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FACTORS TO BE CONSIDERED IN THE USE OF  
AIR-ENTRAINED CONCRETE  
FOR  
HIGHWAY CONSTRUCTION

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DESIGN AND CONTROL OF AIR-ENTRAINED  
CONCRETE FOR HIGHWAY CONSTRUCTION

INTRODUCTION

Air-entraining agents, whether interground with the cement or added to the batch at the mixer have definitely proved their value in producing frost and salt resistant concrete. Problems have been introduced by their use, however, which still have not been satisfactorily solved. In the first place, change in the mix design is necessary when additional air is to be incorporated in the concrete. This is absolutely essential if consistency of the plastic mix and strengths of the hardened concrete are to be maintained at or near those of concrete made without the use of air-entraining agents. In the second place, the problem of field control presents serious difficulties because of the fact that the optimum air content lies within a relatively narrow range and the amount of air introduced into the mix depends upon many different factors. This report has been prepared with the idea of summarizing the factors entering into the design and control of concrete mixtures containing air-entraining agents, particularly Vinsol resin ground with the cement, and the influence of these factors on the use of such admixtures in highway structural concrete and transit-mixed concrete. Special emphasis is placed on the importance of maintaining at all times adequate control over all phases of construction operations by providing the best possible type of inspection.

DESIGN OF MIX

Early in the use of air-entraining agents several important effects were noted when additional air was incorporated in a mix designed for use without such additions: (1) the mix appeared overtendered; (2) the slump and

workability increased; (3) bleeding and segregation decreased; (4) durability increased; and (5) strengths decreased. These effects were more pronounced in lean, wet mixes than in rich, dry ones. Effects (1), (2) and (3) above make possible some adjustments to compensate for effect (5). By reducing the water content, sand-aggregate ratio, or total absolute volume of aggregates while keeping the same cement factor, consistency may be held within workable limits, durability maintained and strengths be made to approach very closely those of concretes produced without added air.

#### Factors Affecting Air Content and Strength of Concrete

As mentioned previously, the introduction of added air into the plastic 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 effect on air content, and conversely, the effect of the air content on processing of the mix and the properties of the hardened concrete. Some of the more significant effects involved will be discussed briefly here.

Water Content: In a given mix air entrainment will increase with increasing water content, the effect being more pronounced in lean mixes than in rich ones. The control of water content in air-entrained mixtures then, is extremely important, more so than in mixing concrete without air-entraining agents, because of its effect on both water-cement ratio and voids in the mix.

Fine Aggregate: The amount and character of fine aggregate, grading particularly, also have a marked influence on the workability and void

content of concrete containing air-entraining admixtures. Kennedy\* gives the following values of air-entrainment for the indicated sieve fractions under identical mixing conditions:

<u>Sieve</u>	<u>Per Cent Air</u>
14 - 28	15 - 20
28 - 48	30 - 35
48 - 100	45 - 50
- 100	0 - 1

It is apparent that variations in fineness modulus may exert considerable influence on the amount of air taken into the mix. Conversely, the quantity of sand required in a given mixture is a function of the air content, the greater the air content the less sand required for workability. With a predetermined cement and air content the less sand used the better, provided satisfactory workability is maintained.

Course Aggregate: The effect of this constituent on void content has been noted in Fulton's\* recent analysis of data on unit weights of air-entrained concrete in the field wherein it was found that increases in unit weight of the coarse aggregate tends to reduce the volume of entrained air. Data on the effect of variations in absolute volume of coarse aggregate per unit volume of concrete on mixes containing air-entraining agents are meager and inconclusive. More information is needed on this point. It is probably safe to say that, with air-entraining agents, as well as without, a larger volume of mortar is necessary for optimum workability with crushed or angular particles of coarse aggregate than with rounded, natural particles, and that coarse aggregate of larger maximum size requires less mortar for a workable mix.

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\*Kennedy, Henry L. - The Function of Entrained Air in Portland Cement. A.C.I. Journal, June 1944, p. 515.

\*Fulton, Roy S. - Effect of Air-Entraining Agents on the Voids of Concrete. Michigan State Highway Department Unpublished Report February 20, 1945.

