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The effect of calcium chloride on air-entrained concrete

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THE EFFECT OF CALCIUM CHLORIDE
ON AIR-ENTRAINED CONCRETE

BY

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A

THESIS

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Thanks are also in order to Mr. William Lerch, Manager, Applied Research, Portland Cement Research Laboratory, Chicago, Illinois, and to Mr. Carl J. Chappell, District Engineer, St. Louis office of the Portland Cement Association for their courteous replies to my numerous letters.

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INTRODUCTION

The essence of the problem is not fully set forth in the title in that all aspects are not covered. In this case, the term "effect" means how the compressive strength and the modulus of elasticity vary with the addition of calcium chloride.

Before discussing the details of the problem, several questions should be answered. First, why was the problem chosen? Second, has the problem ever been approached before? Third, and perhaps the most important, is the problem of any value to the engineer and the engineering profession?

Many pages will be found concerning the relative merits of plain concrete versus air-entrained concrete. All phases of the problem have been covered thoroughly. Investigations have been conducted on both plain and air-entrained concrete to determine the compressive strength, flexural strength, durability and workability. The Solvay Sales Division has compiled the results of a number of tests reported by the National Bureau of Standards, Highway Research Board, American Road Builders Association and the Portland Cement Association. These tests showed the effect of calcium chloride on Portland Cement. Tests included time of set, volume change, workability and ultimate strength. The conclusion was that addition of calcium chloride in excess of 2% by weight of cement is detrimental.

Will calcium chloride affect Portland Cement containing an air-entraining agent in the same manner as it affects plain Portland Cement? At the present time this question remains unanswered in as much as there is no published data available. The problem was chosen for two reasons: (a) to determine the compressive strength of air-entrained concrete containing calcium chloride as an admixture and (b) to see if there is a relation between this compressive strength and the modulus of elasticity.

The second question was partially answered above. The Solvay Sales Division has published a booklet, "The Effects of Calcium Chloride on Portland Cement." This booklet does not show any tests determining the modulus of elasticity but covers every other possible test of concrete containing calcium chloride.

"Entrained Air - A Factor in the Design of Concrete Mixes" - report number C-310 is a publication of the United States Department of Interior, Bureau of Reclamation, Branch of Design and Construction, Denver, Colorado. Valuable information is contained therein concerning the compressive strength and the modulus of elasticity. However, the research engineers did not see fit to add calcium chloride to the concrete. In fact, they emphasize that calcium chloride is not used or to be used for Bureau work to shorten the time of set or simplify the type of protection needed in cold weather.

Portland Cement Association has done nothing on air-entrained concrete using calcium chloride as an admixture. This fact was verified by a letter the writer received from Mr. William Lerch, Manager, Applied Research, Portland

Cement Association, on February 1, 1950. Mr. Lerch stated that they have conducted extensive tests to determine the Dynamic Modulus of Elasticity by the sonic method and that they have not published their results. He further stated that his research staff uses changes in modulus of elasticity as a measure of durability in the freezing and thawing of concrete. All tests have been on Portland Cement using vinsol resin or Darex as the entraining agent.

As far as the third question is concerned, the problem is of definite value to the engineer and to his profession. A definite relationship must be established between the compressive strength and the modulus of elasticity.

In the past few decades the use of concrete as a building material has assumed a major role. Millions of dollars have been spent by public and private enterprise for the sake of advancing our knowledge of concrete. But with the tremendous annual outlay of money, very little has been done on the problem of compressive strength versus modulus of elasticity. Is there a definite relationship between the two? In due time this question must be answered conclusively.

The engineer, whenever he designs a concrete structure, makes certain assumptions. One such assumption is the value of the modulus of elasticity. But in his specifications for the concrete to be used he stipulates its compressive strength. In other words, the compressive strength is known but its modulus of elasticity is not. The engineer rashly assumes this modulus to be anywhere from 2,000,000 psi.

to 4,000,000 psi. This assumption does make a difference in his design, since the term E, modulus of elasticity, is found in all standard deflection equations. It is also found in equations used in reinforced concrete design. A high value of modulus of elasticity could mean an uneconomical design and a resultant waste of money. A low value could mean failure of the structure. Many examples could be given showing how this assumed value of E affects a design problem. Therefore, it is of utmost importance that the designer knows definitely the value of the modulus of elasticity for the mix he specifies.

The writer has chosen four typical mixes having various water-cement (W/C) ratios by weight. Batches were mixed using normal Portland Cement. Then air-entrained cement was used having a constant or nearly constant percentage of air-entrainment. Varying amounts of calcium chloride were added to the latter mixes at the mixer. Increments of 0.4% by weight of cement were chosen. A total of 28 batches were mixed, four batches of plain concrete and 24 batches of constant air-entrained concrete with calcium chloride as an admixture in amounts varying from 0% to 2% by weight of cement.

Each mix consisted of 9 standard compression cylinders as specified by the American Society of Testing Materials. The cylinders were 6 inches in diameter and 12 inches high. In addition to the cylinders, three beams 16 inches long, $3\frac{1}{2}$ inches wide and $4\frac{1}{2}$ inches deep were cast.

The cylinders were tested to failure at the end of seven days, fourteen days, and twenty-eight days at the rate of three cylinders per test. Due to a breakdown of the sonic testing apparatus, the modulus of elasticity could be determined from the beams only at fourteen days and twenty-eight days.

The following discussion has been broken into five parts. Part one is a brief history and basic principles of air-entrained concrete. Part two includes a description of the apparatus used in the research along with pictures of the various machines and test setups. Part three is a resume of the control tests that had to be run on the various materials used. It also shows the various mixes along with the weights of each material used. Part four consists of tables and graphs showing the variation of compressive strength with the addition of calcium chloride. Contained herein are also tables of modulus of elasticity versus water-cement ratio by weight. Part five is an attempt to find a relationship between the modulus of elasticity and the compressive strength.

REVIEW OF LITERATURE

No experimental data has been found on the addition of calcium chloride to air-entrained concrete. Perhaps the reason for this is that concrete containing an air-entraining admixture has only come into its own within the past decade. Therefore, the literature noted below cites previous work done in allied fields.

In March, 1946, the Bureau of Reclamation published two pamphlets by their Engineering and Geological Control and Research Division, Branch of Design and Construction, at Denver, Colorado. The pamphlets are entitled, "Information and Instructions for Use of Air-Entraining Admixtures in Concrete" and "Entrained Air - A Factor in the Design of Concrete Mixes."

The Master Builders Company of Cleveland, Ohio, has a publication giving a series of lectures and experiments on air-entrainment and cement dispersion. The lectures were written in July, 1947, by Dr. E. W. Scripture, Jr., Vice-President in Charge of Research, and edited by Associate Professor Hans F. Winterkorn, Department of Civil Engineering, Princeton University.

Mr. H. L. Kennedy has an article in the June, 1943, Proceedings of the American Concrete Institute Journal, Volume 39, Page 591, on the "Function of Entrained Air in Concrete."

"How to Use Air-Entraining Cements" is an article written jointly by H. G. Farmer and G. L. Lindsay in August, 1944.

This article has appeared in the Engineering News Record of that month, pp. 64-67.

On March 1, 1944, H. F. Gonnerman, Manager, Research Laboratory, Portland Cement Association, presented a paper at the American Concrete Institute annual convention on "Tests of Concretes Containing Air-Entraining Portland Cements or Air-Entraining Materials Added to the Batch at Mixer."

PART ONE

The Research Laboratories of the Portland Cement Association have been conducting extensive studies of air-entrained concrete for a number of years. The studies were originally intended to find a means of preventing surface scaling and severe frost action. Laboratory studies and field experiences have consistently shown that the entrained air vastly increases the resistance of concrete to disintegration by frost action and to scaling by the direct application of salts for ice or snow removal.(1)

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(1) William Lerch, Basic Principles of Air-Entrained Concrete, Portland Cement Association, Page 1, mimeographed pamphlet received by the author from Mr. Lerch.

Air-entrained concrete has been used for approximately ten years in highways by many northern states, where severe frost action is encountered. With its use in pavements, it was noted that a concrete containing air-entrainment has many beneficial properties. The beneficial properties more than offset the detrimental effects. The advantages in using air-entrained concrete are increased workability and increased resistance to freezing and thawing. The so-called disadvantages are a slight decrease in compressive strength and a decrease in the flexural strength.

At the present time air-entrained concrete is specified by a number of state highway departments for use in the pavements built in their state. It is also used in the construction of dams by the United States Army Engineers and by numerous contractors.

The air-entrained admixture, if specified to be used with the Portland Cement, shall consist of any approved substance or compound which will produce entrained air as hereinafter specified. Whether the air-entraining admixture is interground with the cement at the mill or added at the mixer, or both shall be optional with the contractor. The total calculated air content of that portion of the concrete containing aggregate smaller than one and one-half inch square mesh sieve shall be 4.5 plus 1.5% of the volume of the concrete. If it is necessary to add an admixture at the mixer to produce the specified air content when the cement contains an admixture, the same admixture shall be used in both instances.(2)

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(2) Francis S. Friel, Standard Specifications by Albright & Friel, Inc., Consulting Engineers, Philadelphia, Pa., Allan, Lane & Scott, Section 2, Paragraph 2-05, p. 2-2, 1947.

Air-entraining agents have the power of introducing into the concrete a larger amount of air than is found in the usual concrete. Air-entrainment may be defined as the deliberate introduction of numerous, well-distributed, small, discrete air bubbles. Their size may range from one ten-thousandths of an inch up to several hundredths of an inch. For a normal structural or paving concrete, the optimum total amount of air should be in the range of 3%

to 6% of the total volume of the concrete.(3)

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(3) Dr. E. W. Scripture, Jr., Air Entrainment and Cement Dispersion, Master Builders Company, p. 1, July, 1947.

Air-entrainment, by enabling some reduction in water-cement ratio, tends to improve the quality of the paste, and by improving the workability tends to reduce segregation and improve consolidation with a minimum of effort.(4)

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(4) Ibid.

There are a number of materials that can be used as air-entraining agents to produce air-entrained concrete. The commonly accepted materials are natural wood resins, such as rosin, Vinsol resin, Darex, hydrogen peroxide and aluminum powder. Studies of other materials are under way. Of the five air-entraining agents mentioned above only two are accepted by the American Society of Testing Materials. Specification #C175-48T, Specifications on Cement, permit the use of neutralized Vinsol resin NVX and Darex AEA.(5)

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(5) Lerch, op. cit., p. 2.

The entraining agents may be introduced into the concrete in two ways - by intergrinding with the cement clinker, or by adding directly to the concrete materials at the mixer. The former method was used in the problem discussed in the following pages. A prepared air-entrained Portland Cement was purchased having an air content of approximately 4.5% by volume.

