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MORE DURABLE CONCRETE BY AIR ENTRAINMENT

by

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INTRODUCTION

The purposeful incorporation of air in concrete as a means of improving its physical properties has long since passed through the experimental stage, and the principle of air entrainment is now generally accepted and widely used in concrete practice. Considerable information on air-entraining concrete has been written. This material is widely scattered through engineering periodicals and proceedings of technical societies, which makes it most difficult for the average engineer or layman to acquire a general knowledge of the subject without considerable time-consuming reference work.

This paper has been written to meet the need for a concise presentation of approved practice in the manufacture and handling of air-entraining concrete and of the principles involved. It is the hope of the author that the information contained herein will be of general interest to the layman and of value and assistance to engineers who have not had the opportunity to become fully informed on this new phase of concrete practice. Those who seek greater detail on the subject will find the attached bibliography of material a help.

The work discusses the principles of air entrainment in relation to materials, mix design and control of the manufactured product. Important factors associated with the handling and placing of air-entraining concrete produced by conventional or ready-mixed methods necessary for successful results are included. Results and experiences from many studies and field installations are also presented.

AIR ENTRAINMENT IN CONCRETE

The purposeful entrainment of air or gas in different types of materials for beneficial resons is an old art. Common examples are the leavening of flour products through the generation of carbon dioxide by baking powder admixtures and the manufacture of ice cream by means of mechanical agitation. The entrainment of air in concrete for the purpose of creating more durable structures was discovered only a little over a decade ago through the concerted action of many research agencies. At that time engineers were vitally concerned with the problem of concrete deterioration, especially in respect to scaling and subsequent disintegration of concrete pavements.

The Principle of Air Entrainment

The principle of air entrainment consists of introducing into the concrete mixture a definite quantity of air in excess of that normally found in standard concrete. However, unlike the air in ordinary concrete, this additional entrained air must exist in the form of minute, disconnected bubbles, uniformly distributed throughout the concrete mass. Concrete in which air has been entrained in this manner is commonly termed Air-Entraining Concrete.

Effect of Entrained Air on Properties of Concrete: The physical properties of both the plastic and hardened concrete are materially altered by the presence of this entrained air because of the condition in which it exists. For example, freshly mixed concrete is more plastic, possesses better workability, and can be handled with less segregation than ordinary concrete. Furthermore, the appearance of surface water or water gain in the concrete is practically eliminated, thus greatly reducing the time interval between mixing and finishing operations. The hardened concrete possesses excellent durability with respect to alternate freezing and thawing and remarkable resistance to scaling caused by the chloride salts used in ice control. Air-entraining concrete is also highly impervious to moisture. Concrete strengths are decreased slightly in proportion to the increase in air content. Setting properties or early strength gain are not affected by normal air contents at pouring temperatures above freezing (10).

Behavior of the Entrained Air: Laboratory studies indicate that the effect of the entrained air is a function of the number, size and manner of distribution of the air bubbles rather than on total volume of air alone. Through microscopic analysis it is indicated that the small air bubbles which apparently cling to the sand particles act as flexible, inert fine aggregate which tends to lubricate the concrete mass, thus accounting for the marked improvement in plasticity and workability of air-entraining concrete over that of standard portland cement concrete. The chemical effect of the air-entraining material itself has been proven to be inconsequential.

In respect to reduction in bleeding and water gain, it is believed that the presence of the numerous well-dispersed air bubbles tends to immobilize the mixing water through adsorption on the air bubbles, and by interrupting the continuity of water channels or capillaries which have a tendency to form through displacement or readjustment of the ingredients in the fresh concrete during placement (10).

Furthermore, the contribution to durability is considered due to the possible lower water-cement ratio, increased imperviousness of the concrete because of the closing of the water channels, and to the action of air voids in providing reservoirs for the relief of pressure created by thermal volume changes and expansion or hydraulic pressures of water when turning to ice (10) (17).

Methods of Entraining Air in Concrete

At the present time air is entrained in concrete in definite amounts by means of organic compounds generally known as Air-Entraining Admixtures. These materials lower the surface tension of the mixing water thus causing it to foam easily and consequently entrain air under the mechanical agitation of the mixer.

Air-Entraining Admixtures: Air-entraining admixtures which have been successfully employed to date are chiefly those which are soapy in nature and whose inherent foaming action is independent of any subsequent chemical action with the cement. Examples of this type are neutralized Vinsol resin (NVX) and Darex.

There are other so-called air-entraining materials which, in order to cause foaming, must be converted to water-soluble soaps through their reaction with the hydroxides of the alkali metals present in the cement. In this case the actual amount of air-entraining material produced will depend not only on the amounts of these substances added, but also on the amount and availability of the alkali oxides present in the cement. Examples of this type are rosins, flake Vinsol resin, and the various animal and vegetable fats and oils. These materials do not give consistent and uniform results, the amount of air entrained being unduly influenced by mixing time; therefore, their use is not encouraged.

There are many other materials available which have the property of entraining air in concrete and may prove satisfactory if properly used. However, these materials should not be used unless it can be demonstrated through research and experience that they entrain the specified amount of air without impairing the quality of the concrete. Either the flake or neutralized form of Vinsol resin and Darex have been approved for use by the American Society for Testing Materials in the manufacture of air-entraining concrete.

Flake Vinsol resin is a product of the Hercules Powder Company of Wilmington, Delaware, obtained by selective extraction from pine wood and is composed chiefly of a mixture of various resin acids which combine with alkali to form soaps. So-called neutralized Vinsol resin (sodium resinate) is made by treating the resin with commercial sodium hydroxide (caustic soda). Darex AEA is a proprietary material manufactured by the Dewey and Almy Chemical Company of Cambridge, Massachusetts. It is described as a triethanolamine salt of a sulphonated hydrocarbon. Instructions for making a caustic soda solution of Vinsol resin for addition at the mixer, and for the use of Darex, may be found in Highway Research Board Bulletin No. 13 titled, "Use of Air-Entraining Concrete in Pavements and Bridges" (14).

Any of the water soluble air-entraining agents mentioned above may be added to the batch at the mixer or ground with portland cement at the mill to produce air-entraining concrete. The amounts of the materials in solution to be added will vary somewhat with job conditions, brand of cement, the amount of entrained air desired, and the type of air-entraining material used. So-called neutralized Vinsol resin and Darex are water soluble soaps which can be used as an admixture at the mixer as well as in the manufacture of Air-Entraining Cement.

Air-Entraining Portland Cement: Standard portland cement to which air entraining materials have been added at the mill is now procurable in two types designated as Types IA and IIA and is covered by American Society for Testing Materials Specification, Designation C 175-46T. The amount of air entraining material added at the mill is based on the quantity of air which the cement will entrain in a mortar under a definite set of conditions. The air content of the mortar which is prepared and tested in accordance with A.S.T.M. method C 185-47T must be 18 per cent by volume with a tolerance of plus or minus 3 per cent.

The mortar test is developed on the thesis that there would exist a definite relationship between the air in the mortar and the air in the concrete in the order of approximately 3 to 1. Experience indicates that no such clear relationship exists. Such factors as type of aggregate, amount of cement, consistency, water cement ratio, etc., affect the characteristics of the concrete to the extent that the test is not reliable. However, it does afford a control over the amounts of air-entraining material to be used.

Compound Air-Entraining Admixtures: There are on the market numerous compound admixtures containing, in addition to a recognized air-entraining material, various types of accelerators and deflocculators which make possible the required entrainment of air with an accompanying increase in strength and bonding properties. The benefit to concrete quality by the use of such compound admixtures is well established, but the competitive nature and adverse effect of minor quantities of certain materials require the necessity of adequate laboratory performance tests and field control. At the present time, admixtures of this type are added to the concrete batch at the mixer [10].

Natural Cements With Air-Entraining Materials: The blending of air-entraining natural cements with standard portland cement will produce a satisfactory air-entraining concrete. The blending is usually performed on the basis of one part natural cement to five parts portland cement. Air-entraining natural cements can be purchased under A.S.T.M. Specification C 10-37 with the added requirement that they meet the mortar test for air content stated above for air-entraining portland cement. In making the mortar test a blend of natural and standard cements in the proportions to be used in the work must be employed.

Air-Entraining Cements Versus Admixtures

Each method has its advantages and disadvantages. The question of choice between the use of an air-entraining cement or an air-entraining admixture at the mixer will depend almost entirely on how the engineer wishes to control the work. In either case proper control methods must be provided to insure a satisfactory end product at the mixer.

Air-entraining cements contain a fixed amount of admixture which cannot be changed to compensate for excess or deficiencies in air content of the concrete. However, variation in air content can be controlled within certain limits by adjustments in one or more of the variables which influence air content. Separate additions of air-entraining admixtures may be made successfully at the mixer to overcome deficiencies in air content, and excessive amounts of air may be reduced by diluting the air-entraining cement with standard portland cement.

When an air-entraining admixture is added at the mixer, precise control of air content can be exercised by simply changing the amount of air-entraining material once the mix has been established.

Air-entraining admixtures may be added at the mixer by means of a workman with the hazard of mistakes due to the human element or by the installation of an automatic dispensing device of which there are now several on the market. In either case, a water solution containing the correct amount of air-entraining admixture must be prepared in advance in batches of sufficient size to last for at least a day's pour. In cold weather the prepared solution must be protected against freezing. Also measuring containers or dispensing equipment must be kept clean at all times, since air-entraining materials have a tendency to accumulate on the equipment as used.

