Chapter 4. Concrete Materials and Properties

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Soils, Subgrade, and Subbase

For concrete floors to carry a designed load successfully without deterioration, the subgrade and, if needed, the subbase must be uniform and well compacted. The subgrade may need localized blending with backfill to provide adequate support for the structures. A subbase may be required over the subgrade if the subgrade in general is not adequate to support the structures. In some cases, a subbase over the subgrade may not be required, but will add some benefits in construction and performance, Figure 4.1.

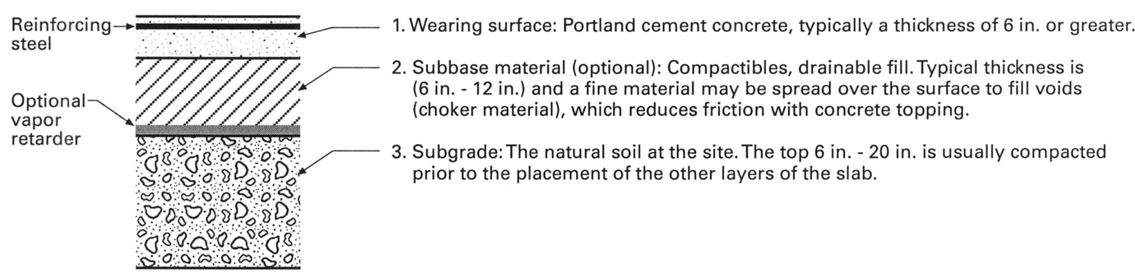

Figure 4.1. Concrete slab on subbase and subgrade.

Subgrade

The subgrade is the original ground, graded and compacted, on which the concrete floor slab is placed. Concentrated loads are spread over large areas by the concrete slab so pressures on the subgrade are usually low. Concrete floors do not usually require strong support from the subgrade, but the subgrade must be uniform, without abrupt changes from hard to soft. The upper portion of the subgrade must have uniform material and density. The strength of the soil (its supporting capacity and resistance to movement or consolidation) is important to the performance of concrete slabs, particularly when the slab must support extremely heavy uniform loads like flat- bottom storage tanks. Soil strength is affected by the degree of its compaction (density) and its moisture content. Compaction by rolling, tamping, or vibrating increases soil density and improves the structural properties of the soil.

The subgrade modulus is one measure of the quality of the subgrade and is related to the soil type. Table 4.1 shows the approximate relationship between subgrade modulus and soil types. The subgrade soil must be classified to identify potential problem soils. Problem soils are highly expansive, highly compressible, or do not provide reasonably uniform support. Where problem soils create non-uniform conditions, subgrade preparation is the most economical and effective method of correction.

Subgrade preparation

The subgrade should be uniform bearing capacity free of organic matter and frost. The subgrade should be either undisturbed or compacted to almost maximum density and moistened with water before concrete is placed. The subgrade cannot have standing or puddled water while the concrete is placed. Minimize variations of the subgrade to provide uniform support under the slab. The following are major causes of non-uniform support.

Expansive soils

Abnormal shrinkage and swelling of high-volume-change soils creates non-uniform support, which can cause the concrete slab to become distorted. Compaction of highly expansive soils when they are too dry can lead to detrimental expansion and softening of the subgrade during future wetting. If expansive soils are too wet when a concrete slab is placed, subsequent drying and shrinkage of the soil may leave portions of the slab unsupported. Selective grading, cross hauling from one part of the site to another, and blending of subgrade soils may be required to obtain uniform conditions in the upper part of the subgrade. For heavy loadings or poor soil conditions, hire a competent soils engineer to make a soils investigation, and design and submit a subgrade construction plan.

Table 4.1. Approximate relationship between soil classifications and subgrade modulus.

A detailed description of the method used to determine the subgrade modulus reaction of soil is given in ASTM D1196, *Non-Repetitive Static Plate Load Tests of Soils and Flexible Pavement components for Use in Evaluation and Design of Airport and Highway Pavements.* When plate bearing tests are not feasible at the jobsite, the k value may be conservatively estimated from the information below. This table is based on *Design of Heavy Industrial Concrete Pavements*, *Appendix A*.