The reasons for purposeful air-entrainment(entrainment of 3 to 5 percent of air in concrete, by volume) are:

(a) increases the resistance of concrete to disintegration from freezing and thawing several fold,

(b) improves the resistance of concrete made with sulfate-resisting cement to corrosive attack by sulfate alkalies,

(c) increases workability at the same slump with substantial reductions in sand, cement, and water content, and in many cases permits use of lower slump,

(d) reduces the amount of vibration necessary for proper consolidation, and minimizes the danger of over-vibration,

(e) appreciably reduces bleeding and segregation,

(f) improves the practicability of using aggregate of larger maximum size,

(g) expedites and shortens the time of finishing operations,

(h) in general, for a given water-cement ratio, produces higher quality concrete with substantial economy in cement requirement, although attaining somewhat less strength.(6)

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(6) Engineering and Geological Control and Research Division, Branch of Design and Construction, Information and Instructions for Use of Air-Entraining Admixtures in Concrete, United States Department of the Interior Bureau of Reclamation, p. 3, March 22, 1946.

PART TWO

This portion of the discussion consists of an explanation of the various types of apparatus used in the thesis problem. Four pieces of equipment were used: a Lancaster batch mixer, a 200,000 pound Tinius-Olsen universal testing machine, sonic testing apparatus and an air-entrainment pressure apparatus.

The Lancaster batch mixer, shown in Figure 1, is a stationary type of mixer having two blades. The mixer used is type SW, #153, and has a capacity of three cubic feet of concrete. The mixer is located in the north end of the basement of Harris Hall.

The 200,000 pound Tinius-Olsen universal testing machine is mechanically operated and is capable of making tension, compression and transverse tests. It has three scales: 10,000 pounds, 100,000 pounds and 200,000 pounds. All the tests outlined later in this discussion were conducted using the 200,000 pound scale. A spherically-seated compression head was used on all test cylinders to insure a uniform distribution of compressive load. All cylinders had to be centered in the machine, Figure 2, to avoid any eccentric loading. Centering was done by eye.

This discussion is not concerned with the theory of the sonic testing apparatus. A number of papers have been written on this subject. The theory involves a thorough knowledge of electronics, which the author does not have.

Computation of the dynamic modulus requires the deter-

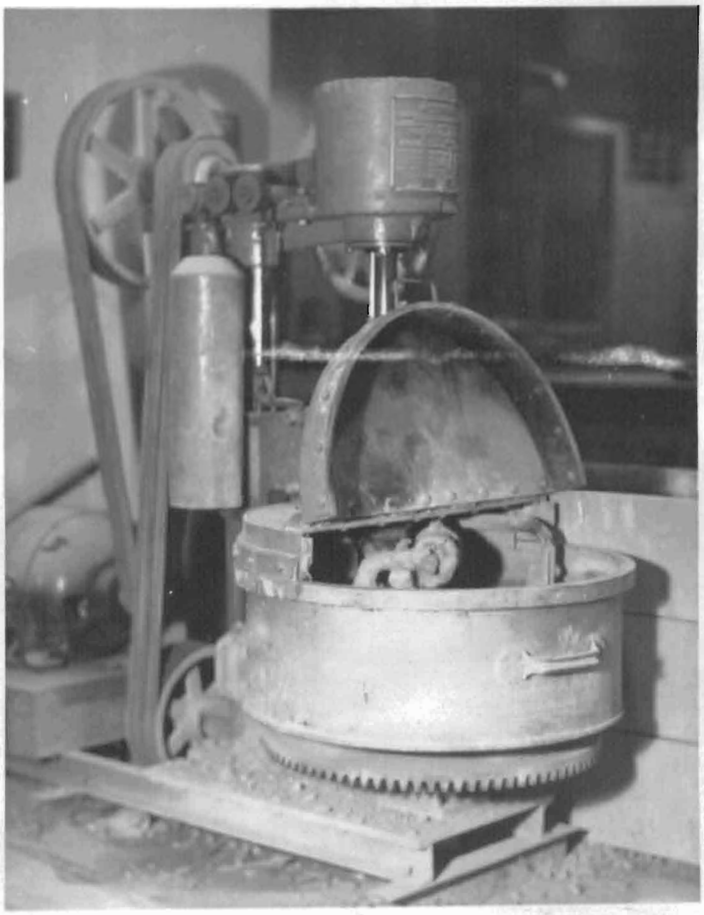

Figure 1. Lancaster Batch Mixer.

Figure 2. A Compression Cylinder that is About to be Tested to Failure in the 200,000# Tinius-Olsen Universal Testing Machine.

mination of the dimensions, weight and resonant frequency of the specimen. The apparatus necessary for the determination of the resonant frequency includes an oscillator, support and driver to produce vibration of the specimen and a pickup and a metering device to indicate the relative vibration amplitudes.

An oscillator, a cathode-ray oscillograph and an amplifier with an output meter are shown in Figure 3. These units are similar to those used by the various universities and laboratories as sonic analyzers.

The cathode-ray oscillograph is a product of the Allen B. DuMont Laboratories, Inc., Passaic, New Jersey. The one used in this problem is #10020, type 164-E. Operating instructions for this piece of equipment will be found in the DuMont publication, "Cathode-Ray Oscillograph, Type 164-E, Operating Instructions." The audio oscillator, specification #11012, is manufactured by Hewlett Packard, Palo Alto, California. This oscillator is continuously variable from 600 cycles per second to 6,000 cycles per second. The amplifier in Figure 3 is in the pick-up circuit and the output, therefore, may be indicated either by the output meter or the oscillograph.

The driver used is an ordinary permanent magnet speaker in which a stem has been cemented to the voice coil to bear against the specimen. The setup for vibrating the beam is shown in Figure 4. It consists of two wooden units. The lower unit rested on a table and the upper unit was placed

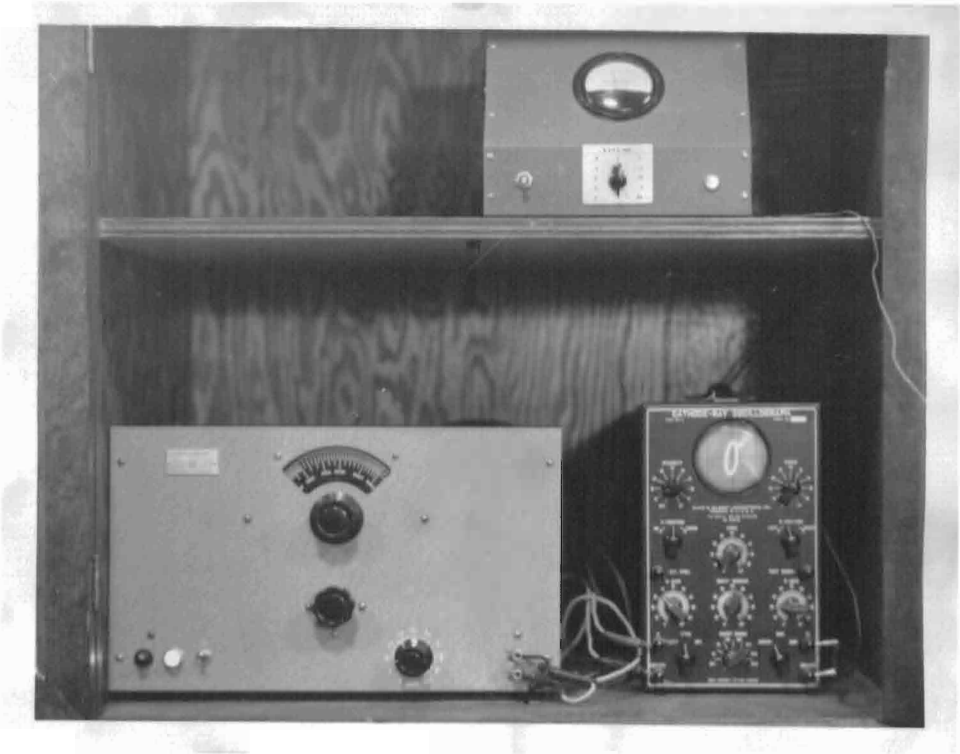

Figure 3. Sonic Testing Apparatus. Upper Right - Amplifier, Lower Left - Audio Oscillator, Lower Right - Cathode-Ray Oscillograph. Oscillograph Screen Shows the Lissajous Figure.

on this unit on sponge rubber supports. The sonic beam was placed on the upper unit and supported at the nodal points by sponge rubber. The sponge rubber was approximately one inch wide, one-quarter inch thick and five inches long. The driver was placed against the rear side of the specimen thereby vibrating the specimen in a longitudinal fashion.

The pick-up was a common phonograph pick-up. It was placed at the end of the beam, Figure 4, where maximum amplitude occurred.

The pick-up output may be indicated by the oscillograph in two ways: (a) a sine wave pattern and (b) a closed or Lissajous figure. The use of the Lissajous figure has been a practice of the Bureau of Standards and other investigators and has proved to be very superior to either the sine wave pattern or the output meter.[7] When the

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(7) Edmund F. Preece, Determination and Use of the Dynamic Modulus of Elasticity of Concrete, Highway Research Board, Proceedings, Twenty-Eighth Annual Meeting, p. 237, 1948.

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beam is driven at resonant frequency, the trace is a circle or at least approximately so. A slight departure in either direction produces a skewed figure.

To insure accurate results, within the limits of the apparatus used, the output meter method was used to determine the resonant frequency. This was done because of the outside interference and this interference reflected itself in the Cathode-Ray Oscillograph. It has been proved by competent authorities that the outside interferences which

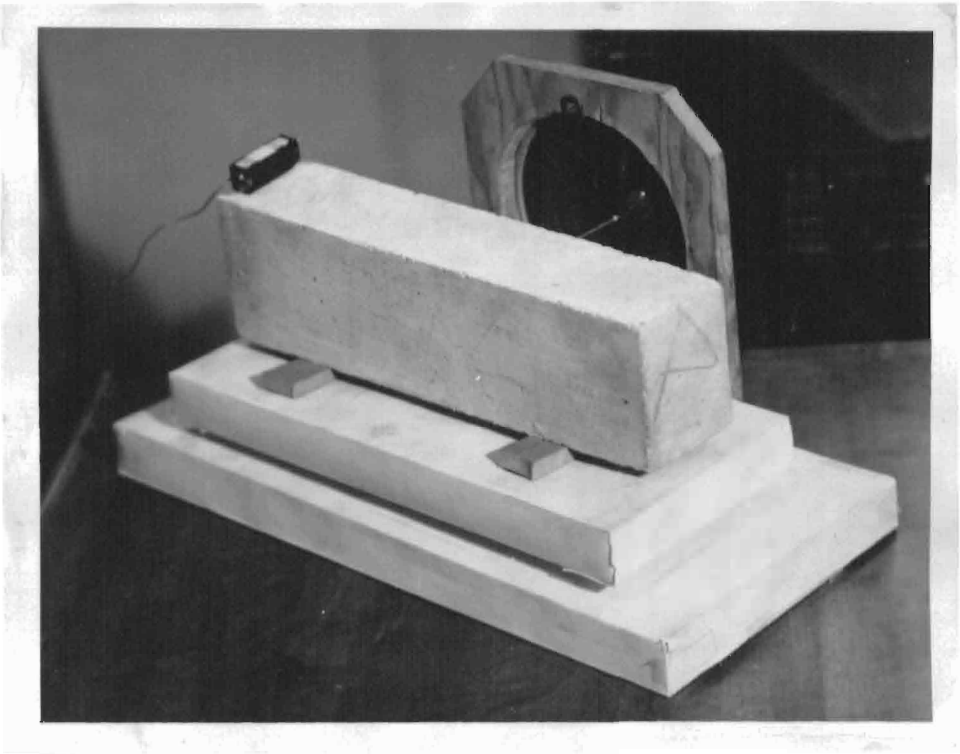

Figure 4. Method of Vibrating Sonic Beam. The Pick-up is shown at the Left End of the Beam.

arise will not interfere with the satisfactory determination of the resonant frequency.