Optimum Air Content

It is generally accepted that satisfactory scale resistance and durability can be obtained without serious loss in flexural or compressive strength if the total air content of the concrete is maintained between three and six per cent by volume computed on the basis of the theoretical weight of air-free concrete of the same proportions. Since the air content of ordinary concrete is normally around 1 to 1.5 per cent, the increase in void content brought about by the introduced air would correspond to a drop in unit weight of the concrete of from about three to six pounds per cubic foot.

FACTORS AFFECTING AIR CONTENT

The introduction of added air into a concrete mixture necessitates changes in mix design and careful control of production if optimum results are to be achieved. Almost every element in concrete making, whether of materials or processes, must now be examined in the light of its effects on air content, and conversely, the effect of the air content on processing of the mix and the properties of the hardened concrete. For instance, in a given mix, air-entrainment will be influenced by the water content, the effect being more pronounced in lean mixes than in rich ones. The amount, character, and grading of both fine and coarse aggregate, the individual properties and amount of cement used, mixing time, method of mixing concrete, concrete temperature, and the amount and type of air-entraining admixture all affect to varying degrees the quantity of air taken into the mix. In addition, there are encountered during the process of manufacturing air-entraining concrete in the field numerous factors which influence the quality and air content of the finished product. Each project becomes an individual problem in concrete mix design and control which requires much more supervision than is necessary when working with ordinary concrete in order to produce a uniform concrete mixture meeting specified design requirements.

Consistency of the Mix

Wet mixes entrain more air than dry, stiff mixes. Therefore, it is important that the consistency of air entrained concrete be controlled within reasonable limits at all times.

Type and Grading of Aggregate

Concrete made with crushed aggregate, such as stone and slag, will entrain about 1 per cent more air than comparable concrete made with natural aggregate. This is probably due to the fact that more sand is required with crushed aggregates.

The grading of the aggregates, especially the fine aggregate, has a marked effect on the amount of air entrained. Work by Walker [11], Kennedy [5] and from departmental studies indicates that the amount of No. 50 to No. 30 sieve size has the greatest influence on air content. See

Figure 1. Also there is indicated that particles passing the 100 mesh sieve may serve as air-entraining depressant. However, at present no definite facts to this effect have been established.

Effect of Mixing Time on Air Content

The effect of mixing time on air content is unpredictable. Evidence (10) (11) supports the fact that with the newer air-entraining admixtures the air content rises slightly during the first few minutes of mixing time (3 to 12 minutes) and then decreases with additional mixing. However, after adequate mixing of the concrete the change in air content is not critical. The total amount of air entrained is also a function of the brand of cement used. See Figure 2.

Effect of Temperature on Air Content

The temperature of the concrete at time of mixing has a significant effect on the amount of air entrained. The amount of air entrained decreases as the temperature of the concrete increases. A relationship of air content to temperature by Walker and Bloem [11] is presented in Figure 3.

Effect of Ratio of Sodium Hydroxide to Vinsol Resin on Air Content

Studies have been made by Walker and Bloem [11] to determine what effect certain variations in proportions of sodium hydroxide to Vinsol resin would have on the air content and compressive strength of the concrete. Results from their work indicate that air content is increased as the weight of the sodium hydroxide approaches the weight of the Vinsol resin. Beyond that point the material becomes less active, due perhaps to a salting-out action caused by the excessive amount of sodium hydroxide. This fact is clearly illustrated in Figure 4.

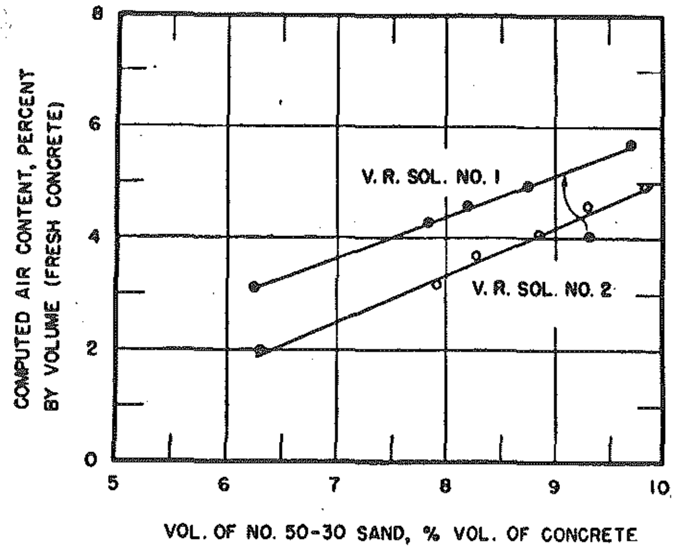


FIGURE 1. EFFECT OF NO. 50 TO NO. 30 SAND PARTICLES ON AIR CONTENT (WALKER-BLOEM).

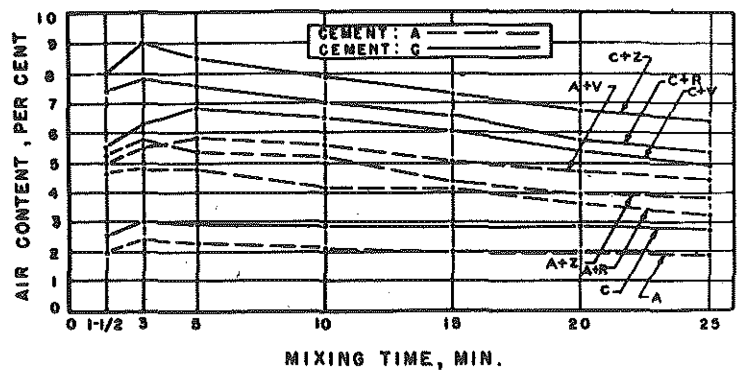


FIGURE 2. RELATION OF MIXING TIME TO AIR CONTENT OF CONCRETE MADE WITH AND WITHOUT ADMIXTURES (WUERPEL) (R-V-Z, TYPE ADMIXTURE).

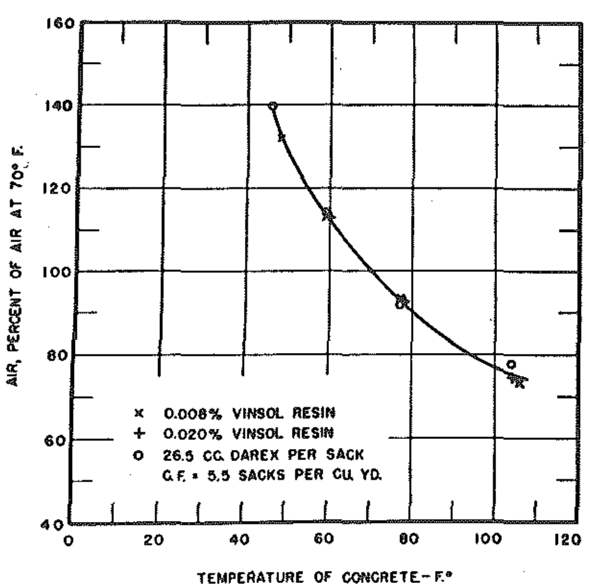


FIGURE 3. EFFECT OF CONCRETE TEMPERATURE ON AIR CONTENT. (WALKER-BLOEM).

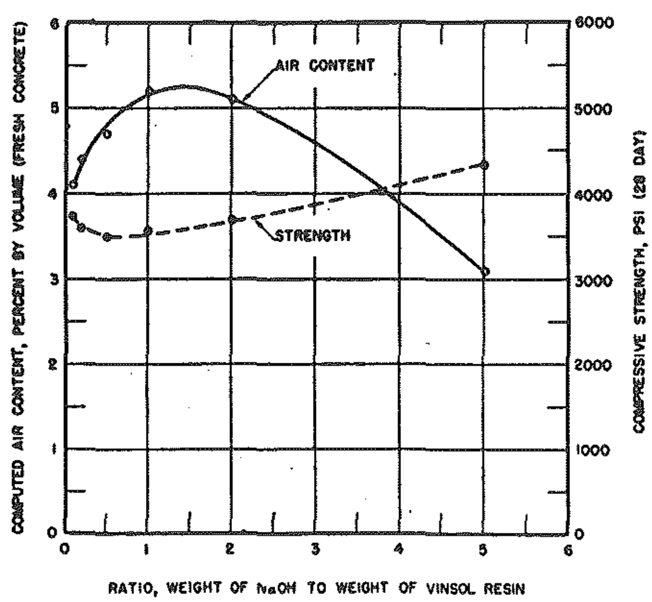


FIGURE 4. EFFECT OF SODIUM HYDROXIDE RATIO ON AIR CONTENT (WALKER-BLOEM).

Effect of Vibration on Air Content

There is a slight reduction in air content as the result of vibration. It is believed that this is due in part to upward migration of the large voids and partial compression of the air content under fluid pressure.

Laboratory studies by Wuerpel (10) indicate that the apparent reduction in air content by vibration is not sufficient to be reflected in the durability properties of the concrete.

Effect of Depth of Concrete on Air Content

Laboratory experiments by Walker and Bloem (11) indicate that in high sections of concrete containing entrained air, the air is partially compressed due to the superimposed concrete and that there is no apparent movement of the air from the bottom to the top of the section.

DESIGN OF AIR-ENTRAINING CONCRETE

In the design of air-entraining concrete, it is customary only to make certain changes or adjustments in the ordinary concrete mix necessary to insure the specified air content and other desirable properties of the concrete with the least sacrifice in strength. Methods of adjusting proportions of the mix vary among different users. Features common to all, however, are reduction in water content and sand content.