	Classification system designation[a]		Design Subgrade Modulus (lb/in^3)[d]
Soil type	**Unified[b]**	**AASHTO[c]**	
Silts and clays	MLA4	CL	100
Sandy soils	GC SW SM SP SC	A-1-b A-2-6 A-2-7 A-3	200
			300
Sand gravels	GP GW	A-2-4 A-2-5 A-1-a	

[a]Soil surveys published by the National Cooperative Soil Survey (a joint effort of the United States Department of Agriculture's Soil Conservation Service and other federal, state, and local agencies) give estimates of the engineering for the major layers of each soil in the survey area.
[b]United soil classification system (ASTM Designation D2387-69).
[c]American Association of State Highway and Transportation Officials soil classification system (ASTM Designation D3282-73).
[d]Soils designated Pt, OH, and CH along with certain soils designated OL and MH in the United soil classification system and certain soils designated A-5, A-6, A-7-5, and A-7-6 in the AASHTO system are NOT suitable for use as a subgrade material.

Hard and soft spots
If the subgrade provides non-uniform support, the slab will bridge over soft spots and bear on hard spots, eventually cracking under heavy traffic loading. Take special care when excavating and backfilling to prevent localized soft or hard spots. Uniform support cannot be obtained merely by dumping granular material on the soft spot. At transition areas where soil types or conditions change abruptly, mix the replacement soil with the surrounding soil by cross hauling and blending soils to form a transition zone with nearly uniform support.

Backfill
Choose fill material that can be thoroughly compacted to improve the subgrade or raise the area to the desired grade. Backfill with soils like those that are in the surrounding area. Moisture and density conditions of a replacement soil should be similar to those found in adjacent soil. Compact backfill in layers no more than 6 inches thick. Plumbing and utility lines should not be placed under secondary containment structures. Poorly compacted subgrade can cause subsequent settlement problems and premature slab failure.

Frost heaving
In cold regions, frost heaving can cause cracks and serious structural damage to concrete floors. To reduce frost heave problems, drain water away from concrete slabs or walls. Construct a runoff control system around the secondary containment structures to keep water from entering the subgrade or base materials. Watch the runoff control system carefully for two to three years after construction as the landscaping around the site settles. Avoid any ponding near the site. In some cases, it may be necessary to build diversions or provide some drainage around the sites to prevent water from running through the site. Drain runoff from nearby buildings or lots away from the site by properly placed gutters and/or curbs.

Subbase
The subbase is a layer of granular material placed on top of the prepared subgrade, Figure 4.1. If the subgrade provides adequate support for the slab, a subbase may not be necessary. However, when grading and compaction do not produce a uniform subgrade, a granular subbase must be used to provide a more uniform support by equalizing minor subgrade defects. The granular subbase also can provide a capillary break to reduce water transfer and a stable working platform for construction equipment. It is seldom necessary or economical to increase the supporting capacity of the subgrade with a thick subbase. When needed, the subbase must be a minimum of 4-inch thick granular material compacted to near maximum density. If the subbase required is thicker, it must be placed in maximum thickness layers of 4- to 6-inch thick and compacted lifts.

Increasing subbase thickness beyond 4 inches results in only minor increases in subgrade support. Granular material for the subbase can be sand, sand-gravel, crushed stone, or combinations of these materials. A satisfactory, dense-graded material will meet the following requirements:
- Maximum particle size: Not more than 1/8 subbase thickness.
- Passing No. 200 sieve: 15 percent maximum.
- Plasticity index: 6 maximum.
- Liquid Limit: 25 maximum.

Vapor retarder
A vapor retarder can be used to provide additional protection against movement of product through the concrete or failure against impermeable coatings. Do not place concrete directly on a

vapor retarder because it prevents drainage of excess bleed water from the slab base during curing and possible ice lenses after. The resulting uneven drying between the top and bottom of the slab aggravates cracking due to plastic and drying shrinkage. If a vapor barrier is used, place a 6- to 8-inch layer of compacted, self-draining granular fill subbase over the vapor retarder before placing the concrete slab, Figure 4.1. Experience has shown that a layer less than 6 inches thick may be slippery and could be damaged easily during concrete placement. Provide good drainage around the structure and a granular fill under the concrete to reduce the exposure of the concrete to subgrade moisture. If an impermeable coating is used on the top of the concrete, water vapor passing up through the concrete is sealed in the slab, which may cause the coating to fail.

Concrete Ingredients

Concrete is a mixture of a paste (consisting of Portland cement and water) surrounding a mixture of coarse and fine aggregates. As the hydration process proceeds, the mixture gains strength. Figure 4.2 shows the relative proportions of the materials used in concrete.

