A CRITICAL APPRAISAL OF THE AIR-ENTRAINMENT IN CONCRETE

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ABSTRACT

This paper attempts to incorporate the available literature and furnish some knowledge for considering the fundamental aspects of air-entrainment in concrete. Various regulating factors, such as concrete temperature, ingredients (materials), consolidation, pumping, and mixing as well as placing techniques, are discussed in details. The development of air-entraining agents is presumably one of the imperative technological advancement in construction materials. It has been used to improve various properties of concrete which is discussed in this work.

KEYWORDS: *Air-entrainment; Air content; Concrete; Durability; Temperature; Workability*

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1. INTRODUCTION

In the context of concrete technology, entrained air means that air which is intentionally introduced into the concrete in the form of uniformly distributed microscopic bubbles. These bubbles on an average are of the order 0.25 mm to 0.025 mm (appropriate amounts) to produce a desired inter-bubble spacing and resultant desirable effect. “Entrapped” air is automatically included during the batching and mixing operations, random in amount, size, and shape of the various inclusions mainly in amounts to a defined percentage or so of the volume. Generally, 400 to 600 billion air-voids are entrained in one cubic yard of concrete containing 3 to 6% of air. Entrained air produces discrete pockets in the cement paste so that no channels for the movement of water are formed and the permeability/porosity of the concrete is not increased. The voids are never filled with the products of hydration of cement as gel can form only in the water filled capillaries.

Entrained air, in the form of finely divided bubbles, uniformly distributed throughout the concrete mass, can be produced in two ways either by using a foaming agent which causes air to be entrained during mixing, or by the use of an agent (with constituents usually present in cement) producing a gas.

The general effects of air entrainment are to increase the consistency, workability & durability, decrease density (unit weight), decrease strength and reduce bleeding & segregation. Air entrained concrete is more resistant to weathering cycles than plain concrete. Air entrainment leads to possible reduction in the sand content of the mix which is approximately equal to the volume of the entrained air. Each percent of entrained air permits a reduction in mixing water of about 3 percent, with no loss of slump and hence some gain in workability. By redesign of the mix to maintain constant workability, the tendency to decrease strength can be partially offset, so that the reduction in strength will rarely exceed 15 percent. The decision of using air entrainment or how much air to entrain generally depends upon to what degree the strengths can satisfy the interest of improved durability.

For average mixes, each percent of air entrained causes reduction in strength of about 3 to 4 percent. Experiments shows that the improvement in impedance to freezing and thawing does not occur unless the air content is greater than about 3 percent depending on the maximum size of aggregate used in the mix & the content of entrain air. In addition to above advantages, due to increase in workability it is easier to work with this type of concrete, it shortens time of setting and vibrations that are necessary for proper consolidation and there is considerable saving in materials especially cement. The use of entrained air has made rapid advances in concrete technology and considerable amount of research and experimental is still going on in U.S.A. in this field. A wider use of air-entertained concrete in future is highly probable.

2. HISTORY OF AIR-ENTRAINMENT

During the 1930s, it was examined that certain length of road in the North-East States of America were able to bear the effects of freezing & thawing conditions and of the existence of deicing salts more than other roads in the area. An experimental investigation revealed that the more durable roads were less dense and that the cement had been obtained from mills where beef tallow had functioned as an air entraining agent and had enhanced the durability of the concrete. This led a more restrained investigation, and in 1939 an air-entrained concrete carriageway was produced by the New York Department of Public Works. Since then interest in the effect has grown rapidly. An extensive amount of experimental work has been carried out in America, new tests and apparatus have been devised and a great deal has been written about the subject. Now in many of the countries air-entrained concrete is used for road work. In U.K., the air entrainment of concrete carriageways and air-crafts runways is now accepted as normal practice and several hundred kilometers of this type of concrete pavements have been in place where a material used as a foaming agent for lightweight concrete, a proportion of animal glue added to further stabilize the bubble structure. Some of the materials were as described below:

2.1 Fatty Acid Salts

The fatty acids are used as air-entrain agents in order to satisfy the requirements such as performance in use, and the ability to form stable aqueous solutions of adequate strength. These fatty acids are present in a distribution of chain lengths, naturally occurring fats and oils such as coconut oil are used in the form of such mixture for concrete. Conventional formulations contain about 20% by weight of fatty acid salt. These products (unlike neutralized wood resins) are compatible in solution with certain lignosulphone and hydroxycarboxylic acid salts to form admixtures acquiring air entraining and water reducing capabilities.

