Guide for Construction of Concrete Pavements

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The primary focus of this guide is pavement construction. Modern slipform paving techniques and time-proven formed construction procedures are highlighted. Quality control, quality assurance, and construction inspection, as well as the environmental, economic, and societal benefits of concrete pavement, are also presented. This guide briefly reviews all aspects of concrete pavement construction for highways and, to some extent, local roads, streets, and airfields. Intended for field and office personnel, this guide provides a background on design issues that relate to construction and reviews material selection.

Note that the materials, processes, quality control measures, and inspections described in this guide should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI certifications or equivalent.

Keywords: concrete pavement; concrete pavement construction; concrete paving; fixed-form paving; paving materials; slipform paving; sustainability.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

In the United States, concrete pavements have been built for over a century. The first street constructed with concrete was built in Bellefontaine, OH, in 1891; a portion of which, built in 1893, still remains in service. Concrete pavements make up an integral part of the national primary and secondary highway system, farm-to-market road system, city streets, parking lots, and airport runways. Historically, concrete pavements have exhibited a higher initial cost than asphalt pavements, but recent construction and market forces have narrowed that gap. Moreover, the longer service life and lower maintenance costs associated with concrete make it a very attractive and sustainable paving material.

1.2—Scope

This guide briefly discusses the construction of hydraulic cement concrete pavements for highways, streets, local roads, and airfields. Design issues are presented in the context of their impact on construction. Today, the slipform method of paving is preferred for roadway construction. This modern construction method is capable of producing a sustainable, high-quality, smooth pavement that can be placed quickly and economically. This guide will focus on pavement constructed using slipform methods; however, where appropriate, formed pavement construction practices are also discussed.

This guide is intended to serve as a reference for field project management, inspectors, and construction personnel by providing background information, illustrations of best practice, and information helpful in solving day-to-day jobsite problems. Designers and specification writers will also find the guide helpful in preparing contract documents and selecting construction methods that assure quality construction under normal jobsite conditions using established and proven practices. Regardless of the type of equipment used, quality construction depends, in large measure, on the skill of crews involved in the construction process and quality of materials used.

CHAPTER 2—ACRONYMS AND DEFINITIONS

2.1—Acronyms

AAR: alkali-aggregate reactivity
ABS: anti-lock braking system
ACR: alkali-carbonate reactivity
ADTT: average daily truck traffic
ASR: alkali-silica reaction
ATB: asphalt-treated base
BPN: British Pendulum Number
BPT: British Pendulum Tester
CBR: California bearing ratio
COTE: coefficient of thermal expansion
CPX: close proximity
CRCP: Continuously reinforced concrete pavement
CT meter: circular texture meter
CTB: cement-treated base
CTE: coefficient of thermal expansion
DF tester: dynamic friction tester
EAC: exposed aggregate concrete
EICM: Enhanced Integrated Climatic Model
EOT: early-opening-to-traffic
FN: friction number
FWD: falling weight deflectometer
GPR: ground-penetrating radar
HPC: high-performance concrete
HRWR: high-range water reducers
HRWRA: high-range water-reducing admixture
IFI: international friction index
IRI: international roughness index
JPCP: jointed plain concrete pavement
JRCP: jointed reinforced concrete pavement
LCA: life cycle assessment
LCB: lean concrete base
LOI: loss on ignition
LTE: load transfer efficiency
LWAS: lightweight aggregate sand
M-E: mechanistic-empirical
MIT: magnetic imaging tomography
MOR: modulus of rupture
MPD: mean profile depth
MTD: mean texture depth
NCHRP: National Cooperative Highway Research Program
NDT: nondestructive testing
NGCS: next-generation concrete surface
OBSI: On-board sound intensity
PCC: portland cement concrete
PI: plasticity index
QA: quality assurance

QC: quality control
R-value: resistance value
SE: sand equivalent
SN: skid number
SPL: sound pressure level
SSD: saturated surface-dry
VPD: vehicles per day
VPM: vibrations per minute

2.2—Definitions

ACI provides a comprehensive list of definitions though an online resource, "ACI Concrete Terminology," http://www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that resource.

dowel—mechanical devices (such as bars or plates) placed across a joint to transfer vertical load while allowing the joint to open and close.

drainage—interception and removal of water from, on, or under an area or roadway.

equivalent single-axle loads (ESAL)—number of equivalent 80 kN (18 kip) single-axle loads used to combine mixed traffic into a single design traffic parameter for thickness design according to the methodology described in the AASHTO design guide (AASHTO 1993).

falling weight deflectometer—device in which electronic sensors measure the deflection of the pavement as a result of an impact load of known magnitude; results can be used to estimate the elastic moduli of subgrade and pavement layers and the load transfer across joints and cracks.

