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HIGH-STRENGTH CONCRETE

CTA 10

HIGH-STRENGTH CONCRETE

SYNOPSIS

In this bulletin, we will discuss methods of design and production of concrete with ultimate strength of 6,000 - 10,000 psi. In some plants, these strengths are attained almost routinely, while for others special materials and considerable care in production and quality control may be required. This paper is intended to be of practical nature for those who are concerned with concrete design and control in precast/prestressed concrete plants. It is meant to supplement the large amount of material that has already been published on the same subject. Two recently published papers from Modern Concrete are included as excellent references on high-strength concrete.

The general usage of high-strength, precast concrete is discussed. Following this, considerable emphasis is given to the behavior and application of materials used in high-strength concrete.

Methods are presented for optimizing mix designs, after which specific references are made to procedures used at Concrete Technology Corporation (CTC). Finally, statistical methods for evaluating production consistency are demonstrated.

APPLICATION OF HIGH-STRENGTH CONCRETE IN P/S INDUSTRY

High-strength concrete is effective in prestressed concrete members because it can economically increase the structural performance, especially for longer spans. Furthermore, concrete with a low water-cement ratio can reduce the amount of volume change and, consequently, the loss in prestress attributable to shrinkage.

Following are two illustrations of how higher-than-normal strengths can be used in the prestressed concrete industry to cause further savings:

The design and manufacture of prestressed concrete beams can include longer spans and wider spacing of girders when high-strength concrete is utilized. For instance, consider typical AASHO Type IV girders with spans and girder spacing as shown in Fig. 1. The maximum span capability for girders with ordinary 6,000 psi concrete is 120 ft., but the same girders can span 140 ft.

or 155 ft., if 8,000 psi or 10,000 psi high-strength concrete is used. More details on the benefits of high-strength concrete for segmental construction of bridge girders will be contained in the Segmental Beam Construction Manual soon to be published by PCI.

Benefits from high-strength concrete can also be exploited in prestressed piling. In the paper, "Ultimate Strength of Prestressed Concrete Piles and Columns," by Drs. Anderson and Moustafa (Journal of ACI, August 1970), applications of interaction diagrams were used in examples of prestressed concrete pile design.

The first example yielded two choices of sections which met the criteria for a typical building foundation pile. They were -

1. 10-inch square pile, f'_c = 8,000 psi.
2. 12-inch square pile, f'_c = 6,000 psi.

The cost of No. 1 is approximately 15 per cent less than No. 2.

In the second example, three choices evolved for a deep foundation pile application. They were -

1. 16 1/2-inch octagon pile, f'_c = 8,000 psi.
2. 18-inch octagon pile, f'_c = 7,000 psi.
3. 20-inch octagon pile, f'_c = 6,000 psi.

The use of No. 1 results in a 15 per cent savings over No. 2, and a 25 per cent savings over No. 3.

Most pile manufacturers do not have a wide range of form sizes from which to choose, so high-strength concrete could be used to increase the load carrying capacities of existing sections.

Sometimes precast and/or prestressed concrete members are too heavy to be used economically in structures; therefore, thinner sections are needed. In some cases, the concrete cover over steel reinforcement could be reduced to 1/2 inch when dense concrete with a low water-cement ratio is used. Tests at CTA have shown the 1/4 inch of impermeable concrete cover is superior to 1 1/2 inches of ordinary, less dense concrete when exposed to seawater attack. Thus, it may be possible to utilize thinner webs in beams and more slender columns.

BEHAVIOR AND ANALYSIS OF MATERIALS

Portland Cement

Many of the desired properties of precast, prestressed concrete are most easily attained with the use of a good quality, high-early strength cement (Type III). In some areas, low alkali, Type II cement is specified because of local aggregate or soil conditions. CTC has been able to get Corps of Engineers approval for use of a Type III cement which satisfies the specifications for Type II. High quality Type III cements are simply not available in some locales because of cement manufacturers' marketing and/or production conditions.

The precaster should look for these qualities in Type III cement:

1) High fineness: 5,000 - 6,000 Blaine.
2) High tricalcium silicate (C_3S) content: 60-70 per cent.
3) Low water demand: usually decreases with decreasing tricalcium aluminate (C_3A) content.
4) Safeguard against severe false set: final penetration of paste = 50% or more of initial penetration.
5) High 28-day compressive strength of mortar cubes: 7,000 - 8,000 psi.

Some Properties of Concrete Affected by Cement:

1. High-early strengths. This is primarily determined by the fineness and C_3S content. Fig. 2 compares the early strength gain of a Type III cement, such as described in the preceding paragraphs, with the early strength gain of a normal Type I cement. These results are for concrete cured at elevated temperatures, but the comparison is similar for normally cured concrete.

   Accelerated curing of concrete as it affects early strength will be the subject of a future CTA Bulletin.

   Large gains in early strength can be obtained by applying heat in an effective manner while retaining moisture in the concrete. When forms are stripped from high strength precast concrete at an early age and drying begins, the rate of progress of hydration slows. Therefore, high-strength concrete should be well cured at an early age in order to develop its full ultimate strength. Curing is difficult to renew, because capillary pores are discontinuous after partial hydration, thereby preventing moisture penetration.

2. Workability. The type of cement and its physical and chemical characteristics have considerable influence on the workability of the fresh concrete. Some Type III cements may have sufficient fineness and C_3S content to provide high-early strengths, but may produce a completely unworkable concrete mix. Lack of workability, when it can be directly attributed to the cement, is caused primarily by the tendency for some cements to false set or prematurely stiffen. This problem is initiated by the action of gypsum in the cement. If the temperature in the cement grinding mill is excessively high, the gypsum added to the clinker may dehydrate to plaster of Paris or soluble anhydrite. This dehydrated gypsum, when it combines with water in the concrete mix, will set and form a delicate skeleton, so as to simulate the actual setting of cement.

   This phenomenon of premature stiffening is often not evident in concrete delivered in a transit mix truck because the skeleton formation can be broken down by reworking the mix. The rapid stiffening is extremely troublesome in precast concrete plants, where mixing times are often short and the concrete is delivered in a bucket to the forms. The batchman will often increase the water content of the mix to compensate for the apparent slump loss which, of course, results in lower strength concrete. Even the added water will not produce concrete with optimum workability.

   Some producers unknowingly operate under the conditions described above. If the cement manufacturer cannot resolve the problem, it is sometimes possible to minimize the slump loss by experimenting with admixtures and/or mixing procedures. This will be discussed further in the "Admixture" section of this paper.

   Similar behavior of the fresh concrete may exist, i.e., lack of workability or slump loss, even when the cement is not false-setting. Some combinations of cement and water-reducing admixtures will result in rapid stiffening, even when retarding, water-reducers are used. This has been known to occur when the cement is manufactured with anhydrite gypsum.

The foregoing discussion is intended to emphasize the need for the concrete producer to know the properties and related manufacturing processes of his concrete materials.

3. Ultimate Strength. Most comparisons of concrete made with Type I or Type III cement show equal compressive strengths at the age of about one year. These tests are generally performed on cylinders moist-cured at 73^{oF}. However, a good quality Type III cement will develop higher ultimate concrete strengths than Type I cement in precast products cured at accelerated temperatures.

   Most precast and prestressed concrete which is moist-cured at elevated temperatures is subsequently stored in a drying condition. Concrete made with Type III cement will usually develop a greater percentage of its ultimate strength during the initial curing period than will concrete made with Type I cement. Many factors affect the strength gain after accelerated curing ceases, such as thickness of the member, type of admixture, relative humidity, moisture condition of aggregate and concrete density. It can be generally stated, though, that most (60-75%) of the ultimate strength is developed in the first 24 hours.

Admixtures

Water Reducing:

Retarding, water-reducing admixtures (ASTM Type D) are used almost universally in our industry today. The economics and benefits of their use are fairly well accepted. There still remains a great deal of controversy about the behavior and role of these admixtures in concrete. The optimum performance of admixture and cement is of greatest concern to the precaster and fairly extensive and well-controlled testing should be done to determine the best combination of materials.

The role of gypsum in cement is to retard the tricalcium aluminate (C_3A) reaction in the cement paste. This is the first reaction to take place and occurs very rapidly. If no gypsum were present, flash set would occur.

There is an optimum amount of gypsum or SO_3 that will produce the strongest, most workable concrete without creating excessive expansion. This is determined by the cement producer for normal mixing and curing temperatures and often it is too low for conditions encountered in prestressed concrete plants.

Stronger retardation is needed for finely ground cements, concrete mixed at higher temperatures (hot-weather concrete), or cured at accelerated temperatures and for high cement content mixes. Most of the common retarding water reducers can be classified into three categories according to their base material. In some formulations, calcium chloride or triethanolamine is added to reduce the amount of retardation.

Lignins - These are salts of lignosulfonic acids (calcium, sodium, or ammonium) which are waste products of the paper-making industry. Some of these industries market the materials themselves; others supply the raw product to admixture formulators. These materials entrain air. If the air is undesirable, an air-detraining agent, such as tri-butyl phosphate can be added.

The lignins are usually mild retarders at a normal dosage of 6 to 8 ounces per sack of cement. Additional retardation and water reduction can normally be obtained by increasing the dosage up to twice normal. Although it doesn't appear from tests at Concrete Technology Corporation that dosages between two and three times normal are harmful to the concrete, there seems to be no particular advantage in that high of an addition rate. In some cases, high dosages of lignins might increase the air content substantially.

Salts of Organic Acids - These are technically hydroxylated carboxylic acids, usually salts of gluconic acid. They ordinarily retard initial set more than lignins. Normal dosage rates are 2 to 4 ounces per sack.

Concrete containing these admixtures usually have a greater rate of bleeding. Researchers generally agree that the organic acids contribute less to concrete shrinkage (or even reduce it) than do the other Type D admixtures.

Hydroxylated Polymers - There appears to be only one company marketing this type. There are many formulations available, not all of which are available in each locale. Recommended addition rates with these vary from 3 to 5 ounces per sack.

Table 1 lists most of the popular water reducers along with their basic ingredients and the manufacturer.

Behavior of Retarding Water Reducers in Concrete - Technical representatives of admixture companies will usually ascribe the water reduction to dispersal of the cement grains, but most available information in the technical literature indicates the reduction to be due to changes in the early hydration reactions of the cement.

Normally, water reducers are added along with the mixing water. Additional retardation and sometimes improved workability and compressive strength can be obtained by delaying the addition of the water reducer until the cement and initial water are combined. In cases where rapid slump loss occurs, delayed additions are sometimes helpful. The length of delay and extent of improved performance must be determined by controlled experimentation with each producer's cement and admixture.

Significant increases in concrete strength and workability can sometimes be made by using larger-than-normal dosages of water reducers. This is particularly true in rich mixes with low slump where improved workability is extremely valuable. Oftentimes, twice the normal dosage can be used with sufficient gains to justify the additional cost. Again, careful evaluations of this should be made for each combination of materials. Research on effects of high-dosage rates will continue in the CTA lab and be reported later.

Retarding water reducers yield the biggest improvement in concrete performance with cements which have low C_3A contents (less then 8 per cent) and low alkalis (less than 0.60 per cent).

The foregoing discussion of cement and admixtures points out the importance of each producer testing his cement with locally available admixtures to arrive at the best and most economical combination.

Air-Entraining Agents:

Air-entraining agents are normally not recommended for use in high-strength concrete. A sizable reduction in compressive strength (10-20%) occurs when concrete, such as is described in this bulletin, is entrained with air to normal specified limits (4-7%). There is little, if any, accompanying water reduction, such as occurs at lower cement factors to compensate for the lower strength. Anyway, precast concrete is rarely exposed to saturation and freezing where air-entrainment is beneficial.

Aggregates

Research performed at Concrete Technology Corporation has indicated that considerable increase in the ultimate compressive strength of concrete can be accomplished by improving the bond of the aggregate to the cement paste. The economics and practicality of some of the methods by which this was done are still questionable and remain outside the scope of this paper. Most concrete producers today are limited to only one or two sources of aggreate, and, with this in mind, the discussion of aggregates will be limited to ideas which might be used to improve existing conditions.

Coarse Aggregate:

Coarse aggregatesshould be washed to remove fines which will increase water demand and reduce the workability of high-strength concrete. A minimum of 0 to 0.5 per cent material passing the No. 200 sieve should be sought instead of the usual 2 per cent. Another benefit of washing is to presoak the aggregate, which reduces slump loss that would normally occur with dry, highly absorptive aggregates. Saturated aggregates provide additional moisture for curing concrete with a low water-cement ratio and improve the later strength gain.

The compressive and tensile strengths of concrete can be increased considerably by reducing the maximum size of aggregate when the water-cement ratio is low. There exists, for each cement-aggregate combination in concrete, a water-cement ratio above which the paste strength controls the concrete strength and below which the cement- to-aggregate bond strength controls the concrete strength. The smaller aggregate has more surface area and, subsequently, higher bond strength if there is sufficient, strong paste to develop the bond.

Fig. 3 shows results of tests done at CTC using 3/8, 1/2, and 3/4-inch maximum size aggregate. It appears from this that 3/4 or 1/2-in. aggregate is best for cement factors below 650 lbs. per cu. yd., and 3/8 or 1/2-inch aggregate should be used at higher cement factors.

A very comprehensive study of "Aggregate-Cement Bond, Cement Paste Strength, and the Strength of Concrete," was made by Alexander, Wardlaw and Gilbert, in 1965, and reported at the International Conference on the Structure of Concrete. In their report, they show that the compressive strength, tensile strength and shear bond strength of concrete are all improved by using smaller maximum size aggregates at low water-cement ratios. In addition to the lesser surface area available for bond, the larger size aggregate is vulnerable to differential loss of bond strength from bleeding onto the bottom surface of the aggregate, even at water-cement ratios of 0.35.

Other than the effect of maximum size and excess fines, the concrete strength is little affected by the coarse aggregate gradation.

Fine Aggregate:

The quantity and gradation of fine aggregate in high-strength concrete is critical for maximum workability and strength. The combination of aggregates in high-strength concrete will be discussed in the following section.

A coarse, natural sand is particularly advantageous for strong, dense concrete. It is desirable to have a minimum of fines passing the No. 50 sieve, i.e., 0 to 10 per cent. These fines add little, if any, to the workability of rich concrete mixes and create a higher water demand with resulting lower strengths and greater shrinkage. The amount passing the No. 30 sieve is not as critical as that passing the No. 50, but it should be maintained between 30 and 40 per cent. This results in a sand gradation with a fineness modulus of about 3.25 which, of course, is considerably higher than the normal range of 2.50 to 2.70 for ready-mix concrete production.

The coarse sand described above makes it difficult to entrain air efficiently when normal dosages of air-entraining agents are employed. If air is required in the concrete, 2 or 3 times normal dosage may be needed.

Slump control is usually much simplier with such a coarse sand, because there is an upper limit on the amount of free moisture which it will hold. The sand used at Concrete Technology has a narrow range of free moisture--from 3 to 6 per cent.

OPTIMIZED MIX DESIGNS

In this discussion, a mix is considered to be at optimum when the maximum strength per pound of cement is obtained while the necessary qualities of impermeability, low shrinkage, and good workability are satisfied.

Concrete materials should be selected after careful analysis of each material and its performance in concrete. After studying the reference material listed earlier and the preceding comments on material behavior, an efficient and informative testing program can be planned and executed.

Of course, the basis for selecting mix proportions is dependent on several factors other than materials, such as type of mixer, method of delivery, placement and curing. The principles described here apply for conditions which exist in many precast and prestressed concrete plants today.

The precaster can generally use much lower sand to aggregate ratios than are used in ready-mixed concrete because lower slump concrete can be utilized. Sand contents of 45 to 50 per cent are common in normal applications of ready-mix, while our industry frequently uses 35 per cent and lower.

The Concrete Technology structural mixes described later were designed for maximum density. This was done by determining a continuous gradation of dry materials, i.e., cement, sand and gravel. The resultant blend contains minimum voids and can be compacted at near zero slump. Fig. 4 shows a gradation curve for CTC structural concrete mix proportions compared to the Fuller Ideal Gradation Curve. The curves compare closely, as can be seen. The Fuller curves provide a good basis for evaluating existing mix proportions, or, as a starting reference, for new mix designs. The development of these curves can be found in "Plain Concrete," by E. E. Bauer, McGraw-Hill Book Co., 1949.

Optimum Matrix Volume:

This mix proportioning results in matrix volumes (volume of cement, sand, water, and air) of about 50 per cent for CTC structural concrete. Most normally graded mixes contain 55 per cent matrix or more. Optimum matrix volume is desirable for high strength and low shrinkage and creep. This occurs where all voids formed by the coarse aggregate are filled and the concrete remains workable. The minimum matrix volume for complete filling of the voids is about 38 per cent, but this is too low for workable concrete. Optimum occurs between 48 and 52 per cent with continuously graded aggregates, and between 45 and 48 per cent for gap-graded aggregates.

Mix Proportioning:

Many theoretical methods for proportioning exist, but most result in dependence on trial mix verification and adjustment. Scientifically proportioned trial mixes tested in the lab and/or plant will yield valuable information on which a plant can base its mix designs for many years or until major changes occur in material supply.

One simple method of proportioning aggregates for maximum density is to simply make several combinations of fine and coarse aggregate and compact them into a given volume which is then weighed. The resultant optimum fine-to-coarse ratio can be used in trial concrete mixes.

Each producer should determine a strength versus water-cement ratio curve for each current admixture combination used in his plant. It is advantageous to test concrete at ages from 14-18 hours to 90 days at normal temperatures, and at a higher maximum accelerated curing temperature. The resultant strength curves then provide a basis for daily operation, which depends on the operational efficiency of the plant, the strength requirements, and the curing conditions. Examples of such curves are shown in Fig. 5.

PRODUCTION CONSISTENCY

Production of high-strength concrete in a consistent and economical manner is a challenge that deserves more attention by the precast concrete manager than it usually receives. Typically, this question is viewed solely as a quality and/or a reliability problem which tends to bias the management decision toward "adding another half-sack of cement" in order to assure adequate release strength. Actually, the problem should be viewed as one of optimizing all the factors influencing concrete production to attain necessary strengths at the lowest overall cost.

Statistical evaluation of daily production tests provides an excellent method for determining the operating efficiency of a plant. Variables commonly found in ready-mix concrete production, such as quality control personnel, frequent changes in mix design, and varying jobsite conditions are usually not found in plant production. Therefore, reliable data can be easily obtained for analysis.

ACI Standard 214-65, "Recommended Practice for Evaluation of Compression Test Results of Field Concrete," is an excellent source for methods of statistical control. Analyses of daily compression tests on each mix design used and each product poured will show variations in concrete production and testing. These are used to determine the amount of overdesign necessary to achieve the desired level of performance. They may also point out shortcomings in quality control or daily concrete production which need attention.

The statistical measure of variability in concrete and testing is the standard deviation which, when expressed as a percentage of the average strength, is called the coefficient of variation, V. Precast and prestressed concrete plants should operate with a coefficient of variation between 5 and 10 per cent. Usually plants operating with large coefficients (10 - 15 per cent) find themselves using cement factors which are considerably higher than necessary. The manager who is using that extra half-sack of cement just to insure release strength will spend an extra $40,000 annually if he averages 200 cubic yards per day.

Typical Aggregate Gradations

	Sieve Size	Per Cent Passing
Gravel	1 in.	100
	3/4 in.	92
	1/2 in.	56
	3/8 in.	27
	No. 4	2
Sand	No. 4	98
	No. 8	74
	No. 16	53
	No. 30	34
	No. 50	12
	No. 100	1

Mixing

Concrete at CTC is mixed for 1 1/2 to 3 minutes in a two cu. yd. Eirich counter-current, pan-type mixer. Aggregates are unloaded directly from rail cars into the bins so they are always in a damp condition from washing at the aggregate plant. The temperature of the fresh concrete is maintained at 55-70^{o}F, except in the hottest days of the summer. Temperatures above 70^{o}F create additional water demand in order to maintain workability.

Slump control is obtained by observing two ammeters, one of which is connected to the pan drive and the other is connected to one of the mixing paddle motors. Frequent visual checks of concrete in the mixer and during placement make it easy to control the water content and concrete workability at all times.

