The durability and maintenance costs of concrete highway bridge decks are highly dependent upon the care exercised during the construction phase, including attendant activities during the preconstruction and post-construction periods. Recommendations relative to these periods are presented, covering the areas of design considerations, inspection, pre-construction planning, falsework and formwork, reinforcement, concrete materials and properties, measuring and mixing, placing and consolidation, finishing, curing, postconstruction care, and the use of overlays.

Keywords: admixtures; aggregates; air entrainment; bleeding (concrete); bridge decks; cements; concrete construction; concrete finishing (fresh concrete); concretes; consolidation; cover; cracking (fracturing); curing; drainage; durability; epoxy resins; falsework; formwork (construction); inspection; maintenance; mixing; placing; protective coatings; proportioning; reinforced concrete; reinforcing steels; resurfacing; scaling; shrinkage; sliding; spalling; specifications; structural design; surface roughness; texture; vibration; workability.

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ACI Committee Reports, Guides, Standard Practices and Commentaries are intended for guidance in designing, planning, executing or inspecting construction, and in preparing specifications. Reference to these documents shall not be made in the Project Documents; they should be phrased in mandatory language and incorporated into the Project Documents.

ACI 345R-91 became effective Sept. 1, 1991 and replaces ACI 345-82 which was withdrawn as an ACI standard in 1991.

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Appendix A

Chapter 1 -- Introduction

1.1 General

The riding surface of a highway bridge deck should provide a continuation of the pavement segments which it connects. The surface should be free from characteristics or profile deviations which impart objectionable or unsafe riding qualities. The desirable qualities should persist with minimum maintenance throughout the projected service life of the structure.

Many decks remain smooth and free from surface deterioration and retain skid resistance for many years, attesting to satisfactory attention to the many details influencing such performance. When deficiencies do occur, they usually take one of the forms described in this chapter. Subsequent chapters of this report discuss the contribution of various aspects of deck construction to such defects, and present guidelines based on theory and experience which should reduce the probability of occurrence to an acceptable level.

1.2 Roughness

Roughness can be periodic, varying in wave length, or it may occur as discrete discontinuities. Excessive sag or camber are deficiencies which cause long wave length roughness. Roughness with short wave length, or “washboarding,” can appear early and result from inadequate cover over reinforcement, other construction practices, or develop subsequently with surface deterioration. Such short wave length roughness may be periodic or random depending on its cause. Discontinuities at joints or near abutment backwalls result in sudden “bumps.”

1.3 Cracking

Cracks may be classified according to their orientation in relation to the direction of traffic as longitudinal, transverse, diagonal, or random. In addition, the terms “pattern cracking” and “crazing” are used to refer to characteristic defects as defined in ACI 201.1R. The severity of cracking is conventionally expressed qualitatively as fine, medium, and wide, based on crack width.
ACI 201.1R defines cracking severity as:

a. Fine -- Generally less than 1mm wide.

b. Medium -- Between 1mm and 2mm wide.

c. Wide -- Over 2mm wide.

Examples of several types of cracking are shown in Fig. 1.1 through 1.4.

A compressive survey of randomly selected bridge decks in eight states provides some insights as to frequency and causes of various categories of cracking, recognizing that most cracks are caused by a number of interacting factors. This survey found comparatively little longitudinal and diagonal cracking. Findings from the survey are described in Sections 1.3.1 through 1.3.4.

1.3.1 -- The most prevalent longitudinal cracking occurred as “reflective” cracks in thin concrete wearing courses over longitudinal joints of precast, prestressed box girder spans, or in areas where resistance to subsidence was offered by longitudinal reinforcement, void tubes, or other obstructions.

1.3.2 -- Diagonal cracking occurred most often in the acute angle corner near abutments of skewed bridges, or over single-column piers of concrete box girder, deck girder, or hollow slab bridges.

1.3.3 -- Transverse cracking was observed on about one-half of the 2300 spans inspected. No one factor can be singled out as the cause of transverse cracking. Among the more important factors were (1) external and internal restraint on the early and long-term shrinkage of the slab and (2) combination of dead-load and live-load stresses in negative moment regions. In general, the observed crack pattern suggests that live-load stresses alone play a relatively minor role in transverse cracking.

1.3.4 -- Pattern and random cracking were usually shallow and may be related to early or long-term drying.
This minor cracking was a common defect. Occasionally, severe cases were encountered in which the probable causes were severe early drying (plastic shrinkage cracking) or unstable conditions associated with reactive aggregates.

1.4 Spalling

Surface spalls are depressions resulting from separation of a portion of the surface by excessive internal pressure resulting from a combination of forces. An example is shown in Fig. 1.5. Spalling exposes reinforcement, decreases deck thickness, and subjects the thinned section to impact. Joint spall is used to designate spalls adjacent to various types of joints. The incidence of spalling varies considerably among the states, but where it occurs it is a serious and troublesome problem. It is related to the use of deicing chemicals, corrosion of reinforcement, traffic column, and quantity and quality of concrete cover.

1.5 Scaling

Scaling, such as that shown in Fig. 1.6, is loss of surface mortar, usually associated with the use of deicer chemicals. Severity is normally expressed qualitatively by terms such as light, medium, heavy, or severe. Gradual loss of surface by abrasion is sometimes difficult to distinguish from scaling. Scaling can be locally severe but, in the absence of studded tires, generally is not a serious problem if accepted concreting practices are followed.

1.6 Slipperiness

Surface friction measurements of highway pavements in the United States are typically made using a locked-wheel skid trailer that meets the requirements of ASTM E 274. This procedure measures the frictional force on a locked test wheel as it is dragged over a wet pavement surface under constant load and at a constant speed, with its major plane parallel to the direction of motion and perpendicular to the pavement. The standard reference speed is usually 40 mph, and the results are expressed as a friction number (FN). Well-textured new pavements will have friction numbers above 60 when tested at a speed of 40 mph.

The FN of the bridge deck surface should not differ substantially from the pavement segments that it connects, and should have and retain the minimum value established for pavement surfaces. Published data for bridge decks are meager, but those available for pavements indicate that low skid resistance or slipperiness can be influenced by materials and construction practices, and by subsequently applied coatings. An example of a surface polished by heavy traffic is shown in Fig. 1.7.

1.7 Summary

Roughness, cracking, spalling, scaling, and slipperiness are the major defects which result when the many details which influence their occurrence are not given sufficient attention. Recognition of the interaction
of design, materials, and construction practices, as well as environmental factors, is the important first step in achieving smooth and durable decks.

Chapter 2 -- Design considerations

2.1 General

The main purpose of this chapter is to emphasize those design factors which may affect the resistance of a bridge deck to the severe exposure condition brought about by the action of deicing chemicals. Hence, the design considerations of this chapter are not concerned, for the most part, with the structural analysis of the bridge deck. The items discussed in this chapter, however, are generally within the purview of the bridge designer.

2.2 Drainage

2.2.1 -- It is vital to establish grades that will insure proper drainage. In addition to provision for storm water removal, attention should be given to the problem of draining the small quantities of water from melting snow and brine from deicing chemicals. The shallow slopes and crowns sometimes found on bridge decks, the small inaccuracies in finish of the wearing surface, the confining effect on the curb or barrier, and the accumulation of dirt in the gutter often prevent a deck from draining completely. An example is shown in Fig. 2.1. This ponding of water and brine on an inadequately drained deck is a basic cause of bridge deck deterioration.

2.2.2 -- Drains should be designed for size and location so that drain water may be removed quickly and will not be emptied on to, or blown against, the concrete or steel below. An acceptable arrangement is shown in Fig. 2.2, and an unsuitable one is shown in Fig. 2.3. An adequate number of small deck drains should be provided in flat surface areas. Metals used in drains should
be able to withstand the corrosive effect of deicing chemicals.

2.2.3 -- Inlets should be sized to prohibit large particles, such as beverage cans, from lodging in the drain conduit and causing stoppages. Sharp angle turns should not be used in drainage conduits, and outfalls should be readily accessible to facilitate cleaning.

2.3 Deck thickness

2.3.1 -- Bridge design agencies usually establish standard details specifying deck thickness and reinforcement arrangement for different bridge deck spans. A nominal minimum deck thickness of 8 in. is recommended (see Fig. 2.5).

2.3.2 -- The high quality of deck concrete that is needed to achieve durability usually results in much higher concrete strengths than needed for the structural capacity of the deck. The advent of higher strength grades of reinforcing steel also necessitates a reevaluation of established standard details. The temptation exists to use thinner deck slabs and thus use these materials more efficiently. However, Committee 345 believes that a conservative approach should be taken in this matter. While there is no direct evidence that deterioration is more likely to occur in thinner, more flexible decks than in thicker, stiffer decks, there is evidence that once deterioration has started, it is likely to progress more rapidly in the thinner decks. Thinner decks also result in greater congestion of reinforcement, and the problems associated with that condition.

2.3.3 -- As with all construction, tolerances must be allowed in design dimensions to insure achieving all critical minimum values. Recent reports confirm that the placing of top deck reinforcement often varies widely. Average cover has been found to be typically equal to the design or “plan” cover, with a standard deviation of about 0.3 in. Thus, to insure that 97 percent of the reinforcement has at least the minimum 2.0-in. cover required in Section 2.4, an average and plan cover of 2.6 in. would be required. When these tolerances are added to the thickness occupied by the reinforcing bars and to the required clearances between bars and slab faces, the required minimum thickness is close to 8 in. Fig. 2.4 shows the relationship of the several component dimensions to the total deck thickness assuming the bar sizes most commonly used.

If corrugated metal stay-in-place forms are used, slight additional slab thicknesses are required even when transverse bars are located in the valleys of the corrugations. The profile positions of the layers of reinforcing bars and the minimum cover over the steel must be maintained. Fig. 2.5 shows one type of deck design where the use of corrugated forms results in an additional 3/8-in. of concrete and a second design with an additional 1 in. of concrete. This design simplifies form placement, particularly on radial structures.

2.3.4 -- Adequate provision for deck haunches (or fillets) is a design feature associated with deck thickness. The designer should select bearing elevations so that the steel or precast concrete girder does not penetrate into the deck slab thickness at any point along its length. The
designer must consider the differences between the roadway profile and the girder profile -- including the possible deviations from expected girder camber -- at various points along the girder length. Small concrete haunches are formed in that portion of the deck where the top surface of the girder is lower than the bottom of the slab. On the other hand, slab thickness is reduced and the placement of reinforcement can be affected where the girder projects into the slab.

2.4 Cover

2.4.1 -- A most important consideration in bridge deck design is the thickness of protective concrete cover over the top reinforcement. It is recommended that 2 in. of concrete, measured from top of bar, be the minimum amount of protective cover over the uppermost reinforcement in bridge decks. The reader is directed to ACI 117, Section 3.4, for construction tolerances. Spalling generally occurs readily on decks having inadequate cover over the bars. Similar requirements for top, bottom, and side faces for reinforcing bar cover should be considered for coastal environments.

Clearly, deviations from the specified cover, as discussed in Section 2.3.3, should be expected to occur in construction. The designer should try to anticipate conditions that could make accurate steel placement more difficult, or where the desired concrete surface might be “undercut” by the action of the strikeoff, as at nonuniform sections of complicated geometrical transitions, and compensate with an increased cover requirement.

2.5 Arrangement of reinforcement

2.5.1 -- In the most common type of bridge deck -- the slab-on-beam bridge using a 7% to 9 in. thick slab spanning between longitudinal girders -- the primary reinforcement is placed transverse to the girders. To use this reinforcement most effectively from a structural point of view, current practice places the reinforcement closest to the top and bottom slab surfaces. The MSHTO Standard Specifications for Highway Bridges provides simple empirical equations to represent the Westergaard analysis of bridge deck behavior. The primary reinforcement is selected on the basis of one-way slab action and pure flexure. Shear, bond, and fatigue are not considered in the procedure. None of the bridge deck durability studies has indicated any structural deficiencies in the deck design procedure with the level of stresses generally permitted. The primary slab reinforcement generally consists of No. 5 or No. 6 bars placed from about 5 to 9 in. on center.

2.5.2 -- Distribution reinforcement, generally consisting of No. 4 or No. 5 bars, is placed transverse to the primary reinforcement to provide for the two-way behavior of the deck. The amount of distribution reinforcement is determined as a percentage of the primary reinforcement, with more being placed in the middle half of the slab span than over the beams.

2.5.3 -- Shrinkage and temperature reinforcement is placed transverse to the primary reinforcement near the top of the slab to control cracking resulting from drying shrinkage and temperature changes in the concrete. Current practice uses No. 4 or No. 5 bars spaced from 12 in. to 18 in. on center and placed underneath the top primary slab reinforcement. Transverse cracks, the most common kinds of cracks found in bridge decks, tend to form parallel to, and directly over, the top primary reinforcing bars, exposing them to attack from chlorides, moisture, and air (see Fig. 2.6). Furthermore, the tensile stresses caused by drying shrinkage are not uniform through the depth of a concrete slab, but are largest near the drying faces. It would appear, then, that a more effective way to “control” (i.e., reduce the widths of) this type of cracking is to place the shrinkage and temperature reinforcement above the primary slab steel (while providing minimum 2 in. cover), in a more strategic location.

2.5.4 -- Prestressed box beam bridges generally display reduced tendencies toward transverse cracking because of their stiffness. However, adjacent box beam superstructures (no space between the beams) often have thin, nonreinforced decks that frequently display undesirable longitudinal reflection cracks over the joints between adjacent beams. One solution is to post-tension the beams together transversely and use a reinforced concrete deck on top.

