INTRODUCING A NEW SENSOR FOR IN-MIXER AIR VOLUME MEASUREMENT

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ABSTRACT

It is well established that freeze-thaw durable concrete requires proper levels of entrained air. As an inexpensive mix component, entrained air can also improve concrete workability. Despite well over fifty years of commercial production of air entrained concrete, the high batch to batch variability of air content is one of the concrete industry's most vexing quality control problems. A sensor has recently been developed that can accurately determine the air volume in concrete based on the impact that air bubbles have on the propagation of low-frequency acoustic waves. This sensor provides continuous, real-time air measurements during the entire mixing process for stationary wall mixers. Knowing the air content in each batch during the mixing process allows producers to adjust practices to dramatically reduce batch to batch air volume variability. This paper will present data developed in a laboratory environment as well as from several precast producers that document the correlation between the acoustically determined air content and that determined via the pressure method in fresh concrete per ASTM C231.

Keywords: Air, Pressure meter, Real-time measurement

INTRODUCTION

Well-controlled air-entrainment in concrete has been universally accepted as a reliable means for enhancing the ability of concrete to resist the potentially destructive effect of repeated cycles of freezing and thawing, as well as altering the workability and yield of cementitious mixtures. Air-entrainment should be mandatory when concrete is to be exposed to such harsh environments, particularly when chemical deicers are being used, as on pavements and bridge decks[1]. Indeed, the ACI 318 building code mandates different levels of air content based upon the severity of the environment that the concrete will be exposed to in service[2]. To achieve different levels of air content, a wide range of surface-active materials have been reported as suitable air-entraining admixtures, which Whiting and Nagi[3] have classified into five broad categories with general performance characteristics for each group. These admixtures are designed to entrain air in the form of small, spherical, discrete air-voids or bubbles dispersed throughout the mixture, in sufficient volume and spatial distribution to provide freeze-thaw durability. A material conforming to the requirements in ASTM C 260 Standard Specification for Air-Entraining Admixtures for Concrete can be classified as an air-entraining admixture[4].

Though air-entrainment in concrete is a well established practice, the amount and form of the air-entrained in concrete can be influenced by some thirty factors which include: (1) the concentration and type of the air-entraining admixture and its influence on surface tension; (2) the use of other admixtures in the concrete mixture; (2) the fineness and composition of cement and supplementary cementitious materials; (3) the amount of mixing energy (time and shear rate); (4) the flow and slump of mortar or concrete mixture; (5) the temperature, water-cement ratio, and water content of the mixture; and (6) the gradation of the fine and coarse aggregates[3,5]. Every one of these thirty or more factors rarely stays constant throughout the day, and in fact one or more factors may often change from batch to batch. The end result is variability in batch to batch air contents that can routinely result in significant material and time inefficiencies, and occasionally durability or structural concerns.

Up until now, the only methods available for determining the air content in plastic concrete (e.g. ASTM C231, ASTM C173, ASTM C138) require removal of a sample of concrete from the mixer, and consume 5 to 10 minutes to carry out. In a precast plant where mixer output is a key determinant of productivity, adding 5 to 10 minutes on any significant percentage of the batches can be quite costly. In addition, many precast producers have no ability to sample concrete prior to discharging the batch out of the mixer. If the air is outside specification limits, the batch must get discarded or re-directed for use in a lower value application. Adjustments are then made on the next batch. However, these adjustments may be futile as the next batch may already have changed. This is analogous to shooting at a moving target based solely upon where it was in the past.

The novel air measurement system evaluated in this study presents a dramatic improvement on the situation described above. The system gives the concrete producer knowledge in real-time of the air contents in the concrete within the mixer as it builds through the mix cycle.

Producers with this device should be able to adjust air entraining agent (AEA) doses and mixing conditions such that every batch is within specification without undue external testing delays.

BACKGROUND

The ability to measure the volumetric air content of industrial liquids and slurries flowing through a pipe using a passive acoustic-based instrument has been commercially available for several years[6]. Using the relation between the speed of sound in a two-phase mixture and the volumetric phase fraction is well known in the case where the wavelength of sound is significantly larger than any process in-homogeneities, such as bubbles[7].

The acoustic-based measurement of process aeration covers several orders of magnitude, from 0.01% to 20% (by volume), and is therefore universally applicable to a wide variation of process conditions. This technology is used in many industrial applications where aeration must be controlled to a desirable level or must be avoided altogether. There are other applications where aeration negatively impacts process control by affecting other types of meters. Examples of these include:

- Tank level/foam control in agro processing applications
- Entrained air in the thin stock flow to a paper machine's headbox[6]
- Entrained air in filling stations for domestic household products
- Dissolving carbon dioxide in beverages
- Errors in consistency measurement of paper stock[8]
- Errors in Coriolis determined volume flow and density as a result of product aeration[9]
- Errors in custody transfer metering resulting from product flashing or aeration

A new implementation of the same technology enables air content measurement of liquids and slurries not constrained within a pipe, such as in stationary-wall concrete mixers.

SPEED OF SOUND IN AERATED CONCRETE

Wood's model[10], for the speed of sound in bubbly liquids describes the acoustic properties of a two-phase mixture where the frequency is much lower than the lowest bubble resonance frequency. This model has been shown to accurately describe the speed of sound in slurries and gas-bearing sediment[11], therefore is also a good basis in the case of plastic, aerated concrete.

Concrete is commonly mixed in a stationary-wall mixer, and in this case will have a static pressure just slightly above atmospheric, always having some level of entrained aeration. Under these conditions and assuming isothermal conditions, the compressibility of the air phase is orders of magnitude larger than the compressibility of the slurry phase, and Wood's equation reduces to Equation 1:

$$c = \sqrt{\frac{P_a}{\phi(1-\phi)\rho}} \quad (1)$$

where, c is the speed of sound, P_a is the absolute static pressure, ϕ is the volumetric fraction of air, and ρ is the density of the concrete slurry.