2.2 Alkyl-aryl Sulphonates

The alkyl-aryl sulphonates tend to find utilization in the production of light weight concrete (LWAC) and not in enhancing the freezing-thawing durability of normal concrete. The common raw material is ortho dodecyl benzene sulphone, a basic surfactant used in a variety of industrial and domestic detergents. The formula for the same is shown in Table 1.

The hydrocarbon base is petroleum derived. The sulphonation process utilized can vary from direct reaction with sulphuric acid to SO_2/SO_3 mixtures; result in some excess sulphuric acid. On neutralization a proportion of sodium sulphate is produced which is preferably kept to a minimum for admixture formulations.

2.3 Alkyl Sulphates

The available literature describes the use of several materials of this type which are summarized in Table 1. These products are also compatible with a number of water reducing agents to produce air-entraining agents which can be further used in the production of air0entraining concrete.

Table 1: Materials Used As Air-Entraining Agents

Material	Formula
Sodium dodecyl Sulphate	$C_{12}H_{25}SO_4Na$
Sodium teradecyl Sulphate	$C_{14}H_{29}SO_4Na$
Sodium Cetyl Sulphate	$C_{16}H_{33}SO_4Na$
Sodium oleyl Sulphate	$CH_3(CH_2)_7CH=CH^-(CH_2)_8\ SO_4NA$

2.4 Phenol Ethoxylates

Phenol ethoxylates are different as they are non-ionic materials. They are not widely used but are very effective at low addition levels and solutions of 2 to 4 % by weight in water perform adequately at low dosage level. The most common material is nonylphenol ethoxylate and there are limited studies about it indicating that the higher value is the most effective.

3. AIR-ENTRAINING AGENTS (AEA)

Details of three air entraining agents are given below:

- **Vinsol Resin**

It is the byproduct obtained during distillation of pine wood and it is insoluble fraction of coal-tar hydrocarbon extract of pine wood. It is generally mixed with caustic soda to give a water soluble product. It is merchandised as dry powder, which must be mixed with sodium hydroxide to prepare a solution for the job. It is also available as solution.

- **Rihand A.E.A**.

In Rihand Dam (U.P.), an Air-entraining agent designated as Rihand A.E.A. when used as 0.003 percent of solid agent by weight a of cement resulted in a saving of 3,00,000 bags of cement valued Rs 18.0 lacs at the dam site. The total quantity of mass concrete used was 14.2 lacs cubic meters.
The Rihand A.E.A. is prepared from the indigenous gum Resin an extract of pine wood. Commercial caustic soda equivalent to 134 to 20 percent of Gum Resin is mixed with it in water. This is cheaper than Vinsol resin and is more efficient for entrainment of air. Rihand A.E.A. has been used 0.003% of solid agent by well of cement. The quantity of Rihand A.E.A. required for entraining 3 to 5% of air is only about 30% of the corresponding quantity of vinsol resin.

- **DAREX**

This is a tri-ethanolimine salt of a sulphonated hydrocarbon which is available in liquid form. It is obtained during refining of petroleum products.

4. AIR ENTRAINING PORTLAND CEMENTS

These cements are produced by inter grinding with Gypsum, clinker & a minute amount of soluble soap, or other air-entrain agent usually not more than 1%. The chemical requirements are given in A.S.T.M. specification for air entrain Portland cement for three types, namely IA, IIA and IIIA, Air-entrained concrete is produced with this type of cement with further addition of A.E.A.
Numerous proprietary brands of air-entraining agents are available commercially but the performance of the unknown brands should be checked by trail mixes in accordance with IS: 1199-1959 which lays down the performance requirements of air-entraining admixture. The main requirements of an air-entraining agent are that it immediately produces a system of finely divided stable foam, (the individual bubbles of which resist coalescence) as the foam have no toxic chemical effects on the cement.
It is invariably presumed that the entrainment of air in concrete leads to a noticeable reduction in the compressive strength. However, it was shown earlier that the re-proportioning of concrete contents will not result much change in the strength of same mass air bubbles in concrete containing 3 to 6% air by volume and at consistent cement content within the range 200 to 400 kg/m^3, will have only negligible loss in strength. Indeed, at the lower cement content there could be an increase in the compressive strength.
However it is useful to be able to predict the 28 days compressive strength of special concretes containing entrained air, perhaps, much higher content for insulation or density reasons, or alternatively in mixes where no water or sand reductions are made. In this case the volume of extra air entrained should be considered in terms of an equivalent volume of water and added to the water previously in the mixture. The new water and air/cement ratio can then be used to estimate the 28 days compressive strength from the standard which gives the change in w/c ratio for prediction purpose for each 1% air entrained.
There are three main ways of incorporating air or gas cells in concrete which is as follows:

- By the addition of some minerals e.g. Aluminum powder or Zinc powder which generates gases by chemical reactions with
- By means of surface active agents that diminishes the surface tension and small air bubbles are formed. These are called A.E.A.
- By the use of cement dispersing agents which are surface active chemical compounds which cause electrostatic chem. to be imported to the cement particles rendering them mutually repellent and thereby preventing coagulation.