Placing

Concrete is dumped from the mixer into one of the buckets shown in Fig. 8. The concrete truck carries a full bucket to the pouring area and returns with an empty bucket. Low-slump concrete is deposited from these buckets into the form with the aid of vibrators shown attached to the side of the bucket and connected to a power source from the concreting crane.

Although it is often assumed that the quality of the coarse aggregate is a major factor influencing concrete strength, it is more likely that a number of the factors under a), above, will play an important role, and they should be carefully investigated before assuming that aggregate alone is the primary factor limiting concrete strength.

CTC has spent considerable time and effort in developing suitable criteria for its material suppliers and in developing equipment to manufacture and consolidate low-slump, high-strength concrete. Following is a description of one of the commonly used structural concrete mix designs used at CTC. A description of the mixing and placing methods employed is also included.

CTC Structural Mix

This mix design is used for I-beams, tees, and other structural products where a release strength of 5,000 psi is required and 28-day strengths of 6,000 - 7,000 psi are generally specified. The actual 28-day strength tests from this mix were described in Fig. 7.

1 cu. yd. Weights (Saturated, Surface-Dry)

Type III Cement: 605 lb.
Sand: 1,090 lb.
3/4-in. gravel: 2,300 lb.
Water-reducing admixture: 40-60 oz. Zeecon R
Water-cement ratio: Usual range - 0.35 - 0.40
Sand to aggregate ratio = 32%
Aggregate to cement ratio = 5.6 to 1 (by weight)
Dry density of concrete = 155 - 158 pcf

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Slump control is obtained by observing two ammeters, one of which is connected to the pan drive and the other is connected to one of the mixing paddle motors. Frequent visual checks of concrete in the mixer and during placement make it easy to control the water content and concrete workability at all times.

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Concrete is dumped from the mixer into one of the buckets shown in Fig. 8. The concrete truck carries a full bucket to the pouring area and returns with an empty bucket. Low-slump concrete is deposited from these buckets into the form with the aid of vibrators shown attached to the side of the bucket and connected to a power source from the concreting crane.

Heavy external vibration from Anderson Vibrators makes it possible to place 0- to 2-in. slump concrete in I-beams, bulb tees, piling, and other structural members. Higher slump concrete with internal vibration is used for double tees, columns, median barriers, etc. Concrete is placed on a vertical front, and under external vibration, the stiff concrete flows along a 45° slope. The formed surfaces are almost free of bug holes and the concrete is nearly impermeable with a density of 155-160 pcf.

Internal vibration is used when necessary to get good compaction to supplement the external vibrators in very heavily congested areas, such as the end blocks of highly prestressed girders.

FUTURE IMPROVEMENTS

The practical limit to the compressive strength of concrete might be taken arbitrarily as the strength of the cement paste. Tests performed at PCA on paste with a water-cement ratio of 0.2 yielded compressive strengths of 25,000 psi. Strengths of 17,500 psi were obtained at CTA on paste with a water-cement ratio of 0.35. The limiting factor in concrete seems to be in the aggregate-to-paste bond.

Improvements in aggregate bond to cement paste by special coatings on existing aggregates might be used to increase the strength of concrete. It has already been demonstrated at the Brookhaven National Laboratory, Bureau of Reclamation, Dow Chemical Co., and elsewhere, that polymers can be used to improve the performance of concrete made from poor quality aggregates and mediocre cements.

New admixtures and equipment are being marketed which should aid considerably in producing low-slump, high-strength concrete.

SUMMARY STATEMENT

One can conclude that there is no simple combination of rules to follow in order to consistently produce economical, high-strength concrete. This paper has presented several factors which we have found to be important to this objective.

Substantial gains in concrete quality can be made by simply applying a thorough knowledge of the behavior of concrete materials gained through testing and research.

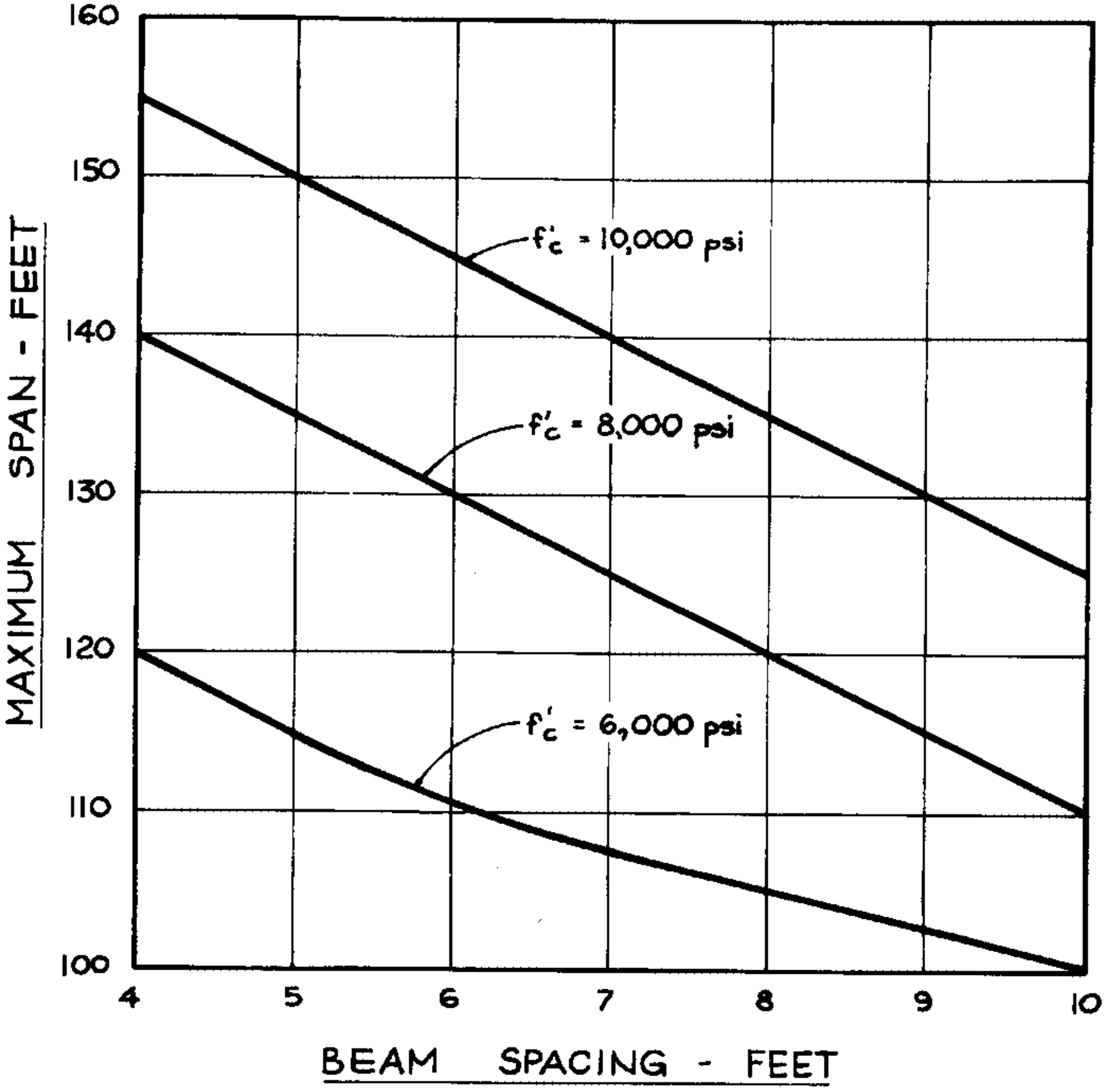

FIG. 1 - SPAN-SPACING CAPACITY FOR AASHO TYPE IV BEAMS

Water-Reducing Admixtures

Trade Name	Manufacturer	Type
Pozzolith 200N	Master Builders	Corn Syrup & Triethanolamine
Pozzolith 300N	Master Builders	Corn Syrup, Triethanolamine and Lignosulfonate
Pozzolith Hi-Early	Master Builders	Corn Syrup & $CaCl_2$
Sikacrete	Sika Chemical Corp.	Sodium Gluconate & $CaCl_2$
WRDA	Dewey and Almy	Lignosulfonate and Triethanolamine
Zeecon N	Crown-Zellerbach	Lignosulfonate and $CaCl_2$
Zeecon R	Crown-Zellerbach	Lignosulfonate