2.6 Positive protective systems

2.6.1 Overlays -- The common forms of bridge deck deterioration, such as scaling, some types of cracking and surface spalling, generally occur within the top 2 in. of a deck. Improper concrete placing and finishing practices often result in a lower quality concrete in this area. Since it is subjected to the most severe exposure and service conditions, the top portion of the deck slab should have the best possible concrete quality. Consideration should be given to placing an overlay on the bridge deck when it is constructed. Many different types of overlays

Fig. 2.6--Halves of a core taken through a vertical crack. Notice the imprint of the top reinforcing bar (which has been removed) and the penetration of road deposits to the level of the top
have been used successfully. Chapter 13 discusses several types of overlays in detail.

2.6.2 Other positive protective systems -- Because of the high cost of repairing corrosion-caused damage, several different positive protective systems are being used for bridge decks in severe deicing salt areas and for some marine structures. In addition to overlays, some of the other successful systems include:

a. Epoxy (electrostatically-applied powder) coated reinforcing steel
b. Silica fume concrete which reduces chloride permeability and improves sulfate and alkali aggregate attack durability
c. Cathodic protection
d. Calcium nitrite admixture

A recent study for the FHWA\(^{3}\) reports on the abilities of several different protective systems.

2.7 Skid resistance and surface texture

2.7.1 -- The requirements for surface texture are dictated by the levels of skid resistance necessary to provide safety under the anticipated traffic speeds and volumes. The skid resistance of pavements has received extensive treatment in the technical literature.\(^{6,7}\) While bridge decks specifically have not been studied in the same detail as pavements, similar requirements would seem appropriate.

Although attempts have been made to set numerical limits for skid numbers, none generally applicable have been established because of problems associated with testing variability, varied local conditions (class of road, geometric factors, etc.).

The general conclusion, however, is that a minimum acceptable skid number determined by a locked wheel trailer, meeting the requirements of ASTM E 274 at 40 mph, should be in excess of 30. Data developed to date suggest that obtaining a satisfactory skid resistance depends on providing a deeper and more severe texture than is conventionally obtained by texturing with burlap or belts.

2.7.2 -- Textures with ridges and valleys perpendicular to the direction of traffic will provide maximum drainage, but will also cause greatest tire noise unless care is taken regarding spacing. Success in maximizing skid resistance and minimizing tire noise have been reported by using several texture configurations.\(^{8}\)

Textures with ridges and valleys parallel to the direction of traffic minimize noise, but require that extra care be taken to provide transverse drainage. The reader is directed to ACI 325.6R for recommended texturing practices.

2.8 Joint-forming materials

The design, selection, installation, and maintenance of joints and joint-forming materials may be found in ACI 504R.

Chapter 3 -- Inspection

3.1 General

3.1.1 -- The primary objective of the inspection and testing should be to aid in obtaining a quality bridge deck by preventing mistakes and assuring adherence to the specifications. The responsibility for inspection should be vested in the engineer as a continuation of his or her design responsibility. If the inspection is not done by employees of the engineer, the responsibility may be delegated to an independent inspection agency. In all instances, the fee for inspection should be paid directly by the owner to those performing the inspection services.

3.1.2 -- The scope and nature of the inspection services will depend primarily on the size and importance of the work. The organization and conduct of inspection services are described in detail in ACI 311.4R. Each inspector should be thoroughly familiar with the content of that publication. This chapter is designed to supplement ACI 311.4R and to direct attention to details that are of particular significance to the construction of bridge decks.

3.13 -- The specifications must define the responsibility of the inspection agency and contractor. In no instance should the inspection agency attempt to assume or accept the contractor’s responsibility for supervision of the job. Specifications should require that the contractor conduct certain specific quality control tests of materials to be used in the job. These quality control tests may be made by his forces, by the testing agency employed by him, or by his subcontractors or materials suppliers. The existence of quality control programs by the contractor does not relieve the inspection agency which represents the owner of surveillance over such testing programs.

3.2 Inspection personnel

3.2.1 -- Personnel responsible for inspection must be qualified by experience and training. Those performing acceptance testing should be certified ACI Grade 1 field testing technicians. Inspection and quality control agencies should meet the requirements of ASTM E 329.

3.3 Inspection functions

3.3.1 -- The scope of inspection required and assignment of responsibility should be defined in the job specifications. The scope will depend on the size and complexity of the job, but should include: inspection and testing of materials; concrete batching and mixing facilities; concrete handling, placing, consolidation, finishing, and curing; inspection of forms, reinforcing, and embedded items; and inspection of stripping and curing operations. More complete lists of functions are given in ACI 311.4R.

3.3.2 -- The items deserving particular attention for bridge decks are as follows:

a. The concrete production and delivery equipment should be reviewed at the preconstruction plan-
TABLE 3.1 -- duties of construction inspectors

<table>
<thead>
<tr>
<th>Batching</th>
<th>Discharging</th>
<th>Placing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verify the use of approved materials</td>
<td>Receive batch certificates</td>
<td>Check clearance and spacing of reinforcement</td>
</tr>
<tr>
<td>Monitor aggregate moisture</td>
<td>Monitor mixing time</td>
<td>Verify adequate vibration</td>
</tr>
<tr>
<td>Check batch weights, admixture quantities, and</td>
<td>Conduct tests on slump, air, and temperatures,</td>
<td>Monitor finishing to guard against drying</td>
</tr>
<tr>
<td>charging sequences</td>
<td>Make test specimens</td>
<td>Verify suitable surface texture</td>
</tr>
<tr>
<td>Prepare batch certificates</td>
<td></td>
<td>Verify cure at proper time</td>
</tr>
</tbody>
</table>

b. Before the placing of the actual deck, full-sized batches of the proposed mix proportions should be mixed and tested.

c. Elevations and dimensions of the forms, reinforcing and screeds must be carefully checked as the work progresses. The amount of cover over the top reinforcing steel must receive special attention, both before and during concreting operations (see Chapter 6).

d. Inspection forces must be prepared to check the air content and slump of practically every batch of concrete, using the ASTM C 231 test method. Rapid checks can be made with the Chace Air Meter and Kelly Ball, but not for acceptance or rejection purposes. Concrete temperatures should be measured on every load. These testing functions should not impede the progress of the work.

e. Placing and finishing procedures must be inspected to avoid unnecessary reworking of the surface, finishing while bleed water is on the surface of the concrete, or sprinkling of water on the surface to aid finishing. The specified grade and crown must be maintained to insure proper drainage of the surface and to avoid irregularities in the surface which will later impound water on the surface.

3.3.3 -- Most agencies now recognize that at least three inspectors are required during concreting operations to insure good construction practice and to keep good records of materials and procedures. There should be one inspector at the point of batching, one inspector at the point of discharging and one inspector at the point of placing. Their more important duties are given in Table 3.1.

Chapter 4 -- Preconstruction planning

4.1 Construction schedules

In those sections of the country where bridge deck performance has been found to be unsatisfactory, new decks should not be placed during periods of extreme weather. Schedules should be drawn to allow for bridge deck placement during daylight hours in the spring and fall, and during nighttime hours in the summer. Where such ideal scheduling is impractical, sufficient flexibility should be built into the schedule to await suitable weather conditions.

In general, from the time all superstructure framing has been completed, one month per work crew should be allowed for casting the first 10,000 ft² of bridge deck, and one week for each additional 10,000 ft² thereafter. One day should be added for each day below 40°F or above 90°F and less than 50 percent relative humidity.

4.2 Coordination of construction and inspection

It is vital that contracting and inspecting forces coordinate their schedules prior to beginning work. Beam elevations must be taken prior to building haunches. Deck forms must be inspected prior to placing reinforcing steel. Reinforcing steel must be inspected in place prior to installation of screed rails. Screed rail elevations and the critical clearance over the top reinforcing steel must be thoroughly checked just prior to ordering concrete to the site.

The following recommended inspection times should be programmed for each 10,000 ft² of bridge deck for the work described above:

a. Surveying deflection control points 1 day
b. Calculating haunch elevations 1 day
c. Inspecting deck forms 1/2 day
d. Inspecting reinforcing placement 1/2 day
e. Checking screed elevations 1 day

4.3 Review of construction method

The contractor's proposed methods should be made clear to the inspection force so that compatibility between the proposed methods and the requirements of the contract can be ascertained and all differences in methods and requirements be resolved. Thus, a preconstruction meeting to review deck construction methods should be held between 30 and 60 days prior to beginning deck forming to provide opportunity for resolution of any differences that may exist.

4.4 Manpower requirements and qualifications

4.4.1 -- Manpower requirements for deck placement vary according to the experience of the workmen, the surface area of the placement, the placing and strikeoff
equipment to be used, weather conditions and the speed of concrete delivery, including delivery from the batching area to the jobsite and from the delivery equipment to the deck forms. A typical deck placement crew consists of a minimum of six people.

4.4.2 -- Minimum manpower requirements are often established by union rules, and maximum manpower is a fundamental prerogative of contractors. Hence, it is not recommended that manpower limits be set forth in the specifications. The judgment of an experienced supervisor is valuable in establishing manpower requirements.

4.4.3 -- The individual on the contractor’s force responsible for deck concreting should have a minimum of 2 years experience for simple span bridges with lengths less than 100 ft and skewed no more than 5 deg from normal, and 5 years experience for all other types of bridges.

4.5 Equipment requirements

4.5.1 -- The following equipment is normally assembled prior to a bridge deck placement: generator (with extra gasoline), vibrator (plus standby), strikeoff machine, 16-ft longitudinal plow handle wood float or equivalent finishing machines, long handle bull float, 10-ft straight edge, two separate foot bridges, texturing equipment, and “fogging” and curing equipment.

4.5.2 -- Self-propelled screeding machines should be required on all bridges of more than one span.

4.5.3 -- Special attention should be given to methods of transferring the concrete from the delivery point to the point of placement, since poorly planned operations in this area can result in excessive delay times which promote such practices as retempering and sprinkling to aid finishing. More thorough discussions of bridge deck construction equipment will be found in Chapters 8, 9, and 10.

4.6 Specialty concretes

The use of specialty concretes as overlays for bridge decks is another area where special attention is required. Examples of such materials include latex-modified concrete, low-slump and low-water-cement-ratio concrete (commonly called the “Iowa” system), and low-water-cement-ratio, higher slump concrete made using high-range water-reducing admixtures. On-site mixing using properly calibrated mobile mixers is recommended for all of the above systems, since such a procedure will facilitate better quality control and permit concrete production and placement at equal rates. Other methods of on-site production may be approved if the quality control is comparable. Bonding of the overall concrete to the base deck is another potential problem area. Bonding grout, if used, must be thoroughly brushed into the clean base concrete and covered with overlay concrete before it dries. Special attention to curing is necessary to minimize shrinkage cracking of the overlay concrete. In general, wet burlap should be applied as soon as the new concrete will support it without deformation. Additionally, each specialty material will undoubtedly exhibit specific properties which require additional precautions. As examples: a specialized heavy finishing machine is required to insure that a low-slump concrete is properly consolidated; the curing normally used with styrene-butadiene latex-modified concrete is to cover for 24 hr with wet burlap followed by air drying; and concrete containing high-range water reducing admixtures often exhibits a higher than normal rate of slump loss with time. To preclude problems, the engineer should contact manufacturers and study the available literature on any specialty concrete prior to use.

Chapter 5 -- Falsework and formwork

5.1 General considerations

5.1.1 -- General considerations for formwork are presented in Formwork for Concrete (SP-4). The section on bridge decks in that document is particularly applicable here.

5.1.2 -- The formwork for bridge decks must be designed to support the loads which will be imposed on it during construction by workers, equipment, reinforcing steel, and plastic concrete. The positioning of the forms affects both the thickness of the deck and the final location of the reinforcing bars. The forms for the concrete should be constructed in a manner to provide smooth lines and a pleasing appearance to the finished structure.

5.1.3 -- Both removable and stay-in-place forms are used in bridge deck construction. The former, used in most construction, serves only the functions of forming the concrete and supporting materials, personnel, and equipment during construction. They are removed when those functions are served. Stay-in-place forms serve the same functions as removable forms, but some of them serve the additional function of a stressed member in carrying service loads.

5.1.4 -- Falsework may be required on certain types of structures, such as slab bridges, and should be designed to support the same loads as the formwork. Indicators, sometimes called “tell tales,” should be installed to check for unexpected settlement.

5.2 Consideration for type of form

The forms, whether removed or remaining in place, must not detract from the appearance and proper functioning of the finished structure.

5.2.1 -- Forms that are removed should be designed for ease and economy in handling both during installation and removal. They should be durable enough to withstand multiple use handling. Benefits in the use of this type of form include:

a. Economy of materials through multiple use forms
b. A clear view of the bottom of the concrete to facilitate inspection
Stay-in-place forms are either steel (Fig. 5.1), concrete (Fig. 5.2), or wood. They should be designed to remain firmly anchored in the finished structure. Steel stay-in-place forms in bridge construction are used for convenience in forming. They are not designed for live load stresses, although they bond to the cast-in-place deck. They offer the following advantages:

a. The nonremoval feature saves construction time, obviates interference with traffic below the deck, and eliminates safety problems associated with form removal
b. Reduced cracking resulting from composite action between the cast-in-place deck and the steel form has been reported.\(^{11}\)

Disadvantages might include:

a. The bottom surface of the cast-in-place deck cannot be seen for inspection purposes
b. Water, and the salts that it might carry, are retained at the interface of the form and the concrete. Such a condition could promote deterioration in that region
c. When minimum cover is maintained between reinforcing steel and the tops of the steel form corrugations, the extra concrete required to fill the corrugations results in extra dead weight. This either necessitates an increase in the capacity of the supporting members or decreases the reserve capacity of these members (see Fig. 2.5)

Prestressed concrete stay-in-place forms are also available. Initially they serve as forms, and later they become an integral part of the load-bearing deck. The cast-in-place deck bonds to the precast, prestressed elements during placement of the deck. In some cases, mechanical interlock is provided through shear lugs which are cast in the precast elements during fabrication. Advantages offered by this type of form are:

a. The nonremoval feature saves construction time, obviates interference with traffic below the deck, and eliminates safety problems associated with form removal
b. Forms can be placed rapidly
c. Provides for economic use of material
d. The double purpose prestressed elements give added advantages structurally. Both field and laboratory tests\(^ {10,12} \) have shown that this type of construction is structurally sound

A disadvantage might include the fact that the bottom surface of the cast-in-place deck cannot be seen for inspection purposes.

