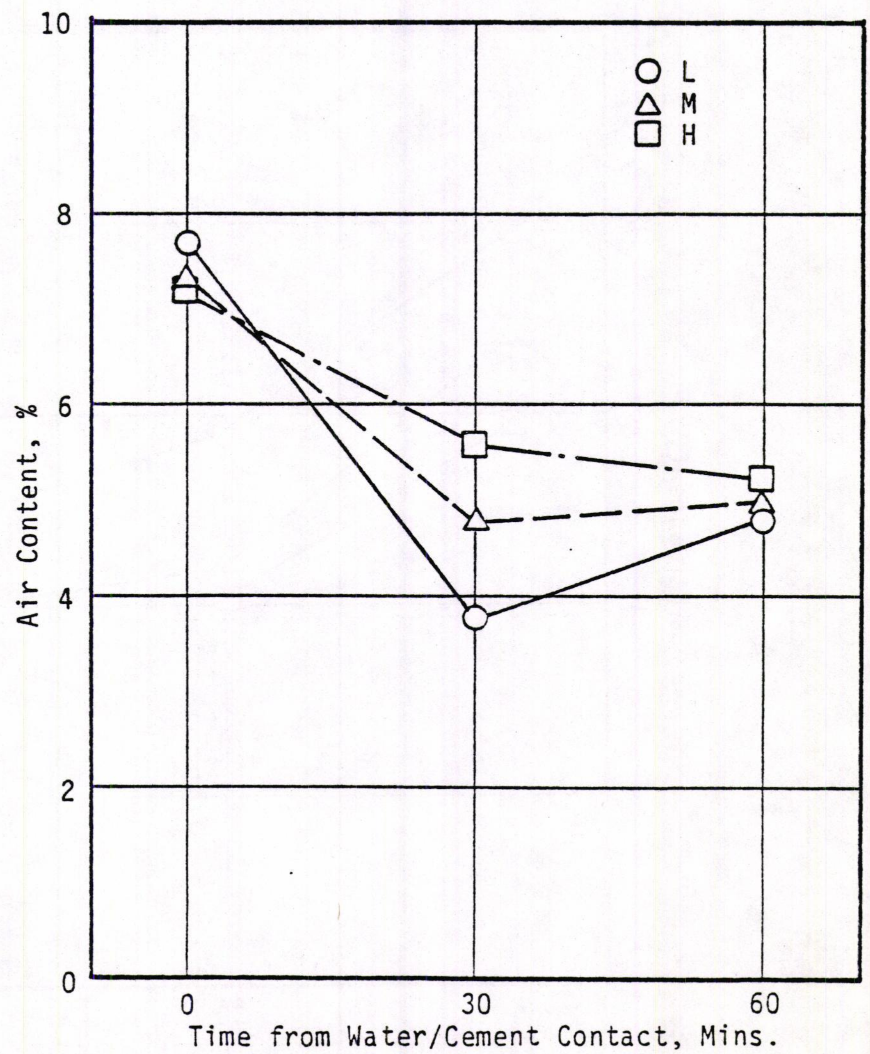


Figure 3.56 AIR CONTENT VARIATION, $\overline{C}$Axxx SERIES

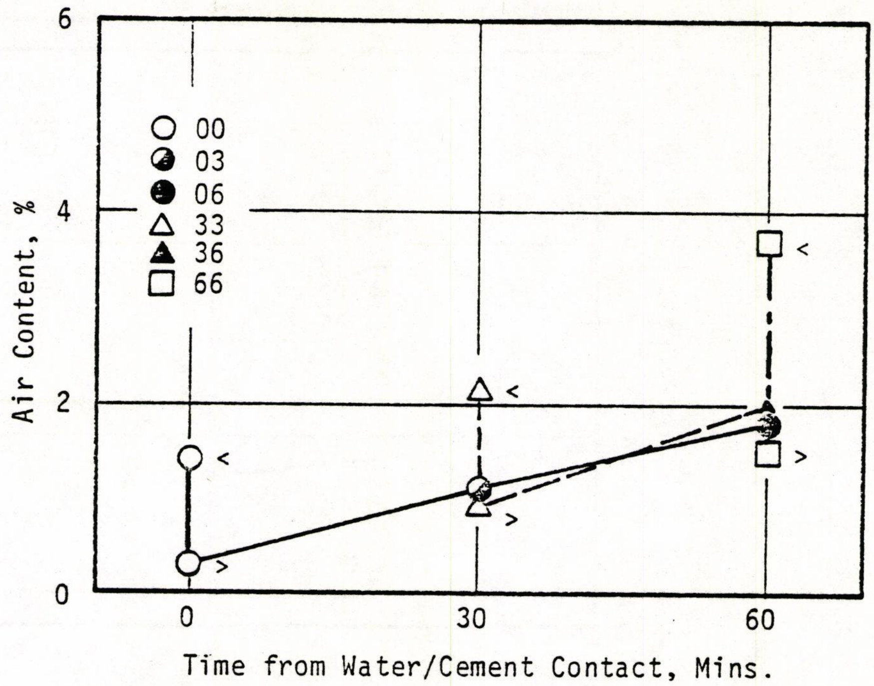


Figure 3.57 AIR CONTENT VARIATION, 1NLxx SERIES

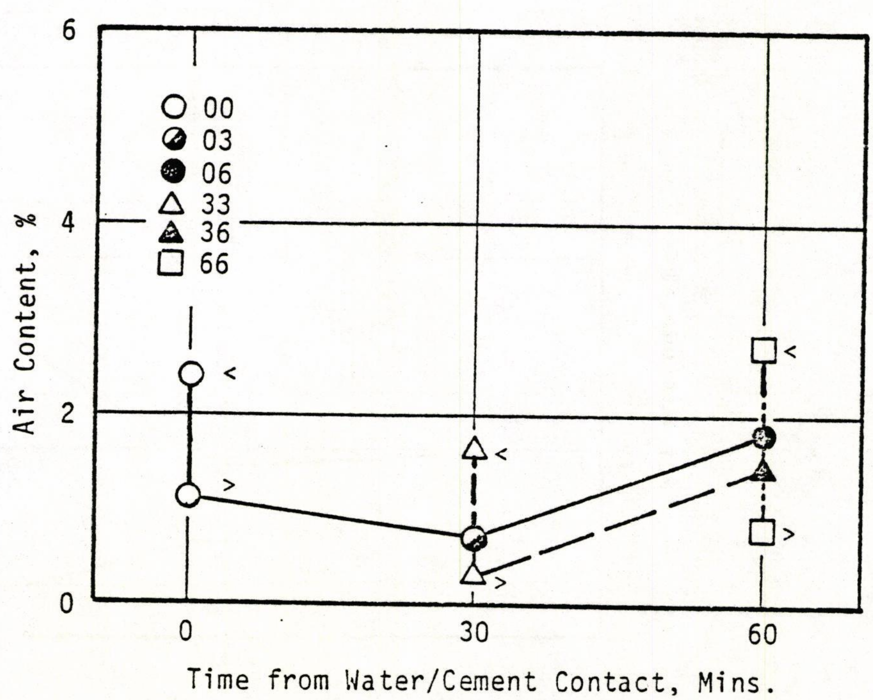


Figure 3.58 AIR CONTENT VARIATION, 1NMxx SERIES

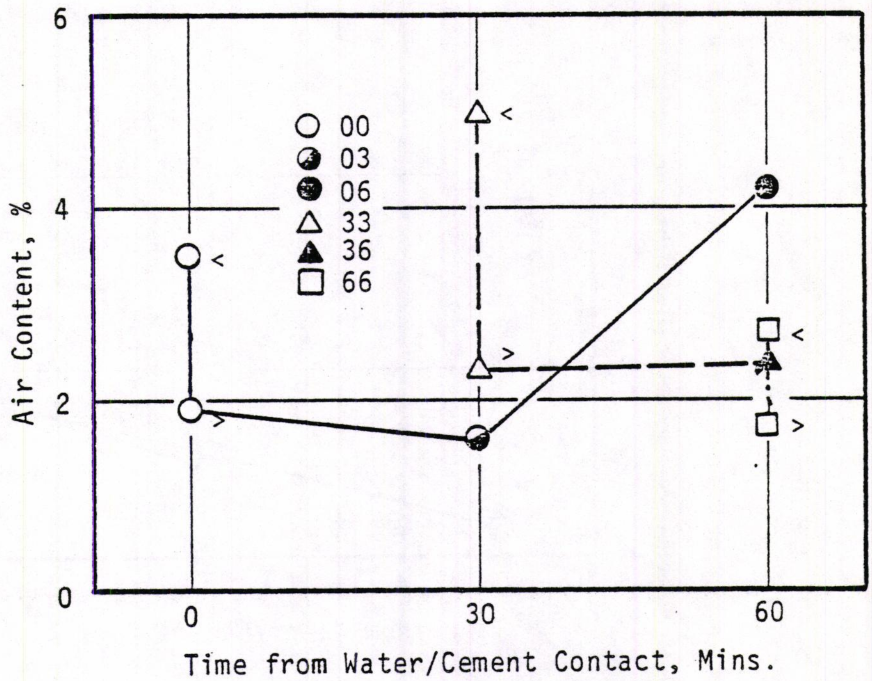


Figure 3.59 AIR CONTENT VARIATION, 1NHxx SERIES

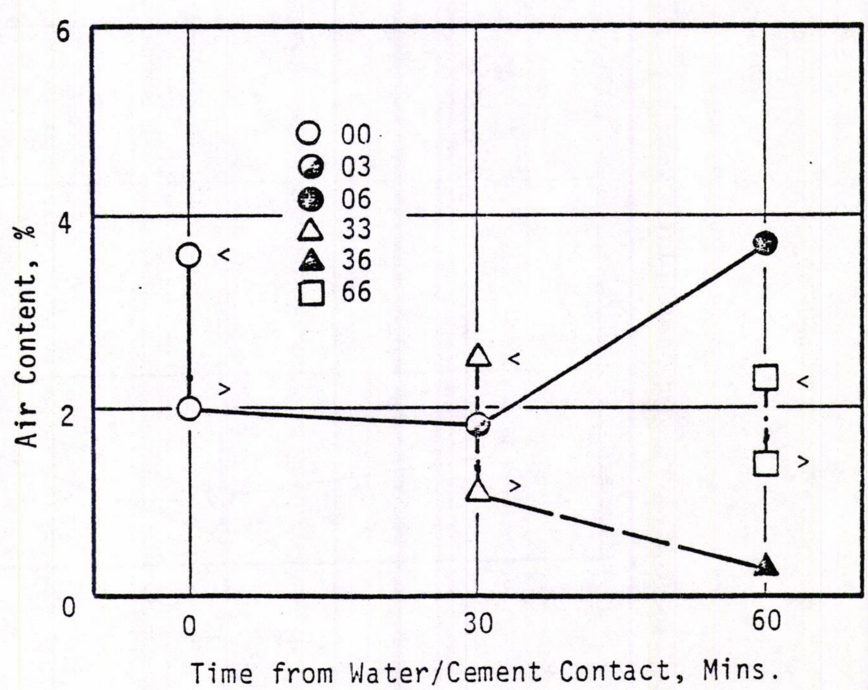


Figure 3.60 AIR CONTENT VARIATION, 1ALxx SERIES

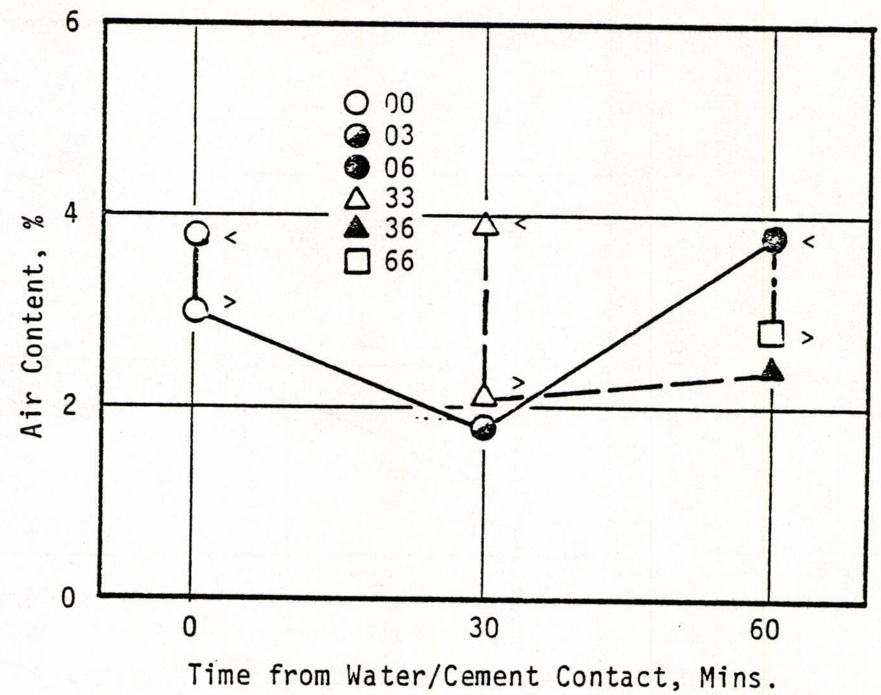


Figure 3.61 AIR CONTENT VARIATION, 1AMxx SERIES

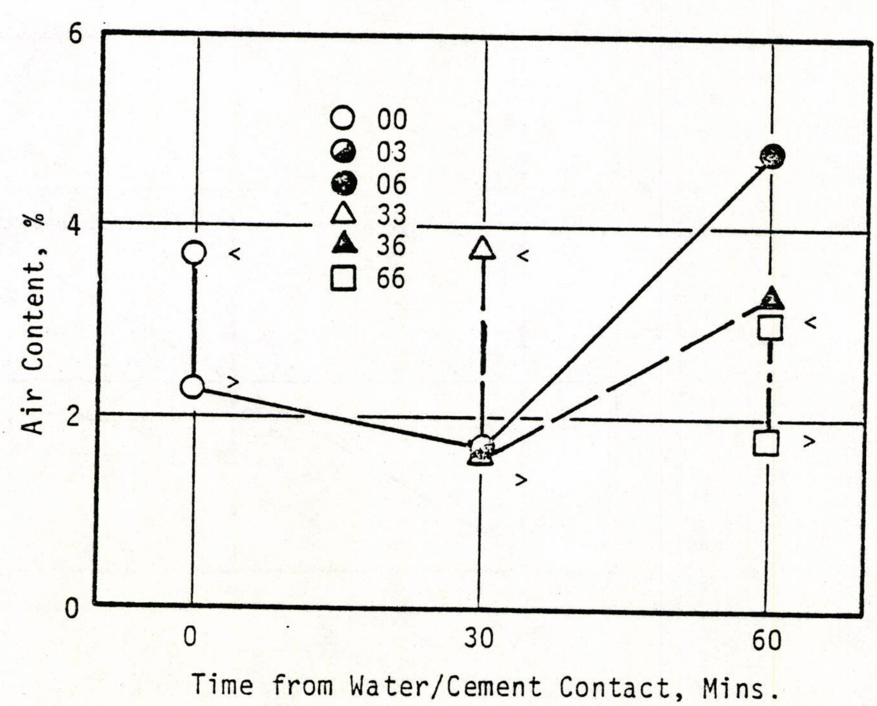


Figure 3.62 AIR CONTENT VARIATION, 1AHxx SERIES

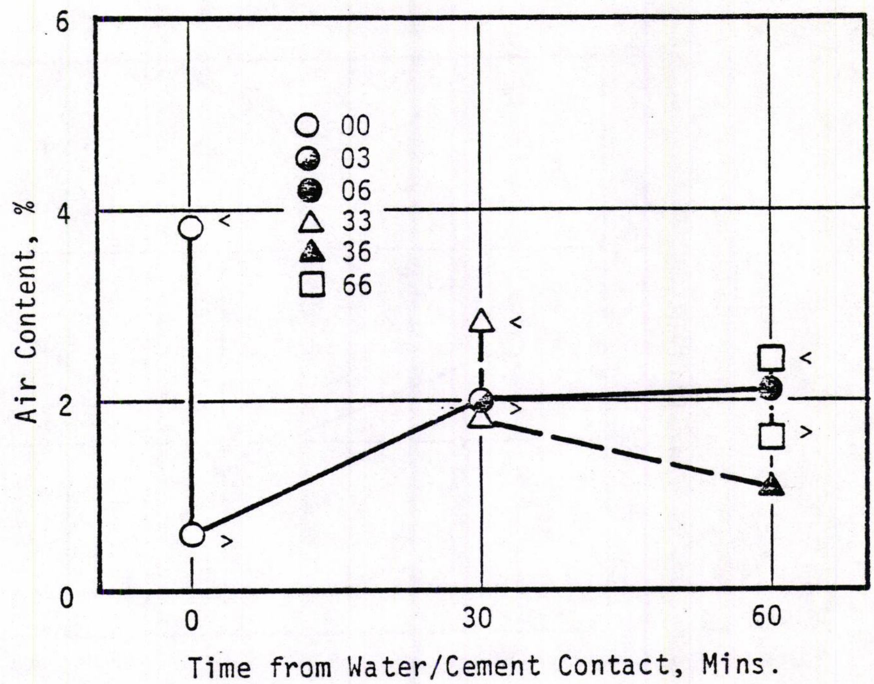


Figure 3.63 AIR CONTENT VARIATION, 2NLxx SERIES

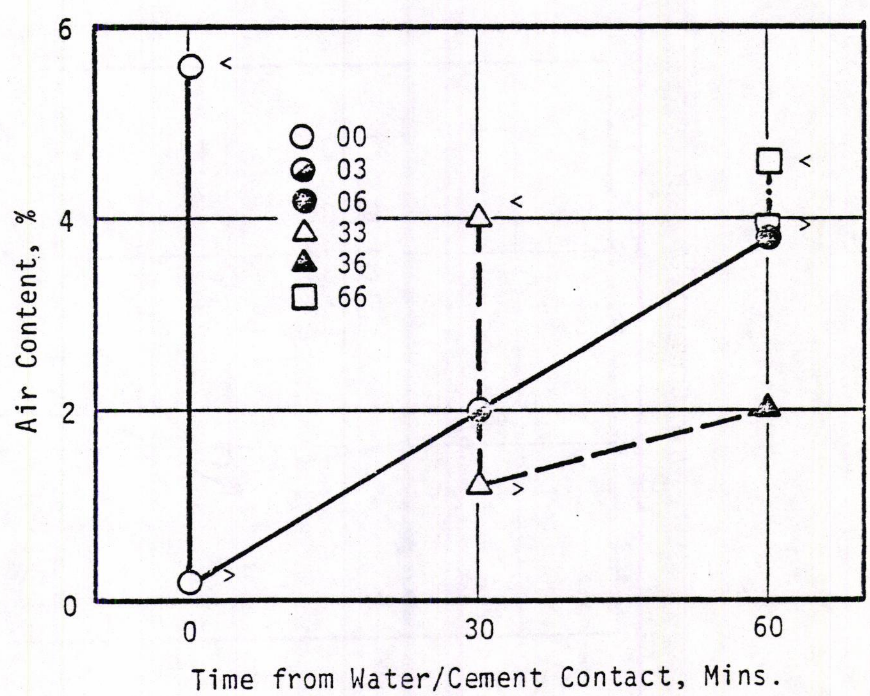


Figure 3.64 AIR CONTENT VARIATION, 2NMxx SERIES

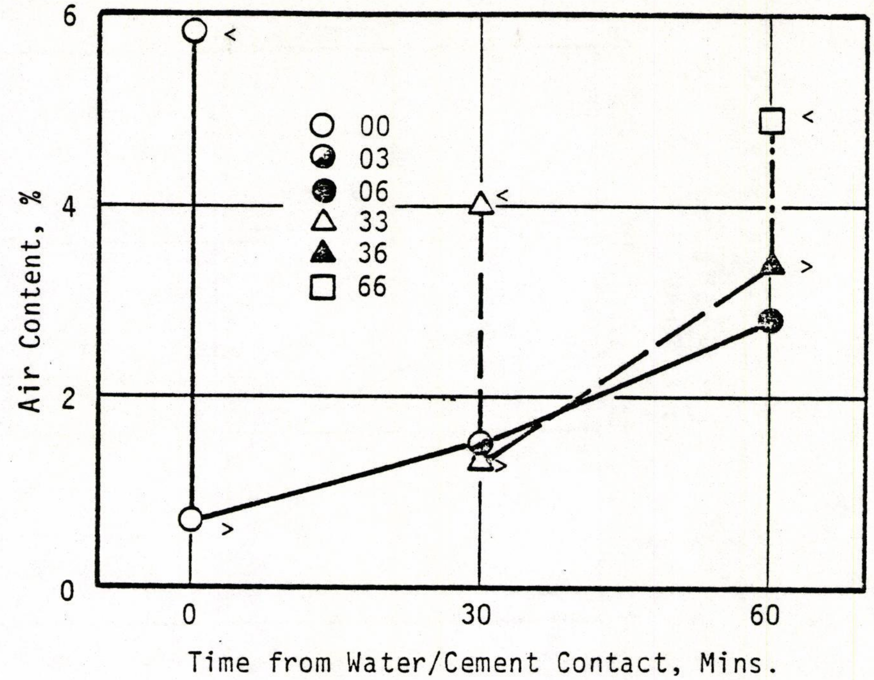


Figure 3.65 AIR CONTENT VARIATION, 2NHxx SERIES

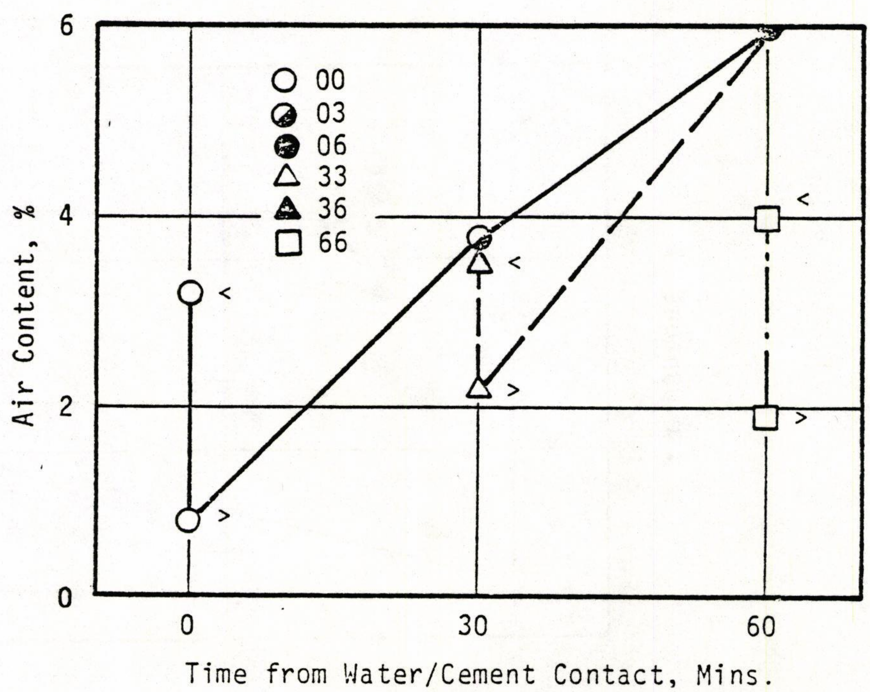


Figure 3.66 AIR CONTENT VARIATION, 2ALxx SERIES

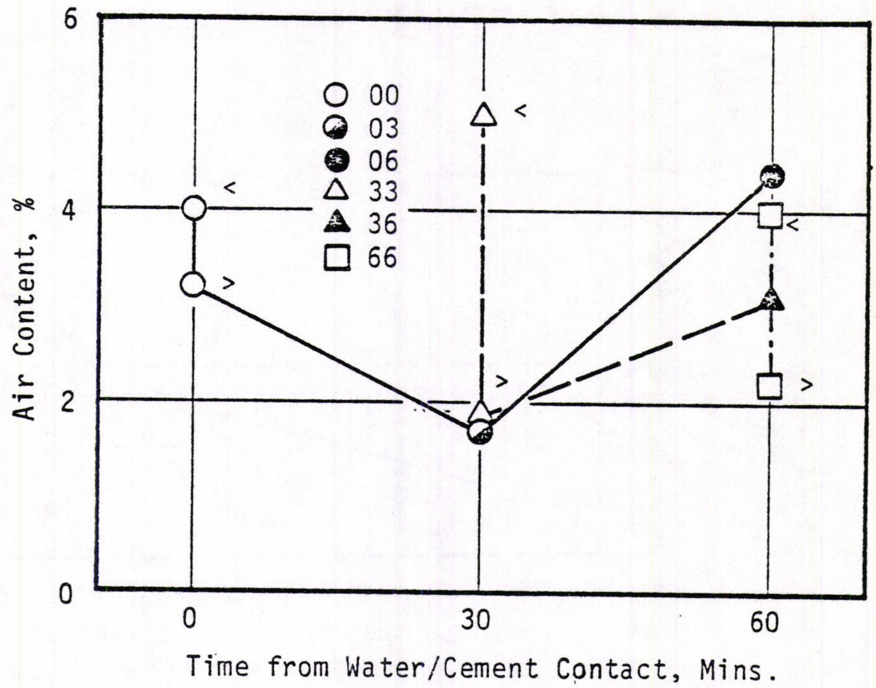


Figure 3.67 AIR CONTENT VARIATION, 2AMxx SERIES

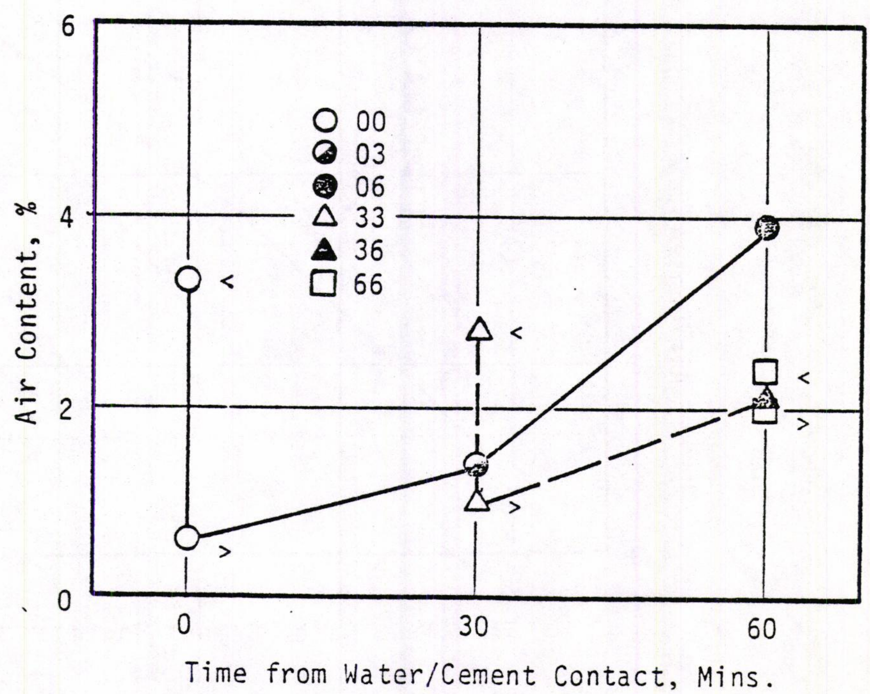


Figure 3.68 AIR CONTENT VARIATION, 2AHxx SERIES

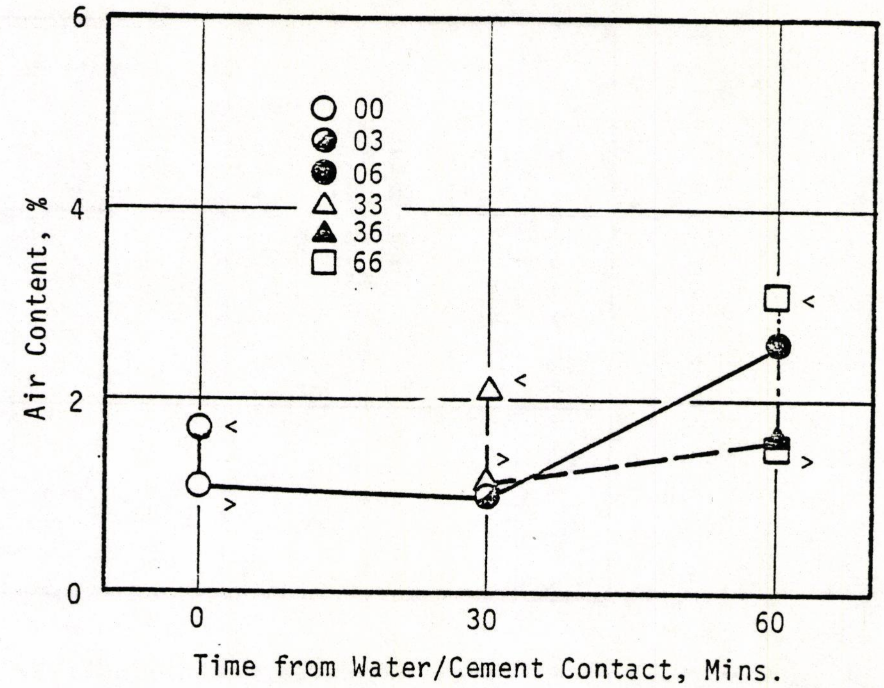


Figure 3.69 AIR CONTENT VARIATION, FNLxx SERIES

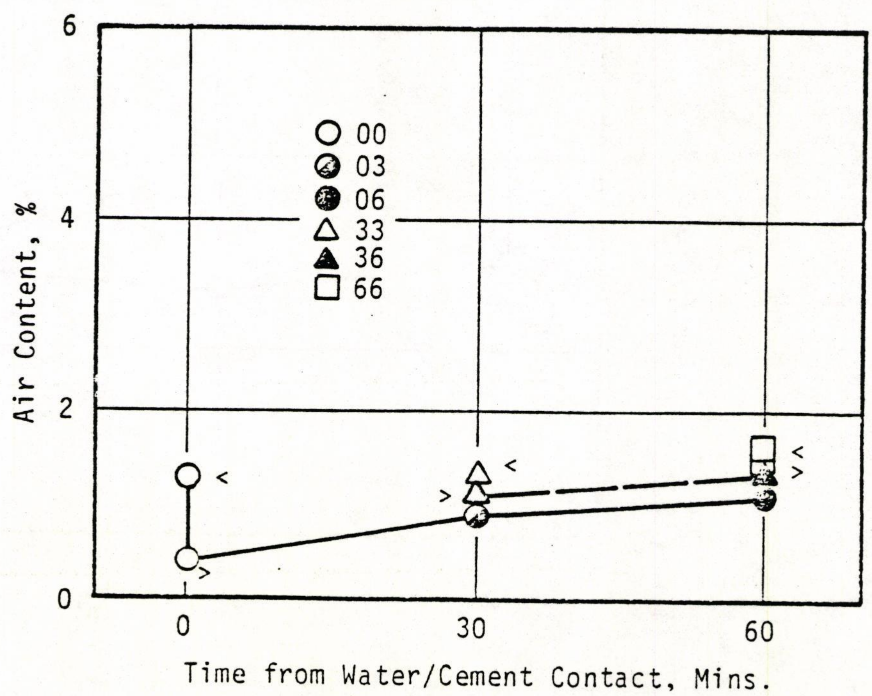


Figure 3.70 AIR CONTENT VARIATION, FNMxx SERIES

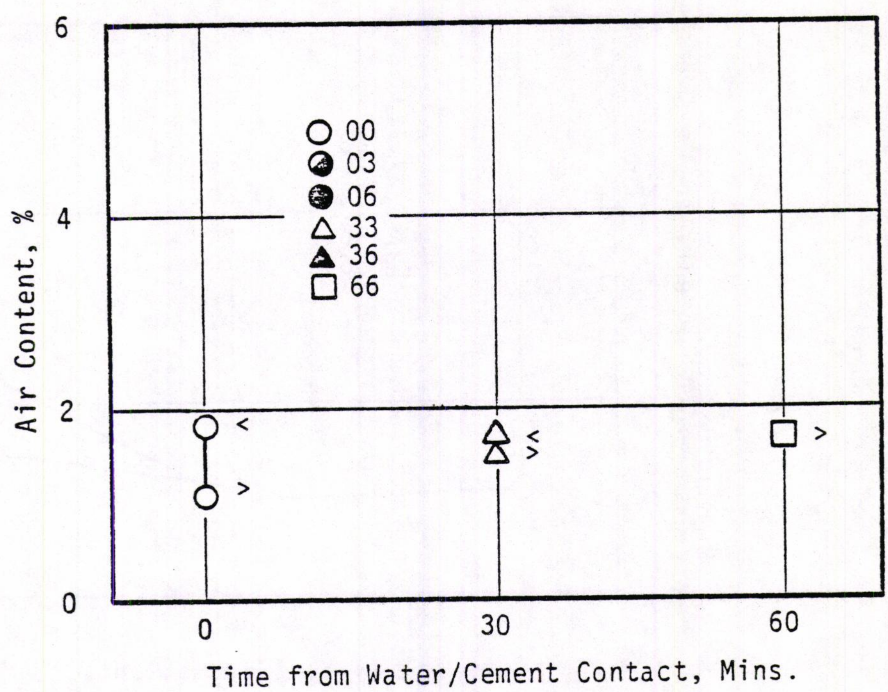


Figure 3.71 AIR CONTENT VARIATION, FNHxx SERIES