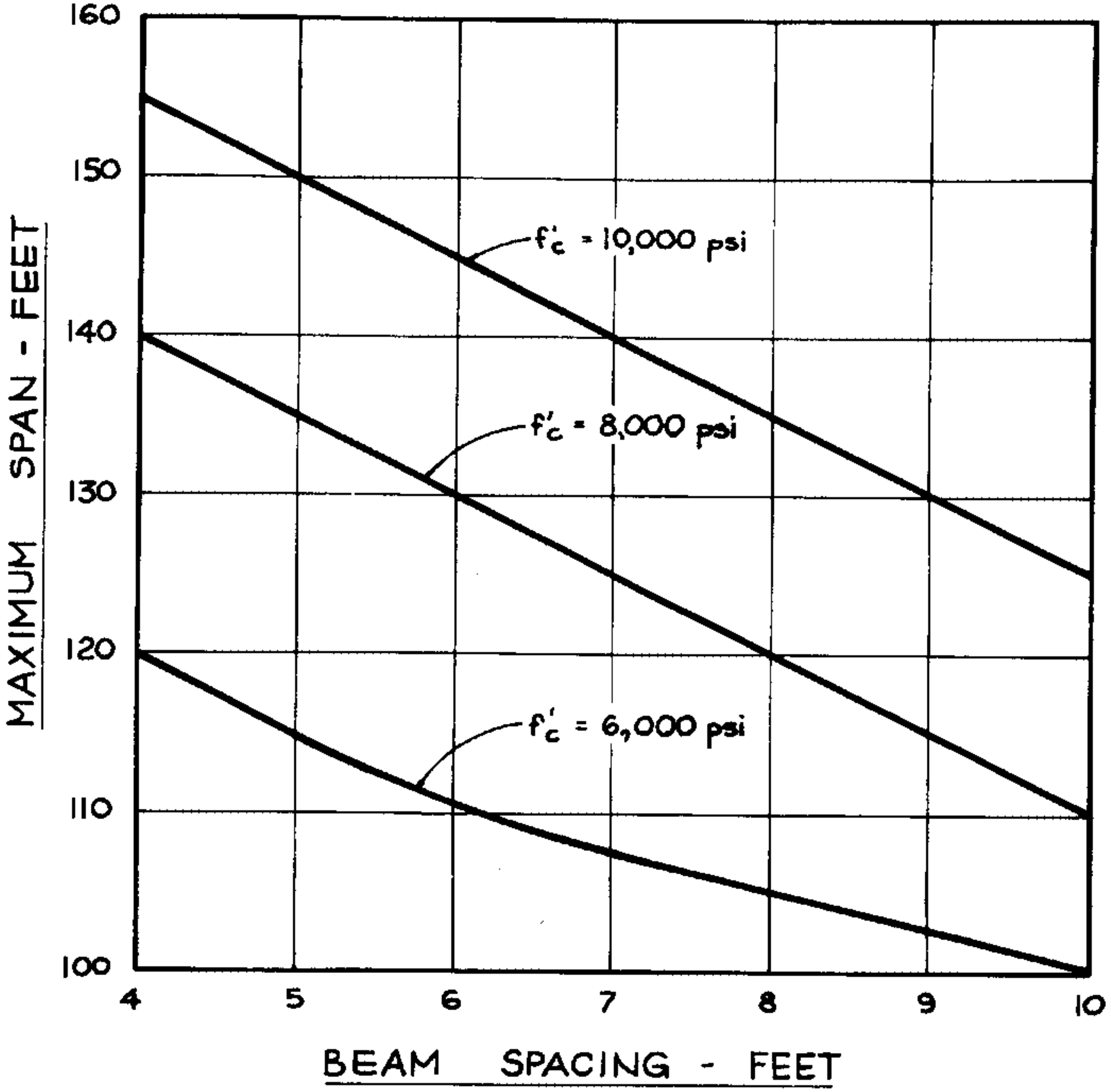

FIG. 1 - SPAN-SPACING CAPACITY FOR AASHO TYPE IV BEAMS

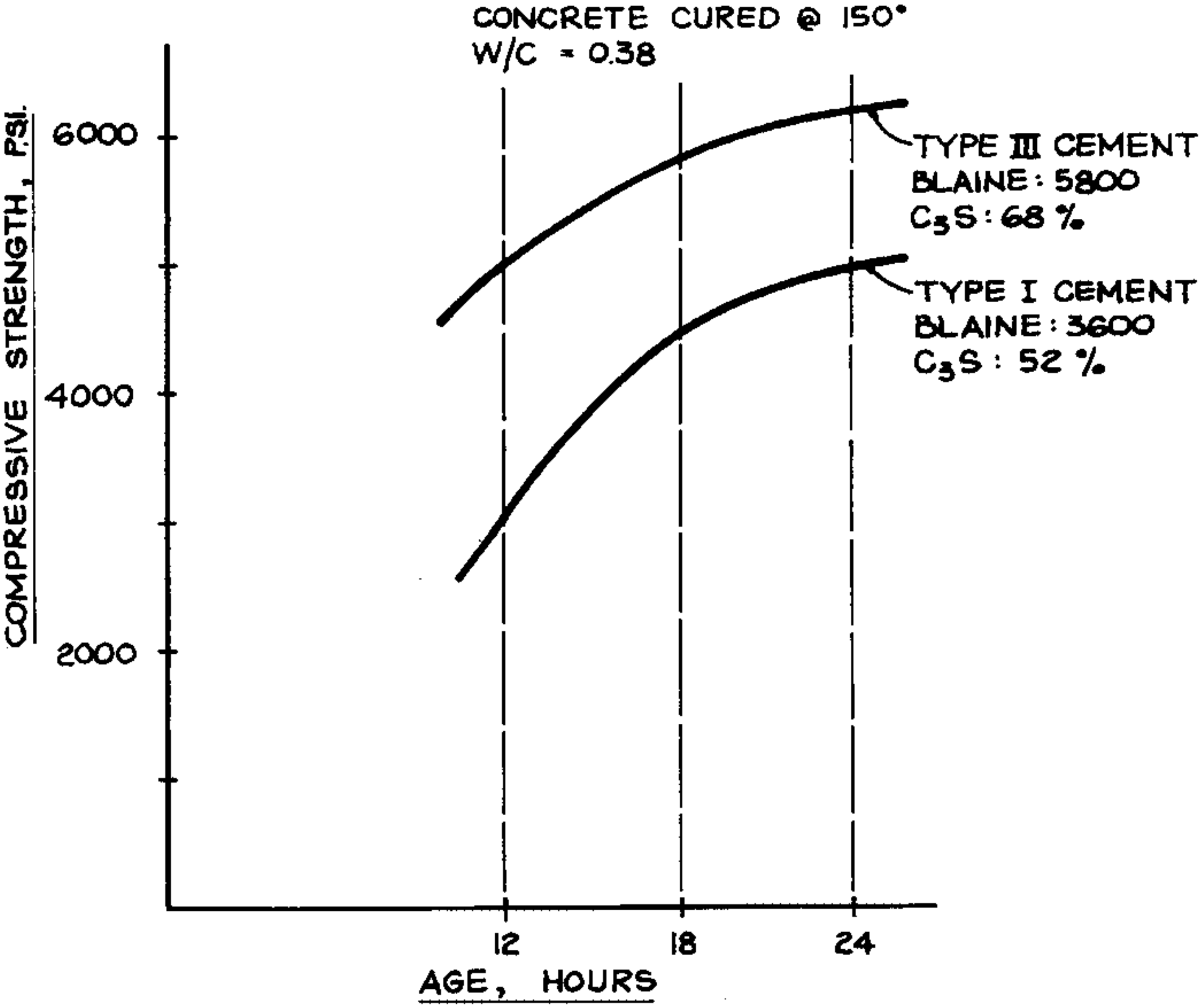

FIG. 2 - EARLY STRENGTH GAIN OF CONCRETE

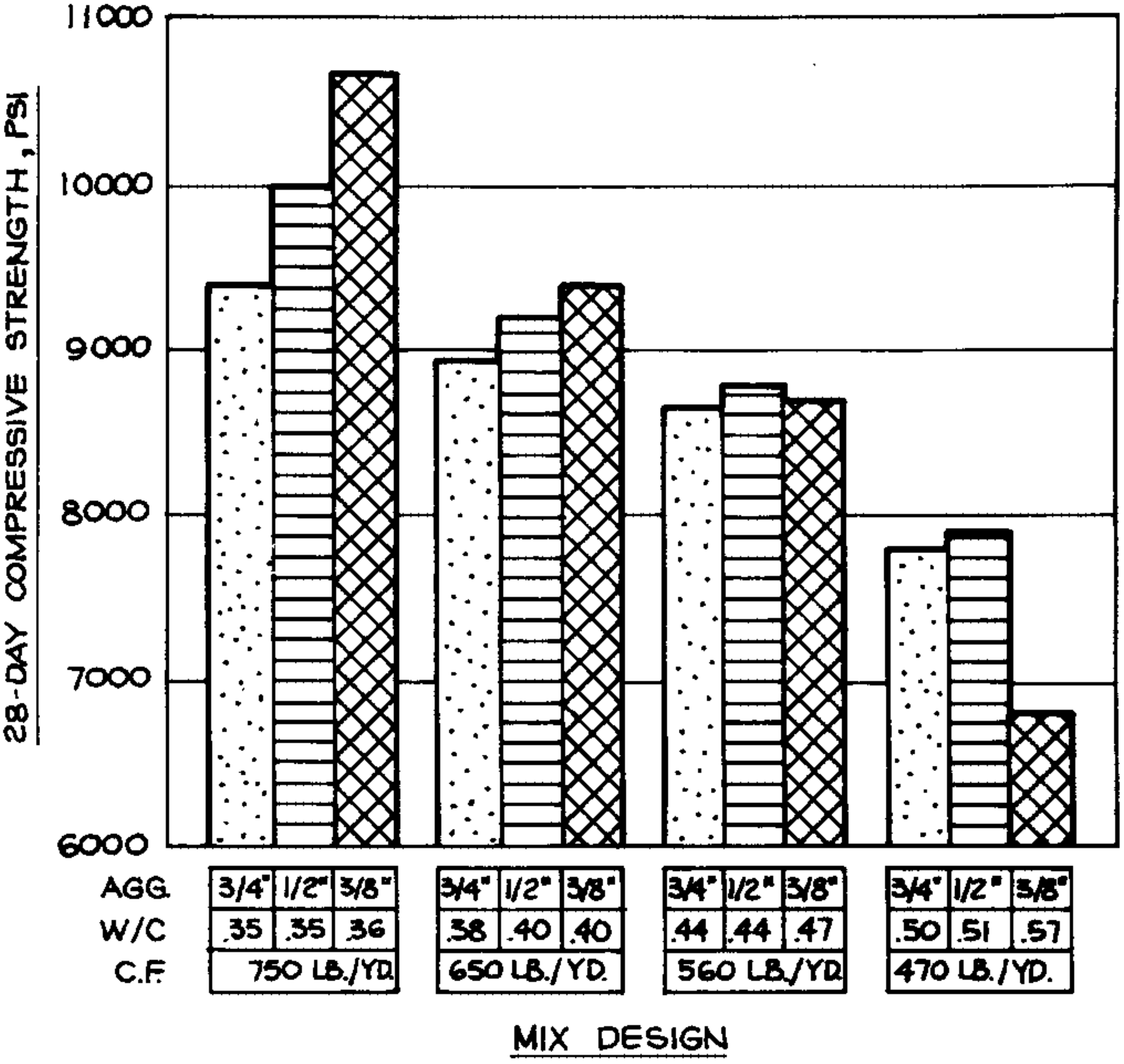

FIG. 3 - EFFECT OF AGGREGATE SIZE AND CEMENT CONTENT ON COMPRESSIVE STRENGTH

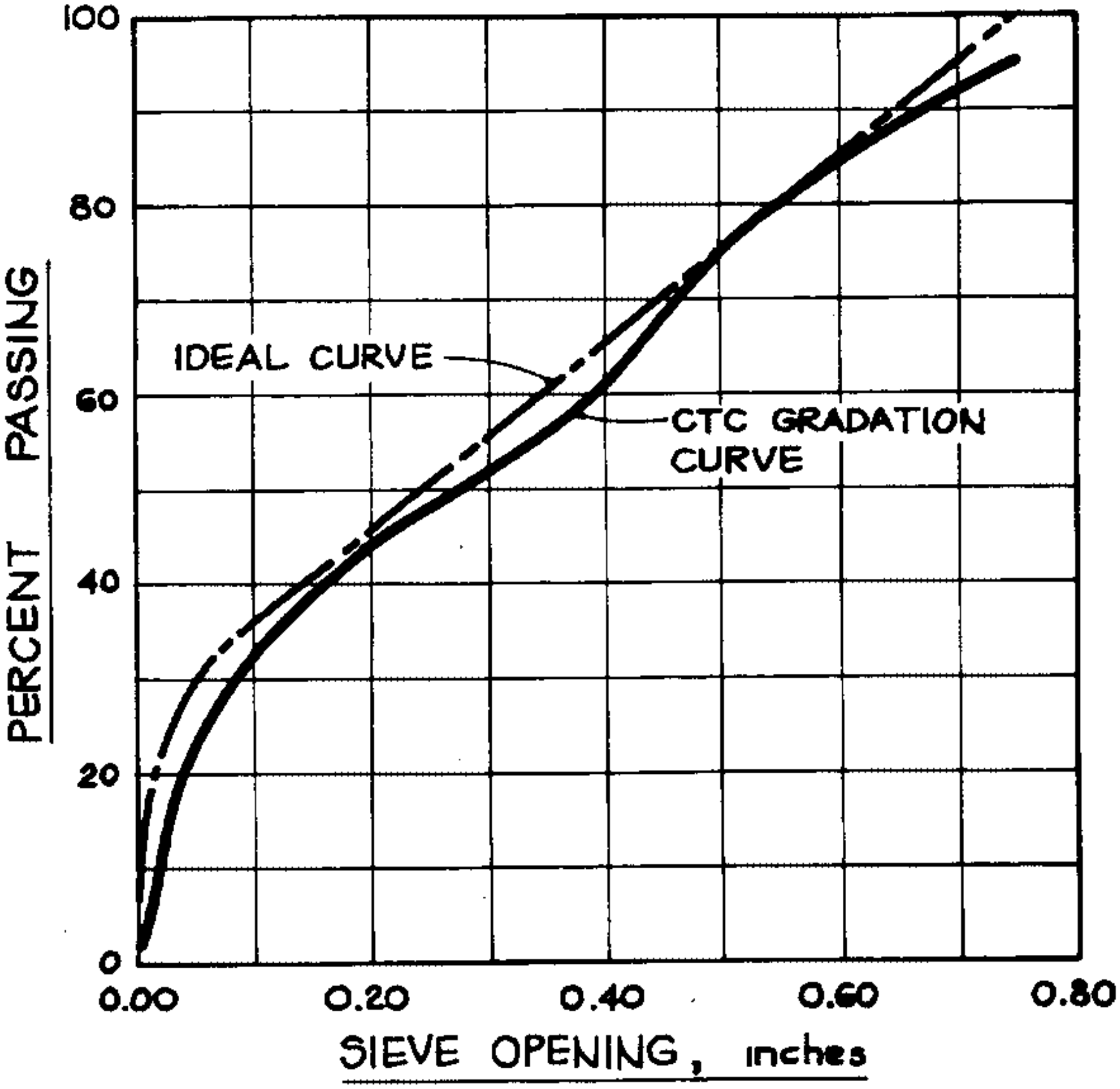

FIG. 4 - CTC COMBINED GRADATION CURVES

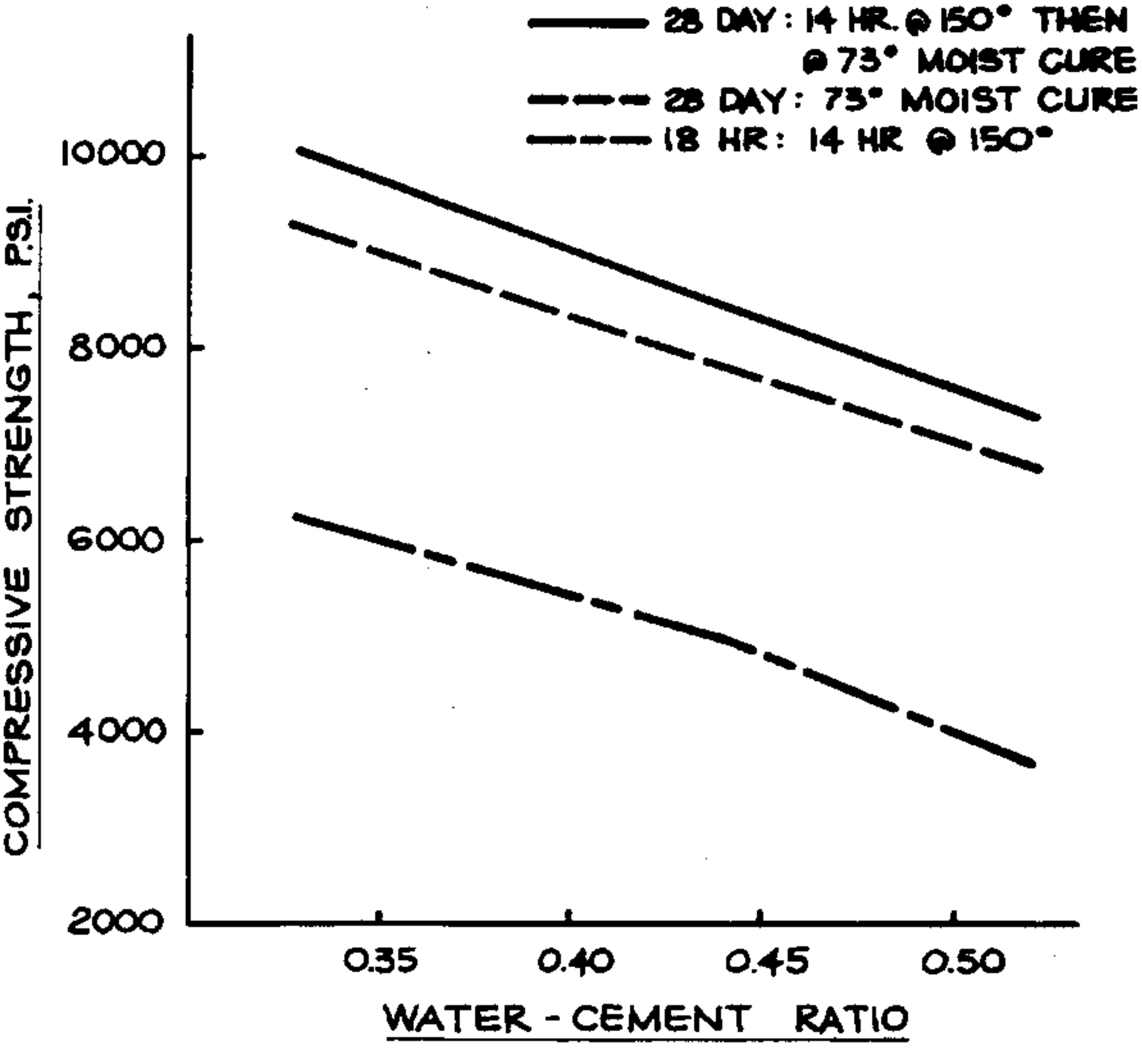

FIG. 5 - COMPRESSIVE STRENGTH VS WATER-CEMENT RATIO

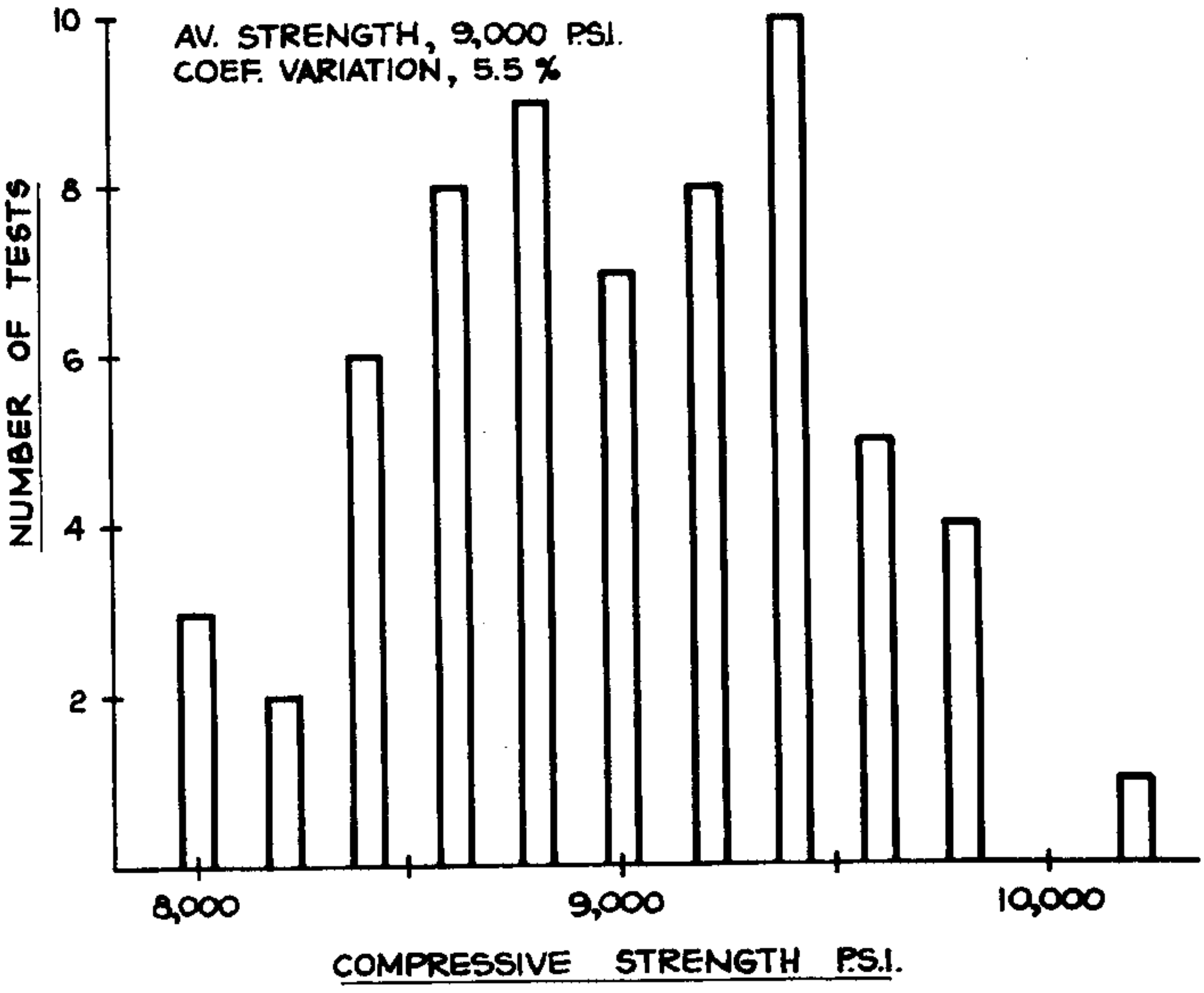

FIG. 6 - STRENGTH OF 28-DAY CYLINDERS FOR PRESTRESSED CONCRETE PILING.

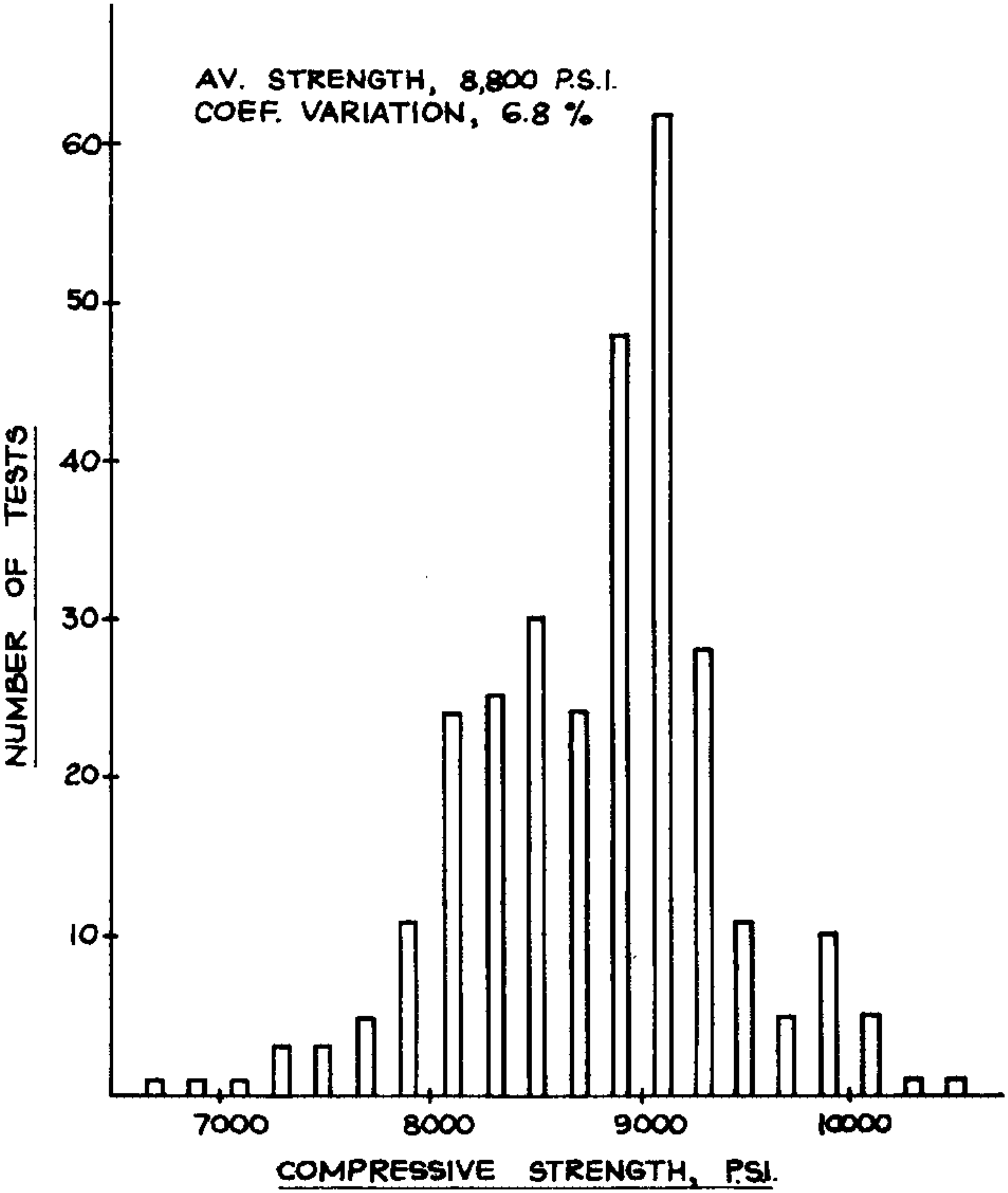

FIG. 7 - STRENGTH OF 28-DAY CYLINDERS FOR FOR CTC STRUCTURAL CONCRETE.

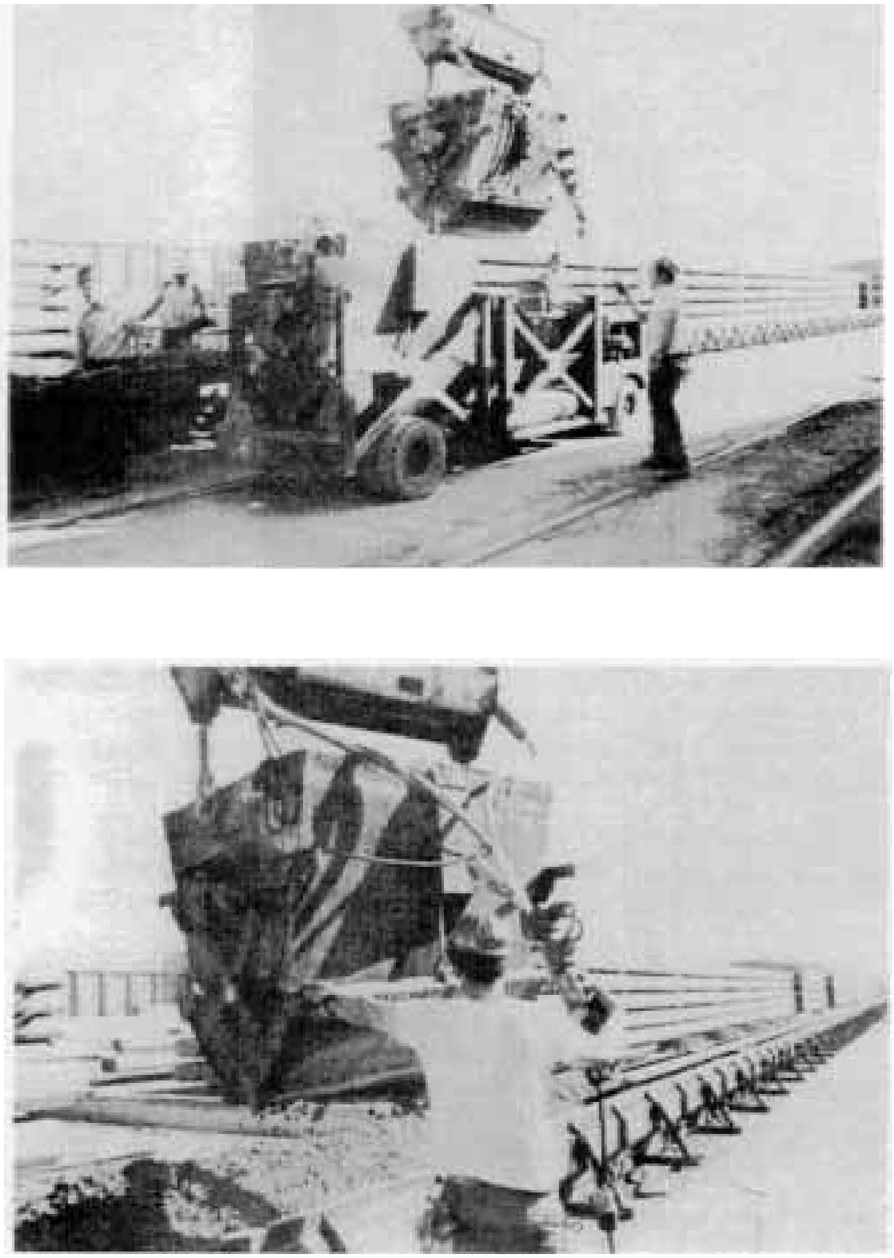

FIG. 8 - CTC TRANSPORTATION AND DELIVERY SYSTEM.

concrete information

PORTLAND CEMENT ASSOCIATION

HIGH-STRENGTH CONCRETE

By **SIDNEY FREEDMAN, Manager**
Concrete Technology and Services Section, Portland Cement Association

Part I: Materials

■ Interest in high-strength concrete has been increasing over the past several years. It is being specified where reduced weight is important or where architectural considerations require more slender vertical load carrying elements. In structures over 40 stories for example, it is often desirable to specify a minimum concrete strength of about 7,500 psi for lower-story columns to reduce their size and increase usable space. In prestressed concrete construction, too, high-strength concrete may allow a reduction in span-to-depth ratios of structural members.

There is, of course, no exact point of separation between "normal" and "high-strength" concrete. For purposes of this discussion, high-strength concrete is classified arbitrarily as concrete with a specified compressive strength of at least 6,000 psi at 28 days. The specified strength of concrete has been based traditionally on 28-day test results. However, in high-rise structures requiring high-strength concrete, the progress of construction is such that the structural elements in lower floors are not fully loaded for periods of a year or more. That is why it is reasonable to specify that the compressive strength be based on 90-day test results.

The ultimate limit of concrete strength at 90 days seems to be about 20,000 psi. The practical and economical strength limit of ready mixed concrete that may be approached in the future seems to be about 11,000 psi for normal weight-aggregate concrete and 8,000 psi for structural lightweight-aggregate concrete.

Through the use of low-slump or no-slump rich mixes, high compressive strength concrete is produced routinely under careful control for precast or prestressed products. The low-slump concrete is consolidated in the forms by prolonged vibration or shock methods. However, cast-in-place concrete requires more fragile forms that do not permit the same compaction procedures, and plastic workable concretes are necessary to avoid segregation or honeycombs.