Out of these second method is used for obtaining controlled air entrained concrete and therefore is adopted. The A.E. agents in this method can be classified as:

- Natural wood resins and their soaps. The trade name for this type of A.E.A. is vinsol resign.
- Animal or vegetable fats and oils such as tallow and olive oil and their fatty acids such as satiric and oleic acids and soaps.
- Wetting agents like alkali salts of sulphonated sulphated organic compounds. The trade name for the type is Darex.
- Miscellaneous materials as the sodium salts of petrole sulphonic acids, hydrogen Peroxide, Aluminum. The essential property of their air-entraining agents in its foam shall be stable. Under normal

conditions there are used in a very small quantity generally between 0.005 to 0.05 percentage by weight of cement.

5. REVIEW OF THE LITERATURE

After an extensive study and reviewing of the available literature, the following effects of entrained air on concrete properties have been reported

Du & Folliard, 2005 reported about the tendency of bleeding and segregation were greatly reduced with increased entrained air. The bond between steel and concrete may decrease with increased entrained air. The compressive strength decreased by 5% for each 1% air increase. The de-icer frost scaling was significantly reduced with increased entrained air. The density of concrete decreased with increased entrained air. The stickiness increased with increased entrained air, which makes it harder to finish. The effect on permeability of concrete with increased entrained air was very little. However, with increased entrained air content and equivalent compressive strength the w/c ratio needed to be decreased, which then lead to reduced permeability. The slump increased with increased air content, approximately the slump increased 25 mm in slump for every 0.5 to 1 percentage increase in air. The thermal conductivity of the concrete decreases 1% to 3% per percentage increase in air. The expansion due to alkali-silica reaction has been reported to decrease with increased air.

Nagi and Okamoto, 2007 deduced the following observations of factors influencing entrained air. The air content decreased with the increased fineness of cementitious materials. Fine aggregates could entrain more air than coarse aggregates. When the slump was less than 150 mm the air content increased with an increase in slump. However, above 150 mm, large air bubbles were more unstable due to buoyant force to escape from the mixture, which reduced the air content. With increased temperature the air content decreased. Maximum air content was achieved at normal mixing time. Mixing too short or too long reduced the air content. Transportation may decrease the air content while pumping often decreased the air content. With the use of other cementitious materials, like fly ash and slag, a higher dosage of AEA was required compared with Portland cement in the same condition. The influence of other chemical admixtures for air entrainment was complex. Normally, most organic chemical admixture could increase the air entrainment.

6. MECHANISM OF AIR ENTRAINMENT

Air bubbles were not formed by air-entraining agents (AEA), but stabilized by them. As the air-entraining agent molecules were inserted between adjacent water molecules at the water surface, the mutual attraction between the separated water molecules was reduced. Lowering the surface tension stabilized the bubbles against mechanical deformation and rupture, making it easier for bubbles to be formed. Without the presence of an air-entraining agent, the smaller bubbles, which have higher internal pressure, coalesced to form larger bubbles that had a greater tendency to escape to the surface and burst. Absorbed AEA molecules at the surface of the bubble form end a film, with their polar heads in the water phase. If the molecule was charged, the bubble acquired this charge (Dodson, 1990). The ends of the AEA molecules that protruded into the water were also attracted to cement grains. This allowed for a coating of calcium salts (i.e., products of cement hydration) to form around each air bubble, making it more stable than bubbles formed in plain water.

7. FACTORS AFFECTING AIR ENTRAINMENT

Certain factors affecting the entrainment in concrete are as follows:

7.1 Cement Alkali Level

For a given dosage of AEA, the air content increases as the alkali content of the cement was increased, because alkalis allow more air-entraining agent to remain in solution during mixing, thereby maintaining lower surface tension for longer period of time and leading to greater volume of air entrained. Some studies have concluded the air bubble systems formed in a high-alkali environment are not stable while others suggest that they are stable, especially in the presence of chemical admixtures (Pigeon, 1992; Greening, 1967; Pistili, 1983).

