A Closer Look at Entrained Air in Concrete

Do we need to reevaluate specification requirements for air content?

BY DIPAYAN JANA, BERNARD ERLIN, AND MICHAEL F. PISTILLI

An appropriate air-void system is needed when concrete will be exposed to a combination of moisture and cyclic freezing. During the past few decades, there has been little change in requirements for air-void system characteristics—air volume, specific surface, and void spacing factor—that affect concrete's resistance to cyclic freezing damage. Although spacing factor is the most critical factor affecting frost resistance, limits on air content (volume) are specified because it can be quickly measured in the field.

Current ACI specifications for air content are shown in Table 1. If the air content of the mortar fraction is about 9%, it's assumed that the air-void system has the characteristics required to produce frost-resistant concrete. Current air content specifications and air-void system concepts, however, evolved from data for concrete containing air-entraining admixtures based on neutralized Vinsol resin, which is seldom used today because of its scarcity.

Some of the newer, synthesized air-entraining chemicals produce double the number of bubbles at a given air content, and thus yield higher specific surfaces and lower void spacing factors because of the smaller bubble size. When these are used, a lower-than-specified air content may yield the desired air-void system.

Some mid-range and high-range water-reducing admixtures produce relatively coarse entrained air bubbles. If the bulk of the entrained air is generated by these admixtures, a higher-than-specified air content may be needed to produce the desired air-void system.

This point of view article is presented for reader interest by the editors. However, the opinions expressed are not necessarily those of the American Concrete Institute. Reader comment is invited.

MORE BUBBLES ARE DESIRABLE—USUALLY

When entrained air is needed to protect against cyclic freezing, the number of bubbles in the paste is more important than the total air volume because larger numbers of bubbles result in a higher specific surface and a lower void spacing factor. That means a lower air volume can protect more paste.

According to industry recommendations, enough bubbles are needed to provide a specific surface of at least 600 $\text{in.}^2/\text{in.}^3$ ($24\ \text{mm}^2/\text{mm}^3$) and a void spacing factor no greater than 0.008 in. (0.20 mm).[3-5] It's desirable to achieve these values with a minimum volume of air because strength usually decreases as the air content increases.

The strength reduction can be accentuated if the air-entraining admixture produces many extremely tiny bubbles, which have a propensity to cluster in aggregate sockets[6] (Fig. 1). The clustering begins to occur at air contents as low as 5% and reduces aggregate-paste bond.

AIR-ENTRAINING ADMIXTURES

Chemicals used to formulate common air-entraining admixtures include:

- Wood-derived chemicals—neutralized Vinsol resin, wood rosin and resin, gum rosin, and tall oil (mixtures of fatty acids and rosin acids);
- Petroleum distillates—salts of sulfonated hydrocarbons; and
- Fatty acids—animal tallow and hydrogenated vegetable oil.

Of these, Vinsol resin has been in use the longest.[7] Newer air-entraining chemicals such as tall oils, fatty acids, and gum rosins, however, do not require as much air volume as Vinsol resin to provide good air-void systems. Because they create finer bubbles, the number of bubbles produced is significantly greater than the number produced by Vinsol resin admixtures that yield the same air content. That means good air-void systems and excellent resistance to freezing and thawing can be obtained at lower air contents.[8]

In high-slump concretes, the newer air-entraining chemicals stabilize bubbles more effectively than Vinsol resin because the larger bubbles created by Vinsol resin sometimes collapse during mixing. Although tall oil-based and fatty acid-based chemicals require longer mixing times to stabilize bubbles than Vinsol resin or wood rosin-based chemicals, smaller bubbles are more stable during prolonged mixing. Sometimes, additional bubbles are created and cause the air content to steadily increase rather than level off or decrease during prolonged mixing.

A comparison of air-void systems created by different air-entraining chemicals at different air contents is given in Table 2 and Fig. 2. These data are based on more than 85 test results for each of the chemicals listed, and for concretes with a 3/4 to 1 in. (19 to 25 mm) nominal maximum aggregate size. Note that even at air contents below 4.5%, tall oil- and fatty acid-based air-entraining admixtures can produce air-void systems with industry recommended specific surface and spacing factors.

