An *IPRF* Research Report

Innovative Pavement Research Foundation

Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-02-1

Stabilized and Drainable Base in Rigid Pavement Systems – Report of Findings

Programs Management Office
5420 Old Orchard Road
Skokie, IL 60077

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Stabilized and Drainable Base in Rigid Pavement Systems – Report of Findings

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The base layer in a rigid pavement system plays an important role in the short- and long-term performance of the pavement. The functions of the base layer include providing a stable construction platform, providing uniform support for Portland cement concrete (PCC) pavement slabs, preventing pumping and joint faulting, providing subsurface drainage in the case of drainable bases (referred to herein as permeable bases), and reducing detrimental frost effects.

Various types of base layers are recommended for use on airfield pavements by the Federal Aviation Administration (FAA) Advisory Circular (AC) for Pavement Design (FAA Advisory Circular [AC] 150/5320-6D). These include unbound granular, chemically stabilized (cement and asphalt), pozzolanic, and mechanically stabilized materials. The focus of this research study, however, was limited to the following base materials:

Stabilized Layers
- Cement-treated base (CTB) (Item P-304).
- Econocrete base or lean concrete base (LCB) (Item P-306).
- Asphalt-treated base (ATB) (Item P-401).

Permeable Layers
- Unbound permeable base (UPB).
- Cement-treated permeable base (CTPB).
- Asphalt-treated permeable base (ATPB).

FAA AC 150/5320-6D requires that stabilized base layers be provided beneath all PCC pavements that are designed for aircraft gross loads of 100,000 lb (45,250 kg) or greater. Most civil airport pavement construction work in the U.S. is performed in accordance with FAA AC 150/5370-10A, *Standards for Specifying Construction of Airports*. The Circular provides guidance on cement-treated, econocrete, and asphalt-treated base layers, referred to as Items 304, 306, and 401, respectively. However, in the case of permeable layers, the Circular provides little guidance even though permeable layers are used in civilian airfields on a routine basis.

1.2 RESEARCH OBJECTIVES

The research study looked at two main objectives:

- Identify criteria being used by pavement engineers to design and specify the qualities and characteristics of stabilized and/or permeable bases consistent with satisfactory pavement performance.

- Present the criteria as a design and construction procedure, published in the form of a practical guide, for the use of stabilized and permeable materials as a base for rigid pavements. This guide will document practices and acquaint the pavement engineer and the builder with criteria that will balance pavement thickness, strength, and other design and construction aspects when using stabilized or permeable bases.

To summarize the scope of work for this project, it is to (a) examine the state-of-the-practice regarding the design and construction of stabilized and permeable bases, (b) identify the design and construction practices that lead to satisfactory pavement performance and prepare guide specifications, (c) verify the effectiveness of the recommended specifications by constructing actual test pavement sections, and (d) develop final project documentation and instructional materials (i.e., Design and Construction Guide, Advisory Circulars) for use by airfield pavement designers and builders.

The term "performance" in this study refers specifically to the short-term performance of the rigid pavement system, as defined by the time frame in which a newly constructed (non-warranted) pavement is still under the control of the Contractor. While this period may vary, it is generally in the order of 3 months. The short-term performance attribute of interest is the occurrence (or non-occurrence) of early-age or premature slab cracking, brought on too frequently by inadequate design and/or construction of the stabilized and/or permeable base layer.

1.3 DEFINITIONS OF KEY TERMS

The meanings of key terms in this report are included. Many of the terms were borrowed from the *Best Practices for Airport Portland Cement Concrete Pavement Construction (Rigid Airport Pavement)* report (Kohn et al., 2003) and from other FAA, Department of Defense (DOD), and Federal and State highway agency publications, as necessary.

1.3.1 Concrete Pavement

The term concrete pavement in this report refers to jointed concrete pavements and, more specifically, short-jointed plain concrete (JPC) pavements specified and constructed in accordance with Item P-501 of the FAA Advisory Circular AC-5370-10. In instances where short-jointed reinforced (JRC) pavements are being discussed, they will be explicitly mentioned.

1.3.2 Base and Subbase Layer

Base and subbase are often used interchangeably in concrete pavement literature to mean the layer immediately below the PCC layer. In this report, the layer immediately below the slab is referred to as the base layer. The layer or layers between the base and the subgrade are referred to as subbase.

1.3.3 Cement-Treated Base (CTB) Course

CTB is a high-quality base course prepared from mineral aggregate and cement uniformly blended and mixed with water and specified and constructed in accordance with Item P-304 of FAA AC-5370-10. CTB materials are nominally designed for a 7-day compressive strength of 750 lb/in^2 (5,170 kPa).

1.3.4 Econocrete or Lean Concrete Base (LCB) Course

Econocrete or LCB consists of aggregate and cement uniformly blended together and mixed with water and specified and constructed in accordance with Item P-306 of FAA AC-5370-10. The term econocrete is used because the materials used are of marginal quality as compared to PCC. These mixtures typically contain 2 to 3 bags of cement per cubic yard of material and are specified to have a minimum 7-day compressive strength of 750 lb/in^2 (5,170 kPa) and maximum 28-day compressive strength of 1,200 lb/in^2 (8,275 kPa).

1.3.5 Asphalt-Treated Base (ATB) Course

An ATB consists of aggregate and bituminous materials mixed at a central mixing plant. This layer is currently specified and constructed in accordance with Item P-403 that is currently published under FAA AC 150/5370/10B.

1.3.6 Permeable Base Course

A permeable base is an open-graded drainage layer with a typical laboratory permeability value of 1,000 ft/day (305 m/day) or greater. The primary function of this layer is to dissipate water infiltrating the pavement surface by moving it laterally towards the edge of the pavement within an acceptable timeframe. Currently there are no FAA specifications that directly deal with these layers.

Permeable bases can be asphalt-treated (ATPB), cement-treated (CTPB), or unbound (UPB), depending on construction and structural requirements. An ATPB typically has approximately 2 to 3 percent asphalt binder mixed with crushed, durable, open-graded aggregates. A CTPB typically contains 2 to 3 bags of portland cement per cubic yard and also uses crushed, durable, open-graded aggregates.

CHAPTER 2. LITERATURE REVIEW

2.1 OVERVIEW

The specific material types of interest in this study were CTB, econocrete, ATB, UPB, ATPB, and CTPB. In order to fully understand the impact of the base layer on the early-age performance of rigid airfield pavements, a review was made of existing literature addressing the design, construction, and specifications of stabilized and permeable layers beneath airfield PCC pavements. The review focused the experiences of the various agencies or researchers with the base types of interest in this study.

The literature review encompassed the following sources of information:

- The Federal Aviation Administration (FAA) and the Department of Defense (DOD) publications (including those from the U.S. Army Corps of Engineers [USACE], Air Force, and Navy), Portland Cement Association (PCA), American Concrete Pavement Association (ACPA), and State highway agencies.
- Searches of internet-based library systems (e.g., the University of Illinois, U.S. Army Corps of Engineers, the Transportation Research Information Service [TRIS], National Technical Information Service [NTIS], and Compendex databases).
- Previous research of the Innovative Pavement Research Foundation (IPRF) and FAA.
- Published proceedings of the American Society of Civil Engineers (ASCE), the Transportation Research Board (TRB), the Federal Highway Administration (FHWA), the International Society for Concrete Pavements (ISCP), and other agencies.

A detailed summary of the findings from the literature review is presented in this chapter. It was obvious at the outset of the literature search that base type is only one of the factors affecting early-age performance of airfield PCC pavements. Therefore, the summary was expanded to include this and other relevant factors.

2.2 ROLE OF STABILIZED AND PERMEABLE BASE LAYERS IN AIRFIELD PAVEMENT DESIGN

There is a broad consensus among airfield pavement engineers that a uniform and durable base is essential for ensuring the long-term performance of a rigid pavement. The main functions of the base layer are as follows:

- Provide a stable construction platform.
- Provide a uniform, long-term support for the pavement while in service.
- Distribute applied loads to the underlying layers including the pavement subgrade.
- Aid in providing subsurface drainage due to infiltration of precipitation or ingress of frost-melt or spring-thaw bleed water (in the case of permeable bases).
- Provide frost protection (where required).

The prominence and importance of the base layer increases corresponding to the importance of the structure being designed. For example, to ensure that the key structural design requirements are satisfied, the FAA requires the use of stabilized bases (ATB, CTB, econocrete) for all new rigid airfield pavements that will be required to support aircraft weighing 100,000 lbs (45,250 kg) or greater (FAA, 1995). The various departments of the military (Army, Air Force, Navy, Marine Corps) also allow the use of stabilized layers in pavement structural design (UFC, 2001).

2.2.1 Incorporation of Stabilized and Permeable Layers into Design

Stiff base layers, such as CTB and econocrete, add to the flexural stiffness of rigid pavement structures and help transmit loads across discontinuities (joints and cracks) in the pavement slabs. Therefore, they enhance the load-carrying capacity of concrete pavements. The structural benefit imparted to a pavement section by a stabilized base is reflected in the FAA design procedure in the modulus of subgrade reaction (k) assigned to the foundation. The k-value of the foundation is adjusted upward based on the thickness of the stabilized base—the higher the base thickness, the higher the k-value and consequently, the lower the required thickness of the overlying rigid pavement. However, an upper limit of 500 lb/in^2/in (136 kPa/mm) is placed on the k-value because values greater than this are usually not reliable due to the difficulty in reading deflections.

The procedures of the Army and the Air Force use the modulus of elasticity of the base as a means to incorporate the effect of the stabilized base on structural thickness design. The latter procedures also allow for structural benefits to be drawn from drainage layers if used under PCC slabs.

The FAA rigid airfield design procedure is based on mechanistic-empirical (M-E) considerations of load-induced flexural fatigue, as well as the procedures of the Army, Air Force, and Navy. It is noteworthy that none of the procedures directly consider the effects of temperature and moisture (curling and warping) on pavement thickness design. These effects are considered indirectly through field calibration of the theoretical fatigue model, application of a design "safety factor," and the guidance provided on joint spacing, slab length to width ratios, and jointing.

2.3 EARLY-AGE DISTRESS OBSERVATIONS IN RIGID AIRFIELD PAVEMENTS

The problem of early-age or premature cracking, as defined in this research, seems to have caught the attention of the industry in recent times. This is perhaps partly due to the increased number of incidences of this problem in the recent past (ACPA, 2002a), increased awareness of the problem, and the increased intolerance towards it from contractors, designers, program managers, and owners—the principal stakeholders involved with airfield construction and operations.

It was difficult to find many documented cases of premature failures through a review of published literature. Perhaps one of the reasons for this is that early-age cracking, in most cases, occurs while a construction project is still under contractor control and the affected slabs are dealt with in the most expedient manner possible at the time (typically, removal and replacement). The priorities during construction do not afford adequate time for a detailed forensic investigation. Nonetheless, there is adequate anecdotal/empirical evidence and a wealth of theoretical information that establishes a consensus that when certain design, materials, construction, and climatic factors align themselves in a particular fashion, early-age distresses can occur. Therefore, it becomes necessary to devise ways to effectively mitigate this problem.

Early-age cracking, on any given project, can take any of the following forms (Kohn et al., 2003):

- Plastic shrinkage cracking (series of shallow cracks with a specific orientation).
- Random cracking (random orientation).
- Longitudinal cracking (cracking parallel to the centerline of the feature being investigated).
- Transverse cracking (cracking perpendicular to the centerline of the feature being investigated).
- Corner cracking (cracking located at the PCC slab corner intersecting the longitudinal and transverse joints).
- Pop-off cracks (cracking that happens just ahead of the sawing operation).
- Later stage cracking (early-age slab bottom cracking propagating to the surface).
- Sympathy cracks (cracking that occurs in adjacent slabs when joints between the slabs in questions are not aligned during new construction).
- Settlement cracks over dowel or tie bars.
- Re-entrant cracks.

In general, the amount of premature cracking that may result on any given project is anywhere from 1 to 5 percent of the total project (more frequently in the 1 to 2 percent range). Furthermore, very rarely does it continue to occur year-after-year on a multi-phased project. In fact, even within the same project, it may or may not appear on all paving days. This would indicate that a confluence of exacerbating factors needs to be present for the cracking to occur. The key is to study those factors that are considered to contribute to the highest risk of early-age cracking and deal with them as practically as possible during specification, design, and construction.

Kohn et al. (2003) developed the decision tree shown in table 1 to identify the most probable cause(s) of the types of cracking discussed above. This table is largely based on experience and empirical observation. Based on this table and other similar literature, the following factors can be considered as the major causes of premature cracking:

- High strength or thick stabilized bases.
- Degree of restraint between PCC slabs and base.
- PCC slab jointing (panel size dimensions and sawing operations).
- Texture of the base.
- Concrete mixture design in the PCC slab.
- Weather and ambient conditions prevalent during the construction of the PCC slab.

The following subsections describe the impact of each of these factors individually. Their combined effect and the types of cracking they can produce are presented in table 1. It should be noted, however, that one factor may dominate the early-age performance for a given situation.

2.3.1 Impact of Base Thickness and Strength

A major contributor to this factor in recent times is believed to be the presence of very thick or very stiff subbases. The cause appears to be associated with the wrongly held notion that "thicker and stronger means better," which does not necessarily hold true for concrete pavements (ACPA, 2002a). It is easy to see why this axiom has come into being in the first place by examining the specification-related aspects and some of the issues surrounding the construction of stabilized bases.

As an example, the current FAA design procedure does not account for temperature and moisture stresses in a direct manner in PCC slab thickness design. As a result, increasing the thickness of the base layers always results in an increase in the slab support value (k-value) and therefore a resulting decrease in PCC slab thickness; this is particularly true for stabilized bases, such as CTB and econocrete. However, if temperature and moisture curling/warping stresses are taken into account in thickness design, an increase in k-value could increase slab stresses and therefore may require a more substantial design to overcome them.

Similarly, CTB layers are designed for a minimum 7-day compressive strength of 750 lb/in^2 (5,170 kPa). This strength requirement was established because at this strength level, the long-term durability of the CTB layer when subject to repeated cycles of wetting and drying or freezing and thawing is virtually assured, as shown in figure 1 (PCA, 1992). As can be seen in this figure, the 750 lb/in^2 (5,170 kPa) value corresponds to approximately 99 percent of the specimens passing the rigorous ASTM D 559 and D 560 freeze-thaw and wet-dry testing.

There is a lot of debate over whether a typical stabilized base layer located under a thick airfield concrete pavement undergoes the number of freeze-thaw and wet-dry cycles this test represents or if the impact of this is certainly true of CTB and econocrete layers, which continue to gain strength over time due to continued hydration of the PCC. While durability is a long-term goal in design to avoid pumping and faulting problems under PCC pavement, there is certainly a need to balance durability requirements specified using strength as a basis with their impact on early-age performance.

Table 1. Decision tree to identify causes for early-age cracking (Kohn et al., 2003).

Cracking Type	Plastic Shrinkage	Random Cracking (No orientation)	Longitudinal Cracking	Transverse Cracking (partial or full width)	Corner Cracking	Cracks Just Ahead of Sawing (Pop-off Cracks)	Late Cracking (after about 7 days to about 60 days or before aircraft loading)	Sympathy Cracks	Settlement Cracks over Dowel or Tie Bars	Re-entrant Cracks
Possible Causes	High rate of Evaporation - Warm temp. - Low humidity - Windy	Slab to base bonding	Late sawing for prevailing conditions	Late sawing for prevailing conditions	Early loading	Late sawing for prevailing conditions	Early-age slab bottom cracking finally becoming visible	Joints in paved lane do not match joints in adjacent lanes	Higher slump Concrete	Use of odd-shaped slab panels
	Dry concrete mix	Concrete slab friction against rough base or concrete penetration into open-graded base	Shallow sawing of longitudinal contraction joint in relation to **actual** slab thickness	Shallow sawing of transverse contraction joints in relation to **actual** slab thickness	Excessive curling and warping due to temperature changes or moisture loss	Sawing against high wind	Frost heave	Different joint cracking patterns in adjacent lanes	Shallow dowel bars or tie bars	Rigid penetrations (in-place structures)
	Dry aggregates	Reflection cracking (from base cracking)	Slabs too wide in relation to thickness & length	Slabs too long in relation to thickness & width	Dowel bars too close to each other at transverse and longitudinal joints		Foundation settlement	Joints match in location but not in type	Delay in setting time	
	Late or inadequate curing	Temperature drop due to sudden cold front or rain	Temperature drop due to sudden cold front or rain		Late or inadequate curing					
	Delay in finishing	Late sawing for prevailing conditions	Misaligned or bonded dowels in adjacent longitudinal joints preventing cracked joints to function	Misaligned or bonded dowels in adjacent transverse joints preventing cracked joints to function	Misaligned or bonded dowels in adjacent transverse joints preventing cracked joints to function					

Table 1. Decision tree to identify causes for early-age cracking (Kohn et al., 2003) (continued).

Cracking Type	**Plastic Shrinkage**	**Random Cracking (No orientation)**	**Longitudinal Cracking**	**Transverse Cracking (partial or full width)**	**Corner Cracking**	**Cracks Just Ahead of Sawing (Pop-off Cracks)**	**Late Cracking (after about 7 days to about 60 days or before aircraft loading)**	**Sympathy Cracks**	**Settlement Cracks over Dowel or Tie Bars**	**Re-entrant Cracks**
Possible Causes	Temperature drop due to sudden cold front or rain	Shallow sawing of Contraction joints in relation to **actual** slab thickness	Excessive curling/ warping	Excessive curling/warping						
	Material incompatibility leading to higher concrete shrinkage and delay in setting time	Poor aggregate gradation (sand too fine; gap gradation)	Poor aggregate gradation (sand too fine; gap gradation)	Retarded concrete						
	Poor aggregate gradation (sand too fine; gap gradation)		Early loading							
			Infill lane restraints	Poor aggregate gradation (sand too fine; gap gradation)						
			Late or inadequate curing	High-shrinkage concrete						
			High-shrinkage concrete	Early loading						
			Slab to base bonding							
Investigative Techniques	Check quality of curing compound	Obtain cores through base to check slab to base Bond	Obtain core to check depth of cracking & aggregate breakage	Obtain core to check depth of cracking & aggregate breakage	Obtain core to check depth of cracking & aggregate breakage				Check dowel depths using a covermeter or GPR or by coring	
	Check quality of curing compound	Check quality of curing compound	Check quality of curing compound	Check quality of curing compound						

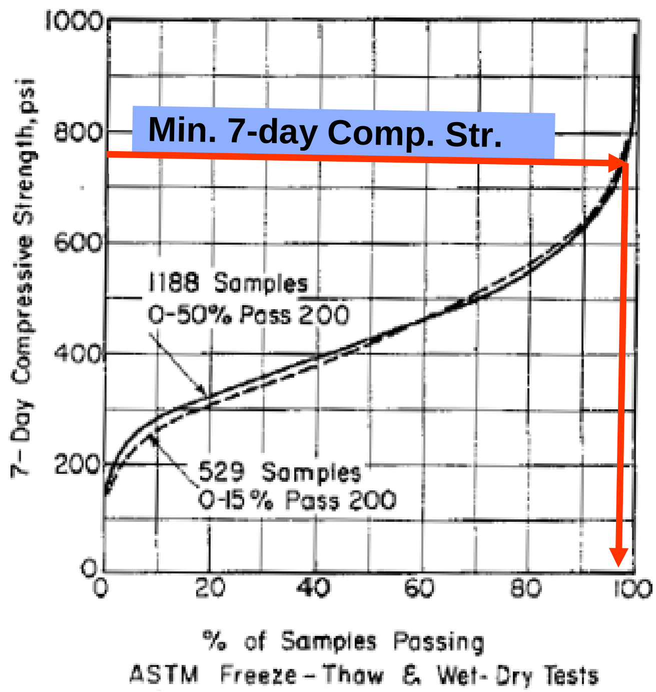

Figure 1. Relationship between strength and durability for CTB (PCA, 1992)

If mixtures designed at higher-strength levels are achieved, steps to avoid random cracking in the base must be taken, since the cracks can reflect into the PCC surface layer. However, this is seldom practiced because the material is accepted based on a minimum density requirement, which sometimes results in very high-strength bases. Furthermore, on some jobs, there is an eagerness on the part of contractors to achieve strengths much greater than the minimum specified to expedite construction. High strength bases increase the slab support value (k), leading to higher curling stresses in the slab. These higher curling stresses have a more damaging impact when the concrete is relatively young. CTB layers with greater than 4 to 5 percent cement also tend to develop shrinkage cracks (Grogan et al., 1999) which can then reflect into PCC slabs.

Arguments similar to those discussed for CTB can also be made for thickness or stiffness of econocrete layers. When combined with thickness, the magnitude of the effect of increased slab support on curling stresses multiplies.

In some cases, the higher base stiffness does not result from a misapplication of the specification. It could simply be due to construction sequencing or the prevalent environmental conditions.

Where the stiffness or strength of the CTB or econocrete base cannot be controlled, it is recommended that joints be made in the base to prevent uncontrolled cracking. In Europe (particularly in Germany), this practice has been used successfully over the past two decades (FHWA, 1992). The current FAA P-306 specification allows this as an option to the Contractor.

Case Studies

Herman (1991)

In summarizing his experience with premature cracking related to high-strength bases, Herman stated that the when using cement-stabilized bases under rigid airfield pavement, adequate attention should be paid to control the strength of the material. Among two projects mentioned by Herman was a 10,500-ft (3,202-m) long by 200-ft (61-m) wide runway section, presumably built in the early 1990s. The slab dimensions were 20 ft by 20 ft (6.1 m by 6.1 m). The slab foundation consisted of a 6-in (152-mm) thick CTB on top of a non-cohesive sand subgrade. The longitudinal joint system included doweled, keyed and tied joints, whereas the transverse joint system was comprised of only aggregate interlocking, except at the runway ends were dowels were placed.

Herman reported an interesting experience with CTB construction. During a significant delay between the construction of slab and base, the compressive strength of the base increased to 2,000 lb/in^2 (13,790 kPa), whereas the design value was only 750 lb/in^2 (5,170 kPA) at 7 days. A few unplanned transverse cracks developed, even though an asphalt bond breaker was placed between the slab and base. Almost all of the cracks occurred on the thinnest pavement sections.

The base material in the cracked areas was more similar to concrete than CTB. The base material was mixed in the concrete mixer at the central plant, after the Contractor discontinued the use of the pug mill. Herman attributed the contraction cracks to the location of the construction joints in the CTB. He suggested that the CTB joints be located exactly under the joints of the concrete slabs. Another recommendation was to place the slab shortly after the placement of the base. If a significant period (e.g., more than 90 days) occurs between the placement of the slab and base, the base should be sawcut to avoid reflection cracks.

This particular case study pointed out the necessity to either control the strength of the base or to sawcut joints in the base to coincide with joints in the slabs.

Grogan et al. (1999)

Grogan et al. performed a study to investigate the in-service performance of pavements that contain stabilized bases. This study included field surveys and non-destructive testing performed on pavement sections at the following locations:

- Atlanta International Airport (ATL) in Atlanta, Georgia.
- Dallas/Fort Worth International Airport (DFW) in Dallas, Texas.
- John F. Kennedy International Airport (JFK) in New York City, New York.
- Sky Harbor International Airport (PHX) in Phoenix, Arizona.
- Stapleton International Airport (DEN) in Denver, Colorado.

The evaluation was done several years into the design lives of the selected sections and therefore does not strictly conform to the scope of this report. However, the following observations from the Grogan study are of direct relevance to this report:

- The strength and stiffness of the CTBs at the airports studied were very high. This makes it very difficult to differentiate the stabilized layer, in terms of modulus values, when conducting a non-destructive evaluation based on data collected with a falling weight deflectometer (FWD) or heavy weight deflectometer (HWD) device. The high strength/stiffness values also indicate that the PCC layers may have been behaving more as a bonded overlay on the stabilized layer rather than a PCC layer resting on a separate stabilized layer.
- From the reconstruction at DFW and maintenance work at other airfields, it appears that current methods of constructing a bond breaker (i.e., application of asphalt emulsion without regard to the time of application) to prevent a bond from forming between the PCC and the underlying stabilized layer, do not perform adequately. In general, the stabilized layer is bonded to the PCC and a slippage plane or horizontal crack develops below the PCC-stabilized layer interface.
- The crack pattern observed in all of the CTBs followed the crack/joint pattern in the overlying PCC layer. Other cracking, which could have been shrinkage cracking that formed at the time of construction, was present in some of the CTBs.
- In general, the results of the condition survey data from DFW did not indicate a difference in the PCC surface condition in areas where the CTB was in poorer condition.

2.3.2 Impact of Degree of Restraint

Like most materials, the nature of concrete is that expansion and contraction occur as a function of the applied "through-thickness" temperature or moisture variations. The degree of movement and the associated tensile stresses developed as a result of these changes are directly governed by the applied temperature and moisture variation, thermal and mechanical properties of concrete, self-weight of the concrete, and the restraint provided at the slab-base interface.

Concrete slabs crack when tensile stresses within the concrete exceed the concrete's tensile strength (ACPA, 2002b). Joints are provided in concrete pavements to relieve excessive stress build-up and to prevent random cracking. However, uncontrolled cracks can still occur in "green" concrete due to stresses driven by volumetric shrinkage and temperature particularly when poor materials, long joint spacing, inadequate or mistimed sawcutting, stiff bases, and rough slab-base interfaces are involved. Rough slab-base interfaces promote a higher degree of friction, which causes excessive axial restraint to volumetric shrinkage and to thermal expansion and contraction.

<u>Types of Friction</u>

Many research projects have been conducted to understand the cracking mechanism of concrete slabs under frictional forces (Goldbeck, 1924; Timms, 1964; Wimsatt and McCullough, 1989). The majority of slab-base friction research has focused on friction developed at the slab-base interface due to horizontal movement from the uniform variation of temperature (i.e., expansion and contraction); this type of friction is termed *sliding friction* (Rufino, 2003). As horizontal forces developed by either drying shrinkage or temperature differential pull the slab in one direction, frictional resistance forces are developed in the opposite direction. This type of friction has been researched the most with regard to early-age cracking problems.

More recently, researchers have explored another type of slab-foundation friction (Yu et al., 1998; Tarr et al., 1999). This friction develops when the wheel load applied to the slab forces contact between the slab and the base. This new friction concept is referred to as *contact friction*. The contact friction problem depends on the location and magnitude of the load, the base type, and whether there is initial contact between the slab and the base. It is widely known that temperature curling affects the contact condition between the slab and base. The contact condition at the slab-base interface before and after loading is of extreme importance for understanding how contact friction develops and the factors affecting it.

Interest in contact friction was generated when analysis of data from the fully instrumented Denver International Airport pavements indicated that the loaded pavement behaved unbonded at times and bonded at other times, even in the presence of a bond breaker between the slab and base layer (Rufino, 2003). Therefore, it is possible to have a bonding action without physical vertical bond or adhesion. By extension, it can be deduced that any forcing function (e.g. thermal and moisture stresses) imparted to the slab when the concrete is still relatively young and untrafficked, can cause apparent adhesion, which can impact the frictional restraint.

Due to the complex interaction of shrinkage-, creep-, and temperature-induced mechanisms that can cause a slab to deform during early age, it may be that the true characterization of the impact of friction on the stresses developed at the slab-base interface must account for both *sliding* and *contact* friction.

<u>Sliding Friction Characterization</u>

According to Ioannides and Marua (1988), Goldbeck (1924) performed the first sliding tests—based on Coloumb's law of friction—to evaluate frictional resistance of bases. They also state that the first theoretical analysis of friction effects on concrete pavements was proposed by Bradbury (1938), and later modified by Kelley (1939). According to Rufino (2003), many other studies have addressed sliding friction, including those by Teller and Sutherland (1935), Friberg (1954), Timms (1964), PCA (1971), and Wimsatt and McCullough (1989).

Wimsatt and McCullough's study (1989) resulted in a standardized test to measure friction called the "push off" test. During the testing, the effect of base type and bond-breaking media (e.g., asphalt emulsion, polyethylene sheeting, etc.) on the frictional resistance offered was measured. In most cases, where a CTB layer was used in the experiment, it stood out as the layer that offered the highest levels of friction resistance.

Although not a subject of experimental investigation, there is growing evidence in the industry that excessive frictional restraint can also develop in concrete pavements placed over ATPB and CTPB, albeit through a slightly different mechanism. According to Voigt (2002), concrete, while plastic and under the extrusion pressure of the slipform paver, will penetrate the open-textured permeable base layer. This penetration can be as much as 1 to 2 in (25 to 51 mm) by some estimates (ACPA, 2002b) and causes restraint to slab movements during thermal and moisture driven contraction and expansion. However, the degree of restraint provided is directly proportional to the gradation of the permeable base and the how easily it can accommodate the axial movements.

Case studies supporting this hypothesis showing that CTB, lean concrete base (LCB), and permeable bases provide restraint that, if left unchecked, can lead to uncontrolled cracking can be found elsewhere in literature (Halm, et al., 1985; Voigt, 1992; Voigt, 1994; Herman, 1991).

Table 2 presents typical friction values for different base types (ACPA, 2002a and 2002b). It is clear from the table that CTB, LCB, and CTPB offer the highest degree of restraint. Therefore, extra precautions need to be taken to ensure that uncontrolled cracking does not happen in the field when using these base types.

Table 2. Coefficient of friction for different base types (ACPA, 2002a and 2002b).

Subbase Type	**Coefficient of Friction**
Natural subgrade	1.0
Lime-treated clay soil	1.5
Dense-graded granular	1.5
Crushed stone	6.0
Bituminous surface treatment	3.0
Asphalt stabilized (rough)	15.0
Asphalt stabilized (smooth)	6.0
Asphalt-treated, open-graded	15.0
Cement-treated ,open-graded	15.0
Cement-stabilized	10.0
LCB/econocrete	15.0

Beginning with Bradbury (1938) and Kelley (1939), several methods have been advanced over the years to model the restraint stresses caused by shrinkage and thermal gradients in slabs. Most of these models have dealt with axial restraint stresses induced in the slab due to slab-base interface restraint. Zhang and Li (2001) presented a closed-form solution for the calculation of restraint stresses based on a characterization of the frictional stress using results from push-off tests.

Rassmussen and Rozycki, (2001) presented a paper that discussed the characterization and modeling of axial slab-support restraint stress, which is based on a finite difference approach. This approach was incorporated into the HIPERPAV program developed by Transtec Inc., under sponsorship of the FHWA. All the models discussed so far considered only axial restraint. Recently, Khazanovich and Gotlif (2002) presented a solution for interface friction for full, partial, and unbonded conditions using just one parameter—bond breaker.

Bond breakers are used to reduce the degree of restraint offered by a given base, along with other design and construction parameters. The most common bond breakers for CTB and LCB are a double-coat of wax-based curing membrane or a geotextile fabric (Kohn and Tayabji, 2003). An asphalt emulsion coat, used as a curing compound for CTB, can also serve as a bond breaker. However, according to Grogan et al. (1999), a fresh application of emulsion 8 to 12 hours prior to paving may be most effective.

There is an on-going debate on what constitutes the best bond-breaking medium for permeable base layers. Geotextiles and choke stone layers (with gradations similar to AASHTO No. 8 or 9 layers) were mentioned in the literature as being able to break the bond and prevent the paste intrusion into the open-graded texture of the base (Voigt, 2002). The advantages of the former are ease of installation, but the disadvantages include (1) restriction of construction traffic from driving over the base once the fabric is installed and (2) the potential of the cement paste to bind the pores in the geotextile, thereby destroying the purpose of installing a permeable base layer. The advantages of the latter include ease of installation and the fact that it is a tried-and-tested method (the USACE specifications use a choke stone layer to stabilize UPB layers during construction).

Another way to limit paste intrusion is to not require a high degree of voids in the permeable base (i.e., reduced permeability requirements). This aspect of the permeable base is receiving quite a bit of attention at the present time among State and Federal highway agencies. In fact, the current UFC criteria on permeable bases suggests that a permeability of 1,000 ft/day (305 m/day) is adequate for permeable bases in most situations, which is far less than what is being used as guidance at the present time.

2.3.3 Impact of Jointing and Jointing Methods

There are several types of joints in rigid airfield pavements—contraction, construction, and expansion. The subject of this discussion is contraction joints which are primarily provided to prevent uncontrolled cracking. Contraction joints are typically formed by sawing the concrete with single-blade, walk-behind saws. For wider paving, span saws may be used to saw transverse joints more expediently. In the past decade, a new class of saw, termed the early-entry saw, has become popular. This particular saw allows sawing sooner than conventional saws (Voigt, 2002).

Joint Spacing

Since the time of Westergaard (1927) and Bradbury (1938), the effect of joint spacing on slab performance has been well known—the longer the spacing, the higher stress due to curling or warping. However, since joint spacing is not a direct input into the FAA or other airfield design procedures, it is determined using empirical guidance and rules-of-thumb. Some of the most common guidelines include the following:

- Joint spacing should be, at most, 5 times the radius of relative stiffness.
- Joint spacing should be limited to 21 times the PCC slab thickness for stabilized bases or 24 times the PCC slab thickness for granular bases.
- Joint spacing (in feet) should be, at most, 2 times the PCC slab thickness (in inches).

