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Air Content and Unit Weight of Hardened Concrete

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PREFACE

Samuel Helms discussed the unit weight and air content of hardened concrete in each of the three preceding editions of this ASTM Special Technical Publication. This present edition makes much use of Helms' clear and concise work, particularly in the area of unit weight. The discussion of air content is more extensive here, however, largely in response to the great deal of new research since the last major update. It has also become evident that the further in time that the industry has come from the landmark contributions of the early workers in air-void systems and frost resistance in concrete, the less understood are the fundamental principles laid down in the late 1940s and early 1950s. Following the pattern set by Helms, the present edition therefore reviews much of this key literature to explain the origins of today's state of the art. Finally, this edition appears when there is a proliferation of the use of the ASTM Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete (C 457) microscopical analysis procedure, which was once exclusively performed by a small cadre of experts. While expansion of the use of the test has produced more data, it has in some cases produced more confusion where less experienced operators have used nonstandardized equipment and procedures. The chapter has therefore been written in part to point out pitfalls and sources of error in performing and interpreting the test.

PART I: AIR CONTENT

Introduction

The air content within a given volume of concrete is the cumulative volume of a large number of air voids of multiple sizes ranging from microscopic bubbles to larger, irregularly shaped air pockets. These voids have their origins in the air initially trapped among the dry constituents, dissolved air in the water, and the air introduced as a result the kneading and folding action of mixing and trapped in the mix while depositing the concrete in the forms [*1*].

The presence of these air voids initially suspended in the mix water among the solid particulate constituents of the concrete influences the workability, consistency, bleeding tendency and yield of the fresh concrete, and the density, strength, and frost resistance of the hardened concrete. The most significant of these effects is the influence of air voids in mitigating the damaging effects of freezing and thawing of absorbed water. The magnitude and utility of these effects depends on not only the total volume of these air voids, but on the entire size-distribution of voids and on their dispersion throughout the concrete. The beneficial consequences of air voids are obtained by using air-entraining admixtures and appropriate concrete production and construction procedures to encourage the retention of the smallest voids, and, by using effective placing and consolidation procedures to reduce the number and volume of the largest voids.

While the concrete is still plastic, however, the air voids have an opportunity to move, become larger or smaller, coalesce, or change shape. Some voids can be removed from the concrete entirely. The total air content and other air-void characteristics therefore depend on the stage in the mixing, transport, placement, and consolidation processes at which the measurement was taken. Once the concrete has hardened, however, permanent void spaces remain, preserving the size and shape of those air voids present at the time of setting. All air voids remaining within a given concrete mass, regardless of their size, shape, or origin, are often referred to as the "air-void system." In order to evaluate the characteristics of the air-void system, it is presently necessary to obtain a sample of the hardened concrete, perform a statistical analysis on a fraction of the exposed voids observed under a microscope, and to estimate the relevant characteristics to various degrees of accuracy and precision. The significance of such sampling, testing, and analysis, and the interpretation of the results obtained are the subjects of this chapter.

Influence of Air Content on the Behavior and Performance of Concrete

Introduction

Incorporating air voids into concrete influences the behavior of the material in both the fresh and hardened states. The magnitude and degree of utility of these influences depends on the total volume, sizes, and dispersion of the voids, and on the material properties of the concrete.

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Workability

A large number of microscopically small voids, well-dispersed throughout the cement paste, will generally increase workability at any given water content. This is because sufficiently small air bubbles can separate solid particles in the mix [2], acting as air-cushions to reduce inter-particle friction. In proportioning concrete mixes, one can take advantage of this increased workability by reducing the water content by 6 to 12%, depending on aggregate gradation and other constituents, while maintaining slump [3].

Cohesion

When air-entraining admixtures are used to stabilize the smaller air voids, a mutual attraction develops between microscopic bubbles and the grains of portland cement. This attraction not only "anchors" the air bubbles to inhibit their loss from the fresh concrete due to buoyancy, but imparts a beneficial cohesion to the mix that resists segregation, settlement, and bleeding [*1*]. In some mixes, this can also cause air-entrained concrete mixes to become "sticky" with increased adhesion to construction equipment and increased drag on finishing tools.

Unit Weight and Yield

By displacing heavier components in the mix, the air voids reduce the unit weight or density of the mix. As described in Chapter 9 and Part II of this chapter, the unit weight test, ASTM Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete (C 138), can therefore be a useful means of measuring air content in fresh concrete.

Strength Reduction

By occupying space between the cement grains, creating a more porous cement paste, and reducing the density of the hardened concrete, air voids can reduce the strength of concrete. Thus, at equal water/cement ratios, the impact of air content decreases compressive strength, with various rules of thumb equating each 1% increase in air content to a 3 to 5% reduction in 28-day compressive strength [*1*]. (Strength reductions of up to 10% per 1% air have been reported [*4*].) However, the water-reducing effect of the air voids permits a reduced water content in mixes intentionally incorporating air, allowing such mixes to have a reduced water/cement ratio without increasing the cement content. The lower water/cement ratio characteristic of well-designed mixes using an air-entraining admixture can compensate in part or in full for the strength-reduction effect of the air voids [*5*].

Frost Resistance

Primary among the multiple benefits of intentionally incorporating air into concrete mixtures is the increased frost-resistance afforded to the hardened cement paste. This is accomplished through several mechanisms as described in the next section.

Nature of Concrete and the Mechanism of Freeze-Thaw Damage

Mechanism of Freeze-Thaw Damage

Concrete is fundamentally a porous material composed of coarse and fine aggregate particles of varying porosity, held together by a hardened cement paste whose porosity depends on the original water/cement ratio, the effectiveness of consolidation, and on subsequent curing conditions. Water can be absorbed into the pores in the aggregate particles and into the "capillary pores" of the hardened cement paste [*6,7*].

These capillary pores can be saturated to various degrees, as influenced by residual, non-evaporated mix water or the subsequent absorption of water from the environment. At sufficiently low temperatures, this water freezes and expands in volume by 9%. When absorption of water has filled the capillaries to the point where the remaining empty pore space cannot accommodate expansion of the ice, the volume of the hardened concrete itself will be forced to expand with accompanying tensile or bursting stresses. Depending on the rate at which the freezing takes place and whether salt water or deicing agents are present, the expansive pressure can originate in the actual expansion of ice, the movement of unfrozen water escaping the advancing ice front [*8*], or in osmotic pressure caused by differential salt concentrations [*6,7,9*]. Since these pressures are generated with the onset of freezing and relaxed with the advent of thawing, multiple freeze-thaw cycles "fatigue" the concrete. Whether physical damage occurs depends on the level of stress and the frequency of these fatigue cycles, and on the strength of the concrete. Air voids are intentionally incorporated into the cement paste to reduce (but not eliminate) the stresses generated with each freeze-thaw cycle, and thus increase the number of cycles to failure.

Influence of Air Voids

Air voids in concrete intersect the network of capillary pores in the hardened cement paste. Since the largest of the capillary pores are typically smaller than the minimum diameter of an air void (0.010 to 0.020 mm or 0.0004 to 0.0008 in.) absorbed water remains in the smaller capillaries, moving towards the air voids only at subfreezing temperatures or when under pressure. Under normal conditions, the air voids therefore remain empty and able to accept either ice or unfrozen water when a freezing cycle begins.

Upon freezing, water and ice move towards the air voids accompanied by a pressure that increases with the required distance of travel [*8,10,11*]. This pressure is minimized by a well-dispersed system of air voids intersecting the capillary network at many points, providing a minimum travel distance from any point in the paste to the nearest air void.

Just how far the water or ice can travel without generating damaging pressures depends on degree of saturation, rate of freezing, porosity, permeability, degree of hydration of the hardened cement paste, viscosity of the water, and the tensile strength of the concrete [*8–11*]. For any given cement paste and set of environmental conditions, one can theoretically compute a critical distance (Powers' term was "critical thickness") beyond which movement of ice or water will generate excessive pressures. Damage results when absorbed water in a portion of the concrete must move further than this critical distance to arrive at the nearest air void. Powers calculated this theoretical distance as 0.25 mm (0.010 in.) "or thereabouts" for commonly encountered pastes and freezing conditions [*11*].

As a consequence of the critical distance concept, any given air void can provide frost protection to only the hardened cement paste falling within a sphere of influence radiating outwards from the periphery of the void. The zone of protected paste occupies a "shell" surrounding the air void with a thickness approximately equal to the critical distance. (Among the mathematical details of the development of the "protected paste shell" concept is a reduction in the critical distance due to the curvature of the bubble surface, and the limiting condition that the volume of freezable water in the shell must be no greater than the volume of the bubble [*10,12*]. Shell thickness is therefore not independent of bubble size, but tends to be so as the bubbles become larger.)

Requirements for an effective air-void system

To effectively provide frost resistance, the air-void system must have a total volume of air voids that equals or exceeds the volume of water or ice not accommodated by empty space in the capillary pore system. (Unsaturated concrete would need less air than saturated concrete, and concrete that is continuously dry would need no air at all.) Of equal importance, the air voids must be dispersed throughout the cement paste so that nearly all of the paste is within the protective shell of one or more air voids [*8,10–12*]. As will be discussed, the precise requirements for volume, dispersion, and spacing of the voids depend on both the concrete and on the environment. Meeting such requirements will not eliminate the stress that accompanies freezing but will maintain it at tolerable levels.