Effect on Mixing Water Required

The entrained air in a concrete mixture materially reduces the amount of water required to give the equivalent slump of a concrete mixture containing no purposeful entrained air. This reduction in required mixing water effects a reduction in the water-cement ratio which in turn is no doubt responsible for the increase in the strength, impermeability and durability of the mortar and reduction in bleeding. Within limits the required mixing water can be reduced as the air content is increased. According to Cordon (11) the water content of an average concrete mix may be reduced approximately 8.0 pounds per cubic yard with rounded aggregate and 8 pounds per cubic yard with angular aggregate for each per cent of air entrained. In normal practice with air-entraining concrete the water content is reduced from 1/2 to 1 gallon per sack of cement.

Walker and Bloem (11) have developed information, as shown in Figure 5, concerning the reduction of mixing water for different cement contents.

Effect of Sand Content on Air Entrainment

In general, the sand content, by weight of total aggregate, may be reduced by approximately 1 per cent for each per cent increase in entrained air up to at least 8 per cent without any appreciable change in slump or workability (11). See Figure 6.

Effect of Air Entrainment on Yield

It has been found by experience that the increased yield resulting from the entrained air can be compensated for approximately by reducing the sand content of the batch by an amount equal to 3 to 4 per cent of the combined weight of the fine and coarse aggregate, or by 1 to 1.3 times the amount of air entrained. It is frequently necessary to make at least part of the reduction in the coarse aggregate when the concrete mixture has a tendency to be harsh.

The Michigan State Highway Department has used the Mortar Voids method for the design of concrete mixes for about twenty years, and a modification of this method is used for air-entraining concrete. The relative water content, an empirical factor used in the design, is reduced from 1.215 to 1.15

to allow for the decrease in water requirement for this type of mix, and the yield and void content are adjusted by reducing the sand content so that the cement factor is maintained at 5.5 sacks per cubic yard of concrete and the total void content kept within specified limits. All of these original adjustments are made at the laboratory and are incorporated in the proportioning chart prepared for the specific materials to be used on a given project. The theoretical weight per cubic foot of air-free concrete is also given on the chart to facilitate computation of air content in the field. Further adjustments of mix proportions may sometimes be necessary after construction has begun, but such adjustments should involve only minor changes in the design quantities.

The air content of a given concrete mix can be determined only on the basis of actual trial batches with all materials to be used. Major adjustments of these trial batches may require control of other factors than sand content alone for optimum results. Such tests may reveal a deficient or excessive air content which would involve too great an adjustment in sand content, and would therefore compel a change of air-entraining cement or the amount of air-entraining admixture.

When air-entraining admixtures are added at the mixer it is possible to adjust the amount of air-entraining material for the particular conditions under which it is working at the time, or may be varied from time to time during the progress of the work as changing conditions require. This can be done to maintain the desired air content without changing the basic conditions of the mixture. In the case of air-entraining cements it is necessary at times to add additional quantities of air-entraining materials directly to the batch in order to raise the air content to the desired quantity. This can be accomplished by adding small quantities of neutralized Vinsol resin, or other water soluble air-entraining admixtures, in solution. Such conditions may be brought about by aggregate characteristics or a deficiency in air-entraining material in the cement due to oxidation during the grinding process, storing, and handling at the cement plant.

It is a general policy at the present time to design an air-entraining concrete mixture by retailoring the plain concrete mix to fit the new conditions. It is believed, however, that in time the entrained air will be considered as a separate ingredient and a new design procedure will be developed accordingly to take into consideration all of the ingredients; cement, air, water, sand and coarse aggregate.

In the design of air-entraining mixtures the following works should be consulted: "Recommended Practice for Design of Concrete Mixes," (A.C.I. Journal, June 1945), and "Use of Air-Entraining Concrete in Pavements and Bridges," (Current Road Problems Bulletin No. 13, Highway Research Board, May 1946).

METHODS OF MEASURING AIR CONTENT IN PLASTIC AND HARDENED CONCRETE

There are three basic methods for determining the air content of the plastic concrete. The first is known as the unit weight or gravimetric method; the second, the displacement method; and the third, the pressure method. Air content of the hardened concrete may be successfully determined by the camera lucida method.

Gravimetric Method

In this method the air content of concrete is determined by comparing the weight per cubic foot of the plastic mixture with the theoretical air-free unit weight in accordance with A.S.T.M. Method C 138-44. The weight per unit volume of the concrete must be known as well as the quantities and specific gravities of the ingredients. The results of this method depend upon the accuracy with which the required data are determined. For example, lack of precise knowledge of specific gravities and moisture contents of the batch lead to relatively large errors in the results.

Volumetric Method

This method is described in A.S.T.M. Method C 173 and permits direct determination of air content. It is necessary to determine the weight of the concrete per unit of volume and on the displacement in water of a weighed sample of the concrete after elimination of the entrained air from the sample while immersed in water. The volumetric method is also subject to common errors in measurements.

Pressure Method

In this method air pressure is applied to a known volume of concrete and the reduction in volume measured. Since the air is the only compressible ingredient in the concrete, the amount of entrained air is readily calculated from a knowledge of the pressure applied and the reduction in volume.

A special magnesium alloy apparatus has been developed to determine the air content by the pressure method. The apparatus is shown in Figure 7. The concrete is placed in the lower part in three layers in the same manner required for the standard yield test (A.S.T.M. Designation C 138-44). The top section is fastened to the base and water introduced until the level is above the zero mark on the glass gage, then adjusted by bleeding to exactly the zero mark. Fifteen pounds air pressure is applied by means of a bicycle pump. When pressure is steady, the water level is read on the gage. This value is the uncorrected reading. This reading must be corrected by running blank determinations on both sand and coarse aggregate to correct for porosity of aggregate grains. The sum of these two values must be subtracted from the first reading to obtain correct gage glass reading.

The percentage of air in concrete is equal to

$$\frac{\text{Volume of air}}{\text{Volume of concrete}} \times 100$$

The pressure method of determining air content is fully described and illustrated by the originator of the idea in the June 1946 issue of the A.C.I. Journal (11).

Camera Lucida Method for Determining Air Content of Hardened Concrete

The method involves the use of a camera lucida in conjunction with a suitable microscope. A camera lucida is a mirror (or prismatic) attachment that permits the simultaneous viewing of both the specimen under the microscope and an enlarged area on which the actual microscopic observations may be accurately traced. In this manner an enlarged tracing is obtained of the air voids and aggregate particles in the suitably prepared surface of the concrete specimen. The method reveals the characteristics of the air voids in the hardened concrete including their size, shape, and distribution and provides a check on any previous methods. The work of Verbeck (18) demonstrates that the results obtained in the determination of the air content of hardened concrete by this method are in agreement with those obtained by other methods applied to the plastic concrete. Typical air voids observed by this method are shown in Figure 8.

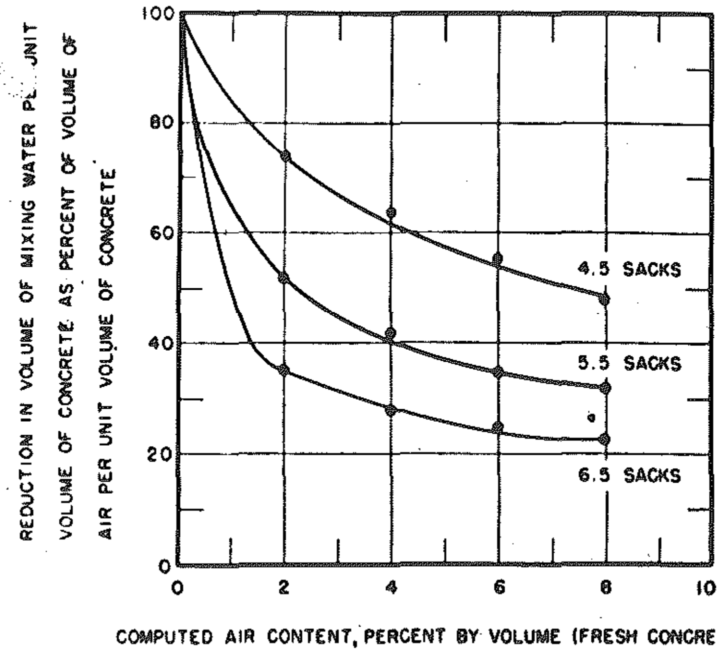


FIGURE 5. EFFECT OF AIR AND CEMENT CONTENT ON REDUCTION IN MIXING WATER (WALKER-BLOEM).

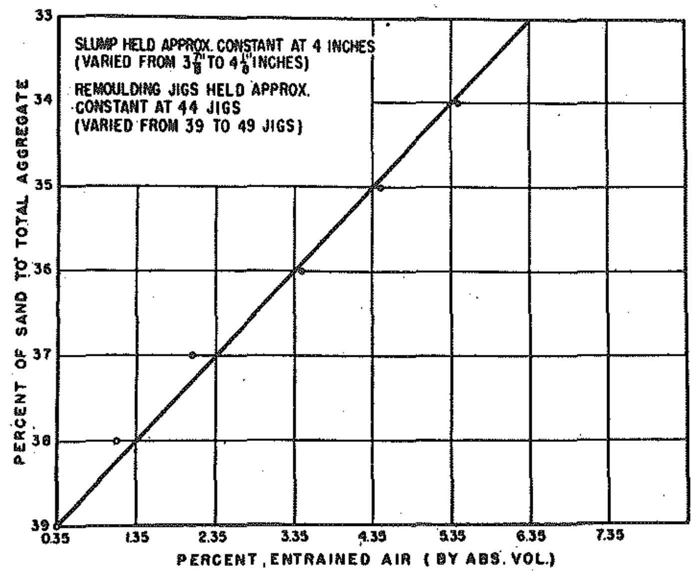


FIGURE 6. EFFECT OF SAND CONTENT ON AIR ENTRAINMENT (CORDON).