All these rules imply that the longer dimensions resulting from the calculations should only be used if sufficient local experience is present to justify them. That joint spacing has an impact on early-age stresses is clear from the discussion on the impact of slab-base interface friction. The higher the joint spacing, the higher the degree of movement of the slab edges with respect to the fixed point in the slab (typically slab center), and therefore, the higher the restraint stresses. This is borne out by all the theories that deal with slab-base restraint stresses, starting from Bradbury (1938) and Kelley (1939). The degree of movement is greatly controlled by the coefficient of thermal expansion of the aggregate and also the prevalent ambient conditions soon after placement. The problem translates to uncontrolled cracking if the concrete is not strong enough to resist these early stresses.

In addition to increased axial restraint stresses in PCC slabs, longer joint spacings also cause increased curling stresses in bending. This is further exacerbated by the presence of stiff stabilized bases, which cannot accommodate themselves to the curled or warped shape of the slab (Road Research Laboratory, 1955).

Another aspect of the joint spacing is the slab length to slab width ratio. Several researchers have suggested that the best practice is to maintain the aspect ratio of the slab (length/width) as close to 1 as possible and never greater than 1.25, in order to avoid long, narrow slabs which can crack. This is particularly important when thinner slabs are used. Herman (1991) suggested that a single plan may not be appropriate for pavements with varying thicknesses, as well as various paving dimensions.

In June 2002, the FAA made a change to AC 150/5320-6D, recommending the maximum panel size be 20 ft (6.1 m) for slabs 12 in (305 mm) and thicker placed on stabilized bases. The change also recommended that joint spacing be a function of the radius of relative stiffness.

Timing of Sawing Joints

In order to derive the anticipated benefit of sawing joints, there is an optimum window of opportunity to sawcut joints. Figure 2 presents the sawing window of opportunity (after Okamoto et al., 1991; ACPA, 1994). This window typically occurs a few hours after the concrete placement, however, the exact timing is variable. The window begins when concrete strength is acceptable to operate saw equipment without excessive raveling at the joints.

The window ends when the concrete's volume reduces significantly (from drying shrinkage or temperature contraction) and restraint of the reduction induces tensile stresses greater than the tensile strength. If sawing is performed after this point, pop-off cracks (i.e., cracks just ahead of the sawing operation) can occur (Voigt, 2002).

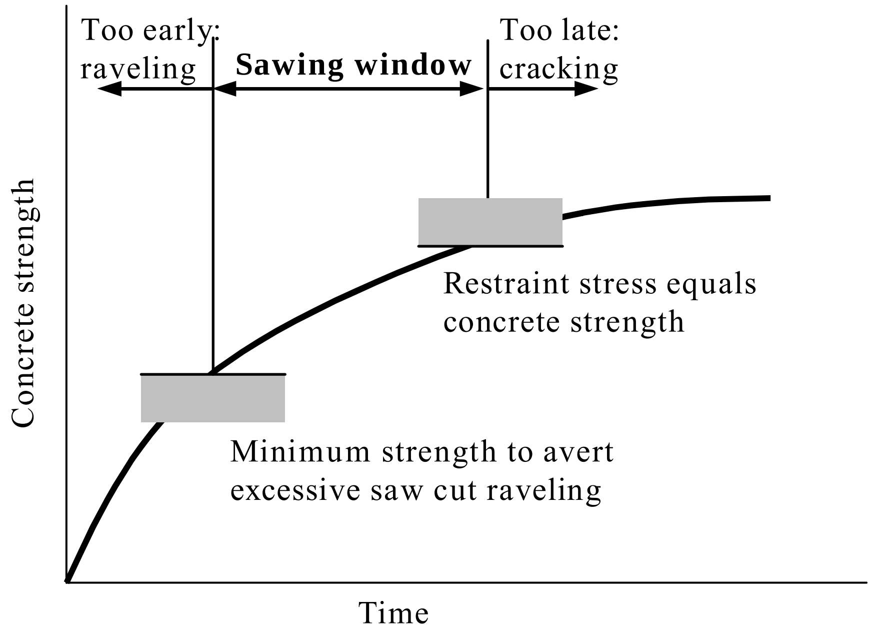

Figure 2. Sawing window of opportunity (Okamoto et al., 1991; ACPA, 1994).

The paving contractor is typically provided with guidance that the saws should be operated on the pavement at the earliest possible time to provide the initial sawcut, without excessively raveling the slab. Typically, the sawing window is long enough and affords adequate amount of time for the paving contractors to make a decision as to when to saw. However, the combination of certain design, materials, and weather-related factors can considerably shorten the window. In extreme conditions, the window can be so short as to be impracticable for crack control (ACPA, 2002b).

Depth of Sawcut

The depth of sawcut, along with the sawcut timing and the equipment used, has a significant impact on the performance of the contraction joint. Table 3 provides recommended sawcut depths for longitudinal and transverse joints (ACPA, 2002a). According to Zollinger et al. (1994), early-entry sawing methods with sawcut depths less than one-fourth the depth of the slab thickness provide better crack control than conventional methods with sawcut depths of one-fourth to one-third the slab thickness.

The issue of sawcutting depth is further aggravated when concrete is placed over open-graded bases courses and the mortar penetrates the void structure of the base or when the concrete bonds to the underlying base layer in the absence of a bond breaker. In both these situations, the effective thickness of the slab is increased and the depth of the initial sawcut may not be adequate to form a control joint increasing the likelihood of random cracking at an early age.

Table 3. Recommended sawcut depths for joints (ACPA, 2002a).

Base Type	Sawcut Depth as Portion of Slab Thickness	
	Transverse Joints	Longitudinal Joints
Dense granular subbases (low friction)	1/4	1/3
Stabilized and open-graded subbases (high friction)	1/3	1/3

2.3.4 Impact of Concrete Mixture Properties

Voigt (2002) stated that, regardless of ambient conditions (i.e., temperature swings, rates of evaporation, hot- and cold-weather paving conditions) at placement, such as subbase restraint, subbase stiffness, etc., a poor concrete mix design can aggravate the problem of premature cracking. The main factors that were brought to fore in the literature with regard to this subject are as follows (Shilstone, 1990; Lafrenz, 1997):

- Mixtures with higher water demand have an increased potential for volumetric shrinkage, which when combined with other factors (excessive strength, excessive restraint, ambient conditions, joint spacing, etc.), can lead to uncontrolled cracking. Factors that increase water demand include higher cement factor concrete (>500 lb/yd^3 [>295 kg/m^3]) and concrete made with fine sand.
- Type of coarse aggregate can influence the temperature sensitivity of concrete.
- The gradation of the combined aggregates affects the workability of concrete mixtures and, therefore, its early-age performance.

Cementitious Material

Mixtures with higher cement factors (quantities of cement and/or pozzolonic and slag additions) require more mixing water, even if the water-cementitious materials ratio is minimized, and consequently a higher potential to shrink. Conversely, mixtures with high contents of pozzolans or ground-granulated blast furnace slag, or lower contents of cement may experience delayed early-age strength development in cooler weather. Depending on the air, base, and concrete temperature, this could delay the concrete set time and the ability to saw without excessive raveling (ACPA, 2002a and 2002b). In the end, the considerations for early-age cracking need to be balanced with requirements of strength and durability.

Sand

FAA specifications, as implemented on several projects, require that the sand for the PCC meet the ASTM C 33 specification. ASTM C 33 provides a gradation band for material passing the ⅜ in (9.5-mm) sieve to No. 100 (150 µm) sieve and stipulates the following acceptability characteristics for the concrete sand gradation:

- No more than 45 percent of material is retained on any one sieve.
- Fineness modulus between 2.3 and 3.1.

When applied indiscriminately, this specification can lead to a mix design that is susceptible to uncontrolled cracking due to the possibility of the production of gap-graded mixtures, with excessive fine sand contents even when criteria noted above are satisfied. The presence of fine sand (excessive minus No. 50 [300 µm] sieve material) increases the bulking potential dramatically and thereby the potential for volumetric shrinkage and early cracking.

To circumvent this problem, the U.S. Air Force (USAF) developed a concrete guide specification (and the handbook for concrete mixture proportioning) with the intent to minimize the potential for early cracking. This specification has discouraged the use of gap-graded aggregates and minimized the cement and water demand. The provisos of the USAF guide specification encourage the use of coarse sand and a minimum cement factor. Both of these mix components directly control the water demand.

In general, concrete with a high cement factor, such as those used in airfield pavement construction, should include coarse sand. ASTM C 33 allows for a reduction of the portion of the sand passing the No. 50 and No. 100 (300 µm and 150 µm) sieves to 5 and 0 percent, respectively, for:

- Pavement grade concrete.
- Air-entrained concrete with cement content more than about 400 lb/yd^3 (236 kg/m^3).
- Non-air-entrained concrete with cement content more than about 500 lb/yd^3 (295 kg/m^3).

If attention is paid to these guidelines, and coarse sand with fineness modulus values in the range of 3.1 to 3.4 is used in pavement concrete, excellent results can be obtained from a volumetric shrinkage standpoint. If sand with a well-graded character and fineness modulus values above 3.1 is not available, then manufactured sand may need to be used (ACPA, 2002b).

Combined Aggregates

Examination of the combined aggregate gradation provides insight into the workability and segregation potential of concrete mixtures. Mixtures prone to segregation are also prone to early distress. Shilstone (1991) provided a tool to evaluate concrete mixture workability and the risk of problems such as uncontrolled cracking, which was validated by the USAF. The factors considered in evaluating a given mixture include the workability factor and the coarseness factor. The workability factor is simply the percent passing the No. 8 (2.36 mm) sieve for the combined aggregate gradation. The coarseness factor is expressed as a fraction of the percentage of aggregate retained on the ⅜ in (9.5-mm) sieve to that retained on the No. 8 (2.36 mm) sieve, multiplied by 100. Using these two factors, a given mixture is evaluated on the basis of the figure 3.

Generally speaking, ideal concrete with the least risk of premature cracking should be made with a combined aggregate with a coarseness factor below 75 and a workability factor above 29. A well-graded combined aggregate will reduce water demand and drying shrinkage potential and provide better workability and improved early strength development (ACPA, 2002b).

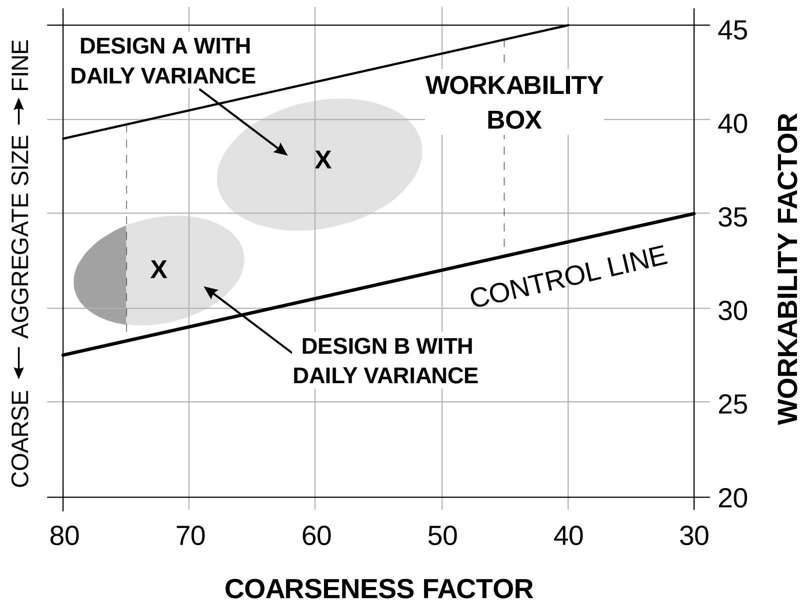

Figure 3. Workability factor chart.

<u>Coarse Aggregate</u>

The type of coarse aggregate used directly controls the volumetric expansion and contraction of concrete mixtures. In a study performed by McCullough and Dossey (1999), aggregate type and placement season were found to be the most significant factors affecting PCC pavement performance. Generally, limestones, granites, and basalts have lower coefficients of thermal expansion than quartz, sandstones, and siliceous gravel (Kosmatka et al., 2002). This means that concrete made with the former materials more insensitive to ambient conditions and will perhaps exhibit lower tendencies to crack at early ages.

2.3.5 Impact of Weather Conditions During Construction

Perhaps the most commonly cited factor affecting premature cracking is weather. Air temperature, wind speed, relative humidity, precipitation, and solar radiation all have an impact on the early-age performance of concrete since they either heat or cool and dry or wet-up the concrete (ACPA, 2002b). They also influence the temperature of the base layer, which in turn influences the heat flow into and out of the concrete layer during hydration. The main weather-related factors that affect early-age concrete performance are as follows:

- Paving temperatures (hot or cold).
- Large temperature swings.
- Precipitation.
- High rates of evaporation.

These parameters when combined with other design, materials, and construction factors, affect the slab movements due to curl and warp, sawing window, and strength development.

2.4 SUMMARY AND CONCLUSIONS

There is adequate empirical evidence available to prove that the phenomenon of premature cracking is real. Several factors including the pavement base affect the early-age performance of concrete. Some safeguards can be built into pavement design and construction to prevent uncontrolled cracking by addressing issues of base thickness and strength. However, an approach to resolving the premature cracking problems involves much more than specifying a base thickness and strength.

CHAPTER 3. AIRPORT PROJECT REVIEWS

3.1 PRELIMINARY IDENTIFICATION OF PROJECTS

To identify specific airport projects for detailed investigation, an extensive search was made for civilian (commercial and general aviation [GA]) and military airports in the U.S. containing PCC pavements built on stabilized and/or permeable bases. The initial search relied heavily upon the following data sources:

- Design and construction records.
- FAA regional offices.
- U.S. Army Corps of Engineers (Center of Expertise and District offices).
- American Concrete Pavement Association (ACPA) and concrete paving contractors.
- Airport Consultants Council (ACC) and airport consulting firms.
- Air Force Civil Engineering Support Agency (AFCESA) and Air Force Major Command offices.

During this search, basic design and construction information was collected for each project to aid in short-listing the projects for detailed evaluation. The specific data items obtained as part of this undertaking included the following:

- Data source.
- Project and/or section identification name/number.
- Airport/airfield name.
- Airfield usage type.
- Airfield location (city and state).
- Facility usage type (i.e., apron, runway, taxiway).
- Type of base course.
- Year of construction.
- PCC design (pavement type, slab thickness, slab dimensions).
- Subgrade type.
- Presence of early-age distress (EAD).
- Other information (annotation of unique cross-section details, soil stabilization, etc.).

Of the 200-plus airfields examined, 119 were found to have pavements with cement-treated, asphalt-treated, econocrete, or permeable base layers. These airfields were spread across 38 states and represented diverse climatic zones, as seen in figure 4. Nearly 900 pavement projects or sections were identified that provided all the base types and facility types of interest in the study, as well as a variety of design, construction, and site factors. Additionally, the projects/ sections included a mix of pavements identified as having

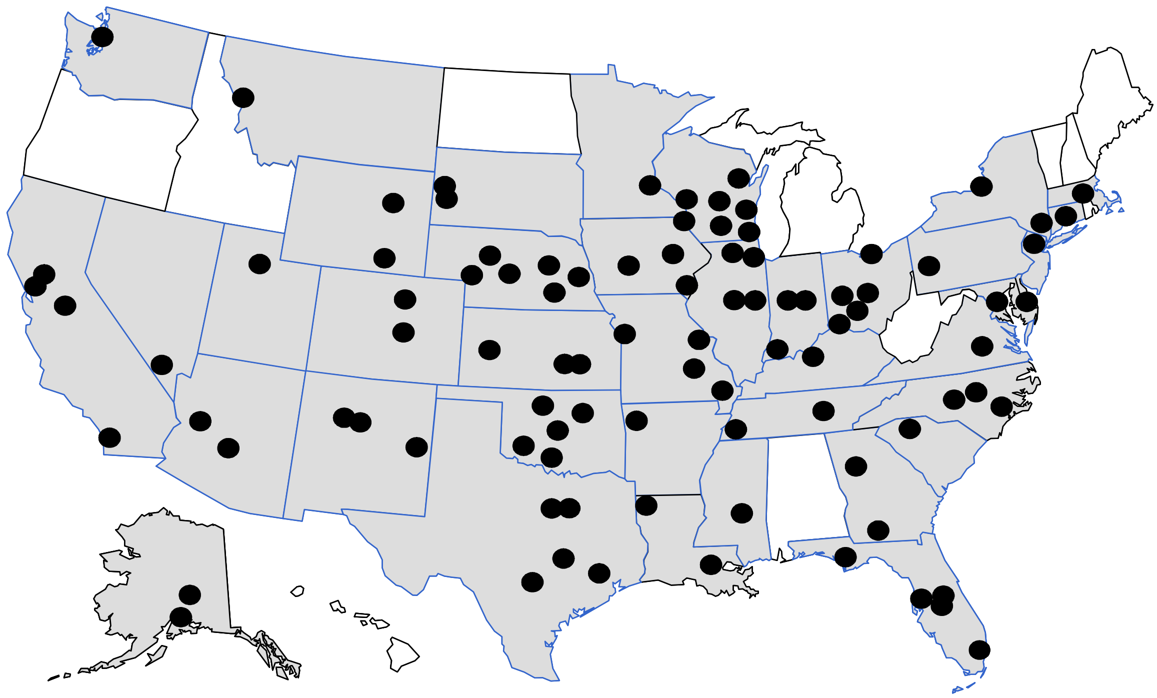

Figure 4. Geographical distribution of airfields with PCC pavement built on stabilized and/or permeable base.

experienced (a) no or negligible amounts of EAD in the form of premature cracking or (b) EAD constituting a serious design and/or construction problem. It should be noted that, because of the difficulty in obtaining subgrade soil type information for a majority of the sections, this data variable was removed from consideration in the study.

3.2 SHORT-LISTING OF PROJECTS FOR DETAILED INVESTIGATION

A systematic set of rules was followed to identify a shortlist of projects from the large pool of candidate pavements. These rules were established in close alignment with the general and specific project objectives presented in chapter 1, as well as the following related objectives:

- How does the pavement base design relate to other design parameters (e.g., slab thickness, joint spacing)?
- What are key materials and construction considerations for the different base types?
- Do stabilized and/or permeable bases have an influence on the impact of extreme thermal changes during PCC construction?

Project selection followed a two-step process. The first step involved grouping the potential projects on the basis of the data gathered from literature and the airport reviews. The groupings were made in accordance with the following categorical variables:

- Performance—2 levels.
  - Presence of EAD.
  - Absence of EAD.
- Climate—3 categories.
  - Wet-freeze (WF).
  - Wet-nonfreeze (WNF).
  - Dry-freeze and dry-nonfreeze (DF and DNF).
- Base type—6 categories.
  - CTB (P-304).
  - Econocrete/Lean Concrete (P-306).
  - ATB (P-401).
  - UPB.
  - CTPB.
  - ATPB.

Table 4 shows the analysis template created to aid in grouping the potential projects, based on the categorical variables.

In the second step of the selection process, projects were selected for detailed investigation according to the following criteria:

- Within the budgetary and time constraints of the study, select a reasonable number of EAD projects, such that at least two sections per base type are selected for further review.
- Group the selected EAD projects by the primary variable of interest—base type. From the available design and construction data for each project, establish the ranges of the key variables for each base type (e.g., cross-section details, material parameters, construction parameters, and QA/QC plans).
- For each group of EAD projects (sorted by base type), select two or more companion projects that did not exhibit EAD, ensuring that they satisfy the following criteria:
  - Companion projects should envelope the key variables of interest to each base type under consideration. For base types with no representative EAD projects, select companion projects that feature proven best practices.
  - Companion projects should have been constructed within the last 7 years, where possible, and have performed well in terms of early-age behavior.
  - The airfields in which the companion projects are located should have a long history of positive experience with the base types under consideration.
  - Adequate detailed records are available for analysis for both EAD and companion projects.

Table 4. Analysis template used in identifying and selecting airport projects.

Base Type	Early-Age Distress?	Wet-Freeze	Wet-Nonfreeze	Dry-Freeze and Dry-Nonfreeze
CTB (P-304)	Yes			
	No			
Econocrete/ LCB (P-306)	Yes			
	No			
ATB (P-401)	Yes			
	No			
UPB	Yes			
	No			
CTPB	Yes			
	No			
ATPB	Yes			
	No			

Note: The definitions of "wet" and "freeze" climatic conditions were based on the Federal Highway Administration's (FHWA's) Long-Term Pavement Performance criteria. According to these criteria, a wet climate is defined as one receiving greater than 20 in (500 mm) of mean annual precipitation and freezing climate is defined as one where the cumulative annual freezing index is greater than 150°F-days (83°C-day).

The overall project selection methodology was specifically formulated to enable a detailed comparison between the EAD and the companion projects, thereby providing insight into the causes of EAD and to aid in the development of design and construction recommendations for preventing it from occurring.

3.2.1 Grouping of Projects (Step 1)

The project short-listing procedure was applied to the database of airfield pavement sections assembled in the preliminary project identification task. The first step of the exercise clearly illustrated that substantially fewer sections with reported EAD issues were available for detailed investigation, as compared to those with no EAD. Furthermore, none of the UPB and ATPB sections identified and only one of the ATB sections identified had experienced premature cracking.

Table 5 shows the number of EAD and companion (no EAD) projects identified for the analysis matrix presented earlier in table 4. Figure 5 shows the locations of the various projects identified as having early-age cracking problems. The number of EAD projects indicated in this figure provided sufficient impetus to investigate the reasons for EAD and to develop appropriate guidance that identifies the causes.

Table 5. Analysis template following completion of step 1 of project shortlisting.

Base Type	Early-Age Distress?	Wet-Freeze	Wet-Nonfreeze	Dry-Freeze and Dry-Nonfreeze
CTB (P-304)	Yes	7	1	1
	No	77	229	98
LCB (P-306)	Yes	2	2	1
	No	75	86	2
ATB (P-401)	Yes	1	0	0
	No	96	52	8
UPB	Yes	0	0	0
	No	4	1	16
CTPB	Yes	3	0	0
	No	9	0	1
ATPB	Yes	4	0	0
	No	86	6	5

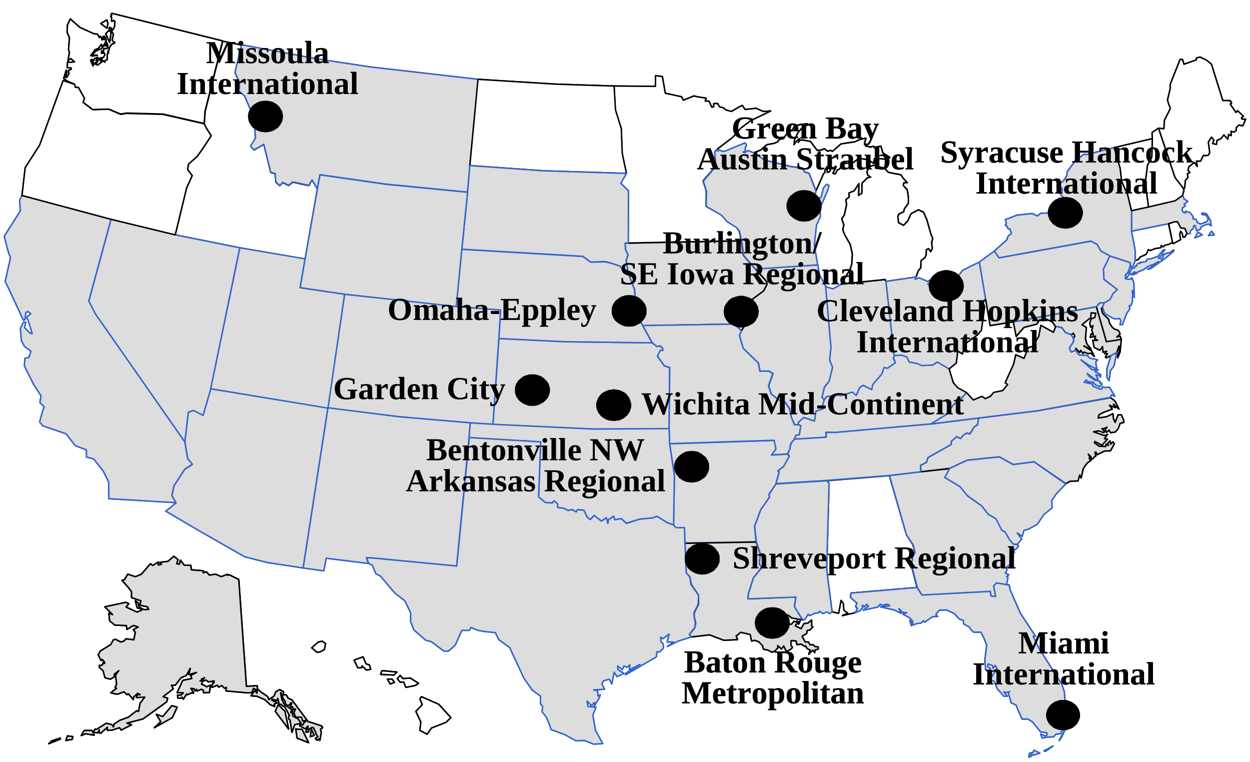

Figure 5. Locations of projects with EAD.

3.2.2 Project Selection (Step 2)

Table 6 lists all the projects with EAD and the reasons cited for their occurrence. It also shows the nine EAD projects that were selected for detailed investigation and lists the reasons for selecting or not selecting the projects.

Table 7 summarizes, by base type, the EAD and companion projects selected for evaluation. Generally speaking, projects that were chosen were done so because of their overall suitability in terms of location (nearby companion projects) and cause of failure (potentially base-related). Additional reasoning behind the selection of projects is provided below.

- CTB (P-304)—The companion projects were all recently constructed (since 1996). They included several projects with CTB and a wide range of design, construction, and site parameters/conditions. Some of the selected airfields had long histories of constructing CTB layers. Some of the other parameters that made for compelling comparisons were curing method used, paving under different weather conditions, range of base and PCC thickness, range of joint spacing, and the use of asphalt and stress-absorbing membrane interlayers (SAMI) as bond breakers. Furthermore, the companion projects were well distributed in relation to the selected EAD projects, with several of them being co-located with the EAD projects (e.g., Bentonville/Northwest Arkansas Regional, Omaha-Eppley, Burlington/Southeast Iowa Regional).
- Econocrete (P-306)—The companion projects were all recently constructed (1996) and consisted of several projects with econocrete bases and a wide range of design, construction, and site parameters/conditions. Missoula International had both EAD and non-EAD projects, making it an obvious choice as a companion. It also represented a unique environment (dry-freeze). Houston George Bush Intercontinental was already on the list of companion projects for CTB, therefore it made logical sense during detailed evaluations to select it as a companion even for Econocrete.
- ATB (P-401)—The companion projects were a mixture of recent and older construction projects having a wide range of design, construction, and site parameters/conditions. The reason for the selection of the older projects was that several of the projects were built in airports with a long history (experience) of building ATB layers. They were also in close proximity to the projects experiencing EAD or were already being visited as part of this study. Moreover, they consisted of several projects of interest and covered a wide range of ATB properties and construction practices.
- UPB—As discussed earlier, no UPB projects experiencing EAD were identified. However, two projects with no reported problems were identified and selected for review on the basis of good practices in design and construction.

Table 6. List of candidate EAD projects and those selected for detailed investigation.

Airport Name	Base Type	Year of Const. (No. projects)	Climate	Reasons Cited for Early-Age Distress	Selected	Reasons for Selection or Rejection
Green Bay (WI) Austin Straubel Airport (GRB)	Econocrete (P-306)	2000 (1)	WF	• October construction. • Big temperature swings (~25 to 30°F [14 to 17°C]). • Inconsistent grade.	Yes	• Two base types (econocrete, ATB) represented at same airport. • Plausible reasons for EAD involve large temperature swings during construction. • Only EAD project for P-401.
	ATB (P-401)	2001 (1) & 2002 (1)	WF	• Summer construction.	Yes	
Baton Rouge (LA) Metropolitan Airport (BTR)	CTB (P-304)	2000 (1)	WNF	• Temperatures during paving ~90 to 95°F (32 to 35°C). • Low relative humidity (20 to 30%) • Plastic shrinkage?	Yes	• Plausible reasons for EAD involve hot-weather paving, low relative humidity, and a high-strength base.
Cleveland (OH) Hopkins International Airport (CLE)	CTB (P-304)	2001 (1)	WF		No	• Could not ascertain reason for EAD, although it was confirmed that cracking was present (CTB). • Design features well-represented in other CTB projects, except for Visqueen bond breaker.
Garden City (KS) Airport (GCK)	CTPB	2003 (1)	DF	• Longitudinal cracks in the base reflected through the pavement, usually within a week • Weather was hot during paving	No	• Presence of nearby project for this base type (CTPB). • Mode of EAD (bonding) represented elsewhere (Syracuse Hancock International)
Syracuse (NY) Hancock International Airport (SYR) (174th Air National Guard)	CTPB	1999 (1) & 2000 (1)	WF	• 1999 project constructed in Fall and had sporadic cracking along one joint. • 2000 project was constructed in June and had cracking due to bonding between PCC and drainage layer.	Yes	• Key base type represented (CTPB). • Multiple projects at the same location. • One of the few military airfields with reported EAD. • Co-located companion projects available at this location for CTPB.
Miami (FL) International Airport (MIA)	Econocrete (P-306)	2002 (1)	WNF		No	• Could not ascertain reason for EAD. • Design represented by Green Bay Austin-Straubel and Missoula International, which are considered.
Missoula (MT) International Airport (MSO)	Econocrete (P-306)	2001 (1)	DF	• Some cracking, but not attributed to base. • Cracking perhaps due to late sawing of joints.	Yes	• Only representative project in this climatic region. • Key mode of EAD: late joint sawing
Bentonville (AR) / Northwest Arkansas Regional Airport (XNA)	CTB (P-304)	1998 (4)	WF	• Issues with early cracking related to CTB. • Weather probably not a factor.	Yes	• Multiple projects available which have experienced EAD for this base (P-304). • Key mode of EAD: cracking due to strength of CTB (independent of ambient paving conditions)
Omaha Eppley (NE) Airport (OMA)	CTB (P-304)	1998 (1)	WF	• 20 panels cracked the day after paving; initially believed to be due to CTB strength. • Additional analysis by Contractor showed that cracking may have been due to heat of hydration occurring at the worst time.	Yes	• Forensic analysis results available. • Key mode of EAD: cracking due to strength of CTB and thermal stress due to excessive heat of hydration. • Co-located companion projects available at this location.
Shreveport (LA) Regional Airport (SHV)	CTB (P-304)	? (1)	WNF	• Early cracking due to a very strong base.	No	• Lack of adequate information from project due to age.
Burlington (IA) / Southeast Iowa Regional Airport (BRL)	CTB (P-304)	2001 (1) & 2002 (1)	WF	• Aug/Sept construction • Early-age cracking due to a very strong base (2,000 lb/in^2 [13,790 kPa] CTB).	Yes	• Key mode of EAD: cracking due to strength of CTB. • Multiple projects have experienced EAD at this location.
Wichita (KS) Mid-Continent Airport (ICT)	CTPB	1998 (1)	WF	• Early-age cracking related to temperature shock due to freak rain event. • Flash setting problems also noticed.	Yes	• Key mode of EAD: cracking due to thermal shock perhaps due to excessive restraint (CTPB). • Co-located companion projects available at this location for CTPB.

Table 7. List of selected EAD and companion projects.

Base Type	Comparison No.	Selected EAD Projects	Companion Projects (no EAD)	
			Primary	Alternative
CTB (P-304)	1	Baton Rouge (LA) Metropolitan Airport (BTR), RW 4L-22R (2000)	NA	NA
	2	Bentonville/Northwest Arkansas Regional Airport (XNA), Various (1998)	Bentonville/Northwest Arkansas Regional Airport (XNA), Apron Expansion (2003)	Houston (TX) Ellington Field (EFD), Various (2002)
	3	Omaha (NE) Eppley Airport (OMA), TW A (1998)	Omaha (NE) Eppley Airport (OMA), RW 14L-32R (2001)	Houston (TX) George Bush Intercontinental Airport (IAH), Various (2000-2002)
	4	Burlington/Southeast Iowa Regional Airport (BRL), TW Alpha Phase I (2001)	Burlington/Southeast Iowa Regional Airport (BRL), TW Alpha Phase II (2002)	NA
Econocrete or Lean Concrete (P-306)	1	Green Bay (WI) Austin Straubel Airport (GRB), TW Mike (2001)	Green Bay (WI) Austin Straubel Airport (GRB), TW D (2001 & 2002)	Milwaukee (WI) General Mitchell Airfield (MKE), Various (1996-2002)
	2	Missoula (MT) International Airport (MSO), Air Carrier Apron Phase I (2001)	Missoula (MT) International Airport (MSO), Air Carrier Apron Phase IV (2002)	NA
ATB (P-401)	1	Green Bay (WI) Austin Straubel Airport (GRB), Air Carrier Apron Expansion (2000)	Green Bay (WI) Austin Straubel Airport (GRB), Air Carrier Apron Expansion (2001)	Milwaukee (WI) General Mitchell Airfield (MKE), Various (1996-2002)
	2	NA	Janesville/Southern Wisconsin Regional Airport (JVL), RW 13-31 Extension (2002)	Milwaukee (WI) General Mitchell Airfield (MKE), Various (1996-2002)
UPB	1	NA	Ft. Benning (GA) Army Airfield, Various (2003)	NA
	2	NA	McConnell (KS) Air Force Base, East Runway (1986)	NA
CTPB	1	Wichita (KS) Mid-Continent Airport (ICT), TW Echo (1998)	Wichita (KS) Mid-Continent Airport (ICT), North Air Cargo Apron (1995)	Vance (OK) Air Force Base, Center Runway
	2	Syracuse (NY) Hancock International Airport (SYR), 174th ANG Apron (1999)	NA	NA
	3	NA	Kansas City (MO) International (KCI), Terminal Apron (2000/01)	NA
ATPB	1	NA	Memphis (TN) International Airport (MEM), TW Mike (2000/01)	NA
	2	NA	Memphis (TN) International Airport (MEM), RW 18R-36L (2002)	NA
	3	NA	Tinker (OK) Air Force Base, Center Runway	Fort Sill (OK) Army Airfield, Tactical Equipment Track

NA = Not available. Companion projects selected for identification of good design and construction practices.