Principle of achieving dispersion and an acceptably small bubble spacing

Achieving dispersion and an acceptably small spacing for a given air content requires that the air-void system be comprised of a large number of small bubbles. As the same volume of air is subdivided into smaller and smaller bubbles, the total bubble surface area expands geometrically, as does the cumulative volume of the protected paste shells around the bubbles.

Influence of factors other than air volume and air-void dispersion

The volume of freezable water initially present in the pores, or the "degree of saturation" will depend on the initial porosity and age of the concrete, curing conditions, and environmental exposure. Similarly, the velocity at which the water or ice must move through the capillaries enroute to the air voids depends on the rate of freezing, another environmental variable. As pointed out earlier, rapid freezing conditions probably induce water movement, while slow-freeze conditions are more likely to induce the movement of ice [*6,8–11*]. Mattimore and Arni et al. [*13,14*] demonstrated reduced freeze-thaw damage at slower rates of freezing, while Flack [*15*] produced data showing rate of freezing effects to be more complicated.

It can also be shown that the pressure developed as water moves towards the air voids depends on the permeability of the paste and on the viscosity of the water [*6,8–11*]. The additional component of osmotic pressure is influenced chiefly by the presence of deicing salts.

Details of the interaction of air-void geometry, material properties of the paste, and environmental conditions are described in detail by multiple researchers [*6–12,16–20*].

Influence of Frost Resistance of Aggregates

Freezing and thawing damage to concrete can result from the mechanisms of paste destruction described, or from the expansion of absorbed water in the aggregates, or both. The air voids protect only the hardened cement paste and do not improve the inherent frost resistance of the aggregates. As Powers described it, concentrating on air voids "ignores 75% of the problem" of the frost resistance of concrete (assuming 75% of the volume of the material is composed of coarse and fine aggregates) [*11*]. Obtaining frost-resistant concrete therefore requires the selection of frost-resistant aggregates combined with the incorporation of appropriately sized and dispersed air voids in the paste. The selection or testing of frost-resistant aggregates is discussed in other chapters of this publication.

Origin and Geometric Characteristics of Air-Void Systems in Concrete

Introduction

With or without the use of an air-entraining admixture, air is unavoidably present in fresh concrete as a remanent of the air initially present in and among the dry mix ingredients [*8*], and subsequently incorporated by the kneading and folding action of mixing and as a result of transporting and depositing the concrete in the forms [*1,16*]. While the regular action of controlled mixing can stimulate formation and entrapment of a fairly well-defined gradation of predominantly small air voids, the more random activity of depositing the concrete in the forms tends to trap randomly sized voids, generally much larger than those created in the mixing process.

Air-void systems without benefit of an air-entraining admixture

In ordinary concrete mixed without the stabilizing effects of an air-entraining admixture, a large number of the smaller air voids initially formed in the mixing process are lost from the system, leaving primarily larger voids in the hardened concrete. The problem with this is not that the larger air voids do not provide frost resistance; a protected paste shell exists around the periphery of all air voids in concrete regardless of their size or origin [*9*]. The problem is that unless the air content is extraordinarily high, the large voids offer too little volume of protected paste. (The volume of protected paste relative to the volume of the air voids themselves increases for smaller air voids.) Large voids are therefore not ineffective, they are simply less effective in providing frost resistance than a much greater number of smaller voids occupying the same total air volume.

Function of Air-Entraining Admixtures

Air-entraining admixtures stabilize the smaller air voids in the mix by promoting their formation, retention, and dispersion. These admixtures, related to soaps, detergents, and the general class of chemicals known as "surface active agents" initially reduce the surface tension of water, promoting the formation of smaller bubbles. They also provide an attractive force between the bubbles and the cement grains to resist air loss due to buoyancy. Finally, the electrical charge effects responsible for anchoring the bubbles to the cement grains cause the bubbles to repel one another, discouraging coalescence [*1,21–24*]. As pointed out by Whiting and Stark, however, [*1*] "entrained air is produced by the mechanical stirring, kneading, and infolding actions of the concrete mixer"; the air-entraining admixture merely stabilizes these bubbles once they are formed.

Air-void system resulting from the use of an air-entraining admixture

As reported by Powers, "Comparison of sections of concrete made of the same materials, with and without an air-entraining agent, indicates that the voids present when an entraining agent is not used are also present when the agent is used" [*11*]. The consequence of using an air-entraining admixture is therefore to augment the coarser or "natural" air voids with a large number of the smaller voids stabilized during the mixing process. The resulting air-void system is therefore a "composite" [*11*] of the smaller voids stabilized and trapped in the concrete during mixing combined with the much larger voids trapped in the concrete as a result of handling and placing.

The term "entrained air" as conventionally used is intended to apply to those voids trapped during mixing and stabilized by the air-entraining admixture; the term "entrapped air" is generally intended to apply to those voids trapped in the concrete during handling and placement. Given that these larger, so-called "entrapped" air voids reduce the density and strength of the concrete to a greater degree than is justified by their limited contribution to frost resistance [*4,25*], it is normally advantageous to remove them from the fresh concrete by appropriate consolidation techniques.

The Composite Air-void Gradation

While not implied in the literature, a common industry misinterpretation of the terms entrained and entrapped is that air voids in concrete are of two sizes only: large "entrapped" voids and small "entrained" voids. It is observed that the voids actually occupy a broad gradation of sizes ranging from 10 μm to several or hundreds of millimetres—a size range from smallest to largest of more than a factor of 1000. As shown in Fig. 1, the air voids occupy the broadest range of sizes of all the constituents of concrete.

Despite this continuous gradation of voids, the simplest way to describe the air-void gradation is to report the

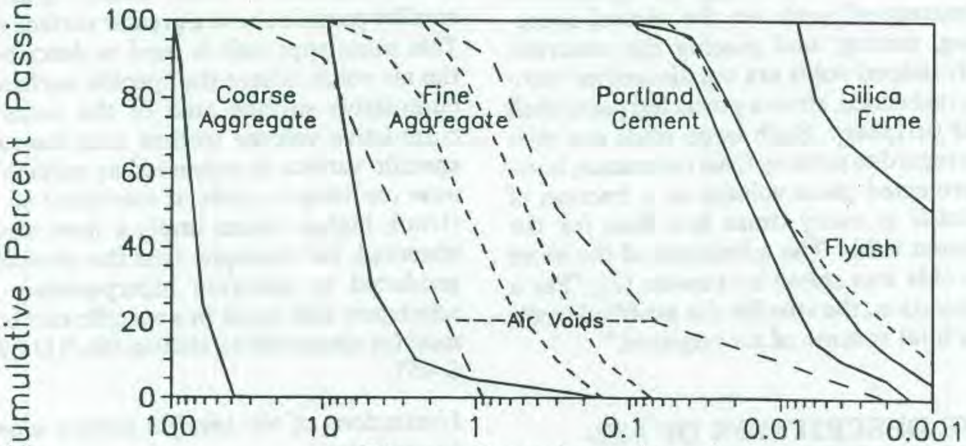

FIG. 1—Example gradation curves of concrete constituents. Vertical axis represents the mass or volume "finer than" the size indicated on the horizontal axis. Mass or volume percent is shown as a fraction of the total mass or volume of that particular constituent. Coarse and fine aggregate gradation bands are from ASTM C 33. Cement gradations are examples of a coarse and fine grinds. Fly ash and silica fume examples are taken from Ref 76. In the coarser of the two air-void gradations, 90% of the total air volume is contained in voids larger than 1 mm in diameter. In the fine air-void gradation, 90% of the total air content is contained in voids smaller than 1 mm in diameter. An air-entraining admixture is normally required to stabilize the air bubbles in such a mix.

number or volume of voids larger than, and smaller than, some predetermined size. ASTM Terminology Relating to Concrete and Concrete Aggregates (C 125) sets a size criterion of 1 mm (0.04 in.) and defines "entrapped" air voids as those above this nominal limit, and "entrained" air as those below. Underlying this definition by size may be the observation that retention of a significant number of air bubbles much less than 1 mm in diameter is unlikely without the stabilizing influence of an air-entraining admixture. Alternatively, air voids of greater than 1 mm in diameter or so can be present with or without the influence of an air-entraining admixture [*11*].

The Shape of Air Voids

While the smaller air voids in concrete are generally observed to be spherical in shape or nearly so, the larger voids are often seen to be nonspherical and irregularly formed. The observation that void shape becomes increasingly irregular with void size is observed in many other physical systems [*26*], and is however not necessarily related to the use of an air-entraining admixture or to the effectiveness of the air voids in providing frost protection.

Caveat concerning terminology

As described earlier, the terms "entrained air void" and "entrapped air void" as defined in ASTM C 125 have specific meaning only in regard to the size and shape of the voids. These same terms can be misleading when used to imply the origin, evolution, or effectiveness of the voids. As has been discussed, "air-entraining admixtures" do not strictly "entrain" air into fresh concrete. Further, the smaller voids classified as the entrained air voids are in fact the result of air having been "entrapped" in the mix and stabilized via the admixture. The term "entrapped" when used correctly to denote void size is analogous to the term "coarse" when describing an aggregate gradation. Finally, large or "entrapped" voids are the natural consequence of batching, mixing, and placing the concrete. Large or irregularly shaped voids are not altogether without benefit to frost resistance, since a protected paste shell exists around their periphery. Such large voids are relatively inefficient in regard to proving frost resistance, however, since their protected paste volume as a fraction of the void volume itself is many times less than for the smaller, more efficient voids. The advantage of the more efficient, smaller voids was stated by Powers [*8*], "For a given degree of protection, the smaller the air-filled cavities the smaller the total volume of air required."