Cement: The individual properties of the cement and the amounts used have considerable effect on the void content and strength of the finished concrete. Cements with interground air-entraining agents are generally ground finer than those without the addition. Chemical composition of the cement may largely determine its air-entraining ability when saponifiable materials are ground with the clinker as air-entraining agents. The cement factor also has a marked influence on the quantity of air taken into the mix, considerably more voids occurring in lean mixes than in rich ones. This means that there is far less latitude in the adjustment of water and sand quantities in rich mixes than in those of lower cement content. It may also be said that as the cement factor increases, the beneficial effect of adding air-entraining materials decreases.

Air-Entraining Agent: In general the amount of air entrained in a given concrete mix depends to a considerable extent upon the quantity of air-entraining material added. Vincol resin is not in itself an air-entraining agent. In order to affect the surface tension of the water in the mix to cause foaming it must be converted to the water-soluble soap by saponification through the action of hydroxides of the alkali metals. By intergrinding the resin with the cement, the amount of air-entraining material produced will depend not only on the amount of resin employed, but also on the amount and availability of the alkali oxides present in the clinker. Further, the amount of resin is so small that it is difficult to secure homogeneous dispersion throughout the cement and there is evidence to show that appreciable variations in air-entraining power may exist from batch to batch of the same cement.

Due to these differences in amount and availability of alkalis between individual cements, it was possible to occlude too little air with the maximum resin content of the former A.S.T.M. specification (.045 percent by weight of cement) and too much air with the minimum resin content (.025 percent). Two recent developments have contributed materially to the amelioration of these difficulties. The use of solutions of pre-saponified resin added to the clinker before grinding improves the uniformity of Winsol resin cement by stabilizing the actual amount of air-entraining agent present and making possible a more homogeneous dispersion throughout the grind. The second development is the A.S.T.M. specification governing air content of a standard mortar as a basis for acceptance which was substituted for that controlling Winsol resin content. It has been repeatedly demonstrated, however, that the amount of air entrained in a standard mortar in the laboratory does not indicate the amount of air which will be introduced into a concrete mix in the field.

Mixing Time: It has been shown by experience that the time of mixing also influences the amount of air produced in concrete containing air-entraining cements. This is probably due, in part at least, to the use of unsaponified Winsol resin in the cement, the soap-forming reaction progressing as mixing continues. It is also possible that some added air will be brought in through a more thorough mixing of ingredients. On still further mixing the air content may fall gradually. This fact, of course, must be taken into account when transit-mix concrete is used.

Method of Mixing: Still another factor influencing the air content produced by air-entraining agents is the method of mixing the batch. For a given mix, hand mixing will entrain less air than machine mixing. Probably the type and condition of field mixing equipment will also affect to some degree the amount of air entrained.

### Methods of Adjusting Proportions for Durability and Strength

Because entrained air functions essentially as fine aggregate in the mix, thus making possible a reduction in sand and water content, the adjustments to be made have the effect of reducing the water-cement ratio and increasing the cement-aggregate ratio in a given volume of concrete. All possible advantage must be taken of these opportunities for adjusting the mix so that maximum strength may be obtained, at the same time maintaining the minimum air content necessary to insure durability. It is generally accepted that a minimum total void content of 3 percent by volume is sufficient to assure durability; more than 5 percent needlessly impairs strength without noticeable improvement in resistance to frost and salt action. Since the air content of a standard cement concrete is normally around 1 to 1.5 percent, the increased void content of 2 to 4 percent would correspond to a drop in unit weight of the concrete of from about 3 to 6 pounds.

Methods of adjusting proportions of the mix vary among different users. Features common to all, however, are reduction in water and sand content. Other adjustments are possible under certain conditions and no hard and fast rule can be applied to these adjustments. Some of the essential factors entering into the modification of mix design when air-entraining agents are used will be brought out in the following critical comment on our present mortar voids method of proportioning concrete mixtures.

Present Procedure: In designing mixes using Vincol resin cements it has been customary in our Department laboratories to use data obtained in the laboratory work of the mortar voids method to determine the amount of air and total voids in the mortar while using an empirical reduction in relative water content from approximately 1.215 to 1.15 to allow for the decreased water requirement for this type of mix.

