BENEFITS OF REAL-TIME MONITORING OF AIR CONTENT IN FRESH CONCRETE

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The following commentary suggests benefits derived from continuous, real-time monitoring of air content in fresh concrete, while that concrete is being mixed or agitated inside the drum of a stationary- or transit-mixer.

Part I: Introduction and Background

Air in concrete

All hardened concrete includes air voids formed as the fluid cement paste stiffens around more or less spherical air bubbles acting as pneumatic void-formers. All such bubbles are trapped inside the matrix of the fresh concrete as a result of mixing the concrete ingredients in an otherwise air-filled container. Add to these the irregularly shaped and randomly dispersed pockets of air trapped in the fresh concrete during handling and placing. Subtract from these the air bubbles that float to the concrete surface or are broken due to vibration or the effects of shock, pressure, or depressurization.

When it is desirable to retain a preselected volume of air in the fresh concrete, a liquid or powdered detergent, otherwise known as an “air-entraining admixture” is routinely added to stabilize air bubbles formed and trapped during mixing (the so-called “entrained air”). When such a chemical has been added during batching the concrete is known as “air-entrained concrete,” and the desired total volume of air is specified.

When no such air content is preselected, an air-entraining admixture is not normally used, and the resulting concrete is commonly known as “non-air-entrained concrete.” (This term does not mean “zero” air content, because non-air-entrained concrete can routinely have from 1 to perhaps 4% air content, and even more in unique circumstances). Sometimes a maximum air content is specified for “non-air-entrained concrete” to prevent the problems described later, but unless air entrainment is specified, the air content of fresh concrete is often not measured.

Why do we want air in concrete?

The primary reason for intentionally incorporating microscopically sized air bubbles in fresh concrete is to provide freeze-thaw durability to the hardened concrete. Typical concrete is a porous material with an interconnected network of capillary voids and channels that can absorb both fresh and saltwater during normal environmental exposure. At sufficiently low temperatures some or all of this absorbed water can freeze and expand, generating stresses that are high enough to crack, and in some cases disintegrate, the concrete. Incorporation of air bubbles in the fresh concrete produces air voids in the hardened concrete that act as pressure-relief zones into which ice and unfrozen water can expand during freezing. A typical cubic yard of air-entrained, freeze-thaw resistant concrete will contain about 10 billion air bubbles ranging in size from that of the coarse aggregate particles (10-20 mm) to that of the cement particles (5-10 µm).

Achieving resistance to multiple cycles of freezing and thawing depends on parameters in at least four categories. First, pressures generated in freezing (and relieved in thawing) depend on the porosity, permeability, and tensile strength of the specific concrete in question. Second, the intensity of the freeze event depends on the rate at which the temperature drops, the lowest temperature achieved, and the duration over which that low temperature is held, in combination with the degree to which the pores were full of water prior to the freeze event. Third, for a fixed set of the first two conditions, freeze thaw durability depends on the number, size, spacing, dispersion, and cumulative volume of air voids in the hardened cement paste. Size of the air bubbles matters because generally speaking, the smaller the air-void the more effective it is in providing freeze thaw durability *per unit volume of air*. Finally, the air void system and material properties in the hardened concrete in-place, are also influenced by changes in the air bubbles and cement paste during concrete production and transport, and construction operations. Influential factors include ambient and concrete temperatures, chemistry of other materials present, type and RPM of mixing and time from batching to discharge, method of concrete placement and consolidation, and methods and timing of finishing (texturing) and curing the concrete surface.

Over the almost 70 years since the introduction of air- entrained concrete this complex combination of factors has been reduced to a few general rules and specifications that focus on the cumulative volume of air bubbles in the fresh concrete. (See Appendix). While general conformance with these basic specifications generally leads to satisfactory concrete performance under freezing and thawing exposure, there are cases of unsatisfactory durability for which the many other contributing factors must be examined to define causes and remedies.

Are there other reasons for wanting air-entrained concrete?

Fresh, air-entrained concrete is generally “stickier” than non-air entrained concrete. (This is likely due to the electrostatic attraction between cement particles and air bubbles.) This can be desirable by giving fresh concrete more cohesiveness and resistance to segregation. Although “stickier,” air entrained concrete can also be a bit “creamier,” increasing finish-ability at moderate air contents of perhaps 3% or less. (At higher air contents the cohesiveness becomes a liability.) Incorporation of an air-entraining admixture also generally makes it possible to reduce the amount of water required to achieve workability by approximately 10% with potential benefits for strength and durability. If water content is not intentionally reduced the consequence of increased air content is generally an increase in the workability (slump) of the concrete, and increasing the air content of concrete that is already mixed almost always increase slump.