Wood's simplified model is only dependent on the static pressure and slurry density. Both of these properties are relatively consistent for most concrete mixing applications, and the small variations that do exist can generally be ignored. Figure 1 illustrates the relation between the mixture sound speed and air content for typical concrete slurry.

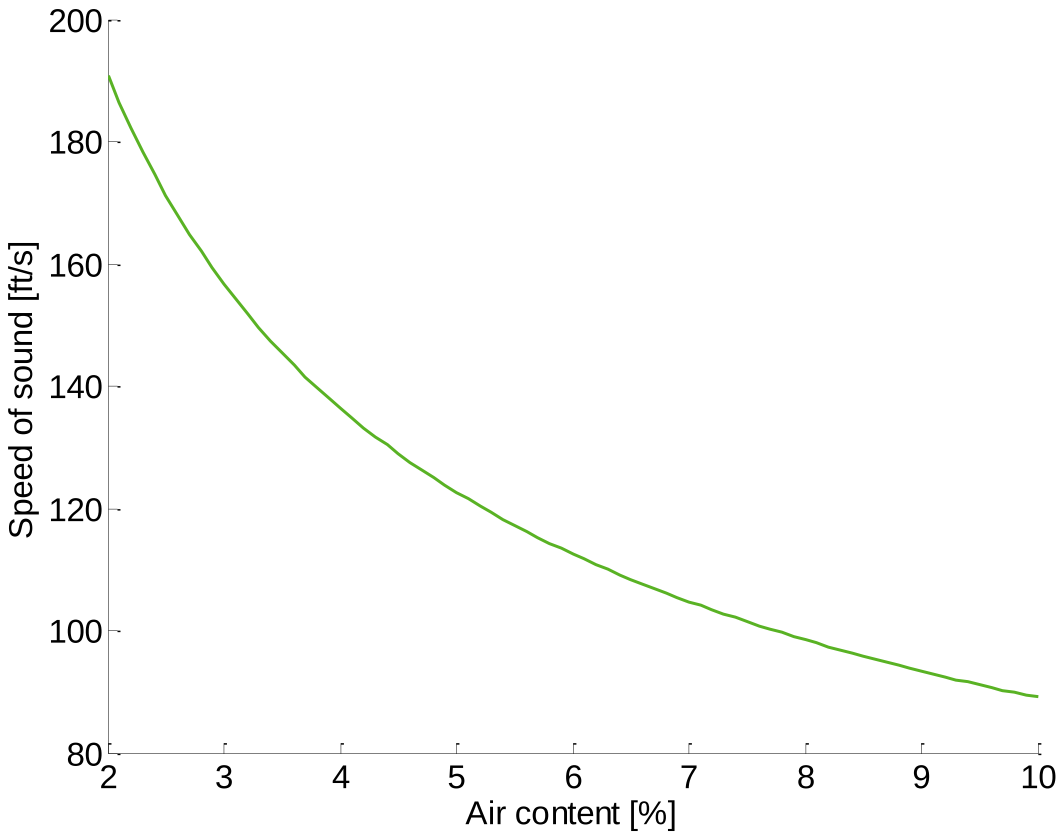

Figure 1: Wood's simplified model for plastic concrete

SPEED OF SOUND IN AERATED CONCRETE

To determine the speed that sound propagates through plastic concrete, the time-of-flight between a sound source and a sound receiver, spatially separated by a known distance, is measured. The sound source consists of a baffled piston driven at a relatively low-frequency, well below the lowest bubble resonance frequency. A temporal cross-correlation between the source drive and receiver signals yields the propagation time and therefore the speed of sound.

Because a relatively low frequency sound is used, the sound waves are not directional but rather propagate with near equal strength in all directions. Therefore the sensing surface of the receiver can be located on the same plane as the source. This is important for use in a concrete mixer since nothing can protrude into the mixer; otherwise interference with the mixing paddles would occur. The source and receiver are packaged in a single probe which is mounted through the floor or side wall of the mixer such that the face of the probe is just flush with the inside mixer wall and is in contact with the concrete slurry as it is being mixed. Additionally, the mechanical design of both the source and receiver must be such that they will operate reliably in the abrasive environment inside a concrete mixer. Figure 2 shows the installed unit in the bottom of the laboratory-scale pan mixer for this study.

Figure 2: Sensor installed in laboratory pan mixer

EXPERIMENTAL APPROACH

In this initial study, air contents obtained by the ASTM C231 pressure meter were compared to measurements acquired by the acoustic sensor. Two mix designs were considered: a high-range water-reducing concrete (HRC) mix with a target slump of 6-8 in (150-200 mm); and a self-consolidating concrete (SCC) mix with a target slump flow of 25-27 in (640-690 mm).

These mix designs are common to the precast industry. With the slump or flow held constant, three air ranges were targeted: 2-4%, 4-6% and 7-9%. Air targets were achieved by adjusting the air-entraining admixture (AEA) dosage. For each mix design, several mixes were repeated to validate performance.

MIX DESIGN AND PROTOCOL

The mix designs for the HRC and the SCC are given in Table 1. The water-to-cement (w/c) was held constant between the two mixes while a polycarboxylate high-range water-reducer (HRWR) was used to adjust slump. A planetary, lab-scale pan mixer was used to produce 1.4 ft^3 (0.04 m^3) of concrete using the mix protocol in Table 2.

Table 1: Mix designs

	HRC	SCC
Cement [lb/yd^3, kg/m^3]	625, 370	750, 450
Sand [lb/yd^3, kg/m^3]	1450, 860	1450, 860
Stone [lb/yd^3, kg/m^3]	1700, 1000	1450, 860
Water [lb/yd^3, kg/m^3]	275, 160	330, 200
HRWR [oz/cwt, mL/100kg]	4.6, 230	5.5, 270
AEA [oz/cwt, mL/100kg]	0.10-1.0, 5-50	0.05-0.70, 2.5 - 35

Table 2: Mix protocol

Material addition	Mix time and speed
Add stone, sand, water, AEA	1 minute at high speed
Add cement	1 minute at high speed
Add HRWR	2 minutes at high speed
None	2 minutes at semi-static speed

Measurements taken included: 1 slump or slump flow, 2 unit weights, 2 air-pot readings, 2 cylinders each for 1 or 3 day and 7 and 28 day compressive strengths. Two different operators supplied the unit weights and pressure meter readings.