There is no question that concrete of 9,000 to 10,000 psi (90 days) can be produced by ready mixed concrete plants. At present, concrete with 9,000 psi *at 56 days* is being delivered by several ready-mix firms. While no new technology is required, careful adherence to every aspect of the best practices for production and control is absolutely essential. A successful high-strength concrete job also requires close cooperation and special effort from all parties —the engineer, the ready-mix producer, the contractor, and the testing agency.

A ready-mix producer should not attempt to supply high-strength concrete mixes without an extensive mix development program, which may be time-consuming and expensive.

High-strength concrete is achieved by optimization of the following factors: (1) characteristics of cementing medium, (2) characteristics of the aggregate, (3) proportions of the paste, (4) paste-aggregate interaction, (5) mixing, consolidation and curing, and (6) testing procedures.

Materials selection

Production of high-strength concrete may or may not require purchase of special materials. The producer must know the factors affecting compressive strength and know how to vary those factors for best results. Each variable should be analyzed separately in developing the mix design. When an optimum or near-optimum procedure is established for each variable, the procedure then should be incorporated as the remaining variables are studied. An optimum mix design is then developed for the materials on the basis of performance, cost, and quality control.

■ *Cement*: Selection of portland cement for high-strength concrete should be based on comparative strength tests of concretes tested at 28 and 90 days. A cement which yields the highest compressive strength at extended ages (90 days) is obviously preferable. The tests should be made with mixes containing between 660 and 940 lb. per cu. yd. of each cement—amounts will vary depending on target strengths. Other than changes in sand content as cement content increases, the concrete samples should be as nearly identical as possible with the slump between 3" to 4". The water-cement ratio also should be adjusted so that equal workability becomes a basis of comparison. Some of the more finely ground portland cements such as Type III (high-early-strength) will have higher mixing water requirements for equal workability, particularly at low water-cement ratios, and

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Fig. 1 shows that, in concrete having a 4" slump with cement content exceeding 600 or 700 lb. per cu. yd., higher compressive strength will be produced with the smaller-size aggregate. Fig. 2 shows the effect of the maximum aggregate size on compressive strength of concrete with varying cement content at 28 and 91 days. Both figures also demonstrate that a water reducer-retarder is beneficial to strength development.[6]

In concrete of a constant cement content and maximum aggregate size, variations in compressive strength are attributed mainly to differences in mixing water requirements among aggregate sources. Aggregate shape and surface texture and deleterious coatings are apparently responsible for these variations in mixing water requirements of similarly graded materials from different sources. As particle shape departs from a smooth, rounded configuration and becomes increasingly rough and angular, mixing water requirements in conventional strength concretes increase with corresponding decreases in strength unless cement content is increased. However, the cement-aggregate bond increases as the particle shapes change from smooth and rounded to rough and angular and this must be considered in selecting the aggregate for high-strength concrete.

Coarse aggregate void content can be used as an index of differences in particle shape and texture of aggregates of the same grading. Mixing water requirement tends to increase as coarse aggregate void content increases because of changes in particle shape and texture. For each 1% increase in coarse aggregate voids, the mixing water requirement of concrete increases about ½ gal. per cu. yd. However, the shape of fine aggregate particles rather than that of coarse aggregate has markedly more effect on water demand. Measurements of void content for fine and coarse aggregates from the same source show similar trends. This similarity allows the producer to use fine aggregate void content to predict mixing water demand and the resultant effect on the compressive strength of concretes made with aggregates from a given source.[7]

In concretes of equal water-cement ratios, different types of aggregate will produce concretes of different strengths. The strength variations attributable to aggregate type apparently are due to the degree of bond developed between the paste and aggregate (both porosity and surface texture being important) and to the strength of the aggregate particles themselves. Bond of the paste to aggregate particles generally increases with roughness, although other aggregate characteristics also influence bond.

In making high-strength concrete trial mixes, it is important to select relatively hard and strong coarse aggregates that do not break down and produce fines during mixing and which have

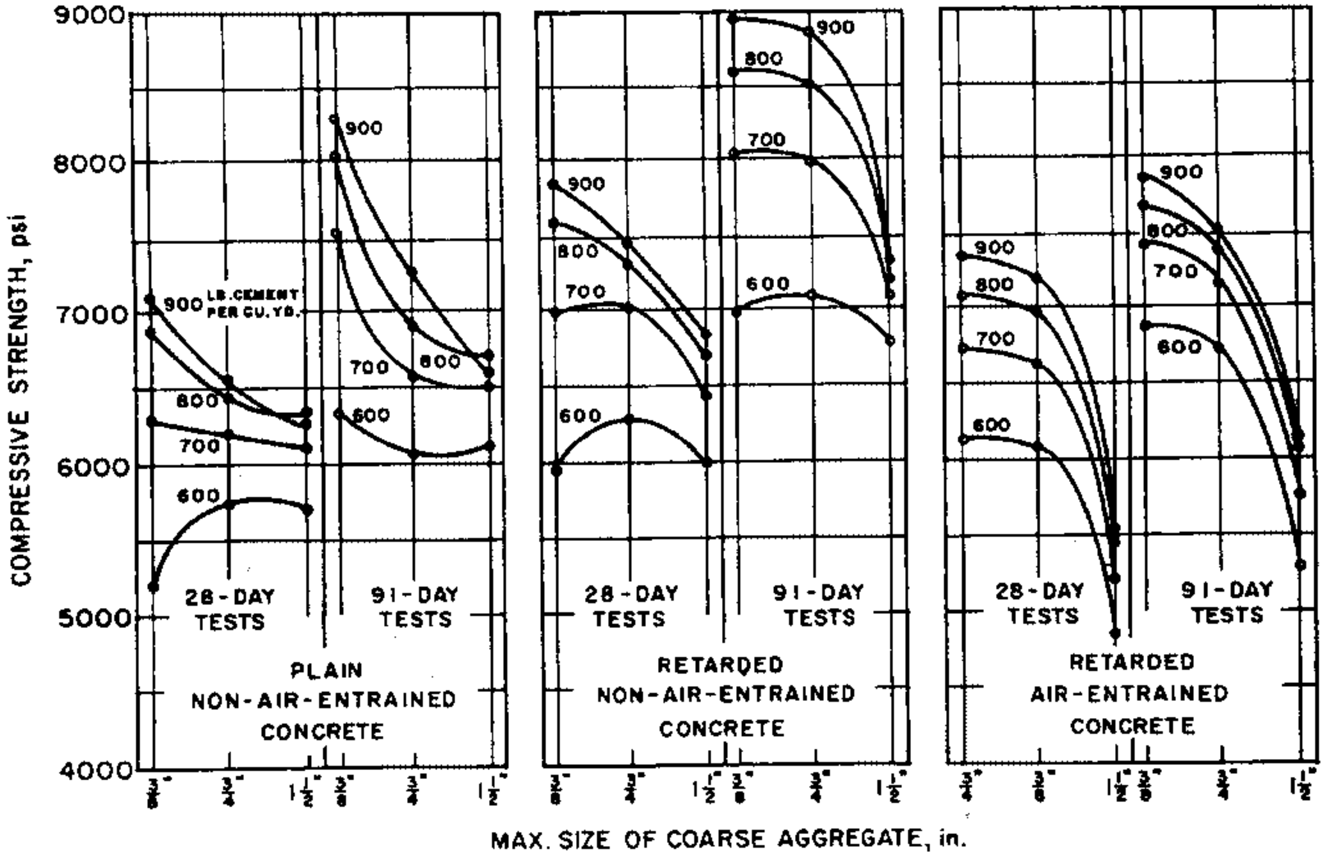

Fig. 2. Effect of size of coarse aggregate on compressive strength in different types of concrete (adapted from Ref. 6).

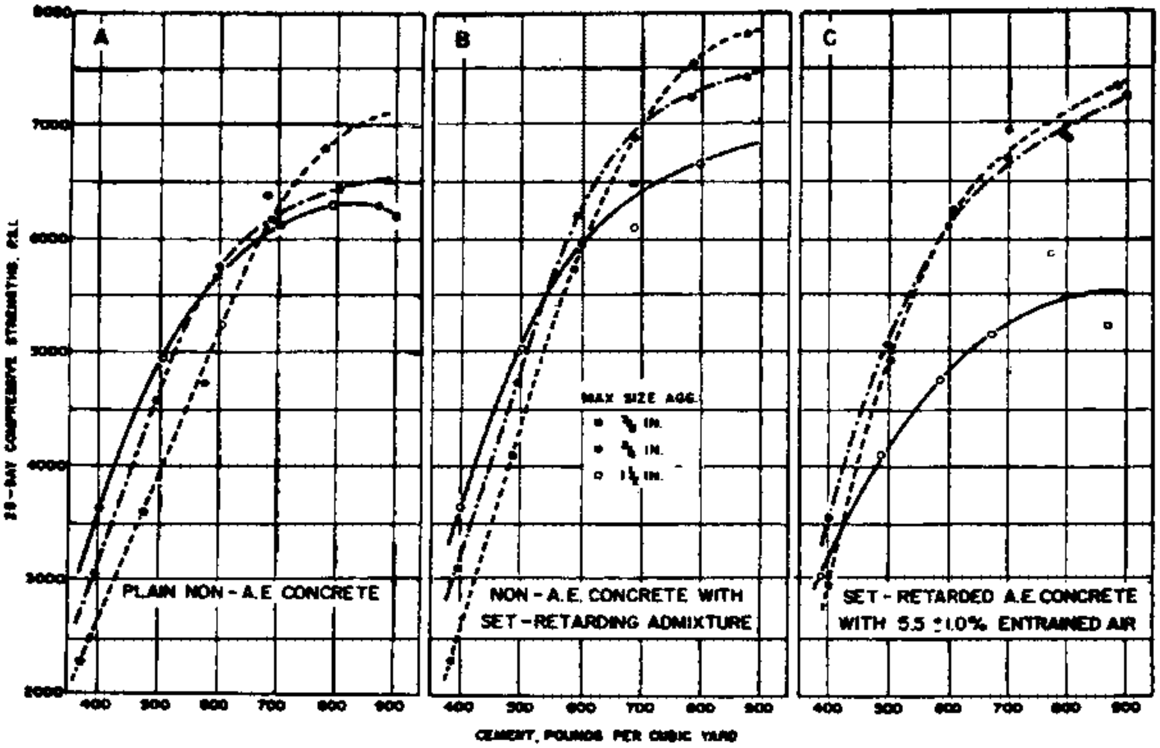

Fig. 1. Effect of cement on compressive strength for various maximum sizes of aggregate in different types of concrete.[6]

may promote more rapid stiffening in hot weather. Either Type I (normal) or Type II portland cements should be satisfactory.[1] However, if ready mixed concrete is to be used in products to be steam-cured, it may be beneficial to use Type III portland cement.[2,3]*

• *Coarse Aggregate*: Since aggregates comprise a large fraction of the volume of concrete, the characteristics of the aggregate significantly influence the properties of the concrete, including strength.

The strength of concrete up to about 5,000 psi depends essentially on the quality of the hardened cement paste that holds the aggregate particles together. The aggregates at this strength level nearly always have a much greater strength than cement paste. However, two additional factors become important in high-strength concrete: (1) the strength of the aggregate, and (2) the bond or adhesion between the cement paste and the aggregate.

Coarse aggregate gradation is of minor importance in mixes with high cement contents. The grading of a coarse aggregate of a given maximum size may be varied over a relatively wide range within the ASTM limits without appreciably affecting the strength if the proportion of fine aggregate produces concrete of good workability.

Determining the optimum size of coarse aggregate for different concrete strength levels has practical value for concrete producers. The optimum maximum size of coarse aggregate depends on such factors as (1) the relative strength of the cement paste, (2) cement-aggregate bond, and (3) strength of the aggregate particles. However, in a sense none of these factors are adequately measured by readily available standard tests. They are also difficult to evaluate, when considering a specific choice of two available aggregates, without making trial batches. There is a considerable difference in the strength of concretes produced by different aggregates of the same size and gradation from different sources when they are mixed in comparable batches of identical proportions. The difference is greater in flexure than in compression.[4]

In normal strength concrete, as coarse aggregate size is increased, mixing water requirement is reduced. The net effect is a lower water-cement ratio and higher strength. The water requirement is a function of the overall fineness of the solid ingredients. However, the large sizes of coarse aggregate tend to reduce concrete strength, probably because of the smaller surface area for bond and the disruption of the continuity of the concrete. In rich, high-strength concrete mixes, the effect of size itself (use of small aggregates — ¾″, ½″, or ⅜″) usually is sufficient to offset the effects of the higher mixing water demand, and strength increases with decrease in aggregate size.[5] Therefore the producer should make trial batches using coarse aggregates meeting the requirements of ASTM C33, *Specifications for Concrete Aggregates* for size numbers 57 (1″), 67 (¾″), 7 (½″) and 8 (⅜″). Some ready-mix producers have found that ½″ maximum size appears to give optimum strength for their aggregates.

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*Superscript numbers designate references at end of each part.

range of the fineness modulus is 2.70 to 3.20 with about a maximum of 2% passing the No. 100, 0 to 10% passing the No. 50, and 35 to 45% passing the No. 30 sieves.[1]

Washing the sand may be necessary, and natural sands containing large quantities of mica, certain clay minerals, or other deleterious materials should be avoided as they may increase water demand and affect hydration and bond of the cement paste. The emphasis should be on uniformity of grading from batch to batch of both the fine and coarse aggregates because of their effect on workability.

- *Mixing water*: Use of cool mixing water (40° F.) instead of normally warm water (70° F.) will increase the slump of the concrete about 1" to 2", which is very desirable in terms of workability. If, in turn, the amount of mixing water is reduced, the strength of the concrete may be increased.[1] However, cool mixing water is seldom available and the problems encountered in the use of ice are not worth the effort for the small, if any, increase in strength.

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Part II: Materials and Proportioning

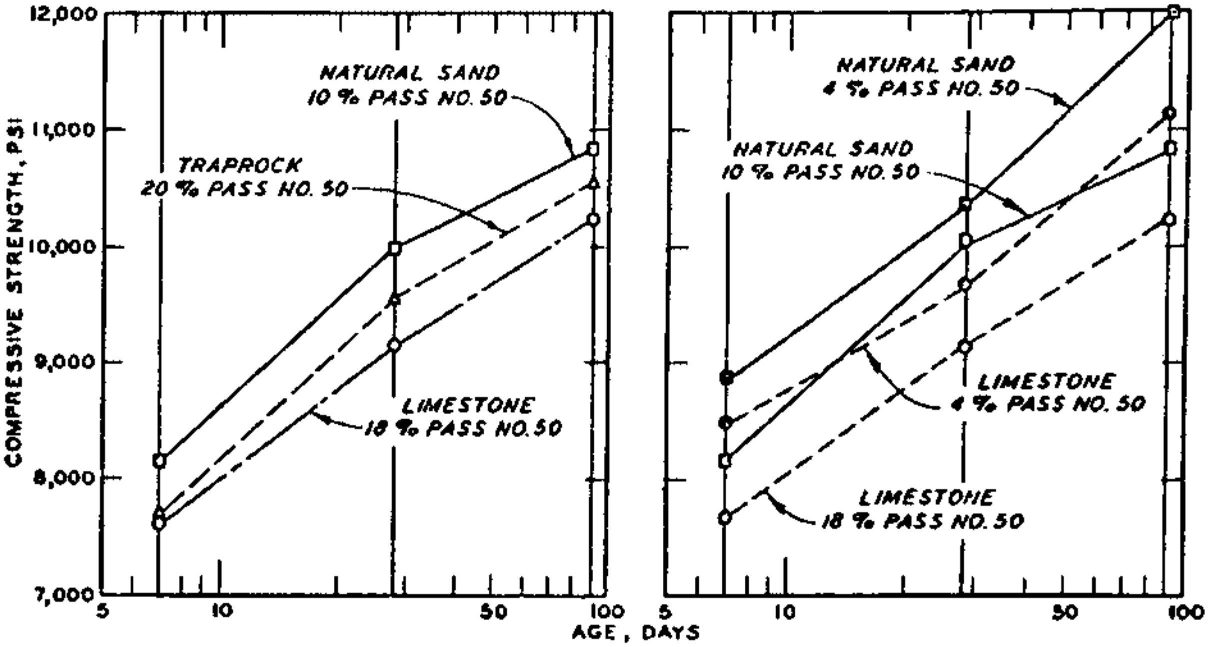
- *Admixtures*: Chemical admixtures for concrete, including high-strength concrete, should meet the requirements of ASTM C494, *Specifications for Chemical Admixtures for Concrete*. Trial mixes should be made with the admixture and job materials at temperatures and humidities anticipated on the job. This permits evaluation of the compatibility of the admixture with other admixtures and job materials as well as the effects of the admixture on the properties of the fresh and hardened concrete. The amount of admixture recommended by the manufacturer should be used until trial batches have established that an adjusted higher dosage is more effective for the materials to be used and that the desired strength is obtained at the specified age.

Almost all cast-in-place, high-strength concrete is used for applications that do not require air entrainment. Therefore, no air-entraining agent should be used in these concretes. Entrapped air contents usually will be in the range of 1 to 2%. However, if high-strength concrete is to be used under saturated freezing-and-thawing conditions or if de-icers will be applied (for example, the exposure of precast, prestressed bridge beams), air-entrained concrete should be used despite a potential loss of 5% in strength for each 1% of entrained air.[1] The amount of entrained air used should be on the low side of the recommended range for normal strength concrete for the particular aggregate size.

The use of water-reducing retarders should be considered. They generally will result in a higher concrete strength if the water content is reduced for a given mix and if the cement content and slump are kept the same. In high-strength concrete mixes, the reduction in water-cement ratio achieved by eliminating excess mixing water may produce greater strength improvement than a similar reduction obtained by adding cement.

The most widely used water-reducing, set-controlling admixtures are based upon any of three classes of organic compounds or mixtures of these compounds. These are (1) salts of sulfonated lignin, (2) salts of hydroxy acids, and (3) hydroxylated polymers. Each of these three classes of chemicals produces set retardation of the concrete and may appreciably modify the strength development. The retardation can be decreased by simultaneous use of accelerating or catalyzing substances that may be combined into a formulated admixture product. Water-reducing retarders usually are less expensive and more effective in high-strength concrete than water reducers. Water reducers generally still retard somewhat, especially at temperatures below 70° F.

Water-reducing admixtures produce various effects on the amount of air in concrete. Lignin-based admixtures typically entrain 1 to



EFFECT OF TYPE OF SAND EFFECT OF GRADATION OF SAND

Fig. 3. Effects of type and gradation of sand on the compressive strength of concrete.[1]

few flat, elongated particles. Crushed rocks such as traprock (basalt or diabase), limestone, quartzite, or granite usually are suitable. Strengths developed with these aggregates are higher with higher specific gravity and moderate absorption (1.5 to 2.5%) of the particles.

Some natural gravel aggregates may not be as suitable for making high-strength concrete as crushed rock unless the gravel aggregates are unweathered (irregularly shaped) or crushed. In the case of aggregates manufactured by crushing, particles more nearly cubical are generally preferred to angular particles. Air-cooled slag also may be satisfactory, but there has been limited field experience with it.[8] In addition, high-strength concrete has been made with heavyweight aggregates that produce high density for radiation shielding.[9] Structural lightweight aggregates produce wide variations in the properties of concrete even though they may be similar in appearance and produced by similar processes. One reason for the variations is the pronounced but not readily determinable absorption characteristics of these materials. The absorption differences may account for a large part of the strength variations attributed to the aggregate *per se*. Lightweight-aggregate concretes differ considerably in the amount of water required to attain proper workability because of the grading, shape, and surface texture of the aggregate used. Aggregates that require excessive amounts of water to produce proper workability will therefore require excessive amounts of cement to provide adequate strength.

Many of the structural lightweight aggregates can be used for high-strength concrete if the producer selects a maximum aggregate size of ½″ or less. With a fixed cement content and slump, replacement of the lightweight fines with natural sand usually will increase the compressive strength with many lightweight aggregates, particularly those with an unfavorable particle shape in the lightweight fines. With a few aggregates, the use of natural sand has little or no effect on compressive strength but will improve other properties of the concrete. The natural sand will, of course, raise the unit weight of the concrete and decrease the advantages accruing to lower weight. However, the weight of concrete is of very little significance in columns—the typical use of high-strength concrete.