There may also be some temporary increase in resistance to both sulfate attack and alkali silica reaction due to the expansion space provided by the air voids in the hardened concrete. However, each of these benefits is not only secondary to the primary benefit of improved freeze-thaw resistance, but each can be obtained more reliably by other methods. There is however the undeniable benefit of producing concrete with a lower density by increasing the air content, which can be taken to the extreme by a variety of foaming techniques. There has also been some recent interest in intentionally *lowering* the strength and stiffness of concrete by means of increased air content for applications in which less brittle concrete is desirable. The reduction in strength associated with air entrained concrete is generally a disadvantage and will be discussed more fully.

When DON'T we want air-entrained concrete?

The compressive and tensile strength of concrete decreases as air-content increases. This is because of the increase in porosity brought about by air voids that contribute zero strength. The magnitude of this effect varies, but a typical estimate is a loss of compressive strength at an age of 28 days of about 200-250 PSI per percent increase in air content. (For example, concrete at 5% air would be about 200-250 PSI stronger than the same concrete mix at 6% air at 28 days.) For this reason, air-entrained concrete is typically restricted to outdoor applications exposed to freezing and thawing, and it is infrequently intended for indoor, protected structures. To meet a given strength requirement with air-entrained concrete, the concrete producer may increase the amount of portland cement per unit volume of concrete, with an associated increase in both cost[1] and carbon footprint[2]. The increased cement content may also exacerbate heat- and alkali-related problems and increase concrete shrinkage. The impact of air content on concrete strength (and stiffness) can become much more severe when the air content is high enough to trigger "clustering" of air bubbles between the cement paste and the surface of the aggregates. This mechanism dramatically reduces bond between paste and aggregates and can lead to a much greater reduction in strength and stiffness.

Another major problem associated with air in concrete is the emergence of "slab blisters," or shallow delaminations in the concrete surface, 1 to 2 inches in diameter. These are most commonly identified in smooth, steel-troweled concrete surfaces in which the air content of the fresh concrete was greater than about 3%. Even though the mechanism by which air bubbles near the surface of the fresh concrete contribute to the formation of blisters is not entirely clear, air entrained concrete and steel-troweled finishes have been so frequently associated with the subsequent emergence of slab blisters that standard industry documents warn of this phenomenon. For example, ACI 301-16 (Specification for Structural Concrete) states the following:

> "4.2.2.4(d) Concrete for slabs to receive a hard-troweled finish shall not contain an air-entraining admixture or have a total air content greater than 3 percent."

The American Society of Concrete Contractors (ASCC) has gone on record with the following:

> "ASCC concrete contractors will hard-trowel air-entrained concrete if required by specification, but only with the acknowledgment that the risk associated with delamination or blistering and the changes in hardened air void parameters are entirely the responsibility of the specifier."

One other finishing-related problem associated with air content is the fact that the presence of air bubbles, electrostatically attached to cement grains, impedes the vertical rise of mix water to the surface of recently cast concrete. The appearance of water on the concrete surface is known as "bleeding." Experienced concrete finishers wait for the appearance and subsequent evaporation of bleed-water prior to initiating finishing operations. At higher air contents the delay of bleeding can significantly impact the timing of finishing and may make it difficult to achieve the desired surface texture. A related problem is the

[1] The small cost of the air-entraining admixture may cause the specifier to assume that air entrained concrete is likewise an inexpensive option. The real cost of air-entrained concrete comes from the additional cement or other admixtures and the subsequent problems associated with air entrainment.
[2] The production of 1 ton of portland cement releases approximately 1 ton of carbon dioxide into the atmosphere, a factor that varies with cement chemistry and production.

unintentional “softening” of the surface of a concrete floor that is been cast with concrete with an excessive air content. This is critical in industrial applications where abrasion resistance is required.

The dosage of air-entraining admixture is only one of the factors that influence the volume of air in fresh concrete, and choosing to not use an air-entraining admixture will not always lead to low air content. The effectiveness of any given air-entraining admixture is dependent on a host of other mixture- and equipment-specific factors. *Other* admixtures, ingredients, and impurities combined with characteristics of the mixing equipment can stabilize or de-stabilize air bubbles with or without of an air-entraining admixture.