There are two recognized methods used to determine the amount of air-entrainment in a concrete mix: (a) the volume method and (b) the pressure method. The pressure method for determining the air content of fresh concrete is established as the most reliable and the most convenient. Once the apparatus has been calibrated, the percent air can be read directly on the water column gage. The apparatus used for this problem was a portable Acme air-entrainment meter, #291, manufactured by E. W. Zimmerman, Chicago, Illinois. This apparatus is shown in Figure 5.

The test itself can be made on the job site in a few minutes. With each new type of aggregate used, an aggregate correction factor must be determined. Pressure corrections should be made with each substantial change in temperature and atmospheric conditions to insure accurate results.

Since nearly ideal conditions were had in the laboratory, as far as atmospheric conditions and temperature were concerned, the apparatus was calibrated every day and not with each mix. Aggregate correction factors were also determined daily. The operating pressure varied from 15.0 psi. to 15.2 psi., a variation of only 0.2 psi., while the aggregate correction factor varied from 0.20% to 0.25%.

Once the operating pressure and the correction factor are determined, it is an easy matter to determine the percentage of air entrained. The concrete is placed in the

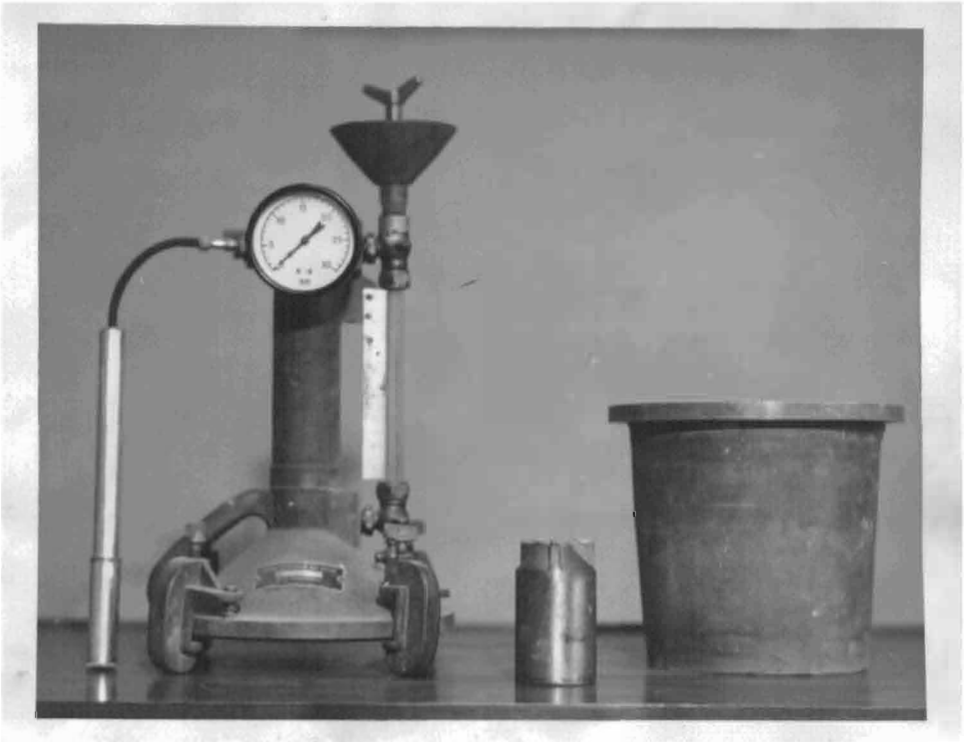

Figure 5. Air-Entraining Pressure Apparatus used to Determine the percent Air-Entrained in a Concrete Mix.

bowl of the apparatus in three layers, rodding each layer twenty-five times. The bowl is then tapped with a rubber mallet to remove cavities. The pressure apparatus is then assembled and filled with water. A pressure of about 8 psi. is applied and once again the bowl is tapped with a rubber mallet to remove any entrapped air. The pressure is released gradually and the excess water is removed, so that the water level reads zero on the water column gage. An operating pressure of from 15.0 psi. to 15.2 psi., depending on the pressure factor for that day, is applied. Once again the bowl is tapped to release all entrapped air. The water column gage reads the apparent air content in percent. The percentage of air entrained in the fresh concrete is the apparent air content in percent less the aggregate factor in percent. For the following discussion the air content of all concrete mixes varied from 4.5% to 4.7%, a variation of less than 5%. The air content was held within these close limits because the cement was purchased with an air-entrainment admixture added by the manufacturer. Such control as this is not readily obtainable on the job, since the air-entraining admixture is usually added at the time of mixing. As noted in Part One, a variation of 33% is allowed in most standard specifications when using air-entrained concrete.

The dynamic method of measuring Young's modulus of elasticity of the concrete beam is based upon the determination of the natural frequency of vibration, the weight and the dimensions of the specimen. By means of the sonic testing apparatus, the natural frequency of vibration in cycles per second can be determined.

In any textbook on vibrations or sound there may be found the equivalent of the following expression:

$$N = \frac{m^2 K}{2\pi L^2}\sqrt{\frac{E}{d}}$$ Equation 1,

where N equals the natural frequency of vibration in cycles per second, k equals the radius of gyration of the section in centimeters, L equals the length of the beam in centimeters, E equals Young's modulus of elasticity in dynes per square centimeter, and d equals the density of the beam in grams per square centimeter.

The terms k, L and d can be measured directly and m, a constant dependent primarily on the mode of vibration, can be evaluated, as will be described later. Then with N known, E can be found.

When a beam vibrates, a cross-sectional element may be thought of as executing two movements: (a) a motion of translation laterally and (b) one of rotation relative to the position of the unbent neutral axis.(8) In the deriva-

(8) T. C. Powers, Measuring Young's Modulus of Elasticity by Means of Sonic Vibration, American Society of Testing Materials, Proceedings of the Forty-First Annual Meeting, Vol. 38-Part 2, Technical Papers, pp. 460-469, 1938.

tion of the above equation the rotatory inertia was neglected for the sake of simplicity and because in most cases the error introduced thereby is not large. But if the thickness of the beam is a relatively large fraction of the length, as it is in this thesis problem, the rotatory inertia must be taken into account.

Several scientists, famous in the fields of vibrations and sound, have set up empirical equations to correct for the rotatory inertia. The most direct and exact corrections are given by Mason in terms of "m" as affected by the ratio of thickness to length.(9)

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(9) Ibid.

This new term, m', can be substituted in place of m, but this equation neglects the effect of another inertia, namely, that due to lateral contraction and expansion of the beam. This is proportional to Poisson's ratio, λ, which, for concrete, may be taken as 0.16 without serious error. Mason shows that the correction for both rotatory and lateral inertia can be made in one operation with the aid of Figure 6 simply by using instead of the ratio of thickness to length, R, a value of $R(1+\lambda)^{\frac{1}{2}}$.(10)

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(10) Ibid.

Thus for this particular thesis problem $R(1+\lambda)^{\frac{1}{2}} = \frac{4.5}{16}(1+\lambda)^{\frac{1}{2}} = 0.281(1.16)^{\frac{1}{2}} = 0.303$ and the corresponding value of m, which may be designated as m", is, from Figure 6, 4.36.

With the notation just indicated, Equation 1 becomes, when corrected for lateral and rotatory inertia,

$$E = \frac{4\pi^2 N^2 d L^4}{K^2 (m'')^4}$$

and, when the values for the 3½ inch by 4½ inch by 16 inch beam are substituted, $E = 6.355 \times 10^{-3} N^2 d$,

where N is the fundamental frequency of vibration in kilocycles per second and d is the density of the beam in pounds per cubic foot.

The first step in the sonic method is to determine the mode of vibration of the beam. This is easily accomplished either by mathematical analysis or, if the beam is small, by holding it by one end and then tapping along the length of the beam, noting the positions of the "dead" spots - the nodes. If the fundamental frequency of vibration is being given, two nodes will be found, each exactly 0.224L from the nearest end, regardless of the dimensions of the beam.(11)

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(11) Ibid.

To obtain the fundamental frequency of vibration, the beam is rested on narrow sponge rubber supports at the two nodal points, 0.224L from each end, as shown in Figure 7.

Mr. T. C. Powers, in his paper, "Measuring Young's Modulus of Elasticity by Sonic Vibrations," recommends that the specimen be not vibrated above a natural frequency of 3,000 cps. because of the relative size of depth to length. He further presents evidence that the dynamic modulus of elasticity is a true measure of the modulus, since the

CURVE SHOWING RELATION BETWEEN "R" AND "m"" [12]

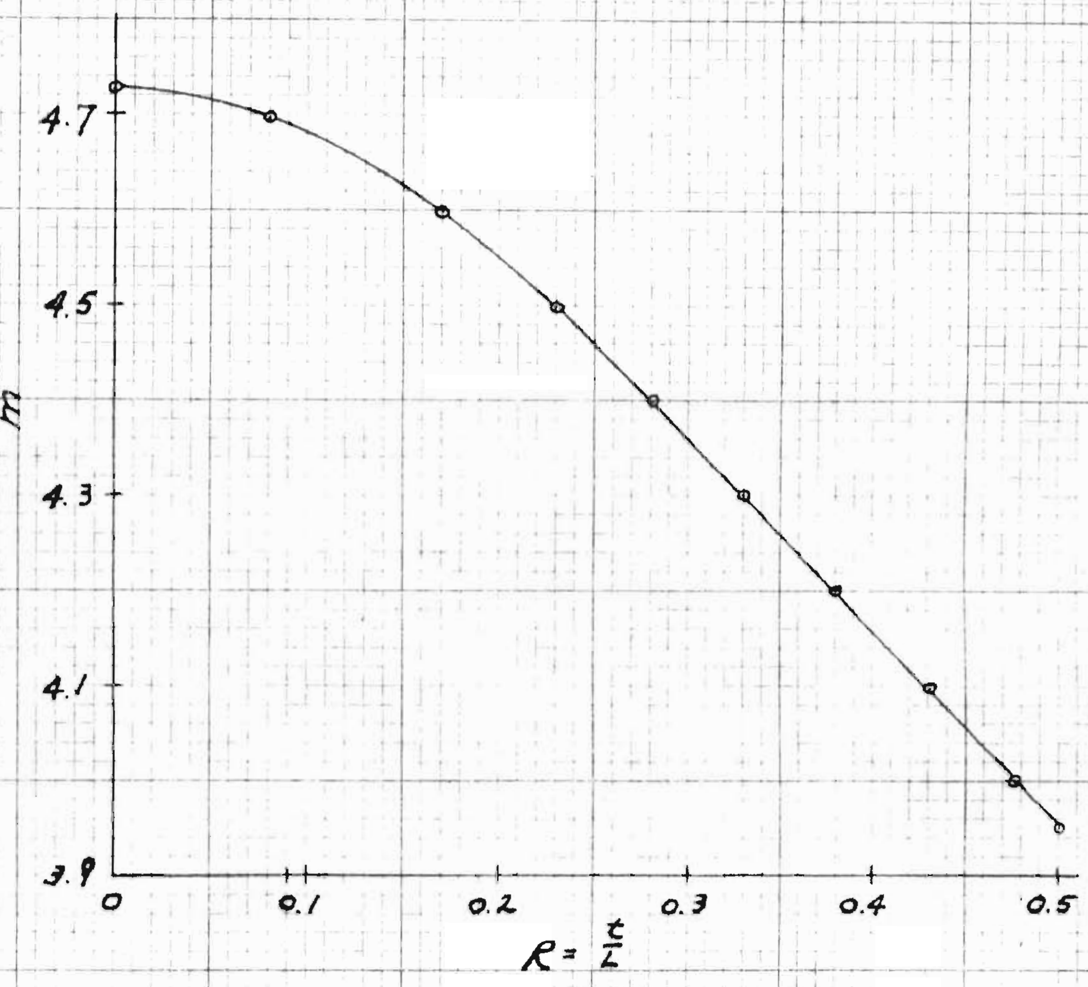

FIGURE 6.