- CTPB—Two primary companion projects and an alternative companion project with similar design and construction parameters were also selected. Wichita Mid-Continent had a long history of constructing CTPB and also had recently constructed both EAD and non-EAD projects. The Kansas City International project was in close proximity to the Wichita EAD project and had a proven record of successful early-age performance over several construction seasons. Therefore, it was an obvious choice. Vance Air Force Base provided information on Air Force's approach to design and construction and was considered a good candidate. Collectively, these sections represented a wide range of parameters of interest (e.g., 4- to 8-in [102- to 204-mm] base thickness, 12.5- to 25-ft [3.8- to 7.6-m] joint spacing, etc.).
- ATPB—There were no ATPB projects experiencing EAD, however, two companion projects along with an alternative project with similar design and construction parameters were identified. The companion projects included several projects with ATPB bases and possibly a wide range of design, construction, and site parameters/conditions. One of the reasons for selection of the commercial companion project was that it was recently completed (1998). The Tinker AFB and the Fort Sill Army Airfield sections were chosen to gain the Air Force and Army's perspective on ATPB design; both of these agencies routinely use such bases.

The specific locations of the EAD projects (and co-located companion projects) within each selected airfield are illustrated in figures 6 through 13.

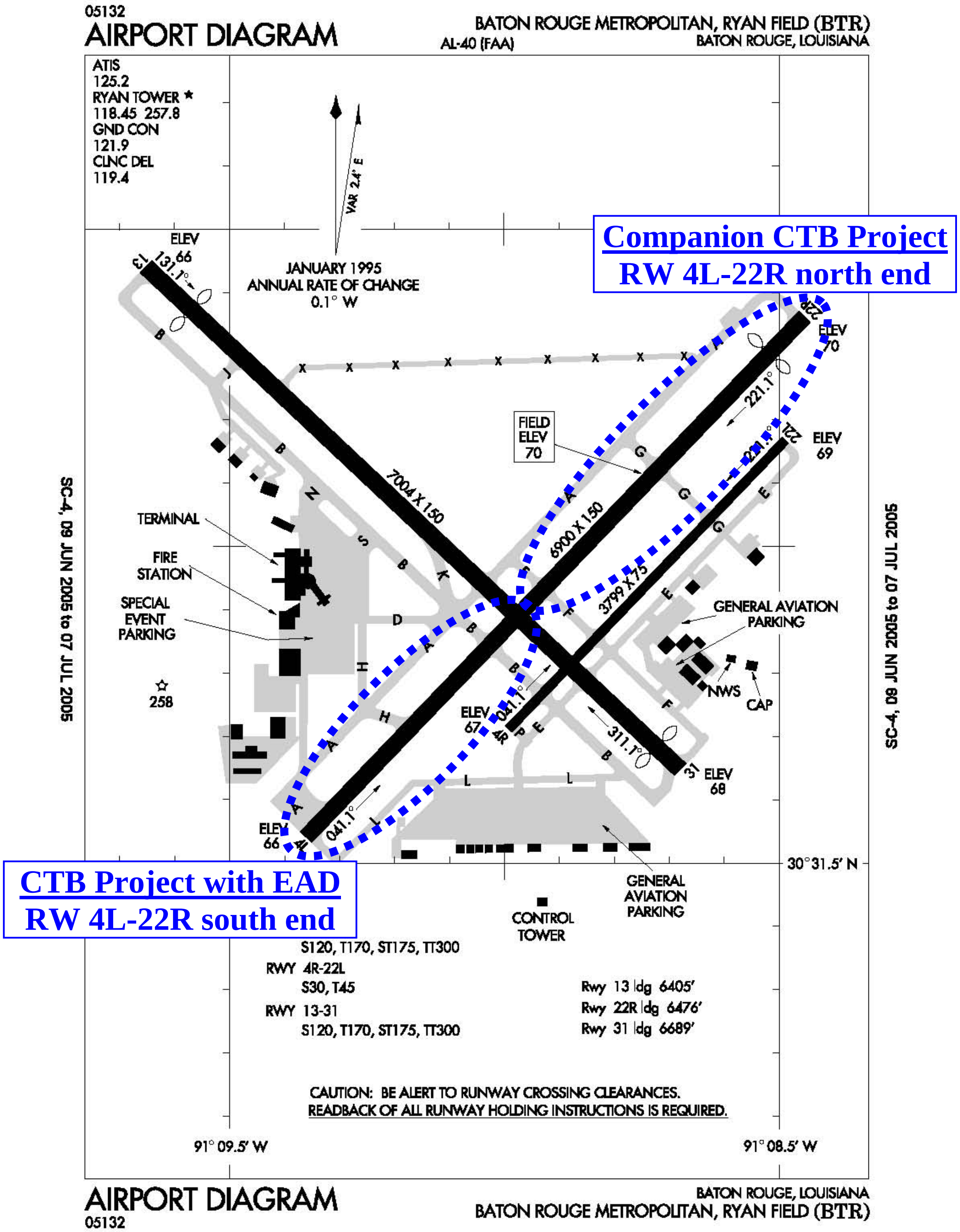

Figure 6. Location of pavement projects evaluated at Baton Rouge Metropolitan Airport (map courtesy FAA Aviation System Standards).

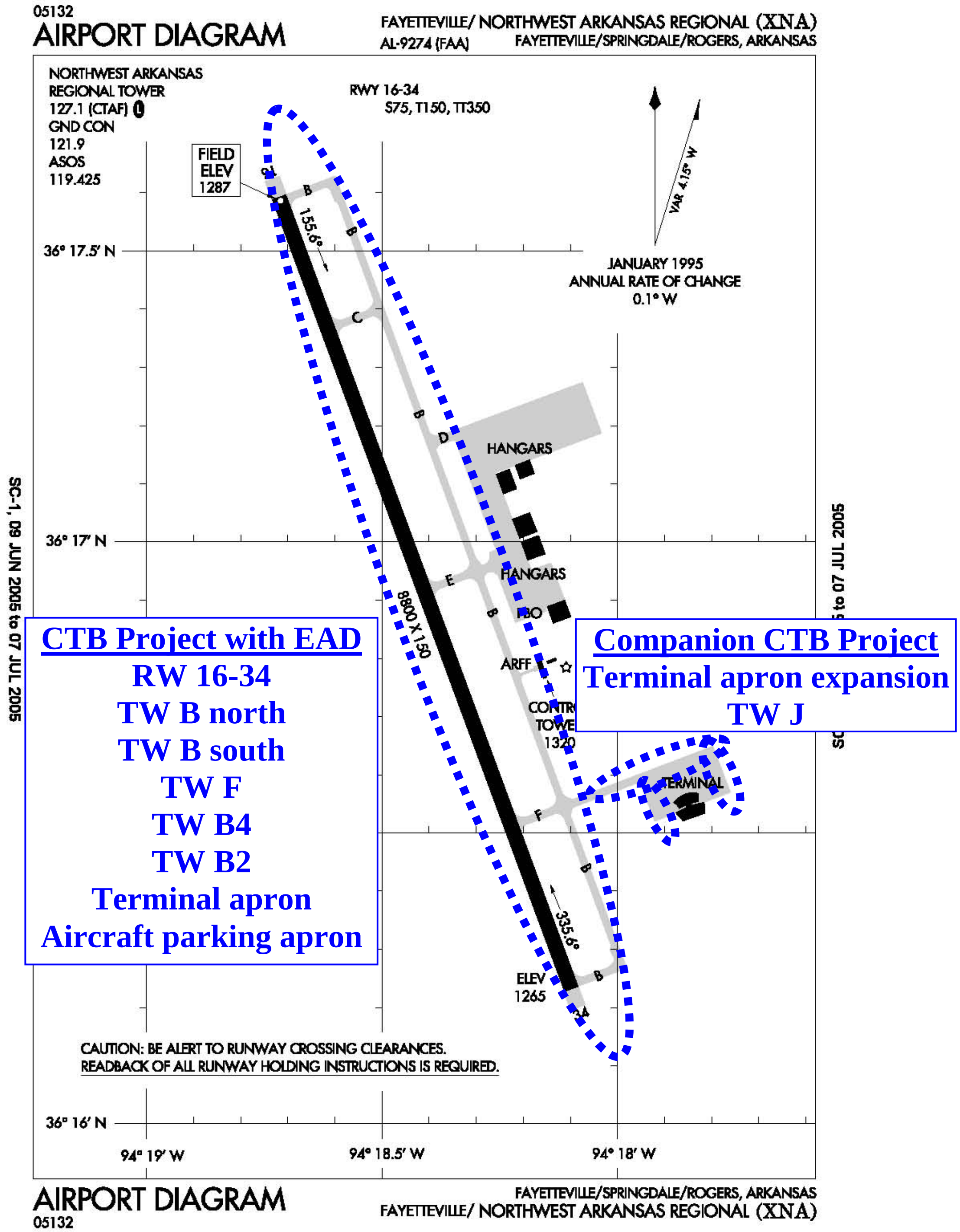

Figure 7. Location of pavement projects evaluated at Bentonville/Northwest Arkansas Regional Airport (map courtesy FAA Aviation System Standards).

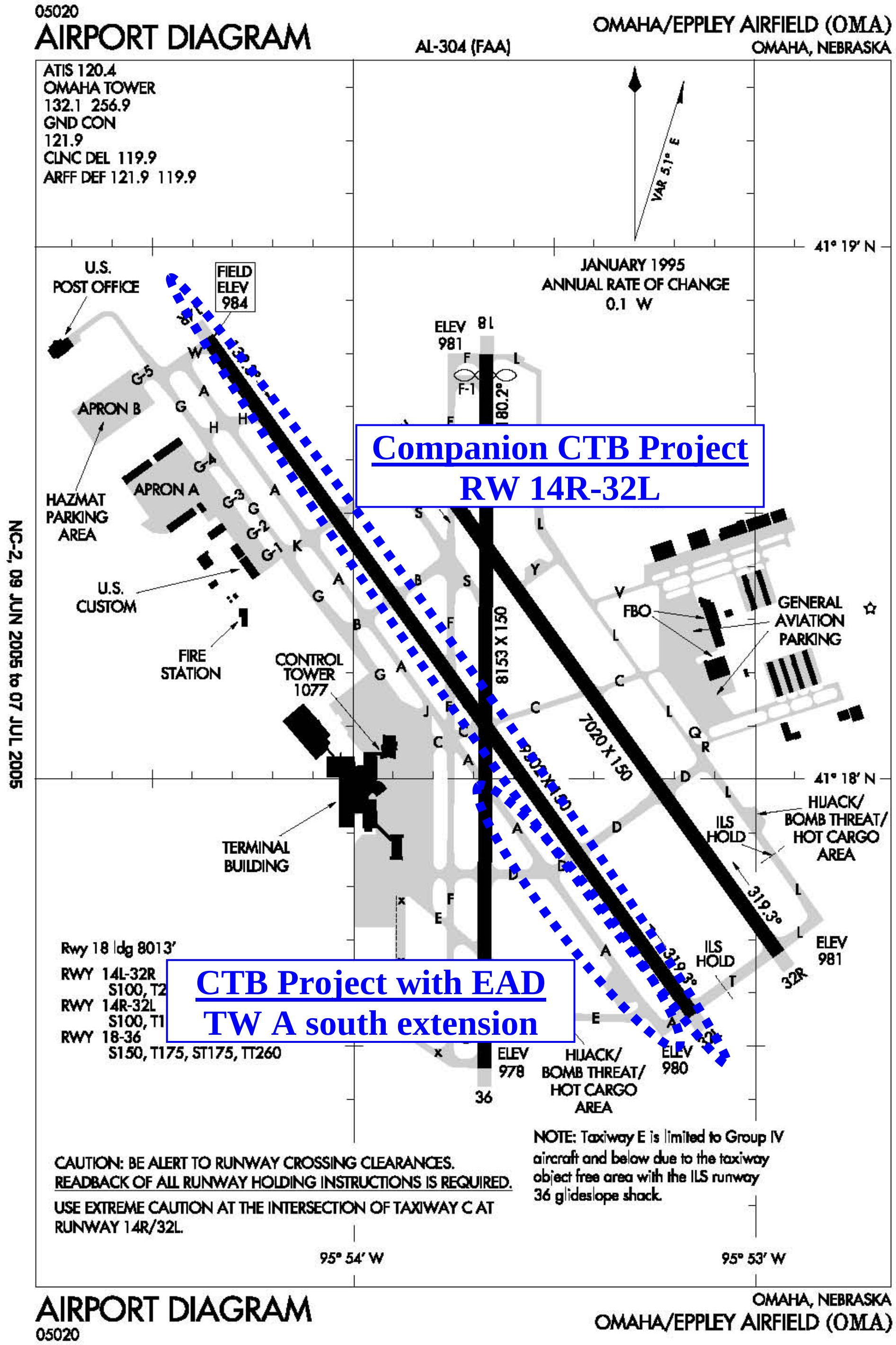

Figure 8. Location of pavement projects evaluated at Omaha Eppley Airport (map courtesy FAA Aviation System Standards).

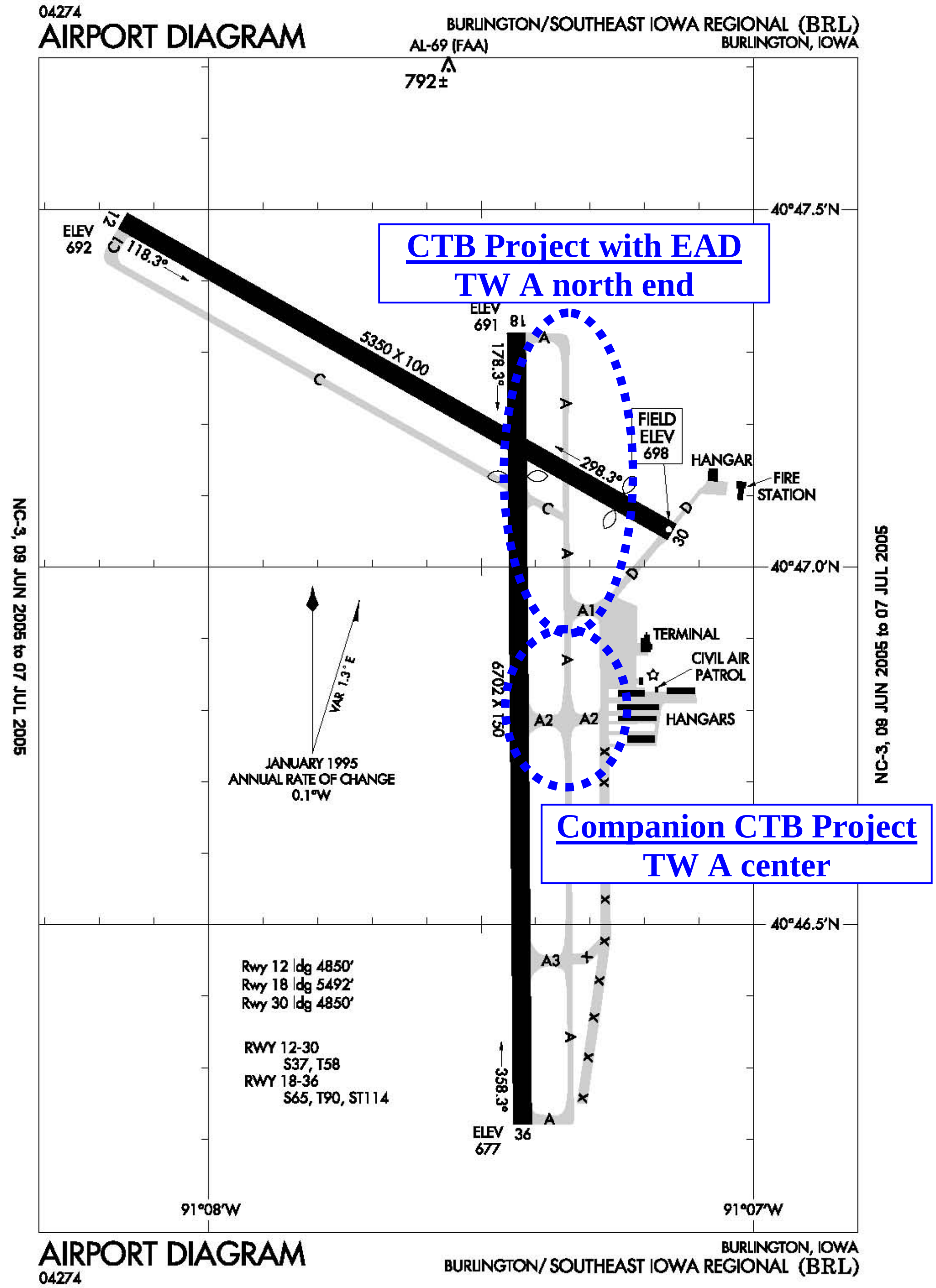

Figure 9. Location of pavement projects evaluated at Burlington/Southeast Iowa Regional Airport (map courtesy FAA Aviation System Standards).

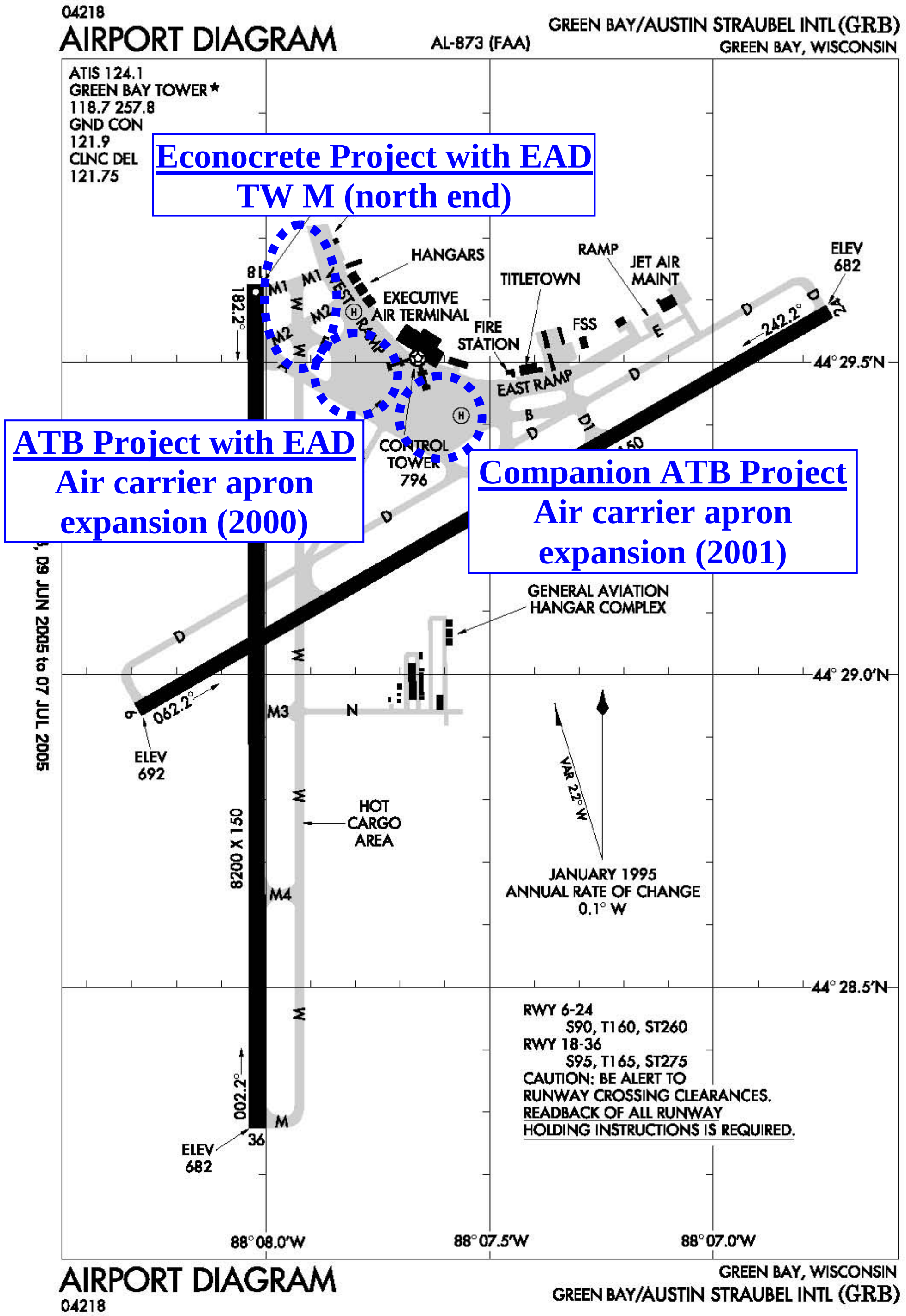

Figure 10. Location of pavement projects evaluated at Green Bay Austin Straubel Airport (map courtesy FAA Aviation System Standards).

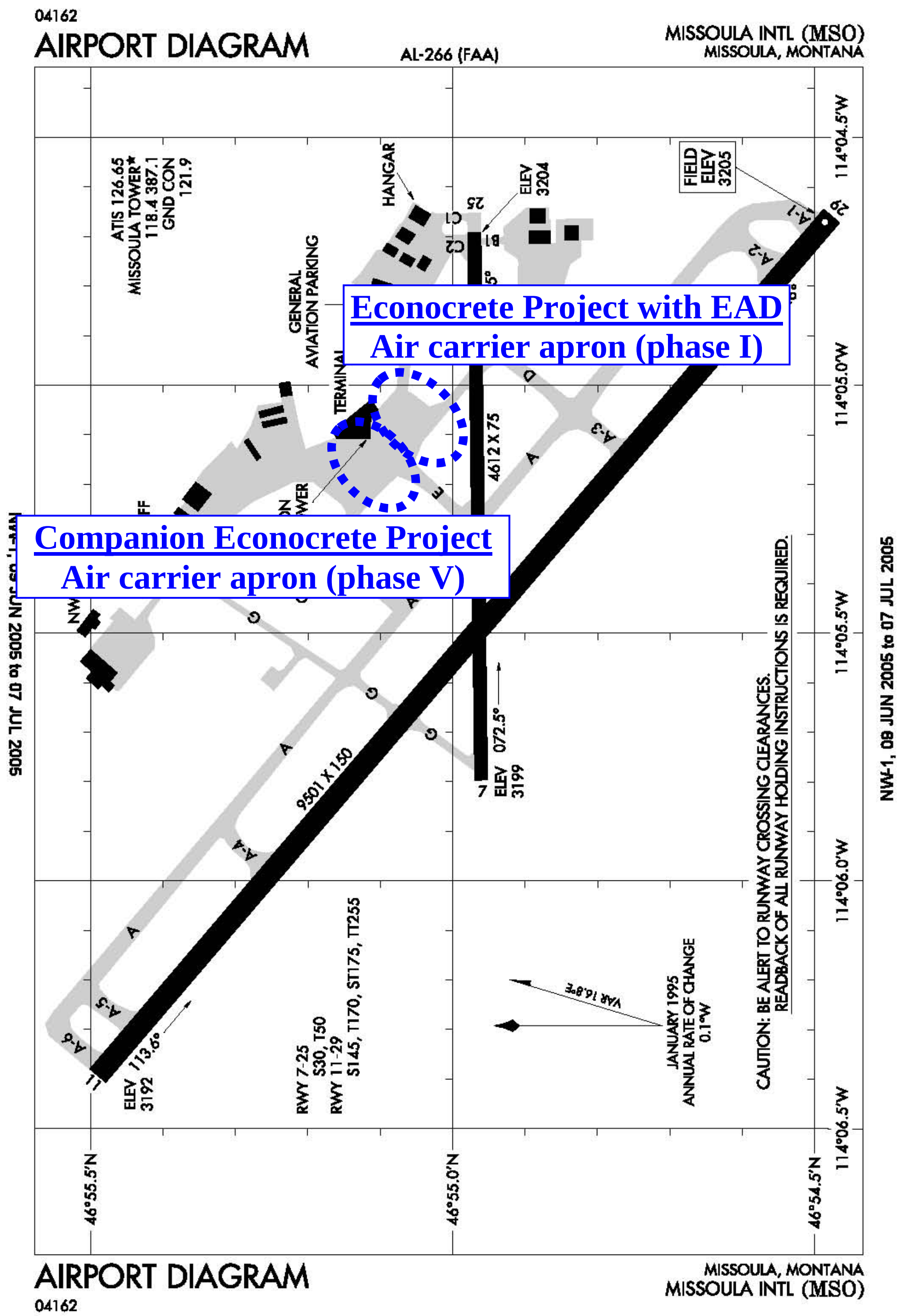

Figure 11. Location of pavement projects evaluated at Missoula International Airport (map courtesy FAA Aviation System Standards).

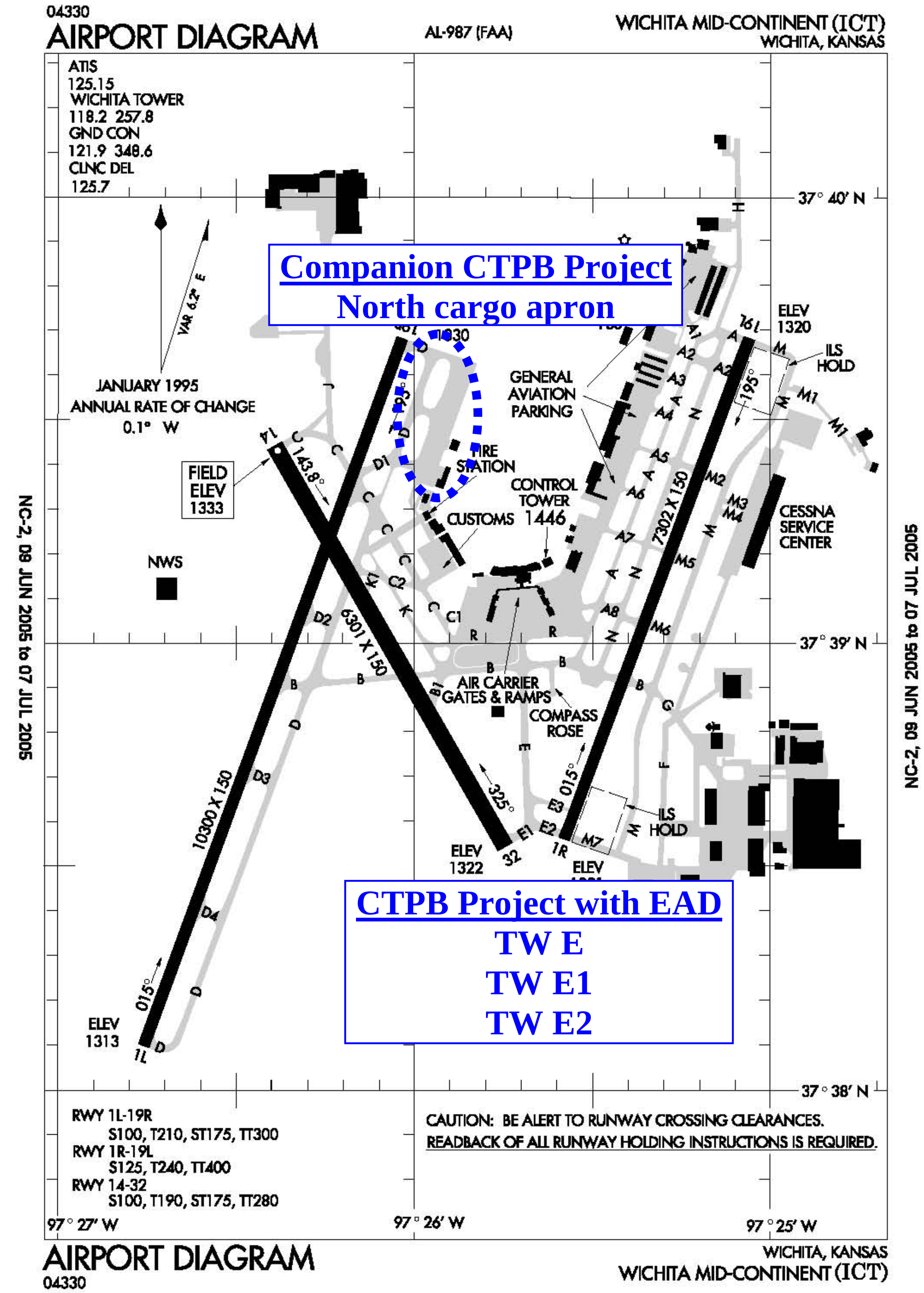

Figure 12. Location of pavement projects evaluated at Wichita Mid-Continent Airport (map courtesy FAA Aviation System Standards).

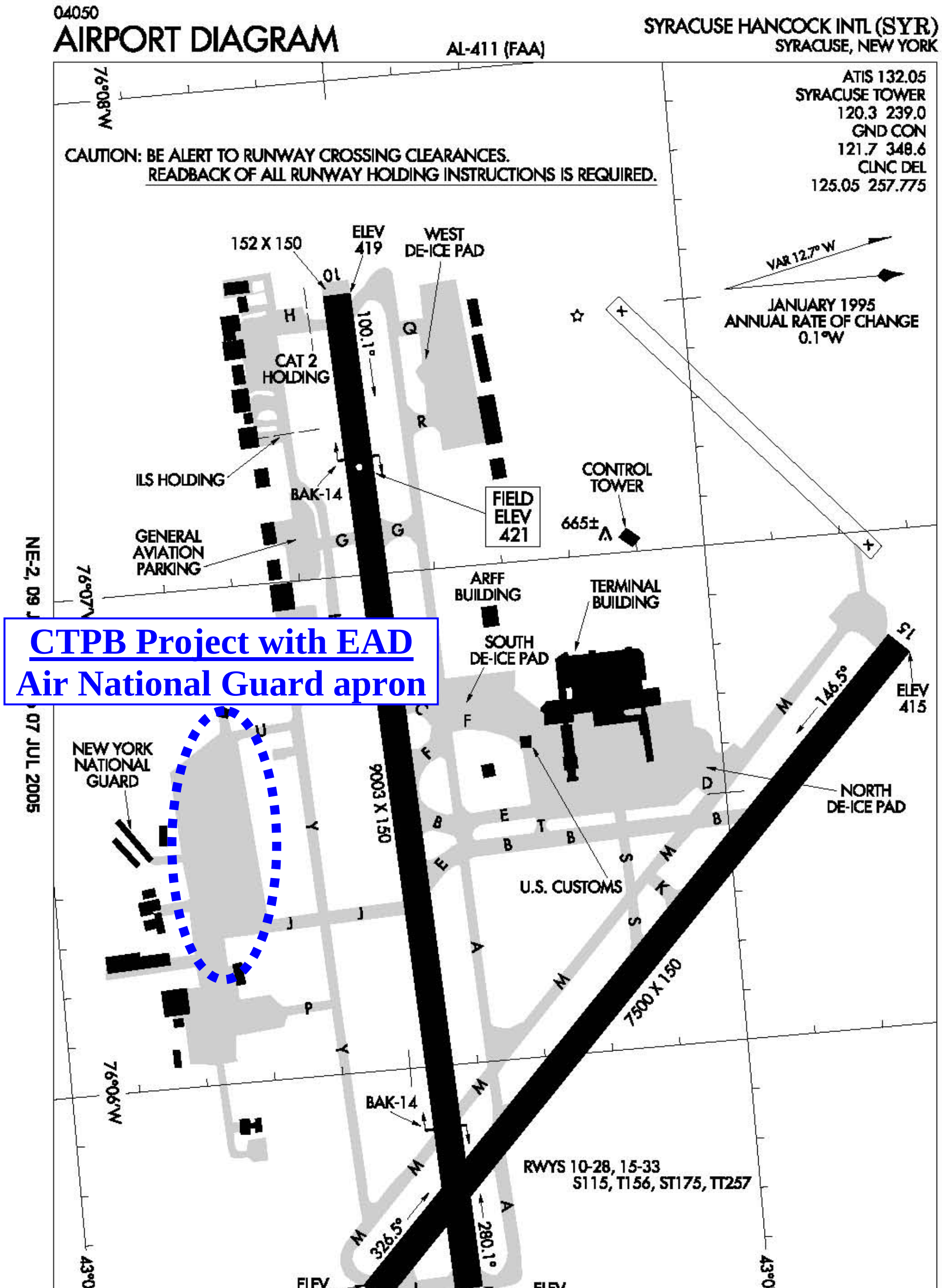

Figure 13. Location of pavement projects evaluated at Syracuse Hancock International Airport (map courtesy FAA Aviation System Standards).