After completing the design with a definite computed yield of 1 cubic yard to 5.5 sacks of cement, it is found that considerably more air is contained in a mixed batch of concrete than was indicated by the tests of the mortar, resulting in a further drop in unit weight and corresponding increase in yield. In order to reduce the yield thus obtained to 1 cubic yard, an absolute volume of sand equal to this excess volume is deducted from the original quantity of fine aggregate and the water requirement reduced by an amount corresponding to the absorption of the sand removed from the mix. Using this procedure, the air entrainment with Vinacol resin cements has been consistently high, too high for maximum strength and almost 2 percent more than that of comparable mixes containing Orvus as the air-entraining material.

Throughout the design, the <sup>above</sup> absolute volumes of coarse aggregate and <sup>the absolute volume</sup> cement in a cubic yard of concrete are maintained at fixed, constant values. The water content, once established by the laboratory mortar tests, is also maintained constant. Any subsequent variation in yield due to fluctuating air content must, therefore, be compensated for by adjusting the sand content. For amounts of air entrained in the laboratory mortar tests this is accomplished automatically by the higher  $v_m$  line on the second chart of the mortar void series ( $v_m - \frac{am}{cm}$  relationship). Additional adjustments are necessary when the actual void content of the mixed concrete exceeds that indicated by the mortar tests, which usually occurs.

Suggested Changes: The method outlined above is open to question on several counts:

1. It is not evident that all combinations of different brands of cement and types of aggregate will require the same reduction in relative water content.



2. Removing sand to reduce the yield reduces only slightly the percentage of voids in the mortar, the principal result being a reduction in volume of mortar in the mixture. This has the effect of lowering the sand-cement ratio producing a richer mix, but a better method would provide for a reduction in void content of the mortar to the necessary minimum.
3. No account is taken of the effect of coarse aggregate characteristics on the amount of air entrained. In the mortar voids method as now used, it is evident that the unit loose weight and specific gravity of the coarse aggregate enter into the design only as they affect the absolute volume of the coarse aggregate in the mix. In other words, two coarse aggregates of widely different specific gravities and unit weights, but of the same absolute volume are assumed to influence the void content identically. That such is not the case seems to be indicated by Fulton's analysis mentioned earlier, and by the fact that particle shape has an influence on both the amount of air entrained, and the amount of mortar required for workability.
4. Adding or removing sand is the only basis of adjusting air content used at present in the laboratory and in the field. Adjustments of other factors such as <sup>loose</sup> absolute volume of coarse aggregate ( $b/b_0$ ) and water content may be desirable in some cases.

From the entire preceding discussion it is evident that the air content of a given concrete mix can be predicted only on the basis of actual trials with the materials to be used. There seems to be no reason why the present mortar voids method cannot be used as a basis for the mix design so long as the mortar tests are supplemented by trial batches of concrete mixed in the laboratory. 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 compel a change of air-entraining cement. Any additional adjustments could then safely be made by varying the sand content of the mix in the field at the beginning of the job and thereafter as may be necessary under conditions encountered during the progress of the work.

## CONSTRUCTION FACTORS AFFECTING AIR CONTENT AND QUALITY OF CONCRETE

Even though special precautions are followed in the laboratory to design a satisfactory concrete mixture with air-entraining agents, there are encountered during the process of manufacturing concrete in the field numerous factors which influence the quality and air content of the finished product. Therefore, it is absolutely necessary that steps be taken to eliminate or control these influencing factors if we expect to attain a uniform concrete mixture meeting specified design requirements. The factors will be enumerated and discussed in the following text under the headings of Batching Plant, Mixing Operations, Placing, and Finishing and Curing.

### Batching Plant

At the batching plant there are three recognized major sources where trouble may be encountered. They include the air-entraining cement, (when air-entraining materials are ground with the cement), proportioning of the materials and handling of the aggregates.

Air-Entraining Cement: Caution must be exercised in handling of air-entraining cements during batching operations. These cements have a greater tendency to flow in the dry state than normal portland cements and special precautions should be taken to prevent leakage through cracks and openings of any kind. Proper inspection of all equipment which carries and measures the cement to see that all separators and cutoffs are tight and well-fitting will obviate any difficulty from this source.

Proportioning of Materials: It is usually difficult to obtain uniform batches of concrete for several reasons:

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

2. Variation in moisture content of the aggregates in each batch.
3. Variation in the grading of the aggregates in each batch.

