Air entrainment and concrete

Some things every contractor should know about a combination that assures longer-lasting and more attractive concrete

Everyone likes a short cut. It's just plain tempting. That's why men once searched for a means of transforming base metals into gold. It seemed so much easier to make it than earn it.

In the area of concrete construction, where much depends on know-how, patience and careful workmanship, it was only natural that short cuts should be offered in the form of admixtures. Of all the many products put on the market in the last few decades, one has risen head and shoulders above the others in its effectiveness. It is, of course, the air entraining agent.

Even this admixture is no wonder-worker, however. It is not intended to replace correct procedures in mix design or concreting. Rather, it complements these quality concrete practices to produce a finished product that will be more durable and satisfactory to all concerned. Let's take a closer look at this pre-eminent admixture.

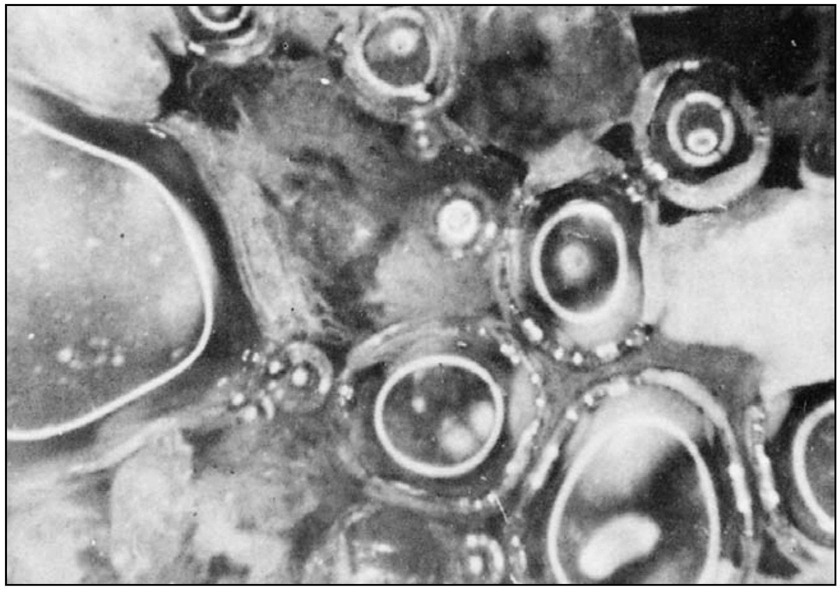


Photo courtesy of Portland Cement Association

This photomicrograph of air entrained plastic concrete suggests how minute bubbles of air function as very small ball bearings which make the concrete more workable than a non-air entrained mix.

What air does

The introduction of air into concrete mixes has some pronounced effects on the characteristics of both the plastic and the hardened concrete.

In fresh concrete, the tiny air bubbles act as a lubricant in the mix which improves its workability and increases its slump. Also, in a sense, the bubbles function as a third aggregate. Because of their small size, the bubbles act as fines, thereby cutting down the amount of sand needed. Because air entrainment affords increased slump, it is possible to decrease the amount of water to get higher strengths without affecting workability. Less water means less drying shrinkage —always a desirable feature. Bleeding in concrete is cut approximately in half by entrained air. This reduces considerably the adverse effects of a higher water/cement ratio at the surface of slabs and of laitance forming on concrete surfaces. Air also produces stickier, more cohesive concrete; as a result, less segregation is experienced and more attractive surfaces are achieved.

In hardened concrete, the outstanding attributes of air entrainment are the enhanced weatherability and resistance to scaling afforded. Damage to concrete by freezing and thawing is caused when enough ice forms in the capillaries to create a pressure greater than the tensile strength of the cement paste. This disrupts the capillary walls. Where enough air voids are present, however, hydraulic pressure created by freezing forces the remaining water into the air voids. These air voids in air entrained concrete act thus as a safety valve by giving the water a reservoir into which to flow. When thawing occurs, compressed air in the voids forces the water back into the capillaries, thereby freeing the voids for use again during the next freeze.