internal curing—a method to supply water throughout a freshly placed cementitious mixture using reservoirs, via prewetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation.

jointed plain concrete pavement—hydraulic cement concrete pavement system characterized by short joint spacing and no distributed reinforcing steel in the slab, with or without dowels.

jointed reinforced concrete pavements—hydraulic cement concrete pavement system containing dowels, characterized by long joint spacing and distributed reinforcing steel in the slab to control crack widths.

load transfer device—mechanical means designed to transfer wheel loads across a joint.

pavement structure—combination of subbase, base, rigid slab, and other layers designed to work together to provide uniform, lasting support for imposed traffic loads and distribution of loads to subgrade.

pavement surface friction—the retarding force developed at the tire-pavement interface that resists longitudinal sliding when braking forces are applied to the vehicle tires (Dahir and Gramling 1990; AASHTO 2008b).

shoulder—portion of the roadway contiguous and parallel with the traveled way provided to accommodate stopped or errant vehicles for maintenance or emergency use, or to give lateral support to the subbase and some edge support to the pavement, and to aid surface drainage and moisture control of the underlying material.

soil support value—index characterizing the relative ability of a soil or aggregate mixture to support traffic loads imposed through flexible and rigid pavement structures.

stabilization—the modification of soil or aggregate layers by incorporating materials that will increase load-bearing capacity, stiffness, and resistance to weathering or displacement, and decrease swell potential.

CHAPTER 3—DESIGN ISSUES RELATING TO CONSTRUCTION

3.1—Introduction

The overall goal of pavement design is to create a structure that is reliable, economical, constructible, and maintainable throughout its design life while meeting or exceeding the needs of the traveling public, taxpayers, and owning agencies (FHWA 2012). In general, the pavement structure should be able to support the expected level of traffic and resist weathering until the next scheduled rehabilitation or reconstruction.

3.2—Design principles

3.2.1 *Introduction*—Design and construction of the roadbed is key to the long-term performance of any pavement structure. A layer of materials that provides a foundation for the riding surface characterizes a roadbed. For concrete pavements, the foundation is typically composed of a base layer on top of the subgrade soil. Proper care and attention should be paid to design and construction of the subgrade and base layers to ensure structural capacity, stability, uniformity, durability, and smoothness of any concrete pavement over its design life. Concrete pavement slabs constructed over the subgrade should have adequate strength and durability to endure exposure to traffic loadings and environmental effects (ACPA 2007).

3.2.2 *Slab characteristics*—Pavement concrete typically has a 28-day flexural strength ranging from 550 to 750 psi (3.8 to 5.2 MPa) or greater, and an elastic modulus ranging from 4 to 6 million psi (28,000 to 41,000 MPa), which helps to provide a high degree of rigidity. This rigidity enables concrete pavements to distribute loads over large areas of the supporting layers. As a result, the stresses on the layers beneath the pavement slab are low.

3.2.3 *Influence of foundation strength on pavement thickness*—The degree of support provided by the foundation for a concrete pavement structure is typically quantified in terms of the modulus of subgrade reaction, or the *k*-value. The magnitude of increase in the *k*-value from the inclusion of base layers in the design of pavements depends on the material type. Normal variations in estimated subgrade or composite *k*-values would not appreciably affect pavement thickness for a typical range of *k*-values (100 to 500 psi/in. [27 to 136 MPa/m]). It is not economical to over-design the base layers for the sole purpose of increasing the *k*-value, as adequate structural designs can be achieved by other means (for example, increasing the slab thickness or concrete strength) (ACPA 2007).

3.2.4 *Influence of foundation stiffness on stresses and strains in concrete pavement slabs*—If a concrete pavement is placed either directly on the subgrade or on any number of base layers, the properties of these foundation layers will directly influence the stresses and strains in the concrete slabs and, in turn, will have an impact on the long-term performance of the pavement structure. If a concrete slab is in complete contact with the foundation, a stiffer support will result in reduced deflections and, thus, reduced stresses under heavy loads. Stiffer support systems, however, will increase deflections and stresses under environmental effects (thermal curling and moisture warping). If a concrete pavement is constructed on a very rigid foundation, the foundation might not conform to the shape of the slab and a significant increase in curling stresses can result.

Higher curling stresses have a more damaging impact when the concrete is relatively young and has not developed the strength required to resist cracking. If the stiffness of the base becomes too great, the curling stresses in the slab will increase, and the potential for midpanel cracking will also increase. The thicker the base layer is, the greater the increase in the support stiffness. The pavement design engineer should recognize that base thickness and stiffness are important properties in the foundation design process (ACPA 2007).