A great deal of this trouble could, no doubt, be eliminated by the use of more advanced precision weighing equipment which would automatically compensate for the weight of moisture in each batch of aggregate. In addition, such a weighing system would naturally be equipped with an automatic recording device which would preserve the actual weight of each batch, including the weights of its component parts.

The grading of the aggregates will be influenced to a great degree by the handling process.

Handling of the Aggregates: Handling of the aggregates in such a manner as not to alter too greatly their original grading characteristics has been of great concern to highway engineers. The major problems have been:

1. Stockpiling of aggregates to prevent segregation.
2. Transfer of the aggregates from stockpile to batch bins without destroying the grading characteristics.
3. Storage of aggregates for a sufficient time to allow excess moisture to drain from stockpile with the intent of providing for a more uniform condition in the aggregates as they are used.

Rigid inspection and control over handling and storage of aggregates seem to offer the only practical approach to the solution of these problems.

#### Mixing Operations

Under this heading are mentioned the effects of some of the conditions encountered during the operations of adding the mixing water and mixing the batch on the uniformity and quality of the finished product.

Mixing Water: Although the quantity of mixing water is fixed by design requirements, the consistency of the concrete mixture may vary from batch to batch for the following reasons:

1. Variation of water content due to leaky water equipment.
2. Common practice of changing the water content of the batch to satisfy the workmen's desire for a concrete of easy workability.
3. Variation in moisture content of the aggregates as they arrive from the batching plant.

These factors do not constitute a major problem since their influence could be greatly reduced or eliminated by rigid inspection of equipment and operations, and by improved batching methods at the plant.

Mixing of the Concrete: Since the time of mixing is generally fixed, there remains the speed of rotation, the mixing characteristics and physical condition of the mixer drum to influence the properties of the mixed concrete. These factors may be controlled on any project by rigid inspection and proper specifications based upon experience and research.

#### Placing

The manner of placing, spreading and finishing the fresh concrete on the subgrade has a deciding effect on subsequent performance of the hardened concrete. It is essential that the mixer operator spread the concrete from the bucket in such a manner as not to cause segregation or dense areas in the structure. To overcome these irregularities, equipment in the form of concrete spreaders have appeared on the market. Whether or not this equipment is justified from a practical standpoint has yet to be determined for air-entrained concrete. Proper inspection as well as cooperation from the mixer operator in these matters will go a long way towards eliminating these factors.

### Finishing and Curing

In the finishing operations on air-entrained concrete pavements there are several factors which enter into the subsequent behavior of concrete surfaces. They are:

1. Improper coordination of the strike off and finishing screed of the finishing machine and longitudinal float. The improper coordination of this equipment will necessitate too many passes over the concrete surface resulting in an over-finished and uneven surface.
2. Excessive hand finishing due to faulty machine finishing mentioned above.
3. Inadequate curing.

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

When air-entraining agents are used, the mix becomes somewhat sticky and better results are usually obtained by increasing the number of alternations of the transverse float for a given longitudinal travel. Use of a steel-shod float may also facilitate the finishing operation. Finishing and curing operations on air-entrained concrete can and should be started much earlier after placing than on normal concretes.

## AIR-ENTRAINED CONCRETE IN BRIDGE STRUCTURES

In general it may be stated that the evidence supports the use of an air-entrained concrete in structures provided proper precautions are taken in the design and control of the concrete mixture to insure satisfactory bond and compressive strengths. In this respect it is imperative that the air content shall be controlled within definite limits and that full advantage be taken of the possible reduction in water-cement ratio and sand-aggregate ratio made possible by the greater plasticity of air-entrained concrete.

Pertinent facts concerning the use of Winsol resin cement in reinforced structures may be summarized as follows:

1. Strength of bond between concrete and steel is not materially affected by the addition of Winsol resin to the cement, provided the mix is properly designed and the air content kept within limits corresponding to a drop in weight of 3 to 6 pounds per cubic foot.
2. Compressive and flexural strengths of concretes containing air-entraining agents may be made to closely approach or equal those obtainable without the use of such agents, with the same provisions stipulated in the previous item.
3. The concrete mix must be designed to take advantage of reduction in the water-cement ratio and sand-aggregate ratio in order to secure maximum strength.
4. Close control of unit weight must be exercised in the field to insure uniformly high strength and durability.

There is no apparent reason why air-entrained concrete cannot be used in structures provided proper control methods are exercised by the Department as discussed in the text.