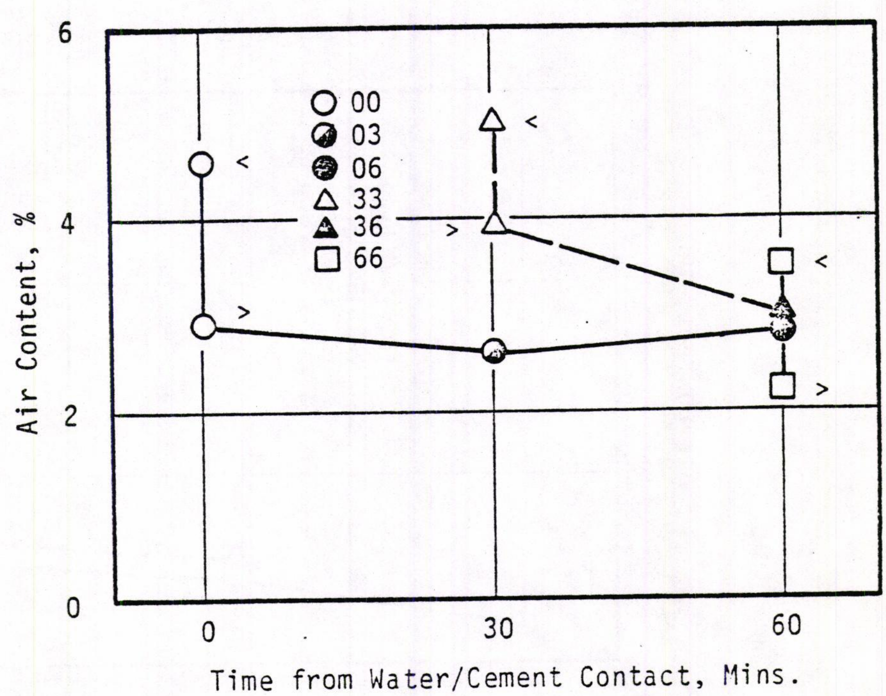


Figure 3.72 AIR CONTENT VARIATION, FALxx SERIES

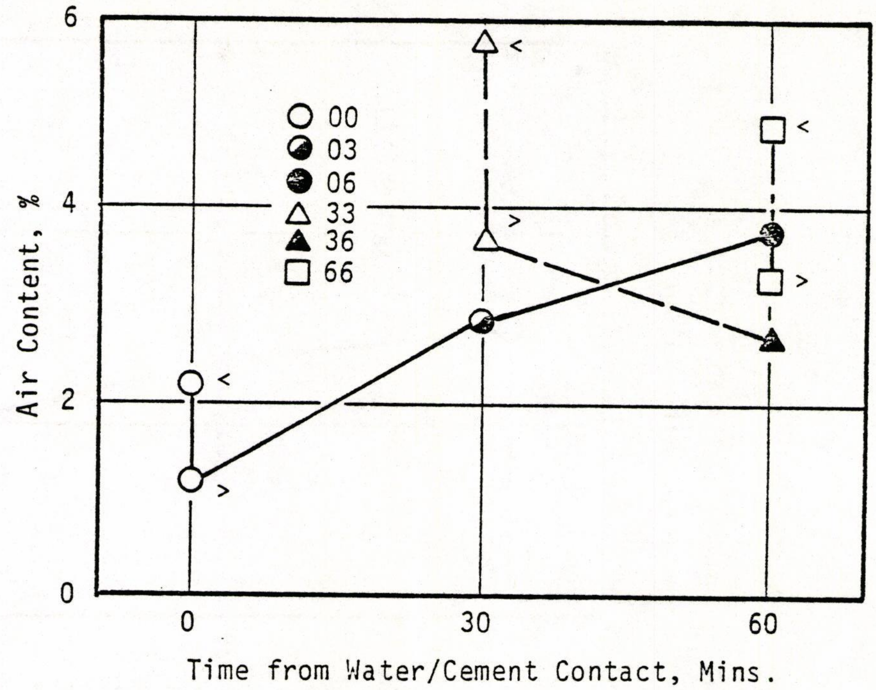


Figure 3.73 AIR CONTENT VARIATION, FAMxx SERIES

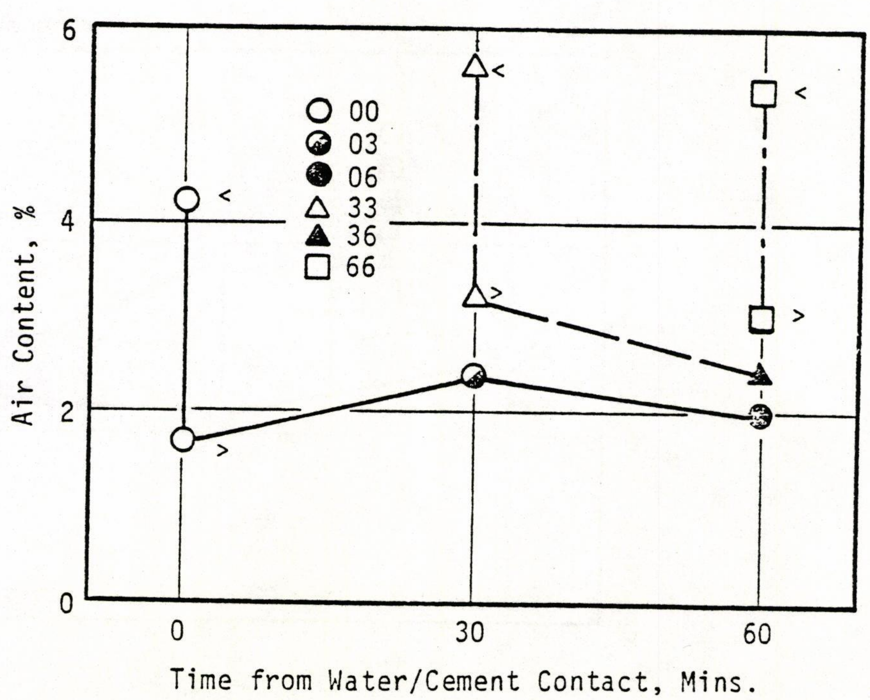


Figure 3.74 AIR CONTENT VARIATION, FAHxx SERIES

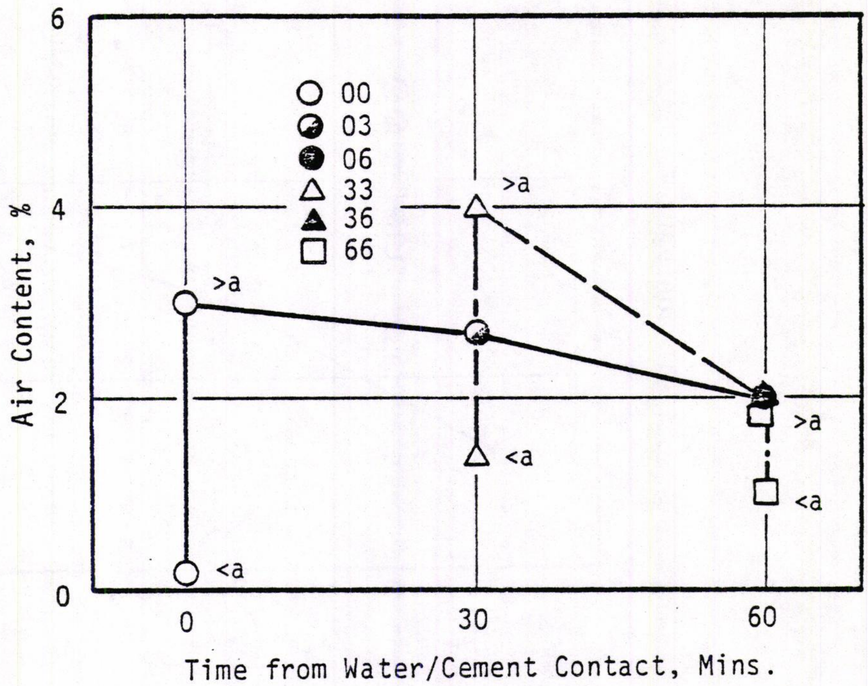


Figure 3.75 AIR CONTENT VARIATION, 1AM'xx SERIES

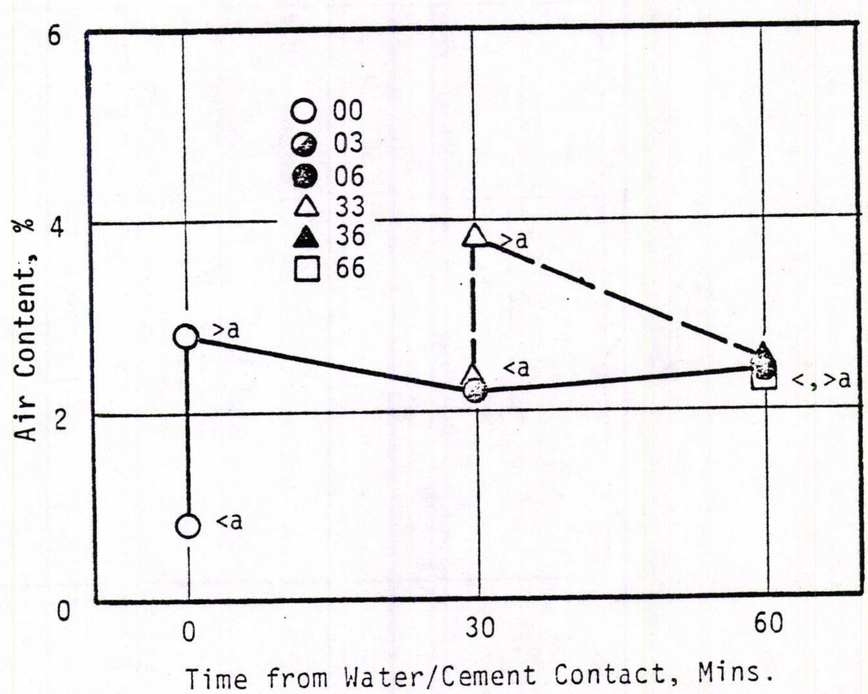


Figure 3.76 AIR CONTENT VARIATION, 2AM'xx SERIES

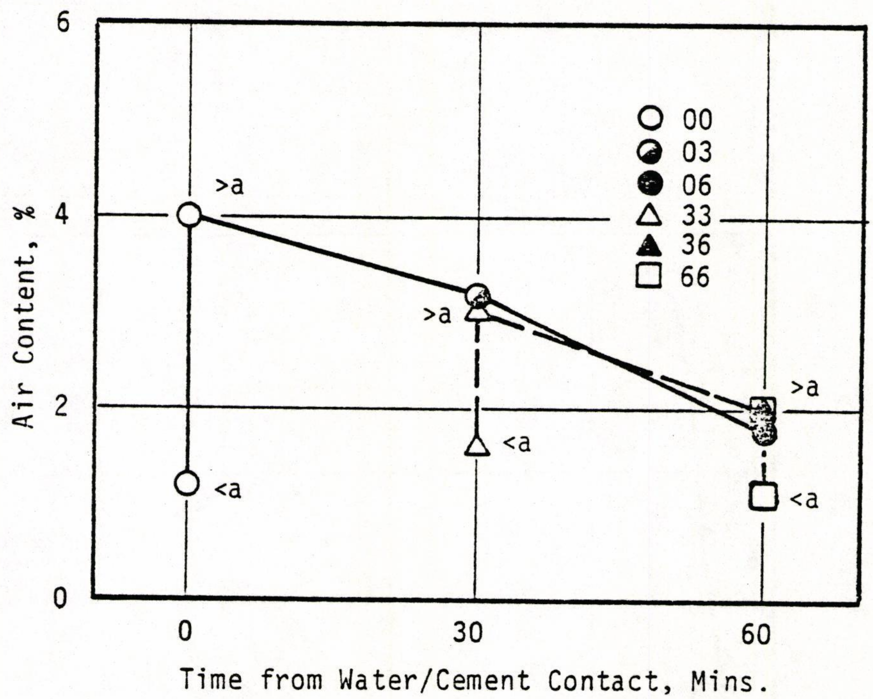


Figure 3.77 AIR CONTENT VARIATION, FAM'xx SERIES

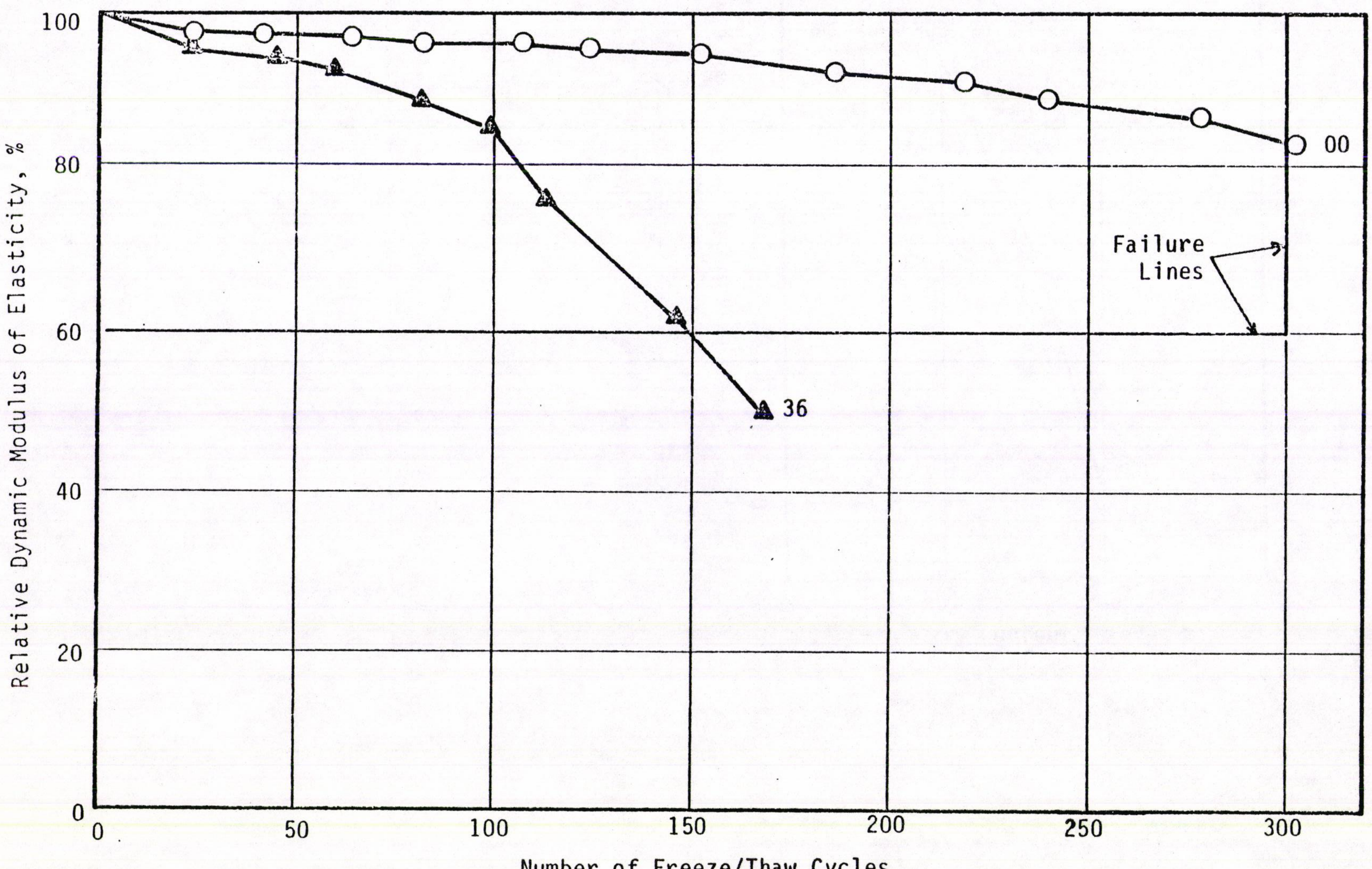


Figure 3.78 SAMPLE FREEZE/THA[hole punch] HAVIOR CURVES FROM 2AM'xx SERIES

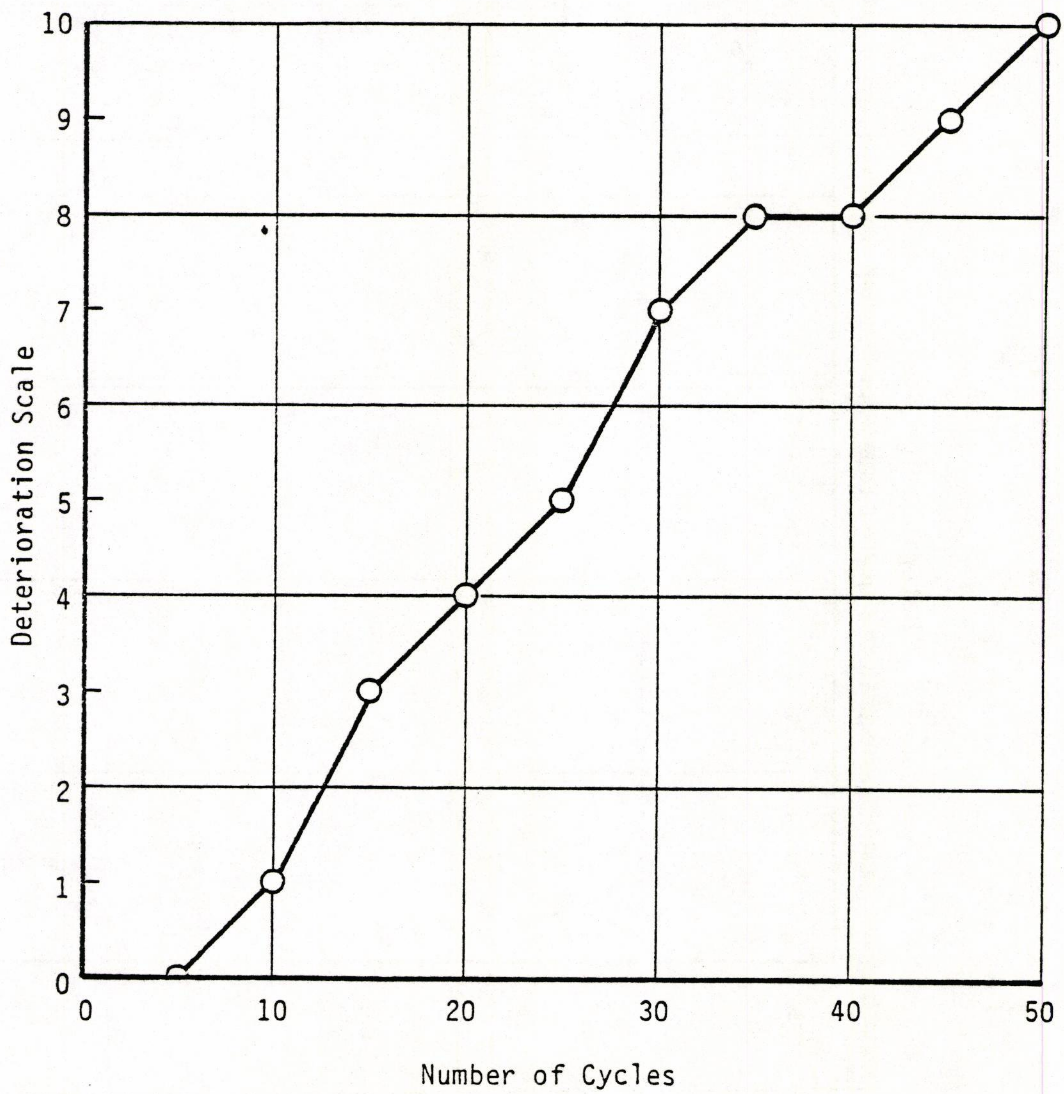


Figure 3.79 COMPLETE DEICER SCALING CURVE -- $\overline{C}$AL06 SPECIMEN

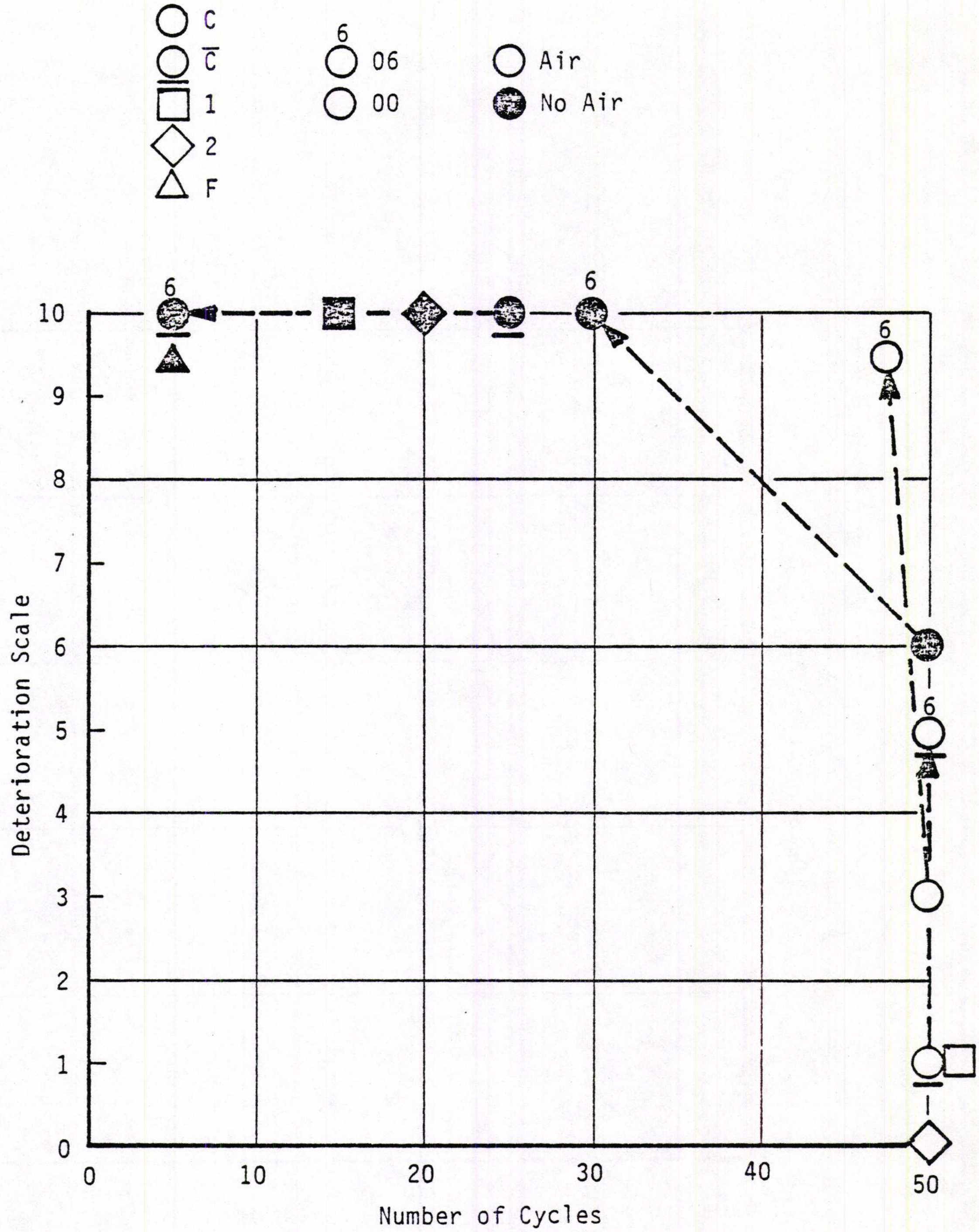


Figure 3.80 SAMPLE DEICER SCALING BEHAVIOR -- MIDDLE TEMPERATURE SPECIMENS

IV. CONCLUSIONS

The following conclusions may be drawn from the results of tests performed on specimens of plastic concrete as described in the two previous chapters. All of the conclusions listed below must be considered very general. They are based solely on the limited data received from the tests reported above. They are meant to serve only as guides to the expected plastic behavior of concrete mixes made with the particular superplasticizer studied. Actual behavior for a given project should be confirmed in each individual case by actual trial batching and standard tests.