EXPERIMENTAL RESULTS

The acoustic sensor provides real-time air content as shown in Figure 3. The different steps in the mix protocol can be clearly seen to affect the air output. At time T_1, the concrete is in a state where the air can be confidently measured by the acoustic sensor. Prior to this time, the mix of aggregate, water and cement is not sufficiently cohesive to give a meaningful reading. At time T_2, the HRWR is added, and the mix becomes sufficiently flowable to distribute the AEA and subsequently increase air content. At time T_3, the high speed mixing is completed, and the speed is reduced to a semi-static state. No significant agitation is provided, but the concrete is simply being moved slowly and continuously over the sensor. This serves to increase the volume of concrete that is exposed to the sensor.

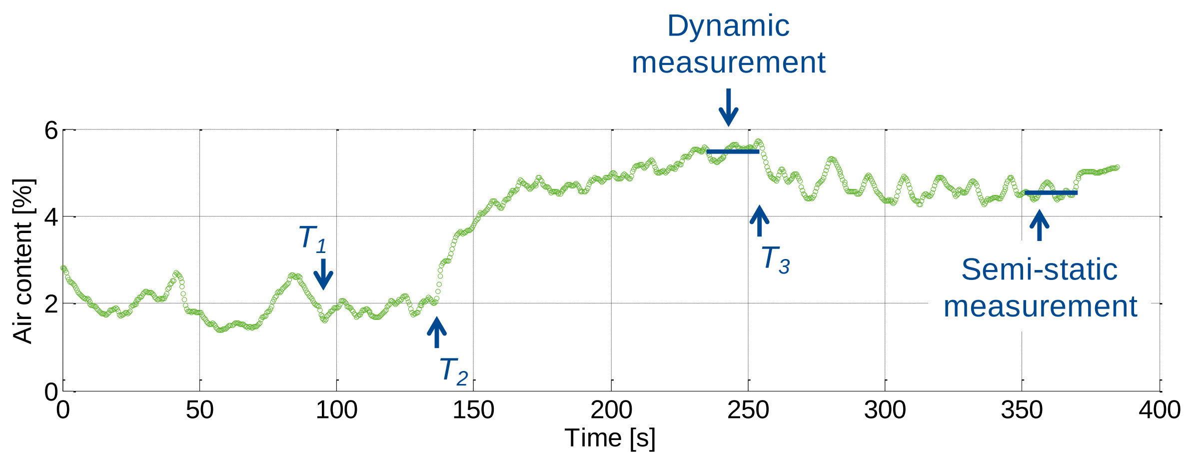

Figure 3: Real-time output from the novel air measurement system

Figure 3 also illustrates the measurements considered in this study. The first reading is the dynamic measurement, representing the air content in the concrete during high speed mixing. The reading is taken as the average over 10 seconds before the speed is changed. The second reading is the semi-static measurement, representing the air content in the concrete without mixing. This reading is also taken as an average over 10 seconds, but before the concrete is dumped. Preliminary results have shown the acoustic sensor to be quite repeatable, as demonstrated in Figure 4, which shows 3 replicated concrete trials.

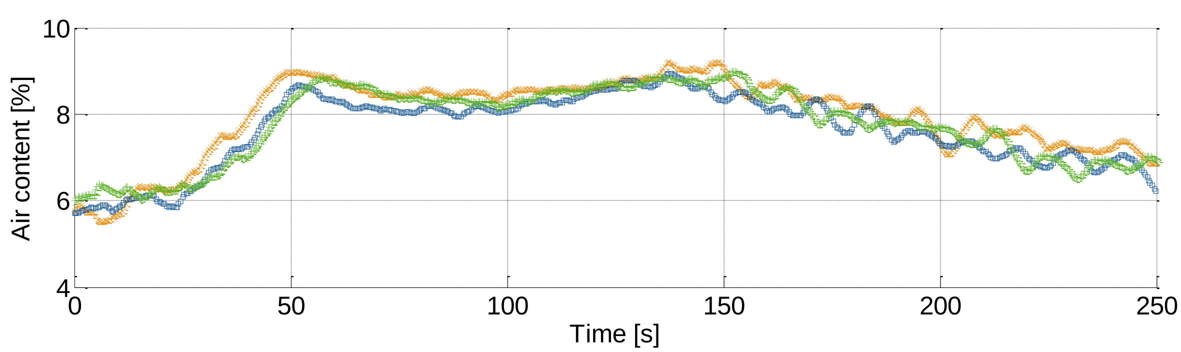

Figure 4: Repeatability of air measurement system

It is important to understand that external energy (i.e. mixing, pouring or rodding) can both create and destroy air bubbles within a concrete mixture. Thus, depending on the concrete system, when the mixing speed changes from high to semi-static, air can decrease (no energy to maintain air) or stay the same (no energy to destroy air). This is demonstrated in Figure 5, where both these scenarios are observed. For the top graph, the change from high to semi-static occurs around 250 seconds and a decrease in air content can be seen. However, for the bottom graph, the air content continues to increase even after a change to the semi-static speed (again, around 250 seconds). A noticeable change in the oscillation of the sensor output is observed as the mixing speed is changed. When the mixing blade moves past the sensor at the semi-static mixing speed, it briefly uncovers the sensor, causing the output to increase. As the concrete closes up over the sensor, the reading decreases.