TABLE 1:
ACI 318[1] AND ACI 301[2] RECOMMENDED AIR CONTENTS FOR FROST-RESISTANT CONCRETE (TOLERANCE IS ± 1.5%)

Nominal maximum size aggregate, in. (mm)	Air content, %	
	Severe exposure	Moderate exposure
3/8 (9.5)	7.5	6
1/2 (12.5)	7	5.5
3/4 (19.0)	6	5
1 (25.0)	6	4.5
1-1/2 (37.5)	5.5	4.5
2 (50.0)	5	4
3 (75.0)	4.5	3.5

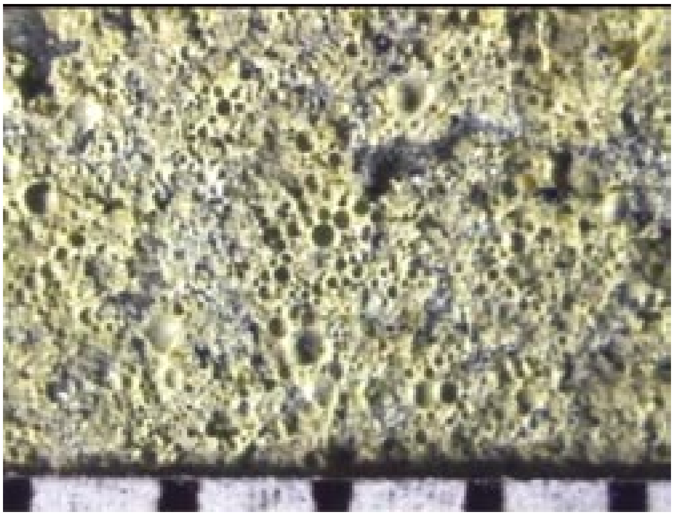


Fig. 1: Frothy textured air voids in a coarse-aggregate socket of concrete containing one of the newer air-entraining chemicals. The scale is in 1/16 in. (1.6 mm) increments

EFFECTS OF MID-RANGE AND HIGH-RANGE WATER-REDUCING ADMIXTURES

High-range water reducers added during concrete batching are reported to cause some loss of air during simulated intermittent agitation—with greater air loss occurring in concretes with higher air contents.[11] But when these admixtures are added to ready mixed concrete at job sites, we've often noted an opposite effect—increasing air content—especially when the original air content is near the top of the specified range. We've noted the same effect when retempering water is added to concrete with a high air content. In either case, the higher air contents can cause strength problems and may also contribute to finishing problems such as blistering and delamination of lightweight concrete. More frequent field measurements of air content may be needed to document any gain or loss in air content with extended agitation time, retempering, or field dosing of high-range water reducers.

When used in conjunction with air-entraining admixtures, many high-range water-reducing admixtures create void spacing factors up to 0.010 in. (0.25 mm), exceeding the accepted maximum of 0.008 in. (0.20 mm). There is controversy about whether or not the greater void spacing factor adversely affects resistance to freezing and thawing. Most laboratory studies and field experience indicate that the higher void spacing factors are adequate to provide freezing and thawing protection. Thus, concrete with a spacing factor higher than 0.008 in. (0.20 mm) may still result in adequate resistance to cyclic freezing if the strength is high enough.

We've examined scaled concrete made using mid-range water reducers that create "mid-sized" air bubbles (for example, 0.004 to 0.008 in. [0.1 to 0.2 mm]) that sometimes result in marginal air-void systems even though the air content is within an acceptable range. That's because the coarser air bubbles comprise most of the entrained air and aren't numerous enough to provide the needed spacing factor.

Table 3 illustrates the relationship of air contents to specific surfaces and void spacing factors that may be found in air-entrained and non-air-entrained concrete having 6% air content. In each case, the air content

TABLE 2:
AIR-VOID PARAMETERS FOR CONCRETE MADE USING AIR-ENTRAINING ADMIXTURES CONFORMING TO ASTM C 260[9]