Slump Loss with Time

The increased workability of superplasticized mixes as measured by slump is lost at a rate that exceeds that of control mixes of similar workability. The higher the amount of slump gained through the use of the admixture the more rapid the rate of slump loss. The additional workability is usually effectively lost within the first 30 to 60 minutes after SP addition. With adequate care in mix design and careful construction management, however, the full advantage of this early workability could be fully utilized.

Temperature has a marked effect on the workability achievable with the superplasticizer. Tests were made using only three target concrete temperatures, 50^{o}, 70^{o}, and 90^{o}F. The superplasticizer showed optimum performance at the middle temperature, greatly reduced performance at the lower temperature and significantly reduced performance at the higher temperature. The rate of slump loss was increased at higher temperatures.

Delay between the time of initial water/cement contact decreases the effectiveness of the same dosage of the superplasticizer. The degree of increased workability available with a particular dosage of the superplasticizer is very sensitive to small changes in the water content of the mix.

Air-entrainment seems important in helping the quality control of superplasticized mixes, expecially at high dosages and low temperatures. It may, however, increase the rate of slump loss in mixes in the flowing mode. Adding the air-entraining agent after the addition of the superplasticizer does not help the slump loss problem, although it may have other advantages described below.

Time of Set

For most mixes, both control and superplasticized, lower water/cement ratios will lower the time of initial set, but lengthen the period between initial and final sets. However, in comparison with control mixes, the use of the superplasticizer will shorten the period of set between 0.5 to 1.0 hours.

Higher temperatures and increased agitation before deposition shorten both the initial set and the period of set. Increased superplasticizer dosage will shorten the initial set somewhat proportionately.

Most of these effects are moderated slightly by the use of air-entrainment. But adding the air-entraining agent after the superplasticizer seemed to delay the setting approximately 1.0 hour. Most of the time of set variation is probably more a function of the water/cement ratio changes since there was very little change between the C and corresponding F series, indicating little change in set time when the change was in superplasticizer dosage without a corresponding change in water/cement ratio.

Bleed Water

More bleed water is available, of course, in high slump mixes rather than lower slump mixes. If bleeding is occasioned by the addition of superplasticizer, the longer the agitation before the superplasticizer is added, the less the bleed. The use of air-entrainment and sufficient fines renders the bleed water problem insignificant.

However, it should be noted that in mixes of high superplasticizer dosage, either in a water-reduced or flowing mode, the problem becomes more a problem of "mortar bleed", wherein a thin cement paste rises to the surface, rather than bleed water. Workers smoothing such a surface found it "tacky" with a tendency to stick to the trowel. Problems in finishing such a surface might be significant.

Air Content

In normal use of superplasticizing admixtures, if air-entraining agents are used in conjunction with them, the air-entraining agent is added to the original mix water and the superplasticizer added later in its own solution. In that kind of admixture addition sequence, the following behavior can be reported. The addition of the superplasticizer to a previously air-entrained mixture results in a loss of from 0.5 to 3.0% air content by volume. The larger the dosage, the larger the drop. Long additional agitation of flowing mode mixes will exhibit sometimes a recovery of from 1 to 1.5% air content. This recovery is highly erratic. The freeze/thaw results imply it is probably entrapped rather than entrained air.

If, however, in the few mixes tested, the air-entraining agent is added after the superplasticizer is added and mixed, there is little loss of air content even with continued agitation and the freeze/thaw resistance is greatly improved by comparison to control mixes.

Freeze/Thaw Resistance

Further agitation of mixes consistently lowers the freeze/thaw resistance. Thus, any recovered air content mentioned above is probably entrapped air. If specimens are cast soon after initial mixing of the concrete and adding of the superplasticizer, there is no problem in obtaining an 80% relative durability factor in comparison with control mixes. Except for mixes with very high dosage of superplasticizer, the relative durability factor is closer to 100%. If the air-entraining agent is added after the superplasticizer, the relative durability factor with respect to the control mixes is greater than 100%.

Deicer Scaling Resistance

Air-entrained superplasticized mixes perform as well as the corresponding air-entrained control mixes. Extended agitation substantial lowered the resistance of air-entrained control mixes and will probably do so in air-entrained superplasticized mixes unless the order of admixture addition is reversed.

V. LABORATORY STUDIES

5.1 Materials

The material to be tested in this part of the study was Portland cement concrete containing superplasticizer and an air-entraining agent. The concrete specimens were made of three different coarse aggregates. The primary aggregate used in most of the tests was an Arkansas limestone. In addition, representative tests were made with an Arkansas river gravel and some tests with an Arkansas sandstone. The fine aggregate in all cases was an Arkansas river sand.

5.1.1 Portland Cement

The Portland cement used throughout both parts of this study was a Type I Portland cement available in 94-pound bags manufactured by the Monarch Cement Company of Humboldt, Kansas. A chemical analysis of the major oxides in the cement was beyond the scope of the department's research facilities. However, samples were taken of each shipment and a composite sample made so that later tests may be conducted. No noticeable difference in the properties of the concrete seemed ever to be occasioned by the arrival of a new shipment.

5.1.2 Mixing Water

Mixing water used in all tests consisted of tap water supplied by the City of Fayetteville, Arkansas.

5.1.3 Aggregate

The major portion of the tests described below were done using the same Arkansas limestone for coarse aggregate as was used in the previous part of the study concerned with the plastic behavior of the concrete. In addition, two other typical Arkansas aggregates were used: a river gravel and a sandstone.

The river gravel was obtained from McClinton-Anchor Company of Fayetteville, Arkansas. The gravel, of 1-1/4" maximum size, was identified as having come from the Murfreesboro area of Arkansas. The quarry site for river gravel from the Murfreesboro area is located in Pike County, in Section 7, Township 8S, Range 25W, from a quarterrary terrace. Its bulk specific gravity was measured at 2.58 and its absorption with respect to saturated-surface-dry condition at 0.82%. Other tests on the same material done at other times [31] have shown an L.A. Abrasion (Grade C) of 21.3, a Na_2SO_4 soundness of 0.3, and a percent Insoluble Residue + #200 of 99.6.

The sandstone coarse aggregate was obtained from Arkola Sand and Gravel Company of Springdale, Arkansas. The sandstone, of 1-1/4" maximum size, was identified as having come from their Van Buren quarry in Crawford County, located in Section 4, Township 9N and Range 31W, a part of the Hartshorne formation. Its bulk specific gravity was measured at 2.52 and its absorption with respect to the saturated-surface-dry condition at 1.73%. Other tests on the same material done at other times [31] have shown an L.A. Abrasion (Grade C) of 26.5, a Na_2SO_4 soundness of 2.0, and a percent Insoluble Residue + #200 of 95.6.

The fine aggregate used in all tests of this part of the study described below was a river sand obtained from Arkola Sand and Gravel Company ready-mix plant in Fayetteville, Arkansas. Its bulk specific gravity w measured at 2.59 and its absorption with respect to the saturated-surface-dry condition at 0.41%. Gradation curves of representative samples of all aggregates used in this part of the study met the grading requirements of ASTM C33 for their size.

5.1.4 Superplasticizer

The same superplasticizer, Melment L10A, as used in the first part of this study was used also for the hardened tests.

5.1.5 Air-Entraining Agent

The air-entraining agent used throughout the entire project was Amex 210, also manufactured by the American Admixtures Corporation, and, therefore, assumably compatible with the Melment L10A superplasticizing admixture.

5.2 Organization of Variables

In the second major part of this study, Part B., emphasis was given to examining the properties of hardened concrete made with superplasticizers. The emphasis was, therefore, on the compressive strength, the tensile strength, and the surface hardness as measured by abrasion resistance.

These general qualities were measured with respect to several variables: 1) coarse aggregate type, 2) dosage of superplasticizer, 3) air-content range, and 4) cement factor. In all mixes, by comparison to the variables used in the first part of the study, the superplasticizer was added after initial mixing of the cement, water, and aggregate. The air-entraining agent was added after the addition and mixing of the superplasticizer with the concrete. In all mixes, the target temperature was held at 70^{o}F.

The three coarse aggregates have been described previously. The limestone coarse aggregate was used for a full range of tests. A set of representative comparison tests using only the middle cement factor was made with river gravel as the coarse aggregate, and a number of control comparison mixes were made with the sandstone.

In this series of tests, since compressive strength was of interest, mix designs were made using the water/cement ratio as one of the major variables to achieve the same workability. Thus, in all the tests of Part B, the dosage of superplasticizer was either none or the upper or lower bounds of the range of dosage recommended by the manufacturer, i.e., 20 fluid ounces per hundredweight of Portland cement or 40 fluid ounces per hundredweight.

The air-entraining agent was varied in quantities such as none, so a to achieve a target air content percentage of 4%, and such as to achieve a target air content percentage by volume of 7%.

Finally, the cement factor was utilized as a variable using three separate cement contents of 5.0, 6.0, and 7.0 sacks per yard (470, 564, and 658 pounds of Portland cement per cubic yard of concrete, respectively.)

The combination of these variables range led to the following logical combinations of variables and specimen identification code. Each specimen or separate "data point" was denoted by a combination of one symbol from each of the following columns:

Coarse Aggregate	SP Dosage	AEA Air Content	Cement Factor
L	C	N	L
G	1	1	M
S	2	2	H
	F		

The first column refers to the coarse aggregate type: L (limestone), G (gravel), or S (sandstone). The second column refers to the superplasticizer dosage: "C" for "control", i.e., no superplasticizer; "1" for a single dose of 20 fluid ounces per cwt of cement; "2" for a double dosage of 40 fluid ounces per cwt of cement; and "F" for a flowing concrete with sufficient superplasticizer to get the corresponding "C" mix with a 3" slump to an 8" slump, if possible.

The third column refers to the amount of air entrainment targeted: "N" for a mix to which no air-entraining agent has been added; "1" indicating 4% and "2" indicating 7% targeted air content by volume. The fourth column refers to the target cement factors; "L", "M", and "H" indicating 5, 6, and 7 sack mixes, respectively.

Thus, "L1NM" refers to a mix made with a single dosage of superplasticizer and no air-entrainment using limestone coarse aggregate and a cement factor of 6 sacks per cubic yard. "GC2H" would be a 7 sack mix using river gravel as a coarse aggregate with no superplasticizer but enough air-entraining-agent to give a 7.0% air content by volume.

The full set of unique combinations of variables used and the specimens cast in the second part of the study are given in Table 5.1 following. The total number of unique combinations of variables is 51.

5.3 Conduct of Tests

For each separate data point indicated in Table 5.1, a concrete mix was designed and confirmed by trial batching. From the results of work done in the first part of the study, it was much easier to achieve an adequate mix design than had been true earlier in the study. Nevertheless, it should be noted at this point that great difficulty was experienced throughout the study in being able to achieve repeatability between batches, even successive batches on the same day. Great care was taken in weighing, measuring the moisture content of the aggregates, etc., but the laboratory personnel still had large changes in workability in both directions for supposedly the same mix. The author has come to the conclusion that these difficulties were caused primarily by the combination of a great sensitivity in superplasticized concrete to small changes in moisture content and a scale factor. Most batches made in this study were done in a mixer for which the maximum batch capacity is 1.5 cu. ft. At that size, small unavoidable differences in moisture content would result in a larger percentage change in the workability than if the same magnitude of error were made in a larger batch. This difficulty will be addressed again in Chapter VIII, "Recommendations and Implementation".

For each separate data point, the following tests were made. Each will be discussed in more detail below:

1) slump after mixing was completed,

2) air content by volume after mixing was completed,

3) compressive strength,

4) tensile strength, and

5) abrasion resistance.

In addition, for certain selected data points, additional freeze/thaw specimens were cast to hold for later testing to confirm results found in the initial part of the study. To date, these specimens have not yet been tested.

5.3.1 Slump Tests

For each batch of each separate data point, the slump was measured to ensure compliance with the target workability of the mix. This target slump was either 3" $\pm$1/2" or 8" $\pm$1/2". The latter was applicable in the "F", or flowing mode, with respect to superplasticizer addition. In this latter case, the spread was also taken using the same modification of the German flow table specification as was described in the Cement and Concrete Association paper [1].

5.3.2 Air Content

For each batch of each separate data point, the air content of the mix was measured immediately after mixing to ensure compliance with the target air content of the mix. The measurements were taken in accordance with ASTM C231, using a Type B pressure air meter measuring to the nearest 0.1 percent by volume.

5.3.3 Compressive Strength

For each separate data point, fifteen standard 6" diameter by 12" high cylinders were cast in accordance with ASTM C 192 and tested in accordance with ASTM C 39 using a 400,000 pound capacity hydraulic cylinder tester. The specimens were tested at ages of one day, seven days, twenty-eight days, ninety-eight days, and one hundred ninety-six days. For each age and data point combination, three cylinders were tested and the mean result in pounds per square inch reported.

Because of the large number of specimens and the limited facilities available, the following curing procedure was consistently followed in the case of all cylinders, both tensile strength and compressive strength specimens. From the time forms were stripped, some twenty to twenty-four hours after casting, until the age of seven days, the cylinders were cured in cabinets meeting ASTM C 511, "Specifications for Moist Cabinets and Rooms Used in the Testing of Hydraulic Cements and Concretes". At the age of seven days, the cylinders which had not yet been tested were removed from the cabinets and placed in a submerged condition in fifty-five gallon drums at room temperature until the age of twenty-eight days. At that time, the remaining six cylinders for the long-term tests were removed from the drums, wrapped in a saturated material, encased in a double thickness of waterproof plastic bags, taped shut, and left in a constant temperature basement room. At no time were the specimens allowed to dry from their saturated condition once the curing process began at the occasion of form-stripping.

5.3.4 Tensile Strength

For each separate data point, three standard cylinders were also cast to serve as specimens for a twenty-eight day evaluation of the tensile strength of each mix by means of ASTM C 496, "Standard Method of Test for Splitting Tensile Strength of Cylindrical Concrete Specimens". The specimens had been cured continuously until the twenty-eight day age by the same method as described above for the compressive strength cylinders.

5.3.5 Abrasion Resistance

For each separate data point, three specimens were cast to be used in studying the abrasion resistance of the concrete. The specimens consisted of blocks six inches square in plan view and three inches high. They were cast in one layer, rodded twenty-five times, and struck off and troweled smooth in a light fashion. After twenty-eight days of curing consistent with the same methods used for both the compressive and tensile strength specimens, they were removed from curing and tested using an apparatus meeting the requirements of the U.S. Army Corps of Engineers Method CRD-C 52-54. The apparatus subjects the surface of the specimen to be tested to the rotary grinding action of wheel dressing cutters under a constant normal load of 4,400 grams. The cutting action is continued for a period of two minutes and the amount of abraded material evaluated by the difference in weight of the specimen.

Table 5.1 MIX VARIATIONS EXAMINED AND SPECIMEN MARKS

Limestone	Gravel	Sandstone
LCNL		
LCNM	GCNM	SCNM
LCNH		
LC1L		
LC1M	GC1M	SC1M
LC1H		
LC2L		
LC2M	GC2M	SC2M
LC2H		
L1NL		
L1NM	G1NM	
L1NH		
L11L		
L11M	G11M	
L11H		
L12L		
L12M	G12M	
L12H		
L2NL		
L2NM	G2NM	
L2NH		
L21L		
L21M	G21M	
L21H		
L22L		
L22M	G22M	
L22H		
LFNL		
LFNM	GFNM	
LFNH		
LF1L		
LF1M	GF1M	
LF1H		
LF2L		
LF2M	GF2M	
LF2H		

VI. RESULTS OF TESTS

This chapter describes the results of tests made of hardened concrete specimens made according to the system of variable organization described in the previous chapter. The emphasis here is on the effect of aggregate type, superplasticizer dosage, air content, and cement factor on the resulting compressive strength, tensile strength, and abrasion resistance. Although outside the intended original scope of the project, freeze/thaw specimens have been made of these mixes for later evaluation of freeze/thaw durability and confirmation of trends observed in the first part of the study concerned with the behavior of plastic concrete. At this writing, those additional freeze/thaw tests have not been made.

6.1 Compressive Strength

Table 6.1 lists the thirty-six limestone aggregate data points considered in this part of the study together with the following values. For each data point, the target cement factor in sacks/cubic yard is given, and the target water/cement ratio. On the basis of trial batching and mix design used in the first part of this study and subsequent continued batching in the second part, water/cement ratios were continually projected as reasonable for the next data points. These target water/cement values served as initial guides in the mix design and trial batching procedures for the hardened concrete data points. The next three columns of Table 6.1 give the actual resulting values for cement factor and two water/cement ratios. The first ratio contains the mix water provided divided by the cement provided. The second ratio also contains the water available from the superplasticizer itself. This second ratio is calculated by adding an equivalent amount of water found by multiplying the milliliters of superplasticizer used by its specific gravity of 1.1 and then by a factor of 0.8, which represents the proportion by weight of the superplasticizer that is water.

The discrepancies between the intended and actual values are in part a result of the actual effects of the variables under study and in part the result of the problems of repeatability referred to earlier. These problems of repeatability are understood as a result of the interaction of the sensitivity of the superplasticized concrete to small changes in water content and the scale factor incumbent in the size of the mixer. Thus, the results obtained in this part of the study should not be taken as data that can be precisely repeated but as indicative of trends.

The next column is the superplasticizer dosage and the following column is the measured air content of the mix. The superplasticizer dosage is 0, 20, or 40 fluid ounces per hundredweight of Portland cement for the xCxx, x1xx and x2xx mixes respectively. The first dosage represents a control mix with no superplasticizer. The next two dosages represent the upper and lower recommended dosages of the manufacturer. In these two types of mixes as well as the control mixes, water was used as the variable to bring the mix to the proper workability. The xFxx mixes are "flowing" concrete of a target slump of 8 inches. In these mixes, the water/cement ratios, etc., of the corresponding control mixes were roughly followed and the superplasticizer used as a variable to give the greatly increased slump of 8 inches. When the air content was small in the control mix, that was somewhat difficult to do and problems of normal bleeding or "mortar bleed" as well as segregation were more pronounced. As the air content of the mixes increased, it was easier to achieve the desired change in slump with the same water/cement ratio.

The next to last column in Table 6.1 is the 28-day compressive strength of the mix based on the average of three cylinders. That data will be enlarged later.

Table 6.2 contains the same data as Table 6.1, but now for the twelve mixes for which gravel was the coarse aggregate and for the three control mixes for which the previously described sandstone was the coarse aggregate.

Table 6.3 gives the compressive strength and tensile strength results from the hardened specimens in a more expanded fashion. In addition to the specimen mark and the casting date, the table lists, where available, the compressive strength in psi at one, seven, twenty-eight, ninety-eight and one hundred ninety-six days. The two latter ages of specimen were not always achieved. For a number of specimens cast in the later stages of the study, time was not available for these long-term tests. A few changes from the targeted ages of specimen are noted in the tables. The next to last column is the 28-day tensile strength, f'_{sp}, of the indicated mix based on the average of three split-cylinder tests. The last column of the Table gives a non-dimensional factor, $f'_{sp}/\sqrt{f'_c}$, which will be useful in correlating the tensile strength, f'_{sp}, to the square root of the corresponding 28-day compressive strength result, f'_c. Table 6.4 gives the same data for the gravel and sandstone mixes.

Figures 6.1 through 6.12 plot the same data as Table 6.3 in compressive strength in psi versus age of specimen in days plotted on a logarithmic scale. This semi-logarithimc plot was chosen to be able to see more smoothly and easily the rate of increase of strength with time.

Each figure shows curves for three different mixes with the same first three variable indicators; that is, the three in each figure differ only in the cement factor.

Figures 6.12 through 6.17 plot the same data as Table 6.4 in a similar semi-logarithmic plot. For these figures, all cement factors are "M" corresponding to a target cement factor of 6 sacks per cubic yard. The three different mixes represented in each of these five figures differ only in air content. The three curves on each of these figure represent target air contents of 0, 4, and 7 percent by volume.

6.1.1 General Observations

A number of general observations may be made from the tables and figures referred to above. In data of this type, even with the typical scatter of concrete research results as well as the problems with repeatability experienced in this study, one will expect relatively smooth results with time. However, there are a few curves that exhibit anomalies that should be noted. The strength with time curve from LCNM is erratic and the 196-day results for all three members of the LCN series plotted in Figure 6.1 seem unrealistic. Also, the curve of L12M is similarly erratic as is the 196-day result for LF1M. All of the rest of the stress capacity versus age curves seem fairly smooth and reasonable.

A general trend that can be noted in almost every one of the first twelve figures in this chapter is that strength increases with richness of the mix. The low, medium, and high cement factor curves usually exhibit the same sequence of lower to higher 28-day strength. One exception is that the 28-day strength LC2L is greater than LC2M, but the water/cement ratio of the former is lower than that of the latter, indi cating perhaps again a repeatability problem in water content with respect to a desired workability. Another exception is that L12L strength is greater than L12M strength at 7 days, but this is probably a problem of scatter.

A third rather obvious trend is the lowered water/cement ratios with the use of superplasticizer and the corresponding increase in strength. This will be discussed in more detail later. In addition, however, it should be noted that as the superplasticizer dosage is increased and the water/cement ratio is lowered for the same workability, that the character of the strength versus time curve changes. First, the early strengths increase rather dramatically, but also the latter part of the curve for long-term strengths becomes increasingly flatter. This indicates an increased rate of hydration with the use of superplasticizer. This is consistent with the pictures and discussion of the Cement Association paper [1], which speaks of the dispersing nature of the superplasticizers and the maintaining of fineness of the Portland cement agglomerates during the early stages of hydration. This tendency is especially noticeable in the results of the L22M, L22H, and G22M curves of Figures 6.0 and 6.15.

Figure 6.18 is a plot of 28-day compressive strength (f_c') versus nominal water/cement ratio for all mixes. "Nominal water/cement ratio" indicates the water/cement ratio calculated using the indicated mix water. Figure 6.19 is the same type of plot, but uses the water/cement ratios, where applicable, that include the water provided in the superplasticizer itself. The lines drawn on these Figures are "best fit" lines drawn by the simple method of extended differences. Under time considerations with respect to finishing the report, and the general scatter of concrete compressive strength results, the author did not try for a more accurate non-linear curve fit. The data should be expected to give a curved best fit, especially in the lowest water/cement ratio values. However, for the middle range of water/cement values, the curve would be very flat and the straight line fit does have some value.

The three lines drawn on each of the two figures are fits for points that have the same target air content. The general effect of air content on strength will be discussed in more detail below. The results show very good correspondence with Abrams' law and the increase of strength with reduction of water/cement ratio. The scatter is not too pronounced despite the repeatability difficulties that were experienced. This would reinforce again the notion that the workability is sensitive to small changes in water content in superplasticized concrete.

6.2.1 Effect of Air-Content on Compressive Strength

The best fit straight lines drawn on Figures 6.18 and 6.19 emphasize the influence of air content on compressive strength of the mixes. There was some range in the actual values of measured air versus the targeted values. Those ranges, however, were always within the ±1.0% and usually much closer to the target values. Using a water/cement ratio of 0.45 that is roughly the midpoint of the flatter portion of the actual curves, there is 18.1% loss of strength between the "non-air-entrained" value and the targeted 4% air content line strength, and a 30.6% loss between the "non-air-entrained" value and the targeted 7% air content line for Figure 6.18. These respective values are 16.2% and 32.13% loss when calculated using Figure 6.19. These values appear to be not uncommon. For example, in a popular PCA manual [32], the loss between a "non-air-entrained (no percentage given) for 28-day strength for the same water/cement value is approximately 21%.