7. 2 Supplementary Cementitious Material

Use of supplementary cementitious materials can affect air entrainment. Carbon found in fly ash can attract and absorb surfactants used in air-entraining agents (Klieger and Perenchio, 1976; Ramachandran, 1995). Some fly ashes with a high loss on ignition (LOI) did not necessarily contain significant amounts of reactive carbon, possibly because of carbon phases that become encapsulated in glass spheres during cooling and were prevented from adsorbing the surfactants or when a portion of the LOI results from carbonate (Detwiler et al., 1996). Ground granulated blast furnace slag (GGBFS) was normally used at high dosages, generally up to 50 percent by mass of cementations materials. Because GGBFS is usually finer than cement, up to 100 percent more fine, AEA might be needed when finely ground GGBFS was used at higher dosages. Silica fume was normally used at dosages between 5 and 10 percent by mass of cement (3 to 6 percent in ternary mixes) and did not have a significant influence on the production and stability of the air-void system, but, because of its fineness, greater amounts of AEA were needed (Whiting et al., 1993).

7.3 Chemical Admixtures

Certain combinations of water reducers and air-entraining admixtures could be incompatible in such a way as to lead to unacceptable air-void systems. Planet et al. (1989) indicated that increasing the dosage of water reducers influenced the air-void system. Doubling the recommended dosage of any of three water reducers adversely influenced the stability of the air-void system, but no consistent relationship between the admixture dosage and the resulting air content was found. Accelerating admixtures had a minor effect on the air-void system. Stott et al. (1994) found that the air content and spacing factor of mixes containing both calcium chloride and non chloride accelerating admixtures did not differ from those of the control mixes. Attiogbe et al. (1992) indicated that properly air-entrained concrete containing super plasticizer could have adequate frost resistance, even if the spacing factors were relatively high concrete mixtures with spacing factors exceeding 0.008 in. (0.20 mm) the maximum values recommended by the American Concrete Institute (ACI). Durability Committee were found to have acceptable frost resistance.

7.4 Aggregates

Coarse aggregate surface texture and maximum size could influence the air content. Crushed stone aggregate would entrain less air than gravel aggregate (Dodson, 1990). Because the mortar volume generally decreased as the aggregate size increased and the entrained air was contained within the mortar fraction, the air content of concrete generally decreased. Benfield and Okundi (1999) showed that saturation of the aggregates influenced the air-void system in concrete. When partially saturated aggregate was used in concrete, air bubbles, typically 100 microns in diameter were formed at the surface of coarse aggregates leading to noticeable strength reduction. Air, trapped under pressure inside aggregate particles during water absorption, migrated out between concrete placing and setting to produce the voids. Sand contributes to air entrainment by trapping air bubbles in the void spaces between sand grains. Sand in the middle-size fractions of No. 30 to 100 sieve was the most effective in entraining air, while fine sand (less than 100 meshes) had negligible effect because the effective screen size approached the size of the largest bubbles.

7.5 Mixing

For a given mixer, the mixing time plays an important role in controlling the air content. An adequate air-void system could be achieved in as little as 60 seconds of mixing (Barbee, 1961).Variations in air content were much higher for a concrete produced at extremely short mixing times.

Air bubbles in concrete are firstly entrained by mixing process. Hence, the mixing is important factor which together with the aggregates can affect air entrainment in concrete, since the large air bubbles can be split into smaller ones by the movement of aggregates in the mixer. From the viewpoint of work and energy, the formation of air bubbles in fresh concrete can be explained as follows: The mixing action gives the energy to the fresh concrete creating the interface between air and water and forming the large air voids, and then split them into small voids. However, there is a tendency that the small air voids coalesce into larger ones. From the energy viewpoint it is clear that for the same volume of air, the one contains small air voids has a larger specific surface area and therefore higher energy than the one with large air voids, the latter can always more easily escape from the paste due to its larger buoyant force. So, the mixing action (mixer, mixing time, revolution rate, etc.), can affect the amount of energy that can be turned into free surface energy of the air bubbles which balance the surface tension of the air bubbles. For example, mixing with longer time can of course entrain more air in fresh concrete by applying more work on the paste.

