CHAPTER 9
Properties of Concrete

Quality concrete possesses well defined and accepted principal requirements. For freshly mixed concrete, those requirements include:

- Consistency - The ability to flow.
- Stability - The resistance to segregation.
- Uniformity - Homogeneous mixture, with evenly dispersed constituents.
- Workability - Ease of placing, consolidating, and finishing.
- Finishability - Ease of performing finishing operations to achieve specified surface characteristics.

For hardened concrete, they include:

- Strength - Resists strain or rupture induced by external forces (compressive, flexural, tensile, torsion, and shear).
- Durability - Resists weathering, chemical attack, abrasion, and other service conditions.
- Appearance - Meets the desired aesthetic characteristics.
- Economy - Performs as intended within a given budget.

For different applications, concrete properties need to be controlled within certain ranges. By understanding the nature and basic characteristics of concrete, fresh and hardened properties can be more readily met. The following sections discuss the properties of freshly mixed and hardened concrete.

Freshly Mixed Concrete

Freshly mixed concrete should be plastic or semifluid and generally capable of being molded by hand. A very wet concrete mixture can be molded in the sense that it can be cast in a mold, but this is not within the definition of plastic - that which is pliable and capable of being molded or shaped like a lump of modeling clay.

In a plastic concrete mixture, all grains of sand and particles of gravel or stone are encased and held in suspension. The ingredients are not apt to segregate during transport. When the concrete hardens, it becomes a homogeneous mixture of all the components. During placing, concrete of plastic consistency does not crumble but flows cohesively without segregation maintaining stability.

In construction practice, thin concrete members and heavily reinforced concrete members require more workable mixtures for ease of placement. A plastic mixture is required for strength and homogeneity during hardening and placement. While a plastic mixture with a slump ranging from 75 mm to 150 mm (3 in. to 6 in.) is suitable for most concrete work, plasticizing admixtures may be used to make concrete more flowable in thin or heavily reinforced concrete members.

In general, fresh concrete must be capable of satisfying the following requirements:
- It must be easily mixed and transported
- It must be uniform throughout a given batch (and consistent between batches)
- It should have flow properties such that it is capable of completely filling the forms for which it was designed
- It must have the ability to be compacted without requiring an excessive amount of energy
- It must not segregate during transportation, placing, and consolidation
- It must be capable of being finished properly (either against the forms by means of trowelling or other surface treatment)

Workability

The ease of placing, consolidating, and finishing freshly mixed concrete and the degree to which it resists segregation is called workability. Concrete should be workable, but the ingredients should not separate during transport.
and handling (Figure 9-1). Concrete properties related to workability include the consistency (flow) and stability ( segregation resistance). Further defined flow characteristics (used in high-performance concrete mixtures) include: unconfined flowability, called the filling ability; and confined flowability, called the passing ability. Dynamic stability is the ability to resist separation during transport and placement. Static stability is the ability to maintain a uniform distribution of all mixture components after the fluid concrete has stopped moving.

![Figure 9-1. Workable concrete should flow sluggishly into place without segregation.](image)

The degree of workability required for proper placement of concrete is controlled by the placement method, type of consolidation, and type of concrete. For example, self-consolidating concrete has the unique properties of high workability without loss of stability, and allows for complex shapes and rigorous construction schedules (Scewzy and Mohler 2008). Different types of placements require different levels of workability (see Chapter 14).

Factors that influence the workability of concrete are: (1) the method and duration of transportation; (2) quantity and characteristics of cementitious materials; (3) concrete consistency (slump); (4) grading, shape, and surface texture of fine and coarse aggregates; (5) entrained air; (6) water content; (7) concrete and ambient air temperatures; and (8) admixtures. A uniform distribution of aggregate particles and the presence of entrained air significantly help control segregation and improve workability. Figure 9-2 illustrates the effect of casting temperature on the consistency, or slump, and potential workability of concrete mixtures.

![Figure 9-2. Effect of casting temperature on the slump and relative workability of two concretes made with different cements (Burg 1996).](image)

Consistency. Consistency is considered a close indication of workability. The slump test, ASTM C143, Standard Test Method for Slump of Hydraulic-Cement Concrete (AASHTO T 199), is the most generally accepted method used to measure the consistency of concrete. The primary benefit of the slump test is that it measures the consistency from one batch of concrete to the next. However, it does not characterize the rheology or workability of a concrete mixture quantitatively. Other test methods are available for measuring consistency of concrete (see Chapter 18). A low-slump concrete has a stiff consistency (Figure 9-3). If the consistency is too dry and hard, the concrete will be difficult to place and compact and larger aggregate particles may separate from the mixture. However, it should not be assumed that a wetter, more fluid mixture is necessarily more workable. Segregation, honeycombing, and reduced material properties can occur if the mixture is too wet.

Excessive water used to produce high slump is a primary cause of poor concrete performance, as it leads to bleeding, segregation, and increased drying shrinkage. If a finished concrete surface is to be level, uniform in appearance, and least resistant, all batched or placed in the floor must have nearly the same slump and must meet specification criteria. The consistency should be the lowest water content practical for placement using the available consolidation equipment. See Powers (1952) and Daniel (2006).

Rheology. To understand the fully the concepts of fluidity and stability of concrete mixtures, the science of rheology has been widely used. Rheology is the study of material deformation and flow. Rheology allows researchers, practitioners, mixture developers and others, a more scientific approach to determine the flow and workability of concrete was developed using the Bingham model (Bingham 1916).

The Bingham model describes two properties of the material: the yield stress and the viscosity (Figure 9-4). In fresh concrete, yield stress defines the threshold between static and fluid behavior. Consider a laborer trying to pull a hose along through a pile of freshly mixed concrete. As soon as the laborer exerts enough force on the pile of concrete, it will begin to move, indicating that the laborer has overcome the yield stress of the concrete. As soon as the stress applied to the concrete no longer exceeds the yield stress, the concrete stops moving. The viscosity of the concrete determines how fast it moves (rate of deformation). In order for concrete to flow without assistance, the yield stress of the freshly mixed concrete must be low enough that it can move by the effects of gravity. While concrete does not completely follow Bingham model behavior, it is sufficiently close at low shear rates to be useful in understanding the rheological behavior of concrete.

![Figure 9-3. Concrete of a stiff consistency (low slump) is suitable for a paving or slip-form application.](image)

![Figure 9-4. Basic Bingham behavior curve.](image)

The Bingham model is a means to characterize concrete by two measurable parameters determined with established engineering principles. From a practical standpoint, these two parameters give contractors and producers a means to explicitly specify the fresh property performance parameters best suited for the placement application.

**Bleeding and Settlement**

Bleeding is the development of a layer of water at the top or surface of freshly placed concrete. It is caused by sedimentation (settlement) of solid particles (cement and aggregate) and the simultaneous upward migration of water (Figure 9-5). Some bleeding is normal and it should not diminish the quality of properly placed, finished, and cured concrete.