Wood stay-in-place forms are usually restricted to box girder structures. The construction sequence of a box girder structure is to first construct the bottom slab and webs, strip the web forms, and then form and place the deck. Inasmuch as the interior of the box is not visible to the traveling public and the forms are in no way detrimental to the performance of the deck, they are usually left in place. Also, their removal would be costly.

Materials which have been used in bridge deck formwork consist of wood, metal, concrete, plastic, and wood covered with a form protector. Steel forms which remain in place should be galvanized or coated.

Removal
Forms are usually of the removable type. Therefore, they should be designed so that they can be removed with ease and economy, without destruction or disfigurement to the concrete, and with minimum spoilage in form materials so that reuse is possible.

Workmanship
Forms should be mortar tight, and this can only be accomplished with good workmanship. The underside of the bridge deck is not often viewed, but unless it has a smooth, unblemished appearance, the public develops the feeling that the bridge is not as sound as it should be.
To end up with a bridge deck that will be durable and smooth riding is a very important part of the workmanship that must take into consideration the deflections, precision of joints and final grades that are direct functions of the craftsmen involved in the formwork. The final grades are a function of the screeds that may be a part of the forms. The problems of accurately establishing the form lines are discussed in Chapter 10.

Chapter 6 -- Reinforcement

6.1 General considerations

Reinforcing steel for bridge decks should meet the requirements of AASHTO M 31 or ASTM A 615. Of equal importance, every effort should be made to assure that bars are of proper size and length, that they are placed and spliced in accordance with the plans, and that adequate concrete cover is maintained, especially over top steel. Adequate cover over bottom steel may be equally important in marine environments and grade separation bridges over high-speed trunk lines. Coated reinforcement should comply with AASHTO M 284, or ASTM A 775 and ASTM D 3963.

6.2 Arrangement

Bridge decks depend on accurate placement of steel for designed performance, thus tolerances should be small.

6.3 Reinforcement support and ties

Reinforcement should be held securely by suitable supports and ties to prevent displacement during concrete placement. Precast concrete blocks are sometimes used for support of the steel; more generally, metallic reinforcement chairs, with or without plastic protected ends, are used. Plastic chairs are also available. Coated tie wire and reinforcement supports should be used with epoxy-coated reinforcement. For some deep deck sections, welded support assemblies are sometimes used, or the primary reinforcement may be in the form of resistance welded trusses which simplify accurate placement. Whatever the system used, there must be assurance that the supports will be adequate to carry construction loads before and during placement, will not stain concrete surfaces, displace excessive quantities of concrete, nor allow reinforcing bars to move from their proper positions. The consequences of inadequate use of reinforcement supports are illustrated in Fig. 6.1 and Fig. 6.2. Several suggested systems for support of deck steel are shown in Chapter 3 of the CRSI "Manual of Standard Practice."

While deck strength is not affected by the number of intersections tied, it is essential that sufficient ties and wire of adequate size are used to assure that steel will be held in proper position during the concrete placing and consolidation operations. A safe rule would require that every other reinforcing bar intersection be tied and that wire not smaller than 16 gage be used.

6.4 Cover over steel

6.4.1 -- It is essential that the specified depth of concrete cover over the reinforcing steel be maintained. Concrete cover under the bottom mat is easily controlled by bar supports of the required height. Cover over the top mat is, however, much more difficult to control due to the inherent flexibility of the strikeoff screed system and possible differential deflections of adjacent girders.

6.4.2 -- Several methods for checking expected top mat cover are:

a. Obtain and plot elevations of the top steel on a grid pattern and compare the results with elevations along the strikeoff screeds
b. Stretch a string line between the screeds and measure down to the steel
c. Run the strikeoff mechanism along the screeds and measure the space between the float board and steel, or attach a block of wood to the float board which has a thickness equal to the required cover

In all checking methods, deflections and settlements of the screeds and screed supports must be taken into account.
consideration. This includes differential deflections of exterior and interior steel girders and cantilevered forms due to concrete and strikeoff equipment loading. The third checking method given above -- using the strikeoff equipment -- is preferred because it reduces the number of corrections to be applied.

6.4.3 - To insure that proper allowances were made for deflections and settlements, it is important to measure periodically the actual cover over the steel during deck placement. Stabbing the concrete above the steel with a putty knife is a good checking technique. Also metal detection instruments, specifically designed and calibrated for determining depth of cover of reinforcing steel, are commercially available. They are suitable for use on fresh or hardened concrete.

6.4.4 - Before final acceptance, the actual concrete cover over the reinforcing steel should be ascertained. In addition, the entire deck should be sounded with a rod or other device to locate any subsurface voids or fracture planes. Such areas should be chipped out and replaced with bonded concrete patches.

6.5 Cleanliness

Before placing the concrete, reinforcement should be free from mud, oil, or other coatings that may adversely affect bonding capacity. Most reinforcing steel is coated with either mill scale or rust to some degree. Steel with rust, mill scale, or a combination of both, is considered satisfactory, provided the minimum dimensions, including height of deformations and weight of a hand wire-brushed test specimen, are not less than the applicable ASTM specification requirements.

6.6 Epoxy-coated reinforcing steel

Epoxy-coated reinforcing steel, developed under the Federal Highway Administration research program in 1972-73, is now in widespread use as a technique for eliminating or minimizing detrimental corrosion of the reinforcing steel in deicing salt and coastal environments. Epoxy-coated bars have been used extensively in bridge decks. Bridge decks consisting of high-quality concrete and epoxy-coated reinforcing steel will provide a long-term durability in deicing salt environments. The cost of epoxy-coated reinforcing steel is relatively low in comparison to other protective systems. Recent practice provides that both top and bottom steel must be coated.

Conventional reinforcing bars are heated, cleaned to a near white metal finish (normally by shot- or grit-blasting), conditioned by heating to a specific temperature, usually 400 to 450 F, and then coated with powdered epoxy resin to the required thickness in an electrostatic spray chamber. On contact with the grounded bar, the charged epoxy resin melts and flows. Curing of the epoxy occurs rapidly and the bar is cooled by air or water quenching. The coated bar is then tested with a holiday detection device that electrically examines the reinforcing bar for minute cracks or pinholes in the coating. Holidays are patched with a liquid epoxy which is compatible with the powdered resin coating.

Procedures for handling, fabrication, transportation, and placement of epoxy-coated reinforcing bars are similar to the normal procedures used for uncoated bars, with the exception that special precautions such as padded slings for lifting bundled bars, additional bundle supports during transportation, and nonmetallic coated tie wires and nonmetallic bar chairs are commonly used. The reader is directed to Section 5.7.9 of ACI 301 for further information. Research has shown that damaged epoxy-coated bars (which are not electrically connected to uncoated steel) will not be subject to rapid rates of corrosion at the bare areas. As a result, most specifications do not require field repair of the coating, provided the total damaged area is less than 1 or 2 percent of the bar surface area, and individual damaged areas are small (1/4 in. square or smaller).

Chapter 7 -- Concrete materials and properties

7.1 General

Recent studies have shown that, while attention to the properties of the component materials and the concrete is of importance, other aspects such as design features and construction practices are equally important in determining the performance of a concrete bridge deck. This section will be devoted primarily to a discussion of those aspects of concrete properties and materials which have special significance to bridge deck performance.

ACI 201.2R, Section 4.5, provides important recommendations in this area.

7.2 Materials

Although the bridge deck exposure is recognized as a severe one for concrete, both from an environmental and structural point of view, the quality requirements for the materials used in the concrete do not need to be more restrictive than for materials normally used in pavement concrete. Thus, standard specifications used for concreting materials for these purposes will generally be applicable as indicated below.

7.2.1 Cement -- Hydraulic cement, meeting the following specifications, is recommended for bridge deck construction:

a. ASTM C 150 -- Portland cement
b. ASTM C 595 -- Blended hydraulic cement
c. ASTM C 845 -- Shrinkage-compensating hydraulic cement

Shrinkage-compensating cements have been used in selected bridge decks in a few states. ASTM C 845 cement has been used in the United States, and an expansive component is added to the concrete mixture in Japan.
Potential advantages are:
1. Shrinkage cracking has been reduced by as much as 25 percent, although some authors have reported significantly better results in the United States and in Japan.
2. Significantly higher abrasion resistance than Portland cement concrete at equal strengths or water-cement ratios (ACI 223).
3. Increased concrete flexural tensile strengths in reinforced concrete sections (ACI 223).

Special Considerations are:
1. Higher cost of shrinkage compensating cements (130 to 160 percent of the Type I cement, depending on location).
2. Shrinkage-compensating concrete requires a higher water content (as much as 10 to 15 percent more) than Portland cement concrete. No decreases in durability or strength occur due to the greater amount of chemically-bound water.
3. A higher initial slump is required to compensate for slump loss in shrinkage-compensating concrete with elevated concrete temperatures (exceeding 85°F) (ACI 223).
4. Stricter controls on delivery times and temperatures are required, especially on long-haul projects in warm weather (ACI 223).
5. Curing procedures providing additional water to the concrete are preferred (i.e., ponding, continuous sprinkling, or wet coverings). Plastic sheeting and other moistureproof covers can also be used. Cold-water curing on warm concrete surface should be avoided (ACI 223).
6. Long-term storage may lead to a loss in expansion level, with some materials rich in free lime, so cement should be tested prior to use per ASTM C 845 for mortar bar expansion, as outlined in ASTM C 806.

Additional consideration should be given to the following during construction or design to produce maximum benefits:
1. The expansion level of the concrete, as tested by ASTM C 878, must be adjusted to the degree of the maximum internal steel restraint and the volume-to-surface ratio to provide full shrinkage compensation.
2. Placement patterns are required that avoid “infill” sections which could prevent the deck from expanding in two adjacent directions.
3. Casting decks to precast or prestressed girders and beams is to be avoided as this will present excessive external restraint against potential longitudinal expansion that will prevent the needed internal resilient steel strain required for the shrinkage-compensating action. Casting decks to steel beams and girders has been more successful with appropriate potential concrete expansion levels attained.

When shrinkage-compensating concrete is used, it is recommended that all aspects of good concrete design, mixing, placing, and curing practice be rigidly enforced as outlined in ACI 223.

Regardless of the type of cement used for deck construction, a positive corrosion protection system, such as epoxy-coated reinforcing bars, is recommended for use on concrete bridge decks constructed in deicing salts or coastal environments (see Section 6.6 and Chapter 13).

If the specifications for the structure do not indicate the type of cement to be used, it is recommended that Type I or II Portland cement be used.

7.2.2 Aggregate
7.2.2.1-- Aggregate for bridge deck concrete may be either normal weight aggregate conforming to ASTM C 33 or lightweight aggregate conforming to ASTM C 330. ASTM C 33 (also see ACI 221R) contains a requirement for soundness which is satisfactory for most purposes. The high unit cost of bridge decks, however, justifies giving additional attention to this aspect of aggregate quality. Past performance is a reasonably reliable basis on which to judge whether an aggregate will be durable when exposed to freezing and thawing. In the absence of a service record, an evaluation should be made by laboratory freezing and thawing tests of air-entrained concrete containing the aggregate, such as the freeze-thaw procedures described in ASTM C 666, C 671, C 672, and C 682.

7.2.2.2 -- Since the bleeding characteristics of the concrete are of importance in the potential performance of the concrete deck, it is important that the grading of the fine aggregate, in particular, adheres to the limits prescribed by ASTM C 33, with respect to the amount of material passing the No. 50 and 100 sieves. It is equally important to have uniformity of grading batch to batch so that bleeding and finishability will not be subject to disturbing variability.

7.2.3 Water -- Practically any water that is drinkable and has no pronounced taste or odor will be satisfactory as mixing water for concrete. Sea water should not be used in concrete for bridge decks because of the possibility that corrosion of the reinforcement may be hastened.

Specifications for concrete mixing water are shown in AASHO T-26.

7.2.4 Admixtures
7.2.4.1-- A variety of admixtures, either chemical or mineral, is used in bridge decks. For a detailed exposition regarding types and uses of admixtures, see ACI 212.3R, ACI 226.1R, and ACI 226.3R. Of those discussed, useful admixtures for concrete bridge deck construction include air-entraining admixtures meeting ASTM C 260, and water-reducing, retarding, and accelerating admixtures meeting ASTM C 494, Types A, B, and C. Combination water-reducing and retarding and
water-reducing and accelerating admixtures are also covered under ASTM C 494 as Types D and E, respectively. High-range water reducing (HRWR) and high-range, water-reducing and retarding admixtures are covered by ASTM C 494, Types F and G, respectively. Fly ash and raw or calcined natural pozzolans, ASTM C 618, Types N, F and C, are also discussed in ACI 226.3 R.

7.2.4.2 -- The effectiveness of an admixture is influenced by numerous factors such as type and amount of cement, water content, aggregate gradation and shape, length of mixing period, time of addition to the mix, consistency, and temperature of the concrete. Admixtures should be evaluated in trial mixtures, using the job materials under the temperature and humidity conditions anticipated for the job. Incompatibility between admixtures and other components, particularly the cement, may thus be revealed, and steps taken to remedy the situation. The amount of the admixture used in such trials, or in the actual job when there is no provision for such trials, should be based on recommendations of the manufacturer.