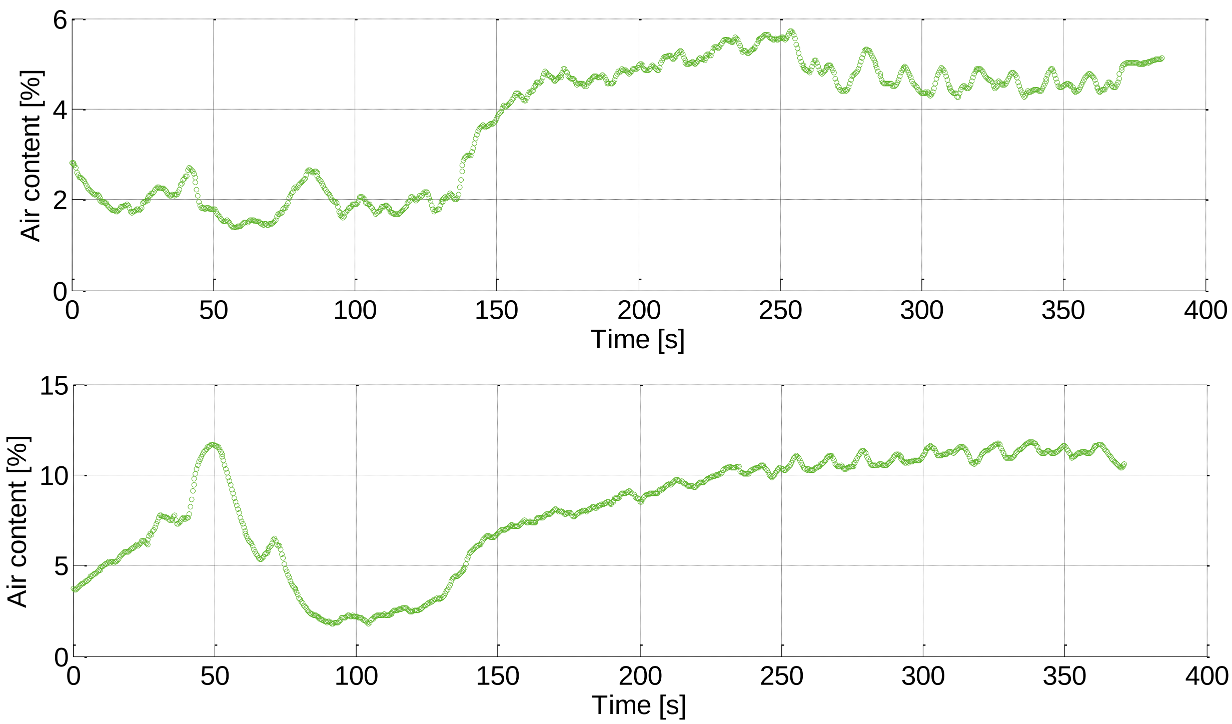

Figure 5: Examples of changes in air due to changes in mixing speed

In Figure 6, the static and dynamic measurements are compared directly. In general, the dynamic measurements tend to be higher than the static measurements (by an average of about 1%). The cement content (which in this case represents the difference between HRC and SCC) seems to have a small effect on the overall relationship.

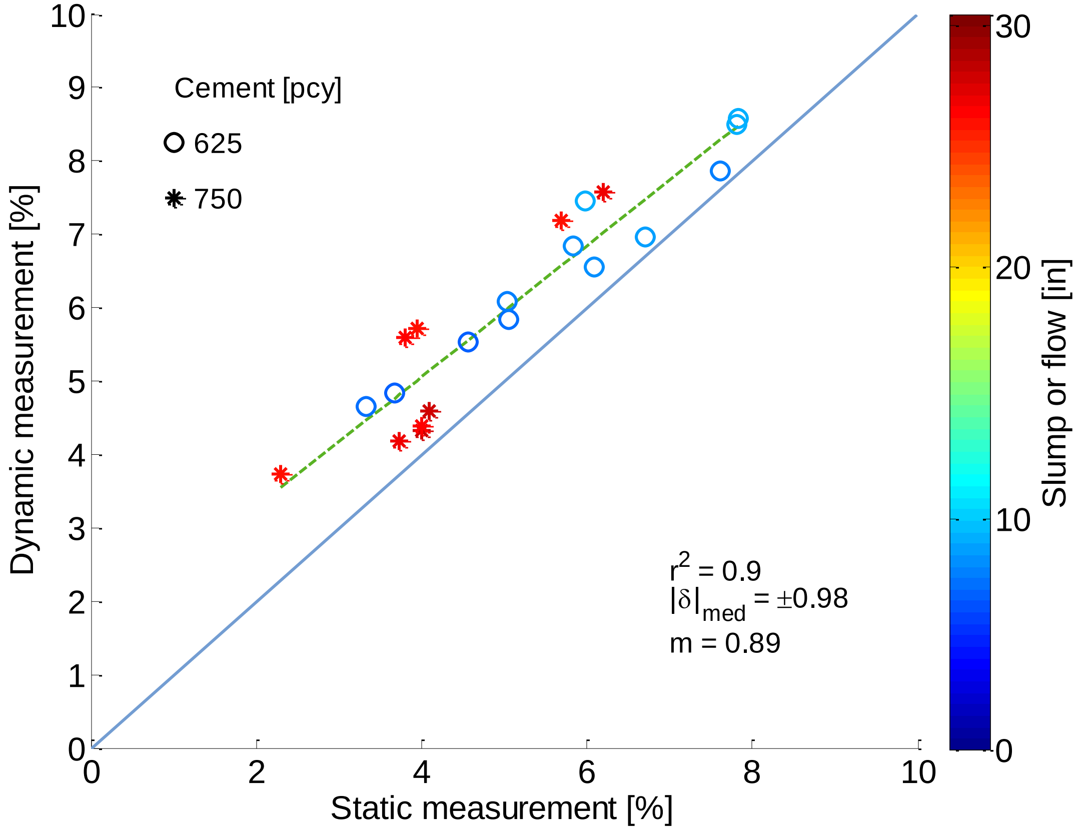

Figure 6: Static versus dynamic measurements

Figure 7 shows the relationship between static measurements and the pressure meter readings while Figure 8 shows the relationship between dynamic measurements and the pressure meter readings. The pressure meter readings are the average of two readings obtained on the same concrete at the same time by different operators. During this study, the median absolute difference between pressure meter readings was ±0.3% air, while the maximum difference was 2.2%. During the study, if the difference was more than 1.5% air, the pressure meters were redone to validate. This occurred twice within the current study. In Figure 7, the relationship is well-centered on y = x line, with a median absolute difference of ±0.44% air. The dynamic reading, as expected based on Figure 6, is higher than the pressure meter, but the slope of the regression line is practically parallel with the y = x line. The median absolute difference for the dynamic measurement is ±0.69% air.