(12) Ibid.

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dynamic modulus is not complicated by plastic flow or creep, as would occur in a static test loading.

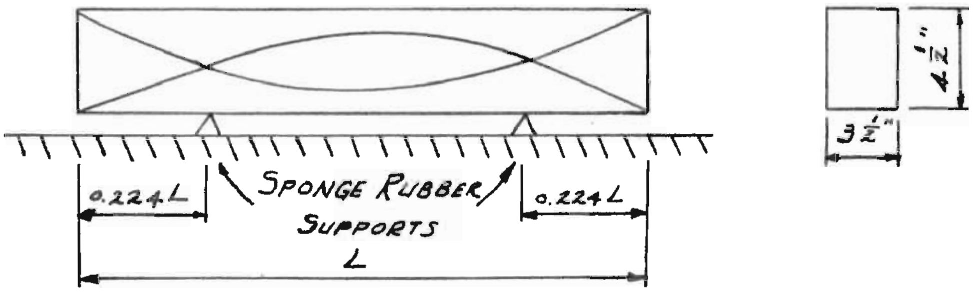


FIGURE 7. TEST SETUP TO DETERMINE FUNDAMENTAL FREQUENCY.

PART THREE

A research problem involving concrete always has a number of variables. A few of these variables are the percentage moisture in the sand and gravel, the fineness modulus of the sand, the water-cement ratio by weight, the method of curing the concrete, the curing temperature, the type of cement used, the additions to the concrete mix, the size and the shape of the coarse aggregate and the slump.

For a particular problem, certain variables must be kept constant. In this thesis problem the percentage moisture in the sand and gravel, the fineness modulus of the sand, the method of curing and the curing temperature of the concrete, the size and the shape of the coarse aggregate and the slump were held constant. Therefore, the variables were the type of cement used, the water-cement ratio by weight and the addition of calcium chloride to the concrete mix.

As far as the method of curing and the curing temperature of the concrete were concerned, all concrete was cured in the moist room located in the basement of Harris Hall. The curing temperature was approximately 70° F. This temperature varied but a few degrees during the entire curing period. The concrete was placed in the moist room immediately upon mixing and kept there until it was time to test the mix.

Rounded limestone coarse aggregate, having a maximum size of one and one-half inches, was used. Before determining the amounts of materials used in the various mixes, the fineness modulus of the sand had to be determined. The term "fineness modulus" is used as an index to the fineness or the coarseness of the aggregate. The grading and maximum size of aggregates are important, because of their effects on relative proportions, workability, economy, porosity and shrinkage.

A number of tests were conducted to be sure that the fineness modulus of the sand remained nearly constant. A typical fineness modulus test is shown below in Table 1. Tests were conducted on every two mixes and, for the fourteen mixes tested, the fineness modulus varied from 2.50 to 2.53.

Table 1.

Fineness Modulus - as Determined by a Test on a Dry Sample of Pacific Sand - Sample - 1000 grams

Sieve Size	Amount Retained (Cumulative)	Percent Retained (Cumulative)
#4	0	0
#8	79.3 gm.	7.93%
#16	265.9 gm.	26.59%
#30	449.8 gm.	44.98%
#50	738.3 gm.	73.83%
#100	977.5 gm.	97.75%
Passing	996.8 gm.	
	Total	251.08

$$\text{Fineness Modulus} = \frac{251.08}{100} = 2.51$$

Slump is a rough measure of the workability of a concrete mix. While this test is not an absolute test of the workability, under uniform operating conditions, it is useful in revealing changes in grading, proportions or water content. As mentioned above, the slump was held constant at three inches plus or minus one-quarter inch. On only two batches did the slump exceed this amount and, since the slump was to be held constant or nearly so on all mixes, these two batches were thrown away.

The percentage moisture in the fine and coarse aggregate is always one factor that gives quite a bit of trouble in a concrete mix. The moisture contained in the sand and gravel must be added as part of the mixing water. This factor was controlled by using air-dried material. Moisture tests were conducted on the aggregates to determine how much water had to be added to or subtracted from the given amount of water to obtain the water-cement ratio by weight. For each mix the total water in the sand and gravel remained less than one percent or 0.01 pound of water per pound of sand and gravel. Since this factor was so low, it was neglected. This can be done without serious error.

The usual amount of water contained in the aggregates was 0.5%. As noted in the above paragraph, two batches were thrown away because the slump exceeded 3 1/4". When the percentage moisture of the aggregates for these mixes was determined, it was found that the moisture content was approximately 5%. This was due to the fact that it rained the morning the batches were mixed and water had leaked into the bin containing the coarse aggregate.

Two types of cements were used: Normal Portland Cement for the first four mixes and air-entrained Portland Cement for the last twenty-four mixes. The air-entraining agent was added by the manufacturer by intergrinding air-entraining additions with Portland Cement clinkers during manufacture. The above two cements met all the standard specifications of the American Society of Testing Materials. This fact was assured by purchasing the cements from reliable manufacturers.

Calcium chloride was the only compound added to the concrete mixes other than the normal ingredients - sand, cement, gravel and water. This compound was added only to those mixes containing air-entrained cement. The calcium chloride was incorporated in the mix with the mixing water, although the Solvay Sales Division says that the calcium chloride nedd not necessarily be added in solution except in very dry mixes. Calcium chloride was added in amounts up to 2% by weight of cement in increments of 0.4%.

Another variable was the water-cement ratio by weight. Four water-cement ratios were chosen to assure a wide variation of compressive strength. Table 2 shows the various amounts of materials used in each mix. Table 3 includes the resultant slump, the percentage of air-entrained and the percentage calcium chloride used. Table 2 consists of the 28 mixes used in this thesis problem, but 32 batches were actually mixed. Two of these mixes were thrown away because the slump exceeded 3 1/4". Two other mixes were trial batches of mix A and D. The trial batches were mixed to determine the strength at seven days and to see if the relative proportions used were sufficient to produce the designed compressive strength.

Mixes A and D were designed for a seven day compressive strength of 1900 psi., and 3600 psi., respectively. The trial mixes tested at values very close to these - within approximately 5%. Therefore, the author used the table of suggested trial mixes for concrete of medium consistency on Page 18 of the Portland Cement Association Publication, "Design and Control of Concrete Mixes," 9th edition.

The amounts of the various materials listed in Table 2 are based on nine standard cylinders 6 inches in diameter and 12 inches high having a total volume of 3060 cubic inches plus three beams each 16 inches long, 4.5 inches high and 3.5 inches wide having a total volume of 756 cubic inches plus a 10% waste factor. Therefore, the total volume mixed was 2.44 cubic feet.

Mix numbers 1 to 4 inclusive in Table 2 and in all subsequent tables were mixed with Normal Portland Cement, while mix numbers 5 to 28 inclusive were mixed using air-entrained Portland Cement.

Table 2.

Various Amounts of Materials Used in Each Mix

Mix No.	W/C Ratio by weight	Cement, pounds	Sand, pounds A B	Gravel, pounds A C	Calcium Chloride, grams
1 - A	0.710	38.06	125.62	174.24	0
2 - B	0.626	43.12	116.82	176.88	0
3 - C	0.531	50.71	110.88	178.20	0
4 - D	0.444	60.94	100.43	178.20	0
5 - AA0	0.710	38.06	125.62	174.24	0
6 - AA1	0.710	38.06	125.62	174.24	69.08
7 - AA2	0.710	38.06	125.62	174.24	138.17
8 - AA3	0.710	38.06	125.62	174.24	207.71
9 - AA4	0.710	38.06	125.62	174.24	276.79
10 - AA5	0.710	38.06	125.62	174.24	345.88
11 - BA0	0.626	43.12	116.82	176.88	0
12 - BA1	0.626	43.12	116.82	176.88	78.43
13 - BA2	0.626	43.12	116.82	176.88	156.80
14 - BA3	0.626	43.12	116.82	176.88	235.43

Note: For all mixes water was held constant at 27.01 pounds.
A - Air-dried material - contains less than 1% moisture.
B - Fineness modulus of sand - 2.50 to 2.53.
C - One and one-half inch maximum size rounded coarse aggregate.

Table 2.
(con't.)

Various Amounts of Materials Used in Each Mix

Mix No.	W/C Ratio by weight	Cement, pounds	Sand,[A][B] pounds	Gravel,[A][C] pounds	Calcium Chloride, grams
15 - BA4	0.626	43.12	116.82	176.88	313.61
16 - BA5	0.626	43.12	116.82	176.88	391.78
17 - CA0	0.531	50.71	110.88	178.20	0
18 - CA1	0.531	50.71	110.88	178.20	92.26
19 - CA2	0.531	50.71	110.88	178.20	184.53
20 - CA3	0.531	50.71	110.88	178.20	276.79
21 - CA4	0.531	50.71	110.88	178.20	368.60
22 - CA5	0.531	50.71	110.88	178.20	460.86
23 - DA0	0.444	60.94	100.43	178.20	0
24 - DA1	0.444	60.94	100.43	178.20	110.90
25 - DA2	0.444	60.94	100.43	178.20	221.80
26 - DA3	0.444	60.94	100.43	178.20	332.24
27 - DA4	0.444	60.94	100.43	178.20	443.14
28 - DA5	0.444	60.94	100.43	178.20	554.04

Note: For all mixes water was held constant at 27.01 pounds.
A - Air-dried material - contains less than 1% moisture.
B - Fineness modulus of sand - 2.50 to 2.53.
C - One and one-half inch maximum size rounded coarse aggregate.

Table 3.

