NATURE AND USE OF AIR-ENTRAINED CONCRETE

Foreword

This report was prepared by a Special Subcommittee of Highway Research Board Committee MC-B5 on Chemical Additions and Admixtures for Concrete. It was reviewed by the committee as a whole and approved by letter ballot for publication.

Air-entrainment has provided great benefits for concrete in many applications, but nowhere more dramatically than in highway construction. The tremendous improvement in resistance to freezing and thawing, especially when such exposure is aggravated by the use of salts for ice removal, has in many cases multiplied the useful service life of pavements and structures. The information provided in this report is not limited in its applicability to highway construction but has been developed and arranged to be of maximum use to the highway engineer.

Introduction

The principle of air-entrainment in concrete and the reasons for its use can be briefly stated as follows: Certain substances, when added to concrete in small quantities, bring about the inclusion of a larger amount of air than is found in ordinary concrete. This added air exists in the form of minute discrete bubbles that affect materially the properties of both the freshly-mixed and the hardened concrete. Air-entrained concrete is more plastic and workable than non air-entrained and can be placed and compacted with less segregation and bleeding. Hardened air-entrained concrete is far more resistant to the harmful effects of freezing and thawing and of salt scaling than is ordinary concrete.

Nature of Air Voids in Air-Entrained Concrete

Ordinary concrete contains about one or two percent air in the form of relatively large voids. This is termed entrapped air. Entrained air, on the other hand, exists as very small bubbles and in an amount that depends on the amount of the air-entraining agent added to the concrete as well as upon other variables of the mixture and environment. In air-entrained concrete the total air content recommended for normal uses varies with the maximum size of the aggregate, and ranges from about four percent for 2-in. maximum size to about eight percent for 3/8-in. maximum size. These values refer to the concrete in place, because the placement process reduces the air content of the concrete discharged from the mixer.

The need for variation in air content with aggregate size is because the cement paste content of the concrete is determined by the maximum aggregate size and all the entrained air exists in the paste. The air content should be adjusted in air-entrained concrete so that the mortar component contains about ten percent air. This value has been found to give the desired beneficial effects, including protection from freezing action. The value could be reduced in locations, such as southern states, where the frost exposure is not severe.

The emphasis on total air content is somewhat misleading, and is the result of its comparative ease of measurement. It is possible, although not likely with the air-entraining agents in current use, to obtain the above recommended values for air content yet not the desired protection against freezing action. The reason is that the bubbles must be small in size and well-distributed throughout the paste component of the concrete in order to furnish proper protection. Extensive theoretical and experimental work has fairly-well established the importance of a parameter called the spacing factor that is, roughly, the average distance from any point in the paste to the nearest air bubble. It has been found that if this spacing factor is less than a critical maximum of about 0.008 in. the concrete will have good durability, provided durable aggregate, suitable water-cement ratio, and proper handling, placing, and curing techniques are employed. If the spacing factor increases above this value, the durability can be reduced. Unfortunately, the experimental determination of this factor can as yet be done only on hardened concrete.

Therefore, the only practical approach is to use an air-entraining agent that has been shown to produce the desired bubble system and in an amount that will give about the aforementioned values of total air content. A good procedure to follow is to proportion the trial mixture according to the report of Committee 613 of the American Concrete Institute, "Recommended Practice for Selecting Proportions for Concrete," and to use an air-entraining admixture that conforms to ASTM Designation: C 260 or air-entraining cement that meets the requirements of ASTM Designation: C 175 or C 205.

Effects of Air-Entrainment on Freshly-Mixed Concrete

Air-entrained concrete is more workable than ordinary concrete and less subject to segregation and bleeding. These changes are the result of the ability of the air bubbles to bear short-time loads, to interrupt the movement of bleeding water to the surface, to buoy up the solids, and to change the effective viscosity of the cement paste. The precise mechanisms of these actions are not well understood.

Experience in the use of air-entrained concrete has shown the necessity for some minor changes in certain construction practices. For example, air entrained concrete is more sticky than ordinary concrete, especially in richer mixes. The concrete may therefore have a tendency to tear under the screeds of the finishing machine. This tendency can usually be corrected by increasing the frequency of the transverse oscillations of the screeds. Sometimes a slight adjustment of the mixture composition, such as a change in the sand-coarse aggregate ratio, will accomplish the desired results.