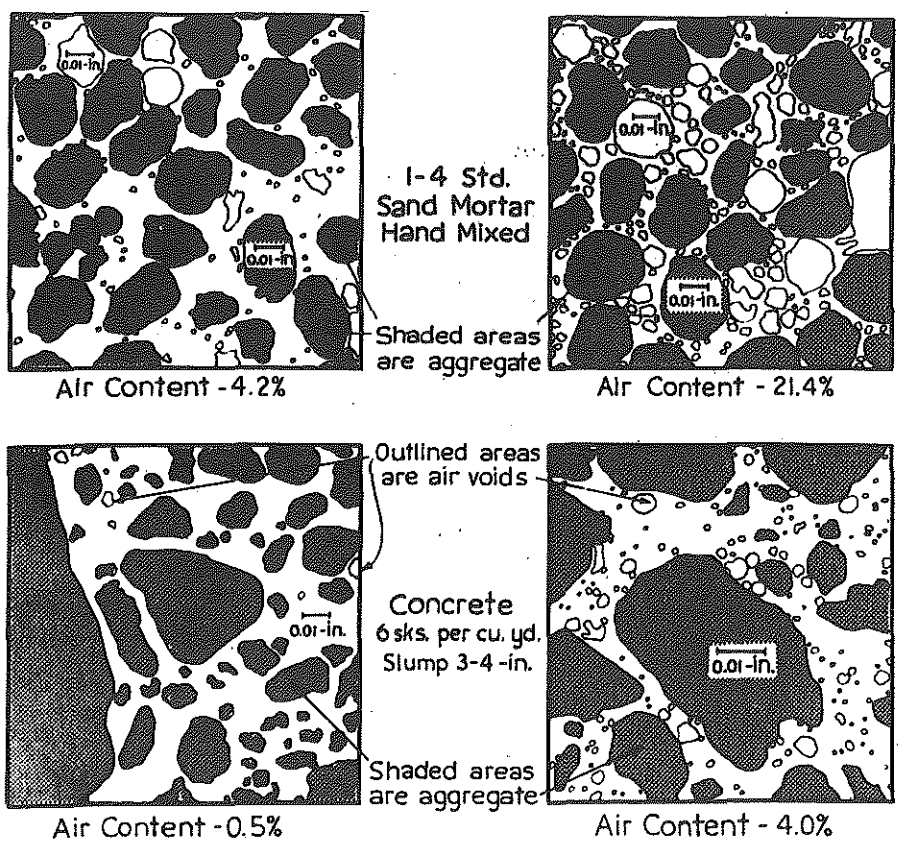


FIGURE 8. TYPICAL OBSERVED AIR VOIDS IN HARDENED SAND MORTAR AND CONCRETE BY THE CAMERA LUCIDA METHOD (VERBECK).

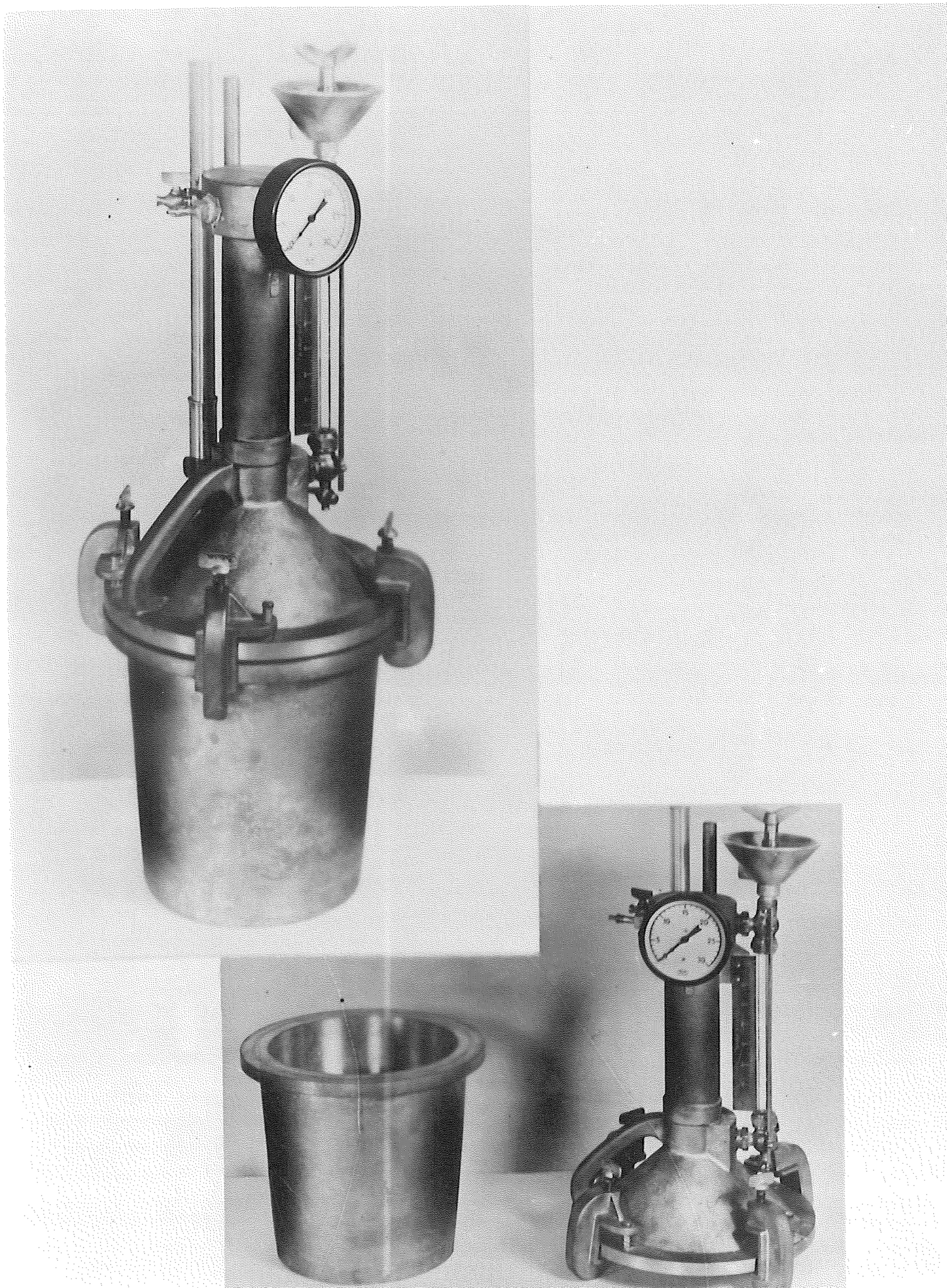


FIGURE 7. EQUIPMENT USED TO DETERMINE AIR CONTENT BY PRESSURE METHOD.

Additional data by the Portland Cement Association [5] concerning the effect of entrained air content on flexural strength is illustrated in Figure 10.

It is generally conceded that by the proper use of air-entrained materials and proper design of the concrete mixture it is not necessary to sacrifice strength materially, either in flexure or in compression.

It should be stated that these strength relationships do not necessarily hold in all cases, especially when a strength accelerating agent is used in conjunction with the air-entraining material.

To meet design strength requirements when air-entraining concrete is used, three courses are open to compensate for loss in strength: either increasing the dimensions of the structure or adding additional cement, or by the use of compound admixtures. However, in any case experience indicates that for maximum results the cement content should not exceed 7.0 bags per cubic yard. In many instances the high factor of safety which is employed in concrete design will allow for such strength reductions in view of the marked improvement in both durability and uniformity of the concrete which can be expected by air entrainment.