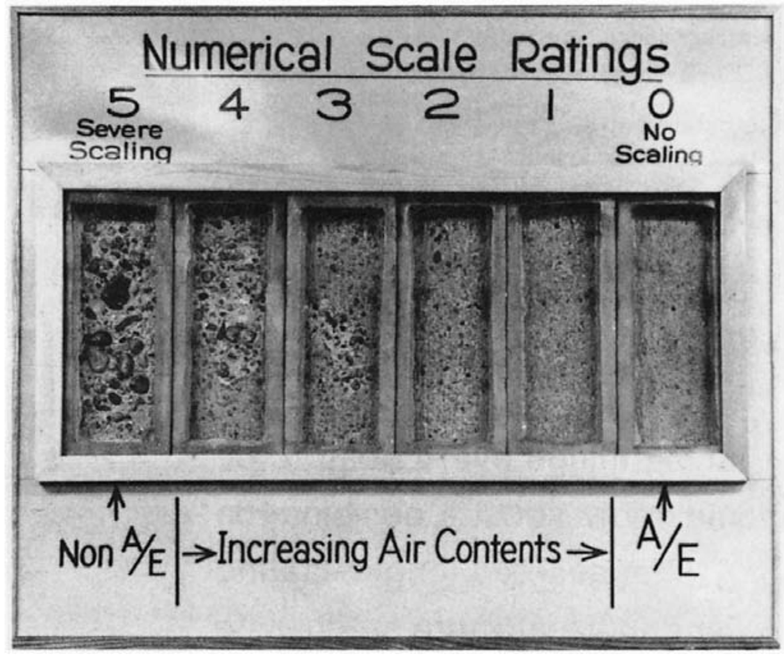
Test sections of pavement in New York State built with and without air entrainment showed dramatically the value of air in exposed work. After 14 years of exposure to the rigors of this northern climate and frequent salting, the non-air-entrained concrete was badly scaled; in some cases 100 percent of the surface was affected. The air entrained pavement, laid next to the other sections, showed absolutely no scaling or D-cracking.

During October 1942, 94 columns cast of concrete made with several types of cements and varying amounts of air entrainment were set on the exposure rack at Treat Island, Maine. At the end of 1 year (188 freeze- thaw cycles) 10 percent of the columns had failed; none were air entrained concrete specimens. After 5 years of exposure (663 freeze-thaw cycles) 26 percent of the columns had failed; again, no air entrained specimens had failed.

Application of deicers to pavements and other flatwork has caused great damage to concrete that is not air entrained. The effectiveness of entrained air in reducing or preventing such damage—called salt scaling—is illustrated in the accompanying photographs of laboratory test specimens. These specimens were covered with water on their top surfaces (the surfaces shown in the photos) and subjected to repeated cycles in which they were frozen and subsequently thawed while deicers were present on the surface of the ice. Specimens were rinsed with clear water before beginning each new cycle.

Sulfate resistance is also heightened by the use of air entraining agents. Although low water-cement ratios and the use of Type II or V cements are of primary importance in lessening the effects of sulfate attack on concrete, air entrainment is also helpful.

Time and again, in laboratories and in the field, tests have unequivocally shown that air entrainment brings about a tremendous increase in the durability of concrete.



The laboratory specimen at the left with no entrained air was severely damaged in laboratory tests of salt scaling. The one at the right, with an adequate amount of air, was undamaged.

How to entrain air

As mentioned earlier, certain alterations in mix design are needed when air is added. The air should be considered as a fifth ingredient when proportioning the mix. The first matter to be considered is the percentage of air desired (see table).

Tests have disclosed that improvement in weatherability is experienced starting at approximately 2 percent air. The lowest amount usually specified, however, is 3 percent. At the other extreme, the maximum air content usually called for is 6 percent. In specifications air content is generally stated as a given figure plus or minus a certain percentage, quite commonly 1½ percent. It is not feasible to hold the percentage constant from batch to batch because air content is affected by so many factors (including maximum size of coarse aggregate, amount of air entraining agent, type and gradation of aggregate, hardness of water, length and means of mixing, brand of cement, and concrete temperature).