Normally, a 1/8 in. backward tilt or lift of the cutting edge of the front screed and a level position of the rear screed have been found best for finishing air-entrained concrete with a transverse finishing machine. A rebound condition has sometimes been experienced behind the finishing machine. This is due to too much material passing under the screeds. The condition can be controlled by changing the tilt, as mentioned above, or by regulating the height of the concrete roll being carried ahead of the screeds. The concrete ahead of the front screed, during the first pass of the finishing machine, should have a uniform depth of 3 to 6-in.

Since bleeding is reduced and little water rises to the surface of air-entrained concrete, it is imperative that the consistency of the concrete be kept wet enough to allow finishing operations to proceed without undue difficulty. Except for concrete placed by vibratory methods, experience indicates the slump of the concrete for pavements should be 2 to 3 in. for best results, and should be as near the lower limit as is consistent with satisfactory finishing. The placing and finishing operations with air-entrained concrete pavements require no more care and attention than those with ordinary concrete, and the most exacting requirements for surface evenness can be met without difficulty.

Effects of Air Entrainment on Hardened Concrete

Durability

The principal reason for the inclusion of entrained air in concrete is to obtain a great increase in durability under freezing and thawing action. Non-air-entrained concrete may have high durability if the mixture is well-proportioned and the concrete is properly placed, finished, and cured, but it is potentially non-durable if it does not contain entrained air. Entrained air can be expected to provide protection for the paste component of the concrete under all ordinary conditions of freezing. It also provides protection against the increased severity of freezing exposure that seems to result from the application of de-icing salts to pavement surfaces and the resultant scaling that frequently occurs. It is especially important to insure that the surface layers of the concrete, which are most influenced by the salting action, contain the proper quantity and quality of entrained air. Certain procedures, such as overfinishing or overvibrating may contribute to surface layers that are non-durable for this reason.

Lack of durability of concrete in freezing can be caused by the presence of non-durable aggregates. Although entrained air protects the paste component, it does not provide much, if any, protection against difficulty arising from the aggregate and no reliance should be placed on it for such protection.

Strength

If there is no alteration of the mix proportions, air-entrained concrete will have a lower strength than that of ordinary concrete. This reduction will be about four percent for each percent of air. However, owing to the increased plasticity imparted by entrained air, it is usually possible to reproportion the mix using lower water and sand contents at constant slump.

This is particularly true of lean concretes or those with a small maximum size of aggregate. Such concretes will therefore not have their strengths reduced; they may even be increased by the use of air entrainment.

Since any increase of the air content above the design amount will result in further loss of strength it is important to maintain close control of the air content by frequent determinations at the job site. A common error is to make too-infrequent checks of the air content.

Abrasion Resistance, Elasticity, Bond to Steel

These properties are influenced roughly in the same manner as is compressive strength. If the use of air-entrainment results in a loss in strength, the abrasion resistance, elastic modulus, and bond strength to steel will be reduced proportionately.

Shrinkage and Thermal Expansion

Volume changes due to changes of water content or temperature of the concrete are not greatly affected by entrainment of air in the usual amounts.

Absorption

There is conflicting opinion regarding the absorption of air-entrained concrete. Theoretically the rate of capillary absorption should be lowered although the total amount should be about the same as for ordinary concrete. Other evidence shows little difference between the two.

Creep

The small amount of available evidence shows no important difference between the creep of air-entrained concrete and that of ordinary concrete.

General

It should be remembered in considering the properties of hardened concrete that air entrainment permits the placement of a more homogeneous material, free from honeycombing, and will therefore be of indirect benefit to all the properties of the hardened concrete.

Materials for Production of Air-Entrained Concrete

Air-entraining agents can be incorporated in concrete either as an addition interground with the cement or as an admixture added at the time of mixing.

Air-Entraining Cements

Portland and portland-blast-furnace-slag cements may be interground with agents at the mill to form their air-entraining counterparts. These products are covered by ASTM Designations: C 175 and C 205, respectively.

The main advantage to the use of air-entraining cements rather than admixtures is convenience. The addition of another component at the mixer and the attendant problems of accurate measurement of small amounts of material are eliminated. Trouble has, for instance, not infrequently come from failure to batch the admixture, either through operator error or equipment malfunction. The use of air-entraining cement eliminates such problems, and furnishes some assurance of durability even when there are no facilities to measure the actual air content.