Air content, %	Specific surface, in.²/in.³ (mm²/mm³)	Air-void spacing factor, in. (mm)
Vinsol resin, pre 2002		
6.5	850 (33)	0.0048 (0.122)
5.0	450 (18)	0.0105 (0.267)
4.5	390 (15)	0.0128 (0.325)
3.6	310 (12)	0.0177 (0.450)
Vinsol resin, current		
6.5	980 (39)	0.0041 (0.104)
5.1	580 (23)	0.0081 (0.206)
4.3	420 (17)	0.0121 (0.307)
3.4	350 (14)	0.0161 (0.409)
Wood rosin and gum rosin		
6.5	1150 (45)	0.0035 (0.089)
5.1	610 (24)	0.0077 (0.196)
4.3	450 (18)	0.0113 (0.287)
3.5	370 (15)	0.0150 (0.381)
Sulfonated hydrocarbons including sodium salts of dodecylbenzene sulfonic acid (DDBSA)		
6.7	1280 (50)	0.0031 (0.079)
4.6	750 (30)	0.0066 (0.168)
4.2	540 (21)	0.0095 (0.241)
3.4	490 (19)	0.0115 (0.292)
Tall oil (mixtures of sodium salts of rosin acids and fatty acids)		
5.8	1150 (45)	0.0039 (0.099)
5.0	900 (35)	0.0053 (0.135)
4.1	670 (26)	0.0077 (0.196)
3.6	650 (26)	0.0085 (0.216)
Salts of fatty acids		
5.7	1310 (52)	0.0034 (0.086)
5.1	1150 (45)	0.0041 (0.104)
4.0	950 (37)	0.0055 (0.140)
3.3	830 (33)	0.0069 (0.175)

Note: All concrete produced with 3/4 to 1 in. (19 to 25 mm) nominal maximum size coarse aggregate conforming to ASTM C 33[10]

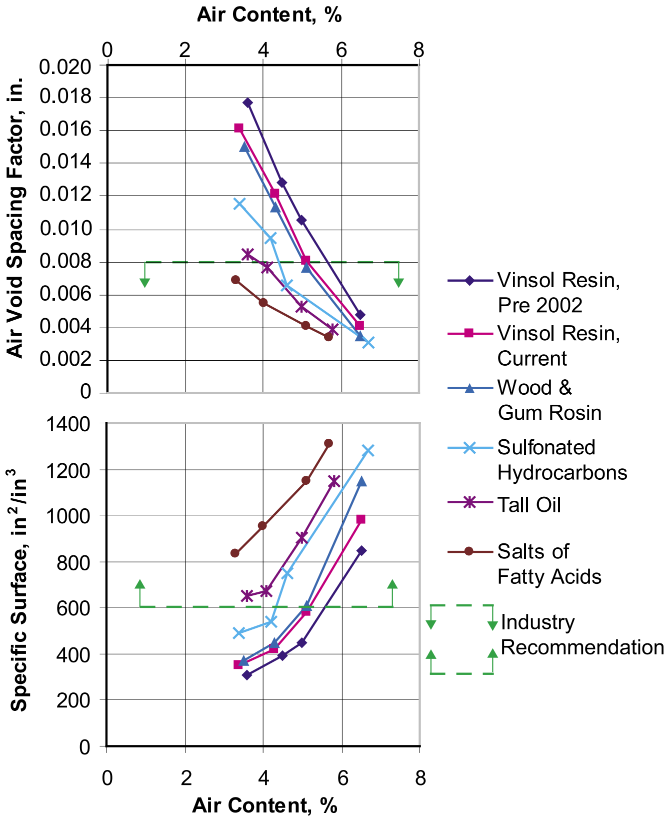


Fig. 2: Effects of air-entraining chemicals on specific surface and spacing factor of the air-void system. (Also see Table 2)

TABLE 3:
COMPARISON OF AIR-VOID PARAMETERS FOR CONCRETE MIXTURES WITH 6% AIR

	Specific surface, in.²/in.³ (mm²/mm³)	Void spacing factor, in. (mm)
Effectively air-entrained	650 (25.6)	0.008 (0.20)
Ineffectively air-entrained	540 (21.3)	0.015 (0.38)
Non-air-entrained	135 (5.3)	0.035 (0.89)

meets specification requirements of 6 ± 1.5% air. Two of the three concretes are air-entrained. Only one of the two air-entrained concretes would be expected to have the desired resistance to freezing and thawing because of an effective air-void system. Obviously, the non-air-entrained concrete is vulnerable to freezing and thawing damage.