- *Fine Aggregate*: The shape and surface texture of the fine aggregate will have a greater influence on the water demand and compressive strength of the concrete than that of the coarse aggregate. In sands of the same grading, a 1% increase in fine aggregate voids may cause a 1-gal.-per-cu.-yd. increase in water demand. The bond of paste to fine aggregate is less significant because of the large surface area available for bonding. Therefore, rounded, smoother fine aggregate particles are better from the point of view of strength than sharp, rough aggregates. Concrete mixtures of the same slump and cement factor and containing natural sand produces higher strengths than concretes containing manufactured sands as shown in Fig. 3.[1] The particle shape and grading of these materials are probably responsible for the strength differences.

The grading of the fine aggregate within typical specification limits is not highly critical except that a slightly coarse sand probably would be beneficial if available and not economically prohibitive. This is because the coarser fine aggregate particles have a lower water demand. If such sands are available, the preferable tarders, improves their water-reducing properties, and increases their capacity to entrain air. This indicates that to obtain higher concrete strength, the water reducer should be added with the last part of the water or after mixing has progressed for a short time. Adding the water reducer late can be a very sensitive procedure—it can cause very heavy retardation. Control at a batch plant producing high-strength concrete must be very dependable. Therefore, it may be safe to add the admixture late in the cycle.

- *Pozzolans*: A pozzolanic material such as fly ash may be employed in high-strength concrete mixes to increase strength at later ages. Such material must be used as an admixture, that is, as an addition to the regular amount of cement, not as a partial substitute for it. Because of their high absorption, low specific gravity and, in some cases, high fineness, many pozzolanic materials increase the water requirement of concrete. However, fly ashes of high fineness and low ignition loss (less than 3%) may have little effect on the water demand. Since the properties of pozzolans may vary widely, acceptance and uniformity tests should be made before they are used. ASTM C618 *Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement Concrete* covers the use of natural pozzolans and fly ash as admixtures in concrete.

Pozzolanic action is a secondary effect, which depends on and follows the hydration of cement. The pozzolanic reaction can be interrupted easily and may or may not proceed to completion. The benefits of pozzolanic activity in concrete are realized only with long periods of moist curing and favorable curing temperatures. Premature drying or cold weather interrupts pozzolanic reaction as well as cement hydration. In high-strength concrete, the high cement content of the mix provides the basic early strength in case the pozzolanic action is prematurely stopped.

A water-reducing agent should be used in a high-strength concrete containing a pozzolan. The quantity of the water-reducing agent used should be based on the total amount of cement.

Proportioning

The trial mix approach to selecting proportions for high-strength concrete mixtures is much more successful than any theoretical approach. The materials can best be optimized by the trial mix method.

To obtain high strength, it is necessary to use the lowest possible water-cement ratio (0.30 to 0.40) and consequently high cement factors.

The water requirement of the concrete increases as the sand content is increased for any given size of aggregate. Because of the high cement content of these concretes, the fine aggregate content can be kept low. However, even with well-graded aggregates, a low water-cement ratio may result in concrete that is not sufficiently workable for the job. Usually it will be necessary to use at least 660 lb. of cement per cu. yd. of concrete to maintain mixtures of sufficient workability to be compacted. A trial mix for 10,000 psi concrete (90-day strength) should contain about 940 lb. of cement per cu. yd. At this level, increased cement content may be an inefficient means of gaining strength. There is, for given materials and given mixing and delivery conditions, a maximum strength that will not be increased by adding cement. Perhaps the best method to increase strength is to reduce the slump, but in most ready mixed concrete this is generally not feasible. The ready mixed concrete must possess sufficient workability to be placed without honeycombs or voids. If lower slumps were possible, additional strength could be obtained by decreasing the sand content and making the mixes somewhat harsher. In some very dry mixes, gap-graded coarse aggregates appear to offer advantages.

The unit strength in psi obtained for each pound of cement used in a cubic yard of concrete can be plotted as strength efficiency (Fig. 5)[3].

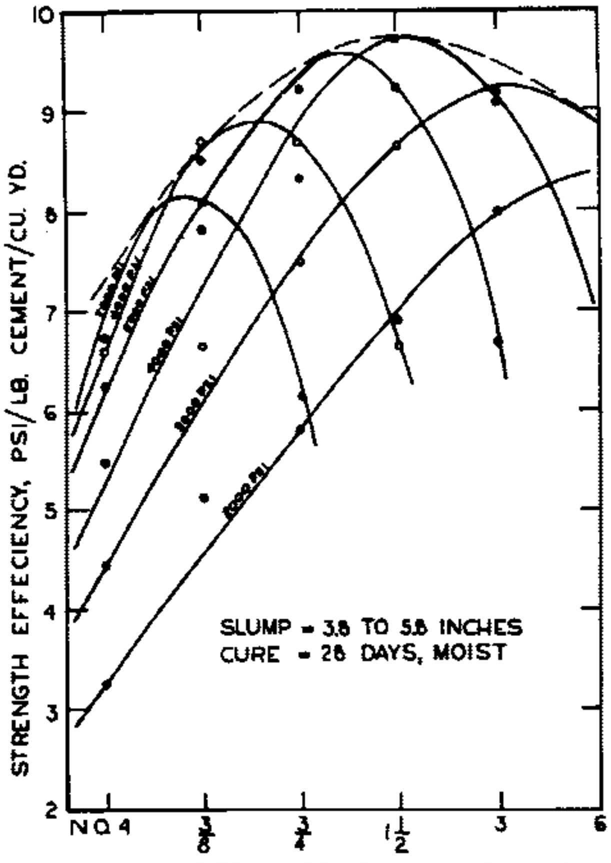
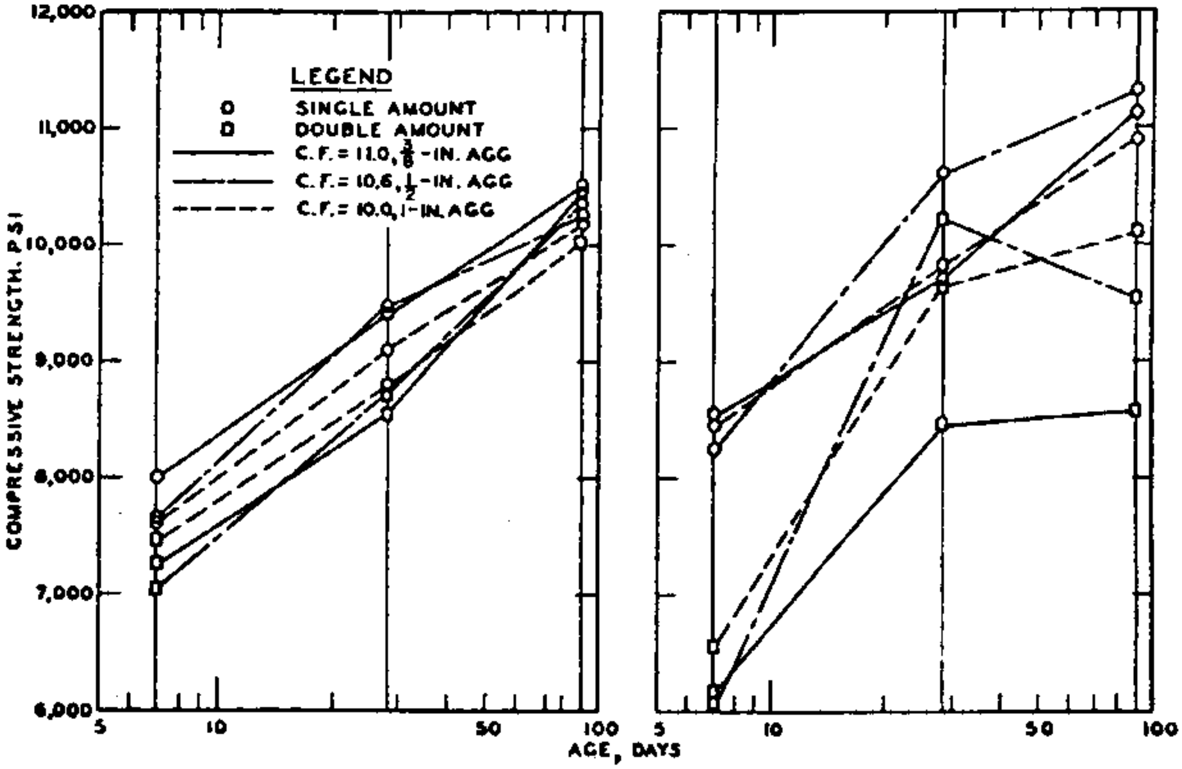


Fig. 5. Maximum size aggregate for strength efficiency envelope.[3]



Admixture "Z"

Admixture "P"

Fig. 4. Effect of quantity of water-reducing admixture on the compressive strength of concrete with admixtures "Z" and "P".[2]

3% air above that characteristic of equivalent non-air-entrained concrete. Some lignins entrain more air than this typical range. Generally, admixtures that entrain air show low water reductions as the cement content is increased because of the reduced effect of air entrainment on water reduction in rich mixes. In non-air-entrained, high-strength concretes it is best to avoid lignin-based admixtures that can entrain air. Air entrainment (when necessary) caused by water-reducing admixtures is hard to control when the cement itself is air entraining. Admixtures based on hydroxy acid salts or some types of hydroxy lated polymers are non-air-entraining unless a surface active agent is included in a formulated product. Nevertheless, the amount of an air-entraining admixture required to produce a given air content in concrete usually must be reduced ½ to ⅓, in the presence of any type of water-reducing admixture, from that normally used without the admixture. This is a minor consideration, however, as most high-strength concretes do not require air entrainment.

Dosages required to produce specific results are usually recommended by the manufacturers. The dosage often can be varied to obtain the desired concrete properties under particular job conditions. Serious retardation of the setting time of concrete has been due in some instances to the use of excessive amounts of water-reducing admixtures. Extreme caution and careful control must be exercised when using more than the manufacturer's recommended dosage. An overdose almost always will reduce early strengths of concretes while later strengths may or may not be significantly reduced (Fig. 4).[2] The *type* of admixture (Z or P, for example) is also important with respect to overdosing.

The effectiveness of water reducers can vary significantly. In general, the effect of a water reducer in terms of both water reduction and degree of retardation will be influenced by increases in cement fineness, changes in aluminate content (C_3A), soluble alkalies, and free lime (CaO) in the cement, and concrete temperature changes. The admixture *must* be compatible with the cement. Water-reducing admixtures may produce rapid slump loss due to premature stiffening or false set, resulting in the undesirable necessity for addition of retempering water. This effect depends on several factors, particularly composition of the cement, composition and rate of use of the admixture, and both concrete and ambient temperatures. The most important cement properties that relate to such admixture incompatibility are the type and amount of calcium sulfate additive and the amount of soluble alkalies. Remedial measures include additional mixing to remove false set, change in the source of admixture, or a decrease in the rate of addition of the admixture.

Water-reducing admixtures usually are added to concrete with the mixing water. Adding water reducers after mixing has started increases their efficiency as set re-

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Part III: Mixing, Placing and Quality Control

Mixing

■ Most of the high-strength ready mixed concrete presently being delivered is produced in central-mix operations, which have been found to allow greater control and efficiency. However, the ability to control the producing operation depends greatly on the personnel involved.

Tests to determine the most effective procedure for charging and mixing should be made for all mixtures. Ribbon loading of materials helps to produce uniformly mixed batches of concrete but other procedures may work equally well. Under usual conditions, up to about 10% of the mixing water is placed in the drum before the solid materials are added. Water is then added uniformly with the solid materials, leaving about 10% to be added after all other materials are in the drum. The materials should be added simultaneously at such rates that the charging time is about the same. If a water reducer is used, it should always be added at the same time in the charging cycle, preferably as late as possible.

With some drum mixers, a very dry mix may require the addition of some water and the coarse aggregate first. Otherwise the coarse aggregate surface does not become sufficiently wetted. With turbine mixers, all materials can be fed simultaneously but not so fast as to overload the mixer motor. The mixer should be running while feeding the materials.

Mixing of high-strength concrete can follow conventional procedures. The mixes with high cement factors probably benefit from slightly longer mixing times. Central mixers should do an excellent job of mixing within 90 to 120 sec. Turbine mixers should be field tested for mixer performance before a minimum mixing time is established. The very cohesive nature of the mix tends to make it adhere to drum mixers. Low-slump non-air-entrained mixes with small aggregate sizes may be very sticky and difficult to mix even though longer-than-normal mixing times are used.

The mixing water and, if necessary, the aggregates should be cooled to obtain the lowest practical concrete temperature down to 40° F. with an upper limit of 75° F. for the concrete delivered to the forms. The mixing water requirement increases with resultant strength reductions as the initial temperature of the concrete increases. Also, the rate of slump loss and the amount of mixing water required to maintain slump at initial levels with prolonged mixing increases markedly with increased concrete temperature. Additions of more than 1 to 2 gal. of water at the job site will adversely affect the compressive strength.

Placing and consolidating

There must be close liaison between the contractor and the concrete producer so that the concrete can be rapidly discharged after arrival at the job site. Final adjustments of the concrete should be supervised by the concrete producer's technicians on the site. Direct radio or telephone communication is necessary between the job site and the batch plant for relaying necessary adjustments. Delays in delivery must be eliminated and sometimes it may be necessary to reduce batch sizes if placing procedures are slower than normal. Rigid surveillance must be ex-

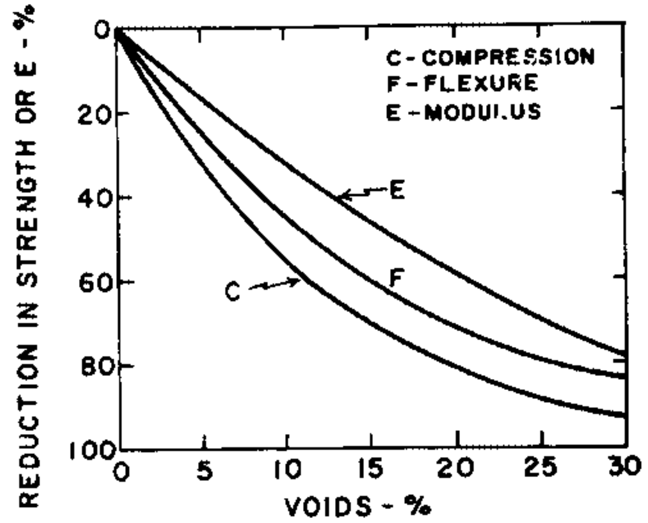
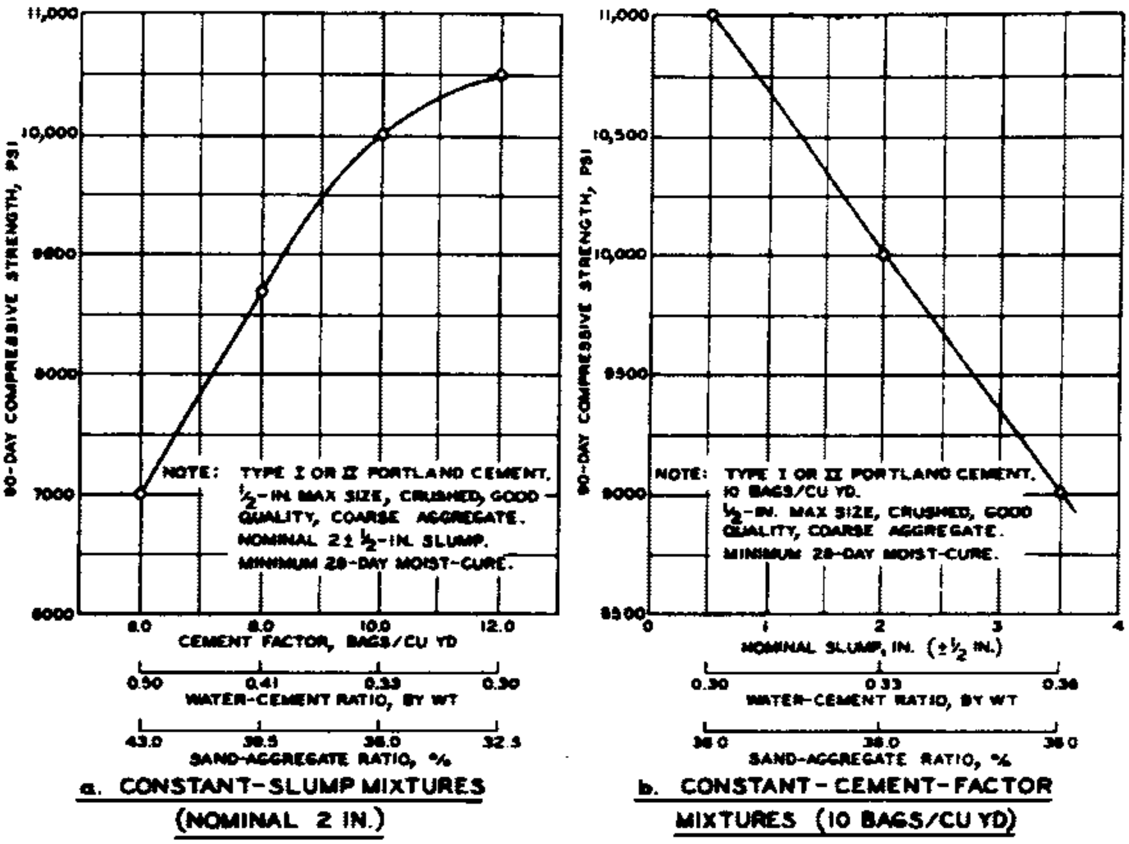


Fig. 7. Comparative effects of incomplete consolidation on concrete properties.[1]



a. CONSTANT-SLUMP MIXTURES (NOMINAL 2 IN.)

b. CONSTANT-CEMENT-FACTOR MIXTURES (10 BAGS/CU YD)

Fig. 6. Proportion guide for high strength concrete.[4]

The figure shows that smaller aggregates provide the most efficient use of cement in high-strength concrete. For example, for 7000 psi concrete strength using this particular material, a maximum aggregate size between 3/16″ and ⅜″ produces the most efficient mix—8.2 psi per lb. of cement per cu. yd. of concrete. This means that approximately 850 lb. of cement is needed to produce 7000 psi concrete at 28 days.

The U. S. Army Waterways Experiment Station prepared charts for several cement factors and slumps to assist in the actual proportioning of mixtures (Fig. 6)[4]. They are intended only as guides; trial mixtures should be proportioned with the individual materials proposed for the project. Data in the charts apply to mixtures containing 1/2″ maximum size, well-graded coarse aggregate comparable to limestone; good quality natural silica and graded to ASTM specifications; Type I or Type II cement; and water-reducing admixture, but no air-entraining admixture. As an example, a 9000-psi mixture can be designed either to have a 3½″ slump, a cement content of 10 bags (940 lb.) per cu. yd., a water-cement ratio of 0.36, and a sand-aggregate ratio of 36% (Fig. 6b), or to have a 2″ slump, a cement content of approximately 8.5 bags (800 lb.) per cu. yd. (by interpolation), a water-cement ratio of 0.39, and a sand-aggregate ratio of 38.5% (Fig. 6a). Adjustments probably will be required in trial mixtures just as with conventional concrete.

A typical mix design for 9000 psi concrete (at 56 days) being delivered by several ready-mix producers is as follows:

Type I cement	846 lb.
Fly ash	100 lb.
Sand	1060 lb.
Stone, ½″ (ASTM No. 7)	1710 lb.
Water, net	317 lb.
Water reducer-retarder	38 oz./batch

A slump of 3″ to 3-½″ is considered desirable by the producers. If 28-day strength is specified, it is 8000 psi with 9000 psi to be attained in 56 days. Backup cylinders are tested at 90 days if there is a question about the 56-day strengths.

The strength levels developed in laboratory trial batches may be impossible to achieve in the field. Therefore, all final mixtures proposed for use should be tested in full-size truck-mix batches under typical job conditions. The difference in strength between laboratory and truck mixers arises because of differences in mixer efficiency, higher concrete temperatures in the field than in the laboratory, shorter mixing times in laboratory, and possibly other factors. These factors may necessitate adding 20 to 30 lb. of additional water per cu. yd. to the truck mixed concrete to obtain the same workability as in the laboratory. This additional water, of course, will have an adverse effect on strength.