7.2.4.3 -- Occasionally, the use of admixtures will produce side effects in concrete, in addition to those particular effects desired. For instance, although water reducers increase the slump of concrete for a given water content, the loss of slump with time may be greater than for concrete without the water reducer. Attention should be directed to this possibility, since some changes may be required in the scheduling of mixing, placing, compacting, and finishing operations. Some water reducers may also cause significant increases in drying shrinkage of the concrete, even though their use may permit less total water to be used. This effect should be evaluated, since an increase in shrinkage can influence the amount of cracking and subsequent performance of the deck. Retarders are used to delay setting time of the concrete so that more time is available for placing and finishing, particularly when casting large deck areas in a continuous structure where setting before completion of placing and finishing operations could result in cracking due to deflections resulting from loads in adjacent spans. Retarders of the hydroxylated carboxylic acid type also generally increase the rate and capacity of bleeding. Changes in bleeding characteristics will require compensating changes in the timing of finishing operations and the provision of sun shades, windbreaks, or fogging to avoid crusting of the surface before bleeding is completed.

7.2.4.4 -- Calcium chloride, the most commonly used accelerator for reducing setting time, generally increases drying shrinkage and may accelerate corrosion of the reinforcing steel. For this reason, calcium chloride should not be used for bridge decks.

7.3 Properties of concrete

Those characteristics of the concrete which influence its watertightness, resistance to freezing and thawing, and abrasion are particularly important as compared with those necessary for other applications of structural concrete. Even when the concrete is made with satisfactory materials, construction operations such as proportioning, transporting, placing, and finishing can detrimentally influence the deck performance unless the desired properties are obtained by diligent attention to the details of good concreting practice.

7.3.1 Workability and consistency

7.3.1.1 -- It is important that the workability of the freshly mixed concrete, as it is being placed in the bridge deck form, should be such that the concrete can be readily compacted, struck off, and finished. Consistency measurements are helpful in control, but the actual operations just mentioned will reveal the need for possible changes in mix proportions, aggregate grading, or some other aspect to enhance workability. Fig. 7.1 illustrates the difficulty that can be encountered in finishing operations with concrete of improper consistency.

7.3.1.2 -- Concrete slump should be kept to the minimum required for adequate compaction and finishing operations. It is equally important that the slump be uniform batch to batch for efficient and effective operations. If structural lightweight aggregate concrete is being used, the slump can be reduced somewhat with little or no sacrifice in workability.

7.3.2 Bleeding

7.3.2.1 -- The bleeding of concrete is a matter of importance in bridge deck construction, particularly during hot weather. Bleeding is controlled by the provision of adequate fines in the concrete; i.e., a relatively high cement content, fine aggregates containing the required amount of materials passing the No. 50 sieve, intentionally entrained air, and the minimum amount of water per unit volume which will provide the desired consistency. Care should be exercised in the use of certain admixtures which may, as a side effect, increase the rate and capacity of bleeding (see Section 7.2.4.3).

7.3.2.2 -- As water is removed from concrete by
bleeding, subsidence of the solid material takes place. Under certain conditions early cracking at the surface of the concrete deck can result from the interaction of the subsidence of the plastic concrete and the restraint provided by the top reinforcing steel or other rigidly fixed items such as void forms.

7.3.2.3 -- It is important to avoid rapid drying at the surface during the bleeding period, particularly when rate and capacity for bleeding are minimized. Exposure to sun and wind can result in the development of a surface crust beneath which bleeding water can collect and produce a zone of weakness, and which is more prone to crack over the top steel under the influence of restraint to settlement forces. Plastic shrinkage cracking may also occur (see Fig. 7.2). Shading from the direct rays of the sun and the use of fine water spray by means of fog nozzles may be required to avoid or minimize such developments (ACI 305R).

7.3.3 Shrinkage

7.3.3.1 -- Hardened concrete responds to changes in moisture content by expanding as moisture content increases and by shrinking as it dries. If kept continuously wet after casting, the amount of expansion is small, usually less than 0.015 percent, and can be accommodated with no problem. Shrinkage on drying, usually evaluated in plain concrete specimens with no reinforcement, generally ranges from about 400 to 800 millionths (0.04 to 0.08 percent) when exposed to drying at 50 percent relative humidity. Reinforced concretes in field exposure generally show movements of about half those noted above for laboratory specimens. Although these are also small movements, all structures have built-in restraints to such shortening, restraints which can result in cracking of the concrete. These restraints consist of reinforcing steel, stringers, beams, shear connectors, section size, etc. Such cracking may make the reinforcing steel more vulnerable to corrosion and increase the change of surface spalling. Accordingly, steps should be taken to minimize the amount of shrinkage on drying.

7.3.3.2 -- The most important controllable factor affecting shrinkage is the amount of water used per unit volume of concrete. Shrinkage can be minimized by keeping the water content of the paste as low as possible and the total aggregate content of the concrete as high as possible. Use of low slumps and placing methods that minimize water requirements of the concrete are major factors in reducing shrinkage. High slumps and high initial concrete temperatures will increase water requirements and should be avoided. Total aggregate content is maximized by using the largest size coarse aggregate consistent with steel reinforcing spacing.

7.3.4 Durability

7.3.4.1 -- The primary potentially deteriorating influences on concrete bridge decks are freezing and thawing, particularly in the presence of deicing chemicals and corrosion of the reinforcing steel.

The resistance of concrete to freezing and thawing, even when various deicers are used, is significantly improved by the use of intentionally entrained air. Air-entraining admixtures meeting the requirements of ASTM C 260, when used to produce the recommended volume of entrained air, provide the proper size and distribution of air voids for effective protection. Air void characteristics representative of an adequate system, as measured in hardened concrete by the linear traverse measurement technique (ASTM C 457), are: (1) calculated spacing factor less than about 0.008 in., (2) a surface area of the air voids greater than about 600 in.²/in.³ of air void volume, and (3) a number of air voids per linear inch of traverse significantly greater (about double) than the numerical value of the percentage of air in the concrete. These characteristics are usually obtained when the air content of the fresh concrete meets the requirements in Table 7.1, Section 7.3.6.

When ASTM C 494, Types F and G high-range, water-reducing admixtures are used in concrete, the above air void parameters still apply. The fact that HRWR's do not affect the durability of the concrete was reported by Whiting and Schmitt in NCHRP-296 (also see Reference 29). Hence, the total air content should still be held within the prescribed limits of Table 7.1.

7.3.4.2 -- The permeability of the concrete is also of importance. Low water-cement ratio and rich mixes with a minimum cement center of 564 lb/yd³ are recommended, since they will provide concrete less permeable to water and deicer solution. For such concretes, the specified compressive strength $f_c$, as defined in ACI 214, should be at least 4500 psi at a test age of 28 days. The
maximum ratio of water to cementing materials for bridge deck concrete should not exceed 0.45 by weight.

7.3.4.3 -- If a mixture incorporating either chemical admixtures (Types A, B, C, D, F, or G of ASTM C 494) or pozzolans (Types F, N, or C of ASTM C 618, Fly Ash and Raw or Calcined Natural Pozzolans) or a combination of chemical admixtures and pozzolans is contemplated, less than 564 lb/yd$^3$ may be used, provided the following criteria are met:

a. Air content recommended in Table 7.1 is obtained
b. Proper slump is used
c. The absolute volume of cement plus pozzolan is equal to or greater than that of 564 lbs/yd$^3$ of cement
d. The average compressive strength is sufficient to ensure that $f'_c$ is equal to or greater than 4500 psi
e. The water-cementitious material (total weight of cement plus fly ash or natural pozzolan) ratio does not exceed 0.45 by weight

7.3.4.4 -- A low ratio of water to cementitious materials is helpful not only with respect to scaling, but also with respect to corrosion of the reinforcing steel. Most deicers are chlorides and their penetration to the steel can result in rapid corrosion. A low water-cement ratio paste provides a more effective barrier to the penetration of chlorides. Rich mixes help by enhancing the probability for reduced water-cement ratios and by increasing the capability for maintaining a high pH in the concrete, an environment which reduces the potential for steel corrosion.

Recent work for the FHWA$^1$ has shown that depth of cover is very important to control galvanic corrosion. With only 1 in. of cover, early corrosion was detected, regardless of water-cement ratio. The only exception was when a silica fume admixture was present in the concrete. It is recommended that 2 in. of concrete be the minimum cover.

7.3.5 Strength -- Concrete strength is primarily a function of the water-cement ratio and the extent of moist curing. Concrete proportions are selected on the basis of strength and durability requirements. For more detailed information, see ACI 211.1 and ACI 211.2 on proportioning, and ACI 201.1R on durability.

In most instances, the requirements for durability previously discussed will govern the selection of water-cement ratio, and the actual strength developed will be more than required from structural design considerations (i.e., the limiting maximum water-cement ratio must be used).

7.3.6 Air content

7.3.6.1 -- Field experience and laboratory studies have shown that the amount of entrained air required is a function of the maximum size of coarse aggregate used, as shown in Table 7.1.

7.3.6.2 -- Air-entraining admixtures which meet the requirements of ASTM C 260 will provide the proper size and distribution of air voids. Current field control practice, however, involves only the measurement of the volume of air in the freshly mixed concrete. The volume of air entrained is primarily a function of the amount of air-entraining admixture used. However, significant changes in air content can result from changes in aggregate gradation and fine aggregate content, slump, concrete temperature, other admixtures, and mixing time. These factors should be controlled within the limits established.

7.3.7 Skid resistance

7.3.7.1 -- The skid resistance of a concrete bridge deck is influenced by the properties of the concrete, the properties of the component materials, and by the texture of the surface.

The most important factor in skid resistance of concrete surfaces, especially at normal highway speeds, is surface texture. Satisfactory textures can be produced by brooming, wire drags, and flexible wire brushes. To promote retention of skid-resistant properties related to texture, deep texturing and practices that minimize wear are desirable. The latter includes low water-cement ratio concrete mixtures, durable fine aggregates, avoidance of placing and finishing practices that tend to bring fines and water to the surface, and proper curing of the concrete surface.

7.3.7.2 -- With increasing pavement wear or slower speeds, the characteristics of the fine aggregate become increasingly important in skid resistance of concrete surfaces. The silica content of the fine aggregate is the primary determinant in this instance, and acid-insoluble (6N HCL) residue contents of 25 percent or greater provide good skid resistance.$^{30}$

Coarse aggregate is relatively unimportant unless conditions have resulted in excessive wear and the coarse aggregate has become exposed at the surface.

### Table 7.1--Recommended air contents for bridge deck concrete subject to freezing

<table>
<thead>
<tr>
<th>Nominal maximum aggregate size, in.</th>
<th>Air Content,*+ percent by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1/2</td>
<td>5 1/2</td>
</tr>
<tr>
<td>3/4</td>
<td>6</td>
</tr>
<tr>
<td>1/2</td>
<td>7</td>
</tr>
<tr>
<td>3/8</td>
<td>7 1/2</td>
</tr>
</tbody>
</table>

*A reasonable tolerance for air content in field construction is ±1 1/2 percent.

*Where deicers are not used, but freezing occasionally occurs, the target air contents may be reduced 1 to 1 1/2 percent.
need for a steady flow of concrete of uniform properties cannot be over-emphasized.

8.2 Reference documents

The basic specifications and practices required are outlined in the following documents:

a. ASTM C 94
b. ACI 304R
c. ACI 305R
d. ACI 306R
e. ASTM C 685

8.3 Measuring materials

8.3.1 -- Cement and cementitious materials should be weighed on a separate scale and in a separate weigh hopper from the aggregates. Typical specifications require that they be weighed to ±1 percent of the amount being weighed. These tolerances need to be broadened somewhat when cement and a pozzolan are weighed cumulatively on conventional batching equipment. In all cases, the cement should be weighed in first. Special precautions are required in handling certain fly ash materials, since they flow through small cracks and crevices much more readily than cement. Compartments between cement and fly ash bins must be sealed, and batching valves and devices require close tolerances to assure positive cutoff.

8.3.2 -- Aggregates must be uniform in grading and moisture content if excessive variations in consistency and water content are to be avoided. ACI 304R outlines certain precautions to be observed. Typical specifications require that aggregates be weighed to about ±2 percent of the required weight. For small batches and batches containing lightweight aggregate, ASTM C 94 permits somewhat more liberal tolerances.

8.3.3 -- Admixtures are generally batched by volume, but may be batched by weight. A typical tolerance is ±3 percent, but a somewhat larger tolerance of perhaps ±5 percent (ACI 304R) is considered acceptable. Liquid admixtures should be batched in mechanical dispensing equipment equipped with a visual sight gage or other positive means of determining that the proper quantity has been batched. In general, different admixtures should not be batched in the same dispenser or lines unless provision is made to flush out the system between each use. Similarly, different admixtures should not be intermingled before the start of mixing unless they are known to be compatible. The manufacturer’s recommendations should be followed. When several admixtures are to be used in a batch, they should be batched with different ingredients such as the water or sand, or in separate parts of the water or sand. They should not be batched directly in contact with the cement before mixing. The time of addition of the admixture to the concrete and the presence of other admixtures often affect the amount of each required to produce the desired effect -- air content, retardation, etc. (ACI 212.3R). Often each of a number of different admixture batching procedures can be used successfully. However, once a procedure is selected, it should be carefully followed.

8.3.4 -- The current ASTM C 94 and ASTM C 685 require that added water be measured to within ±1 percent of the required total mixing water. Additionally, the total mixing water, which includes free moisture on the aggregates, is required to be measured to within ±3 percent. This amounts to about ±1 gal/yd³ (8 lb/yd³). Because of the difficulty of determining aggregate moisture contents, it is extremely rare that this accuracy can be obtained by direct measurement. The control of water content is discussed in Section 8.5 of this document. In truck mixers, any wash water retained in the mixer from the preceding batch should be accurately measured, and if this is not practical, the wash water should be discharged.