Of course, this kind of major loss of strength due to air content is not normally appreciated because the extra workability coming from the air entrainment allows for a lower water/cement ratio and corresponding increased strength by comparison to the original non-air-entrained mix.

That effect is seen in Figures 6.20 and 6.21. Each plot 28-day compressive strength versus air-content for specimens with 3 inch target slumps. Figure 6.20 contains data for limestone mixes using limestone as the coarse aggregate, and 6.21 is for gravel and sandstone mixes. Each set of three inter-connected points have the same mix variables except air content. That is, the sequence of points shows the effect on compressive strength as the air content is increased and the corresponding needed water content is reduced. The two digit indicators at the beginning and end of each broken-line show the superplasticizer dosage and cement factor for the three data point mixes of the line. The general trend shows a slight increase or reduction of strength as the air content is increased from "non-air-entrained" to a target air content of 4% followed by a slight to moderate decrease in strength as the air content is further increased to a targeted 7%. There are several curves that do not show this type of behavior and the anomalies of each of those curves seem to be associated primarily with the middle points. Such middle points are labeled and their points on Figures 6.18 and 6.19 are marked with an under-bar. The points on these later figures seem close to the appropriate f'_c versus water/cement ratio lines. It would appear, therefore, that these anomalies are again caused primarily by difficulties with repeatability in relation to the water content versus workability. In any case, it should seem that close quality control should assure relatively moderate loss of strength with increased air content for the same workability.

6.1.3 Effect of Aggregate Type on Compressive Strength

Figure 6.22 is a replotting of part of the data from Figures 6.20 and 6.21. All data points are of a medium cement factor, 6 sacks per cubic yard, target value. The type of aggregate is indicated by the shape of the data point as described by the legend. The single digit notation at the beginning and end of each curve gives the superplasticizer dosage for the three points of each curve.

A comparison of the limestone points with the gravel points indicates a value in the order of 500 psi extra strength coming from the use of the gravel. It would seem that the extra smoothness and lack of angularity of the gravel as compared with the limestone gave sufficient extra workability to allow a lowered water/cement ratio and thus increased strength. The one curve available for sandstone comparison is a "control" curve which, like the limestone "control" curve, is atypical. However, it would appear that a best fit line for the two would be fairly close with the sandstone curve higher than the limestone. The sandstone is also fairly angular and sandstone mixes with larger superplasticizer dosage could well have given smoother results, probably in the same range of strength as the limestone. The actual strength of the aggregate themselves are not factorable from this data.

6.1.4 Effect of Cement Factor on Compressive Strength

Figure 6.23 plots 28-day compressive strength versus cement factor for all limestone mixes. All the gravel and sandstone mixes were medium cement factor (target of 6 sacks per cubic yard). The curves demonstrate increased strength with increased richness of mix in the order of about 750 psi increased strength per sack from a 5 to a 6 sack mix, and approximately 500 psi increased strength as the richness is increased from 6 to 7 sacks per cubic yard.

6.1.5 Effect of Superplasticizer Dosage on Compressive Strength

Figure 6.24 plots nominal water/cement ratio versus superplasticizer dosage for all the limestone aggregate mxies of 3 inch target slump. Figure 6.25 does the same for the gravel aggregate mixes. There are several obvious irregularities in the shape and slopes of the curves, again due most probably to difficulties in repeatability from batch size. Nevertheless, there is enough uniformity in general slope in the two figures to be able to evaluate a general reduction in water/cement ratio per ounce of superplasticizer per hundredweight of Portland cement in the mix. These water/cement reductions combined with the compressive strength versus water/cement ratio lines of Figure 6.18 give the following general results for this particular superplasticizer when mixed with the examined Arkansas material. The extra compressive strength gained by the use of this particular superplasticizer ranges between 18 to 35 psi/ounces/cwt with the predominant rate being 20 psi gain/ounce/cwt of Portland cement.

6.2 Tensile Strength

Three cylinders for each mix were tested at twenty-eight days by means of the split cylinder test (ASTM C 496) for the tensile strength of that mix. The penultimate column of Tables 6.3 and 6.4 contains the results expressed in psi. Tensile failure in concrete usually correlate with the square root of compressive strength. It is often modeled by some constant times such a square root. The modulus of rupture from beam tests is often modeled as 7.5 $\sqrt{f'_c}$, or 6.0 $\sqrt{f'_c}$ in the presence of orthogonal compressive stress. The last column of Tables 6.3 and 6.4 contains, therefore, the tensile strength results of the split cylinder tests divided by the square root of the corresponding 28-day compressive strength.

That ratio of $f'_{sp}/\sqrt{f'_c}$ for all the limestone mixes is plotted versus 28-day compressive strength, f'_c , in Figure 6.26 and for the gravel and sandstone mixes in Figure 6.27. The mean for the limestone mixes is 6.81 with a standard deviation of 0.66 if all the points are considered. If the three top points above 7.5 are discarded and the two bottom points below 5.8 are also discarded, then the mean remains 6.81, but the stand deviation becomes 0.35. Thus, it seems reasonable to say that the split cylinder strength for the limestone mixes may be predicted by $(6.8 \pm 0.7) \sqrt{f'_c}$. This ratio is normally in the range of 6 to 7 for hard-rock concrete [33] and the modulus of rupture is usually between 1.25 to 1.75 f'_{sp} . Thus, our results seem quite reasonable and one might expect an actual f_r value between 8.5 to 11.9 times $\sqrt{f'_c}$.

The mean for the twelve gravel specimens is 6.17, with a standard deviation of 0.42. This is insufficient specimens to get a firm value for the $f'_{sp}/\sqrt{f'_c}$ ratio, but it would seem to be in roughly the same range of value as the limestone.

The three values available for the sandstone give a lesser mean value of 5.38. The split cylinder test often fails through the aggregate as well as the Portland cement matrix. Therefore, these values may we represent a reduced value of tensile strength of the sandstone as compared with the limestone and gravel.

6.3 Abrasion Resistance

Table 6.5 lists mixes and the average weight loss in grams for three specimens for each mix. The procedure followed was described in the previous chapter. The losses were all quite small, most under 1.0 gram. Figure 6.28 plots the average loss in weight versus the 28-day compressive strength of the same mix. No pattern emerges from this data except that most values are under 1.0 gram loss. Eliminating the four data points greater than 1.0 gram, the mean is 0.40 gram for all aggregates with a standard deviation of 0.25, putting essentially all data within the 1.0 gram loss range.

The concrete strengths are obviously great enough to ensure adequate wear resistance for normal usage.

TABLE 6.1. MIX VARIABLES AND 28-DAY COMPRESSIVE STRENGTH - LIMESTONE AGGREGATE

Data Point	Target Cement Factor	Target W/C Ratio	Actual Cement Factor	Actual W/C Ratio	Actual W/C Ratio with SP	SP Dosage Oz/cwt	Air Content Percent	28-Day Strength psi
LCNL	5	.60	5.12	0.601	-	0	0.6	4200
LCNM	6	.50	6.24	0.503	-	0	1.6	4304
LCNH	7	.42	7.16	0.422	-	0	0.6	5247
LC1L	5	.48	4.86	0.481	-	0	3.2	4190
LC1M	6	.42	5.92	0.396	-	0	4.0	5080
LC1H	7	.38	6.81	0.371	-	0	4.5	5290
LC2L	5	.44	4.72	0.437	-	0	6.6	3845
LC2M	6	.38	5.60	0.443	-	0	7.1	3776
LC2H	7	.36	6.95	0.371	-	0	6.2	4827
L1NL	5	.51	5.02	0.545	0.555	20	1.0	4044
L1NM	6	.43	5.73	0.457	0.469	20	1.1	5336
L1NH	7	.36	6.93	0.430	0.441	20	1.2	5648
L11L	5	.44	4.98	0.511	0.524	20	4.2	3542
L11M	6	.40	5.86	0.371	0.380	20	4.3	5370
L11H	7	.34	6.84	0.342	0.352	20	4.5	5726
L12L	5	.40	4.77	0.400	0.412	20	7.1	4248
L12M	6	.36	5.77	0.360	0.372	20	7.2	4878
L12H	7	.34	6.84	0.322	0.333	20	7.4	5136
L2NL	5	.52	5.08	0.515	0.538	40	0.6	4428
L2NM	6	.44	6.03	0.419	0.442	40	0.7	5578
L2NH	7	.38	7.05	0.321	0.344	40	0.9	6202
L21L	5	.37	4.72	0.352	0.375	40	4.0	5320
L21M	6	.32	5.75	0.341	0.364	40	4.0	5534
L21H	7	.30	6.75	0.297	0.320	40	4.3	5960
L22L	5	.34	4.83	0.345	0.368	40	7.6	4628
L22M	6	.31	5.92	0.284	0.307	40	7.6	5411
L22H	7	.28	7.00	0.257	0.280	40	6.2	6346
LFNL	5	.57	4.95	0.548	0.592	76.2	0.5	4366
LFNM	6	.46	6.00	0.463	0.472	16.2	0.5	5355
LFNH	7	.42	6.98	0.419	0.430	19.4	0.9	5829
LF1L	5	.44	4.85	0.480	0.502	38.85	3.6	4270
LF1M	6	.40	6.04	0.399	0.417	30.76	4.8	4811
LF1H	7	.38	7.09	0.403	0.414	19.42	3.6	5249
LF2L	5	.44	4.67	0.436	0.454	33.24	7.1	3456
LF2M	6	.38	5.94	0.443	0.453	16.35	6.7	3886
LF2H	7	.36	7.20	0.412	0.420	13.48	6.8	4157

TABLE 6.2. MIX VARIABLES AND 28-DAY COMPRESSIVE STRENGTH - GRAVEL AND SANDSTONE

	Target		Actual					
Data Point	Cement Factor	W/C Ratio	Cement Factor	W/C Ratio	W/C Ratio with SP	SP Dosage Oz/cwt	Air Content Percent	28-Day Strength psi
GCNM	6	0.43	6.07	0.390	-	0	0.7	5883
GC1M	6	0.34	5.80	0.360	-	0	4.7	5291
GC2M	6	0.32	5.99	0.334	-	0	6.8	4995
G1NM	6	0.40	5.91	0.369	0.380	20	1.2	5730
G11M	6	0.32	5.75	0.331	0.342	20	4.5	5906
G12M	6	0.30	5.78	0.314	0.325	20	7.1	5176
G2NM	6	0.32	5.72	0.373	0.396	40	0.7	6048
G21M	6	0.30	5.88	0.300	0.323	40	3.7	6137
G22M	6	0.27	5.99	0.270	0.293	40	6.7	5923
GFNM	6	0.43	5.98	0.396	0.410	24.28	0.5	5948
GF1M	6	0.36	5.99	0.381	0.399	29.14	3.7	5105
GF2M	6	0.34	5.93	0.353	0.370	29.14	6.8	4806
SCNM	6	0.50	6.18	0.515	-	0	0.4	5300
SC1M	6	0.40	5.74	0.463	-	0	3.8	4056
SC2M	6	0.38	5.89	0.380	-	0	6.5	4339

TABLE 6.3. COMPRESSIVE STRENGTH SUMMARY - LIMESTONE AGGREGATE

Specimen Mark	1980-81 Date Cast	Compressive Strengths, psi, at Ages: 1-Day	7-Days	28-Days	98-Days	196-Days	f'_{sp}, psi 28-Days	$\frac{f'_{sp}}{\sqrt{f'_c}}$
LCNL	7/21	1171	3074	4200	5189	4861	404	6.23
LCNM	7/29	2370	4056	4304	4811	6249	386	5.88
LCNH	7/28	2201	4738	5247	5917	7230	448	6.18
LC1L	7/30	1632	2786	4190	4698	4786	503	7.77
LC1M	7/31	2083	3135	5080	5714	5867	576	8.08
LC1H	9/3	2260	3528	5290	5823	6123	610	8.39
LC2L	9/4	1447	3065	3845	4461	5053	432	6.97
LC2M	9/9,11	1716	3074	3776	4668	5641	309	5.03
LC2H	9/11,12	3994[2]	4637	4827	5717	6249	492	7.08
L1NL	10/9	1580	3266	4044	4955	5376	319	5.02
L1NM	10/15	3239	4484	5336	6148	6366	467	6.39
L1NH	10/16	2842	4650	5648	6548	6632	502	6.68
L11L	11/4	1612	2948	3542	4253	4667	403	6.77
L11M	11/6	2498	4397	5370	5946	6163	517	7.06
L11H	11/7,10	2291	4617	5726	6423	6544	523	6.91
L12L	11/11	1542	3445	4248	4757	5255	447	6.86
L12M	11/12,13	2087	3266	4878	5060	6629	483	6.92
L12H	11/13	2598	4307	5136	5718	6174	501	6.99
L2NL	11/20	2072	3608	4428	5128	5665	433	6.51
L2NM	11/21	2340	4312	5578	6242	6481	517	6.92
L2NH	11/24	1722	5773	6202	6612	7488	534	6.78
L21L	1/19	1740	4071	5320	6034		512	7.02
L21M	1/20,21	2009	4625	5534	6162		540	7.26
L21H	1/22,29,30	2667	4850	5960	6427		499	6.46
L22L	1/30,2/2	1341	3444	4628	5209		486	7.14
L22M	2/4	4099[1]	5148	5411	5541[4]		522	7.10
L22H	2/6	3648	6162	6346	6522		556	6.98
LFNL	2/9,10	1605	3452	4366	4774		453	6.96
LFNM	2/16	3571	4863	5355	5661		513	7.01
LFNH	2/20	4201	5261	5829	5955		536	7.02
LF1L	2/24,25	2203	4105	4270	4434		405	6.20
LF1M	2/26,27	3633	4555	4811[3]	5828		509	7.34
LF1H	2/27,3/9	4110	4805	5249	5546		521	7.19
LF2L	3/12	1462	2885	3456			389	6.62
LF2M	3/12	2664	3467	3886			420	6.74
LF2H	3/13	3245	3866	4157			446	6.92

[1]2-day, [2]3-day, [3]32-day, [4]104-day

TABLE 6.4. COMPRESSIVE STRENGTH SUMMARY - GRAVEL AND SANDSTONE AGGREGATES

Specimen Mark	1980-81 Date Cast	Compressive Strengths, psi, at Ages: 1-Day	7-Days	28-Days	98-Days	196-Days	f'_{sp}, psi 28-Days	$\frac{f'_{sp}}{\sqrt{f'_c}}$
GCNM	3/25	2405	4257	5383			536	6.99
GC1M	3/26	1746	3948	5291			513	7.05
GC2M	3/27	1343	3356	4995			487	6.89
G1NM	4/1	3254	4807	5730			509	6.72
G11M	4/2	2243	4582	5906			448	5.83
G12M	4/3	2069	4212	5176			488	6.78
G2NM	4/6	3337	5010	6048			551	7.09
G21M	4/8	4180	5542	6137			567	7.24
G22M	4/9,10	3874	5648	5923			523	6.80
GFNM	4/13	3738	5504	5948			518	6.72
GF1M	4/14,16	3809	4810	5105[1]			442	6.19
GF2M	4/21	2518	4095	4806			433	6.25
SCNM	4/24	1974	4055	5300			352	4.84
SC1M	4/27	2385	3458	4056			395	6.20
SC2M	4/29	2982	3710	4339			335	5.09

[1] 30-day

TABLE 6.5. ABRASION RESISTANCE RESULTS - ALL AGGREGATES

Limestone		Gravel		Sandstone	
Specimen Mark	Weight Loss Grams	Specimen Mark	Weight Loss Grams	Specimen Mark	Weight Loss Grams
LCNL	0.03				
LCNM	0.23	GCNM	0.80	SCNM	1.23
LCNH	0.13				
LC1L	0.17				
LC1M	0.07	GC1M	0.83	SC1M	0.99
LC1H	0.17				
LC2L	0.37				
LC2M	0.17	GC2M	0.72	SC2M	0.83
LC2H	0.83				
L1NL	0.23				
L1NM	0.43	G1NM	0.37		
L1NH	0.71				
L11L	0.85				
L11M	0.30	G11M	0.23		
L11H	0.33				
L12L	0.53				
L12M	0.20	G12M	0.40		
L12H	0.13				
L2NL	0.40				
L2NM	0.23	G2NM	0.20		
L2NH	0.10				
L21L	0.30				
L21M	0.33	G21M	0.37		
L21H	0.33				
L22L	2.73				
L22M	1.93	G22M	0.23		
L22H	0.47				
LFNL	1.20				
LFNM	0.83	GFNM	0.47		
LFNH	0.50				
LF1L	0.63				
LF1M	0.42	GF1M	0.47		
LF1H	0.21				
LF2L	0.56				
LF2M	0.31	GF2M	0.30		
LF2H	0.20				