CHAPTER 4. DATA COLLECTION AND DATABASE DEVELOPMENT

The task of gathering and organizing the design, construction, QA/QC, and performance data necessary for analysis, required a highly labor-intensive solicitation, collection, and database development effort. As described in the sections below, a series of steps and a number of individuals representing key stakeholders at each selected airport were involved in this effort.

4.1 DATA SOLICITATION

Data were collected and reviewed in order to develop a good understanding of the factors associated with successfully constructing PCC pavements on the various base types of interest. This information included detailed mix design data for the base and P-501 layers, construction methods used, climatic conditions, in-place material properties, specifics of early-age cracking (if experienced), and methods used to rectify early cracking. The process used for soliciting and compiling this information relied heavily on airport managers, design engineers, and contractors. It included formally requesting assistance, defining more specifically the data needs, collecting information through phone interviews, on-site visits, and interactive correspondence.

4.1.1 Data Requests

To ensure airport manager oversight and good participation, three steps were followed in requesting project information. First a formal introduction letter, jointly signed by IPRF and FAA, was mailed and/or emailed to the airport director, manager, or engineer describing the IPRF study and requesting cooperation in the data collection effort. Follow-up phone and/or e-mail correspondence was made with the airport directors, confirming the status of previously identified pavements, identifying other useful pavement sections, and determining the sources and locations of construction data for the projects.

Data request forms, like the one shown in figure 14, were sent to the airport director to help in identifying sources for the information. In many cases, the directors referred the data solicitation/collection process to the design and/or construction management firms involved in the project(s) of interest. Submission of the data request forms to these stakeholders followed thereafter, typically with support and encouragement from the directors.

4.1.2 Stakeholder Interviews

Phone interviews and/or on-site visits were made to collect the necessary information. In many cases, the combination of telephone contacts and mailed submissions from the consultant and/or contractor were sufficient to compile the necessary information.

Janesville / Southern Wisconsin Regional Airport (JVL) Pavement Sections of Interest

Section 1: Runway 4/22 (1000 ft at intersection of RW 4/22 and RW 14/32)
Design: 13" PCC; 4" Asphalt treated base, 6" crushed aggregate subbase.

Section 2: Runway 14/32 (5,200 ft on northwest end)
Design: 13" PCC; 4" Asphalt treated base, 6" crushed aggregate subbase.

Critical Information Needed
We are asking for information which will help lead to an understanding of the base layer design, materials, and construction factors that result in either good performance or early-age cracking.
The information and records that we are requesting include:

1. Detailed design records
   - Location and layout of the pavement section under consideration
   - Project plan sheets
   - Cross-section details including use of interlayers
   - PCC slab design (joint details, dowel and tie bar dimensions and spacing, etc.)
   - PCC and subbase mix design
2. Detailed materials and construction data and records
   - Construction dates
   - Detailed weather conditions for the construction date and the following 14 days
   - Applicable specifications used for pavement construction
   - Materials and QA/QC test results for PCC materials
     - Thicknesses
     - Strength (compressive or flexural)
     - Unit weight
     - Air content, slump, etc.
   - Materials and QA/QC test results for asphalt treated base
     - Thicknesses
     - Density
     - Asphalt content
   - Construction progress reports
     - Base and surface placement operations
     - Base layer compaction
     - Ambient conditions
     - Base and surface curing process
     - Cement type and content in base and surface course
     - PCC slab jointing operation (joint spacing, timing of sawcut, equipment used, and presence of dowels).
     - Bond breaker methods, materials, rate or thickness, problems
     - Hot- or cold-weather paving issues
   - Inspection reports
   - Daily project log books
   - Engineer's project notes
   - As-built project drawings
3. Personal experiences, special concerns/insights regarding design and construction
   - Observed failures and consequential repairs
   - Plausible causes of failure

Figure 14. Example list of requested documents and information.

During the phone interviews, the requested information shown in figure 14 was identified and the consultant and/or contractor then provided hardcopy/electronic files in follow-up correspondence. Formal interviews with roughly 50 individuals were conducted in the process of data collection. Informal, follow-up correspondences made for more in-depth information.

In some cases, staff availability, record complexity, project importance, and other factors made it necessary to conduct on-site visits to the airfield and/or the offices of the consultant and/or contractor. Site visits typically included discussions with airport managers, design engineers, field inspectors, and contractors. On-site records were reviewed and copies of critical documents were made or requested.

Discussions with the stakeholders also provided important insights into the construction processes and undocumented factors that may have contributed to the early-age cracking. Pavement projects to be included in the study were also typically inspected and photographed. On-site visits proved to be the most productive and efficient method for collecting project information.

4.2 DATA COLLECTION

Phone interviews provided information regarding the sources of data and discussions of the history and possible mechanisms of EAD for pavements with stabilized and/or permeable bases. Much of the data collected for analysis was compiled and shipped by the airport consultants and paving contractors. If on-site visits were conducted, the documents were normally provided at the time of the visit or were subsequently mailed. Each interview and site visit varied slightly in scope and process. Typical source and types of information provided by the contractor and consultant included those shown in table 8. Best possible use of the available information was made in fulfilling the project objectives.

Much of the daily and hourly temperature information was obtained from the U.S. Climatological Bureau web site (http://nndc.noaa.gov/?http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00128-PUB-S0001). Hourly climatic information from this site in text and PDF format were easily tabulated and plotted for review.

Table 8. Information source materials and data types.

Information Source	Specific Information Obtained
Design or As-Built Plans	• Layer thicknesses. • Slab layout. • Joint reinforcement. • Sawcut depth. • Material quantities. • Estimated schedule.
Contract Documents and Technical Specifications	• Mix design specifications. • Construction requirements. • Quality control/assurance tests and requirements.
Mix design information (base and PCC)	• Specific design base and PCC mix proportions, materials, gradations, and properties (strength, porosity, air content, slump, w/c ratio, etc.).
Quality control (QC) and quality assurance (QA) testing results	• Subgrade: Density, water content, thickness, lime content, gradations. • Base: Thickness, strength, density, porosity, gradations, stability, air voids. • PCC Surface: Thickness, strength, air content, slump, gradations.
Daily inspection logs	• Construction schedule. • Weather conditions. • Problems encountered and resolutions. • Equipment and methods used.
Photos of construction	• Documentation of methods used for construction.
Crack location maps and photos	• Listing of the number and location of cracks. • Verification of the orientation, extent, and severity of the cracking.
Correspondence regarding early cracking	• Documentation of crack formation and locations. • Discussion of possible causes and forensic evaluation results. • Resolution methods and effectiveness.

4.3 DATABASE DEVELOPMENT

4.3.1 Overview of Database

For each airfield project evaluated as part of this study, a summary report documenting all the information of relevance to the analysis was compiled. The data elements summarized included the following, as a minimum:

- Airport overview and layout.
- Summary of interviews.
- Details of typical sections.
- Joint layout and design.
- Applicable specifications and modifications.
- Construction methods.
- Pavement cracking description (if present).
- Reported personal experiences and results.

- Schedule of construction and ambient conditions.
- Materials information including laboratory, field testing, and QA/QC test results.
- Perspective of the stakeholders concerning the causes of cracking and the project team's interpretation.

The summarized data were stored in an electronic format using the Microsoft Excel® and Microsoft Access® database tools. A unique table was created for each base type of interest (i.e., in all, there were six tables in the database). Each record within each of the tables pertained to a unique section that was identified and reviewed under this study. The data collected through the stakeholder interviews were processed for each record to determine the key parameters/fields of interest to the data analysis procedure. These processed data were entered into the database and can be broadly grouped under the following categories:

- Section identification information.
- Pavement design information.
- Paving materials information.
- Paving related factors.
- Construction related factors.
- Distress information.

4.3.2 Database Fields

The following is a list of the data fields contained in the project database. This list is modeled after the recommendations presented in the *Best Practices for Airport PCC Pavement Construction* manual (Kohn et al., 2003) (as part of the discussion of the data elements to be studied to determine the causes of early-age distress), with some modifications to suit this study. Note that while several fields are common across different base types, some differences do exist between them.

- Section identification information (all sections)—Unique section identification number (combination of airport where the section belongs, feature type, and year built), relevant AIP number, location in the airport.
- Distress information (only sections with distress)—Presence of surface distress, predominant type of distress (random, longitudinal, transverse, corner, diagonal), distress quantity, additional surface distress information, presence and extent of shrinkage cracking in base.
- Design Information (all sections)
    - Typical section details—layer number (numbering starts with subgrade as 1) as-built thickness, material types, and descriptions.
    - Joint design—transverse and longitudinal joint spacing, load-transfer mechanisms (at a typical location within the project), and sawcut depth (as a function of surface layer thickness).
    - Foundation type—soil class and description, CBR, k-value, density, moisture content, and other information.

- Materials Information
  - PCC layer (all sections)—number of mixes used, cement type and source (for representative mix), supplementary cementitious materials (i.e., type of fly ash or slag), cement factor, supplemental material content as a fraction of total cementitious material, water cement ratio, total water content, and paste content.
  - PCC aggregates (all sections)—aggregate information (fine aggregate gradation type [with respect to the ASTM C 33 curve), coarse and fine aggregate type, sieve analysis, source, amount, key sieve information for the combined aggregate gradation, and mineral admixture type and content.
  - Cement type and content (for sections containing CTB, econocrete, or CTPB).
  - Gradation and asphalt content (for sections containing ATB or ATPB).
- Paving conditions
  - Minimum, maximum, mean, and median of ambient and concrete temperatures during paving (all sections for PCC and base layer paving)—3 days prior to construction to 14 days after, where possible.
  - Hot-weather or cold-weather indices.
    - Hot-weather index (all sections for P-501 layer paving)—determined according to if, during paving, there were 3 continuous days where the average daily temperature exceeded 77°F (25°C) or if the temperature over a continuous 12-hr period was greater than 86°F (30°C) for 3 days in a row (particularly around the time early-age cracking was noticed).
    - Cold-weather index—determined according to if, during paving, there were 3 continuous days where the average daily temperature was below 40°F (4°C) or if the temperature over a continuous 12-hr period was greater than 86°F (30°C) for 3 days in a row (particularly around the time early-age cracking was noticed).
  - Presence of large temperature swings (all sections for P-501 layer paving)—particularly for sections with early-age cracking.
  - Minimum, maximum, mean, and median of rainfall data during paving (3 days prior to construction to 14 days after).
  - Wind speed and relative humidity (particularly for sections with early-age cracking).
- Construction data
  - Paving schedules (all sections and surface and base paving)—particular attention to delineate paving of P-501 for sections with early-age distress.
  - Bond breaker information (all sections)—presence, type, and application rate.
  - Base jointing information (for sections containing CTB or econocrete).
  - Base surface condition prior to paving (typical or milled texture).
  - Method of curing (type of agent, rate of application).
  - Number of days of moist curing (if applicable).
  - PCC layer—timing and equipment used for first sawcut (early entry versus traditional walk behind) and depth of sawcut.
  - QA or QC testing (mostly QA testing was used)
    - P-501 (all sections)—mean and standard deviation of 28-day flexural strength, thickness, slump, and gradation indices where available (focused around cracked areas for sections with EAD and more general information for companion sections).

- Econocrete (P-306) base—mean and standard deviation of 28-day compressive strength and thickness.
- CTB (P-304)—mean and standard deviation of density, moisture content, 7-day compressive strength, and thickness.
- ATB (P-401)—mean and standard deviation of gradation indices, asphalt content, and thickness.
- CTPB—mean and standard deviation of gradation (particularly D_{10}, C_u, and C_z), permeability, compressive strength, and thickness.

- Other layer information
  - Thickness and strength information (where applicable) of other layers in the typical section including separation layers for CTPB and ATPB.

It should be noted that some of the data fields contained continuous variables (or numerical values), while others used categorical values.

4.3.3 Computed Parameters

From the raw data presented, a few key computed parameters were derived to help evaluate the contributing factors leading to cracking for the EAD and companion projects. The computed parameters include the following:

- Slab length (longer dimension) to width (shorter dimension) ratio (L/W).
- Slab length to radius of relative stiffness (L/l) ratio.
- Fineness modulus (FM) of P-501 fine aggregate.
- Coarseness factor for the P-501 combined aggregate computed as follows:

$$CoarsenessFactor = 100\left(\frac{Percent \quad Retained \quad above \quad 3/8-in \quad (9.5mm) \quad Sieve}{Percent \quad Retained \quad above \quad No.8 \quad (2.36mm) \quad Sieve}\right) \qquad \text{Eq. 1}$$

- Workability factor (percent passing No. 8 (2.36-mm) sieve) of the combined aggregate.
- Coefficient of uniformity (C_u) and coefficient of gradation (C_z) for unbound permeable bases.
- Effective grain size corresponding to size passing 10 percent (D_{10}) and estimated permeability (k) for treated aggregates. Note that an estimate of k was developed based on the following equation from Moulton (1980):

$$k = [(6.214 \times 10^5)\, D_{10}^{1.478}\, n_{adj}^{6.654}] / P_{200}^{0.597} \qquad \text{Eq. 2}$$

where: k = Permeability, mm/s.
D_{10} = Effective grain size corresponding to size passing 10 percent.
n_{adj} = Adjusted porosity of the treated permeable base, which is a function of porosity of the unbound aggregate structure and the binder content.
P_{200} = Percent passing No. 200 (75 µm) sieve.

The adjusted porosity in the above equation was based on the effective porosity of the aggregates after accounting for the effect of binder content in filling up the voids structure. This latter quantity was empirically determined from the known field density of the permeable base and the percent binder (cement or asphalt) by weight.

- Volume of total mortar content of the concrete mixture expressed as a percentage of the total volume. This is defined as the combined volume of the cementitious materials, sand (passing the No. 8 (2.36 mm) sieve on the combined aggregate gradation), water, and entrapped air content.

Keeping in mind the objectives of the project, the data collection exercise was limited to the most significant and relevant data items for each base type. The key data items collected were based on the discussions provided in the *Best Practices for Airport PCC Pavement Construction* manual (Kohn et al., 2003), as well as the design procedures developed by the FAA (including State and regional office guidance documentation) and the DOD publications. These are listed in table 9 for each of the base types under consideration in this study and were collected as a minimum.

Table 9. Key data items of interest for each base type under consideration.

Key Data Item	PCC (P-501)	CTB (P-304)	Econocrete (P-306)	ATB (P-401)	CTPB	ATPB
Thickness	X	X		X	X	X
28-day Flexural Strength—Design + QA/QC	X					
Compressive Strength—Design + QA/QC		X[1]	X[2]		X	
Density—Design + QA/QC		X		X		
Moisture Content—Design + QA/QC		X				
Coarse Aggregate Type and Gradation—Design + QC/QA	X					
Fine Aggregate Type and Gradation—Design + QC/QA	X					
Combined Aggregate Gradation—Design + QC/QA	X	X	X	X	X	X
Joint Spacing (transverse and longitudinal)	X		X			
Joint Design (transverse and longitudinal)	X		X			
Concrete Mixture Properties—Design + QA./QC	X	X	X		X	
Asphalt Mix Properties—Design + QC/QA				X		X
Plastic Concrete Temperature	X					
Ambient Paving Conditions (temperatures[3], relative humidity, wind speed, rainfall)	X	X	X	X	X	X
Placement Season	X					
Hot- and Cold-Temperature Paving Issues	X			X		X
Curing Type and Process	X	X	X		X	X
Timing of Joint Sawing	X					
Depth of Sawcut	X					
Bond Breaker		X	X		X	X
Surface Condition Prior to Paving		X	X	X	X	X
Base Permeability Indicators					X	X

1. 7-day values required.
2. 7- and 28-day values.
3. Includes temperature.

CHAPTER 5. EMPIRICAL DATA ANALYSIS

5.1 INTRODUCTION

Data analysis was split into two parts—empirical analysis and theoretical analysis. Empirical analysis consisted of a thorough review and analysis of the information gathered on each of the EAD and companion projects for which detailed information was gathered in this project. The objective was to answer the following types of questions to the best degree possible:

- For each section with EAD, what specific environmental conditions and design, materials, and construction factors contribute to EAD?
- How do the parameter values of these factors compare between EAD and non-EAD companion projects?
- What combinations of factors increase the risk of EAD?
- What are the optimum base qualities and characteristics that mitigate EAD?

5.1.1 Identification of Triggers and Variants

An initial review of the data collected revealed that, when certain ambient conditions (i.e., temperature, moisture, and wind speed during or just after placement of the PCC pavement surface) combine with certain design, materials, and construction factors, the likelihood of the occurrence of EAD in rigid pavements systems increases dramatically. For the purposes of this study, these ambient conditions are termed as *triggers* and pavement factors are termed *variants*.

Triggers are the forcing functions that induce deformations in the PCC slabs. They are mostly environment-related and include the following:

- Large Ambient Temperature Swings—For the purposes of this research, a large temperature swing is considered as a change in ambient temperature of 25°F (14°C) or greater shortly after initial set of the concrete. Such swings, which are most prevalent in northern and northeastern climates during late fall or spring construction, can be brought on by a sudden rain or snow event shortly after PCC placement. The effect of a large ambient temperature swing is one that induces a steep thermal gradient in the young PCC slab. This causes curling deformations which, when restrained, leads to stresses.
- Hot Weather—Of particular interest in this category are ambient temperatures greater than 90°F (32°C). Paving under these conditions requires special precautions, which, if ignored, can lead to excessive drying shrinkage in the PCC slabs and moisture warping-induced deformations and stresses. The worst possible combination is to place the concrete at such a time that the maximum internal concrete temperature due to hydration is reached during the hottest part of the day (e.g., morning placements on a hot, clear day). Even though these conditions are prevalent throughout the country during the normal construction season, they more frequently occur in the hotter parts of the West and South.
- High Surface Evaporation Rate—Rates of surface evaporation exceeding 0.1 lb/ft^2 (0.5 kg/m^2) can trigger cracking in the PCC slabs (Kosmatka et al., 2002). High evaporation

rates can occur due to a critical combination of high ambient temperatures and concrete temperatures, high wind speeds, and low ambient relative humidities. High surface evaporation rates generally result in plastic shrinkage cracking, however, they can also lead to early-age cracking due to their ability to cause differential volumetric shrinkage through the slab (slab warping). For this study, evaporation loss quantities for each project reviewed were determined using the Hiperpave II program (Hiperpave reference) and local climatological information for a given project obtained from the National Climate Data Center (NCDC) (http://www.ncdc.noaa.gov).

If the deformations induced by the *triggers* are restrained, as they usually are via the weight of the slab, slab/base friction forces, and embedded tie/dowel bars, increased stresses in the PCC occur. When the imposed stresses exceed the strength of the young concrete material, uncontrolled cracking can occur.

The magnitude of induced stresses in the PCC is controlled by the pavement design, materials, and construction variants existing on any given project. The term *variant* is used to describe these factors, because they can be varied as needed at by the designer, engineer, or contractor to mitigate EAD and improve long-term performance. Critical *variants* that were considered in this study for each project reviewed are discussed below, along with notations concerning their desirable parameter values or ranges:

- Design Variants.
  - PCC slab sizes:
    - Length to width (L/W) ratio—values greater than 1.25 are considered excessive, since they can lead to a biased stress concentration in one of the axes during bending.
    - Maximum slab dimension—dimensions greater than 5*l[1] will lead to excessive curling/warping slab stresses.
  - Base thickness—a base thickness of 6 in (152 mm) is considered adequate under PCC pavements; thicker bases increase the base's flexural rigidity and hence the curling stresses in the PCC slabs.
- Material Variants.
  - Strength of base material—7-day compressive strengths of cement-stabilized bases in excess of 1,000 lb/in^2 (6,895 kPa) have been found to be detrimental to EAD performance; they have a similar effect as the base thickness.
  - PCC cement factors—concrete made with cement factors greater than 400 lb/yd^3 (236 kg/m^3) undergo rapid strength gain due to increased heat of hydration. High cement factor concrete also has a tendency to require more water in the mix and, hence, an increased shrinkage potential. Increased shrinkage potential and high heat of hydration results in an increased risk of EAD in young concrete. High strength concrete also typically has a higher modulus and higher coefficient of thermal

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[1] $l = \left(\frac{E_{PCC} h^3}{12k(1-\nu^2)} \right)^{1/4}$

l = radius of relative stiffness; E_{PCC} = modulus of elasticity of concrete; v = Poisson's ratio of PCC; h = PCC slab thickness, k = modulus of subgrade reaction.

expansion; both of these further aggravate the stresses in the PCC slab. Cement factors in airfield pavement construction average around 600 lb/yd^3 (354 kg/m^3) due to an over-emphasis on strength in the specifications. This leads to a situation aptly summed up as "too strong, too fast."

- PCC strength gain—any factor affecting early strength gain can influence EAD, particularly under certain paving conditions (e.g., use of flyash when cooler ambient temperatures are prevalent can lead to lower initial strength gain).
- Slab/base interface friction—high-strength cement-stabilized bases typically provide a high-degree of slab/base interface bond and friction. In permeable bases, the concrete paste can penetrate the top surface (approximately, 1 to 2 in [25 to 51 mm]), which also increases base interface bond and friction. Similarly, milled asphalt bases offer a greater restraint. A high degree of restraint causes higher stresses at the slab bottom due to restraint and also renders the sawing ineffective; both of these increase the risk of EAD.
- PCC shrinkage potential—materials prone to high shrinkage can affect EAD development. Shrinkage potential is governed by the following factors:
  - Cement factor (previously discussed).
  - Mortar volume—volume proportion of cementitious material, sand (passing No. 8 [2.36 mm] sieve on the combined aggregate gradation chart), water, and entrained as well as entrapped air, to the total volume of concrete. As the mortar volume increases beyond a certain threshold limit (subjectively set at 60 percent for this study), the shrinkage potential of the PCC increases.
  - Water reducing admixtures—some types of water reducing admixtures affect shrinkage volume of concrete.
  - Workability box parameters—workability and coarseness factors (WF and CF, respectively) derived from the combined aggregate gradation (as discussed in chapters 2 and 3).
  - Total water—to prevent excessive volumetric shrinkage, the total amount of water in the PCC mix must be restricted. For this study, a value of 250 lb (113 kg) was subjectively used.
  - Grading of the sand and fineness modulus (FM)—gap-graded fine sands increase water demand and hence shrinkage potential. Generally, for high-cement factor concrete (>400 lb [181 kg] cement factor), an FM in the range of 3.1 to 3.4 and a well graded, coarse sand is preferred to mitigate shrinkage.

- Construction Variants.
  - Timing and depth of sawcuts—late or shallow sawcutting of PCC joints increases probability of random cracking. PCC placed over cement stabilized, permeable bases, or rough-textured asphalt bases may require deeper sawcuts (one-third the slab thickness), due to the bonding or restraint forces present at the slab/base interface.
  - Curing of PCC—timely and adequate curing of the concrete is very important to help the concrete retain the internal moisture and make it less susceptible to drying shrinkage. Curing is particularly important during hot-weather paving or when excessive evaporation losses are anticipated.
  - Surface condition prior to PCC placement—high base restraint and the presence of shrinkage cracks in the base increases the risk of EAD. Milling large areas of CTB or ATB to establish grade is not recommended.

Figure 15 presents a chart of the interaction between the various triggers and variants that could lead to EAD in PCC pavements.

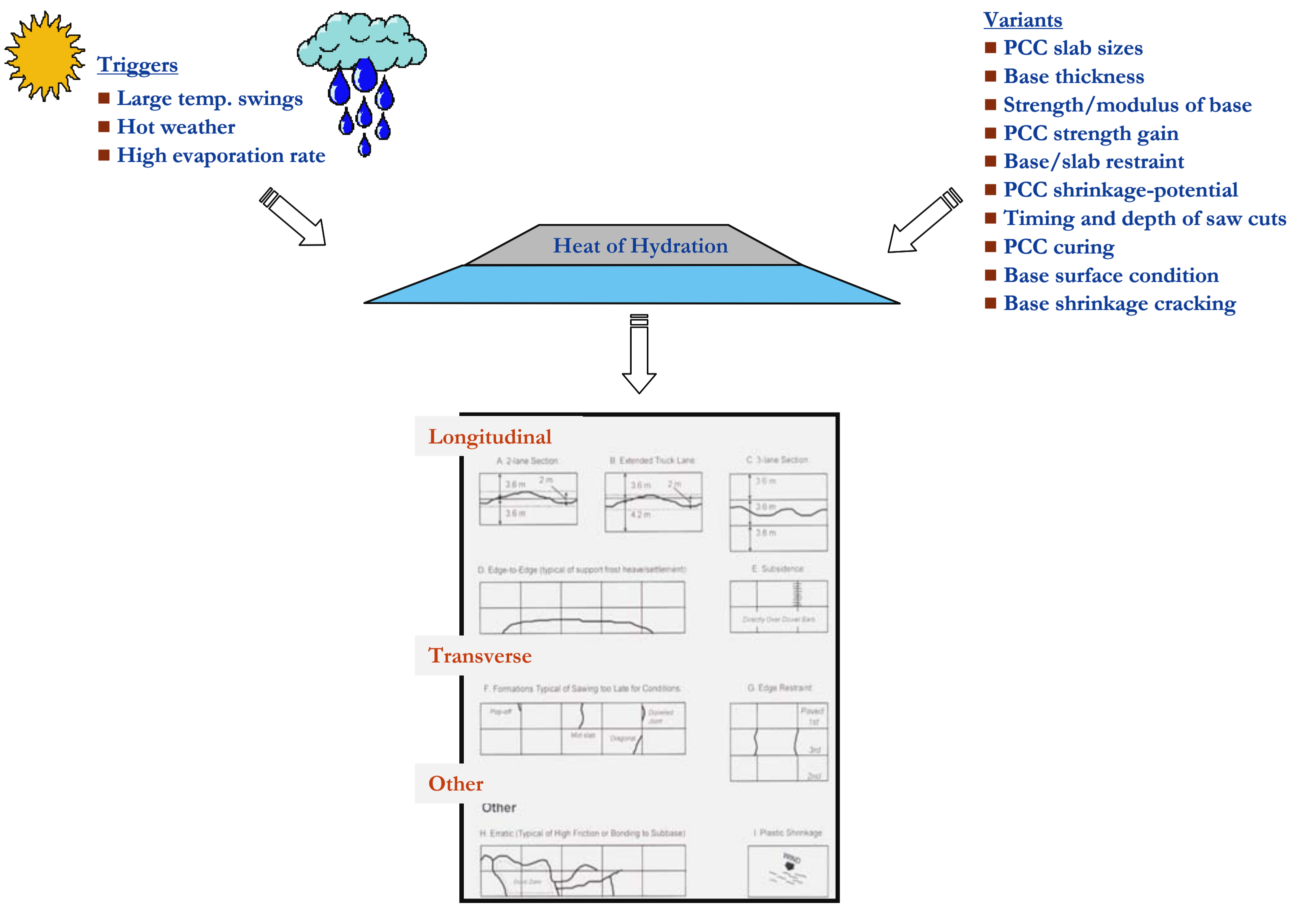


Figure 15. Triggers and variants contributing to EAD in PCC slabs built on stabilized and drainable bases.

5.1.2 Step-by-Step Empirical Analysis Approach

The notion that certain critical combinations of the triggers and variants should be present for the development of EAD in PCC pavements has been a part of conventional wisdom for a long time. The empirical analysis performed in this study is aimed at verifying this hypothesis through detailed reviews of projects with and without EAD. As part of this effort, the data analysis undertaken was performed separately for each of the five major base types studied—CTB, econocrete, ATB, CTPB, and ATPB (note: although data on UPB projects were gathered and reviewed, this base type was not a major focus). For each selected project with a given base type, the following activities were conducted in the sequence noted:

1. Prepare a summary of the key design, materials, construction, and environmental factors of interest. Contrast the parameter values of each of these factors with recommended best practice in the industry (derived from literature) where appropriate or feasible.
2. Compare the key factors of early-age distressed pavement sections with "on-site" and "off-site" companion sections that do not have distress.
3. Prepare a list of factors that could have contributed to the early cracking problems along with the most probable causes based on the observations from step 2.

It should be noted that this analysis is limited to the identification and documentation of triggers and variants that contribute to EAD. A detailed forensic investigation of the factors causing the EAD was not an objective of this research.

5.2 REVIEW OF CEMENT-TREATED BASE (CTB) PROJECTS (P-304)

A total of nine pavement projects with a CTB layer were short-listed for extensive data collection and evaluation. Four of these projects had exhibited EAD. Three of the remaining five projects, which did not experience EAD, were designated as "on site" companions—projects constructed at the same airfield as an EAD project, with similar designs and construction conditions, but using slightly altered design, materials, construction parameters, or different weather conditions that prevented early distress. For the purposes of the empirical analysis, only the four EAD projects and the three "on-site" companion projects were selected.

5.2.1 Summary of Key Variables

Summaries of the parameter values/descriptions of the key trigger factors and variants for each of the selected airfield projects are presented in table 10. Table 11 summarizes the Baton Rouge Airport Runway 4L-22R 2003 reconstruction project (experienced EAD). Table 12 summarizes the Northwest Arkansas Airport 1997 new construction project (experienced EAD) and the terminal apron expansion project at the same airport undertaken in 1998 (did not experience EAD). Table 13 presents information regarding the Omaha-Eppley Taxiway A reconstruction project undertaken in 1998 (experienced EAD) as well the Runway 14L-32R construction project in 2001 (did not experience EAD). Table 14 presents details regarding the Southeast Iowa Regional Airport Taxiway A relocation project undertaken in Phase I (experienced EAD) and Phase II (did not experience EAD). Also provided in each of these tables are the recommended threshold values for the various triggers and variants which, if exceeded, are deemed to increase the likelihood of EAD.

Table 10. List of projects with a CTB layer selected for detailed study.

Section Location	Feature of Interest	Year Built	Early Cracking Present?	Design
Baton Rouge Metro Airport (BTR) Baton Rouge, LA	• Runway 4L-22R	2003	Yes	15 in PCC Surface 6 in CTB Compacted subgrade
Northwest Arkansas Regional Airport (XNA) Bentonville, AR	• Runway 16-34 • Parallel & Connector Taxiways • Terminal Apron	1997 to 1998	Yes	15 in PCC Surface 6 in CTB 4 in CTPB Geotextile fabric Compacted Fill
Northwest Arkansas Regional Airport (XNA) Bentonville, AR	• Expanded Terminal Apron • Connector Taxiways	2003	No	15 in PCC Surface 6 in CTB 4 in CTPB Geotextile fabric Compacted Fill
Omaha Eppley Airfield (OMA) Omaha, NE	• Taxiway A	1998	Yes	17 in PCC Surface 6 in CTB 6 in Crushed Agg. Base 17 in Granular Subbase Geotextile fabric Compacted Subgrade
Omaha Eppley Airfield, (OMA) Omaha, NE	• Runway 14L-32R	2002	No	17 in PCC Surface 6 in CTB 6 in Crushed Agg. Base 17 in Granular Subbase Geotextile fabric Compacted Subgrade
Southeast Iowa Regional Airport (BLR) Burlington, IA	• Taxiway A, Phase I	2001	Yes	8.5 in PCC Surface 9 in CTB Silty Clay Subgrade
Southeast Iowa Regional Airport (BLR) Burlington, IA	• Taxiway A, Phase II	2002	No	8.5 in PCC Surface 9 in CTB Silty Clay Subgrade

1 in = 25.4 mm

Table 11. Summary and comparison of data from Baton Rouge Metropolitan Airport EAD project (2003) with recommended practice.