To better simulate actual job conditions, it is suggested that laboratory trial batches be mixed (or aged) 20 to 30 minutes. At the end of this period the mix should be retempered before casting specimens.

age at lower temperatures but above freezing would tend to increase 28-day strengths while storage at higher temperatures would produce lower 28-day strengths. In the wintertime plywood curing boxes equipped with light bulbs or small thermostatically controlled electric heaters have been used with great success. Maximum-minimum thermometers should be used. Coverings of damp burlap are highly recommended in curing boxes. Curing boxes with a small cake of ice are a practical means of obtaining the desired temperature control in hot weather. When curing boxes are not used in the summertime, coverings of damp burlap will provide some cooling due to the evaporation of water in the shade. In the summertime, coverings of damp burlap with sheet polyethylene over the outside must be avoided since the plastic sheeting prevents evaporation and the burlap provides insulation for the retention of heat due to hydration during the first 24 hours.

Within 24 hours the specimens should be taken carefully to the laboratory and placed in standard moist curing. The failure to bring the specimens into the laboratory for standard curing within 20 ±4 hours is probably the most frequent and perhaps the most serious of all potential violations of standard testing procedures.[4] At all times from molding to testing, the cylinders should be carefully protected from loss of moisture.

Since capping becomes more critical as the strength of the concrete increases, unusual care must be taken in this phase of the testing. The real key to successful capping is the use of an adequately strong material in a very thin layer of uniform thickness. Proprietary sulfur mortars made specifically for capping concrete cylinders should be used. However, many sulfur capping compounds are unsuitable for high-strength specimens, particularly when caps are more than ⅛″ thick. Homemade sulfur compounds and reused compounds must be avoided. A waiting period of at least 2 hr. between capping and testing of cylinders capped with sulfur should be strictly enforced. Frequent tests of 2″ cubes are recommended to insure that capping compound develops 5000 psi in 2 hr.

Capping may be eliminated if the ends of the hardened concrete cylinders are ground or lapped to the required tolerances. This method is expensive and skilled operators and proper apparatus may not be available.

Bearing blocks on testing machines and capping jigs should be carefully checked for planeness and alignment. It is important that cylinders be properly centered in the testing machine. High-strength concrete cylinders explode on breaking. Therefore, a protective screen or curved shield of perforated metal should be used to surround the cylinder or testing machine. The operator should wear goggles, safety glasses or a face shield. Crushing the cylinders to determine the type of failure and fracture should be required. The practice in some laboratories of failing to test a cylinder to fracture should be discouraged. Inadequate caps may be revealed by the appearance of the cylinder after tests. Normally the cylinder should break into two conical end sections with the caps intact. If the break is through the cap or the specimen splits vertically, a careful check should be made of the quality of capping material and planeness of caps and bearing surfaces. Abnormal fracture and reduced strength may result from wedging action or uneven stress distribution when thick irregular caps are used to correct excessively rough surfaces. Specimens of very high strength sometimes split along vertical planes even with proper caps, but splitting may also be evidence of a cap that has flowed and introduced lateral forces.

Quality control

A comprehensive quality control program is required at both the concrete plant and the site to guarantee consistent production and placement of high-strength concrete. Inspection of concreting operations from stockpiling of aggregate through completion of curing is important. Production control that is closer than is normally obtained on most projects is necessary. Also, routine sampling of all mix materials may be necessary to control uniformity of the concrete.

Specifications usually require that the average strength of concrete delivered to a project be above a specified value, and with only very few tests permitted to fall below that value. To meet these requirements, it is necessary to aim at an average strength higher than the specified minimum. The level of the design strength depends on the control exercised over the variables that influence the strength of the concrete. The less effective the control exercised, the higher the average strength required to meet the specification requirements.[5]

The production of concrete hav-

Table 1. Increases in design strength as coefficient of variation increases.

Specified	Coefficient of Variation V = 7%			V = 10%			V = 13%		
Strength	Standard Deviation	Design Strengths		Standard Deviation	Design Strengths		Standard Diviation	Design Strengths	
f'_c		(1)	(2)		(1)	(2)		(1)	(2)
6000	465	6620	6700	693	6930	7200	943	7270	7690
7500	581	8280	8400	866	8660	9010	1178	9080	9740
9000	697	9940	10200	1040	10400	10920	1414	10900	11790

(1) Present Specifications — ASTM C94, ACI 318-63 and ACI 301-66

(2) Proposed Specifications — ACI 318-71, ACI 301

ercised on the job site to control any addition of retempering water. The contractor must be prepared to receive the concrete and he must be equipped to handle, place and consolidate a sometimes sticky, cohesive, low-slump material.

Consolidation is very important in achieving the potential strengths of high-strength concretes. Fig. 7 shows the substantial effects that incomplete consolidation has on compressive strength of concrete.[1] Concrete must be vibrated as quickly as possible after it has been placed in the forms. High-frequency vibrators should be small enough to allow sufficient clearance of the vibrating head between the reinforcing steel.

Over-vibration of very workable normal-strength concrete often results in segregation or loss of entrained air, or both. However, high-strength concrete will of necessity be relatively stiff and contain little air. Consequently, inspectors should be more concerned about under-vibration than over-vibration.

Curing

The strength-producing properties of the cement paste are due to the chemical reactions between cement and water. These hydration reactions require time and favorable conditions of temperature and moisture. Hydration takes place very rapidly at first and then more and more slowly. When the internal relative humidity of concrete is permitted to drop below about 80%, hydration virtually stops.

The rate at which the relative humidity inside concrete decreases as the structural element is subjected to a drying atmosphere is of considerable importance. Moisture migrates very slowly through concrete so that cement continues to hydrate beneath the outer 3" to 4" of concrete for a long period of time after exposure to drying. See Fig. 8.[2] However, to assure adequate curing of the element without adding moisture to the surface, the ratio of the volume of the element, V, to the exposed surface area, S, must be greater than 3 or the thickness of the structural member must be thicker than 12".[3] Also, the relative humidity in concretes having low water-cement ratios decreases more slowly than concretes having high water-cement ratios.

In many instances, membrane curing compounds or water should be applied to the formed surfaces immediately after forms are stripped. This will improve the quality of the surface of the concrete and prevent dusting of the surface.

During hydration, an internal deficiency of water in the concrete may occur unless additional curing water is supplied. If this deficiency (by self desiccation) occurs, the rate and degree of hydration will be reduced. Such deficiencies are more likely to occur in mixes with low water-cement ratios, typical of high-strength concrete. A means of assuring curing moisture for the interior of the concrete would be to use normal-weight aggregates in a saturated condition. This produces increased compressive strength in concretes with low water-cement ratios. Lightweight aggregates absorb considerable water during mixing that can transfer to the paste during hydration. Therefore, deliberate soaking of lightweight aggregate has little effect on compressive strength. However, lightweight aggregates should be prewetted to control the uniformity of the concrete. Saturated aggregates, normal weight or lightweight, should not be used in concrete in a wet environment to be exposed to freeze-thaw cycles unless a long period of drying before such exposure is possible. Otherwise frost damage may occur.

Testing

The testing agency must follow the standard ASTM methods of sampling, molding, curing, and testing the cylinders. Specimens should be cast in reusable steel molds or in disposable tin molds rather than the usual cardboard molds. Most cardboard molds appear to produce specimens with strengths 2% or 3% less than those molded in steel molds, and occasionally strength reductions of 10% to 15% may occur. Even small reductions in strength must be avoided. Cylinders should be consolidated by internal vibration when the slump is 3" or less and rodded when slump is greater than 3".

After cylinders are molded they must be stored carefully at 60 to 80° F. during the first 24 hours and moisture loss prevented by covering them with a metal or glass plate and damp burlap. Stor-

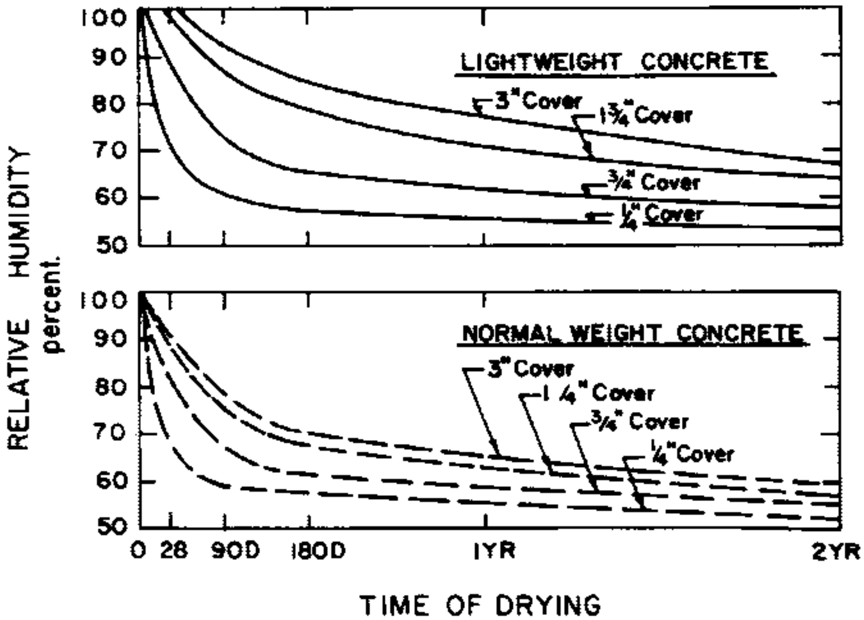


Fig. 8. Typical relative humidity distribution of 6"x12" cylinders—moist cured 7 days then dried at 73° F. and 50% relative humidity.[2]

Another important feature of these curves is that their peaks occur—that is, the maximum stresses are reached—at strains of about 0.0020 to 0.0025, for all tested mix proportions and cylinder strengths. In design it is desirable that the concrete not crush or substantially enter the descending branch of the curve before the steel has reached its yield point. In steel an elastic strain of 0.001 corresponds to a stress of 30 ksi. Therefore, reinforcement with yield strengths between 60 and 75 ksi will reach these yield points before the concrete starts weakening.

The modulus of elasticity of concrete, E_c, depends on the modulus of the cement paste, the modulus of the aggregate, and the relative amounts of paste and aggregate.

The modulus of the paste increases as the degree of hydration increases. Changes in modulus for a given concrete occur because of changes in the modulus of elasticity of the paste and increased bond with aggregate as curing continues. As the modulus of the paste increases, the concrete strength also increases, and for any given concrete mixture and curing condition there is a general empirical relationship between strength and modulus of elasticity. The formula, $E_c = w^{1.5}33\sqrt{f'_c}$ defines this relationship; where w = unit weight and f'_c = compressive strength.

The unit weight of high-strength concrete does not increase appreciably over conventional-strength concrete except for rich all-lightweight mixes. Concretes may comply with this formula only within ± 15% to 20%. Depending on how critically values for E_c will affect the design (as in buckling of long columns), the engineer should decide if the values determined by formula are sufficiently accurate, or if he should determine E_c values from tests made on the specified concrete in accordance with ASTM C469, *Method of Test for Static Young's Modulus of Elasticity and Poisson's Ratio in Compression of Cylindrical Concrete Specimens.*

Modulus of elasticity for a given concrete exhibits a much higher coefficient of variation than the compressive strength. The greater variation results in part from the greater inaccuracies of the test procedures used to measure the small strains.

The moduli of elasticity of pastes are a function of the water-cement ratio and age. They range up to 2.5 to 3.5 x 10^6 psi, while those for aggregates are generally considerably higher, except for most of the lightweight aggregates. Generally, the lower the absorption of the aggregate, the higher the modulus of elasticity of the aggregate. Therefore, the greater the volume of paste per unit of aggregate, the lower the modulus of elasticity should be at comparable degrees of hydration or strength. This merely emphasizes that strength alone is not a good indicator of modulus of elasticity of different concrete mixtures over the whole range of strengths possible with the same materials used in different proportions. What is important is how the strength was obtained for any given set of materials—by a change in mix proportions or water-cement ratio or by longer curing. For any particular mix, however, strength is a good indicator of the modulus of elasticity, the modulus increasing with strength. In the high-strength region, the modulus does not increase as rapidly as strength and may approach some limiting value.

Fig. 10 shows Young's modulus of elasticity for a high-strength and a conventional concrete made with the same crushed limestone. The following table and the figure show that high-strength concrete has a higher modulus than the conventional concrete and that the modulus increases with age or compressive strength[6].

The modulus of elasticity of concretes made with lightweight aggregates is not influenced materially by the volumetric concen-

MEASURED PROPERTIES OF CONCRETES

Concrete Age, days	Compressive Strength,* psi		Modulus of Elasticity,* 10^6 psi	
	7500 + +	3500 + +	7500 + +	3500 + +
28	7940	5540	4.80	4.30
90	9250	6040	5.78	5.25
180	9910	6110	5.84	5.15
365	10300	6050	6.59	5.53
730	10770	6080	7.20	5.38

*Average of two cylinders

+ + Design at 28 days

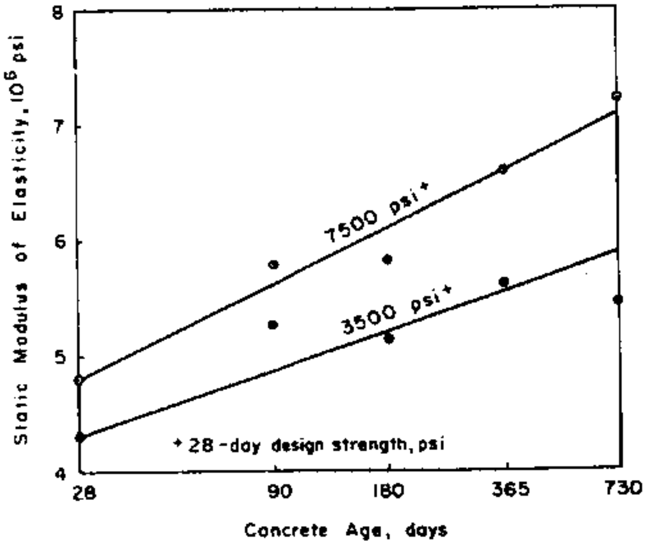


Fig. 10. Modulus of elasticity vs. age of concrete.[6]

ing a high compressive strength will involve achieving a low variance in test results. In most cases, it will not be possible to produce concrete having an average strength significantly higher than the specified strength. Table 1 shows the design strengths for several coefficients of variation and the resultant high design strengths as the control becomes poorer. The lower coefficients of variation normally obtained on high-strength concrete projects are a result of increased vigilance in quality control on the part of the producer rather than a characteristic of all strength tests.

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Part IV: Properties—Modulus of Elasticity; Thermal Properties; and Adiabatic Temperature Rise

■ In the design of concrete structures or products, other physical properties besides compressive strength have considerable significance to designers. The modulus of elasticity, thermal properties, adiabatic temperature rise, drying shrinkage, creep, and bond to steel must be considered. Information on these properties is available for concretes of all types. Most of this information, however, relates to concrete strengths up to 5000 or 6000 psi. The growing interest in high-strength concrete points up the need for more data on these properties.

• *Modulus of Elasticity*: The stress-strain relation and modulus of elasticity of concrete are important design quantities. Static determinations of the modulus of elasticity provide one of the values useful for such design purposes as determining deformation and stress distribution between concrete and steel in reinforced or prestressed concrete members and the buckling effects in long columns. The static modulus of elasticity also is useful for calculating the stresses resulting from shrinkage, settlement or other distortions. Although concrete is not a perfectly elastic material, the theory of elasticity can be applied to it within limits of stress and time. However, marked departure from linearity is noted at near-ultimate stresses. Unreinforced concrete has a certain amount of ductility. This ductility, however, decreases with increasing concrete strength. The stress-strain relation becomes almost a straight line as the concrete strength increases, (Fig. 9)[1]. A feature of these curves in Fig. 9 is that each shows a descending branch after the maximum stress has been reached. Also the maximum strain at failure in compression is lower at higher concrete strengths. The maximum ultimate strain for design at the extreme compression fiber may be below .003 for higher strength concretes.

At a load representing the same proportion of the ultimate strength, the higher strength concrete has a higher strain. However, when comparing high-strength concretes to conventional-strength concretes, the ratio of strains is smaller than the ratios of strengths, so that the modulus of elasticity is greater for higher strength concrete[2,3,4,5].

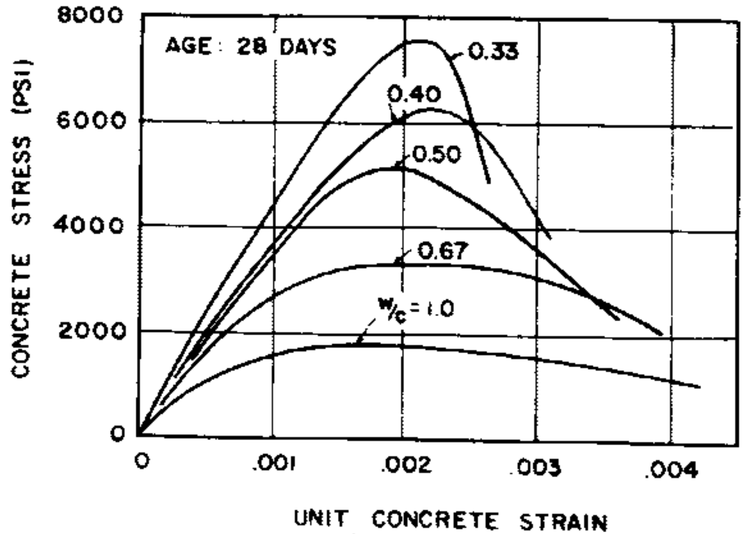

Fig. 9. Stress-strain curves for concrete.[1]

more frequently in high-strength concrete than in conventional concrete because of the rapid compressive strength development and corresponding tensile strength increases.

Heat generation of the concrete depends on the heat of hydration of the cement used, water-cement ratio, and the cement content. The heat generated per unit volume of concrete is directly proportional to the cement content while low water-cement ratios reduce the rate of heat generation. Therefore, the relatively low water-cement ratios in the high-strength concretes tend to counteract the heat generated by the high cement contents. The heat rise in high-strength concretes will be approximately 11 to 15° F./100 lb. of cement cu. yd.[5].

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Part V: Properties—Drying Shrinkage and Creep; and Bond of Concrete to Steel

- *Drying Shrinkage and Creep*: Drying shrinkage of concrete is due mainly to the evaporation of chemically uncombined water. The consideration of shrinkage in design may be highly critical for some structures and unimportant for others. Shrinkage can affect performance and appearance. The amount of shrinkage that is tolerable depends on jointing and design details.

Creep of concrete is the dimensional change or increase in strain with time due to a sustained stress. Creep of concrete may be either beneficial or detrimental, depending on the prevalent structural conditions. The effects of creep as well as the effects of drying shrinkage should be considered and, if necessary, compensated for in structural designs. With increasing heights of buildings, the importance of time-dependent shortening of columns and shear walls becomes more critical because of the cumulative nature of such shortening[1].

Shrinkage and creep of concrete are related phenomena and are controlled by similar parameters. The needed parameters are those which are known or predictable by the designing engineer. These parameters affecting shrinkage and creep include: (1) water-cement ratio of the cement paste, (2) physical characteristics of the aggregate, (3) cement paste content and characteristics, (4) age of concrete when exposed to drying or when an external load is applied, (5) size and shape of the structural member, (6) amount of steel reinforcement, and (7) environmental exposure conditions such as relative humidity, temperature, and carbon dioxide content of the air [2,3,4].

This discussion considers the basic creep and shrinkage characteristics of concrete as measured on small prisms or cylinders. However, the shrinkage and creep of full-scale structural elements is considerably reduced because of size effect, sequence of loading and amount of reinforcement.

In comparing behavior under load of concretes made with different cements, the ratio of the applied stress to the strength at the time of loading should be considered. With respect to the cement, the magnitude and rate of creep strain is influenced by the strength attained by the cement paste at the time of loading. This is controlled to some extent by the chemical composition and fineness of the cement. Cements of different composition and fineness also have variable effects on drying shrinkage. Such differences have been moderated considerably in recent years in most cements by providing the optimum amount of gypsum in the cement. At optimum gypsum content, the type of cement *per se* does not significantly influence creep or drying shrinkage.