8.4 Charging and mixing

8.4.1 -- All batches of concrete, whether mixed in central or truck mixers, must be uniformly mixed and uniform in composition throughout the discharge. ASTM C 94 and ASTM C 685 contain a recommended testing procedure for determining uniformity and established permissible limits for variation of (1) weight per cubic foot (air free), (2) air content, (3) slump, (4) coarse aggregate content, (5) unit weight of mortar (air free), and (6) compressive strength. Although each of the six limits given is important, those on air content are of particular significance in bridge deck construction, and occasional checks of concrete from different parts of the batch during discharge are recommended. If tests show that the ASTM limits on uniformity are not being met, corrective measures must be taken. In both stationary and truck mixers, the method of charging the ingredients can have an important effect on uniformity of mixing. Good mixing is enhanced by blending of all ingredients as they enter the mixer. When cement is charged separately, mixing is likely to be much more difficult and sensitive to minor variations in charging speed, method of addition of water, brand of mixer, and other factors. In these circumstances, different drum and blade designs may require somewhat different procedures. In truck mixers, charging and mixing at drum speeds up to 18 or 20 rpm -- well above typical specification maxima of 10-12 rpm -- may greatly improve uniformity obtained in a given number of drum revolutions.

8.4.2 -- When properly charged, typical large central mixers are capable of producing uniformly mixed concrete in 90 seconds or less. When reduced mixing times are permitted, based on uniformity tests, mixers should be equipped with suitable timers to prevent discharge before completion of the required minimum mixing. When such mixers are operated at short mixing times, a delay in discharge and the resulting additional mixing time may lead to greatly increased air content. For this reason, the mixers must be capable of being stopped and restarted under full load to avoid maximum mixing times.
more than about 60 seconds greater than the reduced mixing time being employed.

The mixing time can be very short when a central mixer is used only to shrink mix or intermingle the ingredients. Here mixing is completed in a truck mixer. The amount of mixing in the truck should only be that sufficient to produce the required uniformity. Older versions of ASTM C 94 required 50 to 100 revolutions of mixing in the truck mixer. These limits are good guides for shrink mixing, but may be unnecessarily restrictive in individual instances.

### 8.4.3 -- When concrete is mixed completely in a truck mixer, specifications generally require 70 to 100 revolutions at mixing speed after all ingredients are in the drum. The number of mixing revolutions required to produce uniformly mixed concrete may be either more or less than this range. The number required will depend importantly on the load procedure, condition of the mixer and other factors. In general, the total number of drum revolutions at both agitating and mixing speed should not exceed 300. This limit is designed to avoid excessive grinding of soft aggregates and cement, the generation of excessive heat and the loss of entrained air. After completion of mixing, the concrete does not need to be agitated continuously and the drum can be stopped if an additional 40 to 50 revolutions at mixing speed are employed immediately prior to discharge. This final additional mixing is needed with all concretes to eliminate segregation and bleeding that can occur in transit.

The interior of all mixers should be periodically examined for accumulations of hardened concrete and excessive blade wear which will reduce mixing efficiency and rate of discharge of low slump concrete. Truck mixers of relatively recent manufacture in good mechanical condition should be able to discharge 2 to 2.5 in. slump concrete without difficulty; however, if 1 to 1.5 in. slump is required, units designed for this purpose may be required.

### 8.5 Control of mixing water and delivery

#### 8.5.1 -- The ultimate quality of the concrete depends on the water-cement ratio or the quantity of water at a given cement content. As mentioned in Chapter 6, increased water content or water-cement ratio decreases strength, increases drying shrinkage, and in general, adversely affects concrete quality. Mixed concrete loses slump with time or requires additions of water to maintain slump at a constant level. The rate at which the chemical reaction between cement and water proceeds, or the rate at which slump decreases depends on many factors, including the temperature and properties of the cement, admixtures, and aggregate.

Direct control of mixing water is achieved by:

a. Limits on maximum water-cement ratio or water content
b. Control of retempering water within water-cement ratio design limit
c. Maximum and minimum slumps
d. Limits on the maximum temperature of the concrete, generally about 90 F, but occasionally lower

Indirect controls such as time limits and total revolutions are quite common. However, these factors are not detrimental if the addition of water is within the limits of the maximum water-cement ratio and the concrete is in satisfactory condition for proper placement and consolidation.

#### 8.5.2 -- The establishment of a maximum water-cement ratio or water content should solve the problem of retempering and insure quality concrete. However, in most situations, aggregate moisture contents are not known with the required accuracy to insure absolute confidence. Additionally, relatively small variations in aggregate grading, and properties of aggregates and cements will affect the level of slump obtained at a given total mixing water content or at a given water-cement ratio and cement content. At the present state of the art, it is very difficult to compute the quantity of additional water required and be certain of obtaining the required slump. Certain adjustments will have to be made, generally by the person responsible for mixing the concrete.

When maximum total water contents are established through the use of trial batches made in the laboratory, care and judgment must be exercised in translating these requirements to the field. Full-sized batches of the proposed mix should be made and used in less critical work areas before it is used in the actual bridge deck. Generally, the maximum water content is specified without tolerances. To provide for unusual circumstances, a tolerance of 25 to 30 lb/yd$^3$ of concrete is required above that needed to produce the desired slump under usual circumstances. Existing specifications generally do not contain such tolerance. This and the concomitant difficulties of accurately establishing the actual water content constitute a major problem in control of the mixing process. Even with this tolerance, aggregates will have to be uniform in grading and moisture content. To obtain uniform moisture contents, coarse aggregates need to be stockpiled 6 to 12 hr, and fine aggregates 24 hr or longer, before they are placed in storage bins for batching. Electrical moisture meters can be useful tools, but they require frequent recalibration and maintenance. Electrical meters are seldom used successfully on coarse aggregates and may be insensitive if sand moisture contents exceed 9 to 12 percent. Electric meters do not work when the sand contains even small amounts of soluble salts. The selection of the location and arrangement of probes are very important. In cold weather when aggregates must be heated, the control of moisture content is even more difficult.

#### 8.5.3 -- Procedures designed to control water-cement ratio or total water content of truck-mixed concrete must permit some tolerance in the total water content batched to compensate for the fact that aggregate moisture contents are seldom known with sufficient accuracy, and that normal variations in delivery times due to traffic and job
delays will affect the quantity of water or water-cement ratio required to produce the desired slump. ASTM C 94 controls the situation by specifying maximum time limits and by limiting the addition of water to the initial mixing and on arrival at the job when the slump is less than specified. When water is added on arrival at the job, an additional 30 revolutions of the drum are required to obtain proper distribution and no later retempering is permitted.

8.5.4 -- Actual mixing of truck-mixed concrete is generally done either at the plant or after arrival at the jobsite. Mixing is rarely done during transit because of the danger of turning over a truck. A system involving mixing to a designated slump in the yard and tempering only on arrival at the jobsite contributes to centralized control, but may limit permissible delivery time or distance. As suggested earlier, after completion of mixing the drum, speed should be reduced to agitating speed, or preferably stopped, on the way to the job.

8.5.5 -- When damp aggregates, cement and part of the water are intermingled during charging, and the mixing is delayed until arrival on the job, a substantial proportion of the cement will be wetted and the slump loss for a given time delay will be only slightly less than if the concrete had been thoroughly mixed at the plant or in a central mixer.32,33

8.6 Communication

Regardless of the method used to produce the concrete, a reliable method of communication is needed between the jobsite and the batch plant to insure a steady continuous flow of concrete and to avoid the delays that occur if mixers accumulate on the job waiting to discharge. In remote locations involving long hauls, extra trucks may be needed in case of a breakdown or rejection of a load.

Chapter 9 -- Placing and consolidating

9.1 General considerations

The procedures outlined in ACI 304R are applicable to the general problem of placing concrete. Only such additional points will be made here as are considered peculiar to or especially pertinent in the case of bridge decks. Concrete bridge decks differ from most concrete placements in their relatively thin sections, high percentage and close spacing of reinforcing steel, numerous points of stress reversal and exposure to the abrasion, impact and vibration of traffic.

The construction conditions associated with transporting, placing, and finishing of concrete bridge decks are far from ideal, and all contribute to the difficulties encountered in control of the finished deck. Chemicals used to melt ice and snow are known to be aggressive to concrete and steel. Decks are also subjected to more freeze and thaw cycles in the winter and wider temperature variations in the summer than slabs on grade.

9.2 Transportation

ACI 304R is again referred to with additional stipulations due to the necessity of placing relatively small quantities of concrete over a large area. The transporting equipment should be geared to the consistencies of concrete proportioned for the job. Admixtures may be used to improve the workability of the concrete, provided the selected water-cement ratio is not exceeded. Some types of truck mixers, bucket gates, or pumps are slow or unworkable when harsh or very stiff mixes are used. Approval of every piece of transporting equipment proposed for use on the project should depend on its ability to handle bridge deck concrete without segregation.

The rejection of concrete for a bridge deck often gives rise to further complications, since the high percentage of reinforcement steel makes bulkheads difficult to install and cold joints are always undesirable. Consequently, the time spent in checking equipment in advance and in checking concrete at the batch plants is well invested.

9.3 Rate of delivery

It is essential that concrete for bridge decks be delivered to the site at a uniform rate adapted to the manpower and equipment to be used in placing and finishing. On one major project on which specific records were kept, bridge deck concrete delivery was found to average 27.2 yd³/hr, with a standard deviation of 5.5 yd³. Sufficient hauling units with at least one spare unit should be determined and established between the contract producer and officials in charge of placing and finishing.

The difficulties of obtaining a satisfactory delivery rate can be overcome by mixing on the job. However, other methods of mixing concrete can serve equally as well when radio or other methods of communication are maintained between batch plant and job site.

9.4 Placing equipment

When mechanical strikeoff equipment is used and the delivery of concrete to the job site is adequate, the movement of the concrete from the delivery point to the deck is often the delaying operation and it should receive particular attention. A variety of types of placing equip-
9.4.1 **Belt conveyors** -- Inclined and horizontal conveyors designed specifically for moving concrete have been used successfully in placing bridge deck slabs. Combined with a radial swing conveyor, concrete has been placed at rates up to 120 yd³/hr. An example is shown in Fig. 9.1. (Another example can be seen in Fig. 10.2.) At such high rates, attention must be given to the equipment and manpower required to stroke off and finish the concrete.

All transfer points in the conveyor system should be equipped with discharge hoods (see Fig. 9.1) to prevent segregation at points of transfer. Length should be controlled so that the transport time, from charging conveyor to point of placement, does not exceed 15 min. Belts should be kept clean by means of one or more scrapers to avoid paste loss that could affect workability.

9.4.2 **Concrete pumps** -- The capacities of pumps used for placing of concrete on bridge decks can vary from 20 to 80 yd³/hr, dependent on height of lift, length of horizontal run, and number of pipe elbows used, plus type and size of concrete pump and pipe. The pumps require attention, guidelines for which are covered in ACI 305R. Delivery of concrete by pumpline is shown in Fig. 9.2.

Inspection of steel pipe should be required prior to use. Hardline pipe must be clean and not severely dented. Couplings should be properly designed and capable of withstanding line pressures and surges.

Flexible pipe, when used, should be of such material that no bending or kinking will occur during use, and so constructed that excessive mortar leakage will not occur at pipe connections. The use of aluminum alloy pipe should be prohibited.

9.4.3 **Concrete buckets** -- Buckets have been in use for many years for placing bridge deck concrete. The bucket should be self-cleaning on discharge, and concrete flow should start on opening of the discharge gate. Opening of the gate to its wide-open position so as to discharge concrete in one solid mass directly below the bucket should be prohibited. Control of bucket and opening should be done in such a manner as to insure a steady stream of concrete discharge against concrete previously placed. Free-fall of concrete from bucket discharge gate to bridge deck should not exceed 30 in. (see Fig. 9.3). The use of two buckets per crane, as shown in Fig. 9.4, is recommended. Depending on the size of bucket, lift, and boom travel, concrete can be placed using two buckets on large deck jobs at 20 to 40 yd³/hr. One bucket of the same size with equal lift and travel can place 15 to 25 yd³/hr. These capacities are based on using a skilled crew.

9.4.4 **Manual or motor-propelled buggies** -- Buggies should work on smooth rigid runways set well above the deck reinforcing steel. Concrete being transferred by buggies tends to segregate during motion. Planking should be butted rather than lapped to maintain a smooth surface. In placing deck concrete from either manual or power-driven buggies, the concrete should be dumped against concrete previously placed. Recommended maximum distance to transfer concrete by manual buggies is 200 ft and for power buggies, 1000 ft. One type of power buggy is shown in Fig. 9.5.

Hand buggies vary in capacity from 6 to 8 ft³. Placing capacity will average between 3 to 5 yd³/hr. Power buggies are available in sizes from 9 to 12 ft³ with placing
9.5 Vibration and consolidation

ACI 304R and ACI 309R should be consulted for general requirements relating to vibration. Deck requirements differ in some respects in that concrete subsidence is restrained by closely-spaced and chair-supported reinforcing steel, and the head of concrete is low. In hot, windy weather, surface crusting is a problem which tends to promote early finishing. This, in turn, forces vibration operations to be completed before the subsidence of the concrete due to bleeding is complete. Sometimes there is concern that concrete will be “over vibrated” or “over finished.” This more than likely implies that the concrete was of a consistency so wet that it should not have been vibrated at all, or that the finishers were working on the drying surface crust an hour or more before bleeding, and subsidence was completed.