	Key Data Item	BTR EAD Project (Runway 4L-22R - 2003)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes			Mainly transverse cracks (7% total panels). Mostly in outer two lanes.
	Ambient PCC Paving Conditions	Max. Temp – 90°F (median) Min. Temp – 73°F (median)	Good hot- and cold-weather management plan and execution.	Yes (initially)	Hot temperatures and low ambient relative humidities increase evaporation loss. Operations changed to nighttime which seemed to have stopped cracking.
		Low relative humidities (20 to 30%)			
	PCC Placement Season	Summer			
Design Variants	Thickness	PCC Design – 15 in Actual – 16 in Average (Avg.) Actual– 0.9 in Std. Dev (SD)			The as-built PCC thickness greater than as-designed. If grade tolerances are met, this implies a high variability in the underlying layer thicknesses.
		CTB Design – 6 in Actual Avg. – NA Actual Std. Dev – NA	CTB thickness: 6 in	No	OK
	Joint Spacing	Trans. Jt. Spacing (L) – 20 ft Long. Jt. Spacing (W) – 18.75 ft	Max. dimension $\leq$ 20 ft	No	OK, although in combination with hot weather and high CTE PCC coarse aggregate, long panels may have a detrimental impact.
			L/W < 1.25	No	
			Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 750 lb/in^2	650 lb/in^2 (28-day)		OK
		Actual – 770 lb/in^2 (avg.) Actual – 33.7 lb/in^2 (std. dev.)			The as-built as and as-designed flexural strengths are quite close. The as-built strength variability is typical.
	7-day CTB Comp. Str.	Mix design – 761 lb/in^2	Between 500 and 1,000 lb/in^2	No	OK
	CTB Density	Max. Dry Density (MDD) – 116.4 lb/ft^3 Actual – 101% (Avg.) Actual – 1.3% (SD)	Actual field density – 97% to 98% MDD		Higher densities imply higher strength/stiffness base. Can increase curling/warp stresses in the PCC pavement.
	CTB Moisture Content	OMC – 13% Actual – 12% (Avg.) Actual – 1% (SD)	Up to + 2 percent for summertime construction		Hot weather and below optimum moisture led shrinkage cracking in CTB. Very high moisture due to a 10 percent cement factor used for CTB. Shrinkage cracking potential in base is high.
	PCC Mixture Properties	Cement Type – Type I			
		Cem. Factor – 517 lbs/yd^3 Pozz. Content – 15% Flyash (FA) "C"	Lowest cement content to achieve strength, durability, and shrinkage char.	Yes	Cement factor > 400 lb/yd^3.
		w/c ratio – 0.42			
		Total Water – 217 lbs.	Less than 250 lb	No	Low water content and paste volume offsets concerns regarding shrinkage.
		Mortar Volume – 53 percent	Less than 60%	No	

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 11. Summary and comparison of data from Baton Rouge Metropolitan Airport EAD project (2003) with recommended practice (continued).

	Key Data Item	BTR EAD Project (Runway 4L-22R - 2003)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Fine Aggregate Gradation	Type – Concrete Sand (fine)	Coarse sand	Yes	Fine sand increases water demand and shrinkage potential.
		Passing No. 50 sieve – 30%	Lower limit of ASTM C33 5 to 30 percent band preferred	Yes	
		Fineness Mod.– 2.4	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Gravel			High coefficient of thermal expansion (CTE) aggregate which can lead to higher curling/warping stresses.
	PCC Combined Aggregate Gradation—Design	Workability Factor (WF) – 34.8	WF > 29 & CF < 75	No	Potential for segregation exists if mixture is not well controlled in the field since the CF is close to the threshold value.
		Coarseness Factor (CF) – 73.6		No	
		Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing– White-pigmented liquid membrane forming curing compound (LMFCC) PCC Curing Rate >1 gal/150 ft^2	Fog spraying and white pigmented curing compound preferred in hot weather.	No	Contractor switched to nighttime paving to offset issues with regard to hot temperature placement and evaporation loss.
		CTB Curing– LMFCC CTB Curing Rate >1 gal/200 ft^2		No	
	Initial Sawcut	Equipment– Traditional	Early entry or traditional wet saws.	No	Contractor had problems with sawing at the start, but all went well after this was rectified.
	Sawcut Depth	Depth – D/4	D/3	Yes	
	Bond Breaker	1-coat liquid membrane forming CC applied at 1gal/200 ft^2	Double coat wax-based curing compound	No	OK if CTB was cured with the same.
	CTB Surface Condition Prior to Paving	Surface was milled prior to paving. Surface wetted prior to PCC paving, but noted as being perhaps inadequate. Shrinkage cracks present in CTB.	Use of trimmer and additional coat of curing compound recommended to obtain a smooth surface.	No	Milled Surface increases base restraint. Shrinkage cracks were covered with 30-lb felt paper. Shrinkage cracks in CTB did not match cracks in PCC always.
	CTB Quality Acceptance Program	Acceptance based only on density measurements (sliding pay factor scale), and surface evenness.	Thickness, density, grade, surface evenness		Typical QA program.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 12. Summary and comparison of data from the Northwest Arkansas Regional Airport EAD (1997/98) and on-site non-EAD companion (2003) projects with recommended practice.

	Key Data Item	XNA EAD Project[1] (1997 to 1998)	XNA non-EAD Project [2] (2003)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Nearly 5.5% slabs cracked for the EAD section. Most cracking in Rwy and Twy B. Crack orientations were corner, trans., long., diagonal, and random. Most cracking in Rwy and Twy B.
	Ambient PCC Paving Conditions	Max. Temp – Varied widely Min. Temp – Varied widely (Aug/Sept)	Max. Temp – 71°F Min. Temp – 50°F	Good hot- and cold-weather management plan and execution.	Maybe (plans found in specs; records not available to follow execution)	Hot temperatures and evaporation loss could be trigger factors for the EAD section. Large temp. swings cause steep gradients in PCC slabs. This could be a trigger factor for non-EAD section; however, precautions were taken.
		Hot paving conditions; several > 90°F days during Rwy and Twy B constr.	No hot or cold 17 temp. swings > 25°F.			
	PCC Placement Season	Summer/Fall/Winter Rwy/Twy B in late Summer	Fall			
Design Variants	Thickness	PCC Design – 15 in Actual – 15.5 in (avg.) Actual– 0.2 in (SD)	PCC Design – 15 in Actual – 15.7 in (avg.) Actual– 0.64 in (SD)			The as-built PCC thickness greater than as-designed. If grade tolerances are met, this implies a high variability in the underlying layer thicknesses.
		CTB Design – 6 in Actual Avg. – NA Actual Std. Dev – NA	CTB Design – 6 in Actual Avg. – NA Actual Std. Dev – NA	CTB thickness: 6 in	No	OK
	Joint Spacing	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 18.75 ft	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 18.75 ft	Max. dimension ≤ 20 ft.	No	OK, although in combination with hot weather and a rough base, long panels may have a detrimental impact.
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 750 lb/in^2	Mix Design – 710 lb/in^2	650 lb/in^2 (28-day)		Eight (8) PCC mixes employed on the job. The number shown is a typical value.
		Actual – 816 lb/in^2 (avg.) Actual -- 63 lb/in^2 (SD)	Actual – 871 lb/in^2 (avg.) Actual -- 58 lb/in^2 (SD)			The as-built strengths are greater than as and as-designed strengths.
	7-day CTB Comp. Str.	Design – 940 to 1230 lb/in^2	Design – 1205 lb/in^2	Between 500 and 1,000 lb/in^2	Yes	Six (6) CTB mixes employed on the job. The strength values are excessive for both EAD and non-EAD projects indicating a very strong base layer.
		Actual –1204 lb/in^2 (avg.) Actual – 414 lb/in^2 (SD)	Actual –1099 lb/in^2 (avg.) Actual – 530 lb/in^2 (SD)			
	CTB Density	MDD – 133 to 137 lb/ft^3 Actual – 98.5% MDD (avg.) Actual – 1% of MDD (SD)	MDD – 139 lb/ft^3 Actual – 101% MDD (avg.) Actual – 4% MDD (SD)	Actual field density – 97% to 98% MDD		OK
	CTB Moisture Content	OMC – 8 or 8.5 % Actual – 7.9% (avg.) Actual – 0.9% (SD)	OMC – 4.2 to 6.1 % Actual – 5% (avg.) Actual – 0.8% (SD)	Up to + 2 percent for summertime construction		Hot weather and high base moisture content can lead to shrinkage cracking in the CTB.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

1 Represents all features built including Runway 16-34, Taxiways B&F, and Terminal Apron.

2 Represents all features built as part of terminal apron expansion project (expanded apron and connector taxiway).

Table 12. Summary and comparison of data from the Northwest Arkansas Regional Airport EAD (1997/98) and on-site non-EAD companion (2003) projects with recommended practice (continued).

	Key Data Item	XNA EAD Project[1] (1997 to 1998)	XNA non-EAD Project[2] (2003)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I/II	Cement Type – Type I/II			
		Cem. Factor – 515 lbs/yd^3 Pozz. Cont. – 0-20% FA "C"	Cem. Factor – 530 lbs/yd^3 Pozz. Cont. – 15% FA "C"	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3
		w/c ratio – 0.42	w/c ratio – 0.41			
		Total Water – 172 to 229 lbs.	Total Water – 217 lbs.	Less than 250 lb	No	OK
		Mortar Volume – 51-53%	Mortar Volume – 56.5%	Less than 60%	No	OK
	PCC Fine Aggregate Gradation	Type – Fine (Natural sand)	Type – Fine (Natural sand)	Coarse sand	Yes	Fine sand increases water demand and shrinkage. Non-EAD section has more bulking potential.
		Passing No. 50 sieve – 11%	Passing No. 50 sieve – 25%	Lower limit of ASTM C33 5 to 30 % band preferred	No - EAD Yes - non-EAD	
		Fineness Mod.– 2.73	Fineness Mod.– 2.42	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Crushed Limestone	Crushed Limestone			Moderate CTE.
	PCC Combined Aggregate Gradation— Design	WF – 30.2	WF – 40	WF > 29 & CF < 75	No	EAD mix designs varied a lot. The non-EAD section mix was well controlled. Although even the latter also had a potential for segregation.
		CF – 84.2	CF – 80		Yes	
		Nom. Max. Agg. – 0.75 in	Nom. Max. Agg. – 0.75 in			
Construction Variants	Curing type & process	PCC Curing– White-pigmented LMFCC (resin-base) Rate >1 gal/200 ft^2	PCC Curing– White-pigmented LMFCC (resin-base) Rate > very thk. application	Fog spraying and white pigmented CC preferred in hot weather.	Yes – EAD No – non-EAD	The thicker applications of curing coat for the non-EAD sections may have helped seal the moisture and in strength gain.
		CTB Curing– LMFCC (wax) Rate >1 gal/270 ft^2	CTB Curing– Bituminous Rate >1 gal/100 to 250 ft^2		No	
	Initial Sawcut	Equipment– Traditional	Equipment– Early entry	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/4	Depth – D/3	D/3	Yes – EAD No – non-EAD	Maybe insufficient depth for the EAD section.
	Bond Breaker	Initially none. Later visqueen	Bituminous	Double coat wax-based curing compound	No	Perhaps inadequate for EAD section.
	CTB Surface Condition Prior to Paving	Surface milled prior to paving. Shrinkage cracks present in CTB.	Surface was smooth.	When CTB is trimmed, additional coat of CC is recommended.	Yes - EAD No – non-EAD	Milled surface increases base restraint and could have contributed to the cracking in the EAD section.
	CTB QA Program	Acceptance based on density and surface evenness.	Acceptance based on density and surface evenness.	Thickness, density, grade, surface evenness		CTB strengths and gradations were monitored additionally.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 13. Summary and comparison of data from the Omaha Eppley Airport EAD (1998) and on-site non-EAD companion (2002) projects with recommended practice.

	Key Data Item	OMA EAD Project (Taxiway A - 1998)	OMA non-EAD Project (Runway 14L-32R - 2002)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Nearly 20 slabs cracked when paving pilot lane between stations 2+00 and 12+00. Cracking mostly longitudinal.
	Ambient PCC Paving Conditions	Max. Temp – 68°F Min. Temp – 41°F	Max. Temp – 68°F Min. Temp – 48°F	Good hot- and cold-weather management plan and execution.	Yes – EAD No – non-EAD	Large temperature swings cause steep gradients in PCC slabs. Sudden temperature drops also trap heat of hydration within PCC slab. Cool paving temperatures retard concrete strength gain.
		Cool ambient conditions prevalent. Temp. swings > 25°F occurred on some days. Evaporation losses noted.	Cold weather present during PCC paving. Temp. swing > 25°F occurred.			
	PCC Placement Season	Fall	Fall			
Design Variants	Thickness	PCC Design – 17 in Actual – NA (avg.) Actual – NA (SD)	PCC Design – 17 in Actual – NA (avg.) Actual – NA (SD)			
		CTB Design – 6 in Actual – NA (avg.) Actual – NA (SD)	CTB Design – 6 in Actual – NA (avg.) Actual – NA (SD)	CTB thickness: 6 in	No	OK
	Joint Spacing	Trans. Spacing (L) – 25 ft Long. Spacing (W) – 25 ft	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 16.5, 18.5, 20 ft	Max. dimension ≤ 20 ft.	Yes – EAD No – non-EAD	Large panel spacings in the EAD section could be an aggravating factor that leads to cracking.
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 800 lb/in^2	Mix Design – 710 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 770 lb/in^2 (avg.) Actual -- 63 lb/in^2 (SD)	Actual – 838 lb/in^2 (avg.) Actual -- 150 lb/in^2 (SD)			As-designed strengths far greater for non-EAD sections. Perhaps a factor that helped alleviate the occurrence of EAD.
	7-day CTB Comp. Str.	Design – 960 lb/in^2	Design – 600 lb/in^2	Between 500 and 1,000 lb/in^2	Yes – EAD No – non-EAD	The CTB in the EAD section seems very stiff. Based on a long-term strength of 5,470 lb/in^2 at 15 months, an approximate value of 2,000 lb/in^2 is estimated at 7-days. The 600 lb/in^2 value of the non-EAD section is in agreement with the recommended range of values.
		Actual – 5,470 lb/in^2 (approx. 15 months after construction)	Actual – NA (avg.) Actual – NA (SD)			
	CTB Density	MDD – 141 lb/ft^3 Actual – 101% MDD (avg.) Actual – 1% of MDD (SD)	MDD – 139 lb/ft^3 Actual – 101% MDD (avg.) Actual – 0.7% MDD (SD)	Actual field density – 97% to 98% MDD		OK
	CTB Moisture Content	OMC – 5.2 % Actual – 5.5% (avg.) Actual – 0.5% (SD)	OMC – 6.8 % Actual – 7.1% (avg.) Actual – 0.8% (SD)	Up to + 2 percent for summertime construction		OK

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 13. Summary and comparison of data from the Omaha Eppley Airport EAD (1998) and on-site non-EAD companion (2002) projects with recommended practice (continued).

	Key Data Item	OMA EAD Project (Taxiway A - 1998)	OMA non-EAD Project (Runway 14L-32R - 2002)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type IP	Cement Type – Type IP			
		Cem. Factor – 625 lbs/yd^3 Pozz. Cont. – 0%	Cem. Factor – 625 lbs/yd^3 Pozz. Cont. – 0%	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3. In the presence of a large temp. swing and long panel spacing (as in the EAD section), this can be detrimental.
		w/c ratio – 0.4	w/c ratio – 0.4			
		Total Water – 250 lbs	Total Water – 250 lbs.	Less than 250 lb	Yes	High total water and mortar volume increases shrinkage potential.
		Mortar Volume – 65%	Mortar Volume – 65%	Less than 60%	Yes	
	PCC Fine Aggregate Gradation	Type – Coarse (gravel-sand)	Type – Intermediate	Coarse sand	No- EAD Yes – non-EAD	Coarse sand and well graded fine aggregate offsets some of the concern regarding shrinkage.
		Passing No. 50 sieve – 7%	Passing No. 50 sieve – 13%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 3.5	Fineness Mod.– 3.5	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	No	
	PCC Coarse Agg.	Limestone	Limestone			Moderate CTE, although can be detrimental in combination with large panels and temperature swings.
	PCC Combined Aggregate Gradation—Design	WF – 33.7	WF – 36.2	WF > 29 & CF < 75	No	Within the well-graded portion of the workability box.
		CF – 51	CF – 53.6		No	
		Nom. Max. Agg. – 0.75 in	Nom. Max. Agg. – 1 in			
Construction Variants	Curing type & process	PCC Curing– White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	PCC Curing– White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	The thicker applications of curing coat for the non-EAD sections may have helped seal the moisture and in strength gain.
		CTB Curing– LMFCC (wax) Rate >1 gal/36 to 90 ft^2	CTB Curing– LMFCC (wax) Rate >1 gal/36 to 90 ft^2		No	
	Initial Sawcut	Equipment– Traditional	Equipment– Early entry	Early or traditional saws.	No	Early sawing in non-EAD section is a significant factor.
	Sawcut Depth	Depth – D/4	Depth – D/4	D/3	Yes – EAD No – non-EAD	Maybe insufficient depth for the EAD section.
	Bond Breaker	1-coat CTB CC	1-coat CTB CC	Double coat wax-based curing compound	Yes	Perhaps inadequate.
	CTB Surface Condition Prior to Paving	Normal	Normal	When CTB is trimmed, additional coat of CC is recommended.	N/A	OK
	CTB QA Program	Acceptance based on density measurements and surface evenness	Acceptance based on density measurements and surface evenness	Thickness, density, grade, surface evenness		Typical QA program.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 14. Summary and comparison of data from the Southeast Iowa Regional Airport EAD (2001) and on-site non-EAD companion (2002) projects with recommended practice.

	Key Data Item	BRL EAD Project (Taxiway A, Phase I - 2001)	BRL non-EAD Project (Taxiway A, Phase II - 2002)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Approximately 5% of paved area cracked. Predominantly transverse cracking. Some longitudinal cracking also present.
	Ambient PCC Paving Conditions	Max. Temp – 86°F Min. Temp – 52°F	Max. Temp – NA Min. Temp – NA	Good hot- and cold-weather management plan and execution.	NA	Several trigger factors present during Phase I PCC paving. No noticeable ambient condition triggers thresholds exceeded during Phase II PCC paving.
		Very hot and windy right after paving. Two significant rain events > 0.15 in accumulation observed which caused large temperature swings.	Relatively mild paving conditions in terms of temperature, relative humidity, and wind speed.			
	PCC Placement Season	Late Summer/Fall (August)	Summer/Fall (Aug – Oct)			
Design Variants	Thickness	PCC Design – 8.5 in Actual – 8.6 in (avg.) Actual– 0.2 in (SD)	PCC Design – 8.5 in Actual – 9.2 in (avg.) Actual– 0.7 in (SD)			The as-built PCC thickness agree with the as-designed thicknesses.
		CTB Design – 9 in Actual Avg. – 9.5 in Actual Std. Dev – 0.5 in	CTB Design – 9.5 in Actual Avg. – 9.2 in Actual Std. Dev – 0.3 in	CTB thickness: 6 in	Yes	Base layer thicker than recommended.
	Joint Spacing	Trans. Spacing (L) – 12.5 ft Long. Spacing (W) – 12.5 ft	Trans. Spacing (L) – 12.5 ft Long. Spacing (W) – 12.5 ft	Max. dimension $\leq$ 20 ft.	No	OK
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 650 lb/in^2	Mix Design – 650 lb/in^2	650 lb/in^2 (28-day)		The as-built flexural strengths are higher than the as-designed values.
		Actual – 739 lb/in^2 (avg.) Actual – 52 lb/in^2 (SD)	Actual – 707 lb/in^2 (avg.) Actual – 72 lb/in^2 (SD)			
	7-day CTB Comp. Str.	Design – 1190 lb/in^2	Design – 1,440 lb/in^2	Between 500 & 1,000 lb/in^2	Yes – EAD No – non-EAD	The non-EAD section CTB strength is much lower than that of the EAD section.
		Actual – 1,321 lb/in^2 (avg.) Actual – 222 lb/in^2 (SD)	Actual – 771 lb/in^2 (avg.) @11-days Actual – 51 lb/in^2 (SD) @ 11-days			
	CTB Density	MDD – 135.7 lb/ft^3 Actual – 98.5% MDD (avg.) Actual – 0.7% of MDD (SD)	MDD – 138.9 lb/ft^3 Actual – 99% MDD (avg.) Actual – 0.6% MDD (SD)	Actual field density – 97% to 98% MDD		OK
	CTB Moisture Content	OMC – 7.6 % Actual – 8.3% (avg.) Actual – 0.5% (SD)	OMC – 5.7% Actual – NA (avg.) Actual – NA (SD)	Up to + 2 percent for summertime construction		Higher than normal moisture content in the base for the EAD section could lead to shrinkage cracking.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 14. Summary and comparison of data from the Southeast Iowa Regional Airport EAD (2001) and on-site non-EAD companion (2002) projects with recommended practice (continued).

	Key Data Item	BRL EAD Project (Taxiway A, Phase I - 2001)	BRL non-EAD Project (Taxiway A, Phase II - 2002)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I	Cement Type – Type I			
		Cem. Factor – 564 lbs/yd^3 Pozz. Cont. – 10% FA “C”	Cem. Factor – 594 lbs/yd^3 Pozz. Cont. – 10% FA “C”	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3
		w/c ratio – 0.45	w/c ratio – 0.43			
		Total Water – NA	Total Water – 255 lbs.	Less than 250 lb	No	Information not available for EAD, however, it is assumed to be similar as for EAD. High total moisture content and high mortar volume increase shrinkage potential.
		Mortar Volume – NA	Mortar Volume – 65%	Less than 60%	No	
	PCC Fine Aggregate Gradation	Type – NA	Type – Coarse	Coarse sand	Yes	EAD section has more bulking potential.
		Passing No. 50 sieve – 14.3%	Passing No. 50 sieve – 9%	Lower limit of ASTM C33 5 to 30 % band preferred	No - EAD Yes - non-EAD	
		Fineness Mod.– NA	Fineness Mod.– 2.8	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential for both sections.
	PCC Coarse Agg.	Limestone	Limestone			Moderate CTE.
	PCC Combined Aggregate Gradation—Design	WF – NA	WF – 47	WF > 29 & CF < 75	No	The non-EAD section has a potential for segregation.
		CF – NA	CF – 80		Yes	
		Nom. Max. Agg. – 0.75 in	Nom. Max. Agg. – 1 in			
Construction Variants	Curing type & process	PCC Curing– White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	PCC Curing– White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	Yes – EAD No – non-EAD	Records review suggests inadequate curing of the PCC for the EAD section.
		CTB Curing– LMFCC (wax) Rate >1 gal/13 ft^2	CTB Curing– LMFCC (wax) Rate >1 gal/13 ft^2		No	
	Initial Sawcut	Equipment– Early entry & Traditional. Reported as an issue.	Equipment– Early entry	Early entry or traditional wet saws.	Yes	Sawing was reported as an issue for the EAD section.
	Sawcut Depth	Depth – D/3	Depth – D/3	D/3	Yes – EAD No – non-EAD	OK
	Bond Breaker	None	None	Double coat wax-based curing compound	Yes	No bond breaker used.
	CTB Surface Condition	Shrinkage cracks present.	Surface was normal.		Yes - EAD No – non-EAD	Not all shrinkage cracks reflected.
	CTB QA Program	Acceptance based only on thickness, density, strength.	Acceptance based only on thickness, density, strength.	Thickness, density, grade, surface evenness		

1 in = 25.4 mm   1 ft^2 = 0.093 m^2 1 gal = 3.785 L   1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

5.2.2 Baton Rouge Metropolitan Airport Runway 4L-22R Reconstruction (2003)—EAD Project

In 2000, Baton Rouge Metropolitan Airport started the reconstruction of the runway 4L-22R. The reconstruction was performed in two phases. During the construction of phase I, the south section (4L end of the runway) was reconstructed, but exhibited early-age cracks. The total length of phase I was 3,300 ft (1,006 m). Figure 16 presents a sketch of the typical section and jointing details of the runway.

Figure 17 presents a sample of the extent of cracking on this project (only a portion of entire project length is shown). A total of 99 slabs out of the 1,072 placed were rejected during the reconstruction of this runway. Of these, 79 slabs were rejected due to “stress” related cracks (perhaps indicating shrinkage cracks) according to an evaluation performed by one of the stakeholders involved. This corresponds to approximately 7 percent of the total slabs placed.

The CTB layer was paved between mid-April and late-May of 2003. The PCC layer was placed between late-May and late-June of 2003. Shortly after placement of the PCC in the first lane on the east side of the runway, cracks started appearing in the slabs. Cracks were mainly in the transverse direction and contained in a single slab not continuing into the adjoining slab.

An evaluation of the data presented in table 11 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC and the design, materials, and construction variants:

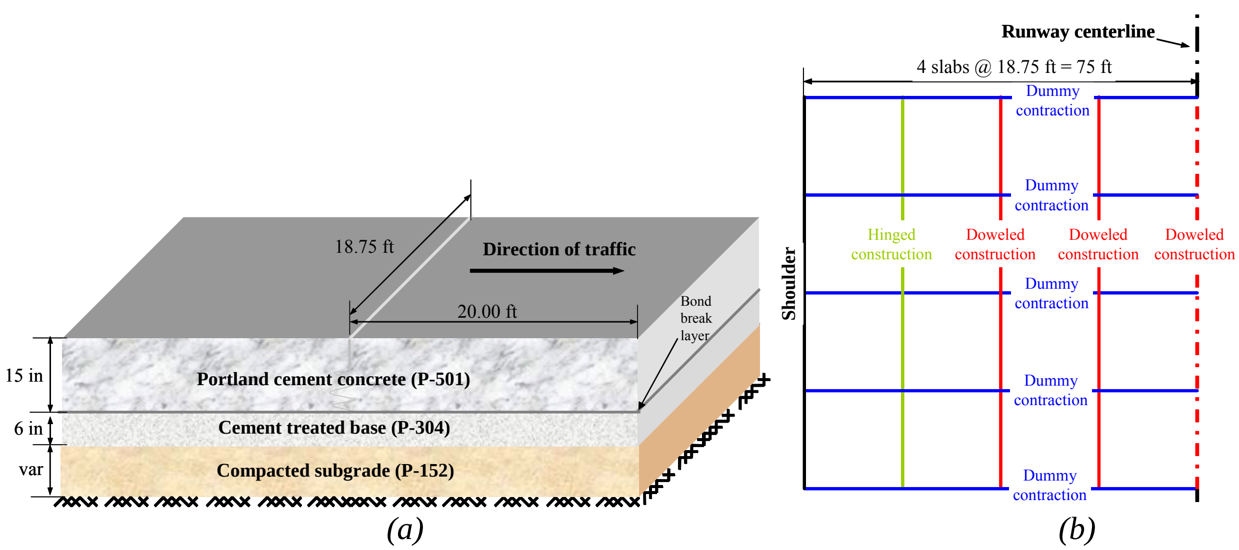


Figure 16. Typical section and joint layout for Runway 4L-22R reconstructed at Baton Rouge Metropolitan Airport.

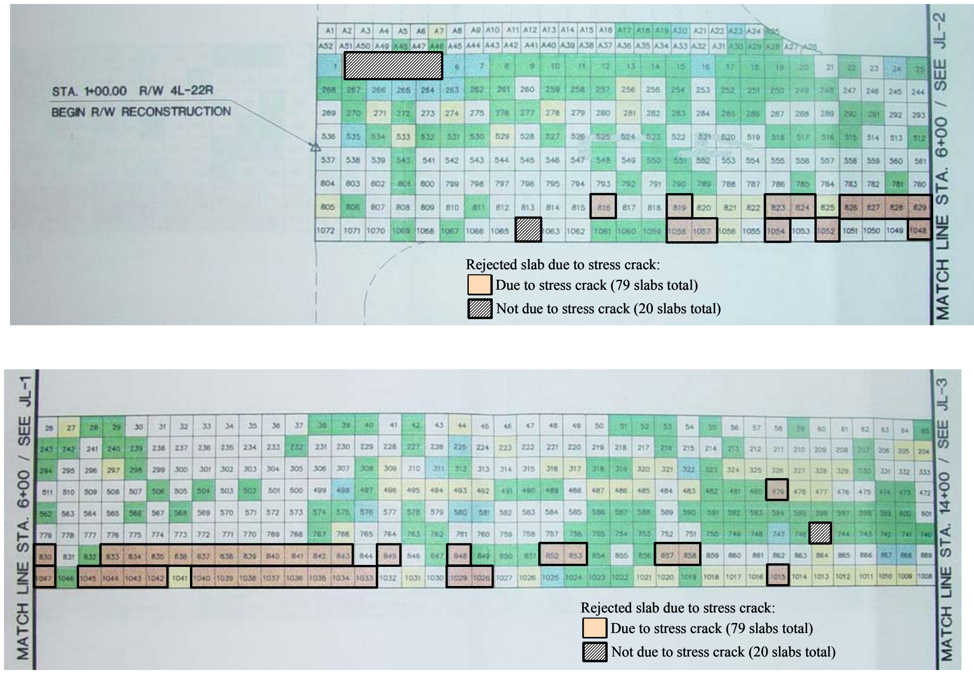


Figure 17. Partial layout of panels with cracking during the 2003 reconstruction of Runway 4L-22R at Baton Rouge Metropolitan Airport.

- The placement, as indicated previously, was in the summer months. The daytime temperature at time of PCC placement was 90 to 95°F (32 to 35°C). The median high and median low temperatures during PCC paving were 90°F and 73°F (32 and 23°C), respectively, with more than 10 days where the maximum daytime temperature was greater than 90°F (32°C). Interviews with stakeholders also indicated that the base was not wetted down (to allow it to cool off) to the degree desirable on some occasions. Low relative humidities (below 30 percent) were also reported during PCC placement. There is a strong indication from records that the high ambient conditions combined with potentially high surface evaporation rates (due to the low relative humidity levels), was the likely trigger condition for EAD. The contractor shifted to nighttime operations after initial cracking was observed and this seemed to have stopped the cracking problems.
- The placement of the CTB was performed in hot months where it is recommended that moisture content of the layer be above optimum to prevent excessive shrinkage cracking. The data reveals that this did not happen. This is combination with the high cement factor in the CTB (10 percent) could have led to the shrinkage cracks observed in the layer. These cracks have a potential to reflect into the PCC slabs. However, it was noted by various stakeholders that the shrinkage cracks in the P-304 layer did not always match the cracking in the PCC layer.
- Although the panel dimensions were within guidelines (< 20-ft [6.1 m] spacing and aspect ratio < 1.25), the longest dimension of 20 ft (6.1 m) for transverse joint spacing could be an aggravating factor causing cracking under unfavorable paving conditions.
- PCC mixture-related issues:

- ➢ The cement factor of 517 lb/yd^3 (305 kg/m^3) (including 15% flyash) used in the P-501 mixture is typical for paving work. The resulting heat of hydration is perhaps not a factor in the development of cracking due to the presence of a pozzolan.
  - ➢ It is clear from the fine aggregate gradation parameters used to batch the laboratory specimens for mix design—the percent passing the No. 50 (300 µm) sieve, the fineness modulus (FM), and the fine aggregate gradation plots vis-à-vis the ASTM C 33 specification (not shown)—that the amount of fine sand, although within the ASTM C 33 specification for fine aggregates, is excessive. Excess fine sand increases the water demand and the shrinkage potential.
  - ➢ The workability and coarseness factors derived from the combined aggregate gradation used in the design mixes are 34.8 and 73.6, respectively. Based on the workability box criteria, the mix appears to have adequate characteristics to be placed without segregation.
  - ➢ Records indicate that the coarse aggregate used in the P-501 mixes were gravels without any further qualifications. Siliceous gravels or chert gravels have high CTEs which mean that they are capable of causing larger movements in the slab due to imposed thermal gradients.
- Records and interviews indicate that the initial sawcut was made with a traditional walk-behind, wet saw to a depth of one-fourth the overall slab thickness (D/4). This depth may not be adequate when the PCC layer is bonded to the CTB layer.
- Based on interviews, sawing of joints proceeded as soon as possible, but the guidance for sawing was not specific. There were some chipping and joint spalling problems during sawing, mainly during the first few days of this operation.
- Some of the stakeholders indicated that the base was milled prior to paving to establish grade. It was also mentioned that a fine layer of sand (unspecified amount of application) was spread to avoid high friction between the slab and the base. Further, as noted above, a wax-based LMFCC was used as a bond breaker. It is not clear what effect the restraint-reducing measures had on the slab/base interface friction.

<u>Conclusions</u>

In reviewing the factors listed above and the data presented in table 11, it is believed that the primary driving force for the cracks was shrinkage-related volumetric reduction due to hot-temperatures and low-relative humidities. Aggravating the situation were the following factors:

- Shrinkage-susceptible PCC mixture.
- High strength base offering a relatively high degree of restraint.
- Inadequate sawcut depth.
- Shrinkage cracks in the base.

Several of these parameters are assumed to be directly correlated to transverse cracking in PCC slabs, according to Kohn and Tayabji (2003).

5.2.3 Northwest Arkansas Regional Airport Construction (1997 to 1998)—EAD Project

The Northwest Arkansas Regional Airport is a relatively new facility. Preparatory exploration work on this airport began in 1995. However actual paving work started only in 1997. The construction activities included building Runway 16-34, parallel Taxiway B, connector taxiways B-North, B-South, F, B4, B2, terminal apron, and the aircraft parking apron. The total end-to-end length of the Runway 16-34 and Taxiway B, the primary features of interest, is 8,800 ft (2,684 m). Figure 18 presents a sketch of the typical section for all the features constructed.