For these reasons we are ALWAYS interested in the air content of ALL fresh concrete, regardless of whether or not the concrete is intentionally air-entrained. There are very few cases in which a knowledgeable producer, contractor, and client would not want to know the air content of fresh concrete. Controlling the air content to within a preselected range, of perhaps 1 to 3%, or perhaps 5 to 7%, (as examples) is so important to the quality and uniformity of the finished product that both ACI 301 (Standard Specification for Structural Concrete) and ASTM C31 (Standard Practice for Making and Curing Concrete Test Specimens in the Field) require that air content be tested every time specimens are cast for testing strength, regardless of whether the concrete is or is not air-entrained. Further, the impact of air content on the workability and finish-ability of the fresh concrete, and on the density, freeze-thaw durability, and potential for blistering on the surface of hardened concrete means that even if the air content of fresh concrete remains above or below some preselected threshold, within-batch, or batch- to-batch variability in air content within that preselected range can lead to variability in fresh and hardened concrete performance.

Why is air content so variable?

Many factors influence the actual air content of concrete, which is expected to vary from initial mixing all the way through the final compaction and finishing of the concrete in-place. Air-entraining admixtures are liquid or powdered surface active agents (detergents) which reduce surface tension at the water/bubble interface and stabilize the fluid boundary enclosing the bubbles. The behavior of these admixtures is sensitive to the chemistry of other admixtures or pigments used in the same concrete, and especially sensitive to the unintentional presence of carbon which may be present in the cement or other cementitious materials, or even from equipment lubricants. Other mixture ingredients (or unintentional impurities in those ingredients) can synergistically increase or destructively decrease air content. With some admixtures it is more difficult to maintain a stable volume during mixing at higher concrete temperature and conversely easier at colder temperature. It has also been observed that the type and RPM of the mixer influences time required to achieve maximum air content, and the duration of mixing at which air content begins to decrease. Buoyant air bubbles suspended in fresh concrete can rise to the surface and break, depending on the degree to which they are held in the interior of the mixture by the “aggregate screen” and electrostatic attraction to the cement particles. (If chemically incompatible, water-reducing admixtures [WRA’s] can interfere with this electrostatic attraction, leading to a loss of air content, or synergistically increase air-content.) Air bubbles are fragile structures that can be broken upon impact resulting from transport (a bad truck-suspension and a lot of potholes can reduce air content) or impact associated with placing the concrete. As elastic spheres, air bubbles have a calculable resonant frequency and vibrations at or near that resonant frequency will cause the bubbles to burst. Air bubbles likewise expand and contract in response to changes of pressure such as generated by concrete vibrators, concrete pumps, or surface-texturing operations. The air content of fresh concrete is thus not a static or constant value but varies with time, construction operations, and external conditions. During the mixing phase in a stationary container and stable conditions the air content in concrete probably reaches a “dynamic equilibrium” in which air bubbles are captured and lost at the air/concrete interface at about equal rates. While some properly executed construction operations have the capacity to increase the air content in fresh concrete, many construction operations can decrease air content; thus it is not uncommon for the hardened air content in-place to be less than the air content in the fresh concrete as it came down the chute of the concrete truck. There have been some exceptions, however, where hardened air content after placing consolidation and finishing, has been equal to or even greater than that at the truck chute.

As a consequence, ASTM C231 (Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method) states:

> “3.3 The air content of hardened concrete may be either higher or lower than that determined by this test method.”

Given that these many factors can simultaneously or sequentially influence the number, size, and cumulative volume of air content in fresh concrete, and therefore the freeze thaw durability of hardened concrete, the ability to continuously monitor air content in fresh concrete during mixing and transport and up to the point of discharge is highly desirable.

The ability to continue to monitor air content through the placing consolidation and finishing stages would be of tremendous value but is beyond the scope of this current discussion.

Part II: Value-Added from Continuous Real-Time Monitoring of Air Content

General purpose process control

Continuous, real-time monitoring of air content would provide the concrete producer with an invaluable process-control parameter. Air content of fresh concrete is a powerful indicator precisely because it is sensitive to time, temperature, intentional and unintentional ingredients, trace impurities, water content, charging sequence, and the speed and efficiency of mixing. The air content of fresh concrete along with slump (or slump-flow), and temperature are **"vital signs."** This is true regardless of whether air-entrained or non-air-entrained concrete is being produced. Stable air content is a likely indicator of *overall* process stability up to the point of discharge. If the air content is stable but lower than target, it is a likely indicator that a higher dosage of air-entraining admixture is required for this particular mix under these particular conditions. When air content is stable but higher than target it is a likely indicator that a lower dosage of air-entraining admixture is required, or that factors other than the admixture are contributing to air content. When air content is unstable it is likely that the instability is triggered by one or more other factors in the production system.