Air can be entrained in concrete by either of two methods: the use of air entraining agents or of air entraining cements. The former include such products as natural wood resins, animal or vegetable fats, wetting agents and water soluble soaps of certain acids. These are

If nominal maximum coarse aggregate size[a] is...		Specify...
⅜ inch	(10 millimetres)	8 ± 2 percent air
½ inch	(13 millimetres)	7 ± 2 percent air
¾ inch	(19 millimetres)	6 ± 2 percent air
1 inch	(25 millimetres)	5 ± 1.5 percent air
1½ inches	(38 millimetres)	4.5 ± 1.5 percent air
2 inches	(51 millimetres)	4 ± 1.5 percent air
3 inches	(76 millimetres)	3 ± 1.5 percent air

[a] Normal weight aggregate concretes only. For lightweight aggregate concretes specify 7.5 ± 1.5 percent air for resistance to freezing and thawing; for workability, specify 5.5 ± 1.5 percent for lightweight aggregate concretes in the 3000- to 4500-psi (21- to 31-megapascal) strength range and 4.5 ± 1.5 percent in the strength range above 4500 psi (31 megapascals).

introduced to the concrete when it is batched. Air entraining cements are those made by intergrinding an air entraining agent with the cement clinker during manufacture.

The air entraining component, by whatever method introduced, lowers surface tension of the water and generates a stable foam that results in formation of microscopic air voids. Laboratory calculations indicate that a cubic yard of concrete with an air content in the range of 3 to 6 percent contains from 400 to 600 billion air bubbles.

Choosing the amount and means by which air is to be added to the mix depends on a great number of variables. (In some areas the naturally occurring fine aggregate contains organisms which add 4 to 5 percent accidental air to the mix.) In general, it is easiest and most profitable to consult the supplier of the ready mixed concrete. He is familiar with aggregates, cements and other pertinent factors in the locality and will be able to deliver an air entrained concrete that is consistent and best suited to the job at hand and thereby save some headaches for the contractor.

Working with it

As can be judged from a listing of profound effects produced by the inclusion of air in a mix, it is necessary to modify somewhat the manner in which the resulting concrete is handled. Contractors who are unfamiliar with these differences sometimes blame poor performance on the use of air. In reality, air entrainment will produce significantly better looking, longer lasting concrete when it is handled correctly.

When the mixer truck pulls in with a load of air entrained concrete it is especially important that forms be ready to receive it. Although opinions vary somewhat, it is generally conceded that the amount of intentionally entrained air increases noticeably with mixing during the first 5 minutes. It then remains relatively constant for about 5 additional minutes, after which time the air content decreases gradually. After 40 to 60 minutes of mixing the percentage of air will be about equal to that at 1 minute of mixing. It is apparent, therefore, that a contractor must be ready to receive ready mixed concrete when it is delivered if he wishes to ensure a constant percentage of air. Since high temperatures tend to dispel air from the mix, prolonged mixing during the summer months would also tend to cause variations in air content. The type of mixer used causes differences in the amount of air entrained; but with ready mixed concrete this problem is avoided by the close control afforded by truck mixers.

Since air entrained concrete is more cohesive and workable than non-air entrained, there is not as much danger of segregation and air pockets. Accordingly, vibration need not be prolonged. Vibration time with air entrained mixes should be shortened and kept reasonably constant since it tends to dispel the air. A normal amount of vibration (about ½ minute) reduces the initial air content about 10 percent. When vibrated 1 minute, air content is lowered 15 to 20 percent. In addition, internal vibration reduces air more than does external vibration. Slump should also be watched since air content increases as the slump increases.

As to appearance, air entrained concrete has an unusually creamy, fatty look. This, coupled with the virtual absence of bleeding, sometimes results in incorrect handling of the concrete. In structural work, difficulties are not usually experienced because the mix easily assumes even intricate shapes. It also flows easily around closely spaced reinforcing bars. In slabs requiring finishing, however, a change of technique is required.

When working with non-air-entrained concrete, it is customary to wait until the water at the surface of the slab (caused by bleeding) has evaporated before finishing operations are begun. This classic approach can cause troubles if applied to air entrained concrete slabwork because, as previously stated, air entrained concrete undergoes little bleeding. Often workers have waited for bleeding to appear until the concrete has set up to an extent that makes finishing difficult or impossible. Generally speaking, finishing should always commence sooner with air entrained concrete. Early finishing is even more important when the air temperature is high, humidity is low or a wind is blowing. Finishing need not be carried on as long as with ordinary concrete. All this means that air entrained concrete can be protected and curing can start earlier than with ordinary

+ Numbers in parentheses are references to the metric equivalents listed with this article.