![Figure 9-5. Bleed water on the surface of a freshly placed concrete slab.](image)

Excessive bleeding increases the water-cement ratio near the top surface which creates a weak top layer with poor durability, particularly if finishing operations take place while bleed water is present. A water pocket or void can develop under a prematurely finished surface which can cause a future surface delamination. Bleed water can accumulate under and alongside coarse aggregate particles (Figure 9-6). This is especially likely when differential settlement occurs between the aggregate and paste, or between the paste and reinforcement. Once the aggregate can no longer settle, the paste continues to settle allowing bleed water to rise and collect under the aggregate. Bleedwater channels also tend to migrate along the sides of coarse aggregate. This reduction of paste-aggregate bond reduces concrete strengths.

The bleeding properties of fresh concrete can be determined by two methods described in ASTM C232, Standard Test Methods for Bleeding of Concrete (AASHTO T 198). Because most concrete mixtures today provide concrete with a normal and acceptable level of bleeding, bleeding is usually not a concern and bleeding tests are rarely performed (see Chapter 19). However, there are
situations in which bleeding properties of concrete should be reviewed prior to construction. In some instances, lean concretes placed in very deep forms have accumulated large amounts of bleed water at the surface.

On the other hand, lack of bleed water on concrete flat work can sometimes lead to plastic shrinkage cracking or a dry surface that is difficult to finish. Some bleeding may be helpful to control plastic shrinkage cracking.

The bleeding rate and bleeding capacity (total settlement per unit of original concrete height) increases with initial water content, concrete height, and pressure (Figure 9-7). The accumulation of water at the surface of a concrete mixture can occur slowly by uniform seepage over the entire surface or at localized channels carrying water to the surface. Uniform seepage is referred to as normal bleeding. Water rising through the concrete in discrete paths, sometimes carrying fine particles with it, is termed channel bleeding. This usually occurs only in concrete mixtures with very low cement contents, high water contents, or concretes with very high bleeding properties (Figure 9-8).

As bleeding proceeds, the water layer at the surface maintains the original height of the concrete sample in a vessel, assuming that there is no pronounced temperature change or evaporation. The surface subsides as the solids settle through the liquid. After evaporation of all bleed water, the hardened surface will be slightly lower than the freshly placed surface. This decrease in height from time of placement to initial set is called settlement shrinkage.

Reduced bleeding may be required for a variety of reasons including facilitating finishing operations, minimizing the formation of weak concrete at the top of lifts, reducing sand streaking in wall forms, or to stabilize the hardened volume with respect to the plastic volume of the concrete.

The most effective means of reducing bleeding in concrete include:
1. Reduce the water content, water-cementitious material ratio, and slump.
2. Increase the amount of cement resulting in a reduced water-cement ratio.
3. Use finer cementitious materials (Figure 9-9).
4. Increase the amount of fines in the sand.
5. Use or increase the amount of supplementary cementing materials such as fly ash, slag cement, or silica fume.
6. Use blended hydraulic cements.

Concrete Constituents. As summarized in Table 9-1, the constituent materials may have a significant effect on air content.

As cement content increases, the air content decreases for a fixed dosage of air-entraining admixture per unit of cement within the normal range of cement contents (Figure 9-10). In going from 240 kg/m³ to 360 kg/m³ of cement (400 lb/yd³ to 600 lb/yd³), the dosage rate may have to be doubled to maintain a constant air content. However, studies indicate that when dosage is increased the air void spacing factor generally decreases. For a given air content the specific surface increases, thus improving durability.

Air Content
Air-entrained concrete is recommended for nearly all exterior concretes, principally to improve freeze-thaw resistance when exposed to freezing water and deicing chemicals (see Chapter 11). A small amount of entrained air is sometimes useful for concrete that does not require freeze-thaw protection because it reduces bleeding and increases plasticity. There are also other important benefits of entrained air in both freshly mixed and hardened concrete.

Air-entrained concrete is produced using either an air-entraining cement or adding an air-entraining admixture during batching. The air-entraining admixture stabilizes bubbles formed during the mixing process, enhances the incorporation of bubbles of various sizes by lowering the surface tension of the mixing water, impedes bubble coalescence, and adheres bubbles to cement and aggregate particles (see Chapter 7).

While minimum air contents are well established for durability, there is also a reason to consider setting a maximum air content to control strength and potential surface degradations. Externally air-lowered compressive strength of concrete (a general rule is 5%-6% strength reduction for every percent of entrained air). When floor finishing operations include steel troweling, a maximum total air content of 3% has been established to reduce the possibility of blistering (ACI 302). This occurs because steel trowels can seal the surface and trap air pockets beneath it, especially when monolithic surface treatments are used. The total air content developed in hardened concrete is impacted by constituent materials, mixture proportions, production and handling, delivery, placing and finishing methods, and the environment as discussed in the following sections.

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### Table 5.1: Effect of Concrete Constituents on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Characteristic/Material</th>
<th>Effects</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alkali content</strong></td>
<td>Air content increases with increase in cement alkali. Less air-entraining admixture dosage needed for high-alkali cements. Air void system may be more unstable with some combinations of alkali level and air-entraining admixture used.</td>
<td>Changes in alkali content or cement source require that air-entraining admixture dosage be adjusted. Increased dosage as much as 40% for high-alkali cements.</td>
</tr>
<tr>
<td><strong>Fineness</strong></td>
<td>Decrease in air content with increased fineness of cement.</td>
<td>Use up to 100% more air-entraining admixture for very fine Type III cements. Adjust admixture if cement source or fineness changes.</td>
</tr>
<tr>
<td><strong>Cement content in mixture</strong></td>
<td>Decrease in air content with increase in cement content. Smaller and greater number of voids with increased cement content.</td>
<td>Increase air-entraining admixture dosage rate as cement content increases.</td>
</tr>
<tr>
<td><strong>Contaminants</strong></td>
<td>Air content may be altered by contamination of cement with finish mill oil.</td>
<td>Verify that cement meets ASTM C150 (AASHTO M 85) requirements on air content of test mortar.</td>
</tr>
<tr>
<td><strong>Fly ash</strong></td>
<td>Air content decreases in less on ignition (carbon content).</td>
<td>Changes in LOI of fly ash source require that air-entraining admixture dosage be adjusted. Perform &quot;furnish index&quot; test to estimate increase in dosage. Prepare trial mixes and evaluate air void systems.</td>
</tr>
<tr>
<td><strong>Slag cement</strong></td>
<td>Decrease in air content with increased fineness of slag cement.</td>
<td>Use up to 100% more air-entraining admixture for finely ground slags.</td>
</tr>
<tr>
<td><strong>Silica fume</strong></td>
<td>Decrease in air content with increase in silica fume content.</td>
<td>Increase air-entraining admixture dosage up to 100% for fume contents up to 10%.</td>
</tr>
<tr>
<td><strong>Metakaolin</strong></td>
<td>No-apparent effect.</td>
<td>Adjust air-entraining admixture dosage if needed.</td>
</tr>
<tr>
<td><strong>Water reducers</strong></td>
<td>Air content increases in mix containing calcium-based materials.</td>
<td>Reduce dosage of air-entraining admixture. Select formulations containing air-detraining admixtures. Prepare trial mixes and evaluate air void systems.</td>
</tr>
<tr>
<td><strong>Retarders</strong></td>
<td>Effects similar to water-reducers.</td>
<td>Adjust air-entraining admixture dosage.</td>
</tr>
<tr>
<td><strong>Accelerators</strong></td>
<td>Minor effects on air content. No adjustments normally needed.</td>
<td></td>
</tr>
<tr>
<td><strong>High-range water reducers (Plasticizers)</strong></td>
<td>Moderate increase in air content when formulated with lignosulfonate. Spacing factor increases. Only slight adjustments needed. No significant effect on durability.</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum size</strong></td>
<td>Air content requirement decreases in increase in maximum size. Little increase over 17.5 mm (1/2 in.) maximum size aggregate.</td>
<td>Decrease air content.</td>
</tr>
<tr>
<td><strong>Aggregate ratio</strong></td>
<td>Air content increases with increased sand content.</td>
<td>Decrease air-entraining admixture dosage for mixtures having higher sand contents.</td>
</tr>
<tr>
<td><strong>Sand grading</strong></td>
<td>Middle fractions of sand promote air-entrainment.</td>
<td>$M_U$ (unit gravitation) and adjust air-entraining admixture dosage accordingly.</td>
</tr>
</tbody>
</table>