Effect of Entrained Air on Scale Resistance

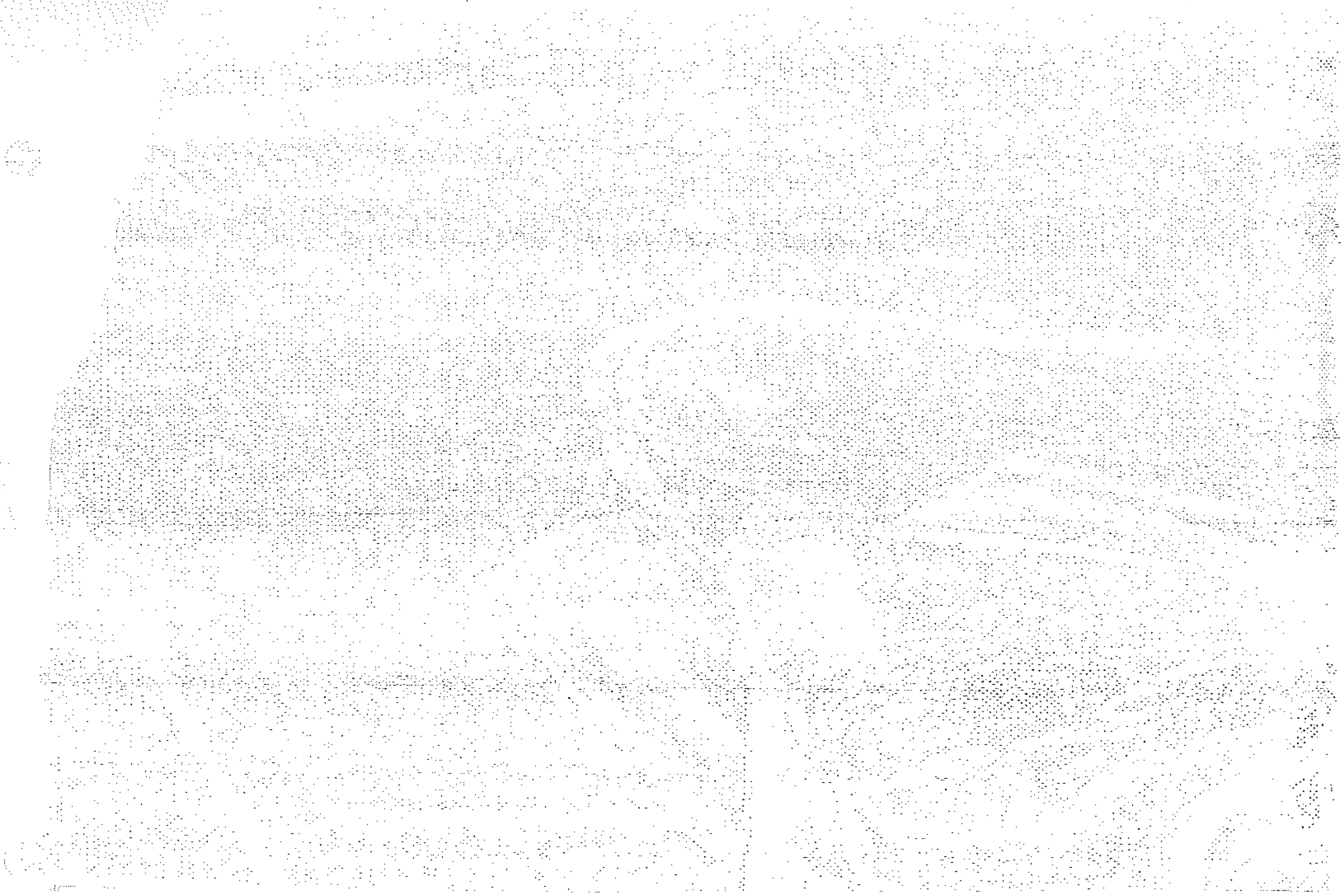
Numerous field studies have demonstrated beyond question that the entrainment of air in concrete greatly increases its resistance to scaling due to chloride salts employed for ice control purposes and by frost action. Figure 11 shows a series of photographs of sections of concrete pavements constructed with and without air entrainment.

EFFECT OF ENTRAINED AIR ON STRENGTH AND DURABILITY OF HARDENED CONCRETE

As pointed out in the beginning, entrained air in the normal amounts of 3 to 6 per cent exercises a profound influence on strength and durability properties of the concrete as compared to standard portland cement concrete. A detailed discussion of the most significant changes which take place in this respect will be covered in the following text.

Effect of Entrained Air on Strength

For normal concrete mixes containing 5.5 sacks per cubic yard or better, there is a definite decrease in strength as the air content increases. Experience indicates that each percentage increase in the amount of air which exists in plain concrete will reduce the compressive strength 3 to 4 per cent and flexural strength 2 to 3 per cent. For the lean mixes containing less than 5 sacks per cubic yard there is evidence [11] to show that compressive strengths are slightly increased for air contents up to 6 per cent air. This beneficial effect on lean mixes is not definitely understood. See Figure 9.



Of further interest is the relationship between air content and scale resistance of the concrete which is given for two types of aggregates in Figure 12. The graphs clearly indicate that the optimum air content in regard to scale resistance is approximately 3 per cent. Greater amounts of air produce but little additional benefit [19].

Resistance of Concrete to Freezing and Thawing Action

Increased resistance of air-entraining concrete to freezing and thawing action has been repeatedly demonstrated in field and laboratory studies by many research agencies. The results from these studies will be found throughout the literature on air-entraining concrete.

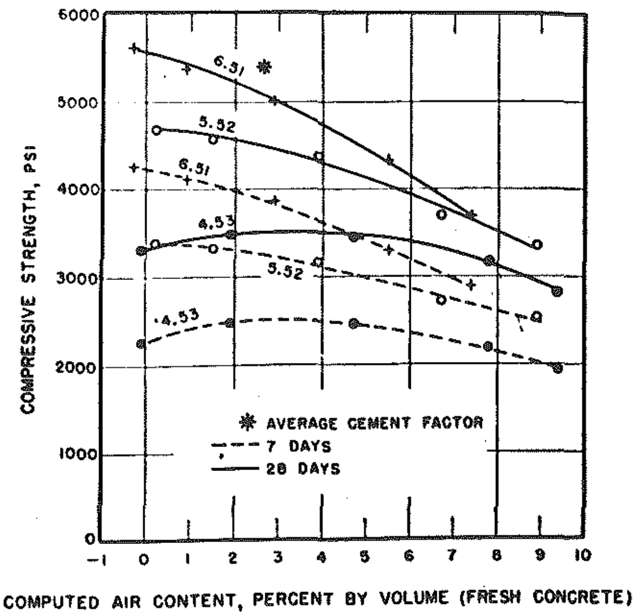


FIGURE 9. INFLUENCE OF AIR AND CEMENT CONTENTS ON COMPRESSIVE STRENGTH (WALKER AND BLOEM).

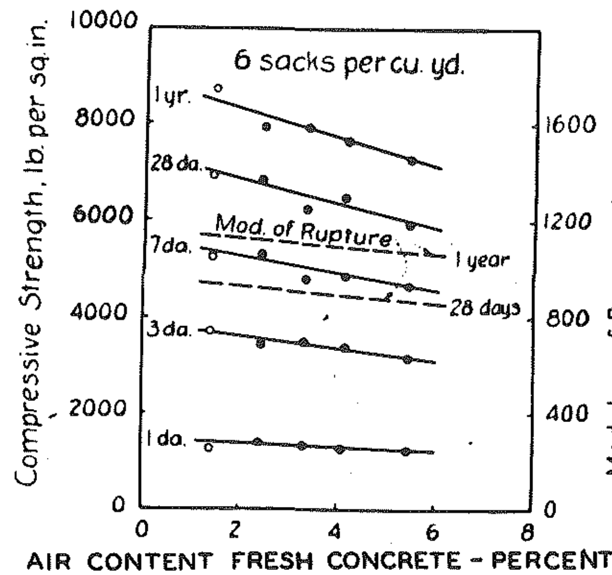


FIGURE 10. EFFECT OF AIR CONTENT ON FLEXURAL STRENGTH (GONNERMAN).

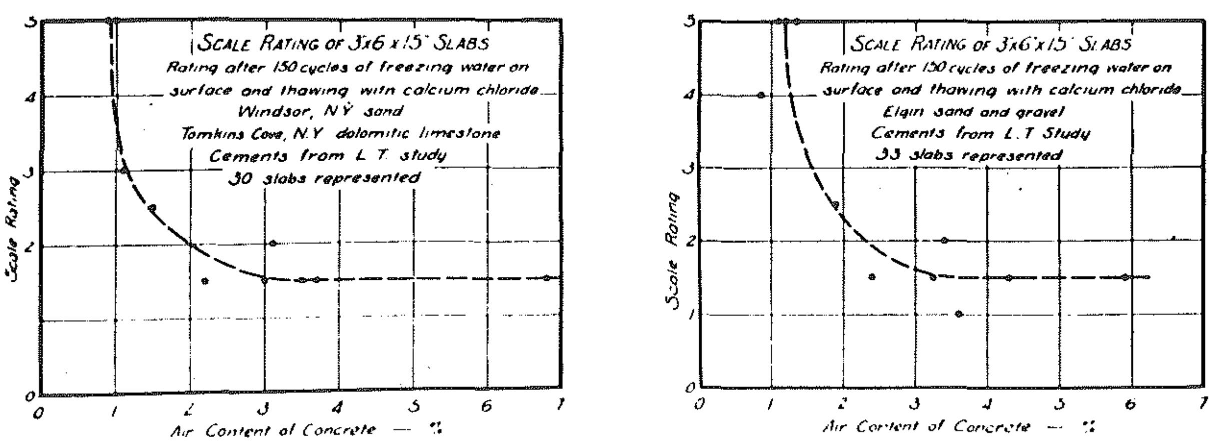


FIGURE 12. EFFECT OF AIR CONTENT ON SCALE RESISTANT PROPERTIES OF CONCRETE (ANDERSON).

Method of Evaluating Durability: Laboratory evaluation of the resistance of concrete to freezing and thawing action is generally accomplished by measuring the progressive drop in dynamic modulus "E" in terms of number of freezing and thawing cycles. The dynamic modulus is determined by a sonic apparatus, similar to that shown in Figure 13.