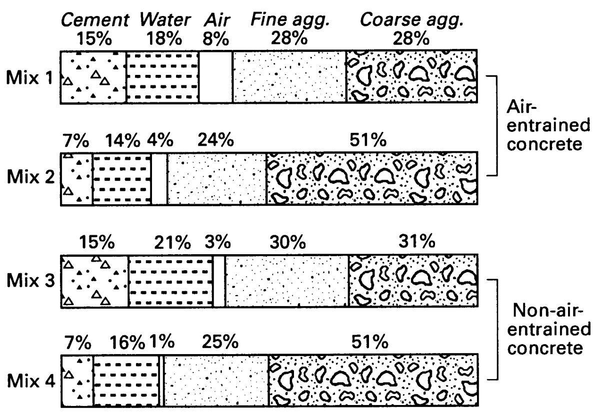

Figure 4.2. Concrete mix proportions.

Portland cement

Portland cement comprises only 7-10 percent of the mix. See Figure 4.2. It is a hydraulic cement (requires water) made up primarily of hydraulic calcium silicates. The Portland cement chemically reacts with water in a process called hydration. The paste (water and Portland cement) added to aggregates acts as an adhesive and binds the aggregates together to form the matrix called concrete. With modern concrete technology, high-strength concrete can be obtained with less cement than before. Where strength alone is the decisive criteria, less cement means greater economy. Surface durability, however, depends upon the surface hardness of the concrete as well as its internal strength and requires more cement. The relationship between cement content, air entrainment, and aggregate size is shown in Table 4.2.

Table 4.2. Cement content, air entrainment, and aggregate size requirements for watertight concrete.
With aggregates well graded up to the maximum practical size, less cement and air entraining are needed, so the mix is more economical.

Maximum size of Aggregate, in.	Cement lb/yd^3	Average air Entrainment, %
1.5	470	5
1	520	6
3/4	540	6
1/2	590	7
3/8	610	7.5

Fly ash

Fly ash and/or other pozzolans can be used to replace some of the Portland cement in the paste. Class F and Class C fly ash replacement of up to 25 percent of the Portland cement is typical. Fly ash as replacement for Portland cement increases strength, reduces permeability, improves durability, improves placing and finishing, and reduces cement content of the concrete. The amount of air-entraining admixture required to obtain a specified air content is normally greater when fly ash is used. Fly ash has a lower heat of hydration, reducing the amount of heat buildup during curing and retarding the setting time of the concrete.

Water

There needs to be enough water to allow the hydration of the paste to complete, but too much water can cause the concrete mix to shrink, which causes cracking. Water can be added only once at the site and only to adjust the slump to the specified value. In a batch, slump can be increased by 1 inch for every 10 pounds of water added per cubic foot of concrete. The potential amount of water to be added to meet the specified slump can be identified on the batch ticket. If the slump is not correct at the site, the owner should reject the load. Additional water can be added, but the owner then relinquishes any warranty on the concrete batch.

Slump

Slump is the measure of concrete workability. Table 4.3 shows slump requirements for liquid tight concrete without water-reducing agents. Excessive slump and consequent bleeding and aggregate segregation are a primary cause of poor performance in concrete slabs. If the finished slab is to be level, uniform in appearance, and durable, it is important that all batches placed have nearly the same slump. Low-slump concrete helps reduce finishing time and shrinkage cracking and can help eliminate surface defects and improve surface durability. Placing low-slump (1.5 to 3 inches) concrete flatwork requires the use of mechanical equipment such as a vibratory screed that rides on the side forms.

Table 4.3. Concrete Slump Requirements.

Slump Requirements	Maximum	Minimum
Flatwork	3 inch	1 inch
Walls	4 inch	1 inch

Water/Cement (W/C) ratio
The amount of water used in a concrete mix is specified as the water cement (W/C) ratio. Concrete needs at least a W/C ratio of 0.4 to provide complete hydration of the Portland cement paste. Figure 4.3 shows the relationship between W/C ratio and concrete compressive strength. A high W/C ratio will have higher shrinkage cracking, as the excess water not used in hydration moves out of the voids. The maximum allowable W/C ratio of 0.45 will provide concrete compressive strength of between 4,500 and 5,000 psi. The relationship between compressive strength and W/C ratio for air-entrained concrete is shown in Table 4.4.