## AIR-ENTRAINING AGENTS IN TRANSIT-MIXED CONCRETE FOR HIGHWAY STRUCTURES

From the experiences of the Department, as well as from those of other users of air-entrained concrete, it is quite evident that air-entraining cements or air-entraining agents added at the mixer are not adaptable to transit mixed concrete as produced at the present time. This is due to the fact that the process in itself cannot be successfully controlled from the moment the materials are introduced into the transit mixer until the time that the concrete has been discharged at the job. Because of the limited amount of control that the Department is able to exercise over transit-mixed concrete and the variation in air content which might be expected under such conditions, air-entrained concrete produced by transit-mixed methods should not be used in bridge structures or pavement slabs of any consequence.

The reason why transit-mix concrete cannot be controlled successfully is based on the following recognized facts:

1. It is necessary to add water in excess of that called for in the mix design to compensate for the drop in consistency of the mixture during transit.
2. The consistency of the mix changes with distance and time of haul and time of discharge.
3. The air content of the mixture will vary with the above conditions as well as with the number of revolutions, the speed of mixing and the mixing characteristics of the transit-mix equipment.
4. A project of normal size will require the use of transit-mix equipment of which no two units will have identical mixing characteristics or operators. Their physical condition will vary considerably.

5. On projects where long hauls are required delays in time of haul due to traffic conditions, forced delays, changes of routes, etc., complicate control possibilities.
6. Different cements and air-entraining agents react differently in transit-mix operations.

## IMPROVEMENT OF INSPECTOR PRACTICE

The question as to whether the air-entraining agent should be added at the mill or at the mixer is of minor significance if a satisfactory end product at the mixer can be obtained by proper control methods. It is believed that it is possible to produce an air-entrained concrete of uniformly high quality practically by means of the following three point program involving education and cooperation, control on the job, and competent personnel.

### Education and Cooperation

In the matter of air-entrained concrete it is believed that a conference should be held at which all highway personnel engaged in concrete construction and all contractors, together with their superintendents or key concrete men, should be invited to attend. At such a conference all phases of modern concrete pavement, design and construction, would be discussed from the viewpoint of the Department, as well as from that of the Contractor. Much good should come out of such a meeting. In addition, all concrete plant inspectors and paving inspectors should be given a thorough schooling in the design and manufacture of air-entrained concrete.

### Control on the Job

At the present time, paving operations are under the control of two men - the plant inspector and the paving inspector. These men are responsible to the project engineer. A review of the Road Construction Manual will show that the present duties of these men are too numerous to insure adequate control of air-entrained concrete, or any concrete for that matter.

The plant inspector should have an assistant. Together these men should exercise close control over all phases of concrete mix operations.

They should be properly trained and adequately equipped with suitable apparatus to perform all duties now stipulated and, in addition, they could determine the air content, yield and consistency of the concrete at least twice a day and as emergency conditions should demand.

The assistant plant inspector could relieve the paving inspector of his concrete control duties and thereupon the paving inspector would have more time to devote to operations near the mixer such as subgrade preparation, placing of the concrete, placing of the steel mesh, and installation of joint assemblies.

At the present time, a project engineer usually has jurisdiction over several projects at one time. Such a policy cannot under any circumstances be conducive to attaining good work. It is recommended that each project of an appropriate size and character should have at all times an engineer with full authority to act on all matters pertaining to normal operations of the job. This so-called project engineer would relieve the paving inspector of certain responsibilities such as the necessity of leaving the mixer unattended for long periods of time in order to attend to outlying duties. Such an arrangement would provide closer adherence to specification requirements on the part of the contractor.

The cost to the state for this additional inspection personnel would be insignificant when compared to the cost of the work for which these men are responsible and to the added quality in the job which would result, thus assuring a more satisfactory job and a greater economic life of the structure.

#### Inspection Personnel

Specifications and control measures are of little value unless qualified personnel are available to enforce them and they in turn are insured of the full backing of the Department. Therefore, it is essential that every effort

be made to procure the best possible men for inspectors. Such men should possess a background of engineering education, experience and character that would enable them to perform their functions with fealty and zeal and allow them to advance to more responsible positions within the organization. The potential source for such personnel will naturally be our colleges and universities. Special inducements will be needed to attract young engineers into the state highway organization.