Another dramatic illustration of how concrete pavements are protected by air entrainment. The pavement shown here is at a busy street intersection subjected to heavy and frequent applications of salt. The concrete in the unscaled portion to the left of the joint is identical to the heavily scaled concrete to the right except for the inclusion of entrained air.

concrete.

Sometimes there is a tendency for air entrained concrete pavement surfaces to tear when using mechanical screeds or finishing machines. This can be corrected by shortening the amount of forward motion per transverse stroke or by maintaining a 2½ to 3-inch [1]+ slump. In addition, a longitudinal float as well as a transverse screed should be used. Transverse finishing machine screeds should be adjusted for a lower tilt than is generally used with non-air-entrained concrete. Usually ⅛-inch[2] backward tilt or lift of the front screed cutting edge and a level rear screed prove most satisfactory with air entrained concrete pavements. Concrete pushed ahead of the front screed should have a depth of from 3 to 6 [3] inches during the first pass of the finishing machine. In hand finishing, better results will usually be encountered with a wood rather than a metal float.

Special applications

Purposefully entrained air in concrete has been found to be of value in a number of special applications. In most cases, its excellent weathering qualities and increased cohesiveness render it decidedly superior to ordinary concrete.

Lightweight concrete. Lightweight aggregate concretes have been enjoying mounting acceptance in recent years. As concrete buildings rise higher and spans grow longer, weight reduction has become increasingly important. Almost all lightweight aggregates are manufactured. They are formed by heating clay, shale, slag, slate, mica and pumice materials to a point that is below fusion but that is sufficient to drive off water explosively, thus effectively expanding the aggregate.

The resulting material is lightweight; but it is also angular, porous and cellular—all of which can result in harsh, unworkable concretes. The quantity of water of convenience (that needed beyond the amount necessary for cement hydration) required in lightweight aggregate concrete work is usually considerable This usually means a high shrinkage rate, laitance because of considerable bleeding and lower strengths or higher cement contents than with normal weight concretes. Air entrainment, by producing a creamier mix, reduces the amount of water needed for handling. This reduction amounts to as much as 335 pounds of water per cubic yard[4] of lightweight concrete. Thus compressive strength, homogeneity and impermeability are all greatly improved. Since the air bubbles have no weight, unit weight is decreased and insulating value is increased. It is obvious that lightweight aggregate concretes are benefitted considerably by air entrainment.

The amount of air to be entrained depends upon the intended use and desired weight of the concrete. Structural concretes should have less air than insulating types. Amount of air is usually inversely proportional to the weight of the concrete— the lighter the concrete, the more air is required.

Unfortunately, some properties of lightweight aggregates conspire against entrainment of air. The great angularity of lightweight aggregates reduces the number of air bubbles entrained because the sharp points and edges break the bubbles while mixing is taking place. Also, aggregate angularity results in large void spaces. The consequent large air bubbles break down easily or rise to the surface of the concrete. Ordinarily this means that greater quantities of air entraining admixtures must be used in lightweight concretes. Unfortunately, if very large amounts are used, the organic makeup of the admixtures might result in delayed sets or lowered strength, especially in winter. However, powerful air entraining agents that largely eliminate these troubles have been developed especially for lightweight aggregate concrete work.

Tremie concrete. Tremie concrete (concrete placed under water by gravity feed through a vertical pipe) has been in use for over a century as a means of placing concrete under difficult conditions—for cofferdams, caissons and underwater foundations and in certain hard-to-reach reinforced concrete situations. It offers the advantages of easy and rapid placement, elimination of dewatering, perfect curing environment and reduction of honeycombing.

Along with these advantages come a number of drawbacks, including nonuniformity, high slumps necessary for flow and high incidence of laitance. In addition, high cement contents are often required. The use of air entrainment has been found to reduce all of these complaints. The greater cohesiveness and workability of air entrained concrete results in greater uniformity and less segregation. Slumps can be reduced and the formation of laitance is greatly retarded. Since the cement content can be reduced, internal heat caused by hydration is lessened. Also, gentler slopes are the rule, thanks to the high flowability of air entrained concrete.