A low W/C ratio provides the following features to concrete:

- Low permeability
- Reduced drying shrinkage and subsequent cracking
- Increased compressive strength
- Increased water tightness
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Table 4.4. Relationship between W/C ratio and concrete compressive strength.

W/C ratio	Compressive strength (f_c')
.40	5,000 psi
.45	4,500 psi
.48	4,000 psi
.59	3,000 psi

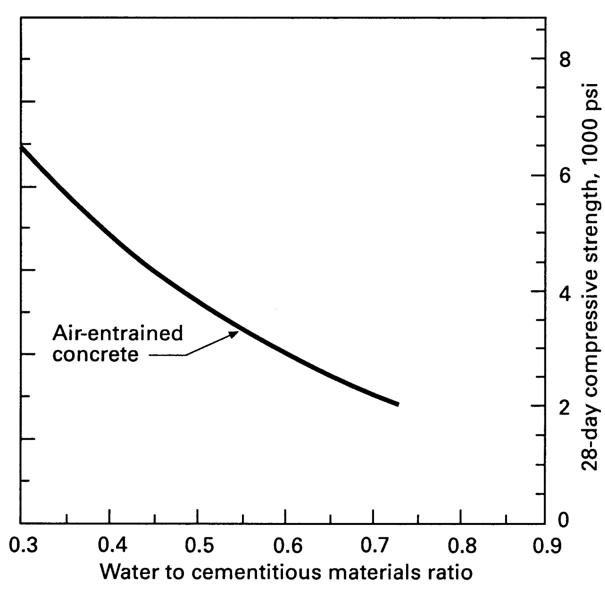

Figure 4.3. W/C ratio and concrete compressive strength.

Water-reducing admixtures

Water-reducing admixtures are used to reduce the quantity of mixing water required to produce concrete of a certain slump. Typically, water reducers can reduce water content 5 to 10 percent. This can help to provide a low W/C ratio. Water-reducing admixtures are needed to improve plasticity for easy placement of dry, stiff concrete mixes, even with air entrainment. Water-reducing admixtures temporarily improve plasticity and flowability (reduce slump) for about 45 to 75 minutes depending on the specific additive and temperature. Thus, difficult-to-place (low slump) mixes can be placed using minimum vibration with little aggregate segregation and no significant voids or bleeding. Eliminating voids improves strength and water tightness. Water-reducing admixtures can increase concrete compressive strength 10 to 25 percent by maintaining the W/C ratio.

Some concrete plants add admixtures as the truck departs the plant so the concrete mixes on the way to the job site. Other plants have the truck operator add the admixture upon arrival at the construction site to fully utilize the available plastic time limit. At a minimum, 25 to 30 revolutions of the mixer at mixing speed are needed to assure uniform distribution of the admixture. Once the time of plasticity passes, the concrete becomes stiff again and begins hardening.

Aggregates

Aggregates are the largest proportion of a concrete mix (70 to 85 percent of the mass). See Figure 4.2. They fill up the voids of the matrix, thereby requiring less paste to bind the matrix together. Aggregates must be of good quality and be just as chemically resistant as the paste. Do not use crushed limestone.

Reduce random shrinkage cracking by using concrete with a minimum shrinkage potential that contains the correct gradation of aggregates. The maximum size and the maximum amount of coarse aggregate (well graded) should be used to produce a mix that is consistent with placing and finishing methods. Selecting a larger aggregate size permits lower water content in the concrete and is more effective in restraining the shrinkage of the cement paste. Table 4.2 shows the maximum allowable aggregate size, cement content, and entrained air.

Coarse aggregate

Use the largest size of aggregate possible to keep the cement content to a minimum. The maximum aggregate size must not exceed:

- 3/4 the clear spacing between reinforcing bars and/or forms.
- 1/3 the depth of a slab.
- 1/5 the thickness of a wall

Fine aggregate

A well-graded aggregate will fill in the voids of the concrete, reducing the amount of cement needed and producing a denser concrete. Table 4.5 shows the specifications for a well-graded fine aggregate. With aggregates well graded up to the maximum practical size, less cement and air entraining are needed, so the mix is more economical.