*Concrete with the same amount of air-entraining material, a low-alkali cement may require 20% to 40% (occasionally up-to-70%) more air-entraining admixture than a high-alkali cement to achieve an equivalent air content. Precautions are necessary when using more than one cement source in a batch plant. (Greening 1967).*

The effect of fly ash on the required dosage of air-entraining admixtures can range from no effect to an increase in required dosage of up to five times the normal amount (Gebler and Klieger 1986). Class C ash typically requires less air-entraining admixture than Class F ash and tends to lose less air during mixing (Thomas 2007) Ground slags have variable effects on the required dosage rate of air-entraining admixtures. Silica fume has a marked influence on the air-entraining admixture requirement. In most cases, dosage rapidly increases with an increase in the amount of silica fume used in the concrete. Large quantities of slag and silica fume can double the dosage of air-entraining admixtures required (Whiting and Nagai 1998). The inclusion of both fly ash and silica fume in non-air-entrained concrete will generally reduce the amount of entrapped air.

Water-reducing and set-retarding admixtures generally increase the efficiency of air-entraining admixtures by 50% to 100%. Therefore, less air-entraining admixture will usually give the desired air content. Also, the time of addition of these admixtures into the mixture affects the amount of entrained air. Delayed additions generally increase air content.

Set retarders may increase the air void spacing in concrete. Some water-reducing or set-retarding admixtures are not compatible with some air-entraining admixtures. If they are added together to the mixing water before being dispersed into the mixer, a precipitate may form. This will settle out and result in large reductions in entrained air. The fact that some individual admixtures interact in this manner does not mean that they will not be fully effective if dispersed separately into a batch of concrete.

Superplasticizers (high-range water reducers) may increase or decrease the air content of a concrete mixture. The effect is based on the admixture’s chemical formula and the slump of the concrete. Naphthalene-based superplasticizers tend to increase the air content while polycarboxylate-based materials decrease or have little effect on air content. The normal air loss in flowing concrete during mixing and transport is about 2% to 4% (Whiting and Dzielski 1992).

Superplasticizers also affect the air void system of hardened concrete by increasing the general size of the entrained air voids. This results in a higher-than-normal spacings factor, occasionally higher than what may be considered desirable for freeze-thaw durability. However, tests on superplasticized concrete with slightly higher spacing factors have indicated that superplasticized concretes can demonstrate good freeze-thaw durability. This may be caused by the reduced water-cement ratio often associated with superplasticized concretes.

A small quantity of calcium chloride is sometimes used in cold weather to accelerate the hardening of concrete. It can be used successfully with air-entraining admixtures if it is added separately in solution form to the mix water. However, calcium chloride is not intended for use with reinforced concrete as it will corrode the reinforcing steel. Calcium chloride will slightly increase air content. However, if calcium chloride comes in direct contact with some air-entraining admixtures, a chemical reaction can take place that makes the admixture less effective. Non-chloride accelerators may increase or decrease air content, depending upon the chemistry of the specific admixture. Generally they have little effect on air content.

Coloring agents such as carbon black usually decrease the amount of air entrained for a given amount of admixture. This is especially true for coloring materials with increasing percentages of carbon (Taylor 1948).

The size of coarse aggregate has a pronounced effect on the air content of both air-entrained and non-air-entrained concrete, as shown in Figure 9-10. There is little change in air content when the size of aggregate is increased above 37.5 mm (1.5 in.).

![Figure 9-11](image_url)  
Figure 9-11. Relationship between percentage of fine aggregate and air content of concrete (PCA Major Series 336).

The fine-aggregate content of a mixture affects the percentage of entrained air. As shown in Figure 9-11, increasing the amount of fine aggregate causes more air to be entrained for a given amount of air-entraining cement or
admixture (more air is also entrapped in non-air-entrained concrete).

Fine-aggregate particles passing the 600 μm to 150 μm (No. 30 to No. 100) sieves entraps more air than either very fine or coarse particles. Acceptable amounts of material passing the 150 μm (No. 100) sieve will result in a significant reduction of entrained air.

Fine aggregates from different sources may entraps different amounts of air even though they have identical gradations. This may be due to differences in shape and surface texture or as a result of contamination by organic materials.

The mixing water used may also affect air content. Algae-contaminated water increases air content. Highly alkaline wash water from truck mixers can affect air contents. The effect of water hardness in most municipal water supplies is generally insignificant. Very hard water from wells used in many communities, may decrease the air content in concrete.

Mixture Design. The concrete mixture design's effect on the air content is summarized in Table 9-2.

An increase in the mixing water makes more water available for the generation of air bubbles, thereby increasing the air content as slumps increase up to about 150 mm or 175 mm (6 in. or 7 in.). An increase in the water-cement ratio from 0.4 to 1.0 can increase the air content by 4%. A portion of the air increase is due to the relationship between slump and air content. Air content increases with slump even when the water-cement ratio is held constant. The spacing factor, L, of the air-void system also increases. That is, the voids become coarser at higher water-cement ratios, thereby reducing concrete freeze-thaw durability (Stark 1986).

The addition of 5 kg of water per cubic meter of concrete (8.4 lb/yard³) can increase the slump by 25 mm (1 in.). A 25-mm (1-in.) increase in slump increases the air content by approximately 0.5% to 1% for concretes with a low-to-moderate slump and constant air-entraining admixture dosage.

This approximation is greatly affected by concrete temperaure, slump, and the type and amount of cement and admixtures present in the concrete. A low slump concrete with a high dosage of water-reducing and air-entraining admixtures can undergo large increases in slump and air content with a small addition of water. Alternatively, a very fluid concrete mixture with a 200-mm to 250-mm (8-in. to 10-in.) slump may lose air with the addition of water.

Production Procedures. The effect of the production procedures on the air content is summarized in Table 9-3.