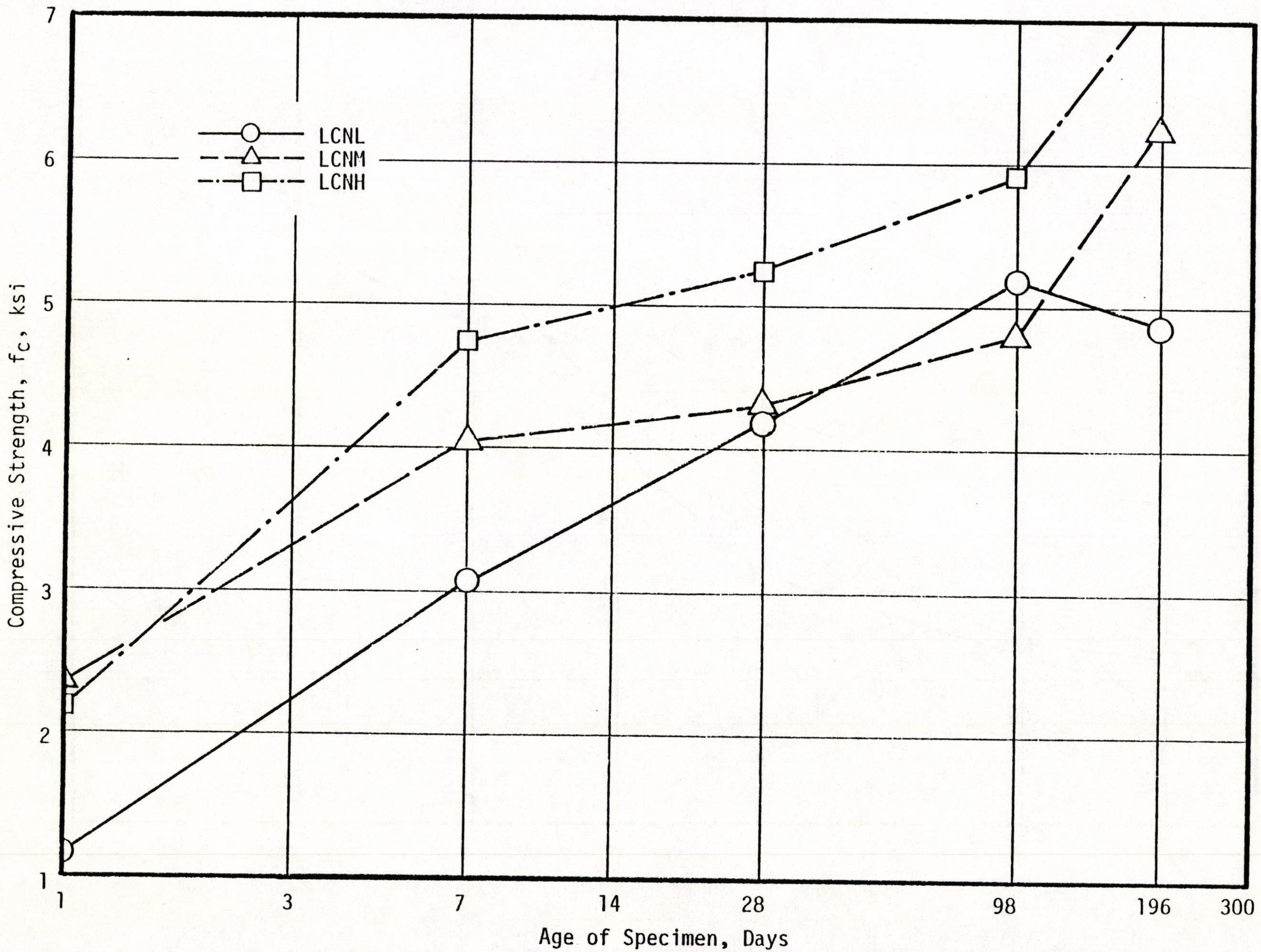


Figure 6.1 COMPRESSIVE STRENGTH VS. TIME -- LCN SERIES

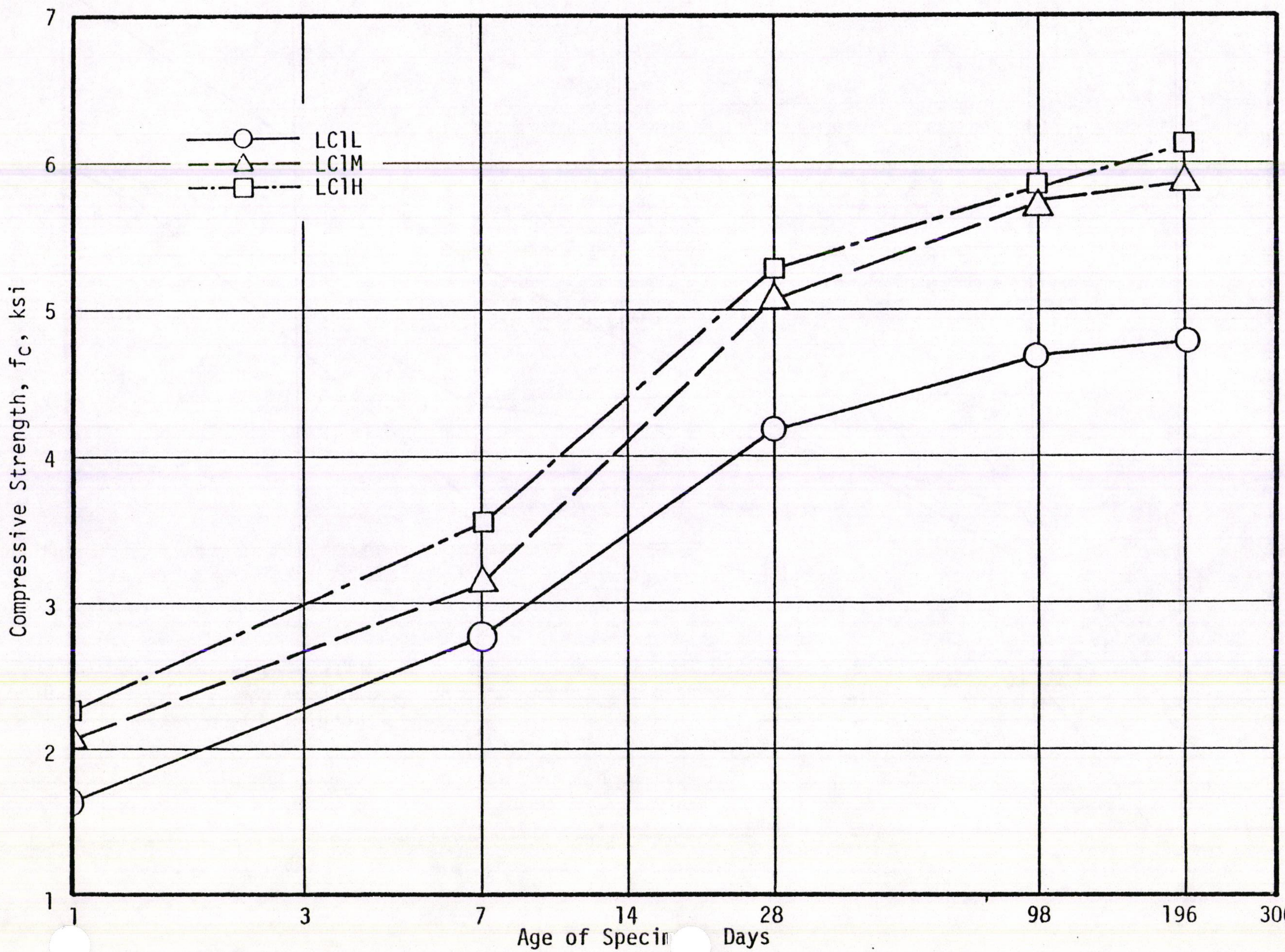


Figure 6.2 COMPRESSIVE STRENGTH VS. TIME -- LC1 SERIES

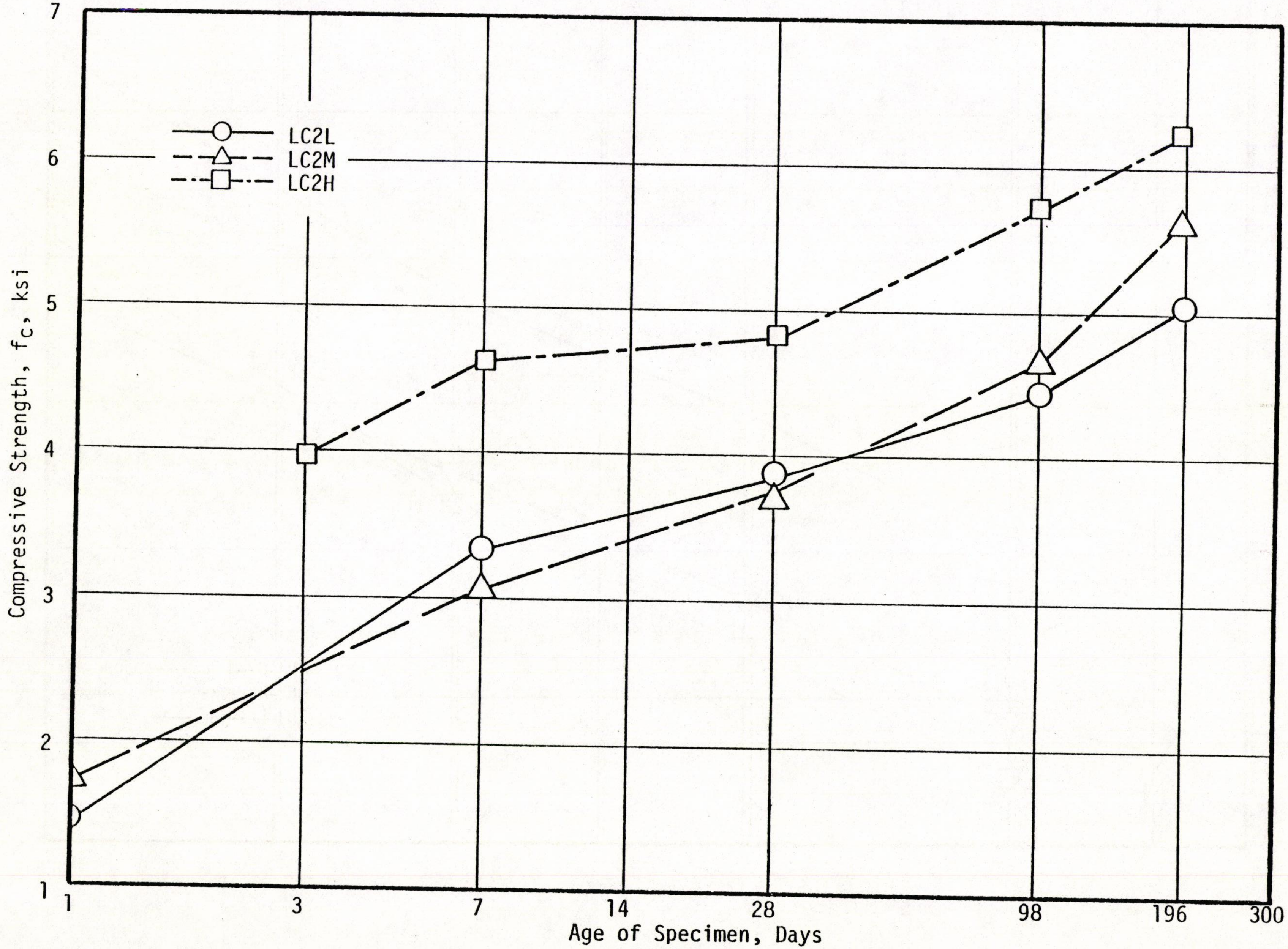


Figure 6.3 COMPRESSIVE STRENGTH VS. TIME -- LC2 SERIES

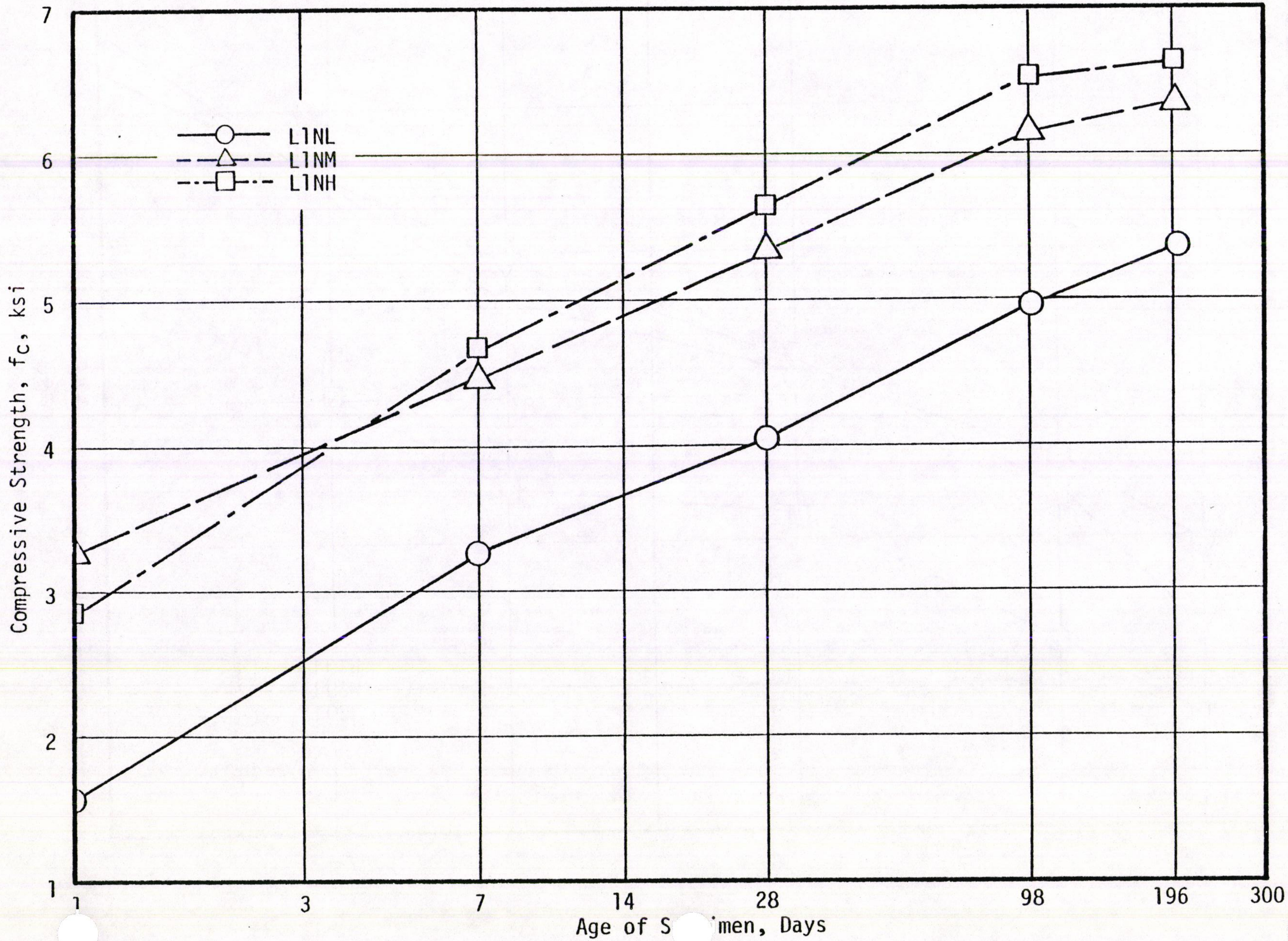


Figure 6.4 COMPRESSIVE STRENGTH VS. TIME -- L1N SERIES

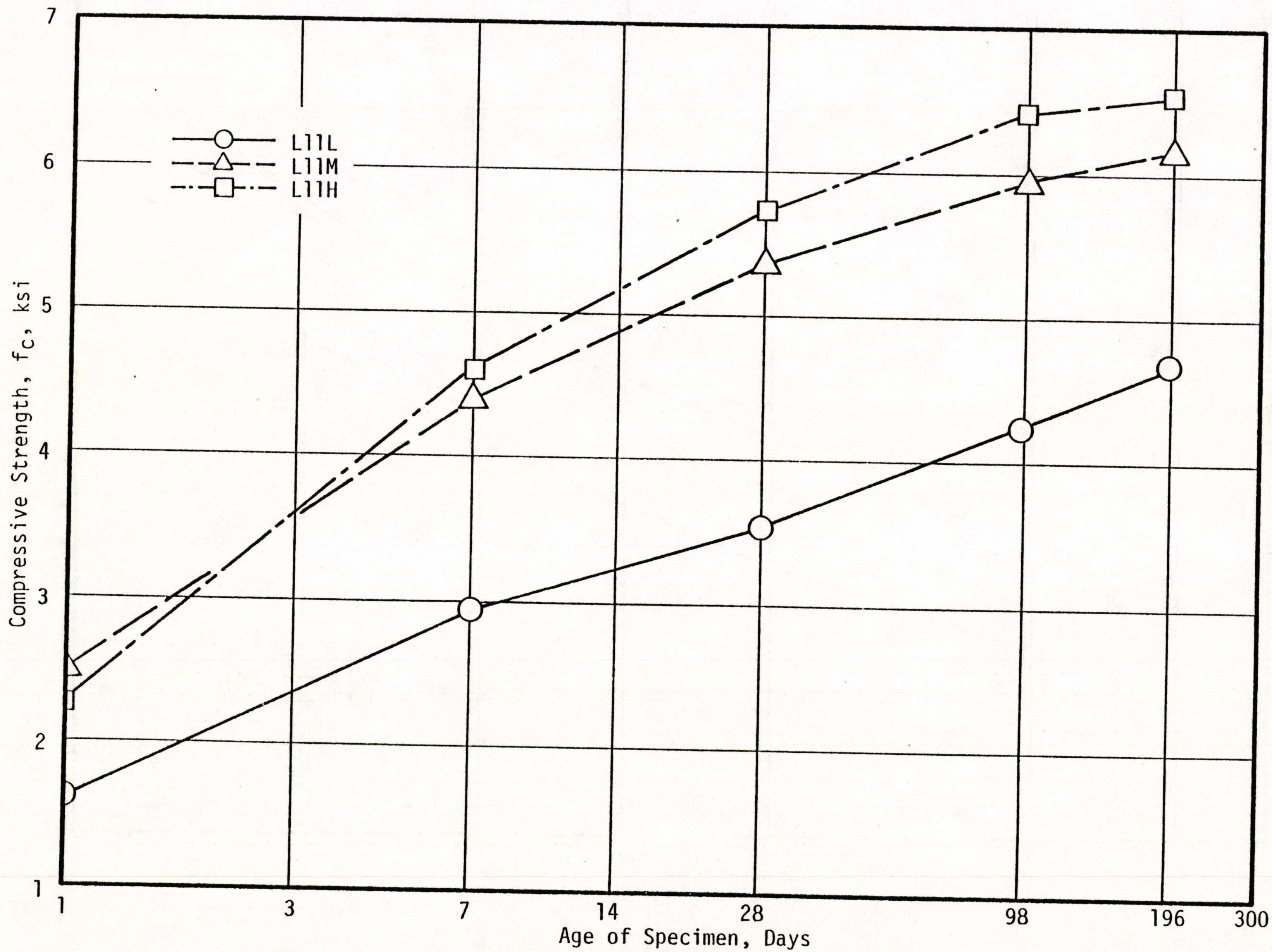


Figure 6.5 COMPRESSIVE STRENGTH VS. TIME -- L11 SERIES

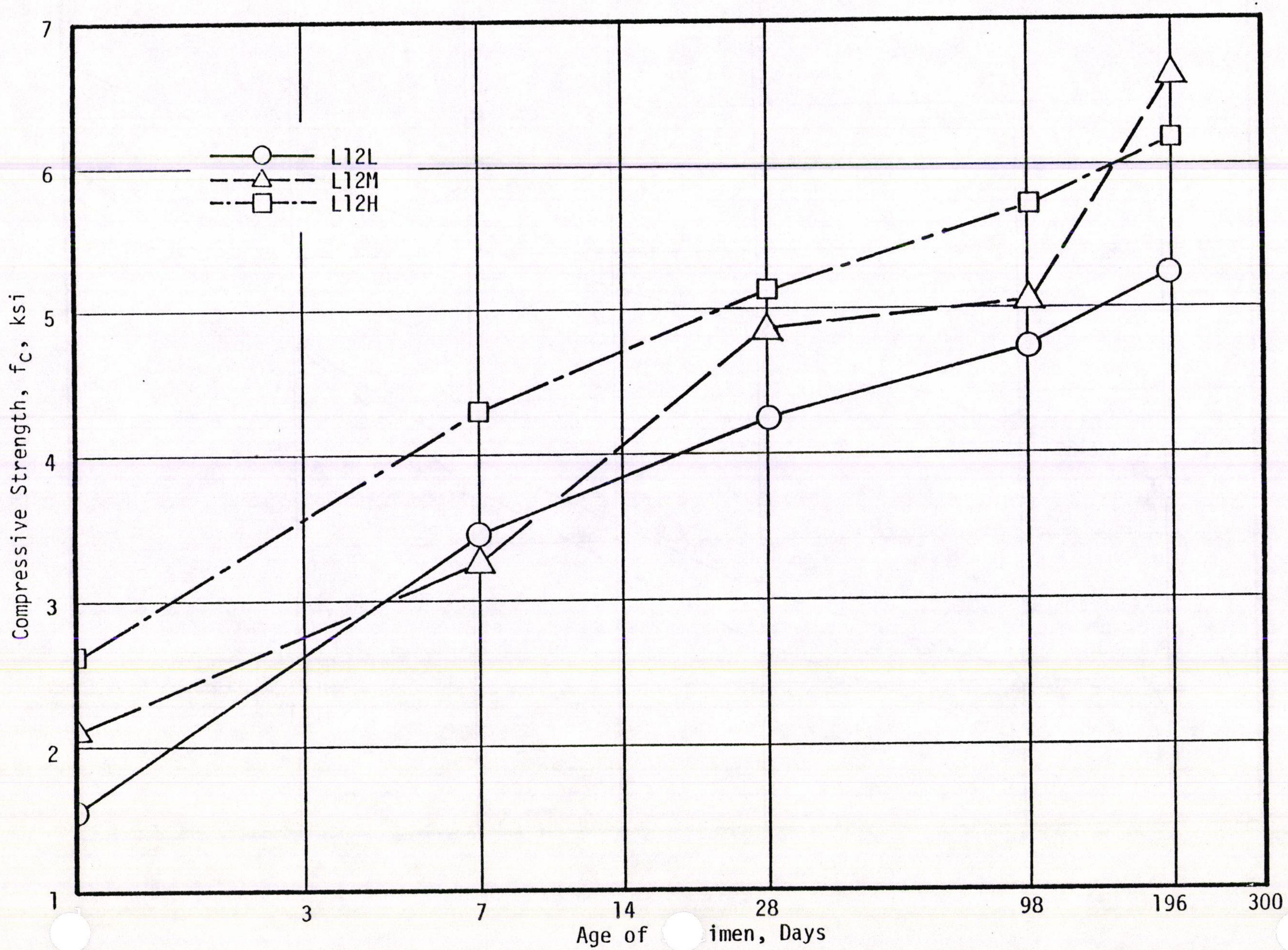


Figure 6.6 COMPRESSIVE STRENGTH VS. AGE -- L12 SERIES

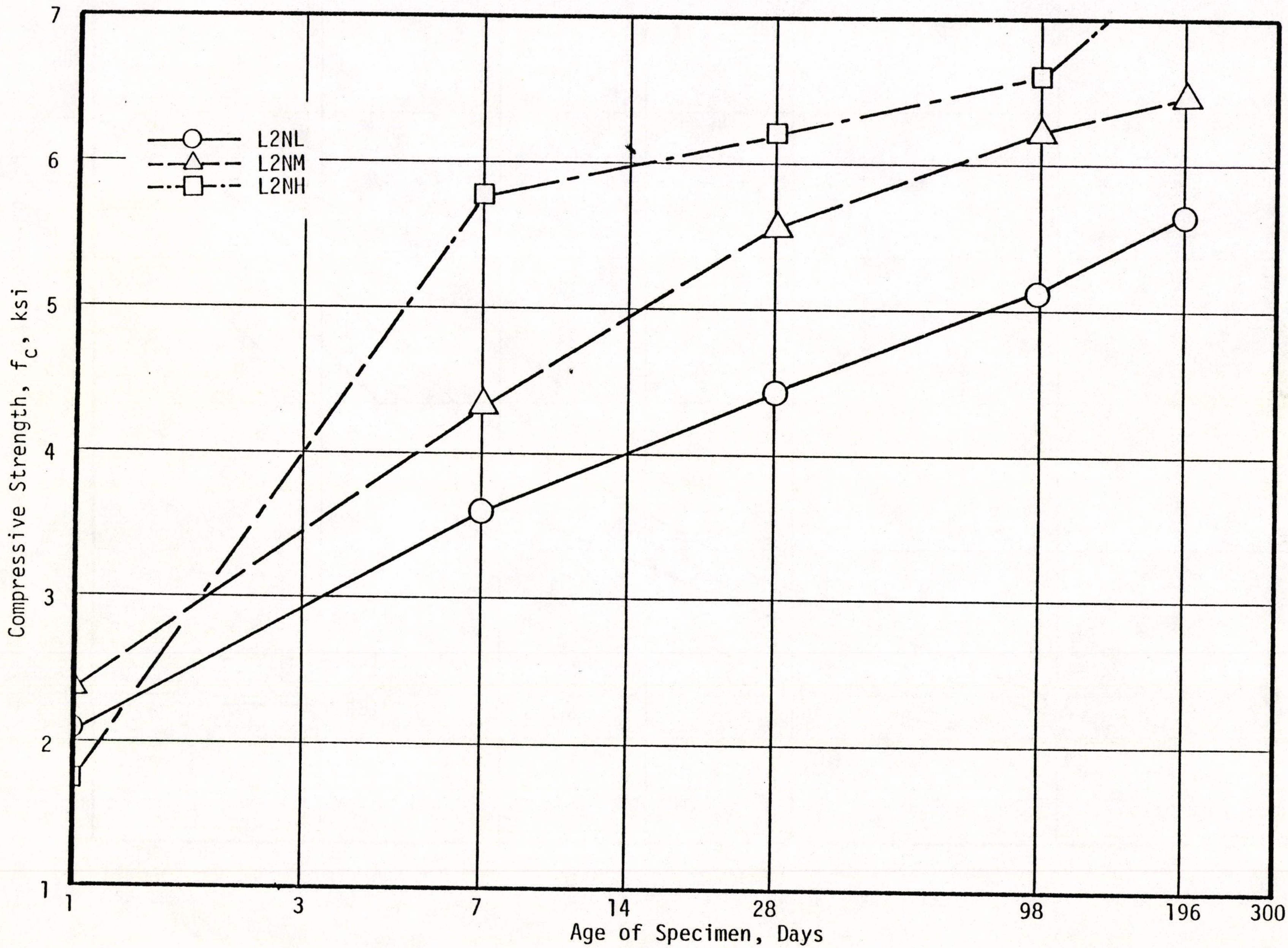


Figure 6.7 COMPRESSIVE STRENGTH VS. TIME -- L2N SERIES

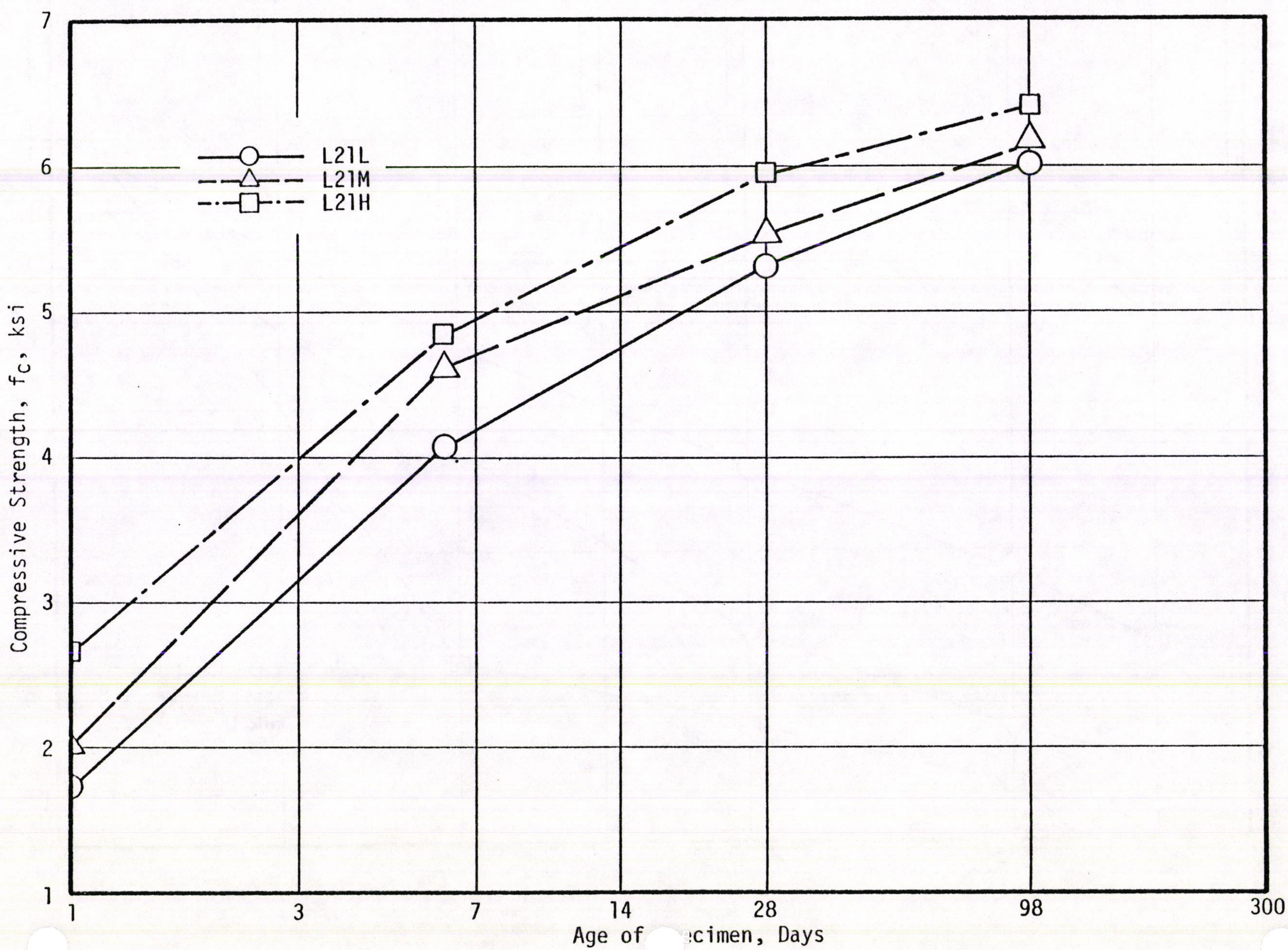


Figure 6.8 COMPRESSIVE STRENGTH VS. TIME -- L21 SERIES

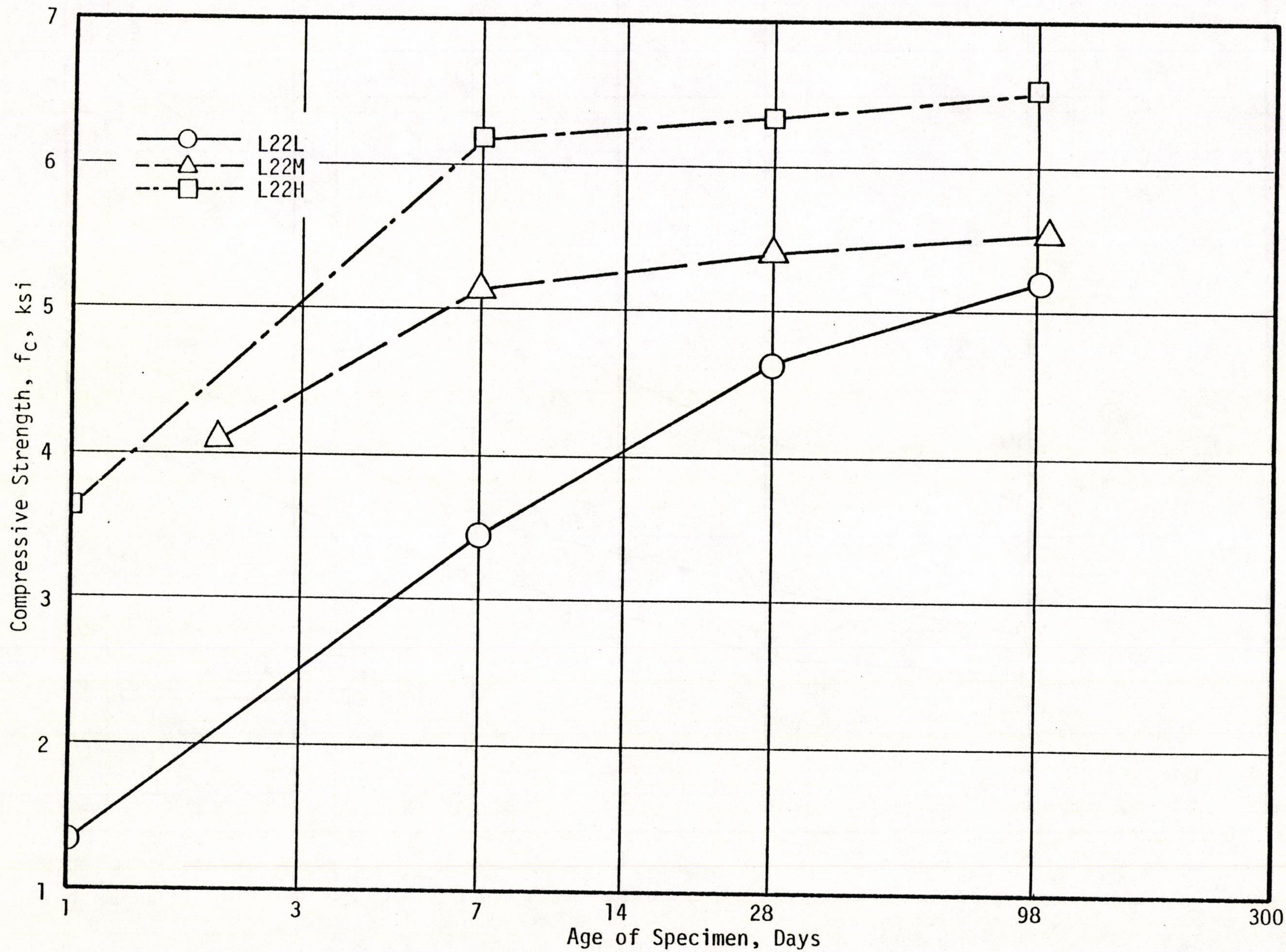


Figure 6.9 COMPRESSIVE STRENGTH VS. TIME -- L22 SERIES

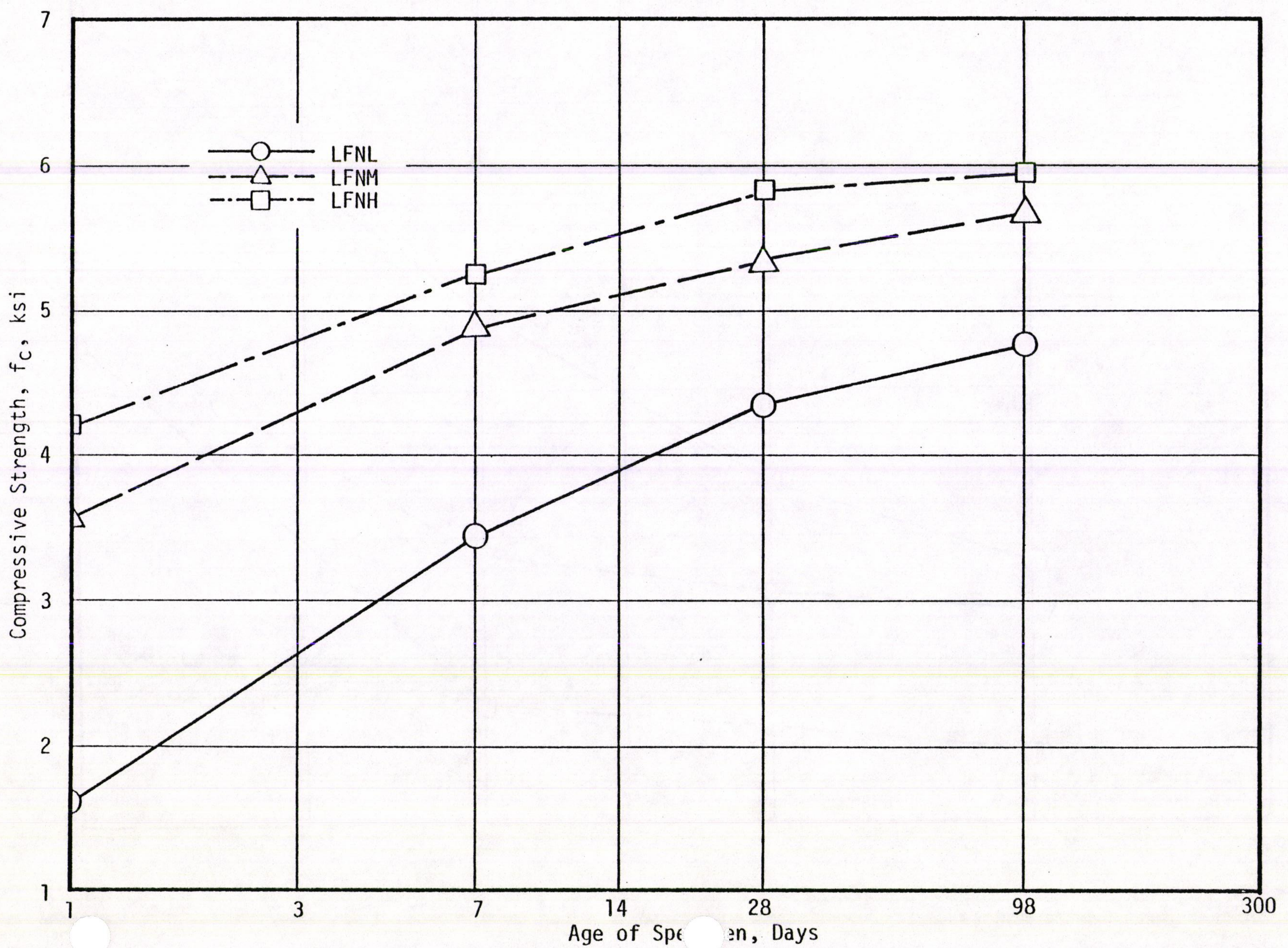


Figure 6.10 COMPRESSIVE STRENGTH VS. TIME -- LFN SERIES

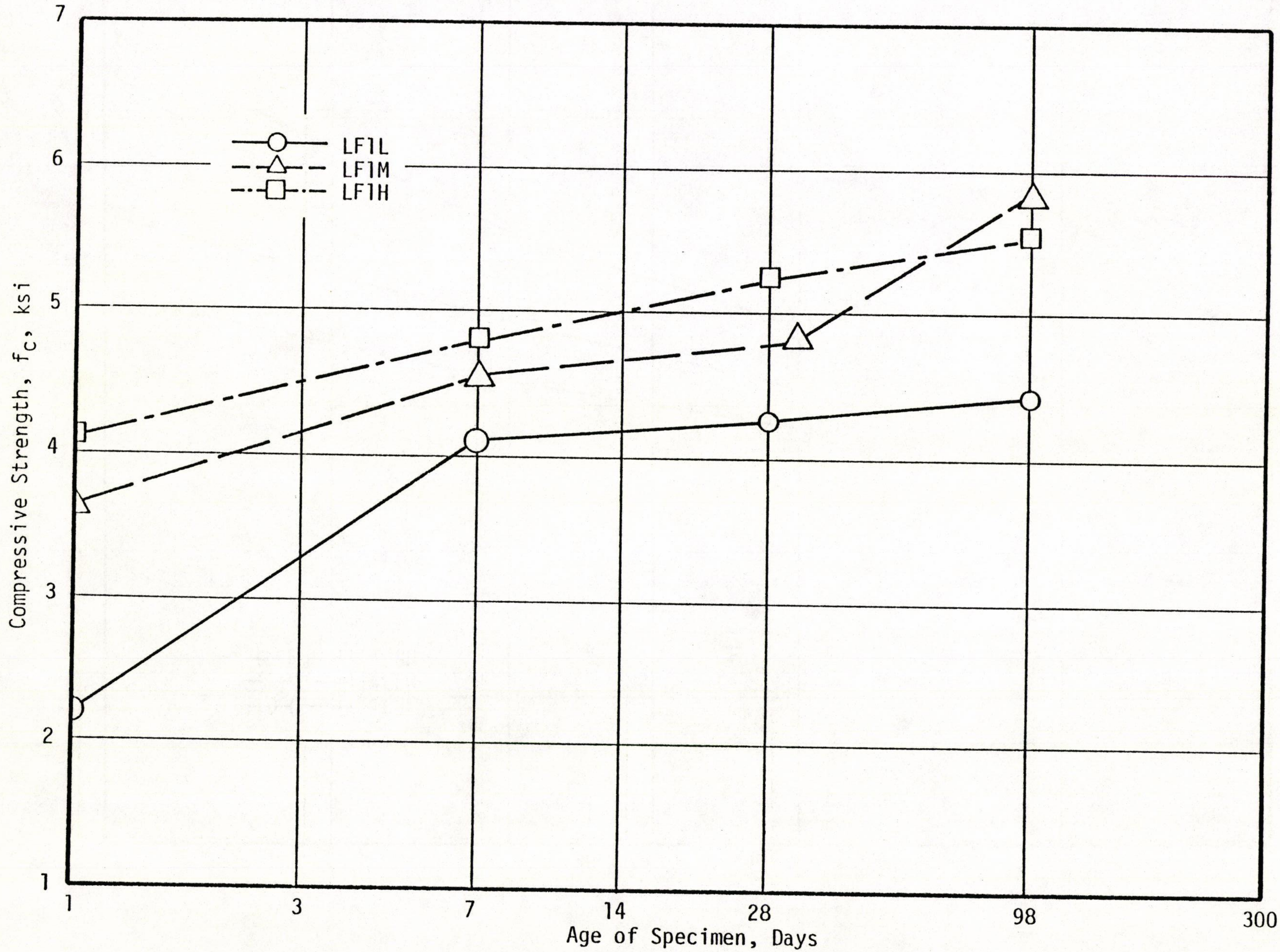


Figure 6.11 COMPRESSIVE STRENGTH VS. TIME -- LF1 SERIES

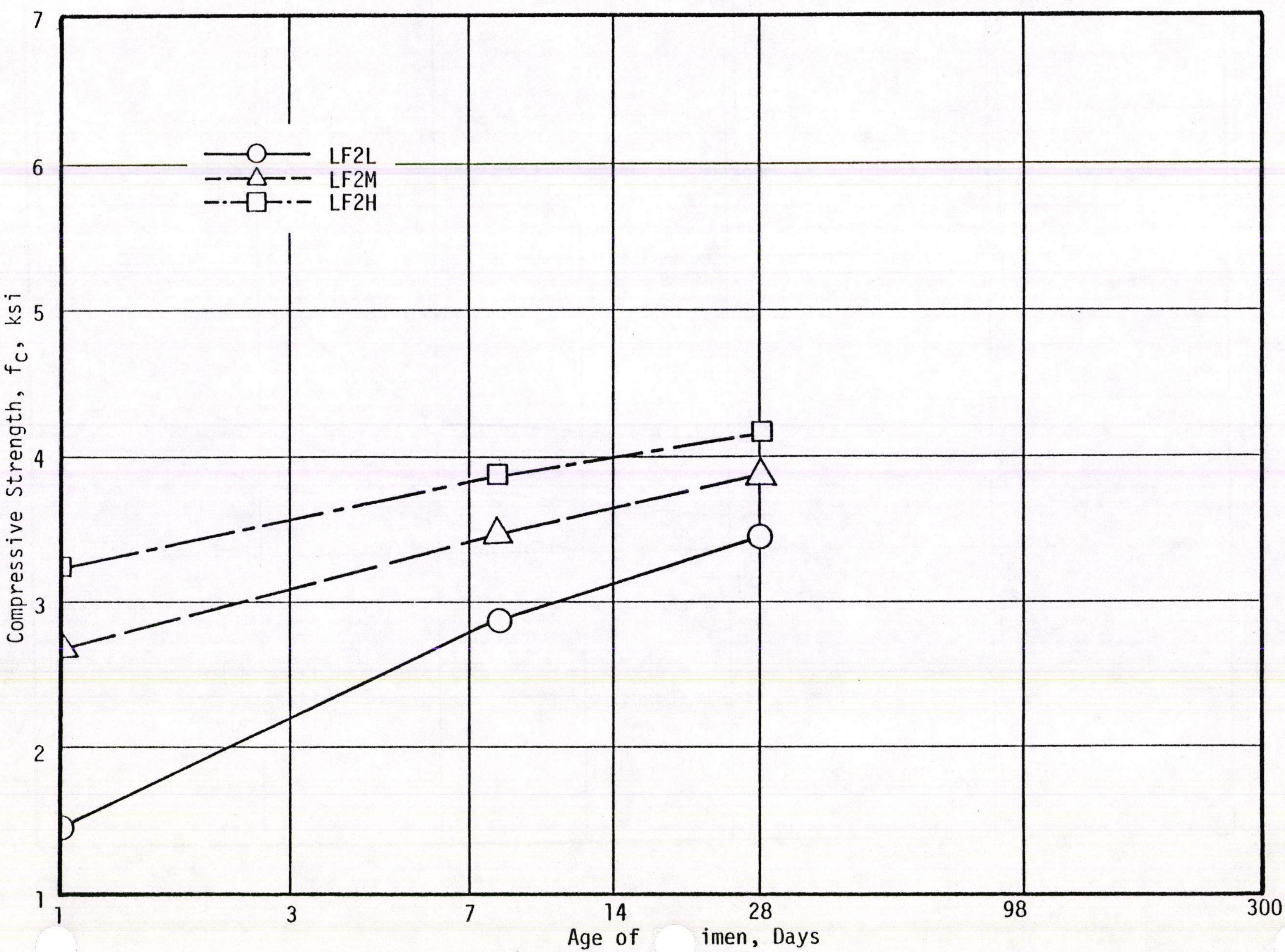


Figure 6.12 COMPRESSIVE STRENGTH VS. TIME -- LF2 SERIES

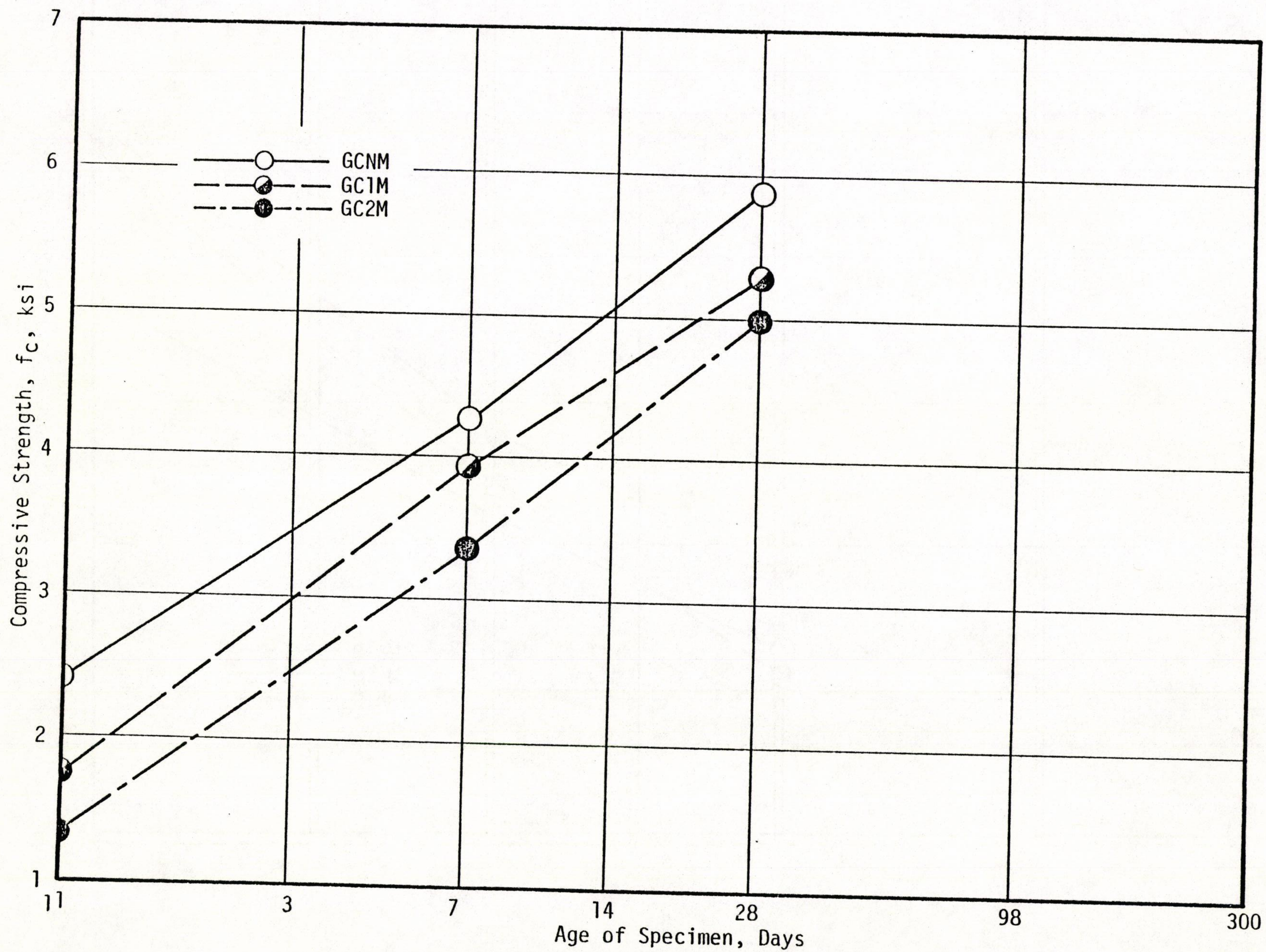


Figure 6.13 COMPRESSIVE STRENGTH VS. TIME -- GC-M SERIES

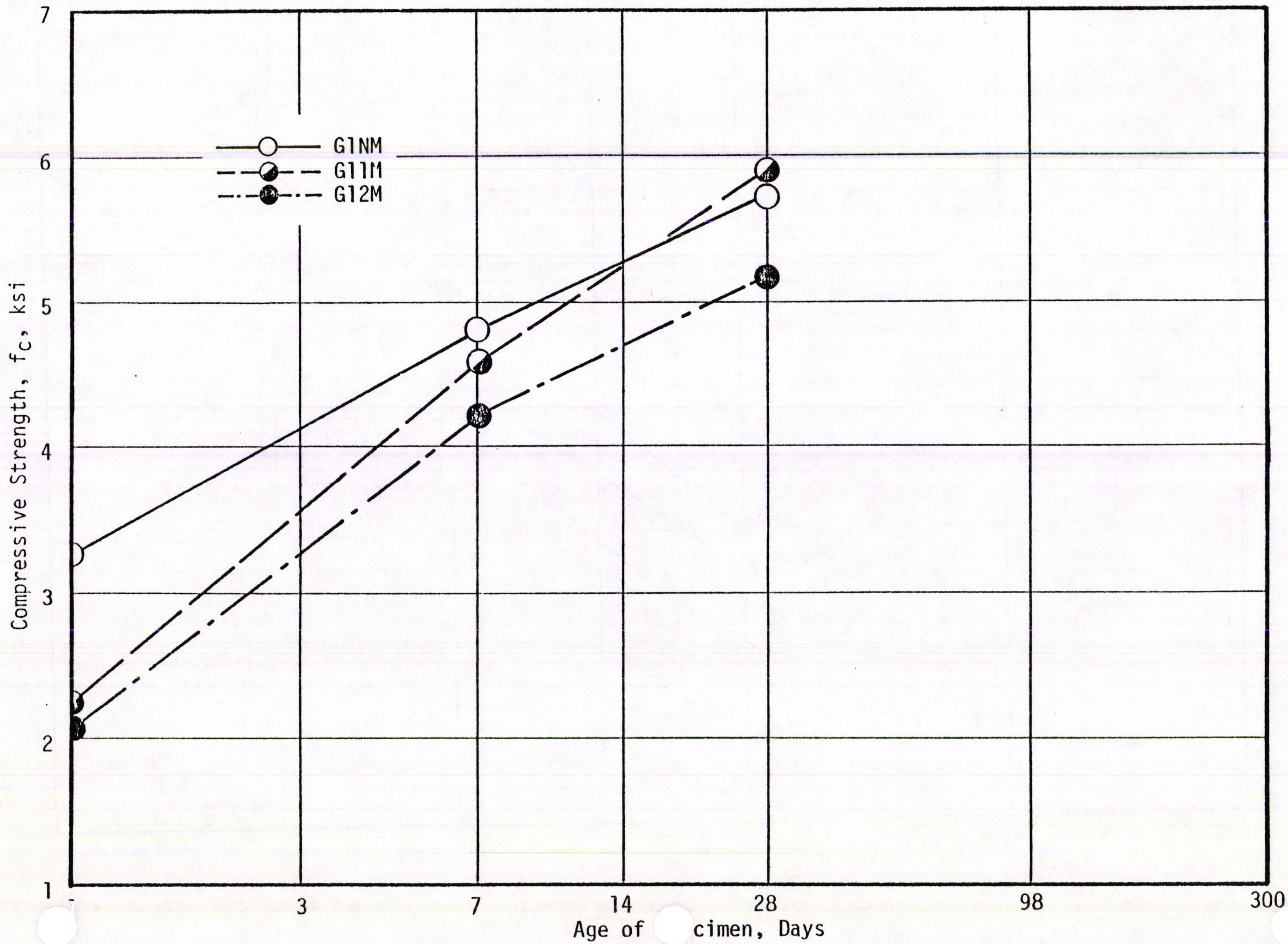


Figure 6.14 COMPRESSIVE STRENGTH VS. TIME -- G1-M SERIES

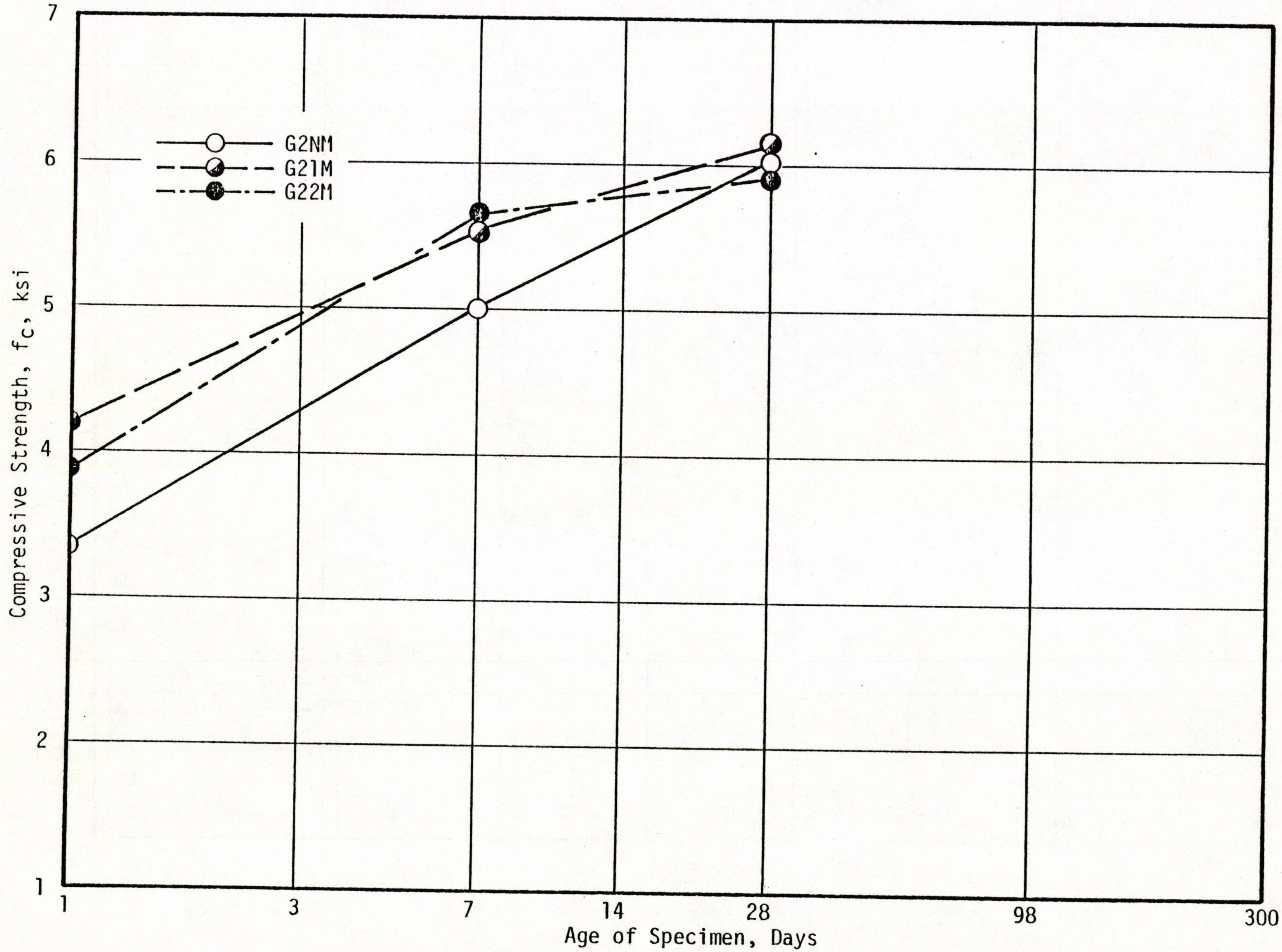


Figure 6.15 COMPRESSIVE STRENGTH VS. TIME -- G2-M SERIES

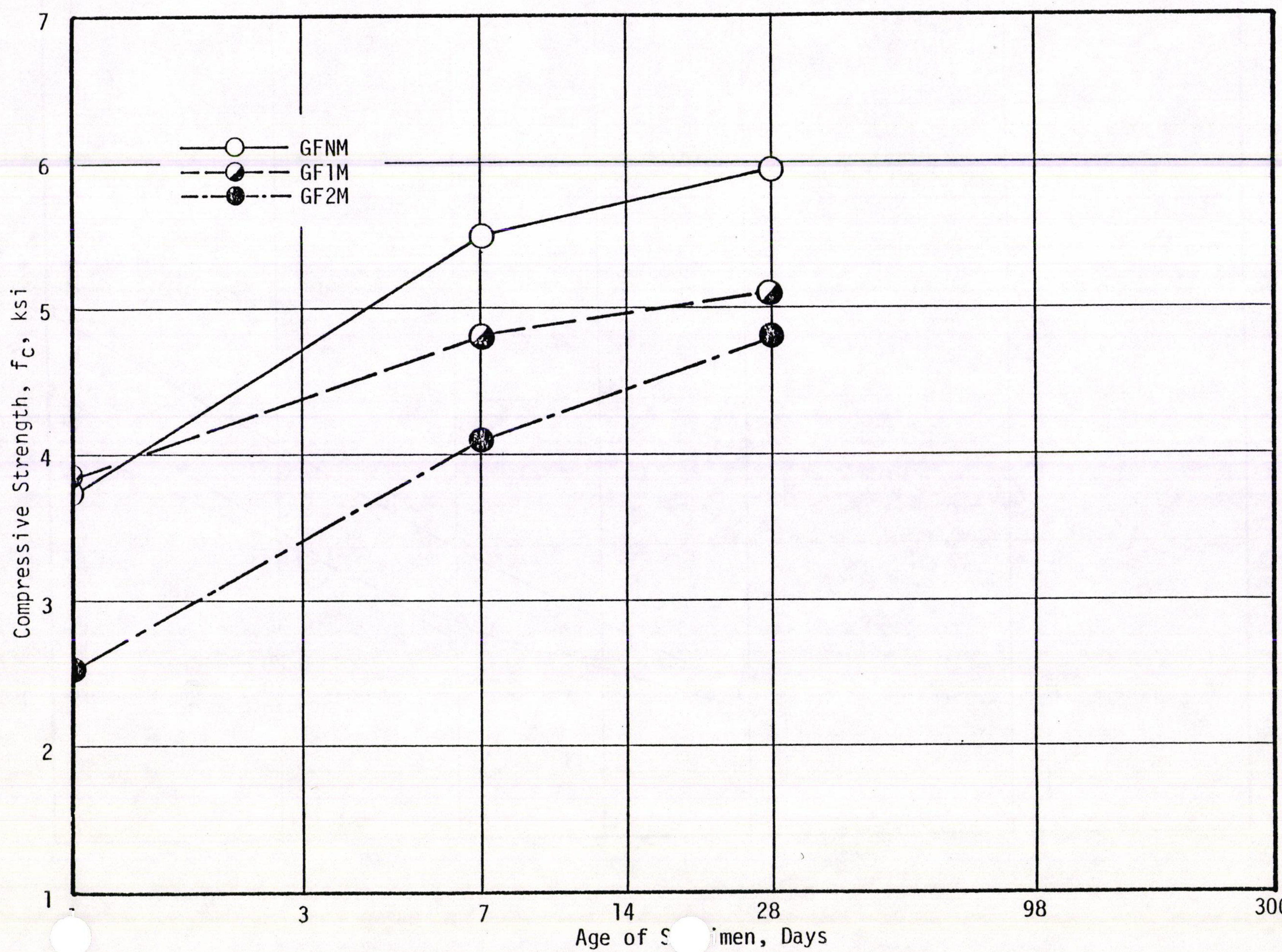


Figure 6.16 COMPRESSIVE STRENGTH VS. TIME -- GF-M SERIES

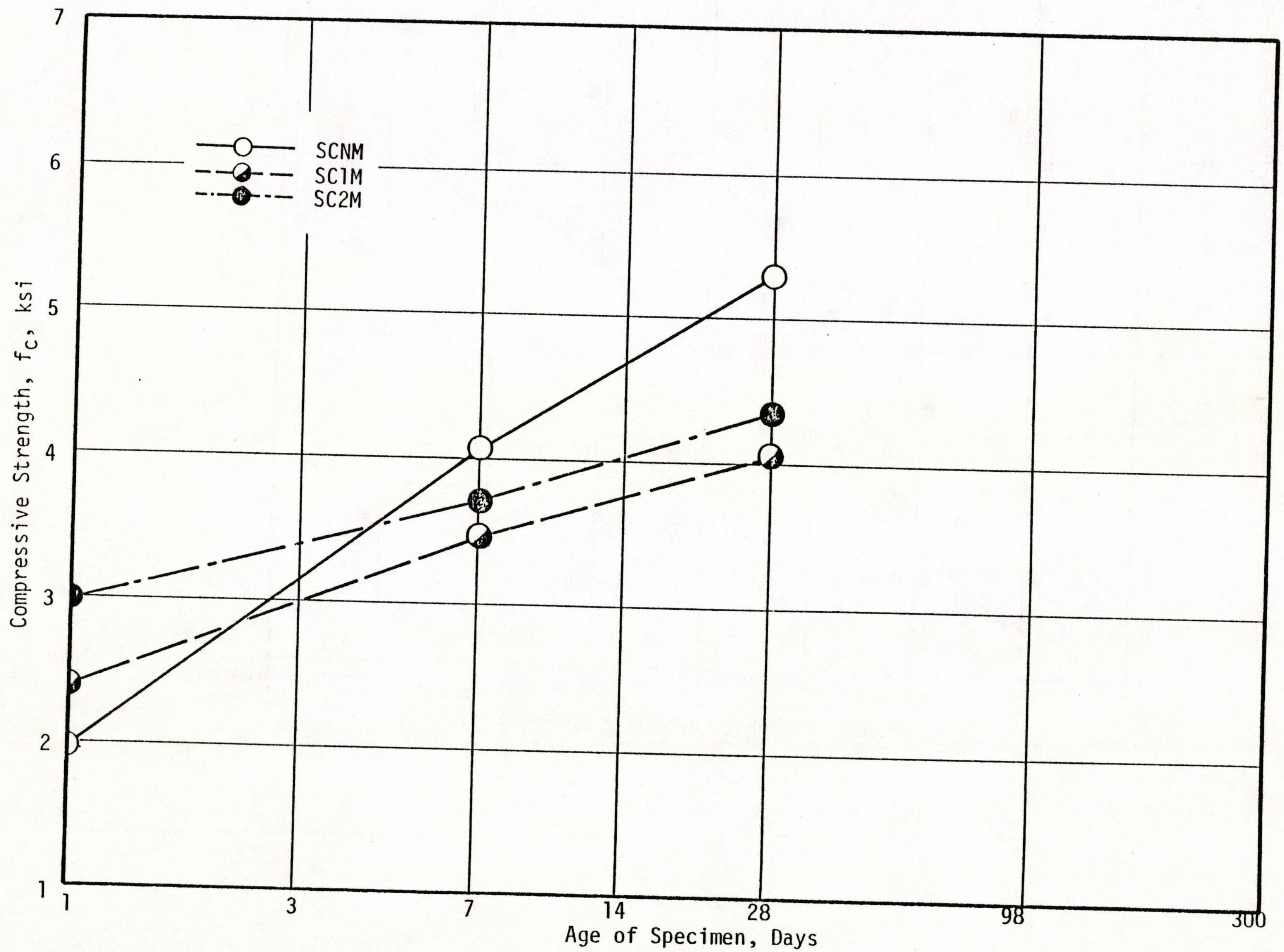


Figure 6.17 COMPRESSIVE STRENGTH VS. TIME -- SC-M SERIES

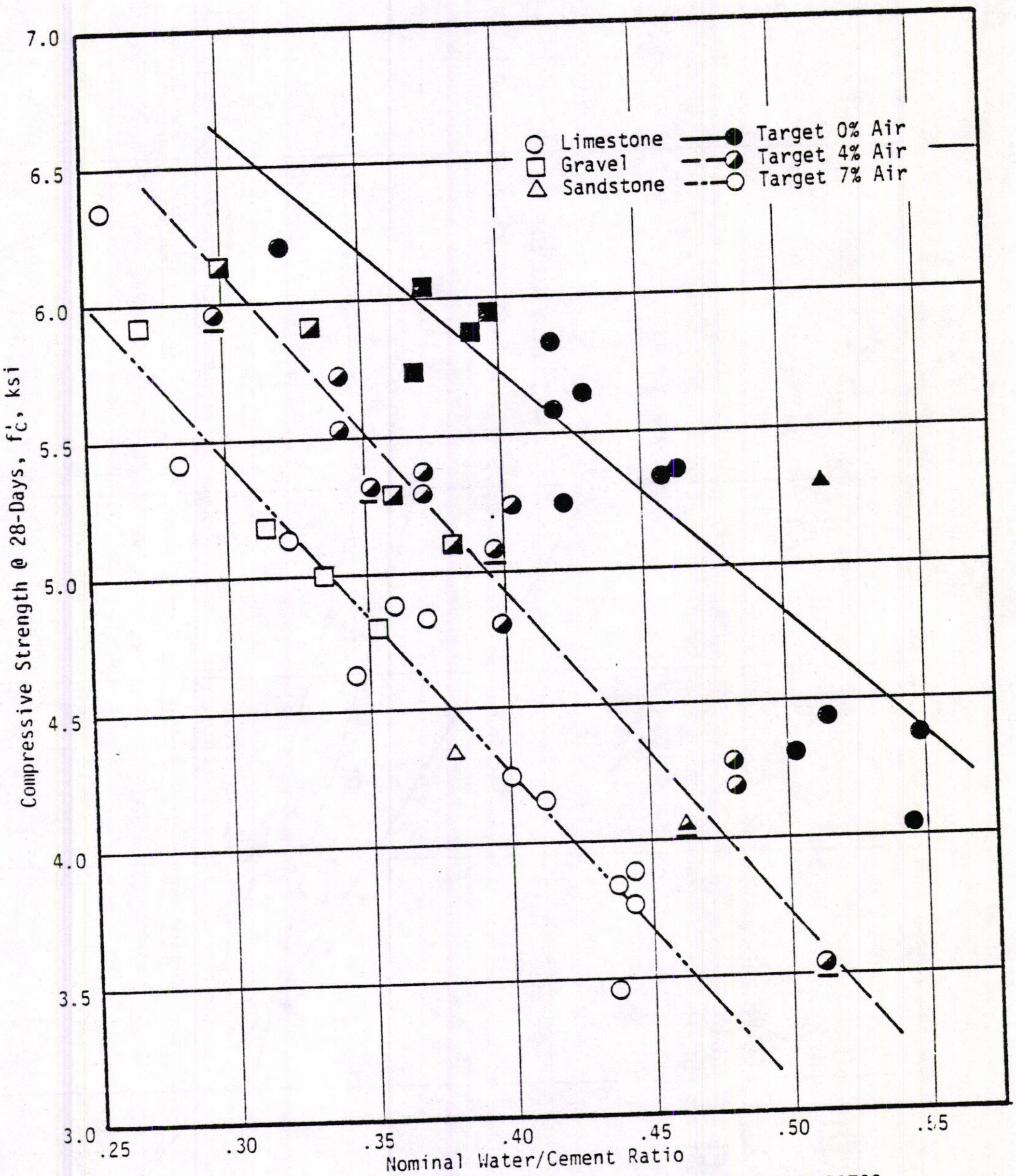


Figure 6.18 COMPRESSIVE STRENGTH VS. NOMINAL WATER/CEMENT RATIO

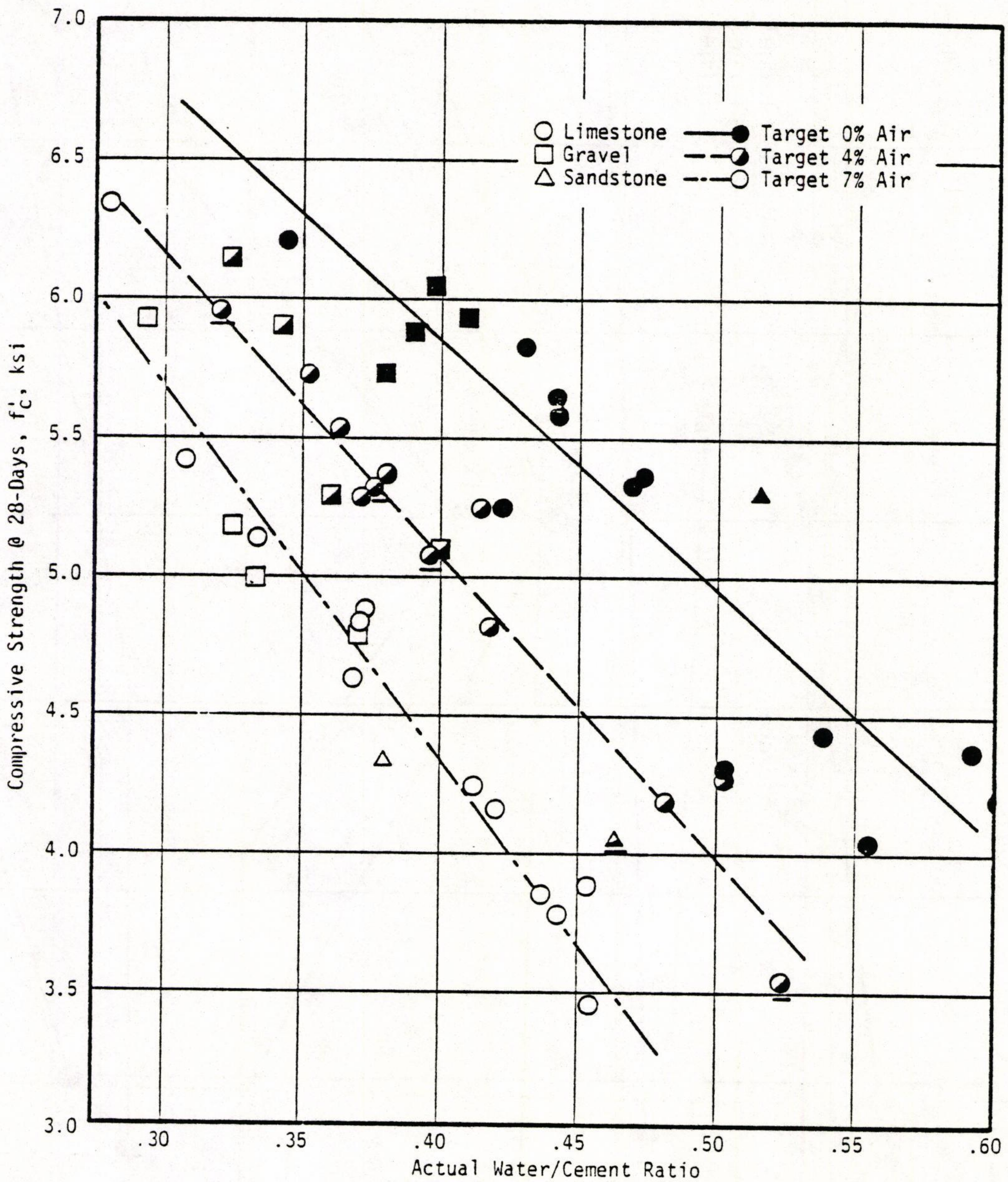


Figure 6.19 COMPRESSIVE STRENGTH VS. ACTUAL WATER/CEMENT RATIO

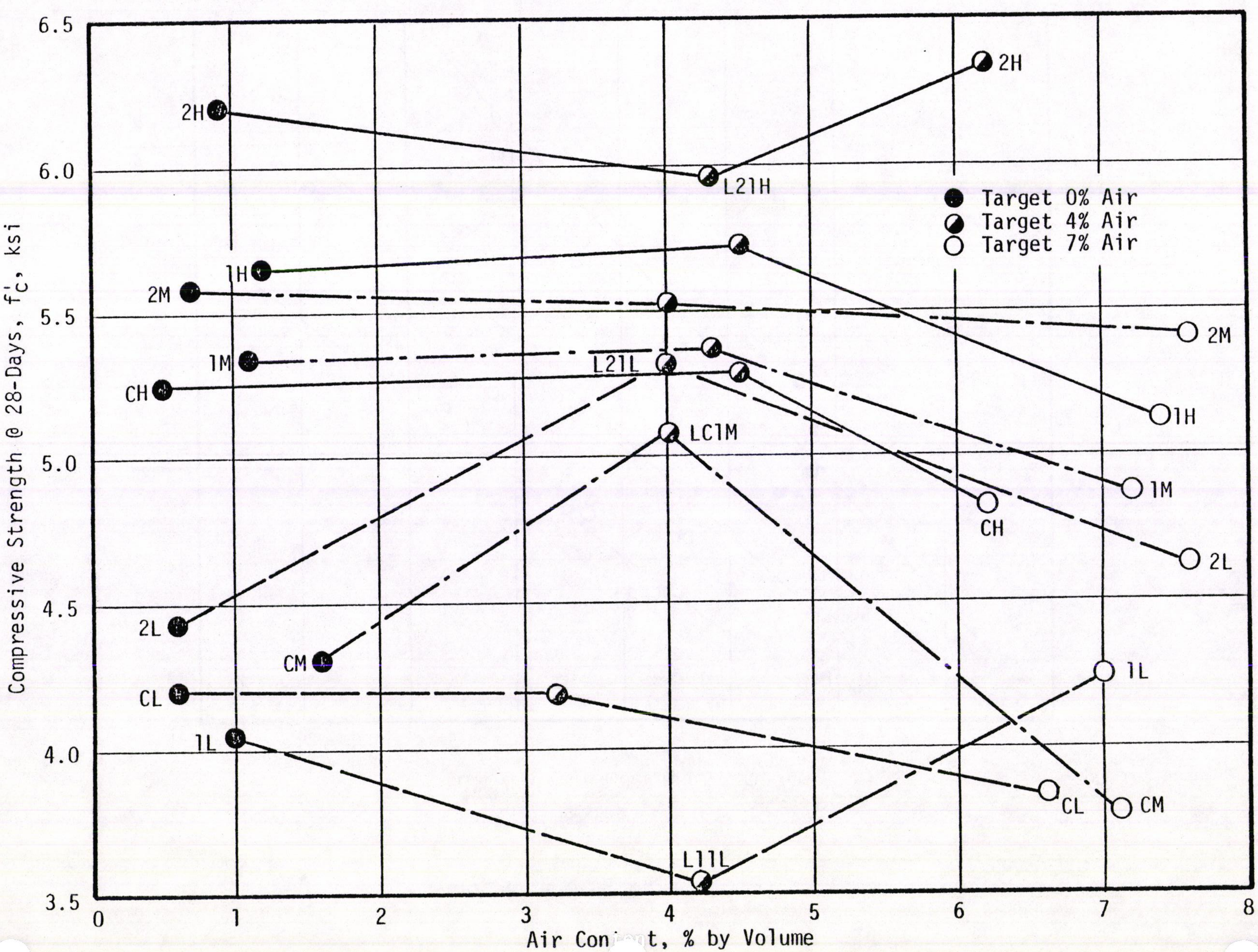


Figure 6.20 COMPRESSIVE STRENG... VS. AIR CONTENT, LIMESTONE AGGREGATE

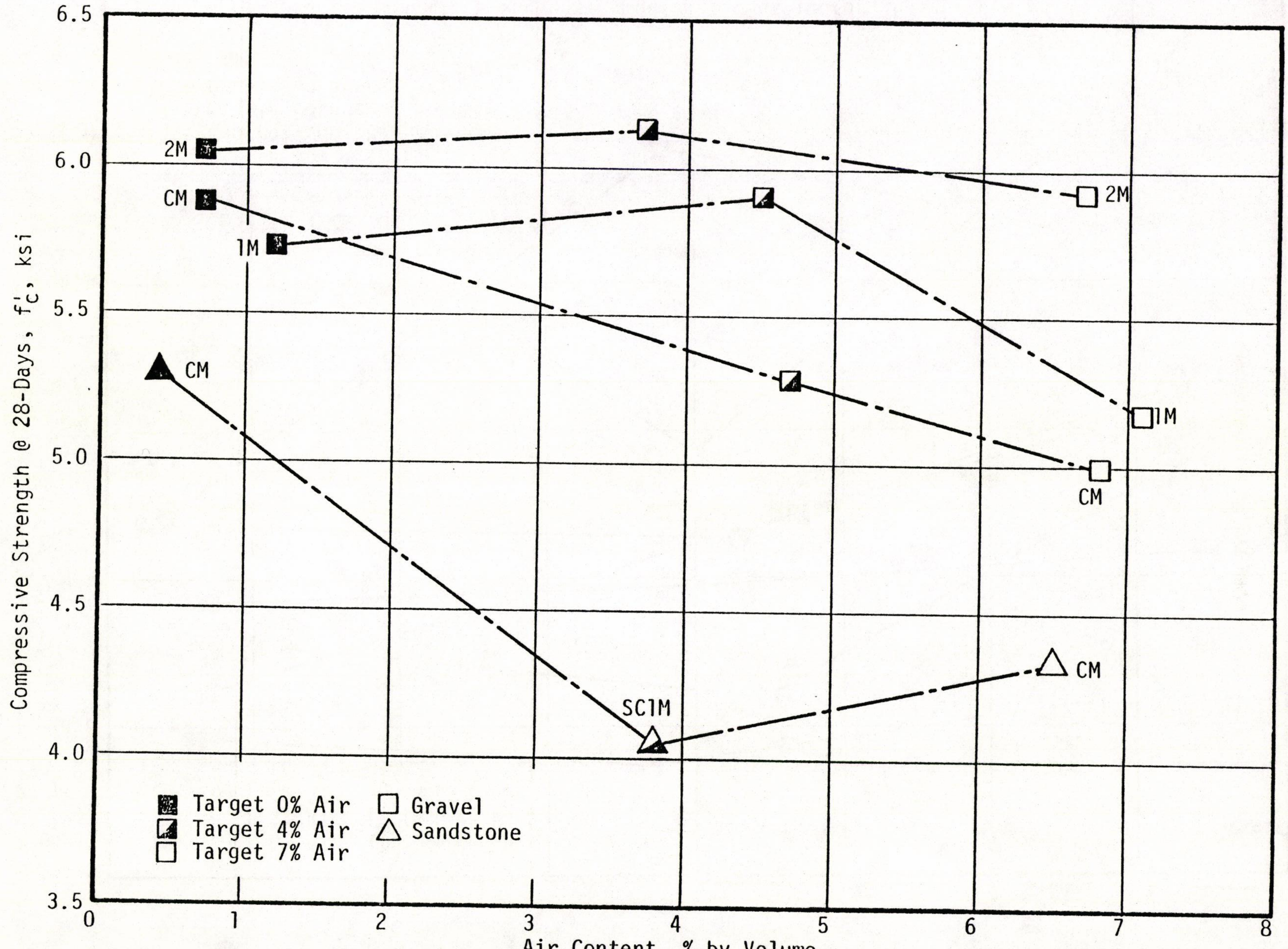


Figure 6.21 COMPRESSIVE STRENGTH VS. AIR CONTENT, GRAVEL AND SANDSTONE AGGREGATE

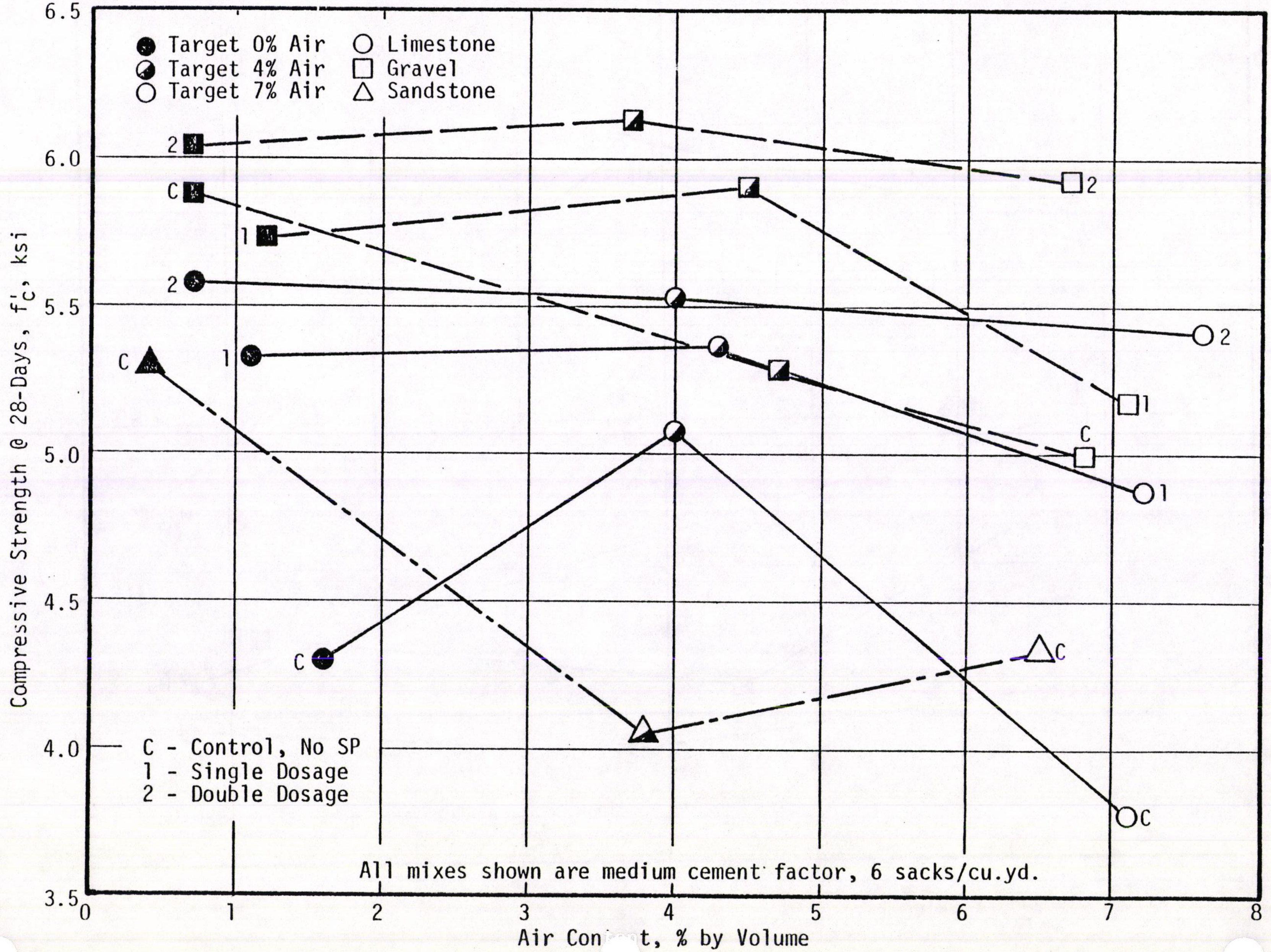


Figure 6.22 COMPRESSIVE ST GTH VS. AIR CONTENT, ALL AGGREGATES

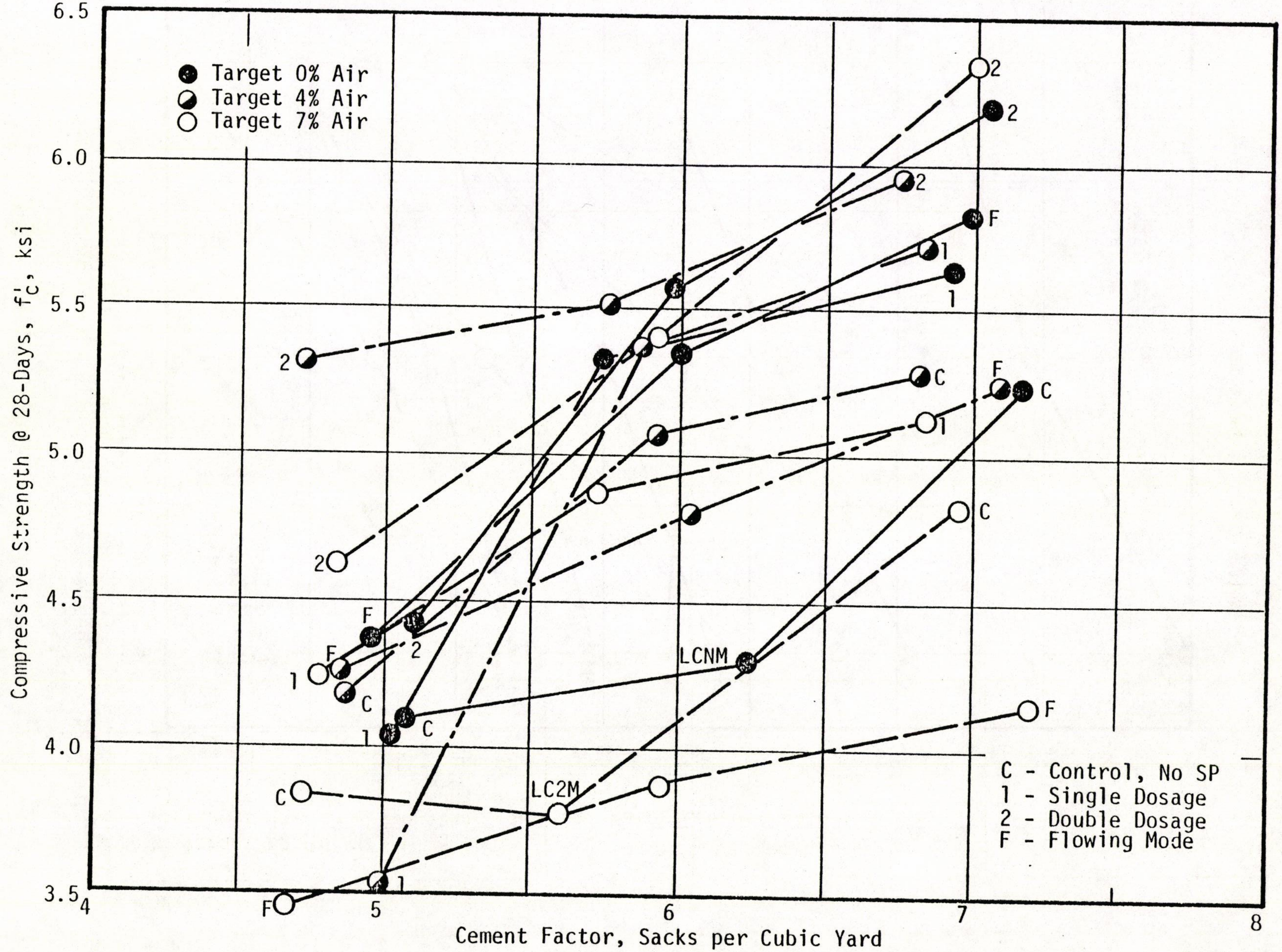


Figure 6.23 COMPRESSIVE STRENGTH VS. CEMENT FACTOR, LIMESTONE AGGREGATE

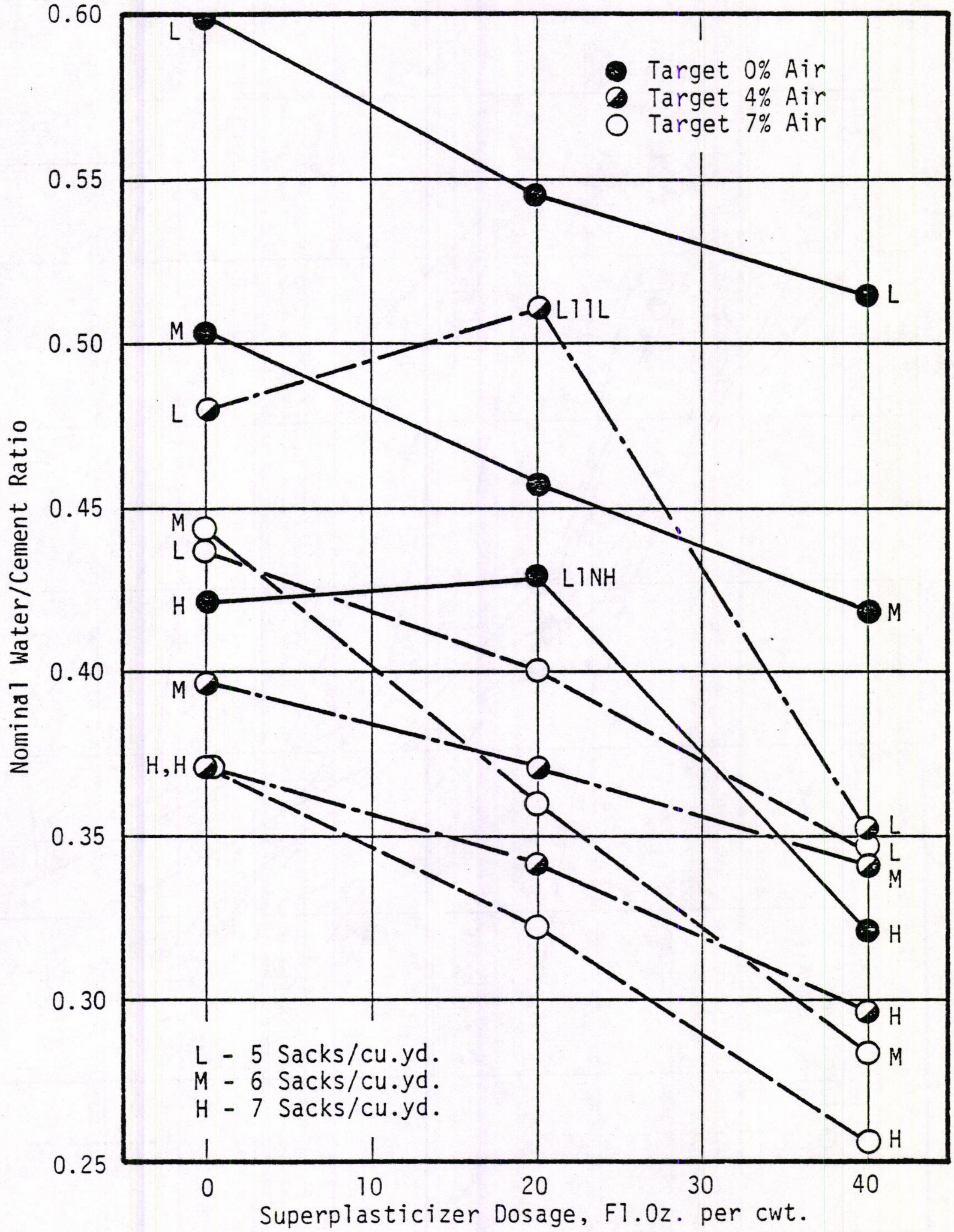


Figure 6.24 NOMINAL WATER/CEMENT RATIO VS. SUPERPLASTICIZER DOSAGE, LIMESTONE AGGREGATE

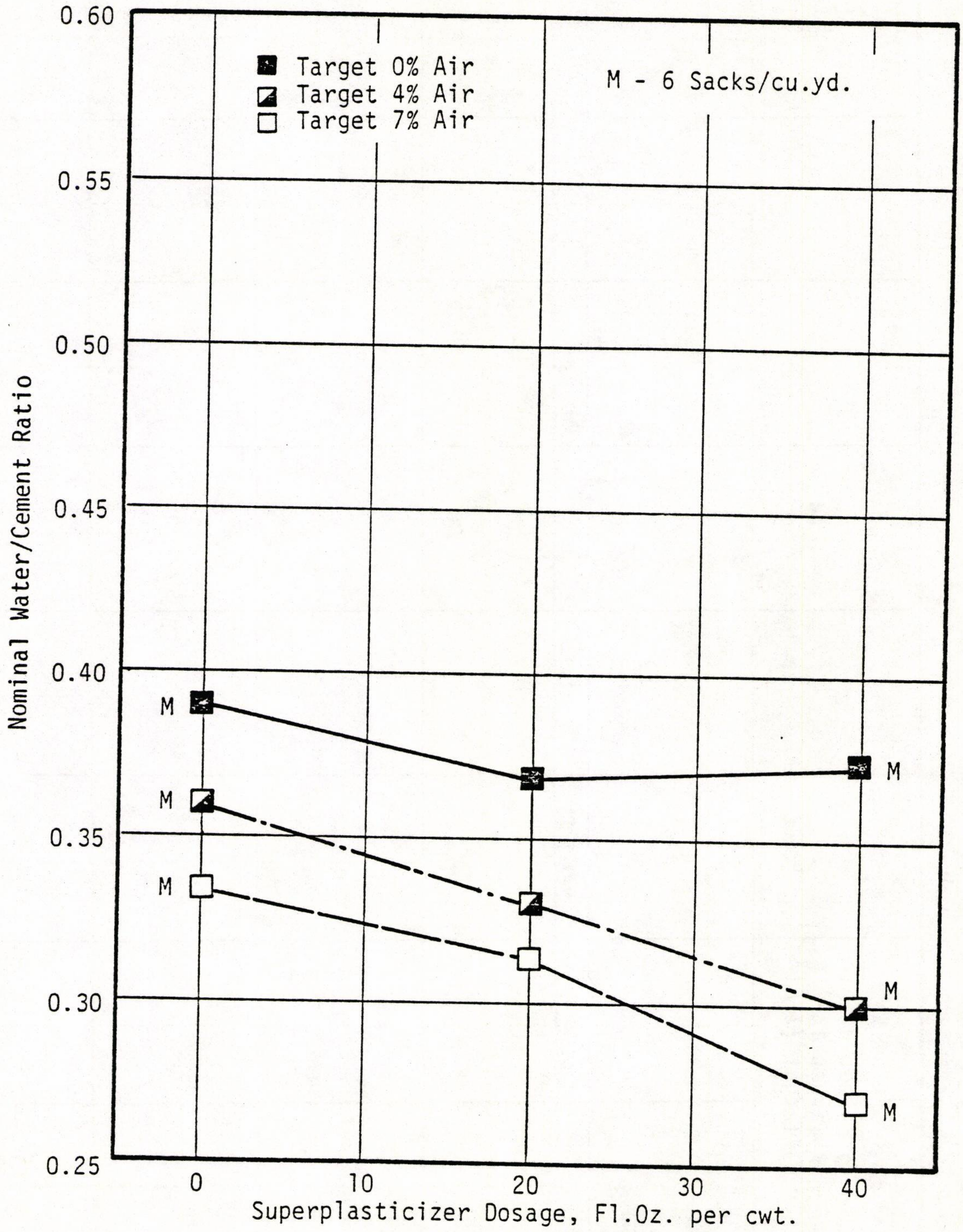


Figure 6.25 NOMINAL WATER/CEMENT RATIO VS. SUPERPLASTICIZER DOSAGE, GRAVEL AGGREGATE

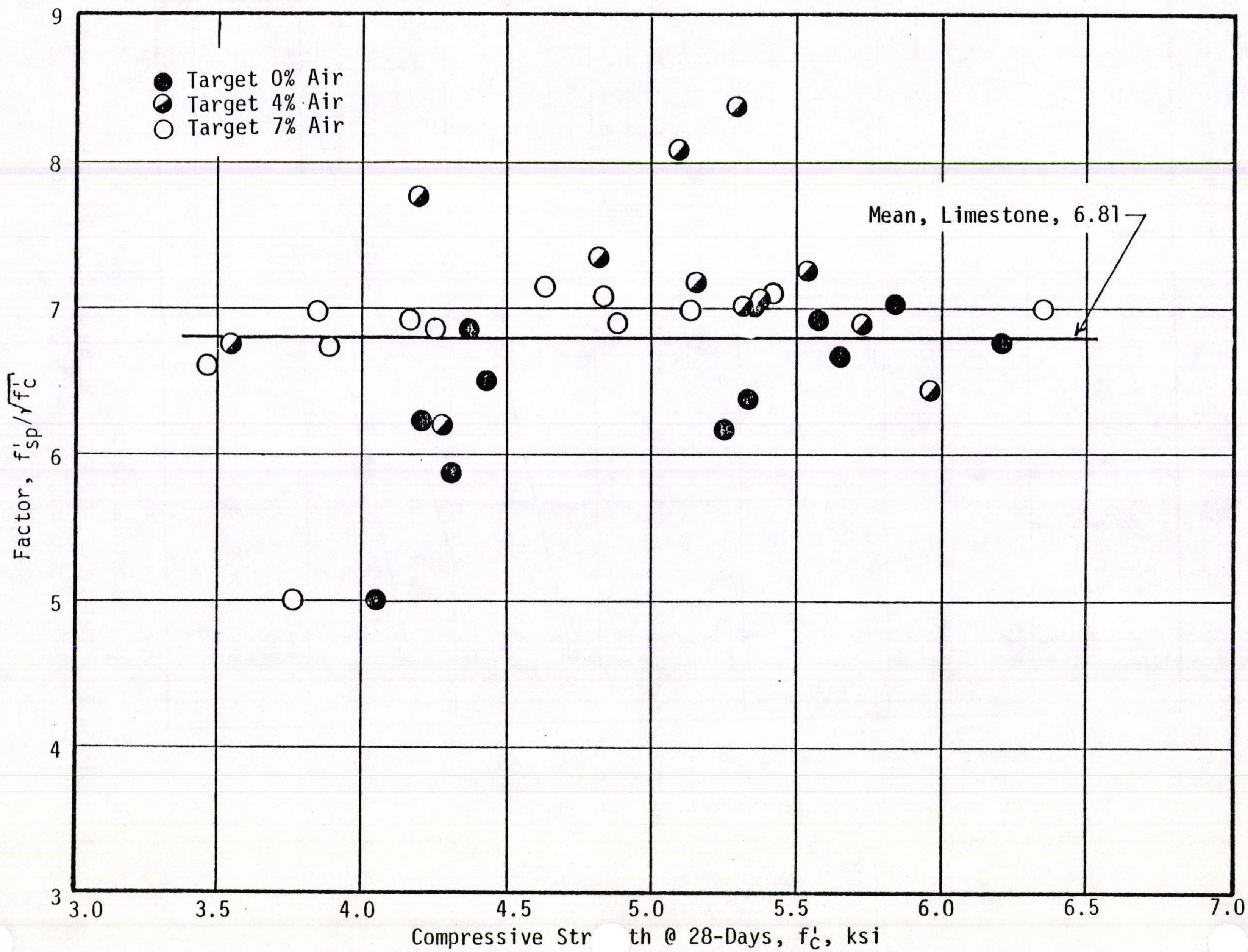


Figure 6.26 FACTOR $f'_{sp}/\sqrt{f'_c}$ VS. COMPRESSIVE STRENGTH, LIMESTONE AGGREGATE

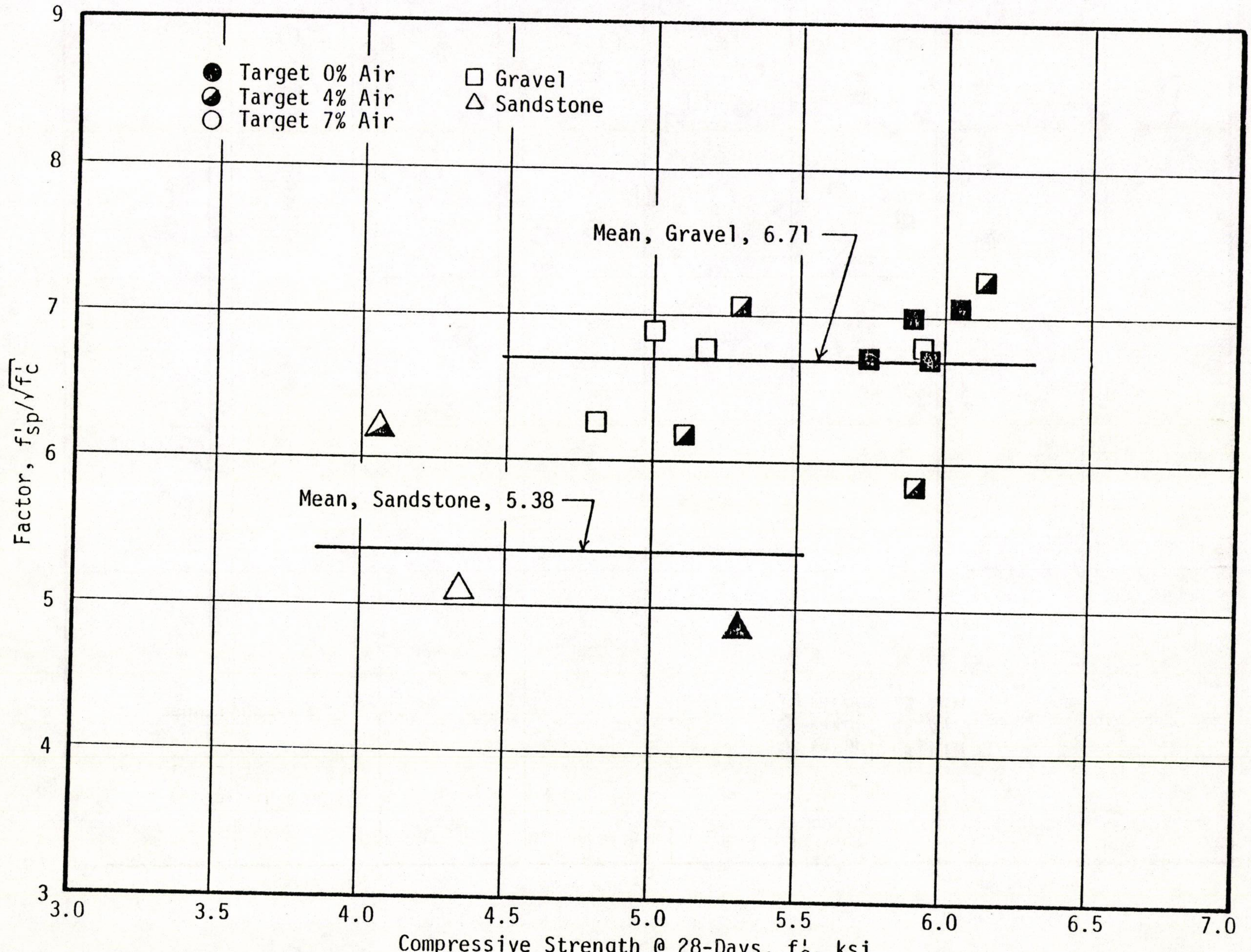


Figure 6.27 FACTOR $f'_{sp}/\sqrt{f'_c}$ VS. COMPRESSIVE STRENGTH, GRAVEL AND SANDSTONE AGGREGATE

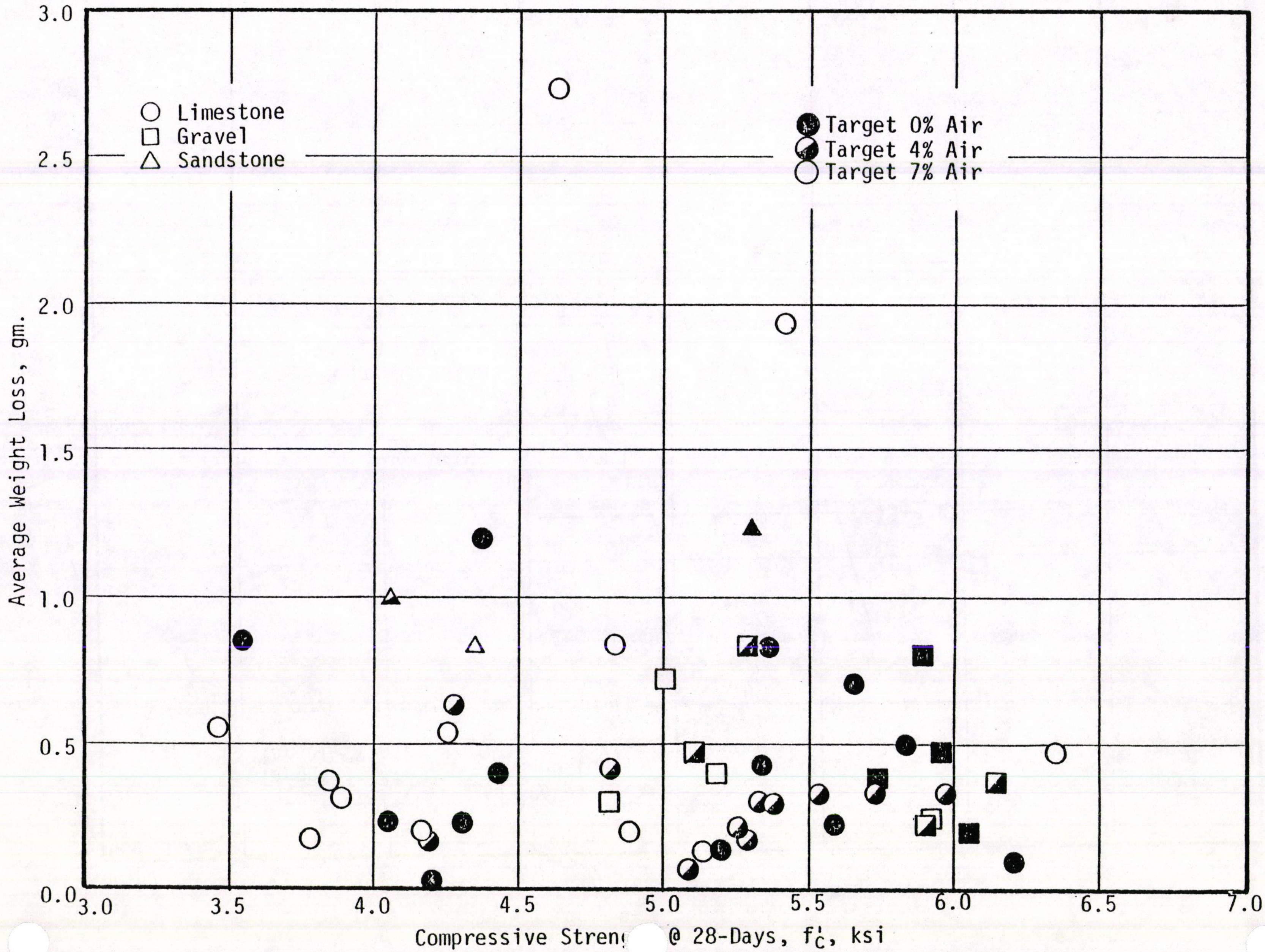


Figure 6.28 ABRASION RESISTANCE VS. COMPRESSIVE STRENGTH

VII. CONCLUSIONS

The following conclusions may be drawn from the results of tests performed on hardened concrete specimens as described in the two previous chapters.

The use of Melment L10A superplasticizer permits the achieving of 28-day compressive strengths in the order of 6,000 psi with adequate air-entrainment to resist the numerous freeze/thaw cycles of the Arkansas climate beginning with a workable slump in the order of 3 inches. In a flowing mode of up to 8 inches, again with adequate air-entrainment, 28-day compressive strengths in the order of 5,000 psi can be achieved. With continued curing, higher strengths will result that are consistent with the usually achieved rates of increased strength with Portland cement concrete.