The sonic apparatus consists essentially of four major parts as illustrated in Figure 13. A radio frequency oscillator (A) furnishes power to a driving mechanism (B), which in turn vibrates the specimen. The driving mechanism (B) usually consists of a radio loud speaker adapted to this purpose. Vibrations in the specimen are transmitted through the pickup (C) to a vacuum tube volt meter (D) which indicates the natural resonance of the concrete by maximum deflection of the dial hand. The frequency at which the specimen is vibrating is shown on the dial (E). If the frequency and certain constants for the specimen are known, the dynamic modulus can be calculated by using the following equation:

$$E = kdN^2$$

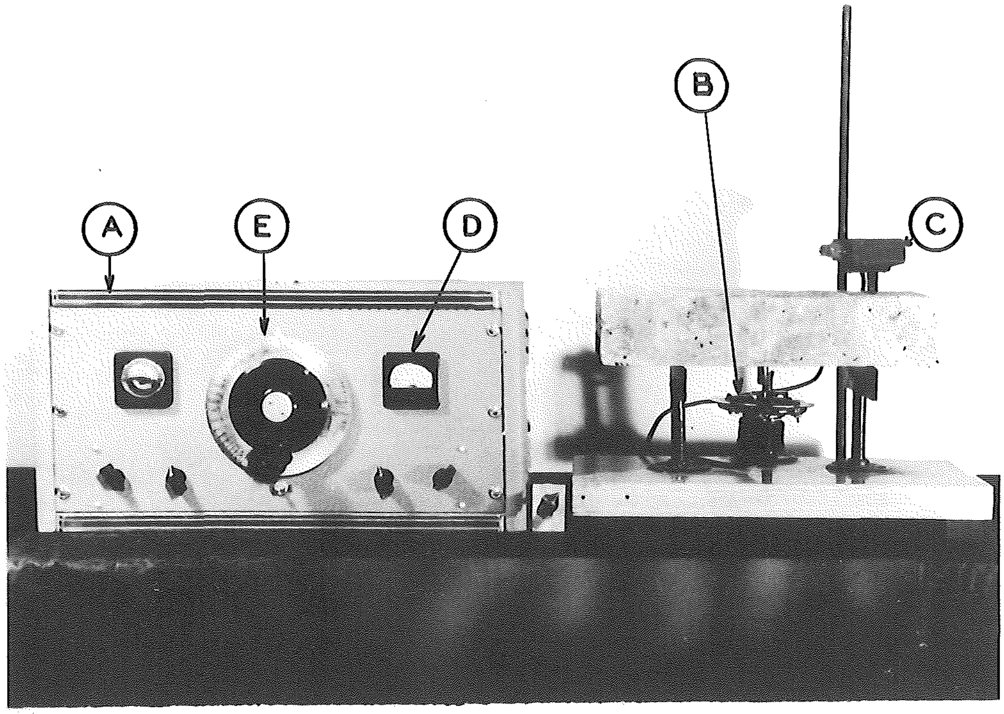
where E = modulus of elasticity, lb. per sq. in.

k = constant depending on dimensions of specimen, mode of vibration and conditions of restraint

d = specific gravity

N = fundamental frequency of vibration, cycles per sec.

Effect of Cement Content and Air-Entraining Material on Durability: The results of studies by Wuerpel (10), as shown in Figure 14, illustrate the influence of such factors as cement content and type of air-entraining admixtures or durability as measured by dynamic E.



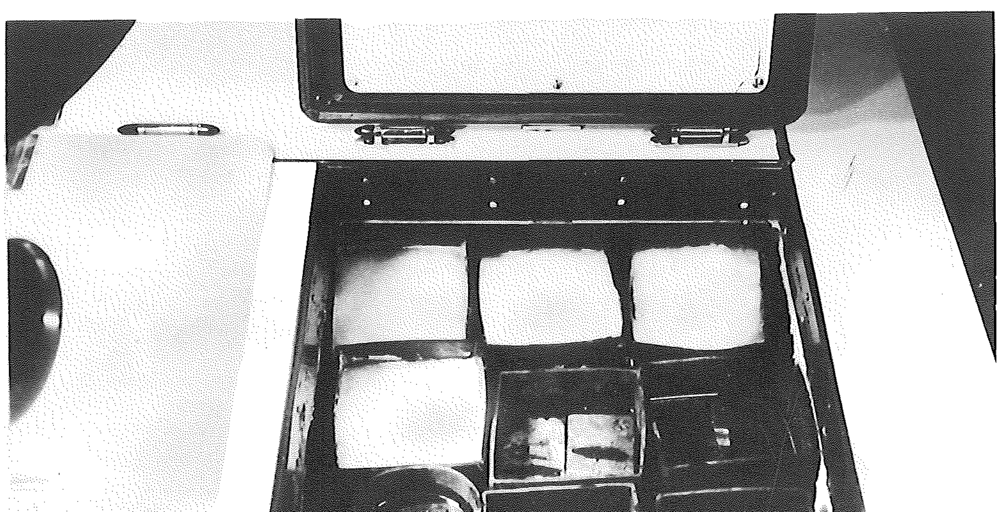
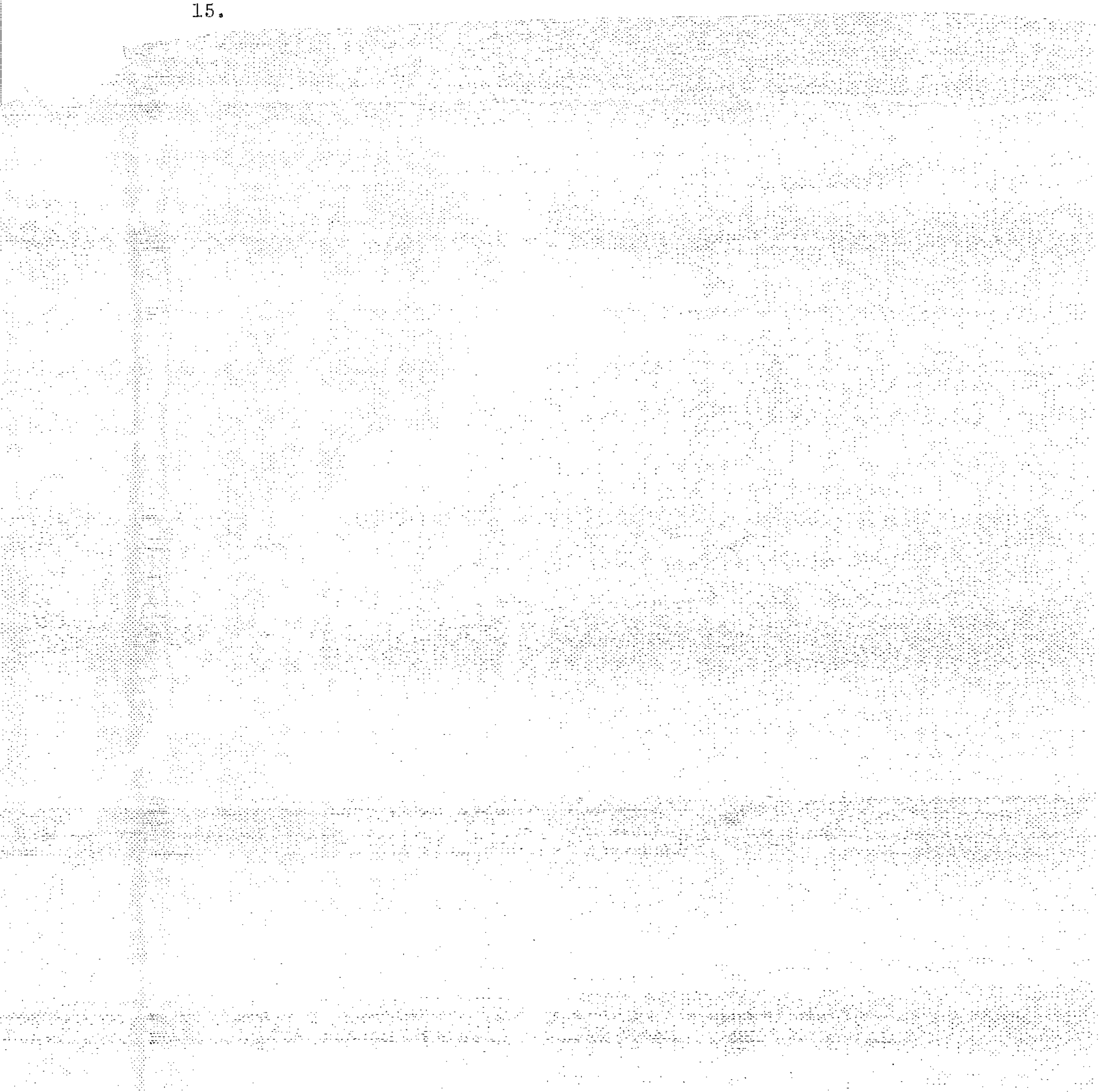


FIGURE 13. TYPICAL SONIC APPARATUS TO MEASURE DYNAMIC MODULUS "E" (ABOVE). METHOD OF FREEZING SPECIMENS (BELOW).

The curve for specimens containing no entrained air is designated by letter "P".

Influence of Water Content on Durability: Further, in the same studies there is shown the influence of variation in water content on durability of concrete containing entrained air. This is illustrated in Figure 15.



Effect of Air Content on Durability: The influence of freezing and thawing action on durability is manifested by loss in weight, expansion of the concrete, and drop in modulus E. The influence of air content on these three factors is clearly brought out by Gonnerman [5], as shown in Figure 16. The graphs bring out very clearly that the optimum air content for desired results is approximately 3 per cent.

Other Factors Affecting Concrete Durability

There are many factors contributing to lack of durability in concrete which air entrainment will not correct. The most outstanding are associated with: (1) proportioning methods; (2) placing and handling problems; (3) structure design and environment; (4) quality of the ingredients; and (5) moisture condition of the aggregates and the concrete. These factors will be discussed briefly as a reminder that they must not be overlooked in the manufacture of air-entraining concrete.

Proportioning Methods: The lack of adequate proportioning methods, handling, and weighing equipment result in variations in batch weight, moisture content and grading of the aggregates, all of which contribute to the production of non-uniform batches of concrete.

Placement Problems: The consistency of the concrete may be changed due to leaky water equipment or by willful addition of water by workmen to make concrete more workable. Improper placement, spreading, and handling in forms may result in segregation, water gain, lamination, and non-uniformity. Finishing and curing methods need careful consideration.

Structural Design and Environment: Improperly designed and constructed joints permit seepage of free water into the structure, which will ultimately cause excessive saturation of the adjacent concrete and subsequent deterioration under freezing and thawing action. Design features which necessitate complicated forming and placement of reinforcement steel may encourage poor workmanship in placing the concrete in the forms, thus resulting in an inferior product.

The location of the structure with respect to water, drainage facilities and general working conditions are important factors in obtaining a durable structure.