Table 9-2. Effect of Concrete/Mixture Design on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Characteristic/Material</th>
<th>Effects</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water chemistry</td>
<td>Very hard water reduces air content. Batching of admixture into concrete wash water decreases air. Algae growth may increase air.</td>
<td>Increase air entrainment dosage. Avoid batching into wash water.</td>
</tr>
<tr>
<td>Water-to-cement ratio</td>
<td>Air content increases with increased water to cement ratio.</td>
<td>Decrease air-entraining admixture dosage as water to cement ratio increases.</td>
</tr>
<tr>
<td>Slump</td>
<td>Air increases with slumps up to about 150 mm (6 in.). Air decreases with very high slumps. Difficult to entrain air in low slump concretes.</td>
<td>Adjust air-entraining admixture dosages for slump. Avoid addition of water to achieve high slump concrete. Use additional air-entraining admixture up to ten times normal dosage.</td>
</tr>
</tbody>
</table>

Table 9-3. Effect of Production Procedures on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Procedure/Variable</th>
<th>Effects</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batching sequence</td>
<td>Simultaneous batching lowers air content. Cement-first raises air content.</td>
<td>Add air-entraining admixture with initial or on sand.</td>
</tr>
<tr>
<td>Miser capacity</td>
<td>Air increases as capacity is approached.</td>
<td>Run mixers close to full capacity. Avoid overloading.</td>
</tr>
<tr>
<td>Mixing time</td>
<td>Central mixers: air content increases up to 90 seconds of mixing. Truck mixers: air content increases with mixing. Short mixing periods (30 seconds) reduce air content and adversely affect air-void system.</td>
<td>Establish optimum mixing time for particular mixer. Avoid overmixing. Establish optimum mixing time (about 60 seconds). Follow truck mixer manufacturer recommendations. Maintain blades and clean truck mixer.</td>
</tr>
<tr>
<td>Mixing speed</td>
<td>Air content gradually increases up to approximately 20 rpm. Air may decrease at higher mixing speeds.</td>
<td>Avoid manual-dispersing or gravity-feed systems and timers. Positive-displacement pumps interlocked with batching system are preferred.</td>
</tr>
<tr>
<td>Admixture metering</td>
<td>Accuracy and reliability of metering system will affect uniformity of air content.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9-12 shows the effect of mixing speed and duration of mixing on the air content of freshly mixed concretes made in a transit mixer. Generally, more air is entrained as the speed of mixing is increased up to about 20 rpm, beyond which air entrainment decreases. In the tests from which the data in Figure 9-12 were derived, the air content reached an upper limit during mixing and a gradual decrease in air content occurred with prolonged mixing. Mixing time and speed will have different effects on the air content of different mixtures. Significant amounts of air can be lost during mixing with certain types of mixing equipment and mixture proportions.

Figure 9-13 shows the effect of increased mixer agitation on air content. The changes in air content with prolonged agitation can be explained by the relationship between slump and air content. For high-slump concretes, the air content increases with continued agitation as the slump decreases to about 150 mm or 175 mm (6 in. or 7 in.). Prolonged agitation will decrease slump further and will also decrease air content. For initial slumps lower than 150 mm (6 in.), both the air content and slump decrease with continued agitation. When concrete is retempered (the addition of water and remixing to restore original slump), the air content is increased. However, after 4 hours, remeasuring is ineffective in increasing air content and may cause clustering of air bubbles (Kozlíková and others 2005). Prolonged mixing or agitation of concrete is accompanied by a progressive reduction in slump.
Transportation and Delivery. The effect of transportation and delivery of concrete on the air content is summarized in Table 9-4.

Generally, some air, approximately 1% to 2%, is lost during transportation of concrete from the mixer to the jobsite. The stability of the air content during transport is influenced by several variables including concrete ingredients, mix time, amount of agitation or vibration during transport, temperature, slump, and amount of remeasuring.

Placement and Consolidation. The effect of placing techniques and internal vibration on air content is summarized in Table 9-5.

Once at the jobsite, the concrete air content remains essentially constant during handling by chute discharge, wheelbarrow, power buggy, and shovel. However, concrete pumping, crane and bucket, and conveyor-belt handling can cause some loss of air, especially with high-air-content mixtures. Pumping concrete can cause a loss of up to 3% of air (Whiting and Nagi 1998).

The effect of slump and vibration on the air content of concrete is shown in Figure 9-14. For a constant amount of air-entraining admixture, air content increases as slump increases up to about 150 mm or 175 mm (6 in. or 7 in.). Beyond that, air content begins to decrease with further increases in slump. At all slumps, however, even 15 seconds of vibration (ACI 309) will cause a considerable reduction in air content. Prolonged vibration of concrete should be avoided.

The greater the slump, the air content, and vibration time, the larger the percentage of reduction in air content during vibration (Figure 9-14). However, if vibration is properly applied, little of the intentionally entrained air is lost. The air lost during handling and moderate vibration consists mostly of the larger bubbles. These are usually undesirable from the standpoint of strength. While the average size of the air voids is reduced, the air-void spacing factor remains relatively constant.

![Figure 9-14](image)

Table 9-4. Effect of Transportation and Delivery on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Transport and delivery</th>
<th>Some air (1% to 2%) normally lost during transport. Loss of air in nonagitating equipment is slightly higher.</th>
<th>Normal remeasuring with water to restore slump will restore air. If necessary, retemper with air-entraining admixture to restore air. Dramatic loss in air may be due to factors other than transport.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haul time and agitation</td>
<td>Long hauls, even without agitation, reduce air, especially in hot weather. Regains some of the lost air. Does not usually affect the air-void system. Remeasuring with air-entraining admixtures restores the air-void system. May cause clustering of air bubbles.</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 9-15](image)

Table 9-5. Effect of Placement Techniques and Internal Vibration on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Procedure/Variable</th>
<th>Effects</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt conveyors</td>
<td>Reduces air content by an average of 1%.</td>
<td>Avoid long conveyed distance if possible. Reduce the free-falling effect at the end of conveyor.</td>
</tr>
<tr>
<td>Pumping</td>
<td>Reduction in air content ranges from 2% to 3%. Does not significantly affect air-void system.</td>
<td>Use of proper mix design provides a stable air-void system. Avoid high slump, high-air-content concrete. Keep pumping pressure as low as possible. Use loop in descending pump line.</td>
</tr>
<tr>
<td>Remeasuring</td>
<td>Minimum effect on freeze-thaw resistance.</td>
<td></td>
</tr>
<tr>
<td>Shortcrete</td>
<td>Generally reduces air content in wet-process shortcrete.</td>
<td>Air content of mixture should be at high end of target zone.</td>
</tr>
</tbody>
</table>

Specified air contents and uniform air void distributions can be achieved in pavement construction by operating paving machine speeds at 1.22 meters/min. to 1.88 meters/min. (4 ft/min to 6 ft/min) and by using vibrator frequencies of 5,000 vibrations/min to 8,000 vibrations/min. The most uniform distribution of air voids throughout the depth of concrete, in and out of the vibrator trails, is obtained with the combination of a vibrator frequency of approximately 5,000 vibrations per minute and a slippform paving machine forward track speeds of 1.22 meters per minute (4 feet per minute). Higher frequency speeds, regularly or in combination can result in discontinuities and lack of required air content in the upper portion of the concrete pavement. This in turn provides a greater opportunity for water and salt to enter the pavement and reduce the durability and life of the pavement (Cable and others 2000).

Finishing and Environment. The effect of finishing and environment on air content is summarized in Table 9-6.