The relationship between 28-day compressive strength and water/cement ratio seems to follow rather closely the inverse relation known as Abrams' Law. For non-air-entrained Portland cement concrete, that relationship is closer to linear and gives approximately a 1,000 psi increase in 28-day compressive strength with a 0.10 decrease in water/cement ratio. Strengths achieved with non-air-entrained concrete mixes will be reduced from 6 to 10% per each percent increase in air content for the same water/cement ratio. However, the increased workability due to air-entrainment will moderate that loss greatly for usual air content percentages.

Rounded gravel will normally allow as much as 500 psi extra compressive strength due to the increases workability of the rounder aggregate when compared with the angular aggregates such as limestone or sandstone.

Compressive strength is increased in the order of 500 to 750 psi by a one sack/cubic yard increase in the cement factor.

Use of Melment L10A superplasticizer increases the compressive 28-day strength in the order of 20 psi per ounce of superplasticizer per hundredweight of Portland cement in the dosage range of 20 to 40 ounces/cwt. The higher the superplasticizer dosage, the more rapid the rate of initial strength gain.

The split cylinder tensile strength of mixes using limestone and gravel as coarse aggregate may be predicted by approximately $6.7\sqrt{f'_c}$.

All of the above conclusions must be considered very general. They are based on the limited data received from the tests reported in the two previous chapters. They are meant to serve only as initial guide lines for the design of mixes using Arkansas aggregates. Actual values should be confirmed in each individual need by actual trial batching and standard tests.

VIII. RECOMMENDATIONS, GAINS, AND IMPLEMENTATION

The following are recommendations regarding the use of superplasticizers in future Arkansas State Highway and Transportation Department projects, an evaluation of the gains made by this research, and suggestions for the implementation and further development of information about superplasticized concrete in the activities of the Department.

8.1 Recommendations

Many researchers have reported erratic results with respect to consistent workability in superplasticized concrete, especially at high temperatures. That has been the experience of the present study as well. In the present project, it would seem that that problem in repeatability had to do primarily with the sensitivity of workability in superplasticized concrete to relatively small changes in moisture content and the scale factor of small size batches. Therefore, the following recommendations are made with respect to mix design and quality control.

a) Careful mix design and trial batching should be done in advance for any use of superplasticized concrete. Initial trial batching should be done using a minimum trial batch size of 1/3 cu.yd. Confirmation batches by the supplier should be made of a minimum of 2.0 cu.yd.

b) Confirmation batches should be made using a range of three temperatures expected in the concrete at the job site.

c) A redesign and reconfirmation of mix properties should be done for any change in Portland cement source, aggregate source, aggregate gradation, superplasticizer, air-entraining agent, or any other admixture used.

d) Mix design with respect to workability should take into account the expected transport and holding time of the mix before deposition.

e) Target slumps for times just previous to addition of the superplasticizer in flowing concrete should be between 1.0 to 2.0 inches and should take into account expected high temperatures at the job site.

f) The upper limit of slump for flowing concrete should be limited to approximately 6.0 inches unless there is a justifiable reason for using a larger slump.

g) Use of a flowing concrete on flat work that requires finishing beyond floating and surface roughening should be preceded by examination of the tendency toward "mortar bleed" that might tend to inhibit troweling.

h) Careful attention should be paid to the superplasticizer manufacturer's recommendations as to maximum and maximum dosage and x mixing procedure.