QUANTITATIVE DESCRIPTION OF AIR-VOID SYSTEMS IN HARDENED CONCRETE—THE AIR-VOID SYSTEM PARAMETERS

Measures of Air Content

The air content of hardened concrete is most commonly expressed as a percentage of the combined volume of all constituents of the concrete including the total volume of air. Klieger [*5,27*] found that it can be more informative to express the air volume as a percentage of the mortar volume (that is, mortar volume = concrete volume minus the volume of coarse aggregate), observing that frost resistance consistently resulted from 9 ± 1% air content in the mortar. Given that air voids contribute to the frost-resistance of the hardened cement paste only, it can be useful to express the air content as a percentage of the paste (volume of cementitious materials, water, and air). When calculating the spacing factor of the air-void system (as will be discussed), the air content must be expressed as a fraction of the "air-free" paste, by dividing the total air volume by the volume of cement and water only.

Measures of Air-Void Size and Size-Distribution

As pointed out earlier, the air-void gradation can range from 20 μm to more than 20 mm—a spread of more than three orders of magnitude. While Willis and Lord [*28,29*] developed mathematical techniques for estimating the complete gradation curve for air voids in concrete, characterization of void size is currently done much more simply and approximately. The size of the air voids is typically defined by a statistical parameter known as the "specific surface," based on the ratio of total air void surface area to total air volume.

The Specific Surface

The specific surface (α) of the air-void system is analogous in some ways to the "fineness" of cement, which is expressed as the estimated total cement surface area per unit mass of the cement (300 m^2 of cement surface per kilogram of cement, for example), ASTM Test Method for Fineness of Portland Cement by the Turbidimeter (C 115) and ASTM Test Method for Fineness of Portland Cement by Air Permeability Apparatus (C 204). Higher fineness values indicate a finer, smaller-grained cement since smaller particles have a greater surface area per unit mass. This same approach is used to describe the gradation of the air voids, where the specific surface is defined as the cumulative surface area of the voids divided by their cumulative volume (rather than cumulative mass). The specific surface is expressed as surface area per unit volume resulting in units of mm^2/mm^3 or 1/mm ($in.^2/in.^3$) or (1/in.); higher values imply a finer air-void system. It is observed, for example, that the air-void system typically produced in concrete incorporating an air-entraining admixture will result in a specific surface of 25 to 45 mm^2/mm^3 (or about 600 to 1100 $in.^2/in.^3$) [*11,17*], see also ASTM C 457.

Limitations of the specific surface alone as an index to void size

The specific surface of air voids and the fineness of cement are two examples of the industry's need to characterize the behavior of multi-sized systems with a single, numerical size-index. The "fineness modulus" of sand (see ASTM C 125) is another example. In each of these cases where a single number is used to represent an entire gradation, critical information is lost concerning the range of sizes included. While single-number indices may imply an "average" fineness of sorts, they provide no information about the actual number of particles or air voids with a fineness near the average value. Such indices do not uniquely define the size distribution, since multiple, broadly different size distributions could be described by the same index.

Powers recognized this limitation of specific surface, citing its utility only for air-void distributions without "extremely coarse voids" [*11*]. When void systems vary considerably in the breadth or overall shape of their size distributions, the specific surface loses much of its value as a comparative index, as do any other indices calculated from the specific surface. Among air-void systems with similar distributions of void sizes, however, the specific surface can be a useful indicator of the relative void fineness.

Air-Void Dispersion and Spacing

As discussed earlier, only those saturated portions of cement paste within the "critical distance" of an air void will be able to tolerate the pressure generated during freezing. While both the air content (expressed as the volume of air per unit volume of air-free paste) and the air-void size (as characterized by the specific surface) will jointly be used to estimate the number of air voids within a volume of paste, it remains to assess the dispersion or spacing of those voids and so determine whether substantial portions of the paste are sufficiently close to one or more air voids.

Characteristics of Actual Geometric Arrangement

As observed under the microscope, actual air voids in concrete are randomly dispersed in regard to both size and location [*16,30,31*], see also ASTM C 457. Mather [*32*] observed an inhomogeneity in bubble size and dispersion such that, "Many samples show variations from area to area, and one cannot escape the conclusion that different parts of such concrete would behave differently with respect to resistance to freezing and thawing."

Spacing Factor

Mathematically rigorous approaches are available for determining the relative proportion of the hardened cement paste within the beneficial zone of influence of one or more air voids [*12,20,33,34*]. A less accurate but far simpler approach has been adopted by the industry, however, in which one computes a theoretical maximum distance from any point in the paste to the nearest air void. Under the assumption that a majority of the maximum paste-to-void spacings in the paste are less than this computed value, the so-called "spacing factor," generally designated by $\bar{L}$, can serve as an index to the effectiveness of the air-void system in contributing to frost resistance.

The simplified model of air-void spacing: Power's spacing factor

Powers developed the concept of the spacing factor as a simplified approach to the complex mathematics of the actual distribution of air-void spacing in concrete [*8,10,11*]. The relevant equations for determining the spacing factor are given in ASTM C 457. To those not familiar with the derivation of these equations, their apparent complexity can imply a level of mathematical rigor beyond the intent of the developer, as the relationships bypass the complexity of the real air-void system and substitute a very simplified model of reality.

The basis for the utility of the spacing factor is that it takes into account the combined influence of the "total" air content, total air-free paste content, and representative void size on the spatial distribution of the air voids. To compute the spacing factor in accordance with the ASTM equations, one needs to first determine the air content, paste content, and specific surface of the air voids. No measurements are required or performed relative to observed distances between voids or from points in the paste to the nearest air void.

After having obtained the relevant input data, the first simplifying step is to replace the multi-sized voids in the actual system with a system of single-sized voids. The void size in the simplified system is chosen to have the same total volume and same total void surface area as in the actual concrete. As pointed out by Willis [*28*] and by Powers [*10*] the "number" of air voids in the actual versus simplified systems may be significantly different.

Next, the random dispersion of air voids in the actual cement paste is replaced in the model with a geometrically regular pattern of single-sized voids arranged in a uniform, three-dimensional grid. As described by Walker [*25*], "Consider a hypothetical set of air voids, all one size, arranged in paste in a cubic, three-dimensional array. Every void is equidistant from six other voids, and imaginary lines connecting the voids are mutually perpendicular" (see Fig. 2). The dimensions of the grid system are determined so that the volume of the air voids relative to volume of "grid space" between them is equivalent to the measured volume of air relative to the measured volume of hardened cement paste. The spacing factor is then determined as half of the greatest distance between any two adjacent air voids. These assumptions and the simplified geometry just described are embodied in the standard equation for spacing factor (ASTM C 457-90, Eq 13).

When it has been determined that air content in the actual system is more than about 23% of the air-free paste volume (normally occurring in only high air content/low paste concretes), an even simpler model is used to determine the spacing factor (ASTM C 457-90, Eq 12). In this case, one simply assumes that the total paste volume is evenly distributed over the combined surface area of the air voids like a uniformly thick coating. The thickness of this hypothetical paste layer is assumed to be equivalent to the spacing factor [*10,11*]. This simplified model likewise ignores the complexity of the actual void sizes and random dispersion.

Approximate nature of the spacing factor

Due to the nature of the simplifying assumptions in constructing this model, Powers himself pointed out that the method "does not give actual spacing" [*11*]. ASTM C 457 reports that the spacing factor is "related to the maximum distance in the cement paste from the periphery of an air void." Philleo [*34*] summarized two primary limitations of the Powers spacing factor, "first, being derived from total void volume and surface area, it [Powers spac-

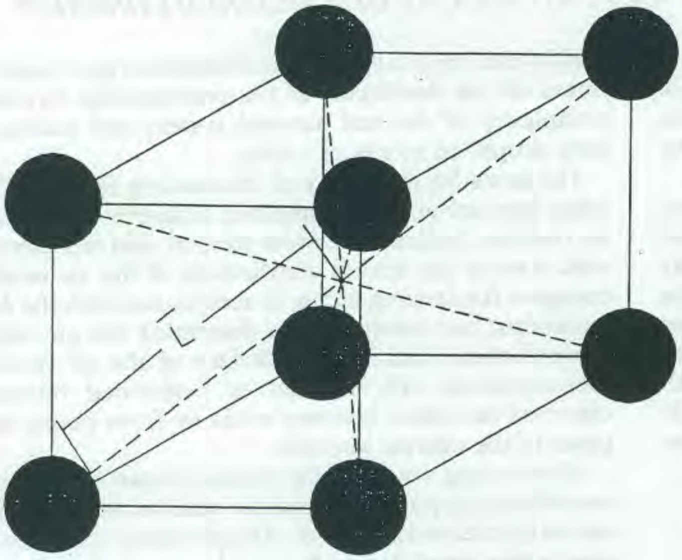

FIG. 2—Air voids arranged in a simple cubic lattice. Calculation of the spacing factor (*L*) is based on the assumptions that all air voids are (1) the same size, and (2) arranged in a simple cubic lattice where each void is equidistant from its nearest neighbor. The ratio of the volume of the unit cube to the volume of the air voids is set to be equal to the ratio of the paste volume to the total air volume in the paste. The spacing factor (*L*) is the distance along the interior diagonal from the center of the unit cube to the periphery of the nearest void, representing the farthest that water or ice would have to travel through paste to get to the nearest air void in the hypothetical air-void system.

ing factor] is strictly applicable only to concretes with similar void size distributions and, second, even if the average spacing is determined accurately, the performance of a particular concrete might be determined by a much larger spacing factor that occurs less than half the time. Thus two concretes with the same calculated spacing factor might not behave the same."