Table 4.5. Grading specifications for fine aggregate.
(ASTM C 33/AASHTO M 6)

Sieve size	Percent passing by mass
9.5 mm (3/8 in.)	100
4.75 mm (No. 4)	95 to 100
2.36 mm (No. 8)	80 to 100
1.18 mm (No. 16)	50 to 85
600 μm (No. 30)	25 to 60
300 μm (No. 50)	5 to 30 (AASHTO 10 to 30)
150 μm (No. 100)	0 to 10 (AASHTO 2 to 10)

Air-entraining admixtures

Air-entraining admixtures are used to introduce and stabilize microscopic air bubbles into the concrete mix. This can improve the durability of concrete exposed to freeze thaw cycles. Workablity is also improved significantly. A small amount of purposely entrained air is useful in all concrete for reducing bleeding and increasing plasticity. To ensure resistance to scaling, concrete that will be exposed to cycles of freezing and thawing and to pesticides and fertilizers needs a total air content of 5.0 to 7.5 percent, depending upon the maximum size of the aggregate. (See Table 4.2.)

Properties of High Quality Concrete

High quality concrete is extremely important for secondary containment structures and mixing and loading pads to resist deterioration from pesticides and fertilizers and to maintain a watertight structure throughout its design life. Low quality concrete experiences rapid surface deterioration due to chemical attack, physical deterioration, and weathering, and it develops cracks that increase leakage and maintenance expense. The quality of the mortar is critical; the hardness and toughness of the coarse aggregate becomes significant only after the surface mortar has worn away. In flatwork, the workability of the concrete and the finishability of the surface are as important as the strength because they significantly affect the quality of the top 1/16 to 1/8 inch of the surface.

Permeability

Permeability refers to the amount of water migration through concrete or the ability to resist penetration by water or other liquids. Generally, the same properties of concrete that make it less permeable also make it watertight. Decreased permeability improves concrete's resistance to freeze thaw cycles and chemical attack. The Portland cement water paste permeability is related to the W/C ratio, the degree of hydration, and the length of time under a moist curing condition. Good quality, well-consolidated concrete at least 4 inches thick is practically impermeable to the passage of liquid water. The permeability of mature, good quality concrete is approximately 1×10^{-10} cm/sec. One of the best methods for decreasing permeability is to increase the moist curing period and to reduce the W/C ratio to less than 0.5.

Watertightness

Watertightness is the ability of concrete to hold back or retain water without visible leaking. Water leakage will be minimal with W/C ratios less than 0.45. Even though concrete will have cracks, it can be relatively watertight if the cracks are well distributed and small enough to not penetrate the entire thickness of the wall or floor.

Watertight concrete depends on nonporous aggregate being surrounded by high quality, watertight Portland cement and water paste. High quality cement paste requires the right amount and ratio of cement and water and proper moist curing for 7 to 28 days. Cements with high water content increase subsequent concrete shrinkage, which leads to excessive cracks in the concrete.

Air entrainment improves water tightness by improving workability, reducing segregation and bleeding, increasing density, and allowing a lower W/C ratio. Proportion mixtures so concrete can be placed without aggregate segregation. Workability of a stiff, watertight mixture requires vibration to consolidate the mass. During finishing, no excess bleed water should rise to the surface. In tests, there was no leakage through concrete disks with W/C ratio of less than 0.5 when moist cured for 7 days. As the length of the moist curing increased, leakage continued to decrease.

Durability
Durability is the ability to resist weathering, chemical attack, and abrasion. The surface durability of a concrete slab depends on concrete strength. Surface durability improves with a reduction in water content, an increase in cement content, or both. Reducing water content and increasing cement content both increase strength.

Freeze-thaw resistance
The most potentially destructive weathering factor is freezing and thawing. Freezing water and the subsequent expansion in the paste and aggregates causes concrete to deteriorate. Air entrainment in the concrete produces a concrete that is highly resistant to this action. Water is displaced in the microscopic air bubbles, relieving the hydraulic pressure the freezing water generates.

Chemical resistance
Type I (normal) or IA (normal with air entraining) Portland cement is commonly used in secondary containment structures. Air entrainment for most concrete is achieved by using air-entraining admixtures rather than air-entrained concrete. Additional protection can be enhanced with the application of suitable protective treatments. Use sealer materials that remain flexible after curing and aging and when subjected to cold weather. Common types of coatings are epoxies, silicones, polyurethanes, and polyureas. Use only Department of Agriculture, Trade and Consumer Protection (DATCP) approved materials for repairing cracks in containment structures.