Resultant Slump, % Air-Entrainment, and % Calcium Chloride Obtained by Direct Measurement

Mix No.	W/C Ratio by weight	Water, gal/sack of cement	% Calcium Chloride by weight of cement	Slump, inches	% Air-Entrainment
1 - A	0.710	8	0	3	0
2 - B	0.626	7	0	2 3/4	0
3 - C	0.531	6	0	3	0
4 - D	0.444	5	0	3	0
5 - AA0	0.710	8	0	3 1/4	4.50
6 - AA1	0.710	8	0.4	3 1/4	4.65
7 - AA2	0.710	8	0.8	3	4.70
8 - AA3	0.710	8	1.2	3	4.70
9 - AA4	0.710	8	1.6	3	4.60
10 - AA5	0.710	8	2.0	2 3/4	4.55
11 - BA0	0.626	7	0	3 1/4	4.50
12 - BA1	0.626	7	0.4	3	4.55
13 - BA2	0.626	7	0.8	3 1/4	4.70
14 - BA3	0.626	7	1.2	3	4.70

Table 3.
(con't.)

Resultant Slump, % Air-Entrainment, and % Calcium Chloride
Obtained by Direct Measurement

Mix No.	W/C Ratio by weight	Water, gal/sack of cement	% Calcium Chloride by weight of cement	Slump, inches	% Air-Entrainment
15 - BA4	0.626	7	1.6	3	4.65
16 - BA5	0.626	7	2.0	3 1/4	4.60
17 - CA0	0.531	6	0	3 1/4	4.50
18 - CA1	0.531	6	0.4	3	4.70
19 - CA2	0.531	6	0.8	3	4.60
20 - CA3	0.531	6	1.2	3	4.50
21 - CA4	0.531	6	1.6	2 3/4	4.65
22 - CA5	0.531	6	2.0	3 1/4	4.70
23 - DA0	0.444	5	0	3 1/4	4.50
24 - DA1	0.444	5	0.4	2 3/4	4.70
25 - DA2	0.444	5	0.8	2 3/4	4.55
26 - DA3	0.444	5	1.2	3	4.50
27 - DA4	0.444	5	1.6	3 1/4	4.70
28 - DA5	0.444	5	2.0	3 1/4	4.70

It is interesting to note the total amounts and the costs of the various materials used:

Normal Portland Cement	- 2.05 sacks @ $1.10	= $2.26
Air-Entrained Portland Cement	- 12.30 sacks @ $1.10	= 13.53
Sand	- 1.59 T. @ $3.00	= 4.75
Gravel	- 2.48 T. @ $3.00	= 7.43
Calcium Chloride	- 11.57# @ $0.05	= 0.58
Standard Cardboard Molds	- 252 molds @ $0.05	= 12.60
		$41.15

The above costs do not include the cost of the labor for making the wooden molds used in casting the beams. The author is indebted to Mr. King, Mechanic for the Civil Engineering Department, for construction of the beam forms.

PART FOUR

This section of the discussion is concerned with the seven, fourteen and twenty-eight day compressive strength test results and the fourteen and twenty-eight day sonic test results. It is broken into several component parts to give a better graphical representation of how the addition of calcium chloride affects the compressive strength.

Two photographs, Figures 8 and 9, are also contained herein. Figure 8 is a shot of what happens to a test cylinder a few seconds prior to reaching the ultimate load and eventual failure. Figure 9 shows a typical failure on a test cylinder for this thesis problem. Some of the cylinders had bond failure, others had aggregate failure and still others had a combination of the two. The author cannot explain why all three failures occurred in the various cylinders. Perhaps it was due to the addition of calcium chloride to the concrete.

All compressive values contained in the tables and on the graphs following are the average results of three cylinders. Likewise, the modulus of elasticity is a statistical average of three sonic beams. As far as the compressive strength is concerned, all figures were rounded off to the nearest 5 psi., although it is impossible to plot such a value as this on the graph paper used.

Table 4, with its accompanying graph, Figure 10, gives the seven, fourteen and twenty-eight day test results of concrete containing Normal Portland Cement and concrete containing air-entrained cement having a constant percent-

Figure 8. A Compression Test Cylinder a Few Seconds Prior to Reaching its Ultimate load.

Figure 9. A Typical Failure of a Compression Cylinder for this Thesis Problem.

age air-entrainment but no calcium chloride. As was expected, the latter concrete lost a certain amount of compressive strength.

Tables 5, 6 and 7, with their accompanying graphs, Figures 11, 12 and 13, respectively, give a pictorial representation of the effect of calcium chloride on the compressive strength of a concrete containing an air-entraining admixture.

The last two tables, Tables 8 and 9, are the results of the sonic beam tests. No graphs were plotted for these tests. By looking at the tables, it can be seen that no relation exists between the water-cement ratio by weight and the modulus of elasticity.

A word of explanation is in order concerning Figures 11, 12 and 13, graphs of compressive strength in psi. versus percent calcium chloride by weight of cement. Only five points were obtained for each, therefore, the author could not predict what would happen between the various points. Whether a smooth curve should be drawn is a question open for discussion. After considerable thought, the author decided to draw a series of straight lines between these points. It is believed that this would give a better representation of the effect of calcium chloride on the compressive strength of air-entrained concrete. Perhaps the strength between the test points is not a straight line function of the percent of calcium chloride by weight of cement. As noted above, the question of a smooth curve versus a straight line curve is one that could be debated.

Table 4.

Test Results - Compressive Stress of Concrete Containing Normal Portland Cement and Air-Entrained Cement

Mix No.	W/C Ratio by weight	Average Compressive Stress, psi. A B	Mix No.	Average Compressive Stress, psi. A C
	7-day results			
A	0.710	1910	AAO	1655
B	0.626	2205	BAO	1920
C	0.531	2795	CAO	2295
D	0.444	3500	DAO	2905
	14-day results			
A	0.710	2350	AAO	2040
B	0.626	2820	BAO	2355
C	0.531	3545	CAO	2915
D	0.444	4375	DAO	3680
	28-day results			
A	0.710	2725	AAO	2260
B	0.626	3270	BAO	2585
C	0.531	4000	CAO	3300
D	0.444	4980	DAO	4210

A - Average of three cylinders.
B - Cylinders contained Normal Portland Cement.
C - Cylinders contained Air-Entrained Portland Cement - 0% calcium chloride.

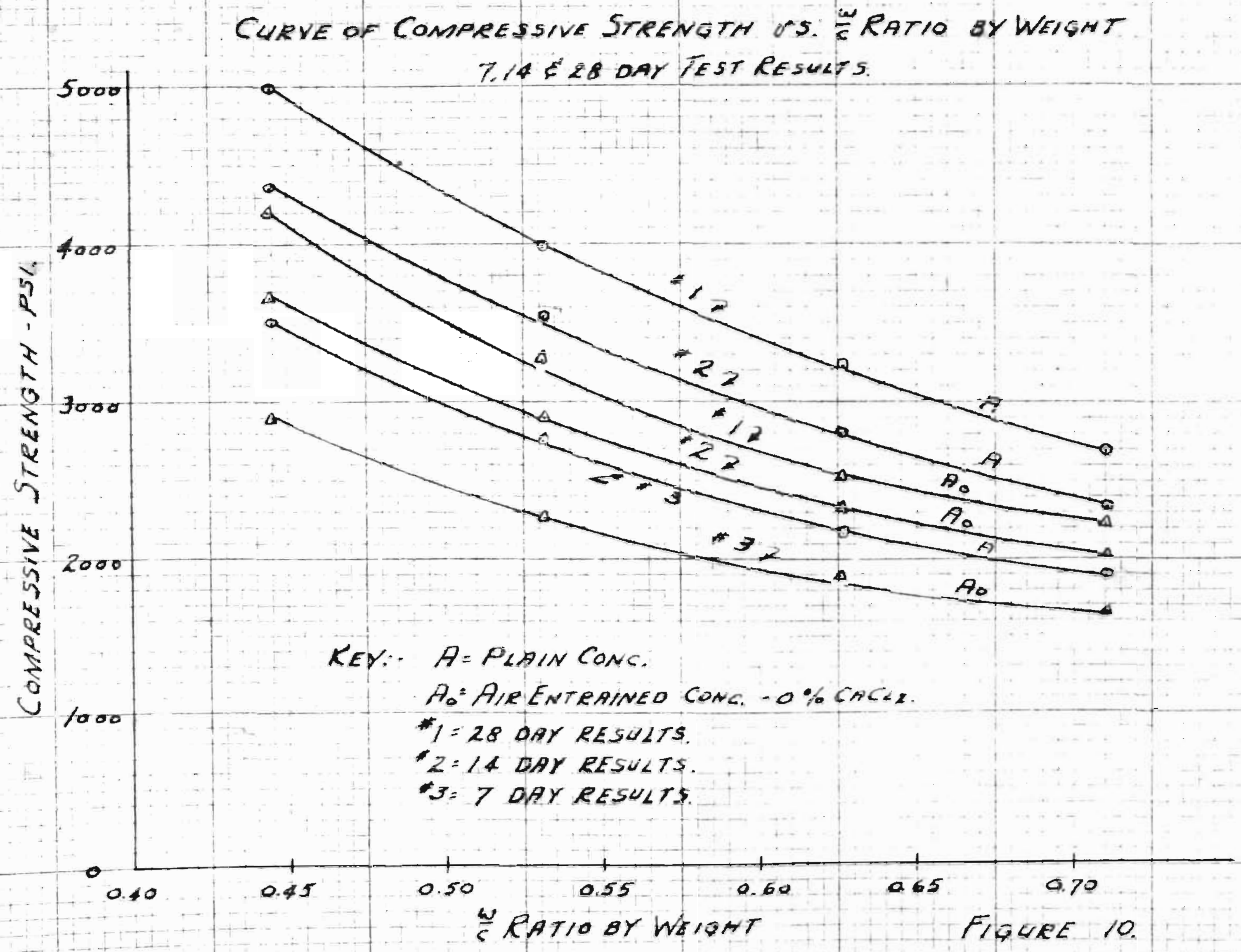

CURVE OF COMPRESSIVE STRENGTH VS. W/C RATIO BY WEIGHT
7, 14 & 28 DAY TEST RESULTS.
COMPRESSIVE STRENGTH - PSI.
5000
4000
3000
2000
1000
0
0.40
0.45
0.50
0.55
0.60
0.65
0.70
W/C RATIO BY WEIGHT
#1
#2
#1
#2
2 #3
#3
A
A
A₀
A₀
A
A₀
KEY:- A= PLAIN CONC.
A₀= AIR ENTRAINED CONC. - 0 % CACL₂.
#1 = 28 DAY RESULTS.
#2 = 14 DAY RESULTS.
#3 = 7 DAY RESULTS.
G.F.N.

FIGURE 10.

Table 5.

7-Day Test Results of the Compressive Strength of Air-Entrained Concrete Containing Calcium Chloride

Mix No.	W/C Ratio by wt.	% Calcium Chloride by wt. of Cement	Average Compressive Strength, psi.	Mix No.	W/C Ratio by wt.	% Calcium Chloride by wt. of Cement	Average Compressive Strength, psi.
AA0	0.710	0.0	1655	BA0	0.626	0.0	1920
AA1	0.710	0.4	2490	BA1	0.626	0.4	3035
AA2	0.710	0.8	2710	BA2	0.626	0.8	3240
AA3	0.710	1.2	2015	BA3	0.626	1.2	2500
AA4	0.710	1.6	1870	BA4	0.626	1.6	2025
AA5	0.710	2.0	1980	BA5	0.626	2.0	1995
CA0	0.531	0.0	2295	DA0	0.444	0.0	2905
CA1	0.531	0.4	3305	DA1	0.444	0.4	3585
CA2	0.531	0.8	3450	DA2	0.444	0.8	3530
CA3	0.531	1.2	2640	DA3	0.444	1.2	2990
CA4	0.531	1.6	2500	DA4	0.444	1.6	2605
CA5	0.531	2.0	2010	DA5	0.444	2.0	2040

Comparison Curve - Compressive Strength vs. % Calcium Chloride by Weight of Cement at 7 Days.