METHODS OF EVALUATING THE GEOMETRY OF THE AIR-VOID SYSTEM IN HARDENED CONCRETE

Introduction

As previously discussed the frost-resistance of concrete depends on environmental conditions, the frost-resistance of the aggregates, material properties of the hardened cement paste, and the air-void system. Once the concrete has hardened, however, frost resistance is normally estimated on the basis of actual measurements of the air-void system, coupled with assumptions concerning material properties and environmental conditions. The current procedure for evaluating the air-void system of hardened concrete is the ASTM C 457.

ASTM C 457 Microscopical Analysis

ASTM C 457 was originally proposed by Brown and Pierson [*35*] on the basis of earlier developments in geological sciences, with modifications for use on concrete. The mathematical foundation for the technique was laid by Powers [*8,10*], Willis [*28*], and Lord and Willis [*29*], and key modifications were made by Mielenz and Wolkodoff [*19*] based on work by Chayes [*36*].

A sample of hardened concrete is sawn to expose a plane surface that is then ground to provide an "extremely smooth and plane section" suitable for microscopic inspection (ASTM C 457). The operator causes the prepared sample to move in a systematic pattern under the crosshairs of a microscope, and makes a series of measurements or countings on only those air voids that come into a narrow field of view. Statistical estimates of air content, paste content, air-void size distribution, and spatial dispersion of voids are computed on the basis of these measurements.

Sampling

Samples submitted for microscopical analysis are often cores extracted from concrete in service, or may be hardened samples cast specifically for the purpose. ASTM C 457 recommends at least three samples per determination when the tests are being performed for "referee purposes or to determine the compliance of hardened concrete with requirements of specifications for the air void system." Actual performance of the test, however, requires only one sample, provided the minimum area requirements of ASTM C 457 can be met by the single specimen.

Specimen Preparation

When observing the specimen through the microscope, the operator must be able to clearly distinguish among the various constituents, with the air voids appearing as sharply defined depressions in the surface. (These depressions are made more visible under the microscope by side-lighting with a harsh, low-angle light.) The less distinct the edges of these depressions the less accurate are the measurements, and sharpness of the void edges depends on the quality of the surface preparation prior to microscopic evaluation.

The current procedure recommends grinding the surface with successively smaller abrasive grits, although alternative methods have been used with success [*30,37–39*]. The end result should be an "extremely smooth" surface, although Brown and Pierson [*35*] and Mather [*40*] recommended stopping short of "polishing."

Conduct of the Test

ASTM C 457 describes two alternative methods, (1) the Rosiwal linear traverse technique (ASTM C 457 Procedure A), and (2) the modified point count method (ASTM C 457, Procedure B). The nature of the measurements differs somewhat between the two methods as will be described, but the ultimate results are essentially the same. Both methods are statistical survey procedures, however, in which inferences about the air-void system of the sample as a whole are made on the basis of measurements of only a fraction of the air voids visible on the specimen surface, which are in turn only a fraction of the total number of air voids present in the sample. For example, a typical 100 mm (4 in.) diameter core taken from concrete in which an air-entraining agent was used may contain something on the order of 20 million air voids. Of these only about 1000 will be evaluated under the microscope.

The inspected surface is a two-dimensional plane cut and ground from the three-dimensional concrete. Three-dimensional air voids intersected by this plane are represented by depressions of various shape and depth in the plane of the sample. Irregularly shaped air voids in the concrete appear as depressions with an irregular outline, while those voids that were spherical or nearly so are represented by depressions that are clearly circular. The diameters of these circles are only indirectly related to the diameters of the original voids, however, as the plane of the surface could have randomly cut the original void at any point [*28,29*]. Only a coincidental and unlikely cut at mid-depth of a void would leave a circle with the diameter of the original void. A small circular depression on the specimen surface could therefore be the two-dimensional artifact of a small void cut near its center, or of a much larger void sliced near its periphery.

It can be demonstrated mathematically, however, that small circles are more likely to have originated in small rather than large spheres, which permits the use of statistical theory combined with a sufficiently large number of observations to project an estimate of the original bubble sizes [*16,28,29,35,37,41*]. Using these principles, one could painstakingly measure the diameters of the circles on the plane of the specimen and from these measurements project an estimate of the distribution of the original bubble sizes. As will be discussed, a simpler operation is performed in lieu of measuring the diameters of the depressions.

Linear Traverse Method

The linear traverse method requires that a series of "preferably parallel and equally spaced" lines be traced across the surface of the specimen as shown in Fig. 3 [*35*]. (In practice, this is done by moving the specimen under the microscope in a regular pattern.) These traverse lines randomly intercept a fraction of the depressions on the plane surface, and the number and length of these intercepts are recorded as the test continues. No attempt is made to direct the lines through the diameters of the circles; the intercepts are therefore random "chord lengths" or "chord intercepts." A typical test may consist of total traverse length of 1400 to 4000 mm per specimen distributed over about 50 to 1600 cm^2 (7 to 250 in.^{2}) of sample surface depending on aggregate size (see ASTM C 457), and can take 2 to 6 h of microscopic observation to complete.

The total air content is estimated from the cumulative length of chord intercepts across air voids, divided by the total length of the traverse, multiplied by 100 to convert to percentage measure (Eq 4 of ASTM C 457-90). Paste or aggregate content is similarly estimated by dividing the cumulative chord intercept across the constituents of interest by the total traverse length.

As previously discussed, it is possible to estimate the distribution of air-void sizes from the distribution of diameters of the depressions on the plane of the specimen. This can also be done, although with less certainty, from the distribution of the chord intercepts. Neither of these steps are generally taken, however, as void-size distributions are usually neglected in favor of determining the specific surface, α. It has been shown that α is readily obtained

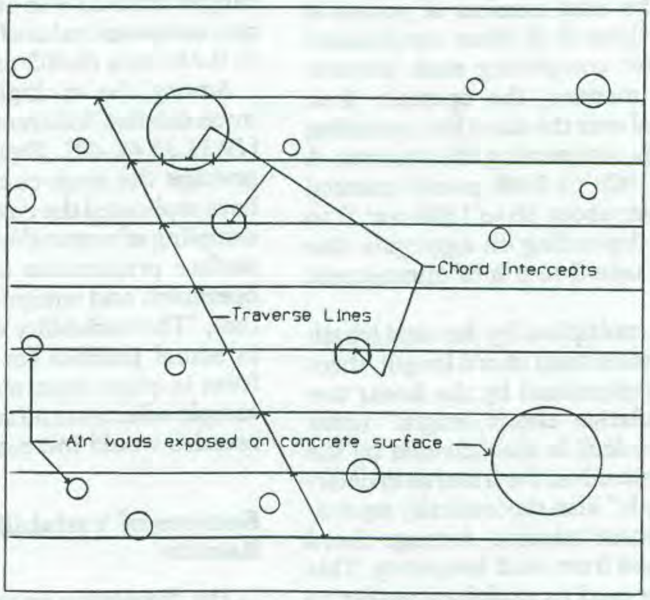

FIG. 3—Schematic diagram of linear traverse procedure. The microscope moves in parallel, closely spaced paths across the prepared concrete surface. Chord intercepts are measured that do not coincide with diameters of the air voids. Note also that the size of the two-dimensional void depressions does not necessarily indicate the spherical diameter of the voids.

directly from the average of the lengths of the individual chord intercepts [*28,29,37*].

The cumulative length of chord intercepts divided by the number of chords intercepted produces the average chord intercept, $\bar{l}$, (ASTM C 457-90, Eq 6). As demonstrated by Willis [*28*] the average chord intercept or average chord length is statistically related to the specific surface of the air-void distribution via the expression

$$\alpha = 4/\bar{l} \text{ (ASTM 457-90, Eq 8)}$$

Having obtained values for the air content, paste content, and specific surface, one computes the spacing factor in accordance with Eqs 12 or 13 of ASTM C 457-90.

One additional air-void system parameter in common use is the number of voids encountered per unit length of traverse, or the "void frequency," generally designated by n. The greater this number, the more voids per unit volume, making the void frequency a useful index. Since the number of voids encountered is equivalent to the number of chords intercepted, the void frequency is equal to the number of chords divided by the total length of traverse. ASTM C 457, Eq 7, relates void frequency and air content to average chord length.

Modified Point Count Method

The alternative to the linear traverse method is the modified point count technique in which a series of traverse lines are superimposed on the sample surface in a manner similar to that just described in Fig. 3. Rather than measuring the individual and cumulative chord lengths, however, regularly spaced stops are made and the constituent directly under the cross hairs is identified at each stop [*19*]. (Regularly spaced stops along parallel, equally spaced traverse lines form a rectangular grid of points, Fig. 4.) The air content is estimated as the number of points falling on an air void divided by the total number of points in the grid. The volume proportions of all other constituents are estimated similarly. After completing each traverse line in this point-to-point manner, the operator then reverses the direction of travel over the same line, counting the total number of air voids intersecting the traverse. A typical test may consist of 1000 to 2400 points counted per specimen, distributed over about 50 to 1600 cm^2 (7 to 250 in.^{2}) of sample surface depending on aggregate size (see ASTM C 457), and can take 2 to 6 h of microscopic observation to complete.