This study and other research reports have demonstrated the rapid loss of the additional workability available from superplasticizers. The rate of loss is higher in higher slump concretes and is generally lost within 30 to 60 minutes of the addition of the superplasticizer. The rate of loss is also greatly increased by high concrete temperatures. This research has shown that the particular superplasticizer examined performs optimally i concretes whose temperature is closer to 70°F than 50°F or 90°F. Therefore, the following recommendations are made with respect to construction procedures, temperature, and dosage.

a) The contractor for a particular job involving superplasticized concrete should be carefully informed of the potential difficulties related to the use of superplasticized concrete. Preferably, both the contractor and the concrete supplier should have increasing experience with superplasticized concrete.

b) Superplasticizer dosage should be added before and as close as possible to deposition.

c) The job organization should be such as to finish placement of the concrete within 30 to 45 minutes of addition of the superplasticizer.

d) If necessary in emergencies, a single re-dosage of superplasticizer can be permitted.

e) Extremes of high or low concrete temperatures should be avoided. Optimum temperature would be in the range of 65° to 75°F. Use chilled water would be preferable to the use of ice. Any ice added to the mixing water should be melted before the addition of the superplasticizer.

f) Differences of exposure of flatwork to sunlight should be avoided. Shading or early morning or late afternoon work schedules should be considered if the possibility of severe differences in setting time are anticipated.

g) Placement should be continuous. Inspection should take careful note of possible changes in concrete temperature, initial slump at delivery before addition of the superplasticizer, and total water content of the mix.

The other major concern related to the use of superplasticizers is the possible change in the air-void structure within the mortar and the resulting reduced freeze/thaw resistance. On the basis of this research and other studies recently reported, it would seem that manufacturers of superplasticizers have made and are continuing to make modifications of their product that improve their performance in this regard. Limited data from this study has indicated that addition of the air-entraining agent after the addition and complete mixing of the superplasticizer may very well be advantagous at least from the point of view of freeze/thaw durability. Therefore, the following recommendations are made with respect to air content in the superplasticized mixes.

a) If the air-entraining agent is added in the mix water, the target initial air content before superplasticizer addition should be approximately 2.0% larger than would normally be the case.

b) If the air-entraining agent is added after the superplasticizer is added and blended with the mix, a normal target air content percentage may be used.

d) Careful monitoring of the air content of the mix just previous to deposition should be continued throughout the duration of the job.

8.2 Gains

In general, the gains of the present research have been to confirm the behavior of superplasticized concrete using typical Arkansas aggregates and to see the differences in that behavior and hardened quality as a function of a number of variables including delay of superplasticizer addition, agitation before deposition, air content, temperature, cement factor and aggregate type. In all these variables, the performance with the particular superplasticizer examined, Melment L10A, was essentially consistent with behavior reported elsewhere.