The disadvantage of the use of air-entraining cements is that one is restricted to a certain amount of addition. These cements are manufactured with sufficient air-entraining addition to give an air content of 19 ± 3 percent in standard mortar when tested by ASTM Designation: C 185. This quantity of addition has been found to be proper for most average jobs. However, many variables of the mixture, handling, and environment influence the amount and quality of the entrained air. Therefore, it is sometimes found necessary when using air-entraining cement to add an air-entraining admixture at the mixer or to add an air-detraining agent or to change some mixture proportion such as the sand content or grading in order to get the desired air content.

Air-Entraining Admixtures

Many surface-active agents can be used as admixtures incorporated in the concrete at the time of mixing to cause air entrainment. The quality of the bubble system obtained depends on the nature of the air-entraining admixture. Those that conform to the requirements of ASTM Designation: C 260 will be satisfactory when the other ingredients are properly proportioned.

The main advantage of the use of admixtures, as opposed to air-entraining cements, is the flexibility they allow. Alterations can easily be made to compensate for the various conditions that influence the air content. The engineer can, therefore, usually keep better control of the concrete mixture when using admixtures.

In order to get the greatest uniformity of the concrete mixture, it is almost universal practice to add air-entraining admixtures in the form of solutions rather than as solids. This point is especially important with reference to the short mixing times used on some classes of concrete work.

Air-entraining admixtures are not usually damaged by freezing, but it may be wise to solicit the manufacturer's opinion regarding the effects of freezing on his product.

Other admixtures, for instance retarders and accelerators, usually increase the amount of air-entrained by a given amount of air-entraining admixture, and there may be some reduction in the quality of the entrained air. Such behavior is not well-understood and, where experience is lacking, a trial batch should be mixed in order to investigate these matters. Generally, air-entraining admixtures should be added to the mixer separately from other admixtures being used, unless tests have shown this to be unnecessary.

Finely-Divided Materials

The addition of appreciable amounts of finely-divided materials, say passing the No. 100 sieve, may seriously inhibit the entrainment of air in concrete. Therefore, when using such substances as fly ash and carbon black it is frequently necessary to add increased amounts of air-entraining admixtures. Such increases may also be necessitated by fines adhering to the aggregate or produced in the mixer by degradation of friable aggregates. It may be necessary in these circumstances to make trial batches to ascertain the correct amount of admixture. It should also be remembered that relatively large amounts of organic materials, such as air-entraining admixtures, may have important effects on the setting and hardening of concrete. These effects should be investigated if large increases in air-entraining agent are necessitated by finely-divided materials in the concrete mixture.

Aggregates

The requirements for aggregates for air-entrained concrete are no different than those for ordinary concrete. Good guides are ASTM Designation: C 33, the report of ACI Committee 621, or the specifications of the highway department of the state in which the work will be done.

Any change in the proportions or grading of the aggregate can be expected to cause changes in the air content of air-entrained concrete. However, there is some evidence that the importance of the sand gradation is not as great as once was thought, particularly with respect to obtaining a proper spacing factor.

Proportioning of Mixtures for Air-Entrained Concrete

The proportioning of air-entrained concrete is similar to that of ordinary concrete. The volume of air is merely another component that is added into the summation of absolute volumes along with those of the other ingredients.

It is recommended that in proportioning air-entrained concrete the procedure of ACI Committee 613 be followed for the trial batch. This procedure incorporates the reduction in water and sand that the greater workability of air-entrained concrete permits. Small corrections can then be made in the proportions of the trial batch in order to secure the desired properties and maximum economy.

If an air-entraining admixture is used and the manufacturer's recommended amounts do not result in the desired air content, it is usually easy to adjust the amount of agent. However, under some conditions it may be necessary to change the type of air-entraining agent. If an air-entraining cement is being used, it may be necessary to change the brand of cement or add an admixture as well.

Effects of Various Factors on Entrained Air

In this section mention will be made of the factors that influence the quantity and quality of entrained air in concrete. Many of these effects are imperfectly understood and the following comments are in some instances based on relatively sketchy or even conflicting evidence.

Amount of Sand

Increasing the amount of sand will increase the amount of air. However, the spacing factor is probably not greatly affected. It is therefore incorrect to attempt to increase the air content by increasing the sand proportion, especially considering the increased water demand such a change would involve.