It is essential that bridge deck concrete be thoroughly vibrated at a time late enough to assure close contact with the reinforcing steel after the concrete has ceased to subside. This may require revibration if bleeding is prolonged, and it generally occurs for a much longer time than is obvious. It may be necessary to use an evaporation inhibitor to delay the time the finishers start and still vibrate at a late enough time to get proper consolidation. Retarding admixture may delay initial set time and permit later vibration, but may not prevent surface crusting due to drying. For interim curing, fog sprays, if they provide a true “fog,” and monomolecular films are helpful.

9.6 Sequence of placing

Concrete should be placed in a uniform heading in a line roughly parallel to the screed machine. Cracking sometimes can be reduced in continuous bridge decks by placing the concrete in a sequence designed to minimize the effect of form and falsework deflections. While this procedure is not as widely practiced as it was a few years ago, it is worth consideration, though it may add several days to the time necessary to complete a deck. By placing the center portions of the spans first, cracking produced by negative bending over the piers is reduced. Sometimes construction joints are placed at the piers.

9.7 Manpower requirements and qualifications

As discussed in Chapter 4, every effort should be made to assure that sufficient competent manpower is on hand to proceed properly with a concrete deck placement.

9.8 Reinforcement --Special care during placing

Assuming that reinforcing steel is properly positioned and securely tied, the freedom from spalling of a bridge deck may largely depend on the degree to which the steel is tightly encased in concrete, without cracks over bars.
CONCRETE HIGHWAY BRIDGE DECK CONSTRUCTION

10.1 General

Finishing operations constitute the most difficult, and yet one of the most important phases of bridge deck construction, with respect to durability and riding quality. The difficulty in handling, placing, and finishing concrete bridge decks, due to the suspended nature of bridges, necessitates the employment of special construction techniques and controls (See ACI 304R, 305R, 306R, AASHTO Specifications, and References 15, 34, and 35).

After the concrete has been struck off by machine and consolidated by vibration, it should be further smoothed and consolidated with a longitudinal float of a suitable design approved by the engineer.

Following the floating operation but while the concrete is still plastic, the contractor should test the slab surface for trueness with a straightedge (10 ft to 16 ft long). The straightedge should be used to check the surface for bumps or depressions and should be advanced along the deck in successive stages of not more than one-half the length of the straightedge. Any depressions should be filled immediately with freshly mixed concrete, struck off, consolidated and refinished. High areas should be cut down and refinished.

10.2 Timing of operations

The entire plan of operation, placing and finishing times, and the equipment of the contractor must be evaluated to insure that the operation can be performed smoothly and efficiently. This phase should be carried out during the preconstruction meeting discussed in Section 4.3.

Final floating should be delayed as long as possible to allow for completion of bleeding of the concrete. This is necessary to prevent “crusting,” the formation of a weakened plane immediately below the finished surface which results in rapid scaling when the deck surface is exposed to deicers and freeze-thaw action.

10.3 Manual methods

Manual methods of strikeoff should not be used except where the use of a finishing machine is impractical or impossible such as on variable width sections or to finish, to a temporary bulkhead, the concrete already deposited in the event of breakdown of the mechanical finisher. When allowed, a manual strikeoff should be accomplished with a steel or steel-shod wood screed.

Floating may be done manually as well as by mechanical means (see discussion of mechanical floating equipment in Section 10.5). Manual methods are commonly employed, using plow-handled floats and long-handled “bull” floats from work platforms spanning the deck transversely as shown in Fig. 10.1. Proper finishing, using manual methods, requires the skills of an experienced pavement finisher.

10.4 Finishing aids

The practice of sprinkling the struck surface of the deck to facilitate floating should be strictly prohibited. This practice may produce a surface that has an excessively high water-cement ratio and low entrained air content. These conditions will contribute to rapid surface
deterioration under the actions of traffic, freezing and thawing, and deicing chemicals.

To aid the finishing operations (floating), especially under hot, dry conditions, a monomolecular filming agent may be applied to the struck surface. The purpose of the filming agent is to prevent rapid evaporation of bleed water and “crusting,” thereby extending the period of time during which floating operations can be carried out.

10.5 Mechanical equipment
10.5.1 Machinery used in the finishing of concrete placed on bridge decks consists of several types. Nomenclature varies because it is possible to describe this equipment in terms of either its direction of travel or the orientation of the striations imparted to the surface. Since the direction of motion and the orientation of the striations may be perpendicular to each other, the potential for conflicting nomenclature is apparent. For the purposes of this standard practice, the direction of striations will be used to designate the machine as “longitudinal” or “transverse.” The direction of travel of the entire machine will be used for secondary identification. It is this latter feature which dictates the geometry of placement and thus influences progressive deflections. Depending on the specific design of the equipment, the motion of the strikeoff plate may not coincide with the direction of the entire machine.

10.5.1.1 Longitudinal finish, longitudinal travel -- Most commonly used is the combination strikeoff and finishing machine shown in Fig. 10.2, which is supported in a structural frame, is self-propelled on rails and travels in a longitudinal direction (i.e., parallel with traffic flow). Strikeoff and finishing machinery is suspended from this frame. It is power driven to perform the task of strikeoff and finishing to the established tolerances. The finishing is accomplished in a longitudinal direction as the power-
driven vibrating and/or oscillating screed (float) travels transversely across the deck. A closer view is shown in Fig. 10.3.

10.5.1.2 Transverse finish, longitudinal travel -- In another type of machine supported on longitudinal rails and traveling in the direction of the traffic flow, finishing is accomplished by the transverse action of the power-driven vibrating and/or oscillating screed. Strikeoff of fresh concrete is obtained through a strikeoff plate attached ahead of the finishing screed, moving placed concrete longitudinally. An example is shown in Fig. 10.4.

10.5.1.3 Longitudinal finish, transverse travel -- The frame supporting the strikeoff and finishing machinery is mounted on rails placed transversely (i.e., 90 deg to traffic flow or on adjacent decks). The strikeoff travels longitudinally; i.e., same as traffic flow; power-driven finishing is performed by a longitudinal oscillating screed while the machine travels transversely across the deck. An example is shown in Fig. 10.5.

10.5.1.4 -- Regardless of the type of equipment used, freshly placed concrete should be distributed uniformly ahead of the strikeoff and finishing machine, and as close to its final position as practicable. Concrete should not be moved horizontally with vibrators or by other methods which cause segregations.

10.5.2 Rails and guides

10.5.2.1 Equipment traveling longitudinally -- The adjustable screed supports provide the initial surfacing control and set the final longitudinal profile. Therefore, they should be set to proper elevation with allowance for anticipated settlement, camber and deflection of falsework, as required to form a bridge roadway deck true to the required grade and cross sections. The screed supports should be vertically adjustable and set by instrument. Temporary supports should be removable with minimum disturbance of the concrete. The rails should be set above finished grade and should extend beyond both ends of the scheduled length for concrete placement, a distance sufficient to permit the float of the finishing machine to fully clear the concrete to be placed.

Fig. 10.6 shows an idealized arrangement for a bridge deck strikeoff machine designed to travel longitudinally and incorporating several important features. These include:

a. Screed rail supports that are placed in an unfinished area requiring later concrete cover
b. Adjustable supports to allow for progressive deflections
c. Screed rails located above the finished surface to avoid disturbing significantly the concrete when the rail is removed

10.5.2.2 -- The question of beam deflections during concreting poses a difficult problem for good bridge deck finishing. All beam deflections should be carefully calculated and compared at the deflection control points. Progressive longitudinal deflections must be carefully considered as concreting proceeds down the length of the span.

The problem of progressive deflections on a typical beam is illustrated in Fig. 10.7 for various conditions of loading. (The figure is grossly exaggerated for clarity.) Screed rails should initially be set coincident with Line 1. If the rails become disturbed or otherwise require adjustment as the work progresses, variations similar to those shown in Lines 2, 3, or 4 must be considered. Note that, except for Lines 1 and 5, one-quarter and three-quarter point deflections are not equal.

The problem of transverse differential deflections is far more difficult to correct and, in fact, cannot be precisely resolved in contemporary practice. Most fascia beams deflect less than interior beams. Yet it is on the fascia beams that screed rails are usually supported. Consequently, cross-slopes are altered as the beams are loaded. These differentials are usually greatest at mid-span and nonexistent at span ends. Therefore, if complete deflection calculations are not available, it is best to use the cross-sloped configuration of the span ends to insure adequate deck thickness and, most important, to insure sufficient cover over the reinforcement steel.

On sharply skewed bridges, the problem becomes considerably more complex, and consultation with the
designer is advised before concreting begins. The finishing machine, when possible, should be set parallel in the skew of the bridge to avoid differential deflection on multigirder bridges.

On short spans or any relatively rigid spans with minor deflections, the problem may be ignored.

10.5.2.3 Equipment traveling transversely -- This type of machine is most often used on simple spans of 100 ft or less, though it has been used on spans of greater length. The transverse screed rails supporting the machine are normally set to the finished grade at each end of the span. The finished elevation of intermediate points on the deck are set on the longitudinal strikeoff edge of the screeding machine. Assuming structural stability of the machine, these elevations remain fixed and are independent of the girder deflections occurring during concrete placement. Consequently, the thickness of the concrete deck is dependent on two major factors which should be recognized during construction. These are:

a. The differential temperatures existing between the top and bottom flanges of the girders during concrete placement, as opposed to those that may have existed when the forming elevations were established

b. The transverse position of the concrete dead loading at the time a final screeding pass is made over a given point on the span

The possible influence of the first factor is illustrated in Fig. 10.8. If no temperature differential exists between the upper and lower flanges of a simply supported bridge girder, it would be in a thermally neutral position (Fig. 10.8A). Due to solar radiation, differential temperatures will generate expansive forces in the upper flange which are resisted by opposing forces in the lower flange. The resulting effect is an upward deflection of the girder (Fig. 10.8B). If the deck forms were established to grades complying with the neutral position of the girder, but the concrete deck screeded to grade under differential thermal conditions, the thickness of the deck will be decreased by an amount (Fig. 10.8C).

The influence of the second factor is illustrated in Fig. 10.9. Conventional design procedures for calculating dead-load deflections normally assume that each girder is free to deflect independently of other girders in a bridge span. Under partial transverse loading conditions such as the example shown; however, the conventional calculation method yields a midspan transverse deflection pattern markedly different from the actual field deflection pattern. Thus, if the concrete were struck off to grade over the first girder, the midspan deck thickness at this point would be decreased by the difference between the two deflection curves. In addition, the finished grade at this point will be low by an identical amount when all the deck concrete is placed.

Neither of the two factors discussed above can be exactly compensated for during construction, but their effects can be minimized by observing the following practices:

a. Establish forming elevations when the thermal conditions on the girders approximates those ant-
Texturing

10.6.1 -- Decks with deep surface textures will retain skid resistance longer than those with shallower textures. Satisfactory textures can be produced by wire brooming, wire drags, and flexible wire brushes (ACI 325.6R).

10.6.2 -- After the concrete has been brought to the required grade, contour, and smoothness, the texture should be applied. It is difficult to obtain a satisfactory texture with a burlap drag unless it consists of multiple layers and several passes are made. At the current state of technology, a broom finish is the most practical method for obtaining a satisfactory texture. Wire brooms are preferable, and the bristles should be spaced so as to give a coarse texture. Due to the importance of securing proper drainage, transverse ridges are preferable unless minimization of noise is of importance.

The broom strokes should be square across the slab from edge to edge, with adjacent strokes slightly overlapped. Brooming may be obtained either manually, i.e., pulling of broom across the surface from a work platform by skilled workmen, or mechanically by self-powered machinery traveling longitudinally with power-driven broom moving transversely.

10.6.3 -- Texturing should not be carried out on deck surfaces that are to be sealed with a waterproofing membrane (see Section 13.6.1).

Correction of defects

After the first pass of the finishing machine, additional concrete should be added to honeycombed and low spots, and the concrete struck off again. These areas must not be eliminated by tamping or grouting. The surface of finished concrete after floating should be checked with a 10 ft straightedge placed parallel to the roadway centerline and at several positions from one edge of the deck to the other before moving to the next location. Successive locations should not exceed one-half the length of the straightedge. Any depressions found should immediately be filled with fresh concrete, re-vibrated, struck off and refinished. Any areas not corrected in the manner described above may have to be corrected by grinding at a considerably greater cost later, and with attendant loss of surface texture.

Chapter 11 -- Curing

11.1 General considerations

The first few days in the life of a concrete deck are critical insofar as its strength and durability characteristics are concerned. A rapid increase in quality during this initial period (which is commonly referred to as the “curing” period) requires favorable temperature and little or no loss of mixing water.

To insure continued hydration at the optimum rate for a given temperature, the cement paste must be kept as nearly saturated as possible. Water must be available to compensate for evaporation from the surface, and to replenish water removed from the pores by the chemical process called self-desiccation. For a typical mixture, the amount of water needed during the first week to replenish depletion due to self-desiccation is about one part water to 24 parts cement by weight.

Particular attention should be given to the equipment which will be used to accomplish the cure. All equipment and facilities must be ready so that the curing may begin without delay as soon as the concrete is ready for it.

11.2 Curing methods

An ideal curing medium or agent will prevent any substantial loss of moisture. Unfortunately, there is no ideal curing agent; however, there are a number of methods by which concrete decks can be kept in a moist condition and at a favorable temperature. The most popular methods either supply additional moisture to the surface (continuous application of water), minimize moisture loss by sealing the surface (membrane curing compound), or by covering the surface (moisture barrier material).

11.2.1 Continuous water cure -- A continuous water cure may be maintained by a continuous spray, ponded water on the surface, or by a surface covering of absorbent material such as sand, cotton mats, old rugs, or straw, which are kept saturated.

When the continuous water method is used to cure concrete, the most important point to keep in mind is that the surface of the concrete must not be allowed to dry out once the curing period begins. Continuity is important because volume changes, due to alternate wet and dry periods, promote the development of pattern cracking. The need for continuous curing is greatest during the first few hours after placement.