Poor screeding, floating, and general finishing practices should not affect the air content. McNeal and Gay (1996) and Falconi (1996) demonstrated that the sequence and timing of finishing and curing operations are critical to surface durability. Overfinishing (excessive finishing) may reduce the amount of entrained air in the surface region of slabs—thus making the concrete surface vulnerable to scaling. However, as shown in Figure 9-15, early finishing does not necessarily affect scale resistance unless bleed water is present (Peto and Hover 2001). Concrete to be exposed to deicers should never be steam troweled.

![Figure 9-16](image)

Table 9-6. Effect of Finishing and Environment on Control of Air Content in Concrete

<table>
<thead>
<tr>
<th>Internal vibration</th>
<th>Air content decreases under prolonged vibration or at high frequencies.</th>
<th>Do not overvibrate. Avoid high-frequency vibrators (greater than 10,000 vpm). Avoid multiple passes of vibratory screws. Close spaced vibrator insertion is recommended for better consolidation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishing</td>
<td>Air content reduced in surface layer by excessive finishing.</td>
<td>Avoid finishing with bleed water still on surface. Avoid overfinishing. Do not sprinkle water on surface prior to finishing. Do not steel trowel exterior slabs.</td>
</tr>
<tr>
<td>Temperature</td>
<td>Air content decreases with increase in temperature. Changes in temperature do not significantly affect spacing factors.</td>
<td>Increase air-entraining admixture dosage as temperature increases.</td>
</tr>
</tbody>
</table>

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Temperature of the concrete affects air content, as shown in Figure 9-16. Less air is entrained as the temperature of the concrete increases, particularly as slump is increased. This effect is especially important during hot-weather concreting when the concrete might be quite warm. A decrease in air content can be offset, when necessary, by increasing the quantity of air-entraining admixture.

During cold-weather concreting, the air-entraining admixture may lose some of its effectiveness if hot mix water is used during batching. To offset this loss, these admixtures should be added to the batch after the temperature of the concrete ingredients has equalized.

Although increased concrete temperature during mixing generally reduces air volume, the spacing factor and specific surface are only slightly affected.

Test specimens may be cast for later testing of strength and other hardened concrete properties. The results of these tests are used to determine that the concrete meets specification requirements. These results also provide a measure of the uniformity of the concrete both between batches and, when necessary, within a batch.

ASTM C94, Standard Specification for Ready-Mixed Concrete, covers criteria for determining the within-batch uniformity of concrete. If the within-batch uniformity is low, this is indicative of inadequate or inefficient mixing. Samples of concrete are taken at two locations within the batch to represent the first and last portions on discharge. The samples are tested separately for density, air slump, and strength and the difference between the test results must be less than the requirements of the specification. For example, if the average of the slump for the two samples is 90 mm (3.5 in.), the difference between the measured individual values cannot vary more than 25 mm (1 in.).

Consolidation. Uniformity of concrete is typically achieved by consolidation. Vibration sets into motion the particles in freshly mixed concrete, reducing friction between them and giving the mixture the mobile qualities of a thick fluid. The vibratory action permits use of a stiffer mixture containing a larger proportion of coarse aggregate and a smaller proportion of fine aggregate. The larger the maximum size aggregate in concrete with a well-graded aggregate, the less volume there is to fill with paste and the less aggregate surface area there is to coat with paste. Thus less water and cement are needed. Concrete with an optimally graded aggregate will be easier to consolidate and place. Consolidation of cement as well as stiffer mixtures results in improved quality and economy. On the other hand, poor consolidation results in porous, weak concrete (Figure 9-17) with poor durability (Figure 9-18).

Uniformity Uniformity is a measure of the homogeneity of the concrete. This measurement includes within-batch uniformity and between batching of concrete mixtures. Samples of fresh concrete collected at the point of discharge are tested on site to determine properties such as: slump, temperature, air content, unit weight, and yield. Sampling of fresh concrete is performed in accordance with ASTM C172, Standard Practice for Sampling Freshly Mixed Concrete.

Mechanical vibration has many advantages. Vibrators make it possible to economically place mixtures that are impractical to consolidate by hand. For more information on consolidation see Chapter 14.

Hydration, Setting, and Hardening

The binding quality of Portland cement paste is due to the chemical reaction between the cement and water, called hydration. As discussed in Chapter 3, Portland cement is not a simple chemical compound, it is a mixture of many compounds. The two calcium silicates, which constitute about 75% of the weight of Portland cement, react with water to form two compounds: calcium hydroxide and calcium sulfate hydrate. The latter is by far the most important cementing component in concrete. The engineering properties of concrete—setting and hardening, strength, and dimensional stability—depend primarily on calcium sulfate hydrate. It is the heart of concrete.

The chemical composition of calcium sulfate hydrate is somewhat variable, but it contains lime (CaO) and silicate (SiO₂) in a ratio on the order of 3 to 2. The surface area of calcium sulfate hydrate is around 300 m²/g. In hardened concrete paste, the calcium silicate hydrate forms dense, bonded aggregations between the other crystalline phases and the remaining unhydrated cement grains. These aggregations also adhere to grains of sand and to pieces of coarse aggregate, cementing all materials together (Copeland and Schulz 1962).

As concrete hardens, its gross volume remains almost unchanged, but hardened concrete contains pores filled with water and air that have no strength. The strength values in this table are the solid part of the paste, mostly in the calcium silicate hydrate and crystalline compounds.

The less porous the cement paste, the stronger the concrete. When mixing concrete, therefore, no more water than is absolutely necessary to make the concrete plastic and workable should be used. Even then, the water used is usually more than is required for complete hydration of the cement. About 0.4 times as much water by mass as cement is needed to completely hydrate cement (Powles 1948 and 1949). However, complete hydration is rare in field concrete placements due to a lack of moisture and the long periods of time required to achieve complete hydration.

Knowledge of the amount of heat released as cement hydrates can be useful in planning construction. In winter, the heat of hydration will help protect the concrete against damage from freezing temperatures. The heat may be harmful, however, in massive structures such as dams because it may produce undesirable temperature differentials.

Knowledge of the rate of reaction between cement and water is important because it determines the rate of hardening. The initial reaction must be slow enough to allow time for the concrete to be transported and placed. However, rapid hardening is typically desirable once the concrete has been placed and finished. Gypsum, added at the cement mill when clinker is ground, acts as a regulator of the initial rate of setting of Portland cement. Other factors that influence the rate of hydration include cement fineness, admixtures, amount of water added, and temperature of the materials at the time of mixing. Figure 9-19 illustrates the setting properties of a concrete mixture at different temperatures.

The setting and hardening of Portland cement can be explained using a simple model showing unhydrated cement grains dispersed in water (Figure 9-20). In this example, time starts when the water is first added to the cement. Upon the addition of water, a chemical reaction occurs between the water and cement—the reaction is called hydration. The solid products resulting from hydration occupy a greater volume than the original
cementitious materials and consequently some of the space between the cement grains is filled in. Eventually the hydration products will connect adjacent grains and a continuous solid network is formed. This is referred to as initial set.