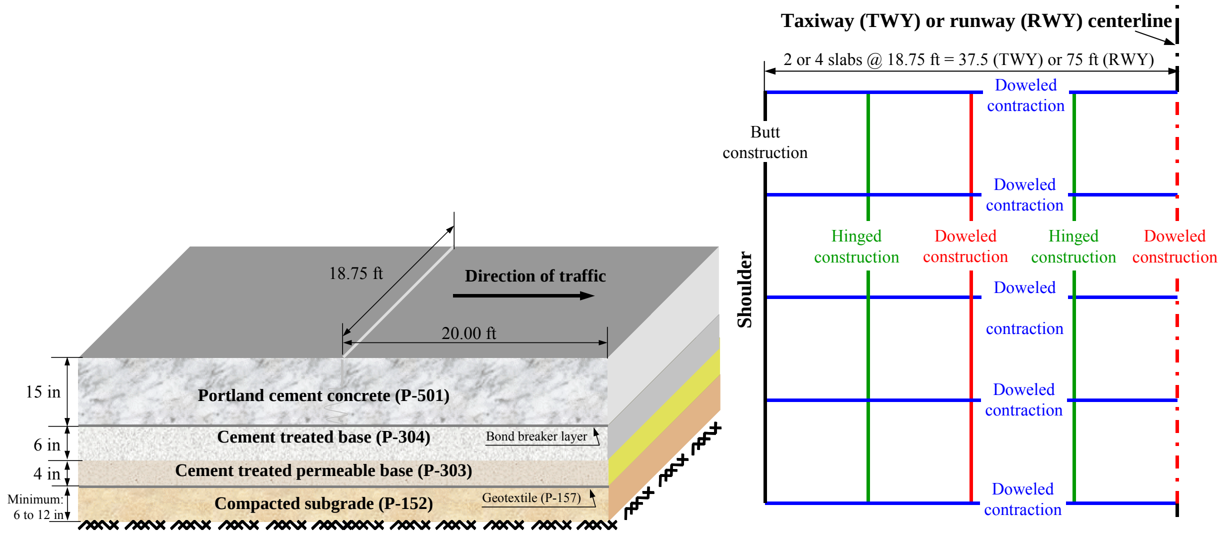


Figure 18. Typical section and joint layout for the runway, taxiways, and terminal apron constructed at the Northwest Arkansas Regional Airport.

Construction at the airport generally proceeded from south to north. The paving work for the CTB layer extended from late May 1997 to early November1997 and the PCC layer from July 1997 through early January 1998. A problem that plagued the airport during construction was the appearance of cracking on the runway and taxiway B within a few days or weeks of construction. The cracking assumed various orientations—transverse, longitudinal, diagonal, random, and corner.

Initial P-501 placement proceeded without a bond breaker and as random cracks were being noticed on the slab, plastic sheeting was required to be placed between the CTB and the PCC layer to serve as a bond breaker. The addition of the plastic sheeting reduced but did not eliminate the occurrence of random cracking, which continued over the several months during which the runway and taxiway were placed. Table 15 summarizes the extent of cracking observed on this airport by feature type based on a 1998 survey conducted by one of the stakeholders. It can be noted from the table that approximately 5.3 percent of 8,819 PCC slabs placed experienced some form of early-age cracking.

Table 15. Summary of cracking noticed at the Northwest Arkansas Regional Airport.

Location	Crack Condition	Total No. of slabs	Percent cracked slabs
Taxiway B	28 corner, 36 transverse, 26 longitudinal, 28 random, 52 diagonal	1,918	8.9
Runway 16-34	69 corner, 53 transverse, 55 longitudinal, 47 random, 41 diagonal	3,520	7.5
Taxiway F	3 corner, 3 transverse, 1 longitudinal, 2 random, 1 diagonal	273	3.7
Taxiway B-4	1 corner, 2 transverse, 2 longitudinal, 2 random	265	2.6
Taxiway B-2	2 transverse, 1 corner, 2 diagonal	235	2.1
Taxiway B-South	2 transverse	134	1.5
Aircraft Parking Apron	1 corner, 3 transverse, 1 diagonal	1,271	0.4
Terminal Apron	1 transverse, 3 diagonal	1,052	0.4
Taxiway B-North	no distress	151	0.0
All locations	**468 out of 8,819 slabs**	**8,819**	**5.3**

An evaluation of the data presented in this table suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC, as well as the design, materials, and construction variants:

- The placement season, as indicated previously, spanned across summer, fall, and even winter. However, Runway 16-34 and Taxiway B, which experienced a majority of the cracking, were paved with PCC in August and September of 1997. The temperatures, throughout this period remained consistently high (perhaps unusually high) with several days where the maximum daytime temperatures were greater than 90°F (32°C). Proper hot-weather precautions need to be taken when paving under these conditions. However, the records review and interviews performed do not indicate to what extent these precautions were taken. Placing concrete during the day can lead to a condition where the maximum heat of hydration is generated around the hottest part of the day; an undesirable situation as explained earlier. There is a strong indication from records that hot paving conditions could have been a key trigger factor.
- Although the panel dimensions were within guidelines (< 20-ft [6.1-m] spacing and aspect ratio < 1.25), the longest dimension of 20 ft (6.1 m) for transverse joint spacing could be an aggravating factor causing cracking under unfavorable paving conditions.
- An examination of the extensive CTB compressive strength data available on the project revealed that 7-day strengths were in excess of 1,200 lb/in^2 (8,274 kPa), on average. The densities of the base layers were also correspondingly high. Figure 19 presents a plot of the 7-day compressive strength achieved on the project for each feature constructed. Another interesting thing to note from this figure and table 15 is that the standard deviations of the compressive strength were also high (COV of 25%), which points to a high degree of variability in the quality of the materials placed.

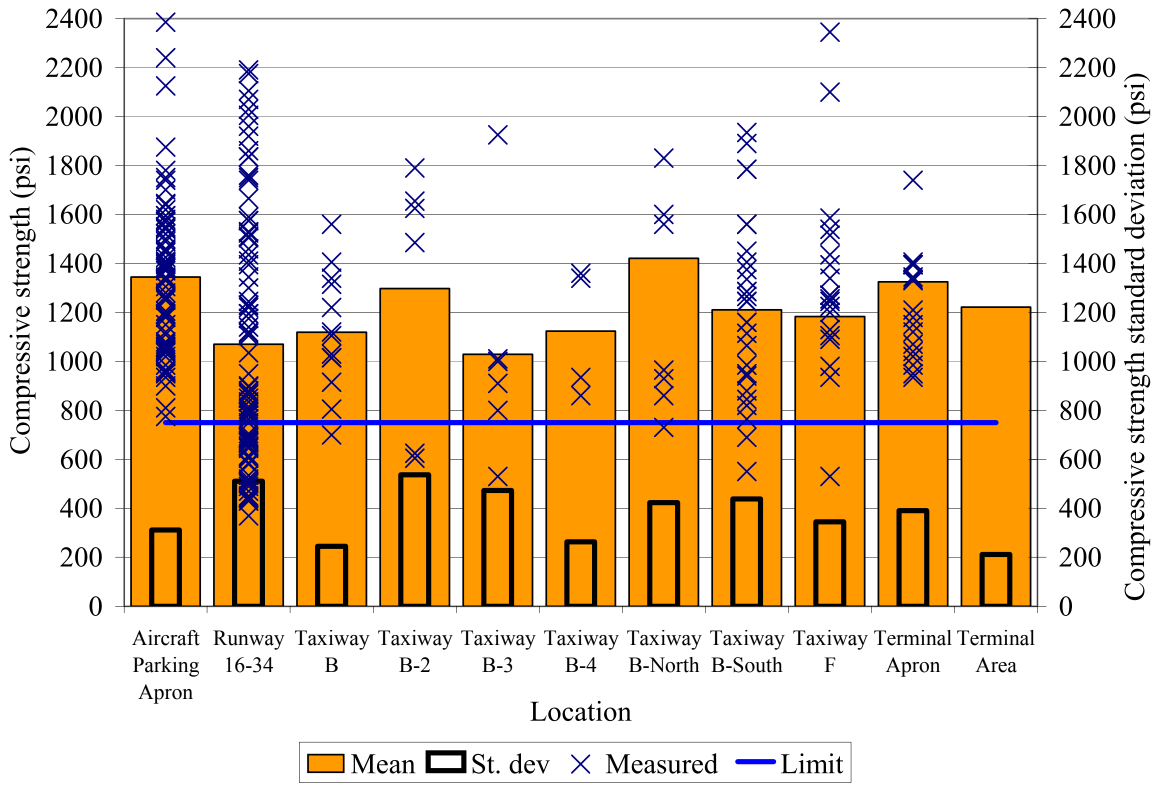


Figure 19. 7-day compressive strengths achieved for CTB layer during the construction of the Northwest Arkansas Regional Airport.

- Several PCC mixtures were used on the project, and it was difficult to pinpoint which mix was used where due to a lack of project construction management records. However, in analyzing all the mix designs presented, it was possible to select a set of mix properties that could be considered as being representative of a typical project mix. An analysis of this mix design reveals the following mixture-related issues:
  - The FM computed for the fine aggregate gradation is 2.73. This is within the ASTM C 33 specification, however, for the cement factor used in this mix design (>400 lb/yd^3) [>236 kg/m^3], an FM value in the range of 3.1 to 3.4 is preferred to provide a shrinkage resistant mixture. The percent passing the No. 50 (300 µm) sieve, a good indicator of bulking potential of the fine aggregate and excess water demand, is close to the upper limit of 30 percent.
  - The combined aggregate gradation appears to be representative of a gap-graded mixture and is a leading indicator of mixture segregation issues. The workability and coarseness factors derived from the combined aggregate gradation were around 30 and 84, respectively. The coarseness factor exceeds the allowable limit of 75 and could result in a mixture that could segregates in the field and lead to early-age uncontrolled cracking. Any variability in the mixtures delivered to the field will further aggravate the issue.

- Records indicate, without any further qualifications, that the coarse aggregate used in the P-501 mixes was limestone. Limestone has a moderate coefficient of thermal expansion. Therefore, this may not be a major contributing factor by itself. However, in combination with the relatively long joint spacing, it can influence the early-age curling stresses significantly.

- The type of curing compound used and its rate of application seem inadequate for the surface layer. This can lead to an excess loss of moisture from the surface of the PCC through drying shrinkage. Drying shrinkage leads to warping stresses in the slab which can also lead to uncontrolled cracking if control joints are not in place quickly enough. This warping effect was perhaps exacerbated by the presence of a stiff layer and the plastic sheeting. The former because a stiffer foundation results in a higher degree of warping stress and the latter because the plastic sheeting traps moisture at the bottom of the PCC layer, leading to a higher moisture gradient.
- Records and stakeholder interviews indicated that the initial sawcut was made with a traditional walk-behind, wet saw to a depth of D/4. Photographs of cores taken at various joints along the project indicate that the control joints did not form as expected, even several months after the concrete was placed (figure 20). This could mean that the sawcutting operation was perhaps not adequate.
- There is evidence from the records reviewed to believe that shrinkage cracks did develop in the CTB layer during construction owing to mix design and environmental conditions.
- Areas of CTB not meeting grade were trimmed with a milling machine; these left a rough surface some of which was covered with plastic sheeting.

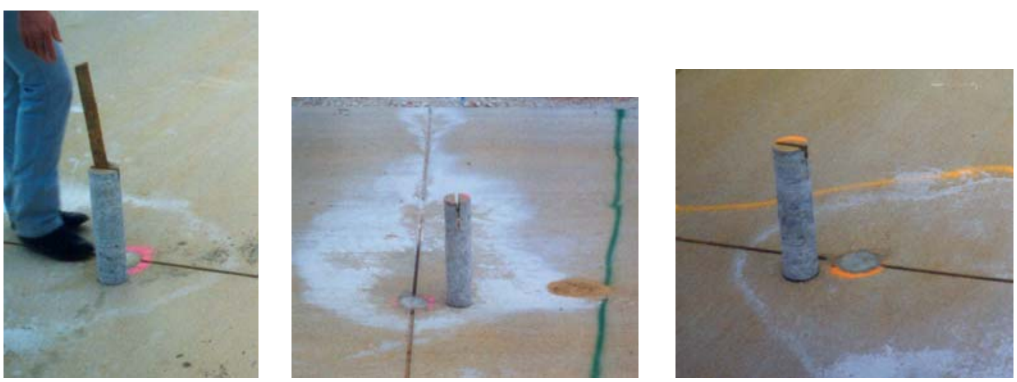


Figure 20. Cores illustrating inadequate sawcut depths at Northwest Arkansas Regional Airport (photos taken in March, 1998 —several months after construction of the pavement).

Conclusions

In reviewing the factors listed above and the data presented in table 15, it is believed that the primary driving force for the cracks was thermal and shrinkage-related mechanisms, aggravated by the following factors:

- Coarse, gap-graded P-501 mixture vulnerable to segregation.
- Inadequate sawcut depth or late sawing.

- High strength/stiffness base.
- Base layer offering a variable degree of restraint.
- Presence of shrinkage cracks in the CTB.
- Inadequate bond breaker.

5.2.4 Northwest Arkansas Regional Terminal Apron Expansion (2003)—Non-EAD Companion Project

The terminal apron at the Northwest Arkansas Regional Airport constructed in 1997-98 was expanded in the year 2003. A connector taxiway was also built as part of this project (Taxiway J). The net effect of the construction activity was to expand the existing ramp areas to twice the existing size. The total extent of paving was close to 61,000 yd^2 (51,071 m^2). The pavement design was exactly the same as the original construction, as shown in figure 18. Only two cracked panels were observed in this job and they were deemed as being unrelated to this research (cracks on either side of a trench drain). Therefore, this project was selected as a good case for being considered as an on-site companion section.

The specifications used to construct the CTB layer were similar to those used in the 1997/98 project described in section 5.2.3, with the following changes:

- A bituminous curing compound was specified in the 2003 specification, as opposed to a LMFCC. Application rates were clearly stated in the 2003 specification (0.1 to 0.25 gal/yd^2 [0.45 to 1.13 L/m^2]).
- The acceptance of the paving lots for the 2003 specification was based on both 7-day strength and density during initial testing over the first 3 days (the intent was only to verify if the minimum strength requirements were being satisfied). During production testing, both density and strength testing was required. However, while density testing was required to be conducted as rigorously as the initial testing (on a lot basis), strength testing was confined to three randomly selected samples per day, unless (a) initial strength was considered deficient by the Engineer, (b) production strength was deficient, or (c) there was change in CTB mix color or composition. In the previous specification, acceptance was based on density and thickness alone and several other tests (gradation, strength, etc.) were run on an additional basis.

The CTB and PCC layers on this project were placed between August and November, 2003. Therefore, the paving season has a large overlap with the 1997-98 construction. Comparing the design, testing, and construction information between this project and the 1997/98 EAD project (presented in table 13), the following observations are made:

- Although the paving season was similar to the original construction, the temperatures experienced during construction of the 2003 project were milder. The median value of the maximum high temperature was around 71°F (22°C) and the minimum low temperature was around 50°F (10°C). This can be considered good paving weather. There were no hot temperature issues on a consistent basis in the 2003 project. Up to 17 large temperature swings were observed, however.
- All the design elements and joint patterns were essentially the same for both projects.

- The 28-day flexural strength of the PCC in the 2003 project was slightly greater than that achieved in the 1997-98 projects. Furthermore, all the mix design factors as related to cement type, content, admixtures, and aggregate types and gradations were all similar.
- A pre-construction conference was held between the contractor, designer, owner, program manager, and industry representatives where key PCC mix design issues were discussed. It appears on examination of records that the mix design used in the 2003 project was finer than that used in the 1997/98 construction. The fine aggregate had 25 percent passing the No. 50 (300 µm) sieve, a fineness modulus of 2.4, a workability factor of 40, and coarseness factor of 80. Therefore, even this mix can be thought as being gap-graded and having a potential for build up of surface latents. As a result, stakeholders were warned to be ready to make adjustments as necessary should a problematic situation arise.
- The 7-day CTB compressive strengths achieved in the field were also comparable, albeit slightly lower in the case of the 2003 construction. The same can be said of the densities achieved.
- A bituminous curing compound was used to cure the CTB in the 2003 project. The PCC layer was coated a white-pigmented LMFCC at the earliest possible time (it was emphasized in the interviews that the entire surface was uniformly and thickly coated) to lock in moisture and prevent curling stresses.
- Early entry saws were used and the initial sawcut was made to a depth of one-third the concrete thickness (D/3).
- A bituminous bond-breaking layer was used ahead of paving to prevent slab-base restraint.

Conclusions

In reviewing the factors listed above, it can be seen that better control over the variants (e.g., curing, sawing, use of bond breaker, and better mix control) aided, in no small measure by favorable paving conditions, led to the prevention of EAD on this project, even though the same materials and design were employed to a large degree. Another notable factor is that, although up to 17 temperature swings of greater than 25°F (14°C) occurred, early-age cracking was not experienced due to the precautions taken during paving. This suggests that temperature swings alone may not trigger EAD if, on the whole, ambient temperatures are milder (i.e., temperatures do not plunge below a point where the PCC strength early gain is arrested).

5.2.5 Omaha-Eppley Field Taxiway A Construction (1998)—EAD Project

The extension of Taxiway A situated in the Omaha-Eppley Airfield in 1998, Omaha, Nebraska is of interest to this study. The total length of the runway extension was about 3,514 ft (1,072 m). However, the focus of this report is a short section of the runway between stations 2+00 and 12+00 which witnessed cracking over 20 slabs panels within a short time after construction. The pavement section of interest had three lanes each 25-ft (7.625-m) wide.

Figure 21 presents a sketch of the typical section and the typical joint layout for the feature of interest. The specifications used for the construction were FAA AC 150/5370-10A, *Standards for Specifying Construction of Airports*. However, PCC mixture design followed the recommendations of the Nebraska highway agency.

The CTB under the entire taxiway was constructed between June and October of 1998 with the portion under the section of interest presumably placed towards the end of this period. The PCC layer was paved in the 1st and 2nd weeks of October. All the cracking observed was longitudinal in nature. Figure 22 presents a sketch of the types and extent of cracking that occurred on the section under consideration.

An evaluation of the data presented in table 14 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC and the design, materials, and construction variants:

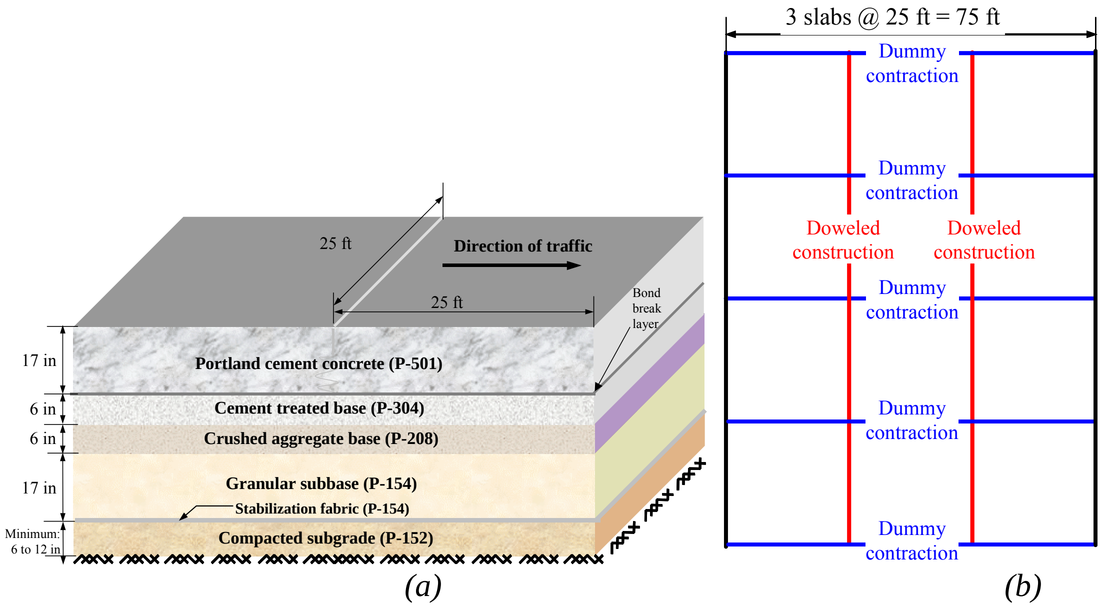


Figure 21. Typical section and joint layout for Taxiway A at the Omaha-Eppley Airfield.

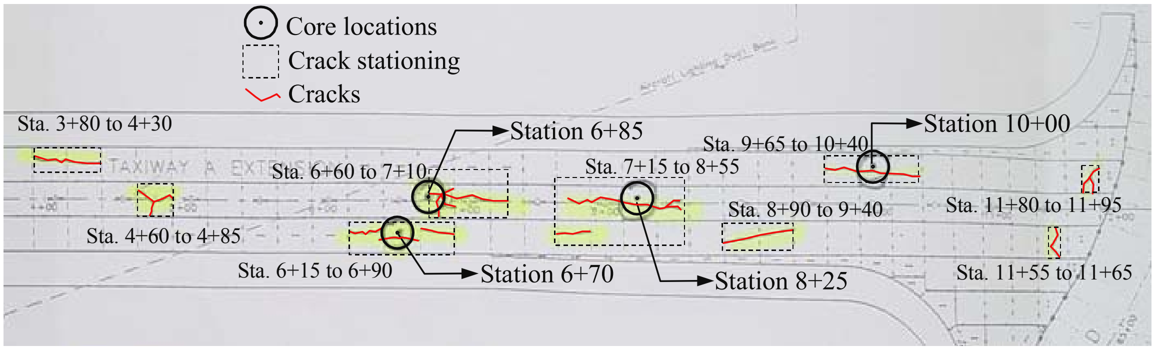


Figure 22. Early-age crack location, station, and cores on Taxiway A, Omaha-Eppley Airfield.

- The PCC placement, as indicated previously, was during the first two weeks of October (Fall paving). Large temperature swings were recorded during the time and shortly after the three P-501 lanes were placed. One such swing amounted to more than 35°F (19°C), as evidenced in figure 23.
- The panel dimensions are above the industry-recognized practical maximum of 20 ft (6.1 m). These long slab dimensions could be an aggravating factor causing cracking under unfavorable ambient conditions (excessive curl and warp stresses).
- Limited CTB compressive strength data were available but none of the data pertained to conditions at the time of construction or shortly thereof. The data available from coring performed nearly 1 year after of construction (November, 1999). Based on this information a reasonable "backcasted" estimate of the 7-day CTB compressive strength would be at least 2,000 lb/in^2 (13,790 kPa). This base therefore qualifies as an excessively stiff base.
- An analysis of the PCC mix design revealed the following mixture-related issues:
    - The cement factor of 625 lb/yd^3 (369 kg/m^3) is a very high value. There is a possibility of generating excessive heat of hydration at the time of set. Flyash and slag were not used on this project. The slab surface cools off more rapidly due to the plunging temperatures during a cold front relative to the bottom in such a situation.

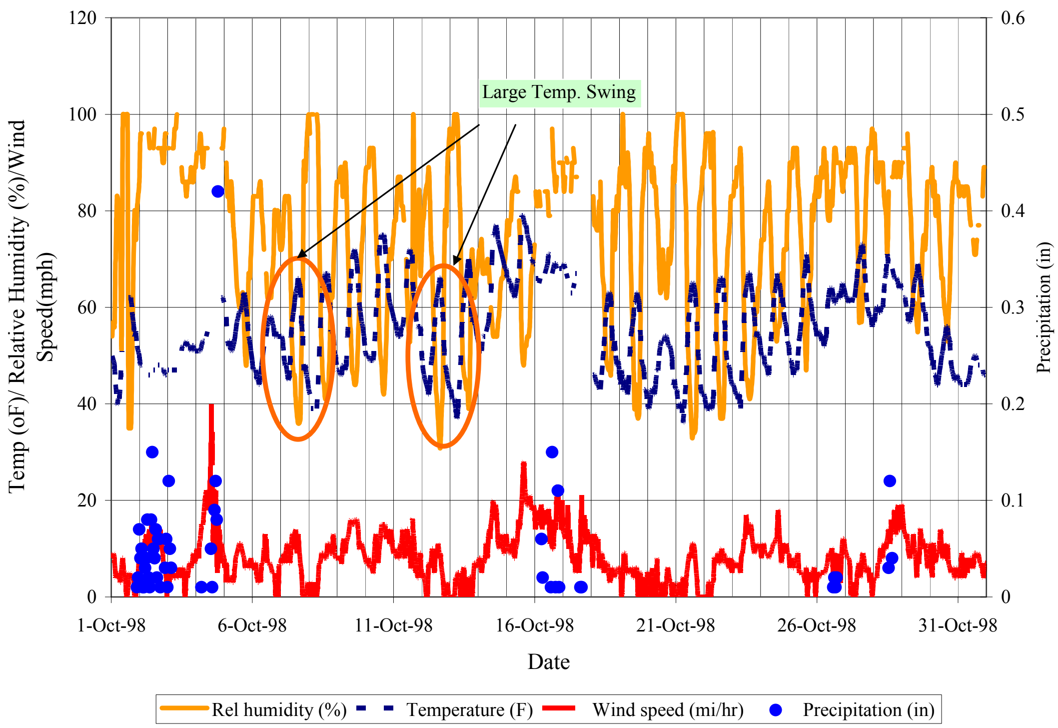


Figure 23. Presence of large temperature swings during paving of Taxiway A in 1998 at the Omaha-Eppley Airfield.

- The computed FM is 3.5, which is considered very good for this mixture. The percent passing the No. 50 (300 μm) sieve is 7 percent, indicating that the mixture does not have excessive fines and has a reduced shrinkage potential. The fine aggregate appeared to be well-graded as well.
- The combined aggregate gradation appears to be representative of a well-graded and workable mixture. The workability and coarseness factors derived from the combined aggregate gradation were around 34 and 51, respectively.
- Records indicate that the coarse aggregate used in the PCC mix was limestone without any further qualifications. Limestone typically has a lower CTE. Therefore, this may not be a major contributing factor by itself. However, considering that the slab dimensions are 25 ft (7.625 m), this will certainly have an impact on the curling stresses developed particularly in young concrete.

- Records indicate that a single coat of a white-pigmented wax-based LMFCC was used to cure the CTB. Another coat was used prior to paving to serve as a bond breaker. The impact of this application on lowering the degree of restraint at the slab-base interface is perhaps inadequate. The application rate was specified at 0.1 to 0.25 gal/yd^2 (0.45 to 1.13 L/m^2).
- Conventional walk-behind saws were used to perform the initial sawcut for all joints. The depth of the initial sawcut was one-fourth the slab thickness (D/4). It was unknown if the sawing crews were alert to the sudden temperature drops; however, for the purposes of this report, this was not considered as a factor.

Conclusions

In reviewing the factors listed above, it can be seen that perhaps the largest driving factor which led to the movements in the slab is the 35°F (19°C) plus temperature swing recorded on the night of the paving. However, the contributing factors that aggravated the situation include the following:

- A high cement factor concrete.
- Large panel dimensions.
- Presence of a stiff base.
- Inadequate sawcut depth.

The high cement factor concrete generates a large heat of hydration heating the mass concrete. However, a sudden variation of temperatures in the top “skin” of the slab can lead to an internal thermal gradient that can cause the concrete to curl upward (just as if a large negative temperature gradient is being applied). This upward curl is resisted by the friction at the slab-base interface and the weight of the slab, leading to tensile stresses at the top of the slab. If these tensile stresses cannot be accommodated by the strength gain in the material, cracks can form as is evidenced in this case. The cracking observed is most likely top-down based on its location in the slab. When large cold fronts are anticipated, it is advisable to look out for factors that could lead to such situations.

5.2.6 Omaha-Eppley Field Runway 14L-32R Construction (2002)—Non-EAD Companion Project

The total length of Runway 14L-32R was 5,185 ft (1,581 m) and width was 150 ft (45.75 m). This project had similar cross-section, materials, and construction factors as the Taxiway A section. However, no early-age cracking was observed on this pavement. Therefore, it was selected as a companion section for detailed comparisons. Only a portion of the total paving job was selected for comparison purposes to ensure that the ambient conditions during paving were comparable between the two projects.

Table 13 presents a detailed one-to-one comparison of the various design, materials, and construction factors between this project and the Taxiway A section constructed in 1998. A few key observations from the comparison are presented below:

- The paving conditions between the two projects were comparable in terms of the maximum and minimum temperatures experienced, as well as the temperature swings noted.
- The control joints were placed at 20 ft (6.1 m) in the longitudinal and 18.75 ft (5.72 m) in the transverse directions. This is a big improvement over the Taxiway A section.
- CTB strength data were not available, however observing the differences in the as-designed CTB values and the cement factors (not shown in table 13), it can be speculated that the as-built 7-day compressive strengths for this project could have been are far below those achieved when constructing Taxiway A.
- The PCC mixture design remained more or less the same between the two projects.
- An early entry saw was used for this project as opposed to a traditional saw to make the initial sawcut. However, the sawcut was made to a depth of D/4, as was the case before.
- The curing compound and bond breaker used were similar on both the projects.

<u>Conclusions</u>

By making small changes to the design and construction process, the potential for early EAD was reduced. These changes included reducing the joint spacing, decreasing the stiffness of the CTB, and using an early entry saw. However, one big factor that is not indicated by table 14 is the effort expended by the stakeholders involved in watching out for adverse weather patterns (cold swings) and taking adequate precautions or avoiding paving during those times.

5.2.7 Southeast Iowa Regional Airport Taxiway A, Phase I (2001)—EAD Project

Under Phase I of a three-phased project to relocate Taxiway A, the Southeast Iowa Regional Airport replaced and reconfigured the northern third of Taxiway A parallel to Runway 18-36. The paving area began with the safety zone limit at the north end of Runway 18-36 (station 10+00) and progressed to approximately station 33+25. Dimensions of the mainline paving portion of the Stage I construction are approximately 2,300 ft by 50 ft (701.5 m by 15.25 m). Cracking in the first two days of paving was reported within a few days after construction was complete. Figure 24 presents a sketch of the typical section and the typical joint layout for the feature of interest.

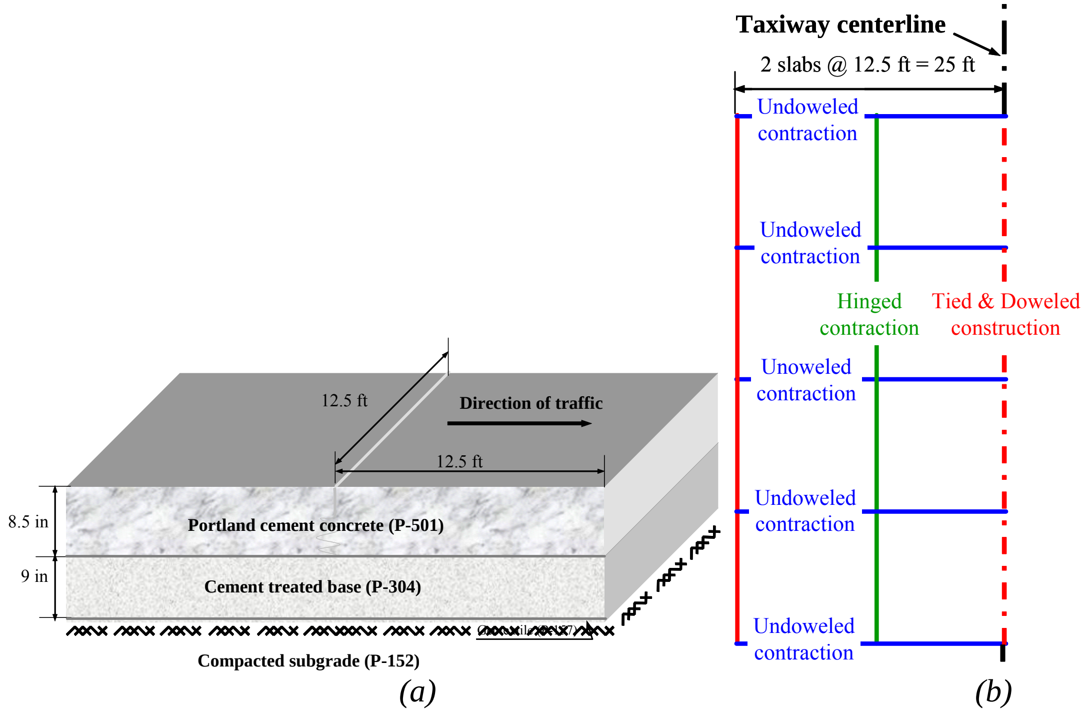


Figure 24. Typical section and joint layout for Taxiway A at Southeast Iowa Regional Airport, Phase I construction.

The CTB under Phase I taxiway was constructed between late July and early August of 2001. The PCC layer was paved in the latter half of August 2001. On August 16, 2001, the second day of PCC paving, random, irregular cracks were found in the first day's paving work. Paving operations were then suspended to determine the cause of the cracking. A total of 32 panels were cracked in the paving project, with two panels containing multiple cracks. The cracking observed was mostly transverse, however, some longitudinal cracking was also noticed. Figure 25 presents some photographs of typical cracking observed. Note that these photographs were taken in 2004, by which time the cracks were already sealed.