The role of the aggregate in concrete is to dilute the paste matrix and to restrain greatly the shrinkage and creep of the paste, thereby reducing the overall shrinkage and creep of the concrete. The effectiveness of the aggregate in reducing shrinkage and creep increases as the volumetric fraction of coarse aggregate in the concrete increases.

tration of aggregate. This is because the modulus of the aggregate is generally about the same as that of the paste. Normal-weight sand often is used with lightweight aggregates to increase the modulus of elasticity. Depending on the type of lightweight aggregate and sand content, the modulus of elasticity of lightweight concrete is generally 20% to 50% lower than that for normal-weight concrete of equal strength, with the greater difference occurring in the low-strength range[3]. A modulus of 3.5 x 10^6 psi has been obtained for sand-lightweight concrete of 7000 psi, 28-day strength, and 118 pcf wet concrete weight.

- *Thermal Properties:* When exterior columns partially or fully exposed to the weather are subjected to seasonal temperature variations, their lengths change relative to the interior columns which remain unchanged in a controlled environment. In low buildings this causes insignificant structural problems that can be ignored. However, in taller buildings with partially or fully exposed exterior columns, temperature stresses must be considered[7].

The thermal properties of high-strength concrete are important in analyzing the effects of temperature variations. These properties —conductivity, diffusivity, specific heat, and coefficient of expansion —of high-strength concrete are within the common range for conventional-strength concrete[5,8,9,10].

Conductivity, k, the rate of heat flow through a unit thickness of material, and diffusivity, the rate at which temperature changes will take place within the mass of hardened concrete, are both greatly affected by the type of aggregate. Within narrow limits, however, conductivity is a function of the unit weight of the concrete. It is also affected by moisture content of the concrete as shown in Fig.11. This figure presents average k values for concretes in oven-dry, normally dry and saturated moisture conditions. The normally dry unit weight of concrete is attained after moisture equilibrium is achieved with normal ambient weather conditions. The water-cement ratio and strength have little or no effect on these properties. Diffusivity of concrete varies between 0.02 to 0.08 ft.^{2}/hr.

Specific heat, the heat capacity of the concrete, varies from 0.20 to 0.28 Btu/lb.-deg. F. Specific heat is affected very little by the mineralogical character of the aggregates or the high cement content of the mixture. In general, the Specific heat varies directly, with variation in the temperature and moisture content of the concrete.

Coefficient of expansion, the change in length per unit length with changes in temperature, is usually between 3.5 to 7.0x10^{-6} in./in./deg. F. The thermal expansion and contraction of concrete varies with such factors as type and amount of aggregate, richness of mix, water-cement ratio, temperature range, concrete age, and relative humidity (degree of saturation of concrete).

Of these, aggregate type probably has the greatest influence.

Ranges for normal weight concretes are 5 to 7 x 10^{-6} per deg. F. for those made with siliceous aggregates and 3.5 to 5 x 10^{-6} per deg. F. for those made with limestone or calcareous aggregate. The values in each case depend on the mineralogy of specific aggregates. Approximate values for structural lightweight concretes are 4 to 6 x 10^{-6} per deg. F. depending on the amount of natural sand used. When a precise value is not required, a coefficient of 5.5 x 10^{-6} per deg. F. is frequently used. If greater accuracy is needed, tests should be made on the high-strength concrete mix.

- *Adiabatic Temperature Rise:* The extent to which hydration of the cement paste heats the concrete depends on the size of the structural element and its environment. Heat dissipation depends on the type of form, amount of exposed surface, and ambient temperatures at the various surfaces of concrete. The low thermal conductivity of concrete results in a slow rate of heat exchange between concrete and its surroundings. Therefore, at early ages, heat is generated in concrete at a higher rate than it can be transmitted to exposed surfaces. The result is a heat buildup approximating adiabatic conditions. Departure from adiabatic conditions is greatest near the cooling surfaces.

The elevated temperatures due to heat generation in high-strength concrete will have no detrimental effects on compressive strength and, in fact, may produce a slight increase in strength. However, in massive sections, such as very large columns, it may be necessary to consider limiting the amount of temperature rise above the final stable temperature, by reducing the temperature of the concrete at the time of placement. Otherwise, temperature stresses may develop if the element is restrained against movement.

Temperature stresses occur as the temperature of the concrete rises and then drops essentially to the temperature of its surroundings. The temperature at the center core of the concrete is higher than that at the exposed surfaces. Thus, as the outer surface cools and tends to shrink, compressive stresses are set up in the center and tensile stresses in the cooler outer surfaces. When these tensile stresses become greater than the tensile strength of the concrete, cracking occurs. However, cracking is not expected to occur any

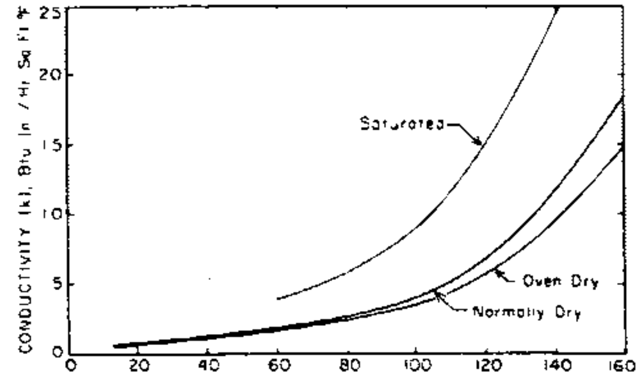

Fig. 11. Correlation of conductivity with unit weight and moisture content.[8]

For constant relative humidity, changes in temperature have a negligible effect on the creep and shrinkage of concrete. Humidity of the air, however, tends to vary inversely with temperature. Hence creep and shrinkage strains tend to be less for lower temperatures because of both the higher relative humidity and the lower rate of evaporation.

Moisture diffusion from concrete becomes increasingly more difficult as cement hydration proceeds, particularly with low water-cement ratio concrete. Consequently the rate and magnitude of drying shrinkage and creep are reduced with extent of hydration. Fig. 12 shows the drying shrinkages of three 3″ x3″x11″ prisms per design strength determined in accordance with ASTM C157 *Method of Test for Length Change of Cement Mortar and Concrete*. In addition one prism per mix was cast with a Monfore humidity well located on the axis near the middle of the prism. The relative humidities in these wells were measured periodically while the prisms were subjected to the same drying conditions as the shrinkage prisms. There is a good correlation between internal relative humidity and drying shrinkage.

A concrete element with its load applied at an early age exhibits a much larger specific creep (actual creep strain at a particular time per unit of sustained stress) than a specimen loaded later. This means that creep decreases with increase in strength-to-stress ratio at the time of loading. Also because of the gradual increase of the modulus of elasticity with age, the elastic shortening per unit stress of older concrete is smaller than that of concrete loaded at an earlier age. Fig. 13 shows creep and drying shrinkage characteristics of two field-obtained concrete mixes (28-day design strengths of 3500 and 7500 psi)[6]. These data are from lab tests of 6″x12″ plain concrete cylinders. Cylinders were removed from moist curing and placed under sustained constant load at 28, 90, and 180 days after casting. The sustained load produced a stress equal to 25% of the nominal concrete design strength. A companion cylinder without load was used to measure drying shrinkage.

Creep is a linear function of the stress-strength ratio for stress up to 50% of the ultimate strength of the concrete (normal working stresses fall below 50 percent). Creep under a constant load will be smaller the greater the increase in strength while the concrete is under load.

The amount as well as the rate of both shrinkage and creep decreases as the ratio of volume to surface area increases, although shrinkage and creep continue longer. Also the use of reinforcement may reduce both shrinkage and creep by as much as 50% depending upon the amount of reinforcing steel resisting the volume change.

- *Bond of Concrete to Steel*: Bond of concrete to steel increases with increase in compressive strength of the concrete. The ultimate bond stress varies approximately as the ratio of embedment length to bar diameter, (l/d), and as the square root of the compressive strength ($\sqrt{f'_c}$). The resulting relationship of bond to compressive strength is curvilinear, bond strength increasing less rapidly as the compressive strength of the concrete is increased. The bond strengths developed by high-strength concretes will be above the maximum allowable average bond stress given in the *Building Code Requirements for Reinforced Concrete* (ACI 318-63) for many of the reinforcing bar sizes [7,8]. The proposed ACI 318-71 reflects lower bond strengths for all-lightweight concrete than for normal weight concrete; that is, sand-lightweight concrete has higher bond values than all-lightweight.

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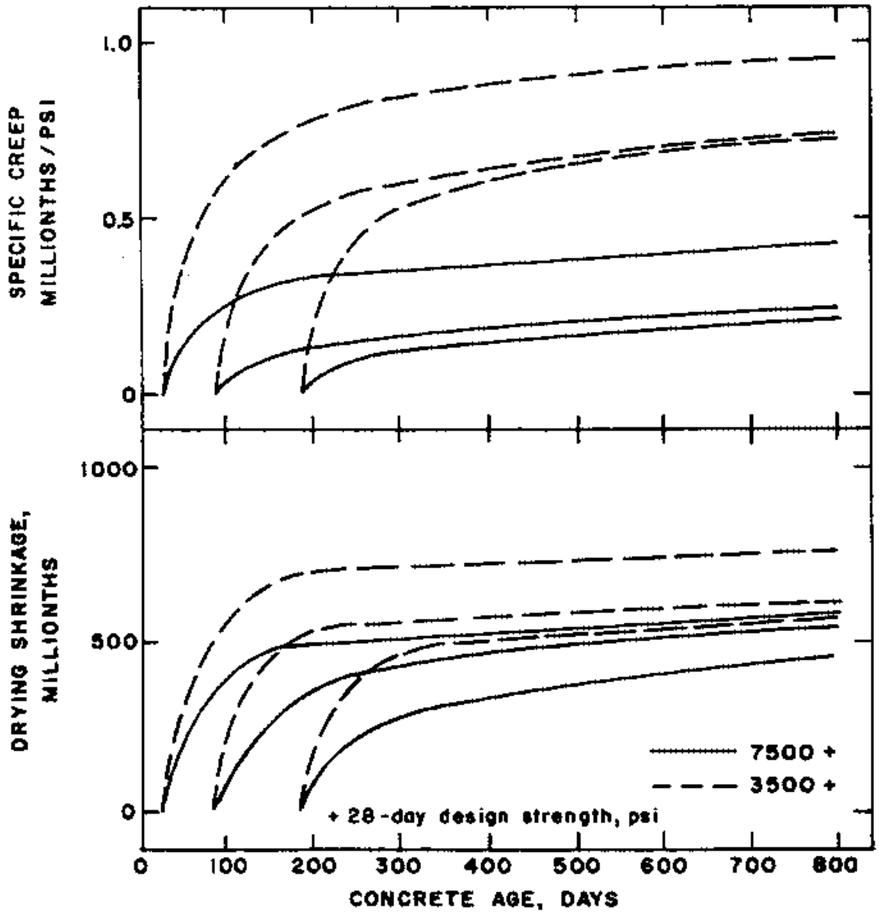

Figure 13.

The mineralogical and physical properties of the coarse aggregate are important in providing restraint to shrinkage and creep. Because of the great variation in aggregate within any mineralogical or petrological type, it is not possible to make a general statement about the magnitude of shrinkage or creep of concrete made with aggregates of different types. Hard aggregates with high density and high modulus of elasticity coupled with moderate porosity or absorption produce concrete with the lowest drying shrinkage and creep. Other aggregate variables such as grading, maximum size, and particle shape have their main influence on shrinkage or creep in the effect they have on the paste content required for adequate workability.

At high compressive strengths, some structural lightweight concretes exhibit lower drying shrinkage than concrete made with average normal-weight aggregates. Partial or full replacement of the lightweight fines by natural sand usually reduces shrinkage for concretes made with most lightweight aggregates. In terms of creep properties, there is little difference between normal and lightweight aggregate at equal high compressive strengths [5].

Little information is available on the effect of admixtures on drying shrinkage and creep, possibly because of the multiplicity of admixtures available and their frequent modification. At present, it is not possible to predict which combinations of admixtures and cements will influence shrinkage or creep.

Chemical admixtures alter the rate at which early hydration reactions occur. This alteration of hydration is affected by a number of factors, as explained in Part II of the series. The use of accelerators such as calcium chloride and triethanolamine results in substantial increases in drying shrinkage and creep of concrete. Some chemical admixtures of the water-reducing type also increase drying shrinkage and creep substantially (age of loading is important), particularly those which contain an accelerator to counteract the retarding effect of the admixture. The materials commonly used to entrain air in concrete (where necessary in precast elements) have little effect on shrinkage or creep.

Concrete containing pozzolanic admixtures which require more water may have increased shrinkage, but most low carbon fly ash will not appreciably affect shrinkage. However, pozzolans may increase creep because of the increase in paste content resulting from the increased volume of hydration products brought about by the reaction of cement hydration products and the pozzolans.

The influence of proportions is best understood by considering interrelated factors such as water-cement ratio, cement content, aggregate content, and total water content. Both the creep and the shrinkage of concrete increase with an increase in water content. Shrinkage is approximately proportional to the percentage of water by volume in the concrete, while creep varies with the water-cement ratio. For mixtures of similar workability an increase in cement content decreases the water-cement ratio. The creep strains are reduced because of the increased strength resulting from the reduced water-cement ratio. If the aggregate-paste ratio is decreased an increase in shrinkage and creep are to be expected.

The amount of drying shrinkage and creep are also functions of environmental conditions and the rate of internal dessication. Obviously, the relative humidity, temperature, and air circulation will influence both rate of drying and ultimate drying shrinkage and creep. Concrete subjected to a continuously dry atmosphere, such as an interior column, will exhibit greater drying shrinkage and creep than concrete exposed to high humidities.

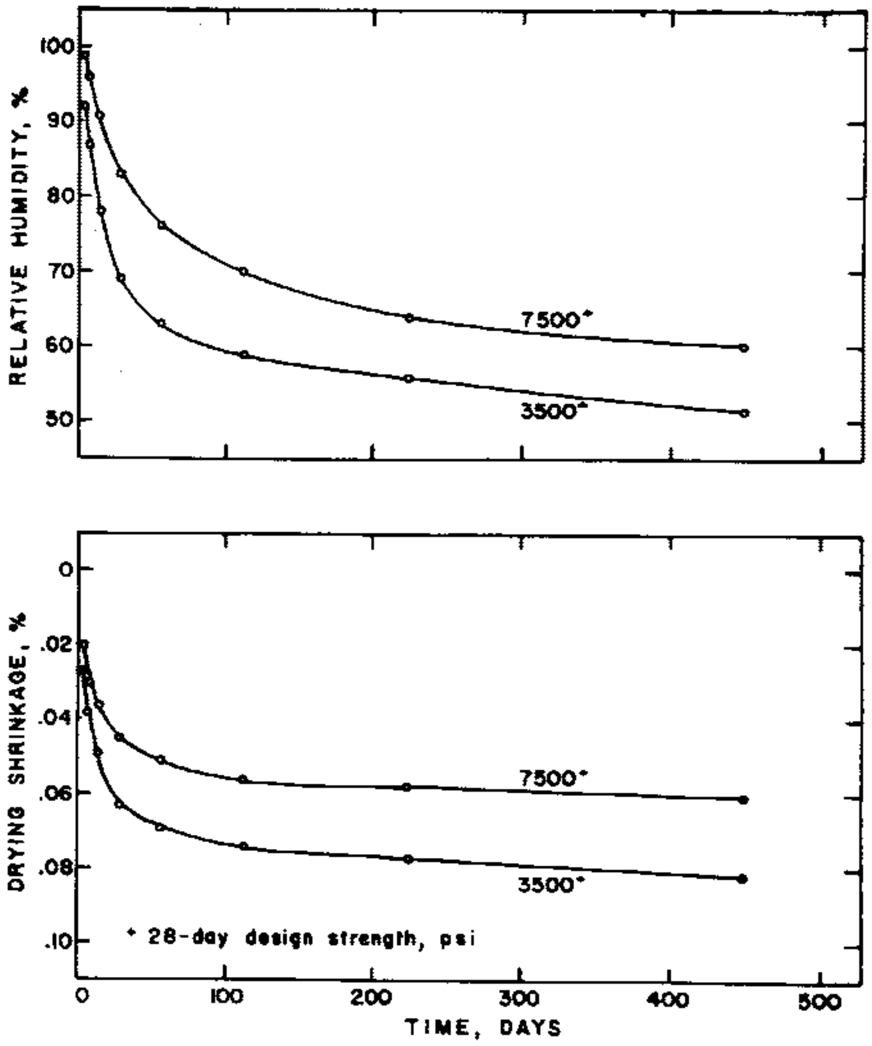

Figure 12.

KEY WORDS: adiabatic conditions, admixtures, aggregates, bond, cements, compressive strength, creep, curing, drying shrinkage, high strength concretes, mixing, modulus of elasticity, placing, proportioning, quality control, testing, thermal properties, water.

ABSTRACT: Discusses the production of high-strength, ready-mixed concrete by optimization of the following factors: (1) characteristics of cementing medium, (2) characteristics of the aggregate, (3) proportions of the paste, (4) paste-aggregate interaction, (5) mixing, consolidation, and curing, and (6) testing procedures. Modulus of elasticity, thermal properties, adiabatic temperature rise, drying shrinkage, creep, and bond to steel are considered.

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Some factors influencing high-strength concrete

By Ronald L. Blick

■ The use of high-strength ready-mix concrete has increased considerably in several areas of the country. Concrete suppliers in the Chicago market, for example, have been supplying high-strength concrete with conventional ready-mix equipment for eight years. This has helped the concrete industry establish a position of renewed respect with the architects, engineers, and contractors. Research and development, progressive thinking, and competent producers willing to accept the responsibility for the performance of their product have renewed confidence in the ready-mix concrete industry.

The definition of high-strength concrete varies with location, but it could be defined in a general way as concrete which possesses compressive strength properties which are difficult to obtain using local materials and practices. Much of the research conducted on high-strength concrete has been centered around compressive strengths in excess of 6,000 psi. For the purpose of this paper, high-strength concrete will be defined as concrete having a minimum compressive strength of 6,000 psi.

Presently, concrete specified for 9,000 psi at 56 days is being delivered successfully in the Chicago market, and research and development programs include ready-mix concrete in the 10,000 psi strength range. This type of concrete provides the architect and structural engineer with a new design tool.

Ready-mix concrete producers should not attempt to deliver high-strength concrete without first developing an extensive testing program to determine the optimum mixture proportions. Close attention to each facet of concrete production is mandatory. The producer must know the factors that effect compressive strength and how to vary these factors for best results. It was

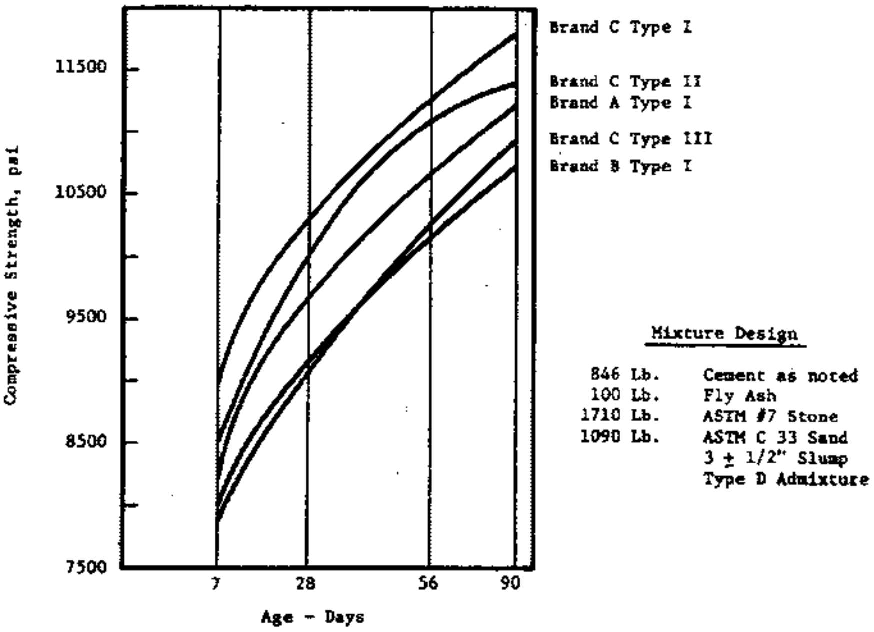


Figure 1. Effect of various cements on concrete compressive strength.