Between the addition of water and just before initial set occurs the paste has little rigidity. If the rigidity of the paste was plotted against time there would be only a small increase in stiffness during this period. This is referred to as the dormant period. During the dormant period the paste is still plastic and the concrete can still be handled and placed. As the cement continues to hydrate, more hydration products are formed and the solid matrix becomes more dense and rigid. This period is called the setting or transition period as it represents the period during which the paste transforms from a fluid to a solid. Eventually the paste can be considered a rigid and solid material with mechanical properties such as strength and stiffness.

**Hardened Concrete**

The following sections will discuss the properties of hardened concrete including: curing, drying rate, strength, density, permeability and water tightness, volume stability and crack control, durability, and aesthetics in more detail.

**Curing**

Increase in strength with age continues provided (1) unhydrated cement is still present, (2) the concrete remains moist or has a relative humidity above approximately 80% (Powers 1948), (3) the concrete temperature remains favorable, and (4) sufficient space is available for hydration products to form. When the relative humidity within the concrete drops to about 80% or the temperature of the concrete drops below 10°C (14°F), hydration and strength gain virtually stop. Figure 9-21 illustrates the relationship between strength gain and curing temperature.

**Drying Rate of Concrete**

Knowledge of the rate of drying is helpful in understanding the properties or physical condition of concrete. Concrete must continue to hold enough moisture throughout the curing period for the cement to hydrate to the extent that desired properties are achieved. Freshly cast concrete usually has an abundance of water, but as drying progresses from the surface inward, strength gain will continue at each depth only as long as the relative humidity at that point remains above about 80%.

During the first stage of drying, liquid water is present at the surface and evaporates into the air over the concrete (Figure 9-23). The rate of evaporation at the surface depends upon temperature, relative humidity, and air flow over the surface. Warm, dry, rapidly moving air will cause faster evaporation than cool, stagnant air. As the liquid water evaporates, it is replenished with water from within the body of the concrete. As liquid water moves from within the body of the concrete to replace water that has evaporated at the surface, the concrete must shrink to make up the volume of water that has left. If the rate of evaporation is very high, the concrete may shrink excessively before the cement paste has developed much strength. This is the cause of plastic shrinkage cracking that may occur within the first few hours after the concrete is placed.

A common example is the surface of a concrete floor that has not had sufficient moist curing. Because it has dried quickly, concrete at the surface is weak and traffic on it creates dusting. Also, when concrete dries, it shrinks as it loses water. Drying shrinkage is a primary cause of cracking, and the width of cracks is a function of the degree of drying, spacing or frequency of cracks, and the age at which the cracks occur. While the surface of a concrete element will dry quite rapidly, it takes a much longer time for concrete in the interior to dry.

When the concrete can no longer shrink to accommodate the volume lost due to water evaporation, the second stage of drying begins (Figure 9-24). Liquid water recedes from the exposed surface of the concrete into the pores. Within each pore, water clings to the sidewalls and forms a curved surface called the meniscus. At the surface of the concrete, water evaporates from the meniscus in each pore into the air over the concrete. Therefore, the rate of evaporation still depends mostly on the temperature, relative humidity, and air flow over the concrete surface. At this point, water still fills the pore structure of the concrete.

**Figure 9-21. Effect of casting and curing temperature on strength development. Note that cooler temperatures result in lower early strength and higher late strength (Ewing 1956).**

If concrete is resaturated after a drying period, hydration is resumed and strength will again increase. However, it is best to moist-cure concrete continuously from the time it is placed until it has attained the desired quality. Once concrete has dried it is difficult to resaturate. Figure 9-22 illustrates the long-term strength gain of concrete in an outdoor exposure. Outdoor exposures often continue to provide moisture through ground contact and rainfall. Indoor concretes often dry out after curing and do not continue to gain strength. See Chapter 15 for more information on curing concrete.

**Figure 9-22. Concrete strength gain versus time for concrete exposed to outdoor conditions. Concrete continues to gain strength for many years when moisture is provided by rainfall and other environmental sources (Wozn 1990).**

**Figure 9-23. Drying Stage 1—Pores in freshly placed concrete (or concrete that has been re-watered) are saturated with liquid water and drying begins by evaporation from the exposed surface (adapted from Scherrer 1980).**

**Figure 9-24. Drying Stage 2—When moisture has retreated below the surface, movement depends on fluid flow along the surface of pores and evaporation into the pores (adapted from Scherrer 1980).**
There are continuous paths for liquid water to flow from within the body of concrete to the partially filled pores at the surface where the water can evaporate. The surface may appear to be dry, but the concrete is just beginning to dry in a very thin layer. The rate of drying during this period steadily decreases.

The third stage of drying begins when enough water has evaporated from just below the surface that the pores are no longer continuously filled with liquid (Figure 9-25). Pockets of liquid water exist but moisture must now move by vapor diffusion within the body of the concrete before arriving at the surface where it can evaporate. This stage is called the second falling rate period because the rate of drying continuously decreases over time and is slower than the previous stage of drying (Figure 9-26). The rate of drying depends less on temperature, relative humidity, and air flow above the concrete surface because moisture must evaporate and diffuse within the body of the concrete before arriving at the surface. The rate of drying during this stage is determined by the quality of the cement paste: low water-cement ratio cement paste offers more resistance to vapor diffusion than high water-cement ratio paste. Concrete made with a water-cement ratio, greater than approximately 0.65, will have a continuously connected capillary pore system. In these concretes moisture vapor moves with much less resistance than concretes made with lower water cement ratios.

Concrete to receive flooring material must be dry enough to permit the adhesive to bond properly and to prevent damage to the flooring. For coatings, the concrete must be sufficiently dry to develop adequate bond and to allow the coating to chemically cure. A concrete surface may look dry, but the slab can still contain sufficient moisture to cause problems after it is covered (Kanare 2008).

Theoretically, it is possible to calculate the drying time for a given concrete (Hall 1997). This calculation requires the absorption characteristics, diffusion coefficients for water and water vapor, porosity and pore size distribution, and degree of hydration. Since this information usually is not available, current practice relies on experimental data combined with measurements of the actual moisture condition of the concrete slab in the field (Kanare 2008).

Many other properties of hardened concrete also are affected by its moisture content: elasticity, creep, insulating value, fire resistance, abrasion resistance, electrical conductivity, frost resistance, scaling resistance, and resistance to alkali-aggregate reactivity. Also see the section on Density in this chapter and see Chapter 10 on Volume Change of Concrete (Figure 10-31) for additional information on drying effects, mass loss, and shrinkage.

Figure 9-25. Drying Stage 3. When moisture is no longer continuously wetting the surface of pores, moisture must evaporate within the body of the paste and diffuse toward the surface (adapted from Scherer 1992).

The moisture content of concrete depends on the concrete's constituents, original water content, drying conditions, and the size of the concrete element (Hedenblad 1996 and 1997). Size and shape of a concrete member possible for air-entrained concrete tend to offset the somewhat lower strengths of air-entrained concrete, particularly in lean to medium cement content mixtures.

Figure 9-26. Stages of drying for concrete. Stage 1 has a constant rate and depends on air movement and relative humidity over the slab while Stages 2 and 3 depend more on the properties of the cement paste (adapted from Hughes 1998).

have an important bearing on the rate of drying. Concrete elements with large surface area in relation to volume (such as floor slabs) dry faster than large volume concrete members with relatively small surface areas (such as bridge piers). After several months of drying in air with a relative humidity of 50% to 90%, moisture content is about 1% to 2% by mass of the concrete.