An evaluation of the data presented in table 14 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC, as well as the design, materials, and construction variants:

- According to project records, the PCC layer was placed on August 14th, 15th, 30th, and 31st of 2001. The ambient temperatures and wind speeds prevalent during this period obtained from climatological records at the airport are shown in figure 26. Furthermore, two significant rain events occurred on the 15th (0.18 in [4.6 mm] accumulation) and the 30th (0.14 in [3.6 mm] accumulation). It is also observed that temperatures and wind speeds rapidly rose immediately after placement on August 15th and so did the temperature swings. Temperatures in excess of 95°F (35°C) were recorded on several days after August 15th. These can be considered as significant trigger factors that could have contributed to the EAD noted on this project.

Figure 25. Photographs of cracking from Phase I Taxiway A construction at Southeast Iowa Regional Airport.

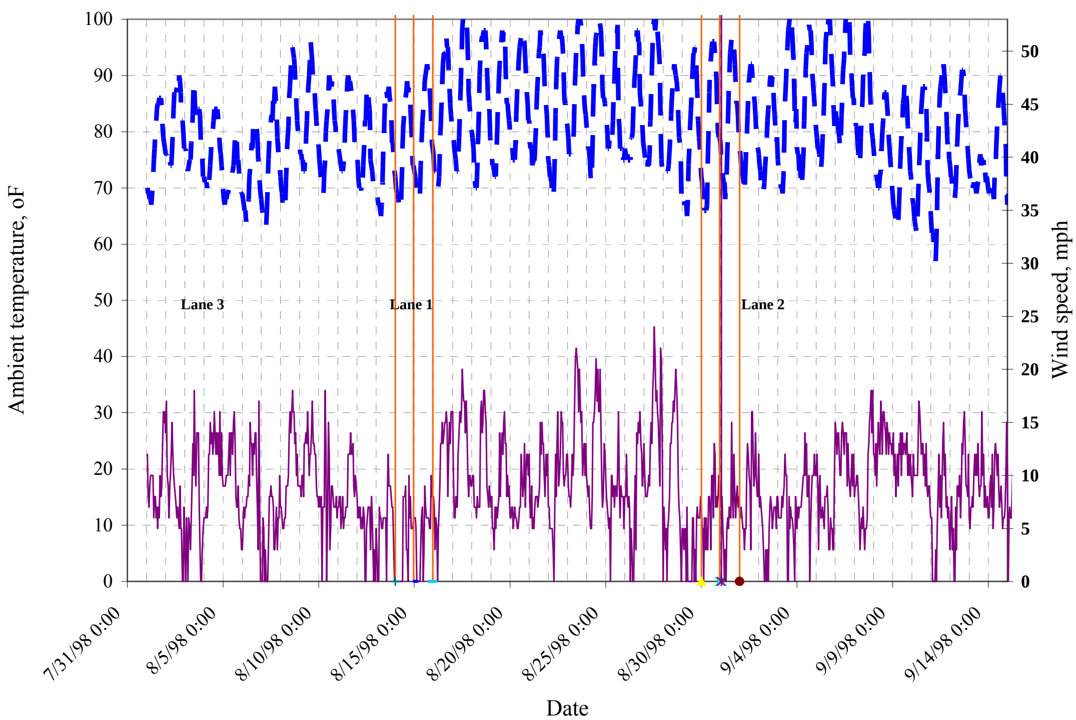


Figure 26. Ambient temperatures and wind speed during paving of Phase I Taxiway A at Southeast Iowa Regional airport.

- The as-designed PCC panel dimensions are well within the industry recognized practical maximum of 20 ft (6.1 m). However, sawcutting the PCC panels was reported as an issue (see below).
- The CTB thickness was above the recommended value of 6 in (152 mm). An examination of the base thickness at sawed edges revealed that the CTB thickness was between 9 and 11.5 in (229 and 292 mm). A thick base contributes to increased flexural rigidity of the CTB layer and hence has an effect of increasing curling stresses in the PCC slab.
- The as-designed 7-day strength of the base was well above the recommended maximum value of 1,000 lb/in^2 (6,895 kPa) (the design specification called for a 7-day compressive strength greater than or equal to 1,150 lb/in^2 (1,034 kPa). This was achieved by increasing the cement factor to 7 percent. The as-constructed values were even higher. A stiff base can curl and warp just like a PCC pavement layer and at the same time also contribute to increasing the curling/warping stresses in the PCC layer.
- Due to unavailability of records, it was not possible to perform a thorough review of the PCC mix design-related issues. The following mixture-related issues were noted based on the extent of information available:
    - The cement factor (which includes 10% flyash) seems typical for paving work; however, it is deemed to be high enough to cause increased water demand and high heat of hydration.
    - The percent passing the No. 50 (300 μm) sieve is 14 percent, indicating that the mixture does have a moderate bulking potential and could be prone to excessive shrinkage.
    - Records indicate that the coarse aggregate used in the P-501 mixes was limestone without any further qualifications. Limestone typically has a lower CTE and if joints were formed as indicated in the design records, may not have been a factor.
- The high cement factor base developed shrinkage cracks which were reported to be roughly transverse to the direction of traffic.
- Records indicate that no bond breaker was used on the project. This leads to excessive restraint at the slab/base interface, which opposes the deformations being imposed by the trigger factors (volumetric shrinkage, curling/warping, etc.), thus leading to the development of tensile stresses in the slab.
- It was noted by one of the stakeholders that the sawcutting was performed in an unsatisfactory manner. An early entry saw was used during the first paving run (approximately 1,100 ft by 25 ft [335.5 m by 7.625 m] runs on the first and second days of paving). A conventional sawcut was used after random, irregular cracks were found in previously placed pavement. The average depth of sawcut reportedly was approximately 2.8 in (71 mm). This depth may not be adequate in light of the apparent bond that exists between the PCC and thick and strong CTB layer. This could be a significant factor particularly when combined with all other triggers and variants.

<u>Conclusions</u>

In reviewing the factors listed above and the data presented in table 14, it is possible that there are several trigger factors could have led to the uncontrolled cracking. However, shrinkage-related deformations due to hot-temperatures is believed to have interacted with the following variants to cause the EAD:

- Presence of a very thick base.
- Presence of a very strong/stiff base.
- Absence of a bond breaker.
- Rough CTB/PCC interface.
- Inadequate sawcut depth.
- Presence of shrinkage cracks in CTB.

5.2.8 Southeast Iowa Regional Airport Taxiway A, Phase II (2002)—Non-EAD Companion Project

Under Phase II of the project to relocate Taxiway A, the Southeast Iowa Regional Airport Authority replaced and reconfigured the middle portions of taxiway A parallel to Runway 18-36. The paving area began with at approximately station 33+25 and progressed to station 45+50. Dimensions of the mainline paving portion of the Stage II construction are approximately 1,225 ft by 50 ft (373.6 m by 15.25 m). This project had similar cross-section, materials, and construction factors as the Taxiway A, Phase I section described earlier. However, no early-age cracking was observed on this pavement. Therefore, it was selected as a companion section for detailed comparisons.

Table 14 presents a detailed one-to-one comparison of the various design, materials, and construction factors between Phase II and Phase I construction. A few points of difference from the comparison are presented below:

- The paving seasons between the two projects roughly coincided with the 2002 construction extending into Fall. Milder temperatures prevailed during the construction of Phase II.
- Although the CTB mix design called for a 7-day compressive strength of 1,150 lb/in^2 (7,929 kPa), only 770 lb/in^2 (5,309 kPa), on average, was realized at 11 days in the field for Phase II construction. This is far less than the value achieved in the field for the Phase I section.
- The PCC mixture design indicates a mixture with a high cement factor, high amount of total water, and high mortar volume. The blended aggregate gradation falls outside the workability box. However, the sand used appears to be coarse sand.
- An early entry saw was used for this project to make the initial sawcut. The final sawcut was made to a depth of one-third the overall thickness (D/3). This is a positive change from the phase I project.

<u>Conclusions</u>

The relatively mild ambient conditions during the paving of the Phase II companion project, aided by small changes in the materials and construction variants, reduced the potential for EAD. These changes included lower CTB strength, use of an early entry saw, and deeper sawcuts.

5.3 REVIEW OF ECONOCRETE BASE PROJECTS (P-306)

A total of five pavement projects with an econocrete layer were short-listed for extensive data collection and evaluation in this study. Two of these projects had exhibited EAD, as defined in this study. Two of the remaining three projects that did not experience EAD, were "on site" companions. For the purposes of the empirical analysis, only the EAD projects and their corresponding non-EAD companions were selected.

5.3.1 Summary of Key Variables

Summaries of the parameter values/descriptions of the key trigger factors and variants for each of the selected projects are presented in table 16. Table 17 presents information from the Austin Straubel Airport Taxiway M extension project undertaken in 2002 (experienced EAD) and taxiway D reconstruction project undertaken in 2001 (did not experience EAD). Table 18 presents information concerning the Missoula International Air Carrier Apron projects constructed in 2001 (experienced EAD) and 2002 (did not experience EAD). Also provided in each of these tables are the recommended threshold values for the various trigger and variant factors which, if exceeded, increase the likelihood of EAD.

Table 16. List of projects with an econocrete layer selected for detailed study.

Section Location	Feature of Interest	Year Built	Early Cracking Present?	Design
Austin Straubel International Apt (GRB) Green Bay, WI	• Taxiway M (Stage III)	2002	Yes	16 in Reinforced PCC 6 in LCB 10 in Lime Treated Subgrade Silty Clay
Austin Straubel International Apt (GRB) Green Bay, WI	• Taxiway D (East of Runway 18-36)	2001	No	16 in Reinforced PCC 6 in LCB 10 in Lime Treated Subgrade Silty Clay
Missoula International Airport (MSO) Missoula, MT	• Air Carrier Apron (Phase I)	2001	Yes	16.5 in PCC Surface 8 in LCB 18 in Subbase course Stabilization fabric Subgrade
Missoula International Airport (MSO) Missoula, MT	• Air Carrier Apron (Phase V)	2002	No	16.5 in PCC Surface 8 in LCB 18 in Subbase course Stabilization fabric Subgrade

1 in = 25.4 mm

Table 17. Summary and comparison of data from Austin Straubel International airport EAD (2001) and on-site non-EAD companion (2001 and 2002) sections with recommended practice.

	Key Data Item	GRB EAD Project (Taxiway M – 2001)	GRB non-EAD Project (Taxiway D - 2001)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Early transverse cracking appeared in Taxiway M slabs shortly after construction. Total cracking was roughly 2 percent of the total slabs placed. Cracking was close to the control joints placed in the PCC.
	Ambient PCC Paving Conditions	Max. Temp – 86°F (median) Min. Temp – 69°F (median)	Max. Temp – 81°F (median) Min. Temp – 45°F (median)	Good hot- and cold-weather management plan and execution.	NA	Hot temperatures increase shrinkage potential. This could be a trigger factor for the EAD section. Large temperature swings cause steep gradients in PCC slabs. This could be a trigger factor for non-EAD section,
		Hot paving conditions; several days with > 90°F temperatures; large temperature swings > 25°F on all days of paving.	Normal paving temperatures. One day with temperature swing of 25°F; no precipitation.			
	PCC Placement Season	Summer	Late Summer			
Design Variants	Thickness	PCC Design – 16 in (reinforced). Actual – 16.3 in (avg.) Actual– 0.3 in (SD)	PCC Design – 16 in (reinforced). Actual – 16.3 in (avg.) Actual– 0.4 in (SD)			The as-built PCC thickness is higher than as-design by a small amount. The variability in thickness is typical.
		LCB Design – 6 in Actual – 6.7 in (avg.) Actual– 0.4 in (SD)	LCB Design – 6 in Actual – 6.9 in (avg.) Actual– 0.7 in (SD)	LCB thickness: 6 in	Yes	As-built thicknesses, greater than as-designed values. This increases the effective slab thickness rendering planned sawcuts ineffective.
	Joint Spacing	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 12.5 ft	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 12.5 ft	Max. dimension ≤ 20 ft.	No	The L/W ratio is 1.6, which is much higher than the recommended value of 1.25. This increases the probability of EAD.
				L/W < 1.25	Yes	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 801 lb/in^2	Mix Design – 801 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 902 lb/in^2 (avg.) Actual – 48.3 lb/in^2 (SD)	Actual – 966 lb/in^2 (avg.) Actual – 59 lb/in^2 (SD)			The as-built strength is greater then the design value. Higher strength increases the cracking resistance but on the other hand it increases the concrete modulus and consequently the probability of cracking.
	LCB Compressive Strength	7-day Actual –NA 28-day Actual – NA	7-day Mix Design – 1,095 lb/in^2 28-day Mix Design – 1,442 lb/in^2	7-day: 500 to 800 lb/in^2	Yes	The as-built strength values are excessive for both EAD and non-EAD projects indicating a very strong base layer leading to increased curling/warping stresses in the PCC pavement.
		7-day Mix Design – 1,070 lb/in^2 28-day Mix Design – 1,465 lb/in^2	7-day Actual –1,132 lb/in^2 (avg.) 28-day Actual – 1,504 lb/in^2 (avg.)			
	LCB Mixture Properties	Cement Type – Type I/II	Cement Type – Type I/II			The cement factor is 1.75 times the recommended value. It is certainly one of the reasons for the high strength. High strength bases increase potential for EAD.
		Cement Factor – 350 lbs/yd^3	Cement Factor – 350 lbs/yd^3	200 lbs	Yes	
		Pozz. Cont. – 40% FA	Pozz. Cont. – 40% FA			
		Water – 30 gal	Water – 30 gal			

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in2 = 6.895 kPa 1 lb/yd3 = 0.59 kg/m3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 17. Summary and comparison of data from Austin Straubel International airport EAD (2002) and on-site non-EAD companion (2001) sections with recommended practice (continued).

	Key Data Item	GRB EAD Project (Taxiway M - 2002)	GRB non-EAD Project (Taxiway D - 2001)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I	Cement Type – Type I			
		Cem. Factor – 565 lbs/yd^3 Pozz. Cont. – 0%	Cem. Factor – 565 lbs/yd^3 Pozz. Cont. – 0%	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3. High heat of hydration couple with a thermal shock can differentially cure the PCC slab. Sawing operations can get disrupted.
		w/c ratio – 0.44	w/c ratio – 0.44			
		Total Water – 246 lbs.	Total Water – 246 lbs.	Less than 250 lb	No	OK, although close to the limit.
		Mortar Volume – 62.4%	Mortar Volume – 62.4%	Less than 60%	Yes	Mortar value greater than recommended.
	PCC Fine Aggregate Gradation	Type – Coarse to fine (Concrete sand)	Type – Coarse to fine (Concrete sand)	Coarse sand	No	Fine sand increases water demand and shrinkage potential.
		Passing No. 50 sieve – 13%	Passing No. 50 sieve – 13%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 3.0	Fineness Mod.– 3.0	3.1 to 3.4 for cem. fac. > 400 lb/yd^3	No	OK
	PCC Coarse Agg. Type	Crushed Limestone	Crushed Limestone			Moderate CTE.
	PCC Combined Aggregate Gradation— Design	WF – 34.0	WF – 34.0	WF > 29 & CF < 75	No	Potentially, a well-graded workable mixture.
		CF – 74.2	CF – 74.2		No	
		Nom. Max. Agg. – 1.0 in	Nom. Max. Agg. – 1.0 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK.
		LCB Curing– LMFCC (resin-base) Rate >1 gal/200 ft^2	LCB Curing– LMFCC (resin-base) Rate >1 gal/200 ft^2	LMFCC (wax-based) or choke stone	No	
	Initial Sawcut	Equipment – Traditional	Equipment – Traditional	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/4	Depth – D/4	D/3	Yes	Maybe insufficient depth in light of the bond between PCC and LCB and also the prevalent temperature conditions for EAD.
	Bond Breaker	None	None	Double coat wax-based curing compound	Yes	Perhaps inadequate.
	LCB Jointing	Joint sawed in LCB according to specification. Joint offset of at least 6 in.	Joint sawed in LCB according to specification. Joint offset at least 6 in.	Saw joints if 28-day max. comp. str. is not limited	No	Good practice to notch LCB.
	LCB Surface Condition Prior	Presence of shrinkage cracks.	NA	When LCB is trimmed, additional coat of CC is recommended.	Yes	Shrinkage cracks in a high strength stabilized base can increase potential for EAD.
	LCB QA Program	Acceptance based only on thickness and strength measurements.	Acceptance based only on thickness and strength measurements.	Thickness, strength, grade, surface evenness		Typical QA program.

1 in = 25.4 mm   1 ft^2 = 0.093 m^2 1 gal = 3.785 L   1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 18. Summary and comparison of data from Missoula International Airport Air Carrier Apron EAD (2001) and on-site non-EAD companion (2002) sections with recommended practice.

	Key Data Item	MIA EAD Project (Air Carrier Apron Phase I – 2001)	MIA non-EAD Project (Air Carrier Apron Phase V – 2002)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Early transverse and longitudinal cracking.
	Ambient PCC Paving Conditions	Max. Temp – 62°F. (median) Min. Temp – 39°F. (median)	Max. Temp – 55°F (approximate). Min. Temp – 40°F (approximate).	Good hot- and cold-weather management plan and execution.	Yes – EAD No – non-EAD	Large temperature swings cause steep gradients in PCC slabs. Likely trigger for EAD. Better control over environmental variables in the non-EAD project. Cool temperatures retard strength gain.
		Cold temperature during paving; rain and snow around the time when cracks happened.	Cold temperatures during paving.			
	PCC Placement Season	Late Spring/Summer	Summer/Fall			
Design Variants	Thickness	PCC Design – 16.5 in (reinforced). Actual – 16.6 in (avg.) Actual– 0.2 in (SD)	PCC Design – 16.5 in (reinforced). Actual – 16.6 in (avg.) Actual– 0.4 in (SD)			The as-built and as-built PCC thickness matches well.
		LCB Design – 8 in Actual – NA (avg.) Actual– NA (SD)	LCB Design – 8 in Actual – NA (avg.) Actual– NA (SD)	LCB thickness: 6 in	Yes	The LCB thickness is greater than the recommended value. Stiff bases increase the l-value of the surface layer and can increase temperature related stresses.
	Joint Spacing	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 20 ft	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 20 ft	Max. dimension ≤ 20 ft.	No	OK
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 767 lb/in^2	Mix Design – 785 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 812 lb/in^2 (avg.) Actual – 91 lb/in^2 (SD)	Actual – 749 lb/in^2 (avg.) Actual – 47.3 lb/in^2 (SD)			The as-built as and as-designed flexural strengths are quite close. The as-built strength variability is typical.
	LCB Compressive Strength	7-day Mix Design – 685 lb/in^2 28-day Mix Design – 960 lb/in^2	7-day Mix Design – 675 lb/in^2 28-day Mix Design – NA	7-day: 500 to 800 lb/in^2	Yes	The EAD LCB layer has much higher strengths than the non-EAD section.
		7-day Actual – 968 lb/in^2 (avg.) 28-day Actual – 1,435 lb/in^2 (avg.) 7-day @ loc. with cracks: 1280 lb/in^2 28-day @ loc. with cracks: 1640 lb/in^2	7-day Actual – 650 lb/in^2 (avg.) 28-day Actual – 894 lb/in^2 (avg.)			
	LCB Mixture Properties	Cement Type – Type I/II	Cement Type – Type I/II			The cement factor is about 1.5 times the recommended design value.
		Cement Factor – 299 lbs/yd^3	Cement Factor – 299 lbs/yd^3	200 lbs	Yes	
		Pozz. Cont. – 13% FA “F”	Pozz. Cont. – 13% FA “F”			
		Air content – 6 %	Air content – 6 %			
		Water – 225 lb	Water – 225 lb			

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

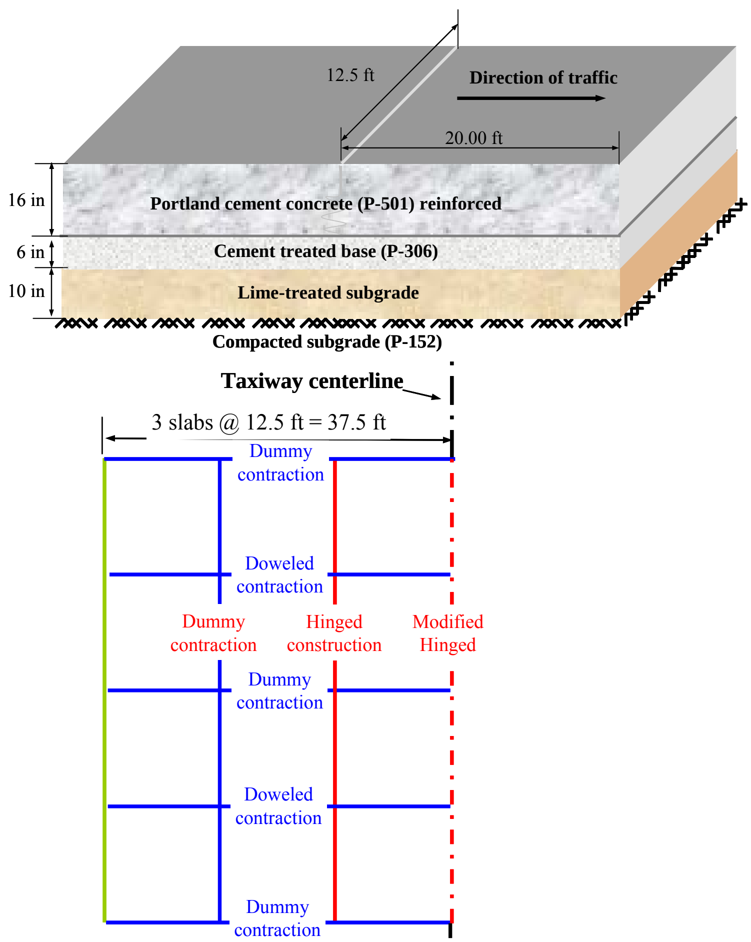
Table 18. Summary and comparison of data from Missoula International Airport Air Carrier Apron EAD (2001) and on-site non-EAD companion (2002) sections with recommended practice (continued).

	Key Data Item	MIA EAD Project (Air Carrier Apron Phase I – 2001)	MIA non-EAD Project (Air Carrier Apron Phase V – 2002)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I/II	Cement Type – Type I/II			
		Cem. Factor – 600 lbs/yd^3 Pozz. Cont. – 16.7% FA “F”	Cem. Factor – 600 lbs/yd^3 Pozz. Cont. – 16.7% FA “F”	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3. High heat of hydration couple with a thermal shock can differentially cure the PCC slab. Sawing operations can get disrupted.
		w/c ratio – 0.38	w/c ratio – 0.38			
		Total Water – 225 lbs.	Total Water – 225 lbs.	Less than 250 lb	No	OK
		Mortar Volume – 59%	Mortar Volume – 59%	Less than 60%	No	OK
	PCC Fine Aggregate Gradation	Type – fine (sand/gravel)	Type – fine (sand/gravel)	Coarse sand	Yes	Fine sand increases water demand and shrinkage potential. Both projects have similar fine aggregate characteristics.
		Passing No. 50 sieve – 15% (field gradation finer)	Passing No. 50 sieve – 15% (field gradation finer)	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 2.8	Fineness Mod.– 2.8	3.1 to 3.4 for cem. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential for both sections.
	PCC Coarse Agg. Type	NA	NA			
	PCC Combined Aggregate Gradation— Design	WF – 37.3	WF – 37.3	WF > 29 & CF < 75	No	Well graded coarse aggregate offsets some of the concern regarding placement.
		CF – 62.2	CF – 62.2		No	
		Nom. Max. Agg. – 0.75 in	Nom. Max. Agg. – 0.75 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (wax-base) Rate >1 gal/150 ft^2	PCC Curing – White-pigmented LMFCC (wax-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	However, reportedly better cold-weather concreting practices for the non-EAD section compared to the EAD section.
		LCB Curing– LMFCC (wax-base) Rate >1 gal/150 ft^2	LCB Curing– LMFCC (wax-base) Rate >1 gal/150 ft^2	LMFCC (wax-based) or choke stone	No	
	Initial Sawcut	Equipment – Traditional	Equipment – Traditional	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/3.7	Depth – D/3.7	D/3	Yes	Maybe insufficient depth.
	Bond Breaker	AMOCO CEF 4552 Non-woven Geotextile	AMOCO CEF 4552 Non-woven Geotextile	Double coat wax-based curing compound	No	OK
	LCB Jointing	No joint were sawed.	No joint were sawed.	Saw joints if 28-day max. comp. str. is not limited	Yes	Not notching the strong LCB could have contributed to cracking in the EAD section.
	LCB Surface Condition Prior	Surface coved with geotextile.	Surface coved with geotextile.	When LCB is trimmed, additional coat of CC is recommended.	Yes	The presence of geotextile could potential decrease the restraint stresses.
	LCB QA Program	Acceptance based only on thickness and strength measurements.	Acceptance based only on thickness and strength measurements.	Thickness, strength, grade, surface evenness		Typical.
	Overall construction quality	Timing of sawing potentially outside the latest possible opportunity. Overnight cold front not anticipated.	Sawcutting was given a lot of attention.			Better construction practices for non-EAD section.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

5.3.2 Austin-Straubel International Airport Taxiway M (2002) Construction—EAD Project

This parallel taxiway is located to the east of the North-South Runway 18/36. The particular job of interest was the extension of this taxiway on the north side connecting to the ramp area leading to the terminals. The taxiway was reconstructed approximately July 2002 through August 2002 (starting from the econocrete layer up to the PCC layer). The approximate extents of the taxiway extension were between station 116"M"+00 on the south end to station 136"M"+00 on the north end. However, the focus of this report is Taxiway M Stage III which had experienced some early cracking. Figure 27 presents a sketch of the typical section and the typical joint layout for the feature of interest.



(a) *(b)*

Figure 27. Typical section and joint layout for Taxiway M (2002 extension) at Austin Straubel International Airport.

The cracking affected roughly 2 percent of the total number of PCC panels placed on this project. The predominant distress was transverse cracking at the joints. The cracks appear to appear right on top of the joints in the econocrete base which was notched (since the upper limit of the LCB strength was not controlled).

Figure 28 presents some photographs of typical cracking observed on this project. In addition to cracking sealant push out was also noticed at the joints suggesting that the cracks were working. Note that these photographs were taken in 2004 by which time some of the cracks were already sealed.

Figure 28. Photographs of cracking from the 2002 Taxiway M expansion at the Austin Straubel International Airport.

An evaluation of the data presented in table 17 was performed to study the circumstances that could have contributed to the formation of the cracking. The following observations resulted from this investigation:

- According to project records, the LCB layer was placed between July 1st and July 9th, 2002 and the PCC layer was slip-formed between July 10th and July 22nd, 2002. Several temperature reversals were observed during the paving operation although the placement was in Summer. On one particular paving day, there was a temperature swing of approximately 30°F (14°C) due to rain. Project records indicate that plastic sheeting was used to protect the pavement.

- Figure 29 presents the prevalent ambient conditions around the time the PCC was placed.
- The aspect ratio of the slab length to width is above the recommended specification of 1.25. This could lead to a biased stress concentration in one of the axes during bending.
- The 7-day and 28-day LCB strengths were far greater than the minimum values (see figure 30). This in combination with the high slab aspect ratio can lead to excessive stresses when the conditions are right for such a situation.
- The cement factor was high (565 lb/yd^3 [333 kg/m^3]). High cement factors cause higher than normal heat of hydration which can set up excessive tensile stresses in the presence of a rough base/slab interface. In the presence of a cold front, differential curing occurs

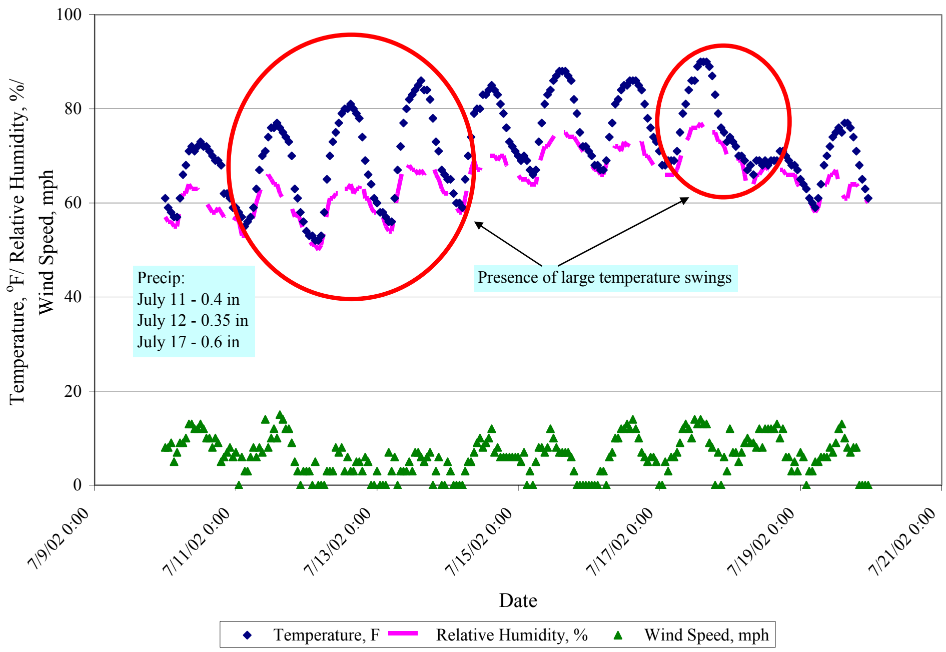


Figure 29. Large temperature swings during PCC paving on the 2002 Taxiway M expansion project at Austin-Straubel International Airport.

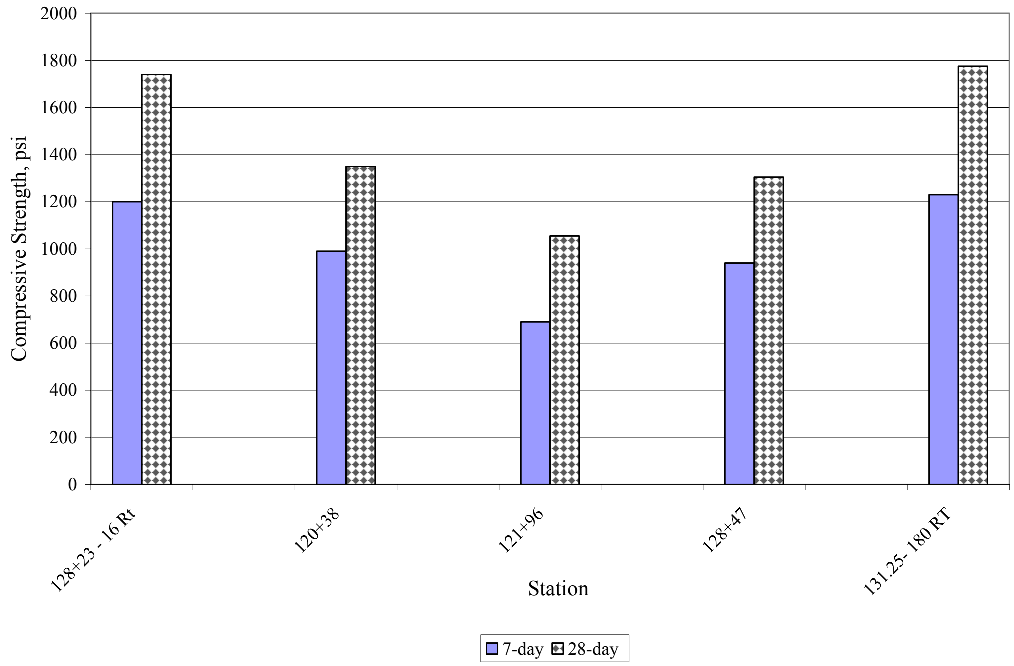


Figure 30. 7- and 28-day compressive strength values for the LCB layer from the 2002 Taxiway M expansion project at Austin-Straubel International Airport.

through the slab thickness (bottom portions cures quicker than the top), which disrupts the sawing operations and the effectiveness of the sawcut.

- The PCC mix seems to be well-graded; the fines contents are not excessive. In all, the mixture will more than likely not contribute to the uncontrolled cracking due to segregation.
- No bond breaker was used to minimize the restraint stresses between the high strength LCB and the PCC. Rather, joints were notched but they were mismatched by at least 6 in (152 mm), as required by the specifications.
- The LCB surface had several shrinkage cracks and appeared uneven.
- Traditional walk-behind saws were used and the sawcut depth was approximately one-fourth the pavement thickness. This depth may not be adequate for a fully bonded PCC/LCB system.

Conclusions

Based on review of the information presented, the key trigger factor causing deformations in the slab is the large temperature swing. Based on a preliminary review of the data, it appears that the mechanisms of the cracking for this project are similar to the ones observed on the Omaha-Eppley Airport Taxiway A project, except that the cracks here are transverse, owing to the highly rectangular shape of the PCC slabs.