If available, a Portland cement that is moderately resistant to sulfates can be used to reduce attack by sulfates and other chemicals. Type II, or Type IIA (air-entrainment incorporated by the manufacturer) Portland cement is suitable to resist 150- to 1,500-ppm sulfate. Type II Portland cement may not be available in many areas. Type V, a cement that is highly resistant to sulfate, is ideally suited to resist severe sulfate exposures of 1,500 to 10,000 ppm but is generally not available and costs more than other cements.

Concrete Mix Design
To get the right quality concrete, the order given to the ready mixed concrete supplier must be clear and contain all the following information: minimum compressive strength, minimum cement content, maximum amount of water, maximum size of coarse aggregate, slump, and amount of entrained air. To help ensure the concrete is impermeable and watertight, DATCP requires the concrete meet the following specifications:

- A compressive strength of 4,500 psi at 28 days
- A W/C ratio minimum of 0.45
- A maximum slump of 3 inches (Use of a water-reducing admixture is recommended to achieve easier workability at placement and improve water tightness and strength of low-slump concrete.)
- Five to 7.5 percent air entrainment

    - Use clean, drinkable mixing water at a pH = 5.0-7.0.
    - Use large (1 to 1.5 inch), clean, impervious aggregate.

Placement

A good quality concrete mix is only part of a good concrete project. The concrete must be placed properly in a well-designed project. To ensure the concrete is placed properly, the following guidelines are recommended:

- Allow no more than 30 minutes between truckloads of concrete during placement.
  Mix 70 to 100 revolutions at **mixing speed**, then an additional 200 to 230 revolutions (maximum of 300 total revolutions) at **agitating speed**.
- Discharge load within 1.5 hours.
- Minimize discharge drop distance by using a discharge chute.
- Continuous pour in one day, with no cold joints if possible.
- Use vibration during placement; vibrate at 5,000 to 15,000 rpm frequency for minimum aggregate segregation.

Placing concrete in hot weather

Hot weather is defined as any combination of high temperature, (generally above 80 degrees F), low relative humidity, and wind velocity tending to impair the quality of fresh or hardened concrete or otherwise resulting in abnormal properties.

Special provisions shall be made to immediately protect and cure the concrete due to rapid drying conditions. Concrete surfaces shall not be allowed to dry after placement and during the curing period. Wood form surfaces shall be kept continually moist.

In extreme conditions, it may be necessary to (1) restrict placement to late afternoon or evening, (2) restrict the depth of layers to assure coverage of the previous layer while it will still respond readily to vibration, (3) suspend placement until conditions improve.

Placing concrete in cold weather

When the minimum daily atmospheric temperature is less than 40 degrees F, concrete shall be insulated and/or heated immediately after placement. The temperature of the concrete and air adjacent to the concrete shall be maintained at not less than 50 degrees F nor more than 90 degrees F for the duration of the curing period.

The curing period may be reduced to 3 days when Type III cement is used. An additional 100 pounds of Type I cement and a maximum of 6 gallons of added water per cubic yard may be used in lieu of Type III cement.

Combustion heaters shall have exhaust flue gases vented out of the concrete protection enclosure and shall not be permitted to dry the concrete.
The contractor shall furnish the Technician a record of daily maximum and minimum outside air and concrete surface air temperatures during the curing period. The record shall include temperatures at several points along the concrete.

Finishing Concrete

Use a float finish on the surface with an aluminum or magnesium float to minimize coarse surface texture to improve washing and cleanup. Concrete surfaces to be coated with a sealant may need added grit for a rougher texture to improve sealant adhesion and worker safety.

Curing Concrete

Chemical hydration occurs when Portland cement and water are mixed, causing moisture evaporation due to heating. Chemical hydration influences concrete strength, durability, and density. Two factors that must be controlled during curing are evaporation rate and temperature. If evaporative cooling of the concrete is properly controlled during mild or hot weather, the concrete surface temperature remains at a satisfactory level.

Proper curing treatment of concrete after it has been finished is essential. Concrete must be kept moist so the cement will continue to combine chemically with the water. Start this curing process as soon as possible. If it is delayed and rapid evaporation takes place in the early stages, the surface may crack, craze, or dust. The longer the concrete can be kept wet, the stronger, more impervious, and more wear resistant it becomes. Exposed slabs are especially sensitive, as improper curing can significantly reduce surface strength development.