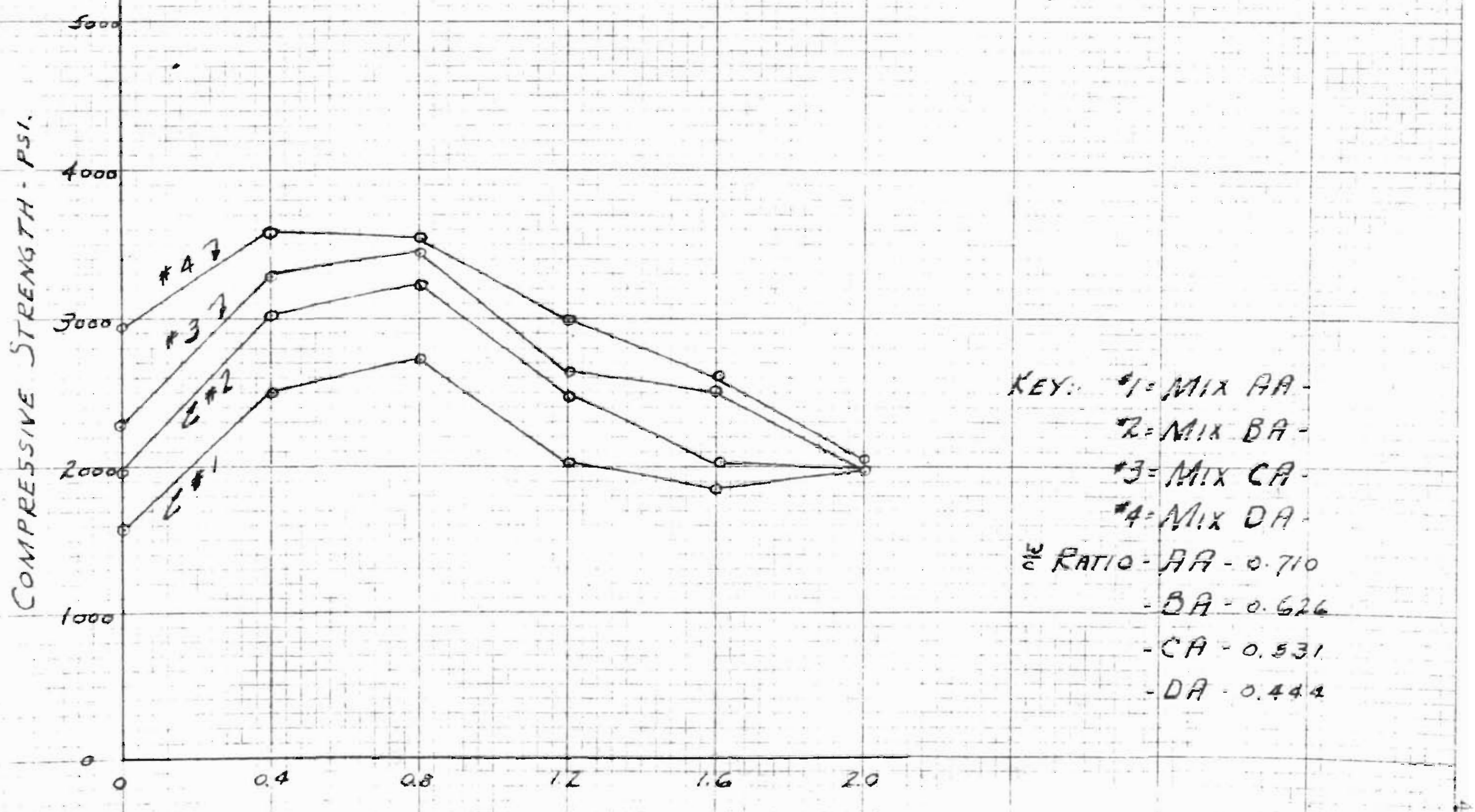


Figure 11.

Table 6.

14-Day Test Results of the Compressive Strength of Air-Entrained Concrete Containing Calcium Chloride

Mix No.	W/C Ratio by Wt	% Calcium Chloride by Wt. of Cement	Average Compressive Strength, psi.	Mix No.	W/C Ratio by Wt.	% Calcium Chloride by Wt. of Cement	Average Compressive Strength, psi.
AA0	0.710	0.0	2040	BA0	0.626	0.0	2355
AA1	0.710	0.4	2875	BA1	0.626	0.4	3260
AA2	0.710	0.8	2995	BA2	0.626	0.8	3435
AA3	0.710	1.2	2340	BA3	0.626	1.2	2780
AA4	0.710	1.6	2130	BA4	0.626	1.6	2210
AA5	0.710	2.0	2150	BA5	0.626	2.0	2300
CA0	0.531	0.0	2915	DA0	0.444	0.0	3680
CA1	0.531	0.4	3505	DA1	0.444	0.4	3850
CA2	0.531	0.8	3590	DA2	0.444	0.8	3724
CA3	0.531	1.2	2960	DA3	0.444	1.2	3230
CA4	0.531	1.6	2835	DA4	0.444	1.6	3005
CA5	0.531	2.0	2255	DA5	0.444	2.0	2315

COMPARISON CURVE - COMPRESSIVE STRENGTH VS.
% CALCIUM CHLORIDE BY WEIGHT OF CEMENT AT 14 DAYS.