The computed air content multiplied by the total length of traverse provides an estimated total chord length, theoretically equivalent to that determined by the linear traverse method. This "cumulative chord length" (even though no chords were recorded) is then divided by the total number of voids encountered on the traverse to determine an "average chord length," also theoretically equivalent to that determined by linear traverse. Average chord length may also be determined from void frequency. This average chord length is then used as explained earlier to estimate specific surface and subsequently the spacing factor.

Precision and Bias

The discussion of precision and bias that accompanies ASTM C 457 includes the results of two studies on precision [*30*]. In tests sponsored by the ASTM subcommittee responsible for the test method and using one set of prepared specimens, it was estimated that in 95% of all cases the expected difference between two independent measurements of air content on a single specimen would be less than or equal to 0.82% air if the two tests were performed in the same laboratory. The expected difference would be less than or equal to 1.16% air if tested in two different laboratories. In Sommer's independent tests [*30*], the expected difference between two measurements of air content on the same specimen would be less than 1.61% air within the same laboratory, and less than 2.01% air if performed in different laboratories. Variations in estimated air content would be greater than these reported values if based on analyses of different samples from the same batch.

ASTM C 457-90 reports Sommer's precision data for spacing factor, showing that at the 95% confidence level two subsequent measurements of spacing factor within the same laboratory could vary by as much as 22.6% of the value of the spacing factor. If the studies were done in different laboratories, the variation could be as much as 56.9%.

Langan and Ward [*42*] conducted a study in which two prepared specimens were sent to various labs for evaluation by various operators within those labs. Results reported for air content ranged between 6.14 and 9.45% air for one of the specimens, and between 2.3 and 2.89% on the other. For the specimen with the higher air content, the specific surface ranged from 21.9 to 27.6 mm^2/mm^3 (556 to 701 in.^{2}/in.^{3}), and values for spacing factor ranged from 0.079 to 0.170 mm (0.003 to 0.007 in.). For their specimen with the lower air content, the specific surface ranged from 21.9 to 46.5 mm^2/mm^3 (556 to 1180 in.^{2}/in.^{3}), and computed values for spacing factor ranged from 0.135 to 0.284 mm (0.005 to 0.011 in.).

Among the multiple studies of the variabilities and uncertainties inherent in the ASTM C 457 procedures [*19,31,35,42–48*], Pleau and Pigeon [*48*] have presented perhaps the most comprehensive. None of these studies have replicated the typical industrial conditions of random sampling of nonuniform concrete combined with variable surface preparation and local variations in procedures, operators, and equipment. ASTM C 457 therefore advises that, "The variability of the test method would be higher in actual practice for specimens sampled and prepared from in-place concrete since additional variation due to sample selection and surface preparation in different laboratories would increase the coefficient of variation."

Sources of Variability and Uncertainty in Test Results

The discussion on precision and bias has demonstrated that the results of the microscopical analysis procedure are not only variable from one sample to another, one

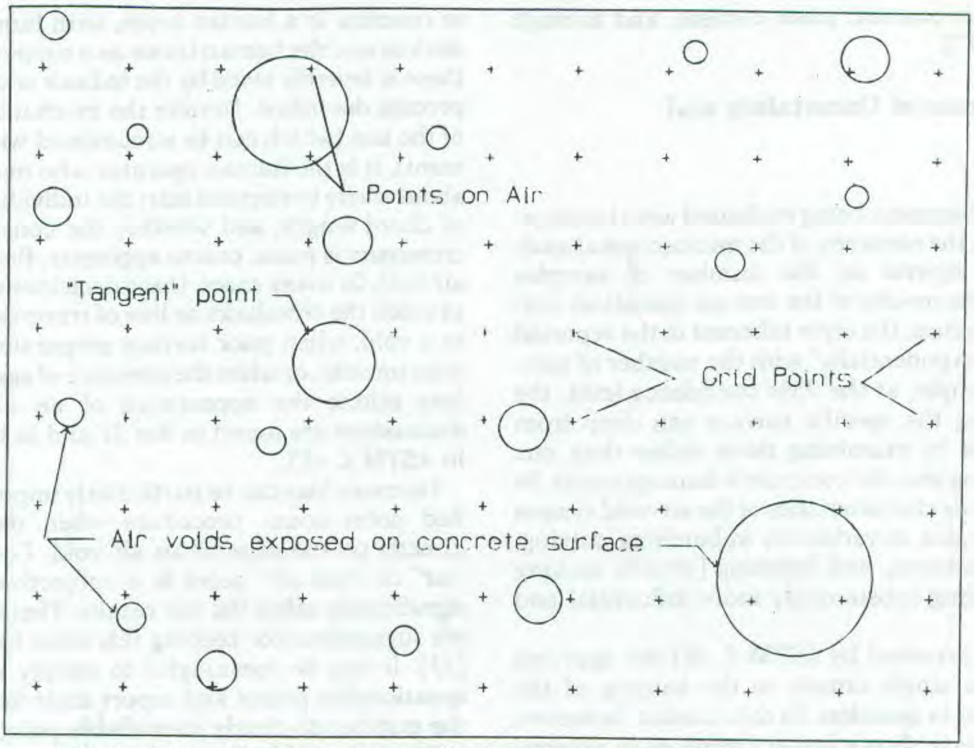

FIG. 4—Schematic diagram of modified point count procedure. The microscope moves in a grid pattern over the prepared concrete surface. Air content is determined by the number of points identified as falling on air voids divided by the total number of points counted. Note that points falling on the edge between air and paste, for example, can complicate the procedure.

laboratory to another, and one operator to another, but being statistical estimates the results are uncertain as well. Specific sources of this variability and uncertainty are detailed subsequently.

Inherent Statistical Uncertainty

The linear traverse and modified point count procedures are based on random statistical sampling of a small fraction of the air voids within a small fraction of the concrete so that test results are statistical estimates based on a limited number of observations. The uncertainty in these statistical estimates depends on the inherent variability of the concrete, the area of concrete sampled, the area of cement paste available, the number of voids measured, and on the breadth of the distribution of void sizes [*31,47,48*].

Multiple studies have been conducted on these sources of uncertainty, independent from the variability caused by operational factors [*19,29–31,35,42,47,48*]. While these references should be consulted for details, it is observed that the uncertainty in air content is primarily a function of the length of the traverse or the number of points counted [*19,35,42*]. The longer the traverse or the greater number of points the more accurate will be the estimate of air content.

To increase the probability of having traversed sufficient concrete surface to have a representative estimate of air and paste content, ASTM C 457 requires a minimum length of traverse for Procedure A, and a minimum number of points for Procedure B. Both these minimum values increase with increasing nominal or observed maximum aggregate size, recognizing that mixes with larger aggregates normally have a reduced paste content [*19,35*]. Note that whether a sufficiently large number of voids has been intercepted to permit a reasonable estimate of void size depends not only on the traverse length but on the void frequency. For concrete with a low air content and a correspondingly small number of air voids, fewer total voids will have been intercepted even when the ASTM C 457 minimum traverse length or number of points has been completed. This condition tends to increase the uncertainty in the estimates of specific surface and spacing factor. It is of interest to note that a microscopical analysis of hardened concrete is most often called-for when a low air content is suspected; yet the lower the air content the less certain are the results of the analysis. Snyder et al. [*47*] have shown that when using the linear traverse method this problem may be minimized by running the traverse beyond the ASTM minimum traverse length as necessary until about 1000 voids have been intercepted.

Fundamental statistical uncertainty in estimating the specific surface depends on both the uncertainty in the air content and the uncertainty in establishing the average chord length or void frequency, while the uncertainty in estimating the spacing factor depends on the combined uncertainties in air content, paste content, and average chord length [*42,47*].

Procedural Sources of Uncertainty and Variability

Sampling

If the concrete placement being evaluated were homogeneous throughout, the accuracy of the microscopical analysis would still depend on the number of samples examined. Since the results of the test are statistical estimates of the true values, the error inherent in the reported values "decreases exponentially" with the number of samples [*31*]. For example, at the 95% confidence level, the error in estimating the specific surface can drop from 25% to about 15% by examining three rather than one specimen, assuming that the concrete is homogeneous. In actual structures, the characteristics of the air-void system vary with location due to variations in batching, mixing, placement, consolidation, and finishing [*49–52*], making the issue of sampling substantially more influential and complex.

No guidance is provided by ASTM C 457 for applying the results from a single sample to the balance of the volume of concrete in question. In this context, however, Simon et al. [*49*] have shown broad variations in air content, specific surface, and spacing factor among multiple samples taken from within 125 to 250 mm (5 to 10 in.) of one another within the same concrete slabs. Such variations can be intensified by the localized effects of consolidation [*49,51*].

Surface Preparation

Faulty or incomplete specimen preparation has been cited as a source of error by many researchers [*16–19,30,31,35,37,53*]. Roberts and Gaynor [*53*] have reported that the effects of specimen preparation alone can skew the results of the ASTM C 457 test by as much as 3% on air content. Sommer reports similar errors stemming from surface preparation [*30*].

Level of Magnification of the Microscope

At higher levels of magnification the operator can see and measure smaller voids. While such small voids have little influence on total air content, they have significant impact on specific surface, and therefore on spacing factor [*54*]. While ASTM C 457 requires a minimum magnification of ×50, Bruere [*55*] reported that in comparison to tests performed at ×120, "Low magnifications (40× and 60×) gave erroneous results since very small bubbles could not be seen clearly." Sommer reported that spacing factor was always decreased by magnification of more than ×50, and a magnification of ×100 instead of ×50 can be assumed to reduce an $\bar{L}$ of 0.25 mm (0.010 in.) by at least 10% [*30*]. Langan and Ward reported the identical effect [*42*]. In light of such observations, Pleau et al. [*31*] suggested a minimum magnification of ×100 and a maximum of ×125.