Floors. Air entrainment is often omitted in floor slab construction because this type of flatwork is not ordinarily exposed to weathering. However, as we have seen, resistance to weathering is only one of many advantages of air entrained concrete.

In slab-on-grade work in localities where sulfate attack is likely to occur, air entrainment can help minimize or entirely eliminate deterioration of the concrete. Since segregation is reduced, it is easier to obtain surfaces able to resist the abrasion of heavy traffic. Better workability can be had with less water resulting in less finishing and higher strength slabs. On occasion, inside floor slabs are subjected to freezing and thawing because of delay in the completion of other portions of a structure. In such cases, of course, the margin of safety provided by air entrainment is most desirable. It should also be remembered that on large jobs there is always the human element to be considered when concretes with and without air are being used on the same job. It sometimes happens on such jobs that non-air-entrained concrete is used for exterior work either inadvertently or because workers are not ready to use it in flatwork at the time it is delivered, and it is diverted to the exterior.

For these reasons many specifiers prefer to use entrained air in all one-course floors and for the bases of two-course slabs. There is no reason for using it, however, for toppings of heavy duty two-course floors. Since these toppings are of such low water-cement ratios and contain such high quality aggregates, air entrainment is not required.

Colored concrete. The last decade has seen a considerable increase in the use of exposed concrete as an architectural feature of buildings. Right along with this trend there has been an increase in the use of coloring agents in concrete. Unfortunately, field experience and laboratory tests have shown that certain coloring agents (especially carbon black and black iron oxide) result in a lowering of the weatherability of the concrete.

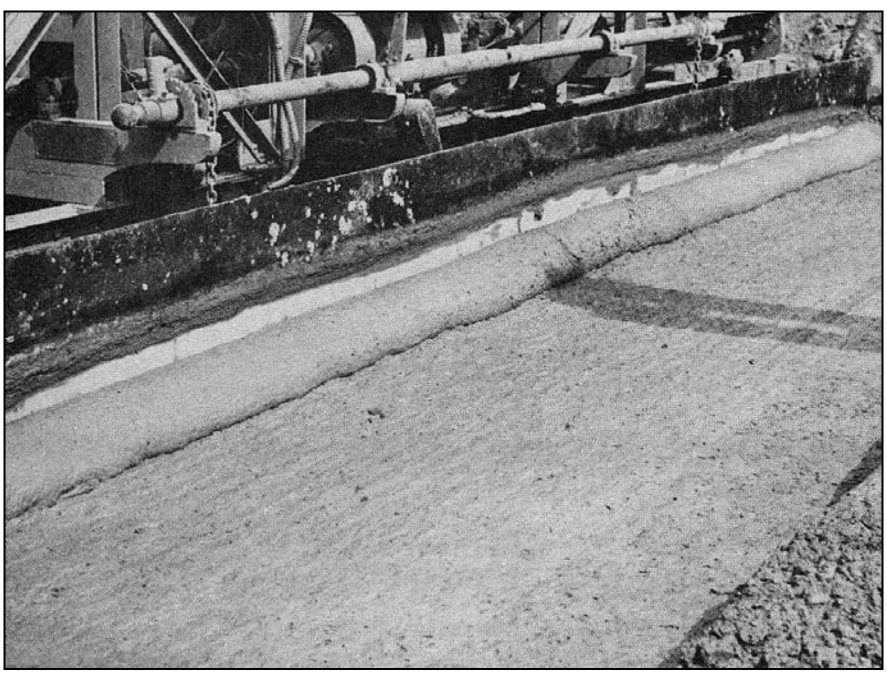
It appears that this adverse effect is a direct result of the action of coloring agents in reducing the air content of fresh mixes. As little as 3 percent by weight of a coloring material in a mix containing 5 percent air results in a reduction in air content to less than ½ percent. When sufficient air entraining agent is used to restore an air content of from 3 to 6 percent, colored concrete resists the action of freezing and thawing and surface scaling to the same extent as non-colored air entrained mixes. Many producers of concrete coloring agents now grind an air entraining agent in with their product.

Strength of air entrained concrete. “But air bubbles don’t have any strength!” And so starts many a discussion on the question of whether air entrainment has an adverse effect on concrete strength. In reality, this question is now resolved with a high degree of certainty to a simple yes and no.