Quality of the Ingredients: Proper attention must be paid to the control of quality, selection and use of the ingredients. The physical properties of aggregates from different sources are sufficiently different to affect the resistance of concrete to freezing and thawing action. Portland cements also react differently under accelerated weathering tests.

Moisture Condition of the Aggregate and Concrete: It is now a well known fact that concrete made with many aggregates containing small pores thoroughly saturated has disrupted to a greater extent under freezing and thawing action than when the aggregates are put in the concrete in a relatively dry condition. Also, any concrete will break down more rapidly under freezing and thawing action when nearly saturated with water. Thus it is important to keep water away from the concrete, or make it as nearly impervious as possible.

All of these factors are intimately associated with, and dependent upon, adequate inspection and control. Specifications and control measures are of little value in the matter of obtaining durable concrete unless qualified personnel are available to enforce them and they in turn are insured the full cooperation and backing of their administration. It is evident from experience that inefficiency and indifference are perhaps the greatest weaknesses at the present time in the manufacture of quality concrete.

The introduction of the principle of air entrainment has done much to improve the durability properties of concrete and mitigate to a certain extent the serious effects of the factors outlined above. However, it is ever more imperative that adequate control be exercised in all cases to insure that the amount of purposefully entrained air is within the desired limits.

EFFECT OF AIR ENTRAINMENT ON OTHER PROPERTIES OF CONCRETE

In addition to improving the durability properties of concrete, the entrained air has a marked effect upon other properties of the concrete of vital interest in concrete design and construction problems.

Effect of Air Entrainment on Bleeding (Or Water Gain)

So-called bleeding or water gain associated with plain concrete is greatly reduced by the presence of the entrained air. This is quite obvious in concrete pavement operations where at times insufficient water on the surface results in difficult finishing. The water gain at the top of tall concrete sections is markedly reduced and the stratification of aggregates at pour levels is practically eliminated when air-entraining concrete is used.

In general, laboratory studies [11] indicate that air-entraining admixtures reduce bleeding of the plastic mixture by at least 40 per cent of that resulting from the use of plain concrete.

Effect of Air Entrainment on Uniformity of Concrete

Experience indicates that air entrainment tends to increase the homogeneity in concrete. Freezing and thawing tests on core sections from the Michigan Test Road durability project definitely indicate that the top portion of the pavement has approximately the same physical properties as the bottom portion, which is not generally true for the pavement not containing air-entraining materials. See Table II, presented previously.

Kennedy [11] in his study of this subject presents data which also bear out this fact. He shows that homogeneity is associated with bleeding. The less bleeding the more uniform the concrete from top to bottom. Thus, since air entrainment reduces bleeding materially, it is logical to assume that homogeneity in the concrete will result from its use. See Figure 17.

Effect of Air Entrainment on Volume Changes

Laboratory studies by Wuerpel [10] indicate that the entrained air exercises no material influence on the normal shrinkage and expansion characteristics of the concrete. These findings are somewhat substantiated by field measurements of slab movement on long sections of concrete pavement containing air-entraining materials associated with the Michigan Test Road.

Bonding Properties Between Concrete and Steel

Work by Wuerpel [10] and the Portland Cement Association supports the fact that the strength of bond between concrete and steel is not materially affected by the use of air-entraining materials, provided the mix is

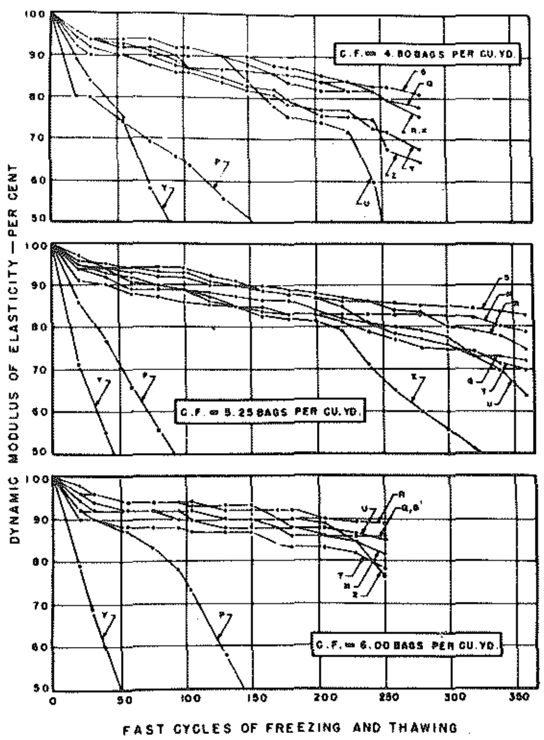


FIGURE 14. INFLUENCE OF ENTRAINED AIR ON DURABILITY OF CONCRETE (WUERPEL).

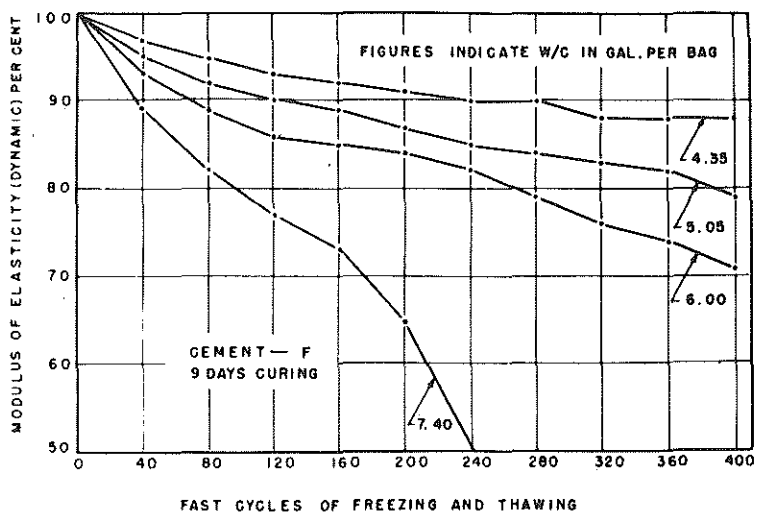
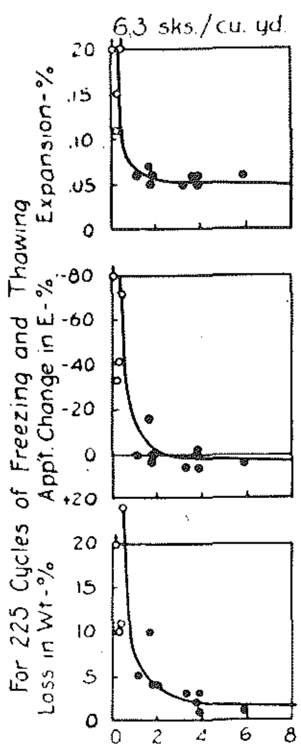


FIGURE 15. INFLUENCE OF WATER CONTENT ON DURABILITY OF AIR-ENTRAINING CONCRETE (WUERPEL).



O CONCRETE MADE WITH CEMENTS WITHOUT ADDITION.

● CONCRETE CONTAINING VINSOL RESIN.

FIGURE 16. EFFECT OF AIR CONTENT ON LOSS OF WEIGHT, EXPANSION, AND DROP IN DYNAMIC "E" (GONNERMAN).

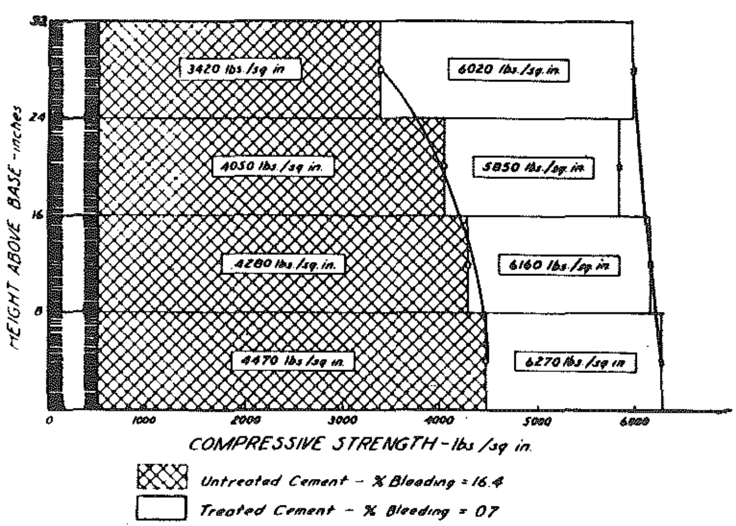


FIGURE 17. EFFECT OF BLEEDING ON HOMOGENEITY OF CONCRETE (KENNEDY).

properly designed and controlled and the air content of the concrete kept within the normal limits of 3 to 6 per cent.

Thermal Properties

Studies by Wuerpel [10] indicate that the presence of the distributed air voids in air-entraining concrete do not materially reduce the rate of heat diffusion when the amount of entrained air is within the limits for best results in concrete. Average thermal diffusivity values in square feet per hour of concrete without air-entraining admixtures was 0.035, and 0.034 when admixtures were used.

EFFECT OF AIR ENTRAINMENT ON DURABILITY OF AGGREGATES

There is evidence [5] [15] to support the fact that purposefully entrained air in concrete tends to increase the durability characteristics of good or bad aggregates. Evidence to this effect, based on recent laboratory studies by the Joint Highway Research Project at Purdue, is shown in Figure 18.