3.2.5 *Drainage*—Drainage is one of the most important factors in pavement design. Water enters the pavement structure either by surface infiltration through cracks, joints, pavement surfaces, and shoulders; or as groundwater from a high water table, aquifers, and localized springs. Where water is trapped within the pavement structure due to inadequate drainage, it reduces the strength of the pavement and subgrade, and also generates high hydrodynamic pressures that might pump out fine material under the pavement, resulting in loss of support. Aggregates used for drainage purposes should satisfy filter requirements. They should be fine enough to prevent the adjacent soil from migrating into them, but coarse enough to carry water with no significant resistance (Huang 2004). In many ways, the pavements built in the United States today, particularly those on interstate highways and routes, are less vulnerable to the detrimental effects of excessive moisture than pavements built in the past because of features such as widened concrete slabs, doweled joints, stabilized base layers, and higher-quality aggregates. Still, at sites with wet climates and poorly draining soils, the need for a subsurface drainage system should be considered. This is particularly true for pavement designs likely vulnerable to moisture-related distress, such as undoweled concrete pavements on untreated aggregate base layers.

3.3—Current design procedures

3.3.1 *PCA design methodology*—The Portland Cement Association (PCA) thickness-design procedure for concrete highways and streets (PCA 1984) can be applied to jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continually reinforced concrete pavement (CRCP). The PCA concrete pavement design procedure evaluates a candidate pavement design with respect to two potential failure modes: fatigue and erosion. The procedure was developed using the results of finite element analyses of stresses induced in concrete pavements by joint, edge, and corner loading. The analyses onsiders the degree of load transfer provided by dowels or aggregate interlock and the degree of edge support provided by a concrete shoulder. The PCA procedure, like the 1993 AASHTO procedure, employs the "composite" k concept in which the design k is a function of the subgrade soil k, base thickness, and base type (granular or cement-treated) (Huang 2004; Hall 2000).

3.3.2 *AASHTO design methodology*—The AASHTO design methodology is the most commonly used rigid pavement design method in the United States (AASHTO 1993). It is based on the empirical equations obtained from the AASHO Road Test, with modifications based on theory and experience. The empirical model for the performance of the JPCP and JRCP sections in the main loops of the AASHO Road Test predicts the log of the number of axle load applications (log W) as a function of the slab thickness, axle type (single or tandem) and weight, and terminal serviceability (Highway Research Board (HRB) 1962). This original model applies only to the designs, traffic conditions, climate, subgrade, and materials of the AASHO Road Test. It has been modified and extended to allow for the estimation of allowable axle load applications to a given terminal serviceability level for conditions of concrete strength, subgrade k-value, and concrete elastic modulus different than those of the AASHO Road Test. The AASHTO design methodology has also been extended to accommodate the conversion of mixed axle loads to equivalent single axle loads (ESALs) of 18 kip (80 kN) through the use of load equivalency factors (Huang 2004; Hall 2000).

3.3.3 *Mechanistic-empirical (M-E) design methodology*—The M-E design procedure uses mechanistic pavement responses such as stress, strain, and deflection; relates them to performance indicators such as cracking, faulting, and roughness; and calibrates them against the field data. The axle load spectra data, rather than ESALs, are used in this design procedure; climatic effects are also considered. An incremental damage concept is used in the M-E design procedure, where the damage is computed monthly and accumulated. The design life is divided into monthly increments and specific materials properties, traffic, and climatic data are used for each increment. The performance criteria considered are joint faulting and transverse cracking for JPCP, punchouts for CRCP, and the international roughness index (IRI) for both pavement types; JRCP is not included in the design methodology. Designs that meet the appropriate performance criteria at a chosen level of reliability are considered feasible from structural and functional standpoints and can be further considered for other evaluations such as life cycle cost analysis and environmental impacts (NCHRP 2004; AASHTO 2008a).

3.4—Critical design inputs for construction

3.4.1 *General*—The key input parameters in any concrete pavement design procedure related to construction are outlined (3.4.1.1 through 3.4.1.3).

Table 3.4.1.1—Subgrade soil types and approximate support values (ACI 330R)

Type of soil	Support	*k*, psi/in. (kPa/mm)	California bearing ratio	*R*	Soil support value
Fine-grained soils in which silt and clay-size particles predominate	Low	75 to 120 (20 to 32)	2.5 to 3.5	10 to 22	2.3 to 3.1
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130 to 170 (35 to 46)	4.5 to 7.5	29 to 41	3.5 to 4.9
Sand and sand-gravel mixtures relatively free of plastic fines	High	180 to 220 (49 to 60)	8.5 to 12	45 to 52	5.3 to 6.1

3.4.1.1 *Subgrade*—Although the *k*-value of the foundation (natural soil and embankment) can be measured by plate-bearing tests, it is usually estimated from correlations with soil type, soil strength measures such as the California bearing ratio (CBR), or by back-calculation from deflection testing on existing pavements (Table 3.4.1.1). The *k*-value is the primary subgrade design variable for concrete pavements (ACPA 2007).