Operator Subjectivity

The most sensitive and sophisticated piece of equipment required in the microscopical analysis of air-void systems in concrete is a human brain, with human eyes as input devices and the human frame as a support system. Each of these is severely taxed by the tedious and time-consuming process described. Despite the mechanically rote aspects of the test (which can be streamlined with modern equipment), it is the human operator who makes the decisions about where to stop and start the individual measurements of chord length, and whether the constituent under the crosshairs is paste, coarse aggregate, fine aggregate, or an air void. In many cases, these decisions are not easy, such as when the crosshairs or line of traverse is nearly tangent to a void, when poor surface preparation makes boundaries unclear, or when the presence of aggregates or pozzolans mimic the appearance of an air void. Detailed discussions are found in Ref *31* and in the text and notes in ASTM C 457.

Operator bias can be particularly important in the modified point count procedure when the crosshairs fall directly on the edge of an air void. Counting this as an "air" or "non-air" point is a subjective choice that can significantly affect the test results. There have been multiple suggestions for keeping this error from accumulating [*31*]. It can be meaningful to simply keep track of the questionable points and report their number along with the number of clearly identifiable points.

Given the subjective nature of these decisions and the need for informed judgement, it is clear that operators must be well-trained and well-experienced. In comparing test results obtained with experienced operators, Rodway [*56*] reported "erratic" results from the inexperienced operators using modified point count procedure, interpreting this as a confirmation of Langan and Ward's previous findings relative to operator variability [*42*]. Mielenz [*19*] reported that "the results of the linear traverse are adequately reproducible provided the operator is trained properly." In one test series, Pleau et al. [*31*] documented operator subjectivity as the cause of variability in computed spacing factor, with an inexperienced operator reporting about 0.145 mm (0.006 in.) and three experienced operators averaging about 0.210 mm (0.008 in.) on the same specimen. While emphasizing the "paramount importance" of training new operators, Pleau et al. conclude that "an intrinsic error due to the operator's subjectivity will always remain."

Arbitrary Deletion of Large Voids

ASTM C 457 states that "no provision is made for distinguishing among entrapped air voids, entrained air voids, and water voids. Any such distinction is arbitrary, because the various types of voids intergrade in size, shape, and other characteristics" (ASTM C 457-90, paragraph 5.3). Some testing agencies have nevertheless found it useful to distinguish at least between the coarse, so-called "entrapped" air voids and the finer, so-called "entrained" air voids, [*30,57,58*]. Other agencies have determined such practices to produce misleading results [*43*]. One justification for discounting the larger voids is to avoid their possible impact on skewing the specific surface as discussed earlier. To delete large voids, however, is to artificially modify the recorded air-void size distribution and calculated specific surface, and to delete the contribution made by the large voids to air content and protected paste volume. The effect of discounting the larger chords is consistently to decrease the reported value of air content and to increase the reported value of specific surface.

Calculations

Several potential errors in the void system calculations are worth noting. First, the equation for spacing factor requires a value for the paste content, and the accuracy of the computed value will depend, in part, on the accuracy of the paste content. In some cases the computed value for the spacing factor is either so great or so small that appropriate conclusions may be drawn without much concern for an accurate paste content. In less obvious cases, an accurate estimate of paste content is essential, and may be determined from either the linear traverse or the point count technique. (However, Pleau et al. [*31*] have observed that microscopical examination always underestimates paste content.) Some laboratories use the paste content determined from the mix design or reported batch weights or, in some cases, will merely assume a value for paste content.

A closely related source of error is the common mistake of using a value for paste content that includes the volume of the air itself. The value required in computing spacing factor is the fractional volume of "air-free" paste.

Image Analysis Techniques

Brief mention is made of the promise that computer-based image analysis techniques can improve the accuracy and reduce the time and effort required to perform the microscopical analysis. Image-based methods preceded the current techniques [*37,59*] and have been subsequently attempted to various effectiveness [*57,60*]. While multiple semi-automated systems are presently marketed, only those in which a human operator discerns the air voids in accordance with ASTM C 457 meet the requirements of that method. It is almost certain that sophisticated equipment will replace the current method in time. Depending on the direction taken by the appropriate technology, it is likely that the critical issues of sampling and surface preparation will remain. It may be that more rapid turn-around on test results or a reduced cost per test will permit a larger number of samples to be examined or each sample examined more thoroughly, with a resulting decrease in overall uncertainty and variability.

Comparing Air-Void System Parameters in Fresh and Hardened Concrete

Total air content is the only air-void system parameter that can be directly compared between the fresh and hardened concrete. This is because of the fundamental inability of any of the standard test methods including ASTM Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (C 231), ASTM Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (C 173), and ASTM C 138 (unit weight) to provide information about void size or dispersion in fresh concrete. These standard test methods indicate the total air content only, regardless of the size or distribution of the air voids. (Developing a test method that can detect void size in the fresh concrete is an acknowledged, high-priority research need in the industry.)

When differences exist between the mixing, handling, placing, or consolidation of the concrete sampled for the determination of air content in the fresh state, and the concrete sampled for later microscopic determination of air content, differences in the two test results are expected. This is because the air voids can change in size, number, shape, and volume within the fresh concrete, and can be removed from the system entirely under the influence of mixing, vibration, pressure, and temperature [*1,50,61–65*]. In fact, the reason for vibrating the concrete is to remove air from the concrete, and not all of the air removable by the vibrator is that which became trapped after mixing and discharge in the process of placing the concrete in the forms [*19,49,51,66,67*].

The procedure for the ASTM C 231 pressure method therefore alerts the user that "The air content of hardened concrete may be either higher or lower than that determined by this method." The ASTM C 231 procedure goes on to explain that the magnitude and direction of the difference between fresh and hardened air contents will depend upon "the methods and amount of consolidation effort applied to the concrete from which the hardened concrete specimen is taken; uniformity and stability of the air bubbles in the fresh and hardened concrete; accuracy of the microscopic examination, if used; time of comparison; environmental exposure; stage in the delivery, placement and consolidation processes at which the air content of the unhardened concrete is determined, i.e., before or after the concrete goes through a pump and other factors."

INTERPRETATION OF TEST RESULTS

Interpreting the Results of Tests on Hardened Concrete

General Comments

A more detailed discussion of criteria for obtaining frost resistance is included in Chapter 16 of this publication. It is useful to keep the following principles in mind, however, when interpreting the air-void system parameters obtained using the procedures already described.

1. The test results themselves are variable and subject to uncertainty, complicating a reliable inference concerning frost resistance.
2. The criteria against which the results are to be compared can be equally uncertain. Natesaiyer [*12,20*] has shown that while present criteria (to be discussed) can identify concrete that is almost certainly frost-resistant and concrete that is almost certainly non-frost-resistant, there exists a broad, marginal zone or "gray area" in which frost resistance is difficult to judge.
3. Some of the difficulty in interpreting frost resistance on the basis of air-void system parameters that are neither "clearly acceptable" nor "clearly unacceptable" is due

to the fact that frost resistance depends also on the mix proportions and material properties of the concrete, and on environmental exposure.

4. The incorporation of a beneficial air-void system in concrete does not eliminate the pressure caused by freezing, but merely reduces it to tolerable levels. In a practical sense, frost damage is minimized, not eliminated entirely, by the incorporation of air [*56*].
5. The frost resistance of concrete in-service depends on its properties in-place. Measures of air content in the fresh concrete, or air-void system parameters determined on concrete samples not handled, placed, consolidated, or finished in a representative manner may lead to incorrect conclusions about frost resistance.

Air Content

Klieger recognized that the necessary air content was dependent on mix proportions [*5,27*]. In two independent studies, he demonstrated that when the coarse aggregate volume (which is not protected by air voids in concrete) is ignored, the optimum air content for frost resistance was consistently *9% ± 1%* of the volume of the mortar. Klieger's observations are reflected in the mix design recommendations of ACI 211.1 [*3*] in which the suggested air content increases as the nominal maximum coarse aggregate size decreases. This is not because smaller coarse aggregate particles are less frost-resistant (the reverse is generally true) [*68*]. It is because the ACI 211 mix design method will correctly result in a higher mortar content in mixes using smaller coarse aggregates. This conclusion was independently reached by Siggelokow [*69*]. As Saucier pointed out, however, while a particular value of air content is necessary to provide frost resistance for a given concrete, obtaining such an air content is not by itself sufficient because of the need to obtain an appropriately sized and distributed air-void system [*65*].

Specific Surface

While frost-resistant concrete is generally characterized by values of specific surface greater than 25 mm^2/mm^3 (or about 600 in.^{2}/in.^{3}), Neville [*70*] reports frost resistance for certain concrete at values as low as about 16 mm^2/mm^3 (400 in.^{2}/in.^{3}.) Specific surface is merely an indicator of bubble size, however, providing no information about volume or dispersion. One could have an air-void system composed of acceptably small bubbles as indicted by specific surface, but there may be too few of these bubbles or they may be nonuniformly spaced so as to leave large gaps of unprotected paste.