REDUCE AIR CONTENT REQUIREMENTS WHEN BUBBLES ARE SMALLER

Many of today's newer air-entraining chemicals produce smaller and more numerous bubbles at a given air content, and thus significantly higher specific surfaces and significantly lower void spacing factors than those achieved with older air-entraining chemicals. The theoretical actual volume of air needed to accommodate water movement into the voids when concrete freezes is less than 1% of the concrete volume.[12]

It follows that effective air-void systems can be obtained at lower than the current minimum air content requirements when more efficient bubble-generating chemicals are used. Both the upper and lower limits on air content could be reduced by at least a conservative 1 percentage point without jeopardizing durability. The air content actually needed would have to be determined for the specified mixture proportions, using ASTM methods for determining the air-void parameters in hardened concrete. Note in Fig. 2 (based on the data in Table 2), that when tall oil- and fatty acid-based air-entraining admixtures are used, air contents near 3.5% would be expected to produce acceptable air-void systems.

The beneficial effects of reducing minimum air contents would include higher strength, a lower probability of finishing problems such as blistering and delamination, and reduced vulnerability to higher-than-specified air contents as a result of job site addition of high-range water reducers or retempering water.

References

1. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

2. ACI Committee 301, "Specification for Structural Concrete (ACI 301-99)," American Concrete Institute, Farmington Hills, MI, 1999, 49 pp.

3. ACI Committee 201, "Guide to Durable Concrete (ACI 201.2R-01)," American Concrete Institute, Farmington Hills, MI, 2001, p. 4.

4. ACI Committee 212, "Chemical Admixtures for Concrete (ACI 212.3R-04)," American Concrete institute, Farmington Hills, MI, 2004, p. 6.

5. ASTM C 457-98, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," ASTM International, West Conshohocken, PA, 1998, 14 pp.

6. Nasvik, J., and Pistilli, M., "Are We Placing Too Much Air in Our Concrete?," *Concrete Construction*, V. 49, No. 2, Feb. 2004, pp. 51-55.

7. Klieger, P., "Air-Entraining Admixtures," *ASTM Special Technical Publication* 169A, ASTM International, West Conshohocken, PA, 1966, pp. 530-542.

8. FHWA *Report* No. FHWA-SA-96-062, "Air-Void Analyzer Evolution," Federal Highway Administration, Washington, DC, 1995.

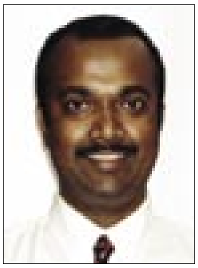
9. ASTM C 260-01, "Standard Specification for Air-Entraining Admixtures for Concrete," ASTM International, West Conshohocken, PA, 2001, 3 pp.

10. ASTM C 33-03, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2003, 11 pp.

11. Johnston, C.D., "Deicer Salt Scaling Resistance and Chloride Permeability," *Concrete International*, V. 16, No. 8, Aug. 1994, pp. 48-55.

12. Private communication, George Verbeck, 1959.

Selected for reader interest by the editors.



Dipayan Jana is President of Construction Materials Consultants, Inc. Jana is a member of ACI Committee 116, Terminology and Notation; 201, Durability of Concrete; and 221, Aggregates. He is also a member of ASTM Subcommittee C 09.65, and is a registered professional geologist.

Bernard Erlin, FACI, is President and a petrographer of The Erlin Co., Latrobe, PA. He is a member of ACI Committee 116, Terminology and Notation; 201, Durability of Concrete; and 222, Corrosion of Metals in Concrete. He is also active in ASTM International and is an Honorary Member of ASTM Committee C 09. Erlin is one of the founders of the Society of Concrete Petrographers.

Michael F. Pistilli, FACI, is the Technical Director for Quality Control, Prairie Materials, Chicago, IL. He is a member of ACI Committee 116, Terminology and Notation; 211, Proportioning Concrete Mixtures; 212, Chemical Admixtures; 234, Silica Fume in Concrete; and 363, High-Strength Concrete. Pistilli is also a member of ASTM C01, C09, and C12 and, the National Ready Mixed Concrete Association's Research and Engineering Standards Committee.