Curing determines the ultimate concrete durability, strength, water tightness, abrasion resistance, volume stability, resistance to freezing and thawing, and chemical resistance to pesticides and fertilizers. Moist curing requires maintaining satisfactory surface moisture content and temperature. Concrete should be moist cured at ambient temperatures above 40 degrees F for at least seven days. In this time concrete will develop 75 percent of its 28-day strength. If possible, a 28-day moist cure is preferred for maximum strength. During cold weather, additional heat and/or insulation will be needed to maintain curing temperatures between 50 and 70 degrees F. Concrete will continue to gain strength as long as it is moist cured. For example, concrete moist cured for 180 days will develop about 130 percent of the 28-day strength. To minimize trapped moisture bubbles in a sealant coating, allow several weeks for green concrete to cure before applying sealants.

Recommended procedures for moist curing concrete include:

- Ponding or immersion.
- Fogging or spraying.
- Periodic spraying. Saturating a covering provides evaporative cooling for hot weather curing.
- Sealing exposed concrete surfaces. Use polyethylene film, impervious paper, or membrane-forming curing compounds as soon as concrete surfaces are finished.
- Supplying additional moisture and heat. Use accelerated, strength-gain curing methods, such as live steam and heating pads, for cold weather curing.

The ponding or immersion method is preferred for hot weather placement, while supplying additional moisture and heat is best during cold weather. Fogging or spraying is an acceptable alternative to ponding or immersion in mild climates. Use insulated blankets, straw, or hay for covering when curing concrete at temperatures below 32 degrees F.

Controlling Cracks in Concrete

Concrete will crack. Proper design is a matter of controlling the cracks. Concrete cracks when tension caused by drying shrinkage exceeds the concrete's internal tensile strength. Cracks result from several reasons, including volumetric change due to drying shrinkage, direct stress due to applied loads, or flexural stress due to bending, frost heaving, and/or subgrade settlement. Cracks rarely affect the structural integrity or the durability of concrete significantly, but they may allow leakage, and they look bad.

Drying shrinkage is an unavoidable, inherent property of concrete that must be recognized and managed to minimize leaking cracks. The magnitude of shrinkage cracking is affected mainly by the water content of the mix measured as the W/C ratio. Less water means less shrinkage. More coarse aggregate in well-graded aggregate also limits shrinkage cracking. ***Do not use admixtures containing calcium chloride to accelerate curing, as they will increase drying shrinkage significantly.***

The following factors affect the amount and severity of cracking:

Water: The amount of water per bag of cement or per cubic yard of concrete is an important factor. Adding excess water increases the tendency towards shrinkage cracking. Water increases shrinkage and reduces strength. Use the lowest practical W/C ratio (0.4 to 0.45, for example, 188 to 212 pounds of water for 470 pounds cement) and aim for a slump of 1.5 to 3 inches.

Aggregate: The smaller the maximum size of well-graded aggregate, the greater the shrinkage of concrete at the same strength. ***Use a graded aggregate with maximum size of 1.5 inches.*** Because clay shrinks more than cement paste, small amounts of certain clays in aggregates cause high shrinkage and cracking.

Bleeding: The upward flow of water in fresh concrete causes pockets of watery paste under the larger pieces of aggregate, especially in deeper sections, which leads to internal voids or cracks and reduced water tightness and concrete strength.

Placing: The rate and conditions of placing affect cracking through bleeding and aggregate segregation in forms or around reinforcement. Let the concrete settle. Use vibration to aid concrete consolidation and settling, but avoid excessive vibration, which causes aggregate separation.

Curing: Moisture conditions during early and subsequent curing are very important. To prevent excessive drying, dampen the subgrade, subbase, forms, and aggregates. Start moist curing immediately using temporary covering or fog spray between placing and finishing, and/or use sunshades to reduce the rate of evaporation.

To reduce cracking in concrete use the following practices:

- Prepare the subgrade properly with correct moisture content.
- Minimize water content by maximizing the size and amount of coarse aggregate and by using low shrink aggregate.
- Use the lowest amount of mix water possible.
- Do not use calcium chloride mixtures.
- Prevent rapid loss of surface water by using spray-on finishers or plastic sheeting.
- Provide contraction joints at appropriate spacings.
- Provide isolation joints between separate structures to prevent restraint.
- If a vapor retarder is used below concrete, use a minimum 6-inch thick layer of slightly damp, compactable, drainable, fine-grade material.
- Properly place, consolidate, finish, and cure concrete.