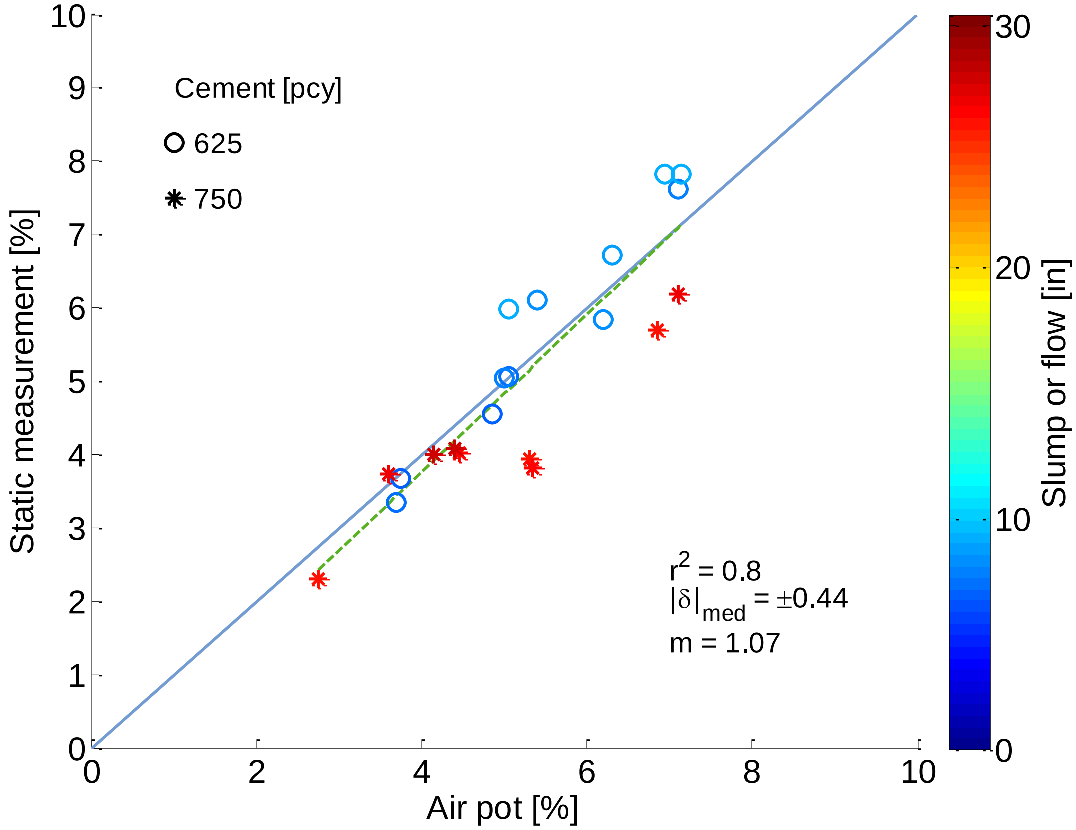

Figure 7: Static measurements versus pressure meter readings

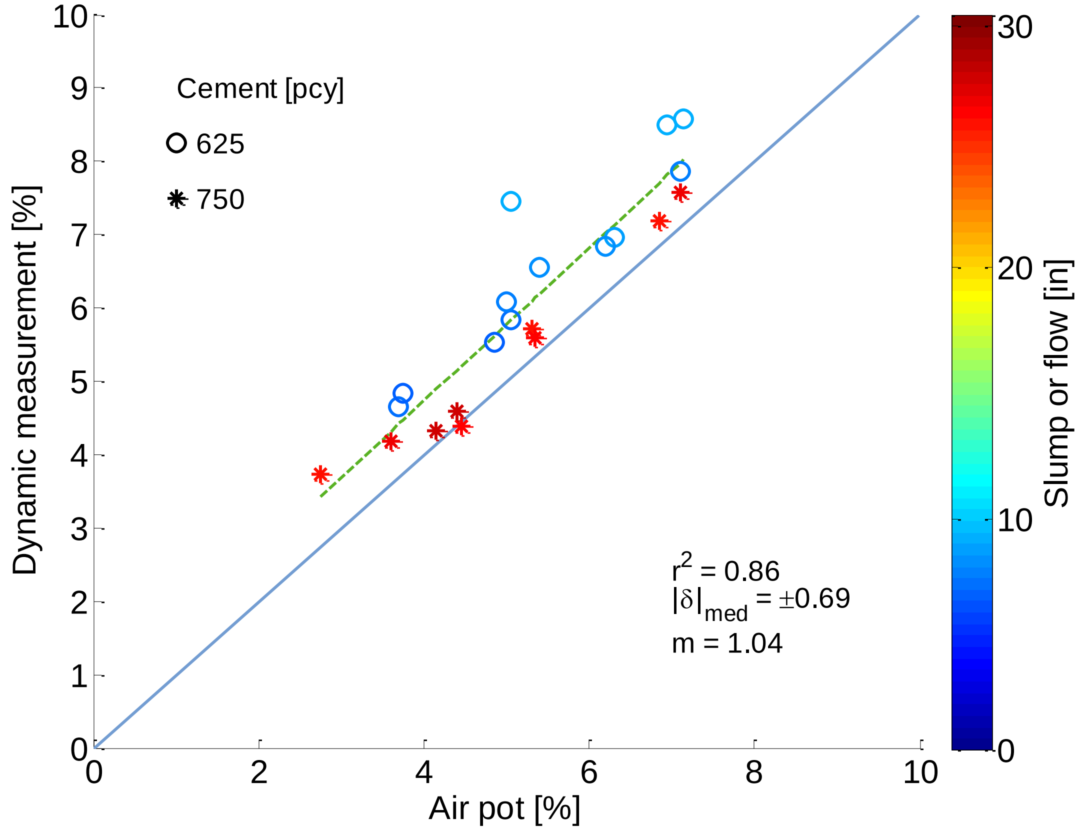

Figure 8: Dynamic measurements versus pressure meter readings

Further research will be conducted to see how these trends develop, but from the preliminary data, it is clear that the novel air measurement system is capable of accurately measuring air content over a wide air content range.

From another perspective, the pressure meter as well as air measurements from the acoustic sensor can be compared to the unit weight and theoretical air content as determined by the gravimetric method. Figure 9 and Figure 10 show the relationship between air content readings and unit weight for HRC and SCC respectively. The dotted line represents the regression line, while the solid line represents the theoretical air content as calculated by the gravimetric method. The median absolute difference between the two is 0.26% air for the HRC and 0.28% air for the SCC.