Richness of Mixture

Rich mixtures entrain less air than lean mixes.

Consistency of Mixture

Wet mixtures entrain more air than dry, stiff mixtures. The air content increases with slump up to a slump of about seven inches; with further increases the air content decreases. Relatively wet mixtures will, however, probably have a spacing factor that is larger, and therefore less desirable, than drier mixtures. Excessively dry mixtures may also have comparatively coarse bubble systems and large spacing factors.

Type of Mixing

Machine mixing will entrain more air than hand mixing. Mixers with different types of mixing action will probably entrain differing amounts of air.

Length of Mixing Time

The amount of entrained air increases with mixing time up to a point beyond which it slowly decreases. This variable is especially important for ready-mixed concrete, for which mixing times of 15 to 90 minutes are the rule as compared with the minute or so in a stationary mixer. Experience indicates the maximum amount of air is entrained in about 15 or 30 minutes in a truck mixer. However, the ensuing slow decrease in air content is not so critical as to cause undue difficulty in exercising the necessary control, especially since the spacing factor is probably little changed.

Temperature of Concrete

The amount of entrained air decreases as the temperature of the concrete increases. Probably the spacing factor is not greatly affected.

Vibration

Placement by internal vibration will usually cause a reduction in the air content of air-entrained concrete. This reduction will be greater the longer the period of vibration. It has been found, however, that vibration has little effect on the smaller bubbles and therefore does not materially change the spacing factor, and such concrete would therefore have good durability in spite of a lower air content than is normally thought proper.

Admixtures

As was mentioned previously, other admixtures used for various reasons can influence the air content and quality of the bubble system. Very little is known of the details of this influence, and each case should be investigated individually if experience in the particular system is lacking.

Test Methods

There are three ASTM standard test methods for the air content of air-entrained concrete.

ASTM Designation: C 138 is the gravimetric method; it involves the determination of the unit weight of the concrete. A knowledge of the mix proportions and the densities of the various components then permits a calculation of the air content. The uncertainties of sampling and of aggregate absorption that are ordinarily found make this method accurate only for laboratory use with a restricted range of materials.

ASTM Designation: C 231 is the so-called pressure method that involves the determination of the change in volume of a sample of the concrete when a known increase in pressure is applied. The assumption of Boyle's law permits calculation of the air content, since air is the only highly compressible component of the concrete. This method is generally useful except for concretes that contain aggregates with large, air-filled void systems. The method is therefore inaccurate when applied to concretes made with many lightweight aggregates, including blast furnace slag.

ASTM Designation: C 173 is the volumetric method in which the air in a known volume of the concrete is displaced by mixing with excess water and its volume determined directly. An adaptation of this method, using the so-called Chace meter and a small sample of mortar from the concrete, is rapid and convenient. It is accurate enough for some routine control purposes, but should not be relied on exclusively.

The foregoing three methods determine only the total air content and, as was mentioned and implied throughout this text, the spacing factor is a more significant parameter than is the total air content. The methods for the determination of spacing factor are given in ASTM Designation: C 457. These methods involve microscopic techniques applied to polished surfaces of the concrete and are applicable only to hardened concrete. The field engineer, then, has only the methods for total air content of the plastic concrete to rely on for his control procedures. Undesirable as this state of affairs may be from a theoretical point of view, it has been found that if, for instance, the concrete has been properly proportioned according to ACI 613 and the air-entraining agent qualifies under the appropriate ASTM specification, the resulting bubble system will almost surely have the desired properties. It may be, however, that changes in the total air content caused by the various influential factors do not have as much significance in terms of frost durability as was formerly thought. Even so, the prudent procedure is for the field engineer to maintain control by frequent checks of total air content and investigation of any changes that occur.

Summary

The practice of air-entrainment in concrete is unquestionably established from the standpoint of increased freezing and thawing resistance, and is also used to obtain other desirable improvements in the properties of the concrete. Proper control is important to assure maintaining the air content within desired limits -- high enough to derive the benefits to durability and workability, but low enough to avoid unnecessary penalty to strength.

Publication Note

The Highway Research Board has recently published and made available under limited distribution a bibliography on "Admixtures for Highway Concrete." This contains annotated references to the literature on air entrainment in concrete and also on accelerators for concrete.

The cost of the publication is $3.80.

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