3.4.1.2 *Base and subbase*—A base course provides a stable platform for construction of concrete slab, improves the smoothness achieved in the paving of the slab, could serve as a drainage layer, and protects the foundation from frost penetration. Some types of bases also significantly reduce bending stresses and deflections in the slab and improve load transfer at joints and cracks. The estimated elastic modulus of the base, its erodibility, its potential for friction and bond with the concrete slab, and its drainability are factors considered in characterizing the support to the concrete slab and the quality of subsurface drainage (ACPA 2007).

3.4.1.3 *Concrete material properties*—For the purpose of pavement thickness design, concrete is characterized by its flexural strength as well as its modulus of elasticity. Concrete flexural strength is usually characterized by the 28-day modulus of rupture (MOR) from third-point loading tests of beams, or it may be estimated from compressive strengths (Eq. (3.5.3.3)). The corresponding elastic modulus *E* can also be measured, but is usually estimated from strength data. In addition to its strength and stiffness, durability of concrete mixture is important to the long-term performance of the pavement (Hall 2000).

3.4.2 *Subgrade considerations*

3.4.2.1 *Load-bearing capacity*—Design methods were devised based on tests that provided an index number related to soil strength that was most commonly considered to represent the shear strength. Some of these test methods and their associated index values are discussed in this section (ACPA 2007).

3.4.2.1.1 *California-bearing ratio (CBR) test*—The CBR test measures the force required to penetrate a soil surface by a circular piston with a 3 in.^{2} (19 cm^2) piston area. The index (CBR) value is the percent of an established reference value for 0.1 and 0.2 in. (2.5 and 5.0 mm) penetration. The reference value of 100 was originally considered to represent the resistance of a well-graded crushed stone. Methods of preparing specimens and conducting the test are given in AASHTO T193 and ASTM D1883.

3.4.2.1.2 *Resistance value (R-value) test*—The *R*-value test is a measure of the material stiffness by way of resistance to plastic flow. This laboratory test was developed as an improved CBR test. Samples are prepared to represent the worst-case scenario during testing and are confined on all sides in the testing apparatus, resulting in a triaxial state of stress. The *R*-value is the ratio of the vertical load applied to the resultant lateral pressures. Standard *R*-value test methods are described in AASHTO T190 and ASTM D2844/D2844M.

3.4.2.1.3 *Resilient modulus of subgrade soil*—The stiffness, as an estimate of the modulus of elasticity, *E*, is measured by this test. The modulus of elasticity is the ratio of stress applied to the strain produced for a slowly applied load. The resilient modulus is the stress divided by the strain for a rapidly applied load. The standard resilient modulus test is given in AASHTO T307.

3.4.2.1.4 *Modulus of subgrade reaction (*k*-value)*—This bearing test, conducted in the field, provides an index to rate the support provided by a soil layer directly beneath the concrete slab. Most concrete pavement design is based on the *k*-value, as used in the Westergaard (1933) equations. The *k*-value is defined as the reaction of the subgrade per unit area of deformation and is typically given in psi/in. (kg/cm^3). Details on conducting the plate-bearing field tests are given in AASHTO T221 and T222 or in ASTM D1195/D1195M (repetitive test) and D1196/D1196M (no repetitive test). The elastic *k*-value (k_e), as determined from the repetitive plate-bearing test (ASTM D1195/D1195M) is a higher value because it considers only the elastic deformation in the *k*-value computation.

Because of slow productivity in conducting plate-bearing tests and their relatively high costs and labor intensiveness, very few agencies routinely conduct them. Instead, most agencies obtain *k*-values through correlations with other properties or through the back calculation of deflection data using the falling weight deflectometer (FWD). The use of the FWD enables collection of a large number of data points that can help evaluate the subgrade variability over a project.

3.4.2.1.5 *Cone penetrometer*—A cone penetrometer is a device used to measure the strength of in-place soil. The test results can be used to estimate the soil shear strength, CBR, and *k*-value. Because these tests are rapid and essentially nondestructive, they are ideally suited for on-site construction, and testing over large areas can evaluate uniformity. The penetrometer is driven into the ground at either a constant rate or by dropping a specific hammer over a given distance. The measured values (load needed to drive the penetrometer or blow counts per unit of depth) are then correlated to CBR, shear strength, or soil modulus value. Profiles of the changes in soil strengths across the project area can be obtained by plotting the load or blow counts versus depth. This can be