7.6 Consolidation

Consolidation through vibration reduced the friction between the aggregate particles to remove pockets of entrapped air and made the concrete more flow able (Whiting and Nagi, 1998). The loss of air content because of vibration depended on the concrete slump, initial air content, vibration frequency, and time of vibration. Studies have shown that for a given vibration frequency and vibration time, the loss of air increased with increased slump (Higginson, 1952). An increase in vibration frequency also had a significant effect on the air-void system. The spacing factor for concrete subjected to 20 seconds of vibration significantly increases as frequency was increased from 11,000 to 14,000 vpm (Stark, 1986). However, the spacing factor remained relatively unchanged for frequencies of 8000 vpm or less, even though the air content was decreased. In some concrete pavement construction, scaling caused by cycles of freezing and thawing was observed in paths following the vibrator heads on the paving machine; it was attributed to excessive vibration (Stark, 1986). Tymkowicz and Steffes (1999) reported that cores taken from longitudinal cracks in Interstate 80 in Iowa contained 3 percent air in the top half and 6 percent in the bottom half; they attributed this condition to excessive vibration. They stated that excessive vibration can occur at lower paver speeds, even though the frequency was low (8000 vpm). Stutzman (1999) conducted a similar study on Iowa pavements and determined that the worst air-void systems of deteriorated pavements occurred in the visible vibrator trails.

7.7 Pumping

Pumping affected air entrainment because of free fall and pumping pressure. When handling concrete, the material was often dropped, accompanying loss in air content. Several researchers have been able to trace of the observed loss of air associated with pumping of concrete. The low frequency but variable intensity pulsing of the concrete was normally associated with the loss of coarser air bubbles and what could be a significant loss of total air content. Because large voids make only a small contribution to freeze thaw protection, such losses are often inconsequential in terms of the in-place durability of the concrete (Hover, 1989; Pleau et al., 1995; Lessard et al., 1996; Hover and Phares, 1996). Pumping can also alter the air bubble system by compressing and subsequently de-compressing the air bubbles. At sufficiently high pressure, the pump can compress the bubbles to the point of dissolution of the air into the mix water. As postulated by Meilenz et al. (1958) and summarized by Fagerlund (1990), smaller bubbles and lower surface tension will favour air dissolution. When the concrete is depressurized, the air comes out of solution at a rate determined by the rate of depressurization. Slow, reversible depressurization allows bubbles to reform into approximately their initial state. Rapid, uncontrolled depressurization allows the air to come out of solution explosively, escaping from the mixture or perhaps forming into large bubbles, immediately susceptible to removal on impact. Several researchers have demonstrated the use of various attachments and hose configurations to control depressurization to reduce air loss (Yingling et al., 1992; Macha et al., 1994; Pleau et al., 1995; Lessard et al., 1996; Hover and Phares, 1996).

7.8 Temperature

The temperature of mixture can affect the air entrainment by many aspects. First of all, as it is well known that higher temperature of water leads to the lower solubility of air in water. The slump value the mixture with higher temperature always get higher viscosity and for the mixture with higher viscosity entraining air will become more difficult.

7.9 Surface finishing

Finishing can affect the air content, but this is mainly at the surface and near-surface of the concrete. Finishing may cause the loss of air in concrete by an effect similar to the compressing and de-compressing as mentioned above. However, normally only coarser voids can be affected.

Other parameters which influence air entrainment in concrete can be enumerated as:

- Fineness
- Cement content in mixture
- Contaminants
- Supplementary cementations materials such as silica fume
- Maximum size, etc.

8. CONCLUSION

Air-entrained concrete is the conventional concrete which contains controlled amounts of air in the form of microscopic bubbles added intentionally in the concrete. Some results related to air entrainment concrete remain fruitful for future aspects; other makes the use of AEA's to be a troublesome issue. While enumerating the advantages from the review study, the noticeable change in workability has been noticed and shortened time and vibrations for proper consolidation. Use of AEA's also reduced the amount of cement and water as well. Entrained air greatly improves the durability of concrete, improves the workability of mix, permits a saving in materials, such as cement, reduces the passage of capillary water, reduces the temperature rise in concrete etc.

Decreased strength of concrete is the major concern towards the usage of AEA's. Hence, the practical implication towards the usage of AEA's can be attributed to the fact that how much strength of a structure can be sacrificed so as to optimize the usage of AEA's.

Thus, It is recommended to use AEA's as per requirements of properties of workability, strength and durability requirements. The criteria of using AEA should be based on the amount of strength decrease acceptable and workability enhancement required. Also, the effect of using AEA, on various grades of concrete should further be investigated along with its effect on split tensile strength and other concrete durability skin properties like water absorption, sorptivity etc.

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