EFFECT OF AIR ENTRAINMENT ON CONCRETE MADE WITH LIMESTONE AGGREGATE

It has been conclusively demonstrated in laboratory and field experiments conducted by the Michigan State Highway Department and by the National Crushed Stone Association [11] that air entrainment in concrete containing limestone aggregates, both coarse and fine, materially improves its

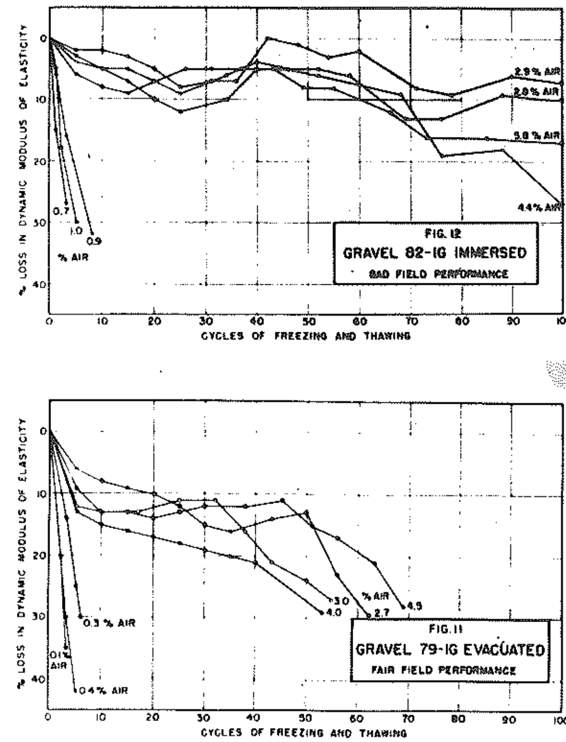


FIGURE 18. EFFECT OF AIR CONTENT ON DURABILITY CHARACTERISTICS OF AGGREGATES (BUGGS).

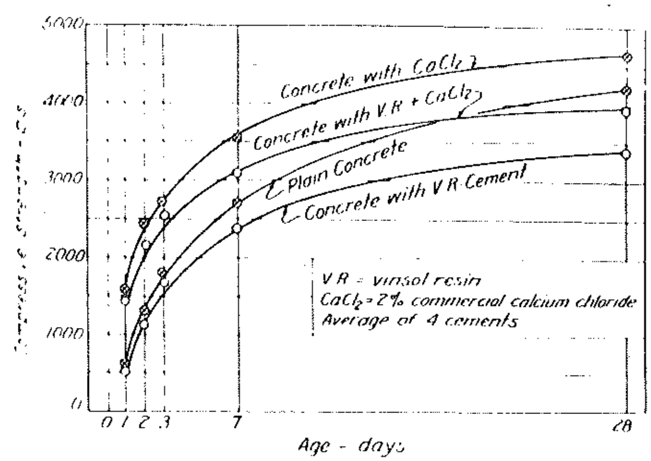


FIGURE 19. EFFECT OF CALCIUM CHLORIDE ON COMPRESSIVE STRENGTHS OF CONCRETE MADE WITH PLAIN AND TREATED CEMENTS (VOLLMER).

durability and resistance to scaling. See Figure 20. It also improves such objectionable characteristics as excessive bleeding, poor workability and difficult finishing.

AIR-ENTRAINING CONCRETE FOR MASSIVE STRUCTURES

In connection with the use of air-entraining concrete for massive concrete structures employing lean mixtures and large size aggregates (above 2-inch maximum size), Wuerpel [10] has brought out interesting information from laboratory studies. Because of the reduction of mortar content due to the presence of the large size aggregate, the total amount of entrained air need be less than in pavements. It was demonstrated that a total air content of 2.7 per cent in a lean concrete mix containing 6-inch aggregate is comparable, insofar as the mortar constituent is concerned, to a total air content of 4.0 per cent in a pavement concrete containing 1-1/2-inch aggregate.

In determining the unit weight of mass concrete the usual procedure of wet-screening the mix to remove the large size aggregate to permit the use of standard containers should not be followed because erroneous results will be obtained. The wet-screening process encourages the loss of considerable amounts of entrained air. When aggregates exceed 2 inches in diameter, a 2-cubic foot measure is recommended for unit weight determinations.

MANUFACTURE OF AIR-ENTRAINING CONCRETE

The manufacture of concrete falls into three categories; namely, site-mixed concrete, central-mixed concrete and transit-mixed concrete. Site-mixed concrete may include the mobile concrete paving mixers and stationary

Figure 20. Influence of entrained air on scale resistance properties of concrete made with limestone aggregates. Project M 75-28,C2, M.S.H.D.

mixing plants at the site of structures where the concrete is transported directly to the forms by manually operated buggies or by pumping methods. Central-mixed concrete is that which is manufactured at a stationary plant and transported over a considerable distance by means of agitating or non-agitating truck equipment. Transit-mixed concrete refers to concrete which is completely mixed in transit by specially designed truck mixers.

Site-Mixed Concrete

Site-mix plants offer no unusual problems in the manufacture of air-entraining concrete. In fact, they are to be desired because better control and inspection of concrete manufacture can be achieved.

In concrete pavement mixers of current design, optimum air contents can be attained in a mixing time of one minute which is consistent with adequate mixing of the ingredients. Smaller stationary mixers require longer periods of time and some standardization of mixing operations is usually necessary in order to obtain satisfactory air contents.

Pumped Concrete: There is evidence that air-entrained concrete has been pumped with excellent results on many projects [5]. Vagaries resulting from this type of work have been no more than those experienced with standard concrete. A slump loss of 1 to 2 inches per 1,000 feet of pipe is normal. Average slump at the mixer is 4 inches using 5-6 bag mixes. Experience indicates that workability is improved by compaction and release of the plastic concrete as it passes through the pipe. Air content is not affected by pumping operations.

Central-Mixed Concrete

Air-entraining concrete may be completely mixed at a central-mixing plant and transported for periods up to 90 minutes without any significant effect on either the amount of air entrained or the slump (11). Truck agitators as well as open top dump trucks have been used successfully to transport the mixed concrete to the point of delivery. Truck mixers operating at agitator speed can also be employed for transporting the mixed concrete. Standard practice indicates that 2 r.p.m. is sufficient for truck agitation. The entrained air does not eliminate entirely the segregation and packing of the concrete in non-agitating hauling equipment. Therefore, agitating equipment should be employed when at all possible.

Transit-Mixed Concrete

From experiences of the Department, as well as from those of others (12), it is evident that truck mixer operations are not adaptable at the present time to the successful manufacture of air-entraining concrete. This is due to the fact that the process in itself cannot be successfully controlled from the moment the materials are introduced into the truck mixer until the time that the concrete has been discharged on the job. The reasons for this are as follows:

1. The consistency of the mix changes with distance, time of haul and time of discharge. Therefore, it is necessary to add water in excess of that called for in the mix design to compensate for drop in consistency.

2. The air content will vary with the above conditions as well as with the number of revolutions, speed of mixing and mixing characteristics of the truck-mixer equipment.

3. A project of normal size will require the use of several truck-mixers of which no two units will have identical mixing characteristics or operators. In addition, their physical condition will vary considerably.

4. Delays in time of haul due to traffic conditions, forced delays, changes in routes, etc., complicate control possibilities.

5. Different cements and air-entraining materials react differently in transit-mix operations.

6. Very few plants have sufficient materials, storage, facilities and capacity to handle large projects without interruption in service or bunching of the truck units.

Specifications for ready-mixed concrete have been approved by the American Society for Testing Materials, Designation C 94-47T, and should be followed where concrete is provided in this manner.

AUTOMATIC DISPENSING EQUIPMENT FOR AIR-ENTRAINING MATERIALS

At the present time it is a foregone conclusion that all cement mills are using automatic dispensing equipment in the manufacture of air-entraining cements.

When air-entraining materials are added at the mixer, a metering device is essential to the accuracy and success of the operation. Dispensing equipment is now available on the market or can easily be made locally for use in ready-mixed concrete plants or on pavement mixers. Several such devices have been described by Kaufman (11) and Brickett (11).

CONSTRUCTION FACTORS AFFECTING QUALITY OF AIR-ENTRAINING CONCRETE

Even though special precautions are followed in the laboratory to design an air-entraining concrete mixture, there are numerous factors encountered during the manufacturing process which influence the quality and air content of the finished product. The only solution to the problem of obtaining a uniform product is by means of rigid inspection and enforcement of specifications as the work progresses.

During the proportioning, manufacture, and finishing of the concrete the following factors must be considered:

1. Variation in batch weights due to faulty condition of weighing apparatus.

2. Variation in moisture content of aggregates in each batch due to stock piling conditions.

3. Variation in grading of the aggregates also due to stock piling conditions.

4. Addition of excess water at the mixer due to leaky water equipment or to deliberately satisfy the workmen's desire for easy workability.

5. Improper placing and spreading which could cause local segregation of the mix.

6. Improper coordination of the strikeoff and finishing screed of the finishing machine and longitudinal float.

7. Excessive hand finishing.

8. Inadequate curing procedures.

All of these factors may be controlled to a great degree by enforcing specifications rigorously as the job progresses.

Air-entraining concrete has a number of peculiarities which necessitate minor changes in construction practice. For example, the resulting mixture has an extremely fatty appearance similar to that of an over sanded mixture. There is little free water on the surface to facilitate finishing operations. On this account it is necessary on paving projects to keep all finishing operations well up behind the mixer, particularly during hot, dry or windy weather. The concrete is inherently more sticky than ordinary concrete. Consequently, steel finishing tools have proven better than wooden ones.

In summary, experience has proven that the problems encountered in the use of air-entraining concrete are simply those involved in adjusting construction practices to the characteristics of the new concrete, and include no more radical changes than might be necessary due to many other changes which are frequently encountered in current job conditions.

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