The gains peculiar to this study might be considered two-fold. The first has to do with the improved freeze/thaw durability potentially inherent in the addition of the air-entraining agent after the addition and blending of the superplasticizer in the mix. During the conduct of this study, this feature was considered to have been a new development. However, additional reading during the preparation of the report found the following statement from an appendix to Prestressed Concrete Institute recommended practice paper on the use of "high-range water reducers" (superplasticizers):

> "Most researchers have found that if the HRWR is thoroughly blended in the mix before adding the air-entraining agent, the air voids will have the proper size and spacing for durability." [34]

The author has not seen any other references to this reverse procedure.

The second possible gain from this study in particular is the recognition that not only does high concrete temperature make the use of superplasticizers problematic, but low concrete temperature reduces their effectiveness severely.

8.3 Implementation

Despite the difficulties associated with slump loss and air-void structures that are inherent to the use of superplasticizers, their advantages far outweigh their disadvantages. They will be increasingly used in American concrete practice although their use will require more careful construction planning and inspection than is the case in much current concrete work. Their successful use will require experience. Therefore, it is important that the Arkansas Highway and Transportation Department gain further experience in the actual use of these admixtures.

In that regard, it is recommended that the Department begin to use superplasticized concrete in a water-reduced mode for high-early-strength in patching. It is preferable that it be used in a region of the state with more severe freeze/thaw problems and where some ready-mix companies already have some experience with their use. Both sequences of addition of superplasticizer and air-entraining agent should be tried and the durability and performance of concretes with each sequence closely monitored and compared.

As experience in the use of superplasticizers is increased, they should be tried in several bridge deck overlays and/or new construction. Again, comparison should be made in the durability performance of concretes with the two admixture sequences.

Further study should be made in the performance of superplasticizers. The present report is made with respect to only one of the commercially available superplasticizers. The work of Malholtra [27] and others indicates that the performances of each different chemical type of superplasticizer may be greatly different from the others. Therefore, it is important for the Department, as experience is gained with one type or brand, to use others as well in the same type of program of patching, etc.

Further studies should be done to establish with a larger number of samples whether the reverse sequence of admixture addition is significant in other superplasticizers as well with respect to freeze/thaw resistance. Also, further studies should be done to establish for Melment L10A and other superplasticizers the optimum range of temperature in which the admixture is most efficient.

Finally, the use of superplasticizers in conjunction with fly ash, particularly Western coal fly ashes, should be examined. The use of fly ash as partial substitution for Portland cement is becoming widespread. Such use adds to the specific surface available for the superplasticizer to react with. Moreover, recent data received by the author from an industrial source indicates an almost linear increase in freeze/thaw durability with percentage increase in fly ash substitition [35]. Most fly ashes in scanning electron photographs show themselves as small hollow spheres [36]. Perhaps the introduction of the fly ash, which partially hydrates in the mix, effectively introduces a further distribution of small bubbles in the mortar. The combination of superplasticizer, fly ash, and some retarding agent might well work together to help solve most of the problems attendant to the use of superplasticizers.

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