Void Frequency

For frost-resistant concrete, the number of voids encountered per unit length of traverse is generally expected to be "one to one and a half times the numerical value of air content" [*71,72*]. Thus, if the air content is 5%, one would expect 5 to 7.5 voids per inch. This rule of thumb arises from the algebraic relationships among the air content, void frequency, and specific surface; when void frequency is about equal to the air content, specific surface is about 16 mm^2/mm^3 (400 in.^{2}/in.^{3}). When void frequency is 1.5 times air content, the specific surface is about 25 mm^2/mm^3 (600 in.^{2}/in.^{3}). Void frequency and specific surface are therefore not independent variables.

Spacing Factor

Various agencies and organizations, such as ACI Committee 212 on concrete admixtures, have recommended a spacing factor of 0.008 in. (0.200 mm) as being indicative of frost-resistant concrete [*71*]. While it is likely that concrete with a spacing factor in this range or smaller will be frost resistant, it is not equally likely that concrete with a larger spacing factor will necessarily be non-frost resistant. Interpretation of frost resistance on the basis of spacing factor is not without difficulty, therefore, in spite of the fact that of the indices available, spacing factor is the most commonly used.

Multiple studies correlating freeze-thaw durability with computed spacing factor have shown a scattered but general trend of increased durability with decreasing spacing factor [*12,20,43,72–75*]. Ivey and Torrans [*73*] concluded that for conventional concretes, "the transition between durable and nondurable concrete seems to be somewhere between an L of 0.008 and 0.010 in. [0.20 to 0.25 mm]." This general assessment appears to remain valid, and coincides with Powers original proposal that "for typical concretes and environmental conditions spacing factors not exceeding 0.250 mm (0.010 in.) or thereabouts" were generally indicative of frost-resistant concrete [*10*]. In this proposal, Powers also recognized that the spacing factor required for frost resistance depended on material and environmental factors.

PART II: UNIT WEIGHT

Introduction

The term "unit weight" as used here refers to the weight per unit volume of hardened concrete. The term unit weight when used to describe the weight of fresh concrete per unit volume, as determined by ASTM (C 138), is discussed in Chapter 10 of this publication. While the unit weights of fresh and subsequently hardened samples of a particular mix are expected to be related, the values are not expected to be identical. The relationship between the fresh and hardened unit weights for a particular concrete mixture will depend on the mix proportions and characteristics of the aggregate, the degree of consolidation, sampling, volume changes, age, and curing.

Significance of Unit Weight as a Characteristic of Concrete

Unit Weight

In some cases, the unit weight of hardened concrete, per se, is critical to the performance of the structure or facility. Examples include setting a maximum unit weight requirement when lightweight aggregate concrete is used to limit structure self-weight, or setting a minimum unit weight requirement when self weight is to be maximized for structural stability or for nuclear shielding. As described by ASTM Test Method for Unit Weight of Structural Lightweight Concrete (C 567), "The test for air-dried weight of concrete determines whether design weight requirements have been met."

Uniformity or Consistency of Materials, Construction Operations, and Testing

Consistent unit weights normally indicate consistency in all phases of concreting operations. This is because the unit weight of hardened concrete is a function of the unit weights of the initial ingredients, mix proportions, initial and final water content, air content, degree of consolidation, degree of hydration, volume changes, and subsequent gain or loss of water, among other factors. Dependence on these factors makes unit weight an effective indicator of the uniformity of raw materials, mixing, batching, placing, sampling, and testing. A significant change in unit weight signals a change somewhere in the process.

For example, if the unit weight is seen to vary among samples of hardened concrete that had been cast at the point of concrete delivery, variability in the constituent materials or proportions could be indicated. On the other hand, in this situation variable unit weights could mean nonuniform batching or mixing, or nonuniform casting of test specimens. Routine weighing of standard compressive strength specimens before testing is recommended to quickly approximate unit weight and get an indication of sample uniformity.

Alternatively, unit weight tests performed on samples of hardened concrete extracted from the structure can be useful for indicating segregation, nonuniform consolidation, or other problems. Because this useful information is so readily obtained, routine unit weight testing for all cores extracted in the field is often recommended, regardless of the primary purpose for obtaining those cores.

Voids Content

In dried, hardened concrete all of the internal voids are air-filled, including capillary pores in the hardened cement paste, voids in the aggregate particles, bleed water channels, water gain voids, microcracks, and air voids intentionally or unintentionally incorporated into the mixture. The volume of some, but not all, of these voids can be determined by the weight of absorbed water when a dried specimen is immersed for a period of time. Those voids that communicate directly with the exterior surface of the sample or are connected to the surface via capillary channels, absorb water upon immersion. These are called the "permeable pores," and represent the pore space measured by drying followed by immersion. Other voids, which include a portion of the capillary void system, some of the aggregate pores, and a fraction of the system of air voids, are termed "impermeable pores." These spaces do not fill with water upon immersion and cannot be measured by these techniques. Because one cannot discriminate among the various types of voids present when determining voids content by absorption methods, the final result is termed "total permeable voids." For a given set of raw materials of fixed unit weights, the lower the unit weight of the mixture the greater will be the voids content. Helms [77] has documented an empirical relationship between oven-dry unit weight and voids content.

The total volume of permeable voids of a sample is related to porosity, a basic characteristic of concrete that influences many of its properties. Numerous studies, beginning with those of Feret and continuing more recently to Popovics, have explored these relationships [*78–83*]. In fact, Feret [*78*] established a clear relationship between the strength of mortars and the voids/cement ratio (volume of voids in the sample divided by the volume of the cement) well before the more currently recognized relationship was established between strength and water/cement ratio. Data published by the U.S. Bureau of Reclamation confirmed that the relationship between voids and strength applied equally well to a wide variety of concrete mixes [*84*]. Helms [*77*] has reported a similar relationship even when lightweight aggregate concretes were tested.

Permeability

While the porosity of concrete can be related to unit weight and voids content, permeability depends not only on the total pore or flow channel volume, but also on the connectivity, tortuosity, and hydraulic characteristics of the channels. Nevertheless, correlations have been demonstrated between certain types of permeability tests and unit weight of hardened concrete [*85–87*]. Such relationships, even if only empirical in nature, suggest a linkage between the unit weight and durability, since the durability of concrete can be related to the degree to which water, water vapor, oxygen, and carbon dioxide can permeate the concrete.

Degree of Consolidation

Analogous to routine measurements in soil mechanics and bituminous materials, one can estimate the degree of consolidation from unit weight measurements of hardened concrete. Degree of consolidation is generally expressed as the ratio between the observed unit weight and some value taken for the "maximum" or "optimum" unit weight. Olsen [*88*] defined degree of consolidation as the unit weight of the hardened concrete divided by the unit weight of the fresh concrete. In Whiting's work [*85*], the maximum unit weight was that obtained from hardened samples that had been consolidated on a vibrating table. (It is interesting to note that within Whiting's laboratory testing program the standard deviation on measured unit weight was approximately 40 kg/m^3 (2.5 lb/ft^3), which may approximate a minimum uncertainty for unit weight tests.) Whiting went on to correlate the degree of consolidation (or "relative unit weight") to compressive strength, bond strength, and rapid chloride permeability. Bisaillon and Malhotra [*87*] also demonstrated the benefits of improved consolidation in reducing the hydraulic permeability of concrete.

Thermal, Acoustic, and Nuclear Shielding Properties

Unit weight is a key parameter in defining the ease of transmission of energy through the concrete, and when such properties are of interest it may be more appropriate to measure unit weight than compressive strength. Valore and Brewer separately [*89–90*] demonstrated the relationship between density of hardened concrete and its ability to transmit heat. Both the modulus of elasticity of concrete and the ultrasonic pulse velocity can be shown to be dependent on density. For that reason, it is often necessary to determine the unit weight of concrete in order to interpret the results of dynamic modulus or the pulse velocity tests.

Although the topic of heavyweight, nuclear-shielding concrete is beyond the scope of this chapter, the key issue in attenuating the transmission of atomic particles is to put as many atomic nuclei in the path of the radiation as possible. This means that, in general, the denser the mass, the better is its shielding ability. The unit weight test is a simple means of determining whether the required density has been achieved.

Inferring Batch Weights and Composition

Just as the unit weight test can lead to estimates of the voids content, some information about the composition of the balance of the sample is theoretically possible as well. The effects of composition on unit weight will be discussed.

Typical Values

Figure 5 [*77,91,92*] displays the approximate range of unit weights and air contents represented by aggregates, concrete, and cementitious materials. The range is bounded at the high-density end with steel shot, steel punchings, and magnetite aggregate used for radiation shielding concretes and counterweights, with unit weights above 5000 kg/m^3 (above 310 lb/ft^3). The low-density end of the range is occupied by cellular concretes with unit weights less than 1000 kg/m^3 (60 lb/ft^3) and with air contents above 25%.