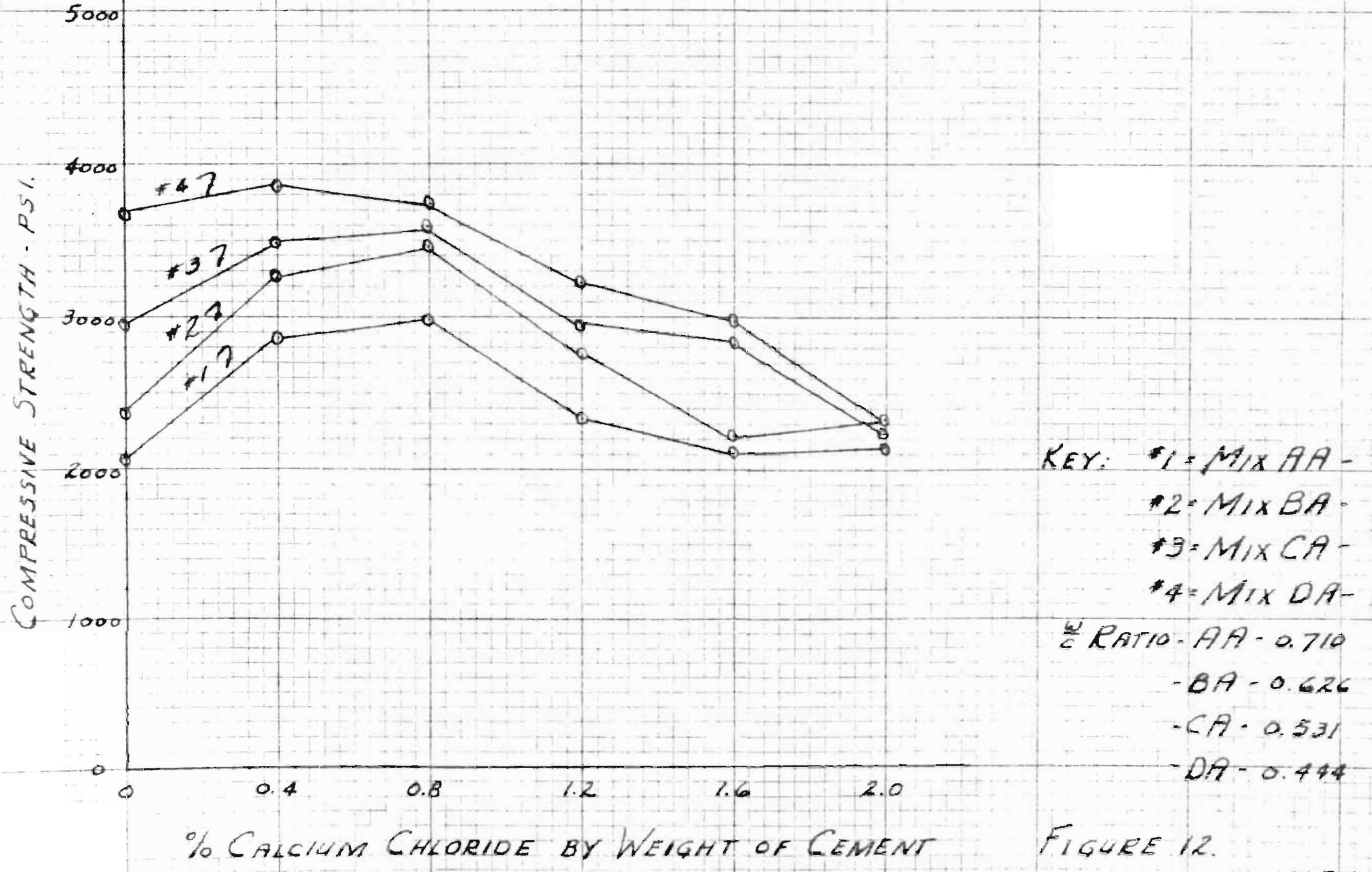


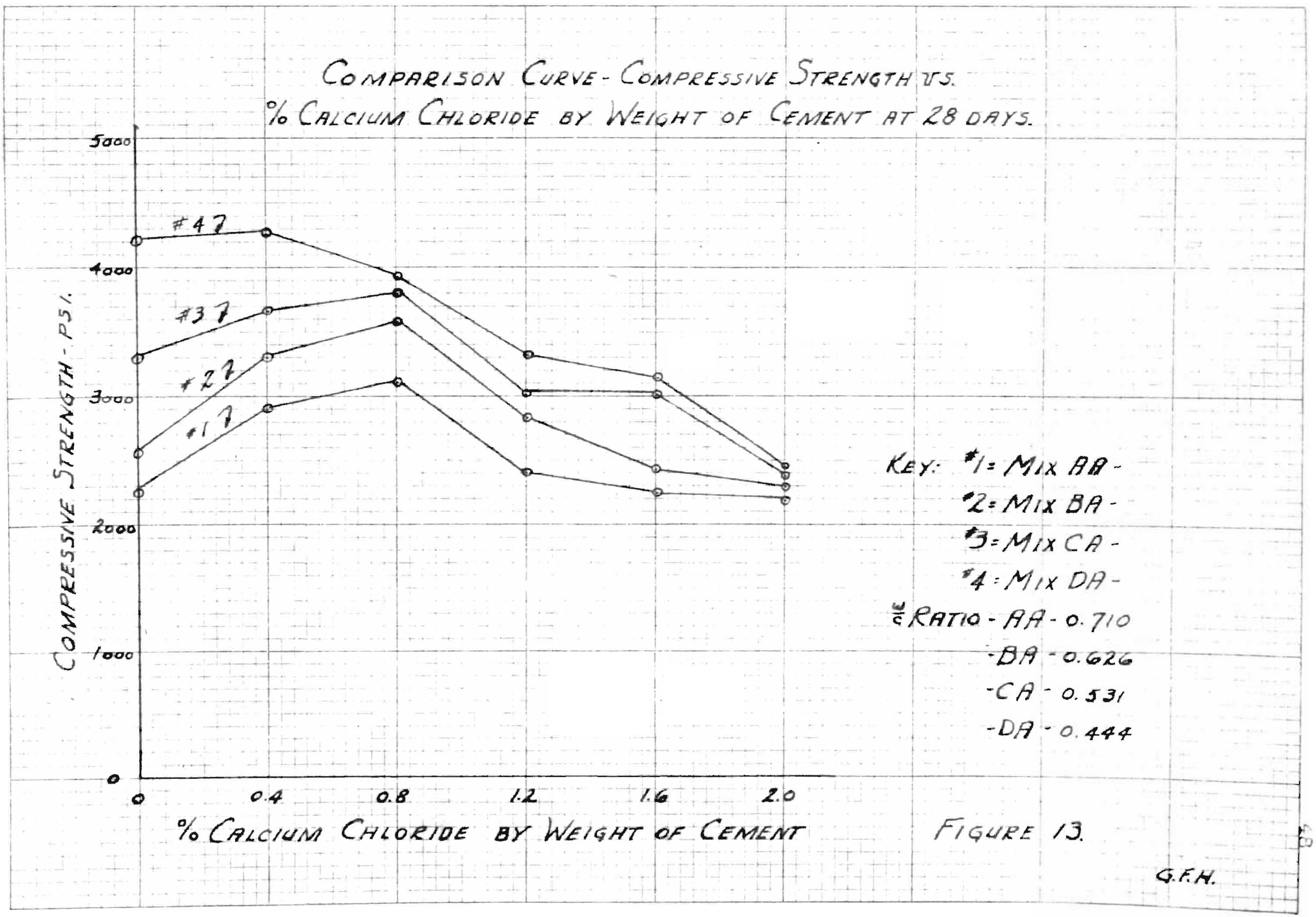
FIGURE 12.

G.F.H.

Table 7.

28-Day Test Results of the Compressive Strength of Air-Entrained Concrete Containing Calcium Chloride

Mix No.	W/C Ratio by Wt.	% Calcium Chloride by Wt. of Cement	Average Compressive Strength, psi.	Mix No.	W/C Ratio by Wt.	% Calcium Chloride by Wt. of Cement	Average Compressive Strength, psi.
AA0	0.710	0.0	2260	BA0	0.626	0.0	2485
AA1	0.710	0.4	2920	BA1	0.626	0.4	3300
AA2	0.710	0.8	3130	BA2	0.626	0.8	3580
AA3	0.710	1.2	2390	BA3	0.626	1.2	2825
AA4	0.710	1.6	2250	BA4	0.626	1.6	2440
AA5	0.710	2.0	2210	BA5	0.626	2.0	2310
CA0	0.531	0.0	3300	DA0	0.444	0.0	4210
CA1	0.531	0.4	3660	DA1	0.444	0.4	4270
CA2	0.531	0.8	3800	DA2	0.444	0.8	3930
CA3	0.531	1.2	3025	DA3	0.444	1.2	3300
CA4	0.531	1.6	3040	DA4	0.444	1.6	3150
CA5	0.531	2.0	2390	DA5	0.444	2.0	2460



Comparison Curve - Compressive Strength vs.
% Calcium Chloride by Weight of Cement at 28 days.
Compressive Strength - PSI.
5000
4000
3000
2000
1000
0
#4
#3
#2
#1
0
0.4
0.8
1.2
1.6
2.0
% Calcium Chloride by Weight of Cement
Key: #1 = Mix AA -
#2 = Mix BA -
#3 = Mix CA -
#4 = Mix DA -
w/c Ratio - AA - 0.710
- BA - 0.626
- CA - 0.531
- DA - 0.444
G.F.H.

Figure 13.

Table 8.

14-Day Sonic Test Results

Mix No.	W/C Ratio by weight	A Weight of beam in pounds	Density in pounds per cubic foot	B Fundamental Freq. in kilo-cycles/sec	E in psi. x 10^6
A	0.710	21.60	148	1.840	3.18
B	0.626	22.35	153	1.950	3.70
C	0.531	23.00	157	1.950	3.80
D	0.444	23.25	159	1.955	3.87
AAO	0.710	19.80	136	1.545	2.08
AA1	0.710	21.00	144	1.775	2.89
AA2	0.710	21.30	146	1.745	2.83
AA3	0.710	21.20	145	1.753	2.84
AA4	0.710	21.40	147	1.780	2.96
AA5	0.710	21.30	146	1.760	2.88
BAO	0.626	20.70	142	1.690	2.58
BA1	0.626	21.40	147	1.850	3.20
BA2	0.626	20.80	142	1.740	2.74
BA3	0.626	21.60	148	1.800	3.05

A - Average weight of three beams.
B - Average frequency for three beams.

Table 8.
(con't.)

14-Day Sonic Test Results

Mix No.	W/C Ratio by weight	A Weight of beam in pounds	Density in pounds per cubic foot	B Fundamental freq. in kilocycles/sec	E in psi. x 10^6
BA4	0.626	20.00	137	1.600	2.23
BA5	0.626	20.20	138	1.580	2.19
CA0	0.531	21.00	144	1.660	2.52
CA1	0.531	20.90	143	1.700	2.62
CA2	0.531	20.20	138	1.760	2.72
CA3	0.531	22.00	150	1.790	3.06
CA4	0.531	20.30	139	1.640	2.38
CA5	0.531	20.60	141	1.700	2.59
DA0	0.444	20.60	141	1.700	2.59
DA1	0.444	21.60	148	1.890	3.36
DA2	0.444	21.90	150	1.830	3.20
DA3	0.444	22.20	152	1.790	3.10
DA4	0.444	21.20	145	1.760	2.86
DA5	0.444	20.70	142	1.740	2.75

A - Average weight of three beams.
B - Average frequency of three beams.

Table 9.

28-Day Sonic Test Results

Mix No.	W/C Ratio by weight	A Weight of beam in pounds	Density in pounds per cubic foot	B Fundamental Freq. in kilocycles/sec	E in psi. x 10^6
A	0.710	21.60	148	1.880	3.33
B	0.626	22.35	153	1.975	3.80
C	0.531	23.00	157	1.982	3.91
D	0.444	23.25	159	1.975	3.95
AA0	0.710	19.80	136	1.600	2.22
AA1	0.710	21.00	144	1.810	3.00
AA2	0.710	21.30	146	1.760	2.88
AA3	0.710	21.20	145	1.790	2.95
AA4	0.710	21.40	147	1.815	3.08
AA5	0.710	21.30	146	1.825	3.08
BA0	0.626	20.70	142	1.750	2.76
BA1	0.626	21.40	147	1.885	3.32
BA2	0.626	20.80	142	1.775	2.84
BA3	0.626	21.60	148	1.810	3.08

A - Average weight of three beams.
B - Average frequency of three beams.

Table 9.
(con't.)

28-Day Sonic Test Results

Mix No.	W/C Ratio by weight	A Weight of beam in pounds	Density in pounds per cubic foot	B Fundamental Freq. in kilocycles/sec	E in psi. x 10^6
BA4	0.626	20.00	137	1.650	2.38
BA5	0.626	20.20	138	1.620	2.30
CA0	0.531	21.00	144	1.710	2.68
CA1	0.531	20.90	143	1.730	2.72
CA2	0.531	20.20	138	1.780	2.78
CA3	0.531	22.00	150	1.840	3.23
CA4	0.531	20.30	139	1.700	2.56
CA5	0.531	20.60	141	1.760	2.78
DA0	0.444	20.60	141	1.750	2.76
DA1	0.444	21.60	148	1.920	3.47
DA2	0.444	21.90	150	1.860	3.30
DA3	0.444	22.20	152	1.830	3.24
DA4	0.444	21.20	145	1.780	2.93
DA5	0.444	20.70	142	1.765	2.81

A - Average weight of three beams.
B - Average frequency of three beams.

PART FIVE

This thesis problem attempts to answer two questions: (a) how will the addition of calcium chloride affect the compressive strength of a concrete containing an air-entraining admixture and (b) is there a relationship between the dynamic modulus of elasticity and the compressive strength?

The test data and the accompanying curves in Part Four answered the first question. The addition of calcium chloride did affect the compressive strength. This is discussed fully in the conclusions and summary.

An attempt is made in this portion of the discussion to find a relationship between the dynamic modulus of elasticity and the compressive strength. Before arriving at the curve contained herein, Figure 14, a careful study was made of Tables 10 and 11. Several graphs were plotted in which the variables were separated, that is, graphs of compressive strength versus dynamic modulus for the various percent calcium chloride additions. Not enough points were available to establish a trend. Therefore, a mass diagram was plotted regardless of the variables. If there is a definite relationship between compressive strength and dynamic modulus, it should make no difference what additions were made to the concrete.

Figure 14 represents this mass diagram. The points are the average of three cylinders and three sonic beams. The graph contains test results at fourteen and twenty-eight days only and 56 points are plotted. The points were plotted with regard to only one variable - the water-cement ratio by weight. It was noticed that there appeared to be some trend for the four W/C ratios by weight. Therefore, the mass diagram was broken into four component graphs having W/C ratios by weight of 0.710, 0.626, 0.531 and 0.444. Whether the trend is a straight line or a curved line is a question to be answered only by further research.

Table 10.

Summary of Compressive Strength of Air-Entrained Concrete and Modulus of Elasticity at 14 Days

Mix No.	W/c Ratio by Wt.	Average Compressive Strength, psi.	E, psi. x 10^6	Mix No.	W/C Ratio by Wt.	Average Compressive Strength, psi.	E, psi. x 10^6
A	0.710	2350	3.18	BA4	0.626	2210	2.23
B	0.626	2820	3.70	BA5	0.626	2300	2.19
C	0.531	3545	3.80	CA0	0.531	2915	2.52
D	0.444	4375	3.87	CA1	0.531	3505	2.62
AA0	0.710	2040	2.08	CA2	0.531	3590	2.72
AA1	0.710	2875	2.89	CA3	0.531	2960	3.06
AA2	0.710	2995	2.83	CA4	0.531	2835	2.38
AA3	0.710	2340	2.84	CA5	0.531	2255	2.59
AA4	0.710	2130	2.96	DA0	0.444	3680	2.59
AA5	0.710	2150	2.88	DA1	0.444	3850	3.36
BA0	0.626	2355	2.58	DA2	0.444	3725	3.20
BA1	0.626	3260	3.20	DA3	0.444	3230	2.10
BA2	0.626	3235	2.74	DA4	0.444	3005	2.86
BA3	0.626	2780	3.05	DA5	0.444	2315	2.75

Table 11.