Prewetting moisture-retaining material before it is placed is an ideal but impractical system due to the
excessive weight. Hence, it is usually placed dry. When placed dry, there is danger that absorption of water from the deck will cause surface damage. To minimize the change for damage, the deck surface should be thoroughly wet down prior to placing the material, and the material should be thoroughly wet down as soon as it is placed.

11.2.2 Membrane curing -- There are three advantages of membrane cure over continuous water cure: (1) It is generally applied earlier; (2) it is not cut off sharply; and (3) it is extended over a much longer period. A disadvantage is that a membrane cure does not offer the cooling effect afforded by a continuous water cure.

For hot weather concreting, white pigmented curing compounds are preferred over clear or lightly tinted compounds because they allow less heat to build up from solar radiation, and offer better visual evidence of uniform application.

Only curing compounds meeting the requirements of ASTM C 309 should be used on bridge deck concrete. Because of the lower allowable water loss, compounds meeting the requirements of federal specifications are preferable (CRD-C-300).

11.2.3 Sheet materials -- Curing by materials such as plastic sheets or waterproof paper is effective only if the humidity is low, water may be evaporated from the surface which often causes irregular, plastic shrinkage cracking (Fig. 7.2).

11.3 Time of application

11.3.1 -- In placing deck concrete in hot weather, it is necessary to keep the operation confined to a small area and to proceed on a front having the minimum exposure surface against which concrete is to be added. A fog nozzle should be used generously to cool the air, to cool the forms and steel immediately ahead, and to lessen rapid evaporation from the concrete surface before and after each finishing operation. Excessive fog spraying (that which would wash the fresh concrete surface or cause water to stand on the surface during floating or troweling) must be avoided.

Without such fog spray between the finishing operations in hot weather, particularly if it is windy and humidity is low, water may be evaporated from the surface faster than it will rise naturally to the surface through bleeding. This will create growing tension in the surface which often causes irregular, plastic shrinkage cracking. The period of positive or controlled curing which follows the setting of concrete is intended to insure the obtainment of reasonable strength at an early age, and to prevent the formation of surface cracks due to rapid loss of water while the concrete is low in strength. For bridge decks, the minimum curing period should be no less than 7 days.

In cold weather concreting, the curing period should be extended if heat is not applied to the concrete. An extended cure period or heat is especially important for increasing the strength of a deck over the supports of continuous structures, and thereby minimizing stress cracking when the span falsework is struck.

11.5 Related information

Further information on curing will be found in ACI 308, ACI 305R, and ACI 306R.

Chapter 12 -- Postconstruction care

12.1 General

In many cases, completion of the deck represents the end of any concern for its care. This is unfortunate because even if all of the constraints and variables described in prior chapters have been successfully accommodated, relaxation of attention to details subsequent to the completion of concreting can impair the long-term durability of the deck. Without question, the problems resulting from improper care subsequent to construction are normally less serious than those derived from poor practices during design or construction. Nevertheless, they deserve attention if the deck is to be given the best possible chance to survive in the very severe environment to which it is exposed. Not all of the precautions listed in this chapter are of equal seriousness, and some are more important in some geographical areas than in others.

12.2 During continuing construction

12.2.1-- Perhaps the most common postconstruction defects result from improper loading of the structure during continuing construction operations. Much construction equipment imposes loads in excess of the service loads for which the slab was designed. The effects of these loads is especially severe because the concrete is required to carry such equipment at an early age before its load-carrying properties are fully developed. Great care should be exercised when loading comparatively new decks with cranes, pavers, ready-mixed concrete trucks, and other heavy equipment to insure that the concrete is not overstressed. Early cracking in negative moment
areas of continuous spans is often caused by such premature loadings.

12.2.2 -- Associated with premature loading but worthy of separate emphasis is the need to protect expansion joints from infiltration of foreign material during the interim between their construction and sealing with expansion joint materials. Moving heavy equipment over improperly sealed or protected joints will result in joint spalls or incipient fractures which will dislodge under service traffic. When non-rubber-tired equipment must be moved over unsealed joints, timber or other protective devices should be employed for protection.

Sealing and/or protection of the joints is also necessary to restrict infiltration of incompressible foreign materials which cause subsequent spalling when the deck undergoes thermal length changes.

12.2.3 -- Too rapid exposure of the surface of the slab to the hot sun at the end of a water cure may cause excessive drying shrinkage in the surface when it is still relatively weak. Also, concrete cured in warm enclosures, as in winter concreting of bridge decks, should not be suddenly exposed to cold ambient temperatures, otherwise thermal shrinkage cracking or restraint cracking may occur.

Whatever the curing medium may be, it should be removed at a time and in a manner that will allow the concrete temperature to change slowly.

12.2.4 -- Storage of stain-producing materials, such as reinforcing steel or oil containers, can sometimes cause objectionable discolorations. Such stains may be of concern from the standpoint of esthetics but are of no detriment to the durability of the slab.

12.3 Construction associated preventive maintenance

12.3.1 -- In areas of freezing, drains should be kept open to prevent ponding of water during construction and should be left open upon completion of the job. As noted earlier, areas of high saturation are especially vulnerable to subsequent deterioration.

12.3.2 -- Although deicing chemicals are not normally applied during construction, it is advisable to remember that such materials should not be applied until the concrete has gained a certain degree of maturity. After the concrete has acquired its design strength, a period of drying should elapse before the application of deicing salts. This drying period should be at least 1 month. Longer periods may be desirable, depending on climatic conditions. It is likely that deicers will be applied sooner than 30 days after completion of the curing period, a surface treatment such as linseed oil or neutral petroleum oil should be used to give additional protection.

12.3.3 -- The use of protective coatings to reduce scaling associated with the use of deicing chemicals has been the focus of research and testing for many years. Many materials have been promoted and studied. These include a wide variety of resins; petroleum products; oils of various kinds including linseed, tung, and tall; and other organic materials. Snyder; Furr, Ingram, and Winegar; and Stewart and Shaffer reported the results from tests of 110, 19, and 32 different materials, respectively. In some cases, several classes of materials have imparted some additional durability to poorly air-entrained surfaces by delaying the onset of scaling. Of the numerous materials studied, linseed oil has repeatedly been shown to be the most efficient when both protection and economics are considered. Thus, it is by far the most widely used. The beneficial influence of linseed oil for non- or poorly air-entrained concrete is thoroughly documented. There is no documented evidence that linseed oil treatments are necessary to adequately protect air-entrained concretes. The difficulties of precisely controlling entrained air in the field have been previously discussed.

A report by Rye and Chojnacki recommended against the use of linseed oil, since it delayed rather than prevented scaling, and led to a “false sense of security.” They emphasized the importance of air entrainment. A detailed comparison of their results with those reported by others discloses no real conflicts, but rather adoption of a different strategy for insuring desired performance.

In considering all of the information available to it, Committee 345 believes that the use of linseed oil or neutral petroleum oil surface treatments is a good investment as added insurance, but that major emphasis should be placed on the control of entrained air and other ingredients of the concrete, along with finishing and curing practices.

Oil treatments normally consist of two applications of equal parts of (1) commercial boiled linseed oil and a solvent such as turpentine, naphtha, or mineral spirits, or (2) neutral petroleum oil and Stoddard solvent. Recommended linseed oil coverages are about 40 to 50 yd²/gal. for the first application and about 70 yd²/gal. for the second application. Petroleum oil is usually applied in equal applications, totaling about 17 yd²/gal. If possible, concrete temperatures should be about 50 °F or higher at the time of application to assure proper penetration and to hasten drying. Since oil treatments will produce a slippery surface until absorbed, it may be necessary to keep traffic off the deck until sufficient drying has taken place, or to apply sand for traction during the drying period.

Chapter 13 -- Overlays

13.1 Scope

This chapter deals with overlays placed on a cured bridge deck as a protective shield against water, chemicals, abrasion, or slipperiness. It does not include considerations of penetrating sealers, such as silanes, used to inhibit chloride penetration.

Throughout this chapter, no distinction will be made as to the age of the bridge at the time of overlay placement. Also, no attempt will be made here to discuss the
relative merits of various overlays to prevent deterioration of concrete bridge decks. It is assumed that overlays will only be placed on structurally sound surfaces, regardless of age.

13.2 Need for overlays

13.2.1 Waterproof barrier -- The primary reason for the use of overlays is the prevention and repair of spalling on concrete bridge decks. Such spalling is the result of expansive forces built up within the deck concrete by the products of corrosion of reinforcement steel. Such corrosion is advanced by the presence of moisture and chlorides. Cracks over the reinforcement or porous concrete can accelerate the rate of deterioration. Thus, where cracks or porous concrete are evident and deicers are used, some type of waterproof barrier should be provided or spalling may be anticipated.

It should be reemphasized that careful attention to good design and construction practices, as set forth elsewhere in this standard practice, should significantly reduce the propagation of cracks and prevent the appearance of poor quality concrete. However, where repair costs have become excessive or where good practice is known to have been compromised, an overlay may be a cost effective means of extending service life.

13.2.2 Slipperiness -- Bridge decks, like all roadway surfaces, must be adequately skid resistant. Occasionally, rapid surface wear, due to construction deficiencies and inadequate skid-resistant aggregates, induces slipperiness. Overlays provide a means for correcting this deficiency.

13.2.3 Wearing course -- The use of studded tires has markedly increased the abrasive wear on some bridges. Consequently, overlays may be considered as a sacrificial wearing course since the loss through abrasion of an overlay would not reduce the section modulus or the critical clear cover over reinforcing steel in the structural slab. Overlays can be replaced with relative ease and cost.

13.2.4 Reduction of wheel load effect -- Asphaltic concrete (AC) overlays are commonly used to provide wheel load distribution and a smooth riding surface which helps reduce impact. They are also used as a riding surface over waterproofing membranes.

13.3 Required properties of overlays

The required properties of overlays depend on their intended purpose, as discussed above.

13.3.1 Properties required of all overlays -- Several properties are generally required of all overlays, regardless of the reasons leading to their use.

13.3.1.1 -- Adhesion to concrete or bond is a fundamental requirement for most overlays. Without adhesion, overlays soon delaminate which, at best, presents an unsightly appearance and, at worst, required extensive repair.

13.3.1.2 -- Cohesion or resistance to shear within the overlay itself is necessary to resist the stresses induced by the turning and braking of the heaviest trucks.

This resistance may be relevant when considering the use of unreinforced thermoplastic materials, such as asphalt.

13.3.1.3 -- Skid resistance is a fundamental requirement of an overlay, whether or not that is the purpose for which it was intended, because the overlay becomes the road surface. This property requires the addition of an abrasion-resistant aggregate to most of the polymer-type materials currently marketed as overlays. Grooving (diamond blade saw cut of hardened concrete) or texturing (of plastic concrete) is usually required when placing concrete overlays.

13.3.1.4 -- Durability, used here as resistance to abrasion, deformation and decay, is another important property. Many materials, such as bitumens, soften under high temperatures and become subject to rutting. Such rutting may be imperceptible in the roadway, but creates an undesirable bump at bridge joints. Other products may become brittle with age or when oxidized, and thus may not retain the properties for which they were intended. Extended service histories should be investigated for any proposed overlay.

13.3.2 Properties required of waterproof barriers -- In addition to the properties listed above, waterproof barriers should be designed, considering the conditions which could lead to the intrusion of moisture and chloride ions.

13.3.2.1 -- Impermeability is an important property of waterproof barriers. Materials may be impermeable in lab test conditions, but may be affected by ultraviolet or by the heat from asphalt paving. Introducing aggregates for skid resistance or as bulk fillers may also create interconnected voids that admit water. Some construction techniques induce foaming and porosity which may increase water intrusion.

13.3.2.2 -- Crack resistance is another important requirement of a waterproof barrier. Development of cracks in concrete is one of the conditions leading to the use of a waterproof barrier. Hence, barrier materials must be capable of bridging such cracks in the underlying deck and remaining waterproof. Reflective cracking in bridge decks is a much greater problem on long-span, cast-in-place decks.

13.3.2.3 -- Bridge decks expand and contract with temperature change, and overlays placed on them must do likewise without loss of bond. Where thermal incompatibilities exist between the concrete and the membrane, shear stresses will be created by temperature change. These stresses are proportional to the membrane thickness. Such stresses may exceed the bond strength of the membrane or the shear strength of the concrete, and the resulting failure will destroy the membrane’s effectiveness. Thus, the coefficient of expansion of any membrane material is a significant property where substantial temperature changes occur.

13.4 Types of overlays

Overlays can be grouped into three categories (Fig. 13.1):
Type I -- Thin overlap
Type II -- Concrete-based overlap
Type III -- Combined-system overlap

13.4.1 Thin overlays -- Thin overlays have thicknesses of 1/2 in. or less and therefore add minimal dead load to structures. Their primary function may be to increase skid resistance on slippery decks or to act as surface membranes to minimize penetration of water and chloride ions. They must generally be applied to dry concrete surfaces. They usually involve durable, abrasion-resistant aggregates glued together by various binders including asphaltic emulsions, polymer resins, and polymer-modified cements. Thin overlays are generally not recommended for badly spalled or deteriorated decks. Specialized expertise may be needed to properly apply these systems. A detailed discussion of these systems is beyond the scope of this document, but additional information may be found in ACI 548.1R.