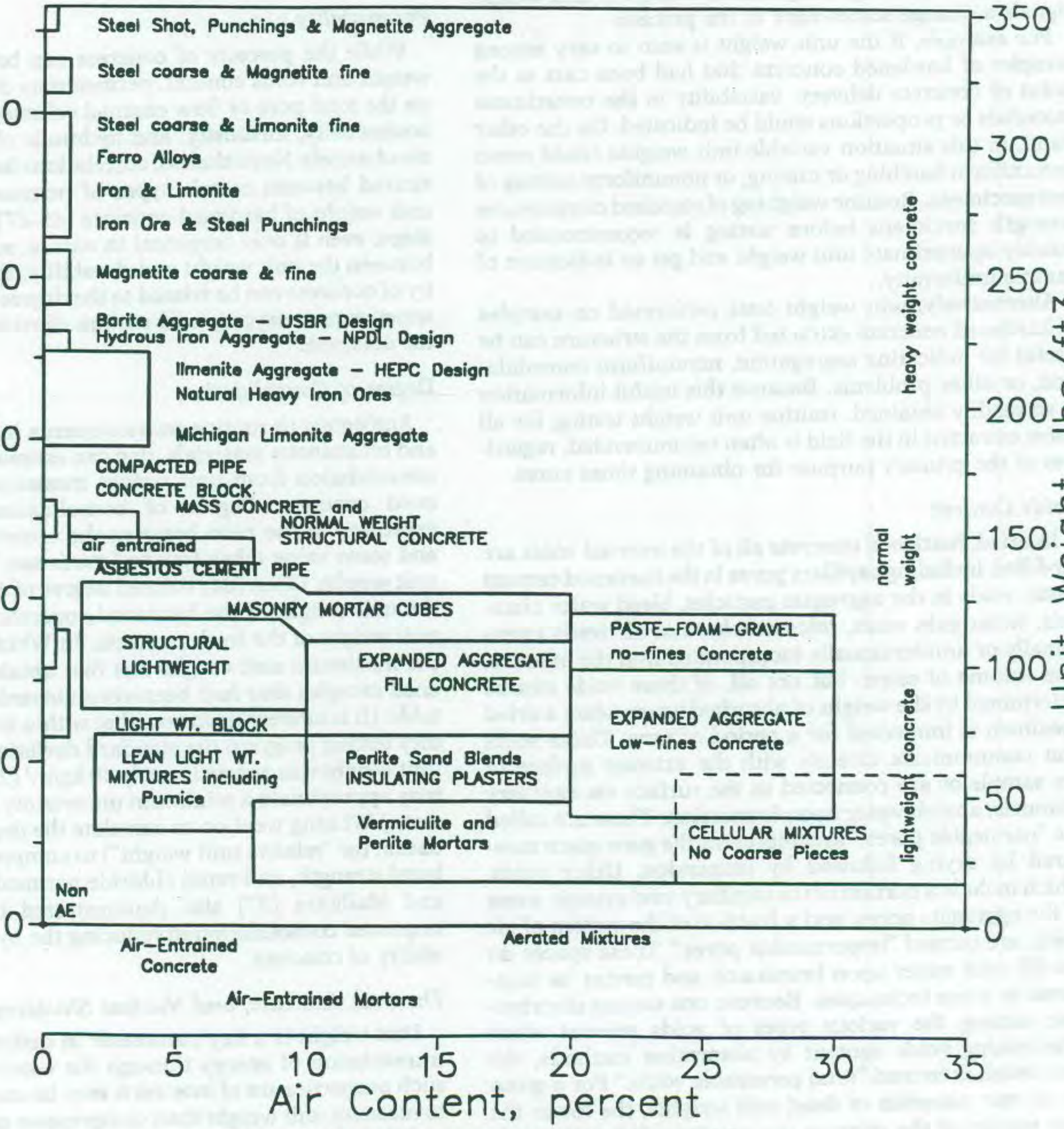

FIG. 5—Unit weight block diagram (after Helms [77]).

TABLE 1—Observed Average Unit Weight (adapted from Ref *96*).

Maximum Size of Aggregate, mm (in.)	Average Values			Unit Weight, kg/m³ (lb/ft³) Specific Gravity of Aggregate, SSD				
	Air Content, %	Water, kg/m³ (lb/yd³)	Cement, kg/m³ (lb/yd³)	2.55	2.60	2.65	2.70	2.75
19 ($^3/_4$)	6.0	168 (283)	336 (566)	2200 (137)	2230 (139)	2260 (141)	2290 (143)	2330 (145)
38 (1$^1/_2$)	4.5	145 (245)	291 (490)	2260 (141)	2290 (143)	2340 (146)	2370 (148)	2405 (150)
76 (3)	3.5	121 (204)	242 (408)	2310 (144)	2357 (147)	2390 (149)	2440 (152)	2470 (154)
152 (6)	3.0	97 (164)	167 (282)	2360 (147)	2389 (149)	2440 (152)	2470 (154)	2520 (157)

Litvin and Fiorato [*93*] have independently prepared the "Lightweight Aggregate Spectrum" that also graphically depicts concretes with compressive strengths ranging from 0.7 to 40 MPa (100 to 6000 psi) with concrete unit weights from 240 to 2000 kg/m³ (15 to 120 lb/ft³).

Methods of Determining the Unit Weight of Hardened Concrete

General

The measurement of density of hardened concrete is based on procedures that are simple and direct, using samples such as molded specimens, drilled cores, or portions taken from hardened structures and trimmed to cylinders or prisms of sufficient size to be representative. Hardened samples are dried or otherwise conditioned, and weight and volume measurements are taken. The specimens are then immersed in water so that the permeable pores are filled. Weight measurements are repeated after immersion and from these data one determines the volume of the permeable pores and weight/volume relationships for the dry and saturated specimens. It is reasonable to require unit weight by displacement measurement to be reported to the nearest 1.6 kg/m³ (0.1 lb/ft³) and within an accuracy of 0.1%. Reference is made to the detailed provisions of ASTM C 567 and ASTM Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete (C 642). (Exceptions to the general simplicity of density measurements are the nuclear methods described in ASTM Test Method for Density of Unhardened and Hardened Concrete in Place by Nuclear Methods (C 1040).)

More advanced, yet nonstandard techniques for determining the density of hardened concrete include mercury pycnometry [*94*], although such methods are more appropriate for very small samples of hardened concrete, mortar, or paste (that is, generally less than 20 cm³).

Procedural Factors Influencing the Results

In principle, the unit weight of hardened concrete is obtained just as the unit weight, specific gravity, absorption, etc. are obtained for aggregates, and the same concerns apply to proper moisture conditioning. This is made more difficult, however, when dealing with concrete samples that are many times larger than aggregate particles, and therefore come to moisture equilibrium more slowly. Other concretes are more absorptive than normal-weight aggregates and therefore can take on water at a faster rate.

The moisture condition to be used for weight determination depends on the purpose of the measurement and the in-service condition of the concrete in question. For example, when specimens are obtained by extracting cores from a structure, care is required to retain the "as-is" moisture condition. Since the density of lightweight aggregate concrete in-service is a critical issue, ASTM C 567 makes special note of establishing in-service and "equilibrium" moisture conditions in the sample.

In both ASTM C 567 and C 642, the volume of the sample is determined by the "displacement method," in which the difference between weighing in air and weighing in water is attributed to the buoyant effect of the water, which in turn is related to the density of the water and the displaced volume. In informal testing, the volume of the specimen is frequently calculated from the physical dimensions of the sample. This latter approach can be useful only when the shape of the specimen is highly regular and the dimensions accurately obtained. Even with standard concrete cylinders, the unevenness of uncapped ends and the tendency to out-of-roundness can introduce significant errors.

The issue of sample size is briefly addressed in ASTM C 642, pointing out the need to have a representative sample. This is more difficult than it may at first appear, particularly given the variations in degree of compaction that exist vertically and horizontally within a given concrete member. Such variations are well documented in work by Simon et al. [*49*] and by Kagaya et al. [*95*].

Influence of Composition on Unit Weight

Effect of Aggregate Density

Since aggregate can occupy 60 to 80% of the volume of most concrete mixes and the specific gravity of normal-weight coarse and fine aggregate is approximately one-third greater than that of the hardened cement paste, the aggregate has considerable influence on unit weight of hardened concrete. The data shown in Table 1 were collected by the U.S. Bureau of Reclamation [*96*] and show a 6 to 7% variation in unit weight for mixes using aggre-

TABLE 2—Effect of Paste Content and Water/Cement Ratio on Unit Weight.

Water/Cement Ratio	Specific Gravity of Paste	Unit Weight of Paste, kg/m³	Unit Weight of Paste, lb/ft³
0.30	1.90	1900	119
0.40	1.68	1680	105
0.50	1.48	1480	92
0.60	1.34	1340	84
0.70	1.22	1220	76

gates of various specific gravities but identical proportions.

Effect of Paste Content

Cook [*94*] reported the dry specific gravity of hardened cement pastes at various water/cement ratios after 56 days of continuous wet cure. The results are shown in Table 2, in which it is clear that the unit weight of hardened cement paste decreases as water/cement ratio increases. Since the densities of normal aggregates usually range from about 2560 to 2800 kg/m^3 (160 to 175 lb/ft^3), it is clear that a reduction of paste volume by substitution of aggregate will increase the unit weight. Further data from the Bureau of Reclamation [*97*] demonstrates this, in which mixes with a 43% paste content had a unit weight of 2206 kg/m^3, while a similar mix with a 22% paste content had a unit weight of 2533 kg/m^3 (137 and 155 lb/ft^3, respectively).

Effect of Air Content

Unit weight is reduced with an increase in the relative volume of pore space in the concrete sample, regardless of the origin of the pores. Therefore, all other factors remaining constant, unit weight will decrease with an increase in air volume, regardless of the size, shape, or distribution of the air voids. The unit weight test cannot discern air-void size, nor can it differentiate between those voids constituting the desirable air-void system in the hardened concrete and spaces such as capillary pores, bleed water channels, aggregate voids, etc. For these reasons, one has to exercise judgement in using measurements of the the unit weight of hardened concrete to evaluate air content.

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