The answer is yes if you refer to identical mixes except for inclusion of entrained air in one of them. Assuming a concrete containing at least 560 pounds of cement per cubic yard[5] and a maximum coarse aggregate size of 1½ to 2 inches, each percentage increase in air content will cause a reduction in flexural strength of 2 to 3 percent and a lowering of 3 to 4 percent in compressive strength. The richer the mix, the greater will be the reduction in strength by use of air entrainment.

The answer is no, however, if proper adjustment of the mix is made. Because air entrainment greatly improves the workability of concrete, the mix design should be altered by reducing the amount of sand and water. If advantage is taken of this characteristic, strengths will be equal to non-air-entrained concretes or, in some cases, even higher. Experiments have indicated that air entrainment mixes are also somewhat less susceptible to the adverse effects of improper curing.

Air entrained mixes are subject to the water-cement ratio law in the same manner as their non-air-entrained counterparts; any desired strength possible with ordinary concrete can be achieved by observing the usual rules of quality concrete.



The roll of concrete ahead of this finishing machine, making its second pass, demonstrates the cohesiveness and workability which are typical of air entrained concrete.

Measuring air content

A number of tests have been devised for measuring the air content of concrete. However, there are basically only three kinds of methods: gravimetric, volumetric or pressure.

The gravimetric method was the first kind of test for air content devised. It consists of obtaining the sum of the absolute volumes of ingredients in a known volume of concrete and subtracting that sum from the measured gross volume. The method is slow, expensive and of questionable accuracy.

The volumetric method simply tests fresh concretes containing any type of aggregate by measuring the volume of entrained air directly. A representative sample of the concrete is placed in the testing apparatus and air is expelled from the concrete by manual methods. A direct reading is made. This technique can also be employed using only mortar (cement, sand and water).

The pressure method measures air content indirectly by noting the volume change concrete undergoes when subjected to a given pressure. Since the only gas in concrete is air, it can be measured by applying a pressure and computing the amount that the concrete contracts. With this test, a correction must be made for the porosity of the aggregate.

Testing the air content of lightweight aggregate concretes by the pressure method calls for special precautions since it measures air in the aggregate as well as in the cement paste. In addition, compression may cause the collapse of air cells in certain soft expanded aggregates. When the mix is excessively harsh, high particle interference and bridging sometimes cause compression of the concrete which is not in proportion to the applied pressure.

Reducing air content

Too much of anything is bad. Use of air entrainment can result in a multitude of beneficial effects. But too much can seriously undermine strengths without improving durability.

Very little weatherability is gained by air contents over 4 percent, but 6 percent air does offer better control of segregation and water gain. Mixes with air contents of up to 12 percent still exhibit the same resistance to weathering as those in the 4 to 6 percent air range. The breaking point appears to occur at slightly over 12 percent, at which point durability begins to decrease markedly.

Although durability is not hurt by such high air contents, concrete strengths are greatly lowered when air rises above 7 or 8 percent. When abnormally high air contents are experienced or when non-air-entrained concrete is required and only air entraining cements are available, there are materials available to remove air from fresh concrete.

Tributyl phosphate is an odorless chemical available from most chemical manufacturers. Ordinarily 10 to 15 millilitres per cubic yard[6] are required to remove all air from a typical mix. Another commonly available chemical, 2-ethyl hexanol, will remove all air from most mixes by the addition of approximately 10 millilitres per cubic yard.[7] Experimentation will be required to determine the exact amount needed to achieve the desired reduction in air content with specific batches in the field.

Here to stay

Air entrainment is with us for good. It has proved its value in so many respects, over such a wide range of uses and for so many years that its future is secure. It is a development in concrete technology that has enhanced the reputation of concrete construction immeasurably by providing at little or no extra cost or effort a material that is more durable and attractive.

Metric equivalents

1. 64- to 75-millimetre
2. 3-millimetre
3. 75 to 150 millimetres
4. 198 kilograms per cubic metre
5. 332 kilograms per cubic metre
6. 13 to 20 millilitres per cubic metre
7. 13 millilitres per cubic metre

This is an updating of the article of the same title published in October 1959, page 1. It is republished here to make the information more readily available to current readers.

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