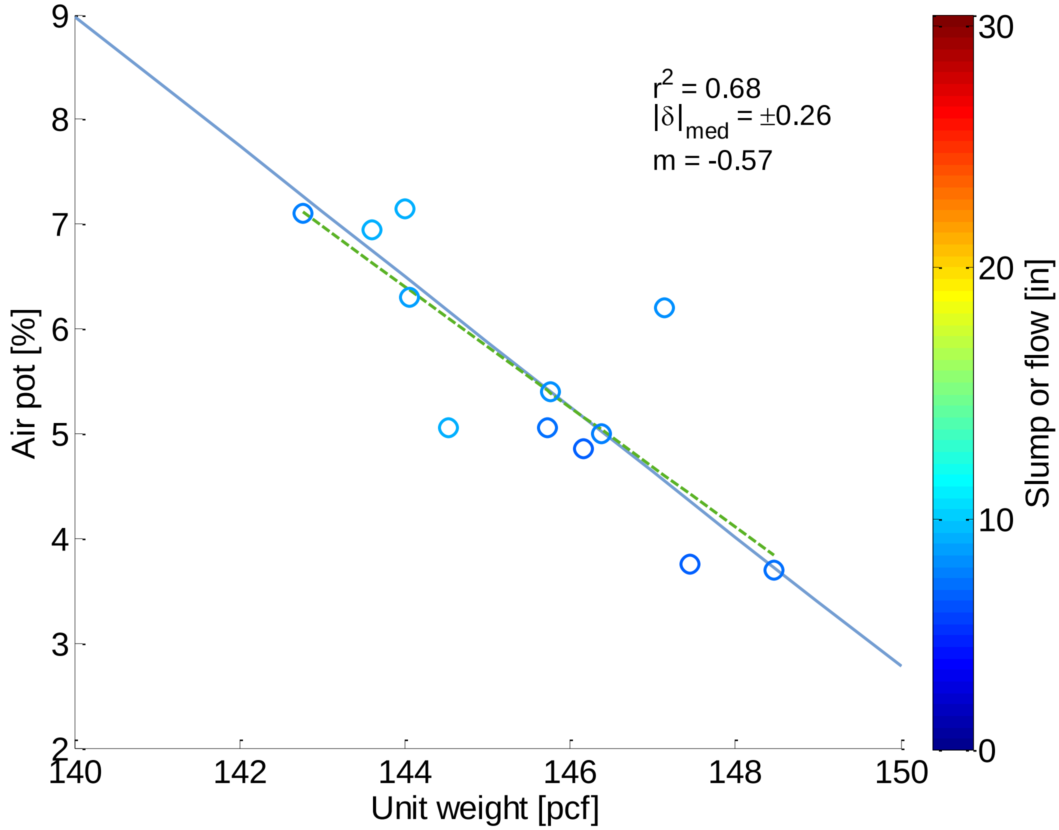

Figure 9: Pressure meter readings versus unit weight for HRC

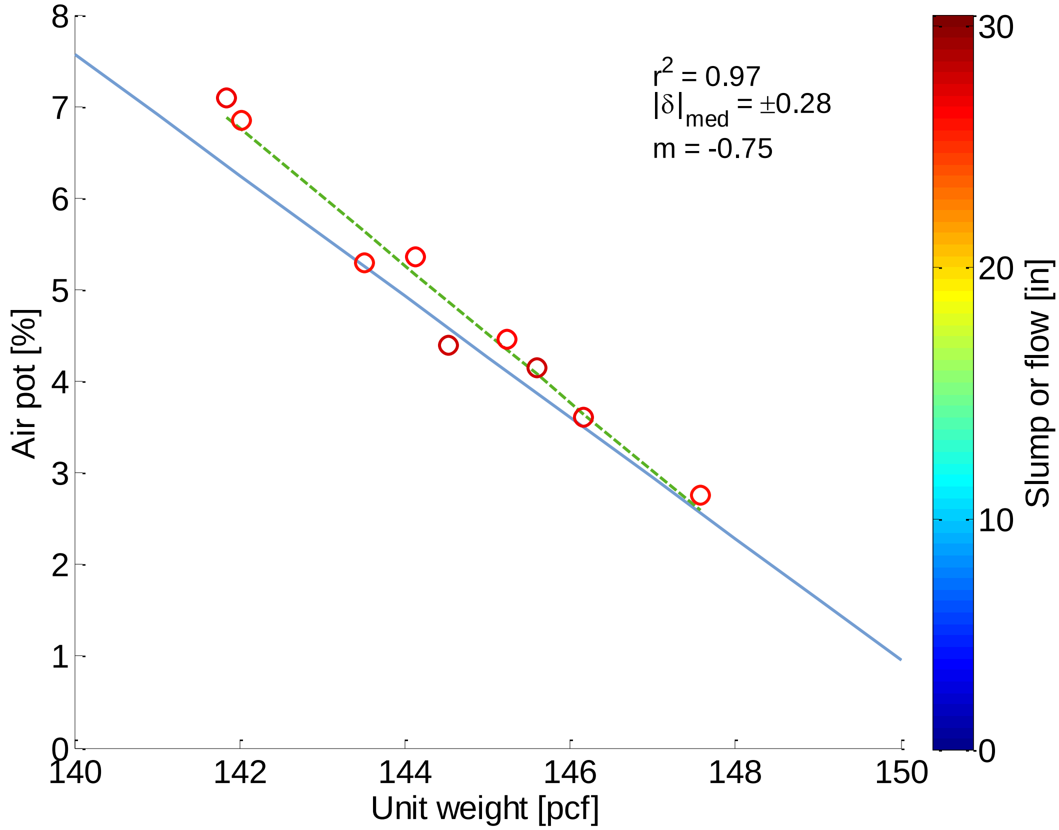

Figure 10: Pressure meter readings versus unit weight for SCC

The same relationships can be plotted for both the static and dynamic measurements. Table 3 summarizes the slope of the regression line and the standard difference between the measured air and calculated air.

Table 3: Pressure meter, static and dynamic measurements compared to air calculated from unit weight

	R^2	$\lvert\delta\rvert_{med}$ [% air]	m
Pressure meter, HR	0.68	0.26	-0.57
Static measurement, HR	0.82	0.49	-0.80
Dynamic measurement, HR	0.74	1.00	-0.65
Pressure meter, SCC	0.97	0.28	-0.75
Static measurement, SCC	0.83	0.26	-0.55
Dynamic measurement, SCC	0.91	0.69	-0.69

Table 3 presents the correlation coefficient (R^2), the median absolute difference between the measurement and the theoretical air calculation ($\lvert\delta\rvert_{med}$) and the slope of the line (m). There is excellent agreement between the pressure meter and the air calculated from the unit weight for both the HRC and the SCC. The static measurement for the HRC has a higher median absolute difference compared to the pressure meter, but more importantly, the slope is different. This may suggest either that there is a fundamental difference between either how the measurements are made, or it may be due to any changes in air content from the time the static measurement