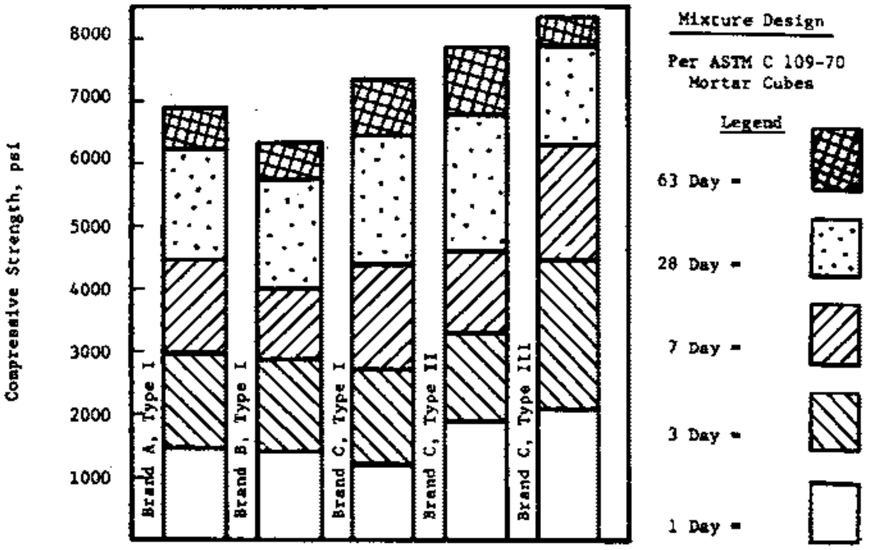


Figure 2. Effect of various cements on mortar cube compressive strength.

Ronald L. Blick is vice-president, sales, Material Service Corp., Chicago, Ill. He directed the high-strength concrete program described in this article. He is active in committee work for the Expanded Shale, Clay and Slate Institute, the Illinois Association of Aggregate Producers, the Midwest Ready Mixed Concrete Association, the American Concrete Paving Association, and the American Concrete Institute. The data in this article was condensed from a paper presented to the 1972 ACI Annual Convention, "Proportioning and Controlling High-Strength Concrete," by Ronald L. Blick, Charles F. Petersen and Michael E. Winter, all of Material Service Corp.

found that the selection of a brand and type of portland cement was the most important factor. Some cements produce very high early strengths but exhibit little strength gain at extended ages. The selection should be made on the basis of its strength producing capabilities in concrete mixtures at 28, 56, and 90 days. Figure 1 illustrates the concrete strength performance data on three brands and three types of portland cement used in trial mixtures; and Figure 2 represents the compressive strength of corresponding ASTM C-109 mortar cubes.

It should be noted that a relationship existed between the mortar cube strength and the concrete strength for Type I and II cements; i.e., the cements that gave the highest strengths in mortar cubes yielded the highest concrete strength. The Type III cement did not follow this pattern, as it yielded the highest mortar cube strengths but produced concrete strengths lower than three other cements. Figure 3 represents further investigation of the relationship of Type I cements tested in mortar cubes and concrete trial batches. The cylinder results were derived from concrete mixtures in which the slump was maintained at 2½" to 3½". This data indicated a correlation of mortar cubes to concrete strengths for the Type I cements. Other data has indicated that a reliable relationship may not exist. It is important not to base your final conclusion solely on the mortar cube test results.

Limits on the physical properties of the selected brand of cement should be established and submitted to the producer for compliance. At this point a periodic sampling and testing program of the cement being used should be initiated to insure uniformity of the product and conformance to the modified limits or specifications. This sampling and testing program is performed by our cement chemist in our own cement and concrete laboratory. Each brand of cement used in our system is sampled and evaluated at least once a week. A similar program could be established in conjunction with a local commerical testing laboratory if the expense of setting up an intercompany laboratory cannot be justified.

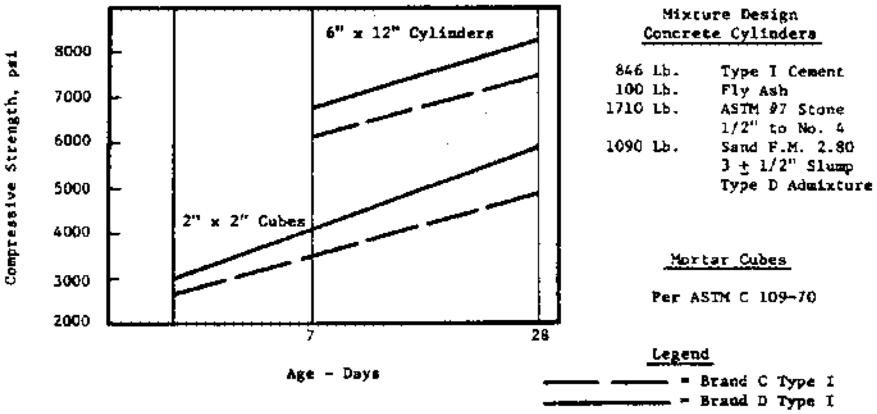


Figure 3. Mortar cube strength versus concrete cylinder strength.

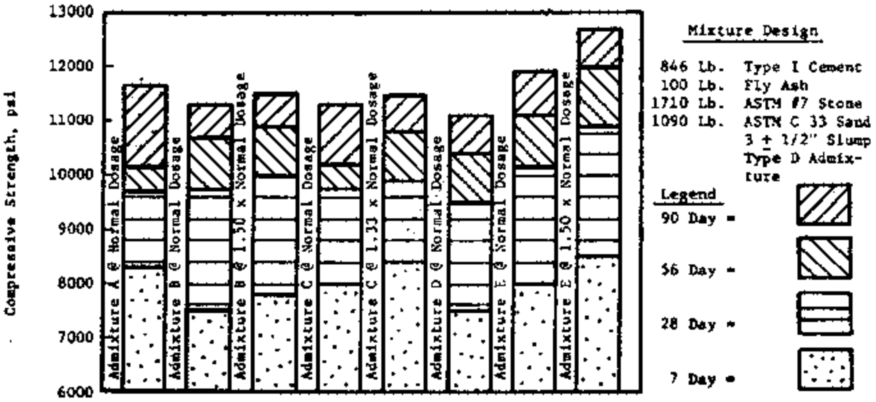


Figure 4. Effect of chemical admixtures on concrete compressive strength.

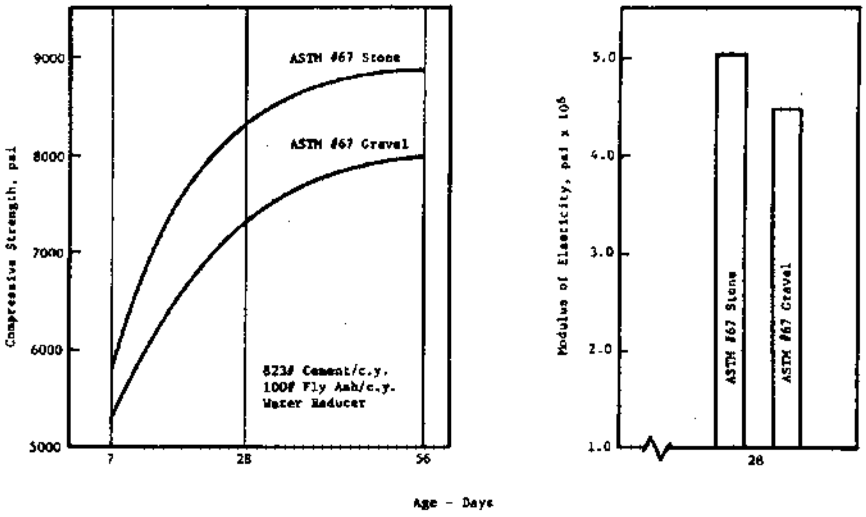


Figure 5. Compressive strength and modulus of elasticity of various sizes and types of coarse aggregate for 7500 psi concrete.

After the selection of the cement is made, the optimum cement content should be obtained through a series of trial mixtures in the laboratory using a single set of aggregates. The trial mixtures should be made at a constant slump. The range of cement content may vary, depending on the design strength being considered but should be sufficient to produce a maximum useful quantity. Since cement in excess of this maximum quantity will not produce additional strength, other materials with strength producing properties should also be evaluated. At this point the benefit of various admixtures should be pursued.

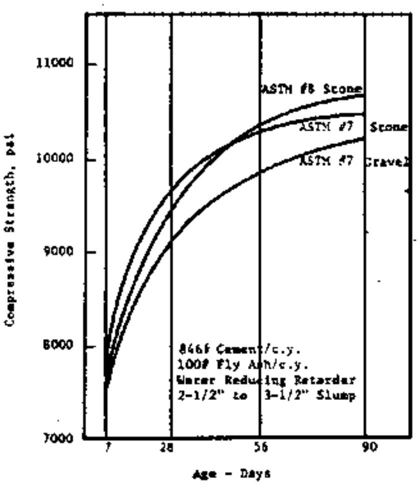
There are basically three different classes of compounds which fall into Type A and Type D chemical admixtures: lignosulfonates, hydrocarboxylic acids, and hydroxylated polymers. The compatability of the selected cement and the admixture being considered should be evaluated in order to determine the most efficient method of utilizing the admixture. Properties such as setting time, workability, water reduction, strength, time of addition, and addition rates are all areas which should be explored.

Variations in dosage rates from the standard recommendations of the admixture manufacturer should be examined. Our data indicated that increased dosage rates as high as 50% above the amounts recommended by the admixture manufacturer resulted in increases in compressive strength up to 10% without detrimental effects (Figure 4). Caution should be taken when using lignosulfonates at an overdose as they tend to entrain air in excess of 3%, which could reduce compressive strength substantially. Extended retardation of the concrete due to the increased dosage rate has not been noted in the field even during winter construction. For optimum efficiency, the addition of the admixture should be delayed until all cement has come in contact with the initial mixing water.

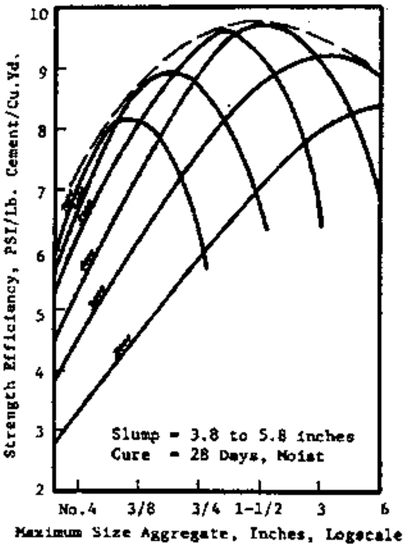
The use of a good quality fly ash is a must in the production of high-strength concrete. A fly ash with an ignition loss of 3% or less is preferable. Other pozzolans may also have similar beneficial effects but were not investigated in this work. The strength gain achieved from the use of 10% to 15% fly ash (by weight of cement) cannot be attained through additional cement.

Air-entraining agents are not generally required or recommended for use in high-strength concrete due to the accompanying strength loss. The primary applications of high-strength concrete (caissons, interior columns, and shear walls) will normally eliminate any need for air-entrained concrete.

During our aggregate investigation phase of the high-strength program, it was found that careful consideration should be given to the shape, surface texture, and mineralogy of the aggregates. It is well known that aggregate shape and surface texture affect the total mixing water requirements and these characteristics, along with the mineralogy of the aggregate, control the bond of paste to aggregate, and, therefore, play a greater role in the strength producing qualities in high-strength concrete.



Compressive strength for various sizes and types of coarse aggregate for 9000 psi.



Effects of variable coarse aggregate content on compressive strength using ASTM #7 stone.

The optimum size and shape of coarse aggregate should be determined by trial batches. Each strength level will have an optimum size aggregate which will yield the greatest compressive strength per pound of cement. In order to determine the optimum size for a given strength, trial batches should be made with aggregates less than 1″ top size at varying cement contents.

The initial investigation of aggregate for high-strength concrete mixtures centered around the 7,500 psi strength level. Coarse aggregates of ASTM #57 and #67 gravel and stone were tested and evaluated in concrete mixtures. These tests revealed that the gravel concrete produced lower compressive strength and modulus of elasticity (Figure 5) when compared with the stone concrete using the same size aggregate and cement content. The smaller size stone aggregate was used throughout the balance of the testing program as it yielded superior results when compared to the larger size stone aggregate. The results of the course aggregate study to determine the maximum size aggregate for 9,000 psi concrete are shown in Figure 6. At this strength level there was a clear distinction between the results of the ASTM #7 and #8 size stone and the ASTM #7 size gravel. The concrete mixtures with the ASTM #8 gradation produced the greatest strength at later ages, but were also the stickiest and hardest to handle. Since workability is a major concern in the field, this prompted the use of the ASTM #7 size stone.

The strength loss normally associated with increased mixing water when using small size and angular shaped coarse aggregate is overcome by the greater bond developed between the cement paste and aggregate. This cement-aggregate bond increase is due to the greater surface area of the smaller size aggregate, angular particle shape, and surface texture.

One of the primary functions of fine aggregate in conventional concrete is its role in providing workability. Sands that provide good finishing characteristics in regular concrete are not as necessary since high-strength concrete contains an unusually high amount of cement and pozzolan. Sands with a fineness modulus around 2.5 produced concrete with very "sticky" characteristics, which resulted in loss of workability and higher water demands. Sands with a fineness modulus around 3.0, which are considered coarse under normal conditions, provided the best workability and highest compressive strength. The influence of sand particle shape and surface texture appears to have at least as great an effect on mixing water and compressive strength of concrete as those of coarse aggregate.

The proportion of fine to coarse aggregate was developed from a modified version of Table 6 in ACI 613-64, *Recommended Practice for Selecting Proportions for Concrete.*

It was found that an optimum amount of coarse aggregate was achieved by increasing the values in ACI 613-64, Table 6, as noted below.

Variation from the standard ACI proportioning guide was necessary because of the extremely high percentage of cementitious materials in the high-strength mixture. Mixtures proportioned in accordance with ACI 613-64 exhibited very sticky characteristics, resulting in the loss of workability. To verify this modification, various percentages of ASTM #7 size stone aggregate were used in trial mixtures, the results of which are shown in Figure 7. It was noted that the optimum amount of coarse aggregate was not limited to a relatively narrow range.

Many researchers indicate the water-cement ratio is the single most important factor affecting the producibility of high-strength concrete. This is true only after selection of the optimum strength producing materials has been made. Our experience has shown that adherence to the following maximum water-cement ratios is needed to produce concrete in the 6,000 to 9,000 psi strength range. For purposes of calculating the w-c ratio of the mixtures, 2/3 of the weight of the fly ash used was added to the cement content.

Strength Specified	Maximum W-C Ratio
6,000	0.38
7,500	0.36
9,000	0.34

In high-strength concrete, normal variations in slump cannot be tolerated since the safety factor for this type of concrete is not of the same magnitude as moderate strength concrete mixtures. The practical limits for concrete delivered by conventional ready-mix trucks appear to be 2½" to 3½".

In order to design a concrete mixture to comply with the requirements of ACI 318, the performance variability must be known so that an adequate over-design strength can be applied. Special consideration should be given to these over-design factors needed for the various strength levels. In some cases the required average strength may be unattainable because of a high variance of test results. The ACI 318-71, *Building Code for Reinforced Concrete*, states that the concrete will be satisfactory if the average of all sets of three consecutive strength test results equals or exceeds the required strength and no individual strength test result falls below the required strength by more than 500 psi. To meet these requirements, the average strength must be higher than the specified strength. The level of design strength is governed by the control of the variables that effect compressive strength. Table I illustrates the influence of poor control on the design strength needed to satisfy a given specified strength. These results would indicate that in most cases a coefficient of variation of less than 10% would be necessary when producing high-strength concrete. Values higher than this would not only result in a very uneconomical mixture, but may very well require a design level which cannot be met.

Compressive strength tests show that a considerable strength gain after 28 days is achieved in high-strength concrete. In order to take advantage of this fact, specifications for compressive strength should be modified from the typical 28 day criterion to either 56 or 90 days. This extension of test age would then allow, for example, the use of 7,000 psi concrete at 56 days in lieu of 6,000 psi at 28 days. In this case the same design mixture could be used to meet this criteria. High strength concrete is generally used in high-rise structures; therefore, the extension of the time for compressive strength test results is reasonable since the lower portion of the structure will not attain full dead load for periods up to one year and longer.

Once the work in the laboratory has proven the value of the various materials and the proportions of the mixture selected, the strength potential of the concrete is evaluated in the field in accordance with ACI 214-68. It should be established that the concrete supplier has full control of all high-strength concrete until it is placed in the forms. Control of the slump, time on job, and the addition of retempering water fall under the jurisdiction of the concrete supplier. Concrete should be rejected if delivery time exceeds ninety minutes unless the concrete can be placed without the addition of retempering water. The maximum concrete temperature as delivered should not exceed 90°F.

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Table I—Required Increases in Design Strength As Coefficient of Variation Increases

Specified	Coefficient of Variation of 7%		Coefficient of Variation of 10%		Coefficient of Variation of 13%	
Strength f'c	Standard Deviation	Design Strength	Standard Deviation	Design Strength	Standard Deviation	Design Strength
6000	465	6700	693	7200	943	7690
7500	581	8400	866	9010	1178	9740
9000	697	10200	1040	10920	1414	11790

Table II—Compressive Strength Cardboard Molds vs Metal Molds

	28 Day Compressive Strength, psi		Percent Difference
	Metal Molds	Cardboard Molds	%
Laboratory Molded	8630	7950	− 7.9
Field Molded	8182	7537	− 7.9
Field Coefficient Of Variation	7.0%	8.0%	+14.3

	Volume of Dry Rodded Coarse Aggregate Per Unit Volume of Concrete for 2.80 Fineness Modulus of Sand		
Maximum Size of Aggregate	From ACI-613-64 Table 6	Modified for High-Strength	From ACI 211.1-70
3/8"	0.42	0.61	0.46
1/2"	0.51	0.64	0.55
3/4"	0.61	0.66	0.62
1"	0.66	0.70	0.67

High-strength concrete

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A competent concrete laboratory must be hired for testing of the concrete delivered to the jobsite. This laboratory should be regularly inspected by the Cement and Concrete Reference Laboratory (CCRL) and conform to the requirements in the *ASTM Manual of Concrete Testing*. A minimum of one set of cylinders should be made for each 100 cu. yd. of concrete placed, with at least two cylinders cast for each test age; i.e., 7, 28, 56, and 90 days. The 90-day cylinders should be made for backup data. Cylinders must be cast and cured according with ASTM C 31, Section 7.3.

Two types of cylinder molds were used for the evaluation of concrete compressive strength; cardboard molds complying with ASTM 470-67T, and single-use sheet metal molds. A significant improvement in compressive strength was noted in the case of the single-use sheet metal molds. Table II shows this comparison for both field and laboratory cylinders using 7,500 psi concrete. Capping of cylinders must be done with extreme precision and only high-strength capping compounds used. All caps on high-strength cylinders must be allowed to develop adequate strength prior to testing. The time required is dependent on the capping compound and must be determined by evaluation of the strength producing properties of the compound. The proper selection of a capping compound is important for all concrete. In the 7,500 to 9,000 psi range, this importance becomes much more significant.

Summary

1. The production of high-strength concrete in excess of 6,000 psi places the primary responsibility for performance on the ready-mix producer.
2. Portland cement of optimum quality from a strength and workability standpoint must be utilized.
3. Modification of locally available cements may be necessary.
4. Limits on the physical properties of the cement should be established by the ready-mix concrete producer.
5. A testing program must be initiated to assure cement compliance.
6. Admixtures are required. Water reducing and retarding admixtures and fly ash must be evaluated.
7. Admixture additional rates should be determined by trial mixtures and may vary from those recommended by the manufacturer.
8. Maximum water-cement ratio of 0.40 is required.
9. Slump range shall be 2½" to 3½".
10. Grading limits established in ASTM for coarse and fine aggregate appear to be adequate.
11. The compressive strength increases as the maximum size aggregate decreases.
12. Angular particle shape of coarse aggregate is required.
13. Proportions of fine and coarse aggregate must be determined through trial mixtures.
14. Water-tight metal cylinder molds are beneficial.
15. Jobsite control must be under the jurisdiction of the concrete supplier.
16. Jobsite testing must be done by a reputable commercial testing laboratory. ■