Summary of Compressive Strength of
Air-Entrained Concrete and Modulus of Elasticity at 28 Days

Mix No.	W/C Ratio by Wt.	Average Compressive Strength, psi.	E, psi. x 10^6	Mix No.	W/C Ratio by Wt.	Average Compressive Strength, psi.	E, psi. x 10^6
A	0.710	2725	3.33	BA4	0.626	2440	2.38
B	0.626	3270	3.80	BA5	0.626	2310	2.30
C	0.531	4000	3.91	CA0	0.531	3300	2.68
D	0.444	4980	3.95	CA1	0.531	3660	2.72
AA0	0.710	2260	2.22	CA2	0.531	3800	2.78
AA1	0.710	2920	3.00	CA3	0.531	3025	3.23
AA2	0.710	3130	2.88	CA4	0.531	3040	2.56
AA3	0.710	2390	2.95	CA5	0.531	2390	2.78
AA4	0.710	2250	3.08	DA0	0.444	4210	2.76
AA5	0.710	2210	3.08	DA1	0.444	4270	3.47
BA0	0.626	2485	2.76	DA2	0.444	3930	3.30
BA1	0.626	3300	3.32	DA3	0.444	3300	3.24
BA2	0.626	3580	2.84	DA4	0.444	3150	2.93
BA3	0.626	2825	3.08	DA5	0.444	2460	2.81

Curve of Compressive Strength vs. Dynamic Modulus of Elasticity.

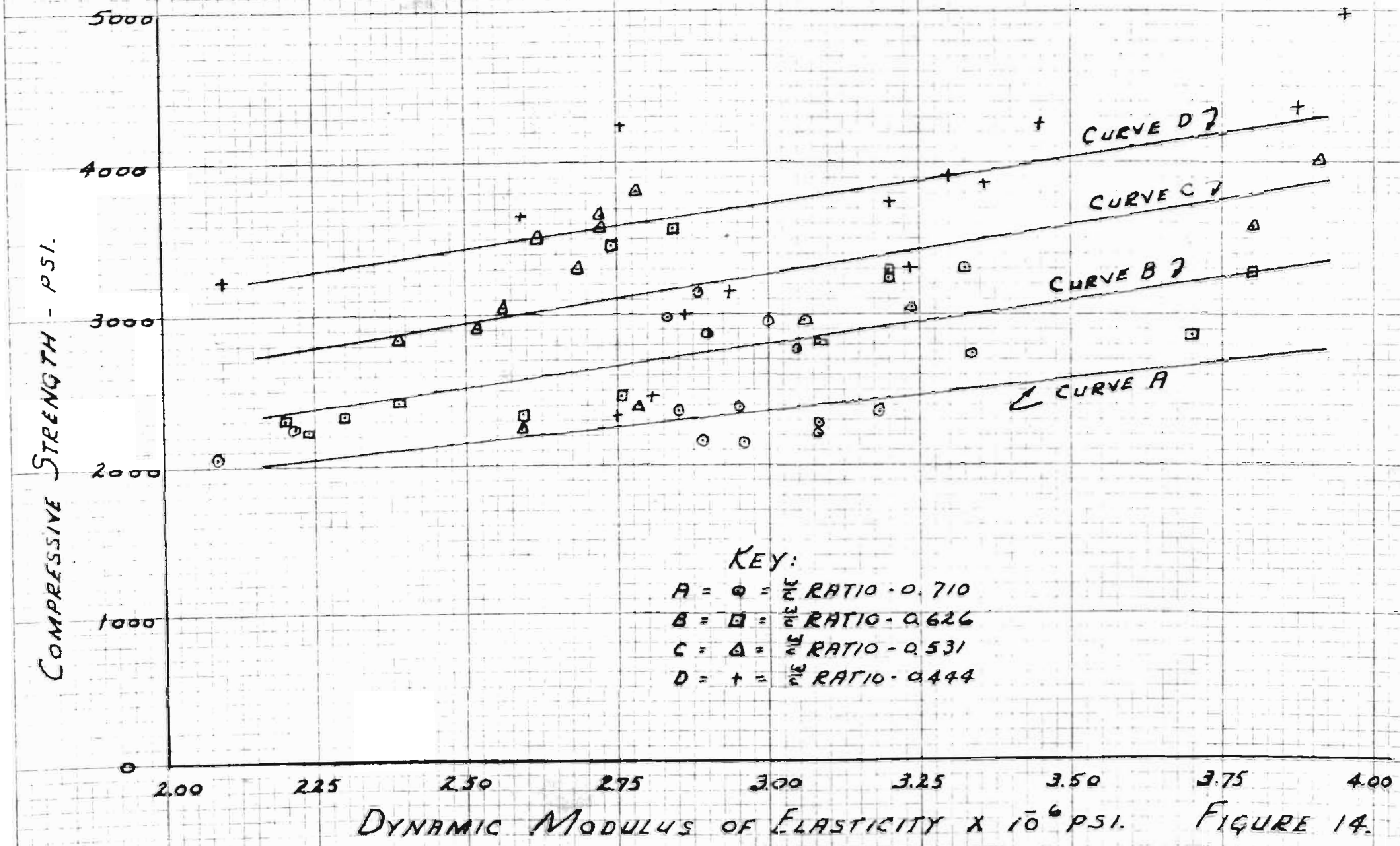


Figure 14.

G.F.H.

CONCLUSIONS AND SUMMARY

Twenty-eight batches of concrete were mixed, each batch consisting of nine standard compression cylinders and three sonic beams. The cylinders were tested at seven, fourteen and twenty-eight days at the rate of three cylinders per compression test. The sonic beams were tested at fourteen and twenty-eight days only. A seven day sonic test could not be run due to a breakdown of the sonic testing apparatus. Therefore, all conclusions noted below are based on only twenty-eight batches.

As was expected, the concrete containing an air-entraining admixture and 0% calcium chloride lost compressive strength when compared with the concrete containing Normal Portland Cement. The loss was approximately 16% or 3.6% per one percent air-entrained by absolute volume. Several features were noted in the concrete containing air-entrained cement. The latter was easier to place, richer looking, worked exceptionally well and weighed less per cubic foot than a concrete containing Normal Portland Cement.

At seven days - the concrete containing air-entrained cement gained strength up to 0.8% calcium chloride by weight of cement for W/C ratios of 0.710, 0.626 and 0.531. For a W/C ratio of 0.444, the strength increased up to additions of 0.4% calcium chloride. From 0.4% to 1.2% calcium chloride, the compressive strength remained higher than with 0% calcium chloride and above 1.2% any further addition proved critical. Therefore, for all W/C ratios, calcium chloride can be added up to 1.2% by weight of cement and an increase in compressive strength is obtained. Above 1.2%, the strength remains nearly constant for W/C ratios of 0.710 and 0.626. Below a W/C ratio of 0.626, any further addition is detrimental to the compressive strength. The same trend is noted at fourteen days but the percentage increase in compressive strengths are not as great.

The test results and graph at twenty-eight days show that additions of calcium chloride below 1.2% for W/C ratios of 0.710 and 0.626 give an increase in compressive strength. Above this point any further addition has very little effect. For a W/C ratio of 0.531, additions up to 0.8% prove valuable; any further addition is detrimental. Adding calcium chloride up to 0.4%, for a W/C ratio of 0.444, gives a slight increase in compressive strength. Additions above this value prove disasterous.

Therefore, the above can be summarized as follows: at twenty-eight days - the optimum amount of calcium chloride is 0.8% by weight of cement. Increases in compressive strength are noted up to this point for W/C ratios of 0.710, 0.626 and 0.531. Any further amounts will do very little harm for the first two W/C ratios. For the third, W/C = 0.531, the compressive strength is decreased markedly. Addition of calcium chloride above 0.4% by weight of cement proved detrimental to the compressive strength at a W/C ratio of 0.444.

Several things were noted in the concrete containing calcium chlorides (a) the initial set occurred in approximately one hour - over two hours faster than concrete containing either Normal Portland Cement or air-entrained cement but no calcium chloride, (b) the mixes were workable at high W/C ratios, (c) the density of the mix decreased and (d) the heat of hydration was released sooner than from a concrete containing no calcium chloride.

Figure 14, a curve of compressive strength versus dynamic modulus of elasticity, contains four separate curves, based upon the four water-cement ratios used. If a straight line is assumed, as was done in this problem, curve A, W/C =0.710, shows that the dynamic modulus of elasticity is approximately 2100 times the compressive strength, and curves B, C and D, W/C = 0.626, W/C = 0.531 and W/C = 0.444, respectively, show that the modulus is 1800 times the compressive strength.

Summarizing, it can be said, within the limits of this thesis problem, the dynamic modulus of elasticity is approximately 1800 times the compressive strength.

More research must be done on the subject of compressive strength versus dynamic modulus of elasticity before definitely saying the above conclusion is correct.

BIBLIOGRAPHY

1. Books:

Bernhard, R. K. Mechanical Vibrations. N. Y., Pitman, 1943. pp. 21-28.

Scripture, E. W. Jr. Lectures and Experiments on Air-Entrainment and Cement Dispersion. Cleveland, Ohio, Master Builders Company, 1947. pp. 1-11.

2. Periodicals:

Gonnerman, H. F. Tests of Concrete Containing Air-Entraining Portland Cement. Portland Cement Association, Bulletin 13, 31 p. (1947)

Klieger, P. Effects of Entrained Air on Concrete Made with So-Called "Sand-Gravel" Aggregates. Portland Cement Association, Bulletin 24, 14 p. (1948)

Menzel, C. A. Procedures of Determining the Air-Content of Freshly Mixed Concrete. Portland Cement Association, Bulletin 19, 32 p. (1947)

Research Staff. Design and Control of Concrete Mixtures. Portland Cement Association Research Laboratory, 9th Edition, 70 p. (1949)

Sales Division. The Effects of Calcium Chloride on Portland Cement. N. Y., Solvay Sales Division, 37 p. (1949)

3. Publications of Learned Societies:

Preece, E. F. Determination and Use of the Dynamic Modulus of Elasticity of Concrete. Highway Research Board. Proceedings. Vol. 28, pp. 233-237 (1948)

Powers, T. C. Measuring Young's Modulus of Elasticity by Means of Sonic Vibrations. A. S. T. M., Vol. 38, Part II, pp. 460-469 (1938)

4. U. S. Government Publications:

Blanks, F. R. Technology of Cement and Concrete. U. S. Department of the Interior, Bureau of Reclamation. 1949. 17 p. From a Series of Lectures at Harvard University Graduate School of Engineering.

Engineering and Geological Control and Research Division. Information and Instructions for Use of Air-Entraining Admixtures in Concrete. Report #C-307. Denver, Colorado, U. S. Department of the Interior, Bureau of Reclamation. 1946. pp. 1-9

Engineering and Geological Control and Research Division. Entrained Air - A Factor in the Design of Concrete Mixes. Report #C-310, Denver, Colorado, U. S. Department of the Interior, Bureau of Reclamation. 1946. pp. 1-7.

5. Unpublished Material:

Lerch, William. The History and Basic Principles of Air-Entrained Concrete. Research Section, Portland Cement Association, Chicago, Illinois.

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