is made and the time the unit weight is recorded. For example, discharging and rodding take place during this time and may lower the air content. The static measurement for the SCC has practically the same median absolute difference. This may be explained by the fact that no rodding was performed due to the high workability. Concerning the dynamic measurements, the median absolute difference is higher in both cases, but this is to be expected since the dynamic measurements tend to be higher than the static measurements.

ACTUAL PLANT DATA

The acoustic sensor has been installed in several precast plants to demonstrate full scale use. The sensor is manufactured to the same dimensions as common moisture meters, and thus can be installed easily in the side or bottom of the mixer, as shown in Figure 11. Figure 12 shows a typical mix cycle for an actual precast plant mixer. Note that the signature is similar to the lab scale mixer at 310 seconds, as the mixer goes from a high mixing speed to a fully static state resulting in a rapid change in air.

Figure 11: Installed sensor at precast plant

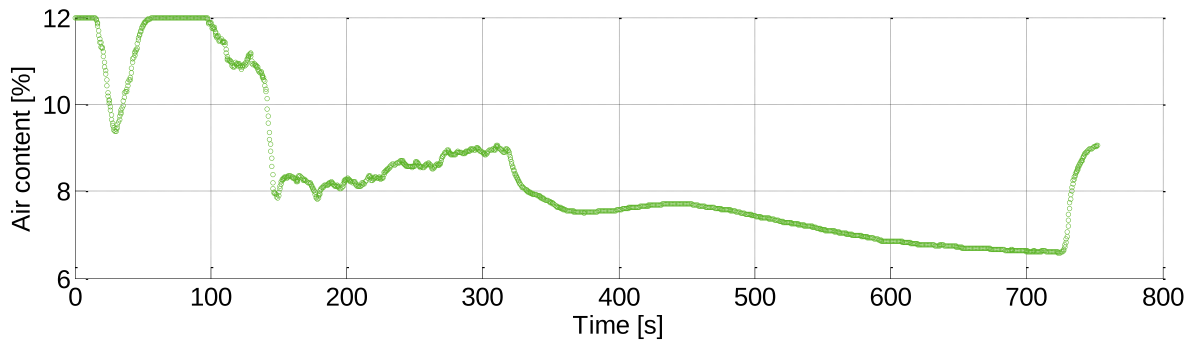

Figure 12: Real-time output from precast plant mixer

Data used in Figure 13 and Figure 14 represents both HRC and SCC over several months at one particular precast plant. Figure 13 compares static measurements (truly static in this case) to the pressure meter readings while Figure 14 compares dynamic measurements.