13.4.2 Concrete overlays -- This type of overlay varies from 1 in. to about 21/2 in. deep. They include latex-modified concrete, polyester-modified concrete, low-slump dense concrete, fast-setting concrete, and some variations involving steel fiber or silica fume, or high-range water-reducing mixtures or cathodic protection. The primary function of these systems is to replace deteriorated concrete or asphalt wearing surfaces with an economical, durable, crack-resistant, low-permeability material without significantly increasing the dead load on the structure. The relative advantages and disadvantages of the systems may vary from one region to another, depending on local economic, climatic and design factors. Choice of a system should involve consideration of the actual problems. Shrinkage and surface cracking of concrete overlays are likely to be significant factors in cold climates where deicing salts are used, as compared with milder climates with little use of deicing salts. Shrinkage cracking is also a significant factor in dry and windy climates. High-slump mixes (higher than 4-in. slump) are not recommended for decks with longitudinal grades exceeding 2 percent. Cathodic protection systems should be routinely monitored to insure continued performance. The use of steel fibers, or admixtures such as silica fume or super-plasticizers, is generally intended to improve crack resistance and impermeability. Prior to use, the field experience of any particular system should be investigated.

13.4.3 Membrane and AC overlays -- This type of overlay involves a waterproofing membrane covered with one or two courses of asphaltic concretes. The total depths usually range from 2 to 4 in. The economics of asphalt when available may make this a good option for using the good riding quality and shock-absorbing qualities of the material. Membranes are not recommended for repairing badly delaminated decks with corroded reinforcing bars close to the surface.

There are many types of membranes, including hot-applied, rubberized membranes; sheet membranes; and liquid-applied, polymer membranes. The membranes should be capable of bonding to concrete, bridging cracks, waterproofing, and bonding to AC overlays without being affected by 300 F asphalt. Some membranes require protection boards and two passes of asphaltic concrete in order to minimize damage during compaction, and these systems may not be suitable for repair of existing bridges that were not designed for the extra dead load. Some sheet membranes may not bond well to concrete, or may debond at later dates if exposed to heat and sunlight, which creates vapor pressure and weakened bond due to temperature. Liquid-applied membranes may require special expertise. Some jurisdictions require warranties on membrane installation.

13.4.3.1 -- Wearing courses are generally asphaltic concretes. The design of such courses is beyond the scope of this standard practice.

An AC overlay should not be used directly on a portland cement concrete deck without a waterproofing membrane. All AC mixtures are inherently porous and readily conduct water and chlorides to the portland cement concrete deck where they cannot be flushed off. Such impounded brine greatly accelerates bridge deck deterioration which is then difficult to observe or measure below the asphalt. The permeability of AC greatly increases with age.

13.5 Design considerations

For Type I, and most Type II overlays, no special design considerations are usually necessary for the concrete bridge deck. On the other hand, for some Type II and all Type III overlays, the designer must carefully consider several details.

Thick concrete overlays, and membrane and AC systems may increase the dead load on an existing deck. If so, structural design calculations should be reviewed, particularly on long-span structures.

In addition, a thick concrete or an asphalt overlay may require raising the bridge deck joints and surface drainage facilities to meet the new grade. The raised end joints, together with the effect of the bridge curbs, may create a void into which the overlay is placed. While water which permeates this wearing course should not affect a properly constructed interlayer membrane, it could, on freezing, disrupt the wearing course itself. For this reason, some designers prefer to install small diameter subsurface drains to conduct the water that ponds below the asphalt through the deck slab. To prevent the leakage from causing deterioration of the deck underside, the drains should extend slightly below the deck or be surrounded by a drip groove. They should also be located so as to miss dripping on the supporting girders, or they may be extended to drip below the level of the girders.

13.6 Construction considerations

13.6.1 Deck construction to accommodate overlays -- Where the use of overlays is anticipated, texturing of the
portland cement concrete surface may be unnecessary. Sheet membranes generally bond better to smooth concrete, while thin overlays may bond better to the roughness created by light brooming.

Manufacturer’s recommendations should be consulted. For Type II and Type III overlays, deck surface tolerances for screeding and flatness need be less stringent than where Type I or no overlays are anticipated. Minor irregularities in profile and cross-slope can be corrected by the subsequent concrete or AC overlay.

Some curing compounds may inhibit the bond strength between Type I and Type II overlays and the deck surface. Where such materials are used, sandblasting or shotblasting should be required before applying the overlay.

13.6.2 Constructing the overlay -- Nearly all Type I and Type II overlays require scrupulous cleaning of the deck surface prior to application. Sandblasting, shotblasting, or waterblasting are generally preferred, although waterblasting is not recommended prior to applying most polymer materials. Manufacturer’s recommendations should be checked. Shotblasting involves less risk or human error than sandblasting and is often preferred. Surface preparation for Type III overlays is also dependent on the kind of membrane selected. Resinous membranes for Type III overlays may require the same degree of surface preparation as Type I and Type II overlays. Bitumen membranes may require only careful sweeping.

The degree of surface dryness required for Type I and Type II overlays is dependent on the type of membrane material. Most epoxies will not bond well to a moist surface. Asphalt also will not bond well to a wet surface. In contrast, the emulsions often used with reinforced membrane systems may bond better to a moist surface than to a dry one. Manufacturer’s instructions should be consulted.

Type II overlays generally bond best to surfaces that are saturated-surface-dry. For low slump, dense concrete overlays, a bonding slurry of cement and water is broomed on just ahead of the concrete placement.

The ambient temperature is significant for nearly all overlays. Virtually all common materials require temperatures above freezing, and most above 40 F, to effect proper cure. One exception is the prefabricated sheets.

In the absence of specific information, a good rule of thumb is that all overlays bond best to a clean, dry (except emulsions), and warm deck.

13.6.2.1 -- Type I overlays may be applied by spraying or pouring the liquid binder, followed by spreading and back-rolling. Aggregates are then cast over the surface. Another method is to premix the aggregates and binder, and screed the overlay, sometimes in narrow longitudinal strips. Sometimes the premix system is preceded by a primer coat.

13.6.2.2 -- Type II overlays are usually applied by screeding in place. Low-slump overlays require mobile concrete mixers and special screeds. Other overlays placed at 2- to 4-in. slump involve conventional screeds. High-amplitude air screeds or the use of air screeds with mix slumps higher than 4 in. are not recommended due to their effect on the concrete air void system and resulting freeze-thaw durability of the overlay. Superplasticized concrete overlays should not be overvibrated or overfinished, to avoid durability problems.

13.6.2.3 -- Type III overlays are constructed according to the kind of membrane used. Membranes similar to Type I overlays are applied as in Section 13.6.2.1. Bitumen membranes are similarly applied except that mesh, usually of fiberglass, may be embedded rather than aggregate. Some types of prefabricated sheets are rolled in place after applying a suitable tack coat. Emulsion-based tack coats are preferred, since volatiles from asphalts may cause blistering in the sheets. Water vapor freed from emulsions may also cause blistering if adequate time is not permitted for the emulsion to cure properly. Some types of sheet membranes are applied by using torches to melt the bottom layer as the sheet is
rolled in place.

Wearing courses are placed, using conventional rubber-tired equipment and care so as not to damage the membrane. Many bitumens used in built-up, mesh-reinforced layers are vulnerable to damage and may require hand application of a binder course, followed by the surface wearing course.

13.7 Other considerations

Not all bridges have the same design and exposure conditions, so the resulting bridge deck problems are not always similar, and neither are the solutions. Several factors should be considered when choosing an overlay.

13.7.1 Geographic and climatic factors -- Annual rainfall, maximum and minimum expected temperatures, annual ranges of humidity, and annual number of freeze-thaw cycles are all significant factors relating to expected service life that vary from region to region. Dry climates generally result in greater shrinkage and cracking of Type II overlays. Warm, wet climates are conducive to rapid rates of steel corrosion. Cold climates create tensile stresses from temperature change and cause many materials to become brittle and fail when subjected to live load stresses. Salt may be present in the aggregates of some regions, or may come from bodies of saltwater or from deicing chemicals used in Northern regions. Abrasive surface wear may be greatly increased by the presence of studded tires or tire chains. Some regions are beginning to experience acid rain. Rates of carbonation also vary regionally. Both acid rain and carbonation lower the pH level of the concrete, which may result in increased reinforcing steel corrosion.

Chapter 14 -- References

14.1 Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation:

American Association of State Highway and Transportation Officials (AASHTO)

Standard Specifications for Highway Bridges

M31 Deformed and Plain Billet-Steel for Concrete Reinforcement
M284 Epoxy Coated Reinforcing Bars
T-26 Quality of Water to be used in Concrete

American Concrete Institute (ACI)

117 Standard Specification for Tolerances for Concrete Construction and Materials
201.1R Guide for making a Condition Survey of Concrete in Service

201.2R Guide to Durable Concrete
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
212.3R Chemical Admixtures for Concrete
214 Recommended Practice for Evaluation of Strength Test Results of Concrete
221R Guide for Use of Normal Weight Aggregates in Concrete
222R Corrosion of Metals in Concrete
223 Standard Practice for the Use of Shrinkage-Compensating Concrete
226.1R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
226.3R Use of Fly Ash in Concrete
304R Guide for Measuring, Mixing, Transporting and Placing Concrete
305R Hot Weather Concreting
306R Cold Weather Concreting
308 Standard Practice for Curing Concrete
309R Guide for Consolidation of Concrete
311.4R Guide for Concrete Inspection
318 Building Code Requirements for Reinforced Concrete
325.6R Texturing Concrete Pavements
503.3 Standard Specification for Producing a Skid Resistant Surface on Concrete by the Use of a Multi-Component Epoxy System
504R Guide to Joint Sealants in Concrete Structures
515.1R Guide to the Use of Waterproofing, Damp-proofing, Protective, and Decorative Barrier Systems for Concrete
548.1R Guide for the Use of Polymers in Concrete
SP-2 ACI Manual of Concrete Inspection
SP-4 Formwork for Concrete

ASTM

A 615 Steel Bars Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement
A 775 Specification for Epoxy-Coated Reinforcing Steel Bars
C 33 Specifications for Concrete Aggregate
C 94 Specifications for Ready Mixed Concrete
C 150 Specifications for Portland Cement
C 191 Test Method for Tie of Setting of Hydraulic Cement by Vicat Needle
C 231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 260 Specifications for Air-Entraining Admixtures for Concrete
C 309 Specifications for Liquid Membrane Forming Compounds for Curing Concrete
C 330 Specification for Lightweight Aggregates for Structural Concrete
C 403 Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C 457 Practice for Microscopical Determination of Air Void Content and Parameters of the Air-Void System in Hardened Concrete
C 494 Specification for Chemical Admixtures for Concrete
C 595 Specification for Blended Hydraulic Cements
C 618 Specification for Fly Ash and Raw or Calcined Natural Pozzolana for use as a Mineral Admixture in Portland Cement Concrete
C 666 Concrete made by Column Continuous Mixing
C 671 Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672 Test Method for Critical Dilation of Concrete Specimens Subjected to Freezing
C 682 Practice for Evaluation of Frost Resistance of Coarse Aggregate in Air Entrained Concrete by Critical Dilation Procedures
C 685 Specification for Concrete Made by Volumetric Batching and Continuous Mixing
C 806 Method of Test for the Restrainted Expansion of Expansive Cement Mortar
C 845 Specification for Expansive Hydraulic Cement
C 878 Test Method for the Restrainted Expansion of Shrinkage Compensating Concrete
D 3963 Specification for Epoxy-Coated Reinforcing Steel
E 274 Test Method for Skid Resistance of Paved Surfaces using a Full Scale Tire
E 329 Recommended Practice for Inspection and Testing Agencies for Concrete, Steel and Bituminous Materials as Used in Construction

The above publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
444 N. Capitol Street, N.W. - Suite 225
Washington, D.C. 20001

American Concrete Institute
P.O. Box 19150
Detroit, Michigan 48219

ASTM
1916 Race Street
Philadelphia, Pennsylvania 19103

14.2 Cited references

3. Woods, Hubert, Durability of Concrete Construction, ACI Monograph No. 4, American Concrete Institute/Iowa State University Press, Detroit, 1968, 190 pp.


42. Newlon, H.H., “Evaluation of Several Types of Curing and Protective Materials for Concrete --
345R-36


# APPENDIX A

## CONVERSION FACTORS----INCH-POUND TO SI (METRIC)*

<table>
<thead>
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<th>To convert from</th>
<th>to</th>
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</tr>
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<tr>
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</tr>
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<td>kip-force</td>
<td>newton(N)</td>
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<tr>
<td>pound-force</td>
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<tr>
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<td>kip-force/square inch (ksi)</td>
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<td>pound-force/square inch (psi)</td>
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### Bending moment or torque

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### Mass

| ounce-mass (avoirdupois)             | gram (g)            | 28.34       |
| pound-mass (avoirdupois)             | kilogram (kg)       | 0.4536      |
| ton (metric)                         | megagram (mg)       | 1.000E      |
| ton (short, 2000 lbm)                | megagram (Mg)       | 0.9072      |

### Mass per volume

| pound-mass/cubic foot                | kilogram/cubic meter (kg/m³) | 16.02       |
| pound-mass/cubic yard                | kilogram/cubic meter (kg/m³) | 0.5933      |
| pound-mass/gallon                    | kilogram/cubic meter (kg/m³) | 119.8       |

### Temperature

| degrees Fahrenheit (°F)              | degree Celsius (°C) | \( t_C = (t_F - 32)/1.8 \) |
| degrees Celsius (°C)                 | degree Fahrenheit (°F) | \( t_F = 1.8t_C + 32 \) |

*This selected list gives practical conversion factors of units found in concrete technology. The reference source for information on SI units and more exact conversion factors is “Standard for Metric Practice” ASTM E 380. Symbols of metric units are given in parenthesis.

+E Indicates that the factor given is exact.

± One liter (cubic decimeter) equals 0.001 m³ or 1000 cm³.

† These equations convert one temperature reading to another and include the necessary scale corrections. To convert a difference in temperature from Fahrenheit degrees to Celsius degrees, divide by 1.8 only, i.e., a change from 70 to 88 °F represents a change of 18 °F or 18/1.8 = 10 °C deg.