Compressive strength is the maximum resistance of a concrete specimen to axial loading. It is generally expressed in megapascals (MPa) or pounds per square inch (psi) at an age of 28 days. Other test ages are also used. However, it is important to realize the relationship between the 28-day strength and other test ages. Seven-day strengths are often estimated to be about 75% of the 28-day strength while 56-day and 90-day strengths are about 10% to 15% greater than 28-day strengths, as shown in Figure 9-27. The specified compressive strength is designated by the symbol $f'_c$ and ideally is exceeded by the actual compressive strength, designated by $f_c$.

Figure 9-27. Compressive strength development of various concretes illustrated as a percentage of the 28-day strength (Lange 1994).

The compressive strength of a concrete achieve is influenced by the water-cementitious materials ratio, the extent to which hydration has progressed, the curing and environmental conditions, and the age of the concrete. The relationship between strength and water-cement ratio has been studied since the late 1800s and early 1900s (Peret 1897 and Abrams 1918). Figure 9-28 shows compressive strengths for a wide range of concrete mixtures and water-cement ratios at an age of 28 days. Note that strengths increase as the water-cement ratio decrease. These factors also affect flexural and tensile strengths and bond of concrete to steel.

The water-cement ratio compressive strength relationships in Figure 9-28 are for typical non-air-entrained concretes. When more precise values for concrete are required, graphs should be developed for the specific materials and mix proportions to be used on the job.

For a given workability and a given amount of cement, air-entrained concrete requires less mixing water than non-air-entrained concrete. The lower water-cement ratio is significant for air-entrained concrete, which tends to offset the somewhat lower strengths of air-entrained concrete, particularly in lean to medium cement content mixtures.

Figure 9-28. Range of typical strength-water-cement ratio relationships of portland cement concrete aged to over 100 different concrete mixtures cast between 1985 and 1999.

To determine, compressive strength, tests are made on specimens of mortar or concrete. The United States, unless otherwise specified, compression tests of mortar are made on 90-mm (3-3/8-in.) cubes, while compression tests of concrete are made on cylinders 150 mm (6 in.) in diameter and 300 mm (12 in.) high (Figure 9-29) or smaller cylinders sized at 100 mm x 200 mm (4 in. x 8 in.).

The compressive strength of concrete is a fundamental physical property frequently used in design calculations for bridges, buildings, and other structures. Most general-use concrete has a compressive strength between 20 MPa and 40 MPa (3000 psi and 6000 psi). Concrete strengths of 70 MPa to 140 MPa (10,000 psi to 20,000 psi) have been used in special bridge and high-rise building applications.

Figure 9-29. Testing a 150 mm x 300 mm (6 in. x 12 in.) concrete cylinder in compression. The load on the test cylinder is registered on the display.
The flexural strength or modulus of rupture of concrete is used to design pavements and other slabs on ground. Compressive strength, which is easier to measure than flexural strength, can be used as an index of flexural strength, once the empirical relationship between them has been established (for the materials and the size of the element involved). The flexural strength of normal-weight concrete is often approximated as 0.7 to 0.8 times the square root of the compressive strength in megapascals (7.5 to 10.1 times the square root of the compressive strength in pounds per square inch). Wood (1992) illustrates the relationship between flexural strength and compressive strength for concrete exposed to moist curing, air curing, and outdoor exposure.

The direct tensile strength of concrete is about 8% to 12% of the compressive strength and is often estimated as 0.4 to 0.7 times the square root of the compressive strength in megapascals (5 to 7.5 times the square root of the compressive strength in pounds per square inch). Splitting tensile strength is 8% to 14% of the compressive strength (Hanson 1968). Splitting tensile strength versus time is presented by Lange (1994).

The torsional strength for concrete is related to the modulus of rupture and the dimensions of the concrete element. Isa (1968) presents torsional strength correlations.

Shear strength to compressive strength relationships are discussed in the ACI 318 building code. The correlation between compressive strength and flexural, tensile, torsional, and shear strength varies with concrete ingredients and environment.

Modulus of elasticity, denoted by the symbol E, may be defined as the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of a material. For normal-weight concrete, E ranges from 1 GPa to 4 GPa (2 million psi to 6 million psi) and can be approximated as 3,000 times the square root of the compressive strength in megapascals (57,000 times the square root of the compressive strength in pounds per square inch). Like other strength relationships, the modulus of elasticity to compressive strength relationship is mixture specific and should be verified in a laboratory (Wood 1992).

**Density**

Conventional, concrete, normally used in pavements, buildings, and other structures, has a density (unit weight) in the range of 2200 kg/m³ to 2400 kg/m³ (137 lb/ft³ to 150 lb/ft³). The density of concrete varies depending on the amount of aggregate and the concrete, the amount of air that is entrapped or purposely entrained, and the water and cement contents, which in turn are influenced by the maximum size of the aggregate. Reducing the cement paste content (increasing aggregate volume) increases density. Values of the density of fresh concrete are given in Table 9.1. For the design of reinforced concrete structures, the combination of conventional concrete and reinforcing steel is commonly assumed to weigh 2400 kg/m³ (150 lb/ft³).

The weight of dry concrete equals the weight of the freshly mixed concrete ingredients less the weight of mix water that evaporates during drying. Some of the mix water combines chemically with the cement during the hydration process, converting the cement phases into hydrates. Also, some of the water remains tightly held in pores and capillaries and does not evaporate under normal conditions. The amount of mix water that will evaporate from concrete exposed to ambient air at 50% relative humidity is about 0.5% to 3% of the concrete weight. The actual amount depends on initial water content of the concrete, absorption characteristics of the aggregates, and size and shape of the concrete element.

There is a wide spectrum of special concretes to meet various needs. Their densities range from lightweight insulating concretes with a density as low as 220 kg/m³ (15 lb/ft³) to heavyweight concrete with a density of up to 6000 kg/m³ (375 lb/ft³) used for counterweights or radiation shielding.

**Permeability and Watertightness**

Concrete used in water-retaining structures or exposed to weather or other severe exposure conditions must be of low permeability or watertight. Watertightness is the ability of concrete to hold back or retain water without visual leakage. Permeability refers to the amount of water migration through concrete when the water is under pressure or to the ability of concrete to resist penetration by water or other substances (liquid, gas, or ions). Generally, the same properties of concrete that make it less permeable also make it more watertight.

The overall permeability of concrete to water migration is a function of (1) the permeability of the paste; (2) the permeability and gradation of the aggregate; (3) the quality of the paste and aggregate transition zone; and (4) the relative proportion of paste to aggregate. Decreased permeability improves concrete’s resistance to freezing and thawing, re-mutualization, sulfate attack, chloride-ion penetration, and other chemical attack (see Chapter 11).

The permeability of the paste is particularly important because the paste envelops all constituents in the concrete.
Occasionally, porous concrete—no-fines concrete that readily passes through water—is designed for special applications. In these concretes, the fine aggregate is either greatly reduced or completely removed. This condition causes a high volume of interconnected air voids. Flow rates in pervious concrete are orders of magnitude higher—often 0.2 cm/s or higher. Pervious concrete has been used in tennis courts, pavements, parking lots, greenhouses, and drainage structures. Pervious concrete has also been used in buildings because of its thermal insulation properties.