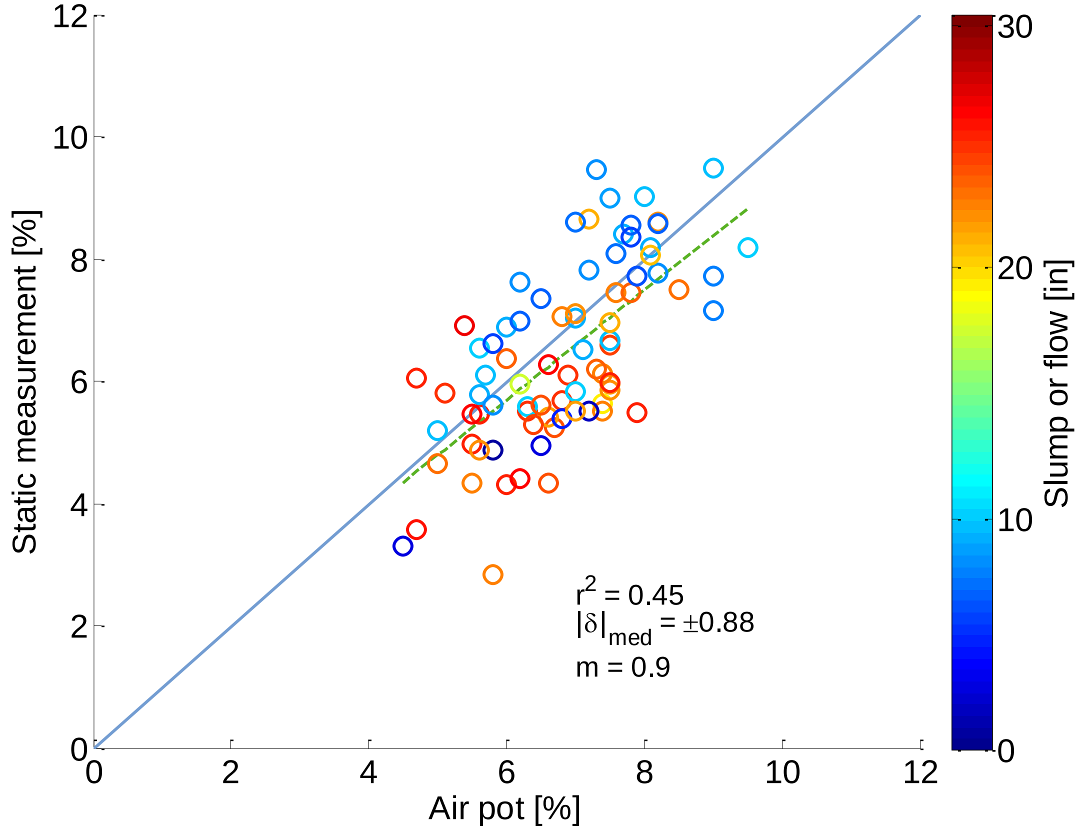

Figure 13: Plant data comparing static measurements to pressure meter readings

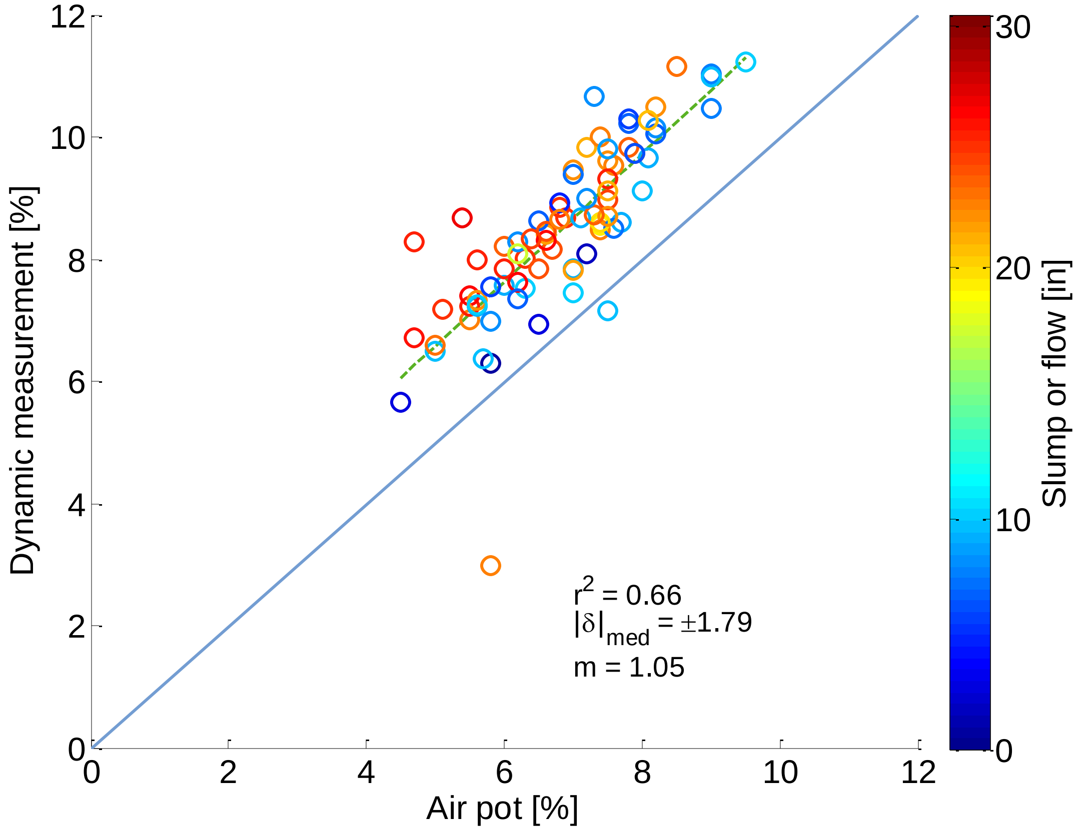

Figure 14: Plant data comparing dynamic measurements to pressure meter readings

The standard errors in both cases were slightly higher, but similar to those found in the lab-scale trials. In addition, the dynamic measurements are also higher than the corresponding static measurements again, due to influences of stopped mixing and rodding that occurs during the pressure meter measurements.

CONCLUSIONS

This preliminary study has demonstrated both at a lab and plant scale that the novel air measuring system provides an accurate and robust air measurement over a wide range of air contents. Real-time measurement also provides a first indication into how air content can change with mixing energy and chemical admixture addition. Future work will aim to test the technology across many different concrete systems including mix design, chemical admixture systems, and mixing sequences.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the concrete crew at W.R. Grace.

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