Establishment of a short- and long-term chronological baseline for diagnosing process changes

A benefit of having a continuous record of air content over multiple batches and over multiple trucks would be the ability to identify precisely when, and under what conditions, the air content began to change. Under the current protocol of intentionally random spot-checks of air content, it is difficult to pinpoint when a change took place in the production process that may have triggered either an increase or decrease in air content. The continuous time record of air content would become a very useful baseline for tracking the times at which other components in the system may have changed. This database becomes even more powerful when extended over multiple projects and multiple concrete mixtures.

The current, random or "spot-check" nature of routine testing may not build a comprehensive database that permits analysis of the impact of changing sources of aggregates, cements, cementitious materials, admixtures, and water. For example, the well-known deleterious effects of carbon (from the cement or fly ash) on air content and the consequential need to increase dosage of air entraining admixture can still surprise the concrete producer when the carbon content has changed (up or down) in the most recent delivery of cement or fly ash. Real-time, continuous monitoring would be expected to indicate a change in air content on the very first concrete batch that contained a substantial amount of the new material (regardless of whether that batch was tested by standard methods in the field). Similar comments apply to the ability to observe problems related to compatibility (or incompatibility) problems among admixtures and various cementitious materials.

Indication of the need to modify the process

Changes in air content that approach preselected limits indicate the need for immediate modifications. On the short-term, and without benefit of comprehensive system diagnosis, a not uncommon response to low air content is field-addition of air entraining admixture.[3] An accompanying response at the batching facility should be investigation of the cause for the low air, and a decision whether or not to increase the admixture dosage for subsequent loads. A similar response is required when the recorded air content is unacceptably high.

Knowledge is power for the concrete truck driver; verification of on-site testing

If the driver ("operator") has a reliable indication that the air content is low even before the testing technician samples the concrete, the driver would have the opportunity on-site to increase the dosage of admixture and re-mix with the potential savings of time, potentially saving the entire load.

Under current testing protocols, the first indication the concrete truck driver has of the air content of the concrete in that load is the result provided by the testing technician on-site. If the driver has a reliable indication of the air content of the concrete, even before discharge, the driver would be prepared to call for a check-test if the field technician's result is significantly different.

An informed driver who becomes aware of low (or high) air content would be even more valuable when *no field testing were performed on that particular load*. Unless the driver performed a standard air test, such information would not be available, and concrete with unacceptable air content would be placed in the structure. Possible consequences range from subsequent expensive and time-consuming testing of hardened concrete, inadequate durability, or concrete defects such as slab blistering or abrasive wear. A real-time monitoring system could inform the driver so that immediate action can be taken, and could alert plant personnel to make system changes for subsequent batches.

Indication of satisfactory fresh concrete more than 90-minutes after batching

The default period for acceptability of fresh concrete is 90 minutes after batching (per ASTM C 94), subject to extension only upon demonstration of satisfactory fresh concrete properties without the need for adding water. (In some jurisdictions, this limit is even shorter for air-entrained concrete.) Although the workability of the concrete has traditionally been the primary concern, a strong case could be made for justifiably extending the batching-to-discharge time based on the vital signs of slump (or slump flow), air content, and concrete temperature. All three of these parameters could be available from continuous, real-time monitoring systems inside the truck drum.

Assessing the impact of concrete handling, placing, and consolidation on air content

A major source of controversy in construction with air entrained concrete is the impact of handling, placing, and consolidating concrete at the point of placement in the structure. The effects of construction operations can vary from negligible to significant losses or gains in air content. But a perennial problem in diagnosing these effects is the establishment of a reliable baseline of the air content of the concrete in the truck prior to discharge. Under current testing protocols it is very difficult to establish such a baseline,

[3] Given that adding air entraining admixture will not only increase air content but will always lower concrete strength, increasing air content in the field must be based on a reliable estimate of air content and with knowledge of the maximum permitted air content. The author is familiar with a massive lawsuit resulting from indiscriminate air content increases based on faulty testing with standard methods.

leading to unreliable estimates of the actual effects of construction processes. Continuous real-time monitoring of air content would provide exactly such a baseline enabling for the first time a much more realistic assessment of the effects of construction operations on air content.

Enhancing the reliability of routine concrete testing

Availability of air content as monitored by a real-time system would provide an immediate comparison with on-site standard test results, and a significant deviation between air content in the truck drum and that reported by the technician would likely result in a check-test (essentially a "do-over"). This unprecedented basis of comparison would encourage attention to detail in standard testing, and would inform developers of the real-time system.