Drying shrinkage is an inherent, unavoidable property of concrete. However, properly positioned reinforcing steel is used to reduce crack widths, or joints are used to predetermine and control the location of cracks. Thermal stress due to fluctuations in ambient temperature also cause cracking, particularly at an early age.

Concrete shrinkage cracks are often the result of restraint. As drying shrinkage occurs, if there is no restraint, the concrete will not crack. Restraint comes from several sources. Drying shrinkage is always greater near the surface of concrete, the moist inner portions restrain the concrete near the surface, which can cause cracking. Other sources of restraint are reinforcing steel embedded in concrete, the interconnected parts of a concrete structure, and the friction of the substrate on which concrete is placed.

Joints. Joints are the most effective method of controlling unsightly cracking. If a sizable expanse of concrete (a wall, slab, or pavement) is not properly restrained by properly spaced joints to accommodate drying shrinkage and temperature contraction, the concrete will crack in a random manner.

Contraction (shrinkage control) joints are grooved, formed, or sawed into sidewalks, driveways, pavements, floors, and walls so that cracking will occur in these joints rather than in a random manner. Contraction joints permit movement in the plane of a slab or wall. They extend to a depth of approximately one-quarter the concrete thickness.

Isolation joints separate a concrete placement from other parts of a structure and permit horizontal and vertical movements. They should be used at the junction of floors with walls, columns, ceilings, and other points where restraint can occur. They extend the full depth of slabs and include a premolded joint filler.

Construction joints occur where concrete work is concluded for the day. They separate areas of concrete placed at different times. In slabs-on-ground, construction joints usually align with, and function as, control or isolation joints. They may also require dowels to load transfer.

For more information on volume changes in concrete, see Chapter 10.

Duraibility

The durability of concrete may be defined as the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties. Concrete is exposed to a greater variety of potentially harmful exposure conditions than any other construction material.

There are many causes of concrete deterioration and most of these involve either the movement of moisture or the movement of species, such as chlorides and sulfates, dissolved in water. Generally, the greater the resistance of the concrete to the movement of water, the lower its permeability and the greater its resistance to deterioration.

The following sections discuss several deterioration mechanisms. For more information on each of these topics and preventive measures see Chapter 11.

Freeze-thaw and deicer salts. Deterioration due to freezing and thawing is a result of the expansive forces that are generated when the water in saturated concrete freezes. If the concrete is not designed to resist freeze-thaw cycles, cracking will occur. As the number of freeze-thaw cycles increase, the cracking will become more advanced and eventually severe deterioration may occur. Damage due to freezing and thawing is exacerbated in the presence of deicing salts. When concrete is exposed to these conditions, particular attention must be paid to ensure that the mixture proportions are appropriate and that the concrete is finished and cured properly. D-cracking or durability cracking occurs when frost-susceptible aggregates are used in concrete exposed to freezing and thawing. In such cases, it is the expansion of water in the aggregate that leads to cracking of the concrete.

Corrosion. Concrete may be exposed to chloride ions during service. Common sources of chlorides include: deicing salt, seawater or chloride-contaminated groundwater. Over time, the chlorides will penetrate through the concrete cover and eventually reach the embedded steel reinforcement. The chlorides breakdown the passive layer, allowing corrosion of the steel to occur. Because the products of corrosion, rust, occupy more volume than the metallic steel, expansive forces develop which can lead to cracking in the concrete. Eventually corrosion can lead to spalling and delamination of the concrete cover. Corrosion of embedded steel reinforcement is the most prevalent form of deterioration of reinforced concrete structures.

Carbamation. Another form of deterioration of concrete due to corrosion is caused by carbonation. Carbonation of concrete occurs when carbon dioxide from the atmosphere penetrates concrete and reacts with the products of cement hydration and reduces the alkalinity of the concrete. When the carbonation depth reaches the steel the protective layer becomes unstable and the steel starts to corrode. Carbonation is typically a very slow process.

A alkali-silica reactivity. Alkali-silica reaction (ASR) is the reaction between the alcalies (sodium and potassium) in portland cements and silica or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates. The reaction product is an alkali-silica gel which has the capacity to adsorb water and swell. Under certain conditions the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Abrasions. Floors, pavements, and hydraulic structures are subjected to abrasion. These applications concrete must have a high abrasion resistance. Test results indicate that abrasion resistance is closely related to the compressive strength of concrete. Strong concrete has more resistance to abrasion than weaker concrete. The type of aggregate and surface finish or treatment used also has a strong influence on abrasion resistance. Hard aggregate is more wear resistant than soft aggregate and a steel-troweled surface resists abrasion better than an untextured surface.

Sulfate attack. Excessive amounts of sulfates in soil or water can attack and destroy a concrete that is not properly designed. Sulfates (for example, calcium sulfate, sodium sulfate, and magnesium sulfate) can attack concrete by reacting with hydrated compounds in the hardened cement paste. These reactions can induce sufficient pressure to disrupt the cement paste, resulting in disintegration of the concrete (loss of paste cohesion and strength).

Other forms of concrete deterioration. There are other forms of concrete deterioration less common or which occur only in special conditions:

1. Thaumasite form of sulfate attack—which differs from classical sulfate attack
2. Delayed ettringite formation (DEP)—which only occurs in concrete exposed to excessive temperatures at early ages
3. Alkali-carbonate reaction (ACR)—which involves the attack by alkalis on carbonate phases of the rock and is much less widespread than alkali-silica reaction
4. Salt crystallization and attack by chemicals other than sulfates

Different concretes require different degrees of durability depending on the exposed environment and the properties desired. The concrete ingredients, proportioning of those ingredients, interactions between the ingredients, and placing and curing practices determine the ultimate durability and service life of the concrete. For more information on the durability of concrete, see Chapter 11.

Aesthetics

Pleasing decorative finishes can be built into concrete during construction. Variations in the color and texture of concrete surfaces are limited only by the imagination of the designer and the skill of the concrete craftsman.

Color may be added to the concrete through the use of white cement and pigments, exposure of colorful aggregates, or addition of score lines to create borders for the application of penetrating or chemically reactive stains. Desired textured finishes can be varied from a smooth polish to the roughness of gravel. Geometric patterns can
be scored, stamped, rolled, or laced into the concrete to resemble stone, brick, or tile paving (Figure 9-32). Other interesting patterns are obtained using divider strips (commonly redwood) to form panels of various sizes and shapes—rectangular, square, circular, or diamond. Special techniques are also available to make concrete slip-resistant and sparkling.

Figure 9-32. Pattern-stamped finish and colored surfaces are popular for decorative concrete.

These surface treatments are just as pleasing in the interior as they are on the exterior of a house or commercial building. Colored and imprinted concrete is an excellent flooring material combining the economy, durability, decorative qualities, and strength of concrete and the thermal mass needed for passive solar buildings. Special concrete finishes (interior or exterior) enhance the aesthetic appeal and value of any property. For more information on decorative concrete see ACI Committees 303 and 310, and Kosmatka and Collins 2004.

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