Fewer returned loads

It has been reported that 1 to 2% of all concrete is returned to the batching facility for all reasons, of which some portion is because the concrete was rejected due to unsatisfactory slump, temperature, or air content, or it has exceeded the 90 minute time-window. In at least one large city, "returned-concrete" expands to approximately 10% of that initially batched. While more specific data are not available it is clear that the ability to respond to continuously recorded slump, temperature, and air content and to make real-time adjustments would (and probably already has) not only reduce the number of truckloads rejected for being out of compliance with specified values, but increase the number of cases in which the 90-minute window could be justifiably extended.

Influence of variability of air content on variability of concrete strength

While it is clear that major contributors to variability of compressive strength include water control and testing, an often overlooked, yet major factor is variability in air content, with each 1% increase in air lowering compressive strength by 200 to 250 psi. This is important because ACI 318 Building Code requirements include statistical provisions for limiting the probability of accepting concrete with unsatisfactory compressive strength. Evaluation of strength therefore takes into account both the average cylinder strength and the variability of strength-test results. For a given specified strength, a concrete producer who has attained low variability in compressive strength via excellent process control can provide fully acceptable concrete at a lower average strength than a competitor with a more variable product. Depending on other specification requirements, the pay-off to the producer for reducing variability is the ability to use less cement or lower admixture doses and still meet Code requirements.

To put the impact of variable air into context, ⅓ to ½ of the typical variability in compressive strength may be explained by variability in air. For a typical "4500 psi, air entrained" mixture, cutting the variability of air content in half via real-time monitoring could save ¼ to ⅓ sack of cement per cubic yard.

Increased confidence in the finished product

The ability to make real-time adjustments to air content would lower the variability of the product as-placed and as as-tested, and would increase producer-, contractor-, and owner-confidence in the quality of the finished structure. All of the concrete could be monitored and fine- tuned rather than the relatively limited percentage of the concrete evaluated under current testing protocols. If an owner had the choice of discovering that the air content of non-air entrained concrete was too high only after slab blisters developed, vs. discovering that fact while the concrete was still in the truck drum, the choice would be clear. Under current protocols the owner would not have that information until it was too late, since air content is rarely tested for non-air entrained concrete.

Likewise, if that same owner had the choice of discovering that the air content of air-entrained concrete was too low, only after outdoor pavements, sidewalks, stairways, loading docks, and patios showed deicer-salt scaling, vs. discovering that fact while the concrete was still in the truck drum, the choice would also be clear. Under current protocols the owner would not have that information for any truckloads not selected for random testing.

Appendix: General Rules and Specifications for Air-Entrained Concrete

The building codes[4] in all 50 states in the United States refer to the International Building Code (IBC), which in turn refers to the Building Code for Structural Concrete produced by the American Concrete Institute (ACI 318). The tables below are extracted from ACI 318 and show the current requirements for air content in fresh concrete.

Extracted from ACI 318-14, Table 19.3.3.1—Total air content for concrete exposed to cycles of freezing and thawing

Nominal maximum aggregate size, in.	Target air content, percent	
	F1	**F2 and F3**
3/8	6	7.5
1/2	5.5	7
3/4	5	6
1	4.5	6
1-1/2	4.5	5.5
2	4	5
3	3.5	4.5

Extracted from ACI 318-14, Table 19.3.1.1—Exposure categories and classes

Category	Class	Condition
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water
	F3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals

[4] Building Codes set minimum standards that may be made more stringent in project specifications.

As seen in the first table, required air content is higher the more severe the environmental exposure. Note also in this same table that required air content *increases* as the size of the coarse aggregate particles *decreases.* This is because mixtures with smaller aggregates require a larger volume of cement paste[5] to coat the surfaces of such particles, and required air content is actually a function of the paste volume rather than the concrete volume (air voids do not influence the durability of the aggregates). For example, it is not uncommon for the volume of the cement paste to be one third or less of the volume of the concrete as a whole. For a given average size of air voids one can show that the appropriate cumulative volume of air is about 18% of the volume of the cement paste. When the volume of air in the paste is about 18%, and the volume of the paste is about one third the volume of the concrete, the cumulative volume of air bubbles is about 6% of the volume of the concrete[6]. It is interesting that even though air volume relative to paste volume is the controlling factor, historically, our standard methods of measuring air have been capable of producing only the air-volume relative to total concrete-volume, which has come to be reflected in our standard specifications. Whenever serious disagreements arise as to the actual or predicted freeze thaw durability of concrete on a particular project, however, the ASTM C457 test (microscopical analysis) is typically employed, in which the air volume relative to paste volume is statistically evaluated.

[5] Cement paste is the binder composed of portland cement (or other cement-like or "cementitious" materials) and water.

[6] This also means that as concrete producers optimize their mixtures and reduce cement content in the process (by any number of means), the volume of air that will actually provide freeze thaw durability can be less than required in our standard codes and specifications.