5.3.3 Austin-Straubel International Airport Taxiway D (2001)—Non-EAD Companion Project

This parallel taxiway is located north of northeast-southwest Runway 6-24. The taxiway reconstruction took place in 2001 as well as 2002. However, only a small portion of the taxiway was built in 2002. Therefore, for the purposes of this study, only the 2001 information is presented. For this portion of the construction, the LCB layer was placed on June 5th and August 2nd through 4th of 2001. Based on a review of the project records, the PCC layer was placed on August 10th, 13th, 17th, 23rd, and 28th through 31st of 2001. This project had similar cross-section, materials, and construction factors as the Taxiway M project discussed in section 5.3.2. However, no early-age cracking was observed during or immediately following the construction of this project. Therefore, it was selected as a companion section for detailed comparisons.

Table 17 presents a detailed one-to-one comparison of the various design, materials, and construction factors between the Taxiway D and Taxiway M projects. A few points of difference between these projects from this comparison are presented below:

- The paving on the Taxiway D project took place in August, 2001; the paving seasons between the Taxiway M project and this project were therefore offset by 1 month. As can be noted from figure 31, milder temperatures, higher relative humidities (not shown), and lower temperature fluctuations prevailed in this construction season. One large temperature swing was noted immediately following PCC placement on one occasion.

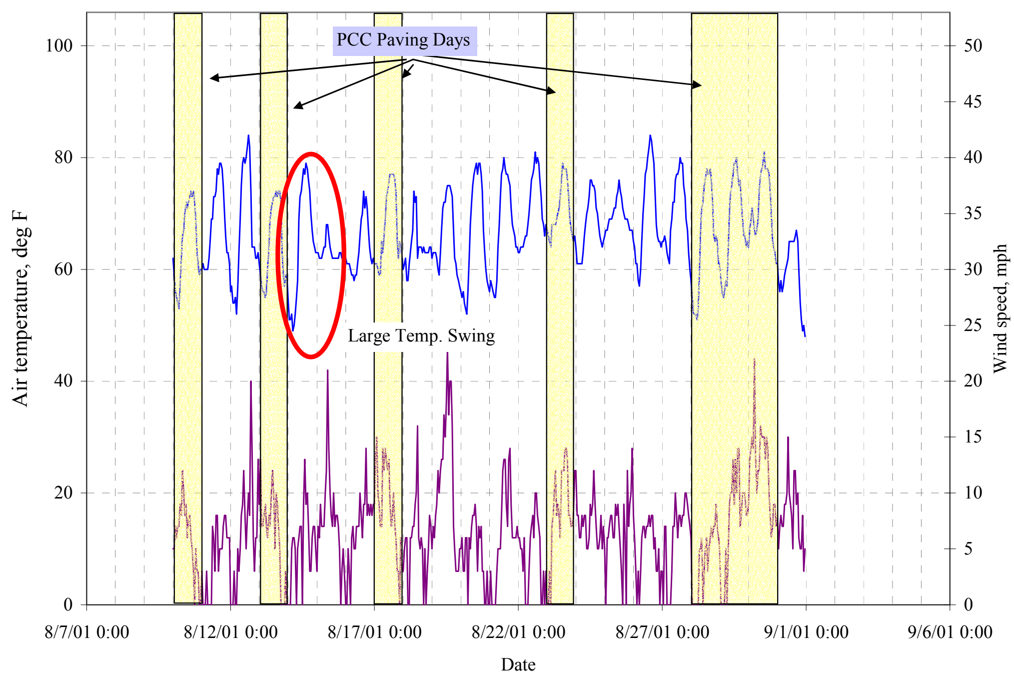


Figure 31. Large temperature swings during the 2001 PCC paving on Taxiway D at Austin Straubel International Airport.

- The LCB compressive strength values from this project (see figure 32) are similar to those obtained from Taxiway M on average.

- All other factors including PCC and LCB mix properties, curing methods, sawcut depths and techniques, use of bond breaker, etc. for this project were the same as those for the Taxiway M project.

Conclusions

Based on a review of the information presented, it appears that the absence of critical trigger conditions (i.e., good paving conditions) was the only reason EAD did not develop on this project. This is despite several of the design, materials, and construction variants exceeding critical threshold values.

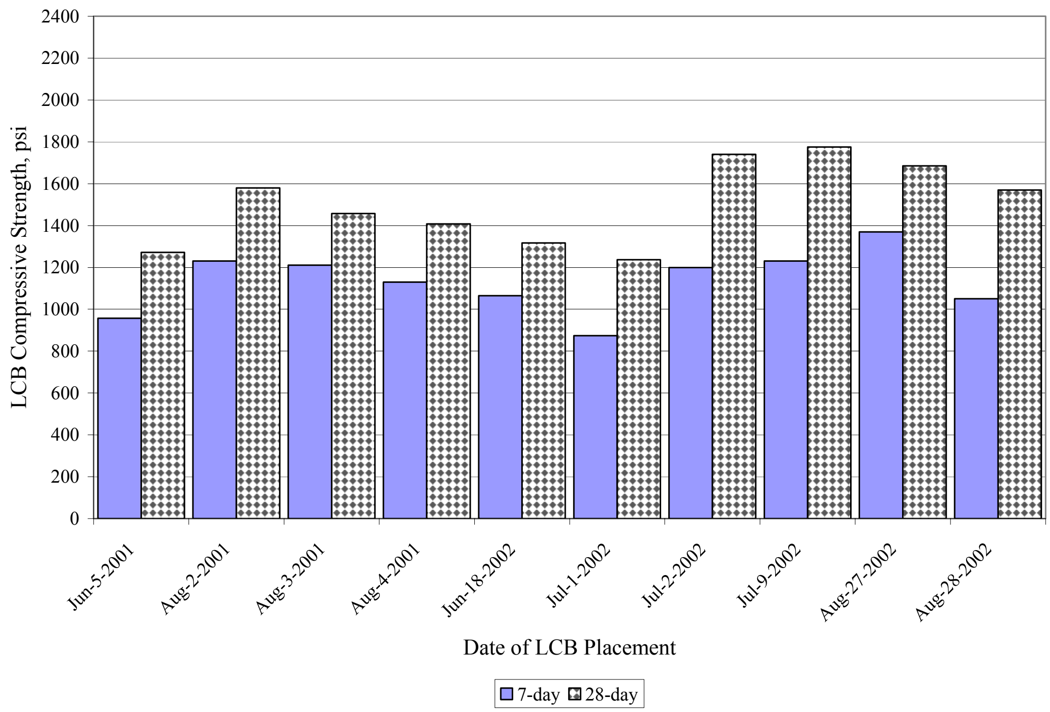


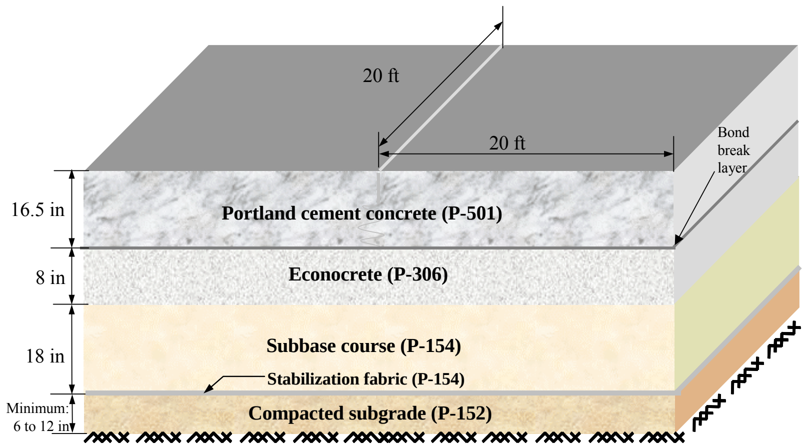
Figure 32. 7- and 28-day compressive strength values for the LCB layer from the 2001 Taxiway D construction project at Austin-Straubel International Airport.

5.3.4 Missoula International Air Carrier Apron Construction, Phase I (2001)—EAD Project

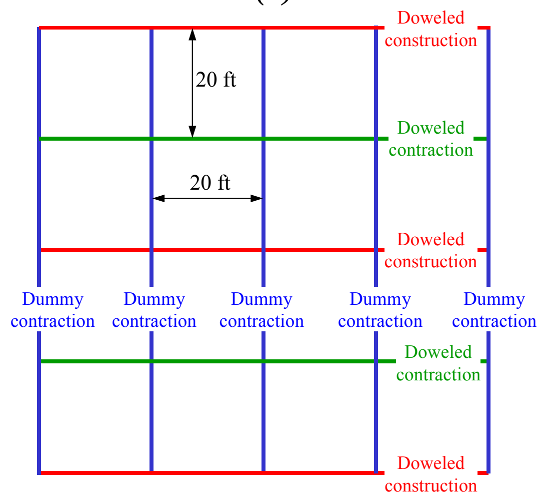
The project involved the construction of an Air Carrier Apron at the Missoula International Airport, Missoula, MT. Phases I, II, and III were constructed in 2001 and Phases IV and V were completed in 2002. The apron is located north of Taxiway E. Transverse and longitudinal cracks were observed on some slabs constructed in Phase I. No cracking was observed in the remaining phases of the project. Figure 33 presents a sketch of the typical section and the typical joint layout for the feature of interest.

The construction of Phase I began on April 9, 2001 and was completed by October 11, 2001. The laydown of the LCB layer began on May 11, 2001. PCC paving took place between May 26th and June 5th. On the morning of June 3rd, a total of 14 cracked slabs were observed from the previous night's paving. These slabs had to be removed and replaced.

An evaluation of the data presented in table 18 for this project suggests the following with regard to the various ambient trigger conditions present during PCC paving, as well as the design, materials, and construction variants:



(a)



(b)

Figure 33. Typical section and joint layout for the Air Carrier Apron at Missoula International Airport.

- Cold temperatures and large temperature swings were present during PCC placement. The unplanned cracks happened during one such extreme temperature swing that occurred after paving on June 2nd. The swing was caused by a cold spring storm in the form of rain and snow. This storm brought the ambient temperatures into the 30's°F (0's°C), as shown in figure 34.

- The panel dimensions are at the recommended maximum of 20 ft (6.1 m). These long slab dimensions could be an aggravating factor causing cracking under unfavorable ambient conditions (e.g., a thermal shock as evidenced here).
- The thickness of the LCB layer is above the recommended value of 6 in (152 mm). A thick base increases the slab support value and can lead to an increase in curling and warping stresses in the slab.

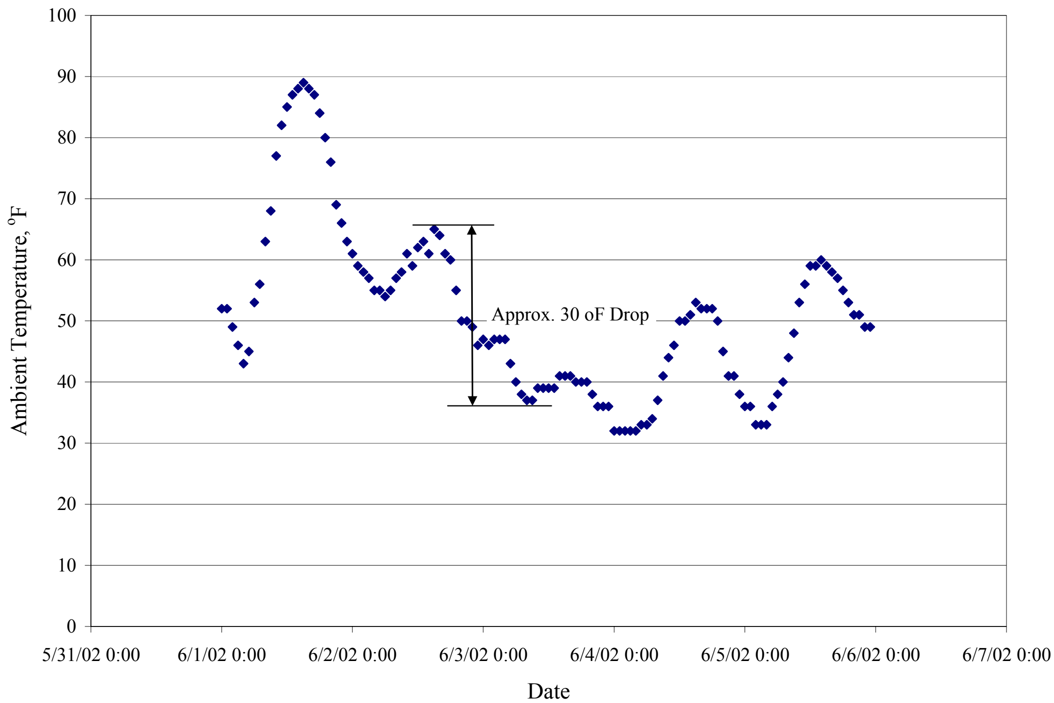


Figure 34. A cold front during the construction of the Phase I Air Carrier Apron in 2001 at the Missoula International Airport.

- The compressive strength of the LCB in areas where cracking was observed is far greater than the maximum recommended value of 1,000 lb/in^2 (6,895 kPa) at 7-days. These values are also much greater than those planned during mix design. As discussed earlier, high strength bases do increase the early cracking potential.
- An analysis of the PCC mix design revealed the following mixture-related issues:
  - The cement factor of 600 lb/yd^3 (354 kg/m^3) with 16.7% type F flyash. This is a relatively high cement factor which, when combined with a sudden temperature drop could prove detrimental, as was observed previously for the Omaha Eppley Taxiway A (1998) and Austin Straubel Taxiway M (2002) projects.
  - The combined aggregate gradation appears to be representative of a well-graded and workable mixture.
- No joints were notched in the LCB despite the high compressive strength values obtained in the field. This further reduces the effectiveness of the planned sawcuts in the PCC slab.

- Records indicate that a single coat of a white-pigmented wax-based LMFCC was used to cure the LCB. A geotextile fabric was used to break the bond between the LCB and the PCC layers. This is considered good practice.
- Based on the review of the records and interviews with stakeholders, it was determined that the timing of sawcut was well outside the latest possible opportunity on this project. The imminent cold front and the higher curing at the bottom of the slab were not anticipated to establish the timing of the initial sawcut. Further, the sawcut depth of nearly D/4 that was used on this project may have been inadequate.

Conclusions

In reviewing the factors listed above, it can be seen that perhaps the largest driving factor which led to the movements in the slab is the 30°F (-1°C) plus temperature swing recorded on the night of the paving. However, factors that could have aggravated the situation include the following:

- High cement factor concrete.
- Presence of a thick base.
- Presence of a very stiff base.
- Late sawing.

5.3.5 Missoula International Air Carrier Apron Construction, Phase V (2002)—Non-EAD Project

The discussion in this section compares the trigger and variant factors present during the Phase V of the Air Carrier Apron construction at the Missoula International Airport with Phase I, discussed previously in section 5.3.4. Phase V was completed in Summer/Fall of 2002 and has similar structural design, slab layout, and PCC material factors. In both cases, a geotextile bond breaker was employed. No EAD was reported during Phase V work. Therefore, this project affords a good side-by-side comparison of the issues leading to the mitigation of early cracking.

The work on Phase V commenced in August 2, 2002 and was substantially completed by October 25, 2002. The LCB layer was placed between September 11, 2002 and September 23, 2002. PCC paving was accomplished between October 4, 2002 and October 15, 2002. Although the construction season for Phase V work appears to be different from Phase I, the prevalent ambient conditions were similar in both the phases.

The following observations are made based on the data presented for these two sections in table 18:

- The overall ambient temperatures were on the cooler side, as was the case with Phase I construction. One cold snap was reported; however, paving was suspended in that period.
- The LCB layer compressive strengths at 28 days were below 1,000 lb/in^2 (6,895 kPa) in Phase V.
- The paving inspector and contractor were alert to cold-weather conditions and had an effective cold-weather management plan (e.g., use of heaters to cure concrete).

- The services of a more responsive sawing crew were commissioned. The sawing crew was vigilant to sawcut timing issues. The sawcut depths and equipment used remained the same between both the phases.

Conclusions

Based on a review of the data, it appears that by having a more effective temperature management plan, a more responsive construction crew, and a less stiff base, the problem of early cracking was well managed.

5.4 REVIEW OF ASPHALT-TREATED BASE (ATB) PROJECTS (P-401)

A total of three pavement projects with an ATB layer were short-listed for extensive data collection and evaluation in this study. One of these projects had exhibited EAD, as defined in this study. The two remaining projects experienced no EAD. One of these two projects was an "on-site" companion. Table 19 lists the projects selected for detailed discussion, along with key project details. In all these projects, the ATB layer was constructed in accordance with the FAA AC 150/5370-10A, Item P-401, *Plant Mix Bituminous Pavements*, with some modifications to suit local practices.

5.4.1 Summary of Key Variables

Summaries of the parameter values/descriptions of the key trigger factors and variants for each of the projects discussed are presented in this section. Table 20 presents information for the Austin Straubel Air Carrier Apron expansion projects constructed in 2000 (experienced EAD) and 2001 (did not experience EAD). Table 21 presents similar information for the Southern Wisconsin Regional airport Runway 13-31 extension and Taxiway B reconstruction projects (non-EAD projects) completed in 2002. Also provided in these tables are the recommended threshold values for the various trigger and variant factors with appropriate comments noting how the as-built properties compare to them.

Table 19. List of projects with an ATB layer selected for detailed study.

Section Location	Feature of Interest	Year Built	Early Cracking Present?	Design
Austin Straubel International Airport (GRB) Green Bay, WI	• Air Carrier Apron Expansion	2000	Yes	16 in Reinforced PCC 6 in ATB 10 in Lime treated subgrade Silty clay subgrade
Austin Straubel International Airport (GRB) Green Bay, WI	• Air Carrier Apron Expansion	2001	No	16 in Reinforced PCC 6 in ATB 10 in Lime treated subgrade Silty clay subgrade
Southern Wisconsin Regional Airport (JVL) Janesville, WI	• Runway 13-31 and Taxiway B Reconstruction and Extension	2002	No	13 in PCC 4 in ATB 6 in Crushed agg. base Subgrade

1 in = 25.4 mm

Table 20. Summary and comparison of data from Austin Straubel International Airport EAD (2000) and on-site non-EAD companion (2001) sections with recommended practice.

	Key Data Item	GRB EAD Project (Air Carrier Expansion– 2000)	GRB non-EAD Project (Air Carrier Expansion– 2001)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Diagonal and transverse cracking appeared right after construction. PCC slabs also experienced migration towards unrestrained edge and sealant push out.
	Ambient PCC Paving Conditions	Max. Temp – 78/65°F (median) for stages I and II, respectively. Min. Temp – 56/44°F (median) for stages I and II, respectively.	Max. Temp – 79°F. (median) Min. Temp – 56°F. (median)	Good hot- and cold-weather management plan and execution.	NA	Large temperature swings (>25°F) cause steep gradients in PCC slabs. This could be a trigger factor for non-EAD section since it occurred on several days.
		Large temperature swings > 25°F on several days with an average of 20°F. One max. temperature was > 90°F and other <40°F.	Large temperature swings with an average of 22°F. No maximum or minimum temperature issues.			
	PCC Placement Season	Early Fall – Stage I Late Fall – Stage II	Summer			
Design Variants	Thickness	PCC Design – 16 in (reinforced). Actual – 16.0 in (avg.) Actual– 0.4 in (SD)	PCC Design – 16 in (reinforced). Actual – 16.3 in (avg.) Actual– 0.5 in (SD)			The as-built and as-designed PCC thicknesses are in good agreement.
		ATB Design – 6 in Actual – NA (avg.) Actual– NA (SD)	ATB Design – 6 in Actual – NA (avg.) Actual– NA (SD)	ATB thickness: 6 in	No	OK
	Joint Spacing	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 12.5 ft	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 12.5 ft	Max. dimension ≤ 20 ft.	No	The L/W ratio is 1.6, which is much higher than the recommended value, increasing the probability of cracking.
				L/W < 1.25	Yes	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 838 lb/in^2	Mix Design – 801 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 867 lb/in^2 (avg.) Actual – 69 lb/in^2 (SD)	Actual – 894 lb/in^2 (avg.) Actual – 57 lb/in^2 (SD)			The as-built flexural strengths are higher than the as-designed flexural strengths particularly for the non-EAD project.
	PCC Mixture Properties	Cement Type – Type I	Cement Type – Type I			
		Cem. Factor – 590 lbs/yd^3 Pozz. Cont. – 18.6% FA “C”	Cem. Factor – 590 lbs/yd^3 Pozz. Cont. – 18.6% FA “C”	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3
		w/c ratio – 0.36	w/c ratio – 0.36			
		Total Water – 216 lbs.	Total Water – 216 lbs.	Less than 250 lb	No	OK
		Mortar Volume – 65%	Mortar Volume – 65%	Less than 60%	Yes	Mortar volume greater than recommended.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 20. Summary and comparison of data from Austin Straubel International Airport EAD (2000) and on-site non-EAD companion (2001) sections with recommended practice (continued).

	Key Data Item	GRB EAD Project (Air Carrier Expansion– 2000)	GRB non-EAD Project (Air Carrier Expansion– 2001)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	As-Designed ATB Mix Properties	Th. Max. Sp. Gr., G_{mm} – 2.53 AC Content – 5.3% (by wt.) AC Grade – PG 58-28 Air Voids – 3% VMA – 14.7%; VFA – 79.6%	Th. Max. Sp. Gr., G_{mm} – 2.53 AC Content – 5.3% (by wt.) AC Grade – PG 58-28 Air Voids – 3% VMA – 14.7%; VFA – 79.6%			The asphalt mix properties indicate that the mix was placed as designed. With the high AC contents and low air voids, the mixture appears to be capable of achieving high stiff nesses.
	As-Built ATB Mix Properties	AC Content – 5.57% (avg.) AC Content – 0.09% (SD) Density – 97.7% of G_{mm} (avg.) Density – 1.2% of G_{mm} (SD) Air Voids – 3.02 (avg.) Air Voids – 0.6% (SD)	AC Content – 5.51% (avg.) AC Content – 0.09% (SD) Density – 97.9% of G_{mm} (avg.) Density – 0.7% of G_{mm} (SD) Air Voids – 2.5 (avg.) Air Voids – 0.2% (SD)			
	PCC Fine Aggregate Gradation	Type – Natural sand	Type – Natural sand	Coarse sand	No	Fine sand increases water demand and shrinkage. Both EAD and non-EAD sections have the same aggregate.
		Passing No. 50 sieve – 14.3%	Passing No. 50 sieve – 14.3%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 2.54	Fineness Mod.– 2.54	3.1 to 3.4 for cem. Fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Crushed Dolomite	Crushed Dolomite			High CTE aggregate.
	PCC Combined Aggregate Gradation—Design	WF – 35.8	WF – 35.8	WF > 29 & CF < 75	No	Both EAD and non-EAD combined aggregate gradations are outside workability box.
		CF – 84	CF – 84		No	
		Nom. Max. Agg. – 1.5 in	Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (water-base) Rate >1 gal/150 ft^2	PCC Curing – White-pigmented LMFCC (water-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
	Initial Sawcut	Equipment – Early Entry every 2 to 3 joints; Wet saw remainder.	Equipment – Early Entry every 2 to 3 joints; Wet saw remainder.	Early entry or traditional wet saws.	Yes	Skip sawing is not recommended. Could be detrimental when temperature swings are large.
	Sawcut Depth	Depth – D/4	Depth – D/4	D/3	Yes	Maybe insufficient depth.
	Bond Breaker	None	None	None recommended.	No	OK
	Whitewashing Usage?	None.	None needed.	Use lime-water to cool surface prior to placing PCC in hot weather or moisten just prior to paving.	No	The base was not whitewashed prior to PCC placement, which could have increased the potential for cracking particularly for the EAD section.
	ATB Surface Condition Prior to Paving	Some reports indicate surface was milled to establish grade.	Milling not performed.	If milling required to correct grade, specify a following leveling layer.	Yes	Milled surface increases base restraint and could have contributed to the cracking in the EAD section.
	ATB Quality Acceptance Program	Mat density, joint density, thickness, smoothness, grade	Mat density, joint density, thickness, smoothness, grade	Mat density, joint density, thickness, smoothness, grade		QA variables according to recommended practice.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 21. Summary and comparison of data from Southern Wisconsin Regional Airport non-EAD section (2002) with recommended practice.

	Key Data Item	JVL non-EAD Project (Runway 13-31 and Taxiway B Extension – 2002)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	No			
	Ambient PCC Paving Conditions	Max. Temp – 60°F. (median) Min. Temp – 40°F. (median)	Good hot- and cold-weather management plan and execution.	NA	The trigger conditions present on this paving project were quite severe.
		More than 35% of the PCC paving days had a temperature swing > 25°F. No hot-weather issues. The minimum temperature was below 40°F on several days.			
	PCC Placement Season	Spring/Early Summer			
Design Variants	Thickness	PCC Design – 13 in (reinforced). Actual – 13.3 in (avg.) Actual– 0.4 in (SD)			The as-built PCC thickness is quite close to the as-designed value.
		ATB Design – 4 in Actual – NA (avg.) Actual– NA (SD)	ATB thickness: 6 in	No	The as-designed ATB thickness is at the low end of the recommended range. It is perhaps adequate for this design.
	Joint Spacing	Trans. Spacing (L) – 20 ft Long. Spacing (W) – 18.75 ft (Rwy)/15 ft (Txy)	Max. dimension $\leq$ 20 ft.	No	OK
			L/W < 1.25	Rwy – No Twy – Yes	
			Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 779 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 665 lb/in^2 (avg.) Actual – 55 lb/in^2 (SD)			The as-built as and as-designed flexural strengths are quite close. The as-built strength variability is typical.
	PCC Mixture Properties	Cement Type – Type I			
		Cem. Factor – 560 lbs/yd^3 Pozz. Cont. – 29% FA "C"	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	The amount of flyash in this mix could be problematic during cold weather, if adequate precautions are not taken.
		w/c ratio – 0.5			
		Total Water – 204 lbs.	Less than 250 lb	No	OK
		Mortar Volume – 64%	Less than 60%	Yes	Mortar volume higher than recommended.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 21. Summary and comparison of data from Southern Wisconsin Regional Airport non-EAD section (2002) with recommended practice (continued).

	Key Data Item	JVL non-EAD Project (Runway 13-31 and Taxiway B Extension – 2002)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	As-Designed ATB Mix Properties	Th. Max. Sp. Gr., G_{mm} – 2.49 AC Content – 5.3% (by wt.) AC Grade – PG 58-28 Air Voids – 4% VMA – 14.8%; VFA – 72.7%			As-built properties are typical of a high quality HMA mixture.
	As-Built ATB Mix Properties	AC Content – NA (avg.) AC Content – NA (SD) Density – 93.5% of G_{mm} (avg.) Density – 0.8% of G_{mm} (SD)			
	PCC Fine Aggregate Gradation	Type – Fine to Coarse Sand	Coarse sand	Yes	Fine sand increases water demand and shrinkage.
		Passing No. 50 sieve – 15.5%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 2.72	3.1 to 3.4 for cem. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg.	Crushed Dolomite			High CTE aggregate.
	PCC Combined Aggregate Gradation— Design	WF – 33.8	WF > 29 & CF < 75	No	Within the well-graded portion of the workability box.
		CF – 72.8		No	
		Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (resin-water-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
	Initial Sawcut	Equipment – Traditional diamond blade saws.	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/4	D/3	Yes	Maybe insufficient depth.
	Bond Breaker	None	Not recommended.	No	OK
	Whitewashing/Fog Spraying During Hot Paving Conditions?	The ATB surface was whitewashed prior to the placement of the PCC.	Use lime-water solution reflect solar radiation or moisten ATB without saturation just prior to paving.	No	From project records, the ATB appears to be whitewashed prior to PCC placement.
	ATB Surface Condition Prior to Paving	NA	If milling required to correct grade, specify a following leveling layer.		It is not known if the base was milled prior to PCC placement.
	ATB Quality Acceptance Program	Mat density, joint density, thickness, smoothness, grade.	Mat density, joint density, thickness, smoothness, grade		QA according to recommended practice.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

5.4.2 Austin Straubel International Airport Air Carrier Apron Construction (2000)—EAD Project

The Austin Straubel International Airport Air Carrier Apron was expanded in 2000 by paving the area bordered by taxiways J, C, F, and A. This reinforced and doweled PCC pavement was constructed over a dense-graded asphalt stabilized base. Stage I of the project was paved in August-September 2000 and the Stage II portion was paved in October-November 2000. By the spring of 2001, cracking was reported on many slabs. Approximately 13,000 yd^2 (10,844 m^2) of pavement were placed in this construction operation. Figure 35 presents a sketch of the typical section for all the features constructed.

Construction of the stage I and II air carrier apron expansion began on July 5, 2000 and was completed on November 15, 2000. Paving of the main portion of the stage I expansion extended from approximately station 20+50 to 27+00 with a width of approximately 100 ft (30.5 m). Paving for the main portion of the stage II expansion progressed from approximately station 18+50 to 25+80 with a maximum width of about 210 ft (64.1 m). Schedules for PCC paving with stationing and offset for both stages are shown in tables 22 and 23, respectively.

Cracking in the pavement surface was first reported in the construction diary on October 20, 2000. The slab layouts shown in figures 36 and 37 indicate the location and orientation of most of the cracks. Cracking patterns vary within each day's pour and for the entire pavement. They include diagonal transverse cracking of various angles and dimensions, cracking parallel to the transverse joints, and meanders from the transverse joint, as shown in the figures. The majority of the cracking appears to be diagonal with the long leg intersection at more than half the width of the slab. Many of the cracks end nearly perpendicular to a longitudinal dummy or construction joint, indicating the possibility of additional future cracking if unchecked.

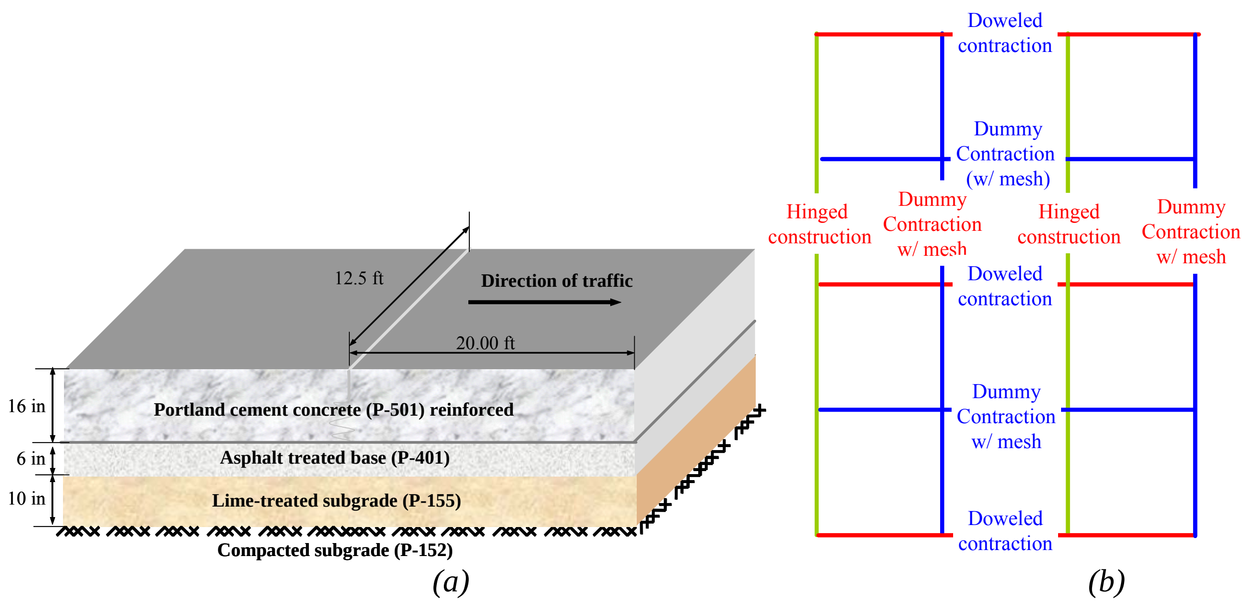


Figure 35. Typical section and joint layout for the Air Carrier Apron expansion project (2000) at the Austin Straubel International Airport.

Table 22. PCC paving schedule for stage I construction of the Air Carrier Apron expansion project (2000) at the Austin Straubel International Airport.

Date	Layer	Begin Station	End Station	Offset
8/24/00	P-501	25+80, 25+80	27+10, 26+80	25-50’ Lt, 75-100’ Lt
8/29/00	P-501			25-50’Rt, 75-100’ Rt
8/31/00	P-501			0-25’ Rt
9/1/00	P-501			0-25’ Lt, 50-75’ Lt
9/5/00	P-501			25-50’ Rt, 75-100’ Rt

Table 23. PCC paving schedule for stage II construction of the Air Carrier Apron expansion project (2000) at the Austin Straubel International Airport.

Date	Layer	Begin Station	End Station	Offset
10/20/00	P-501	25+40, 25+40	20+60, 20+20	25-50’ Lt, 75-100’ Lt
10/23/00	P-501	23+00, 21+40	19+80, 19+40	125-150’ Lt, 175-200’ Lt
10/27/00	P-501			125-150’ Lt, 175-200’ Lt
10/30/00	P-501			100-125’ Lt
10/31/00	P-501			150-175’ Lt
11/1/00	P-501			0-25’ Lt
11/2/00	P-501			50-75’ Lt, 100-125’ Lt

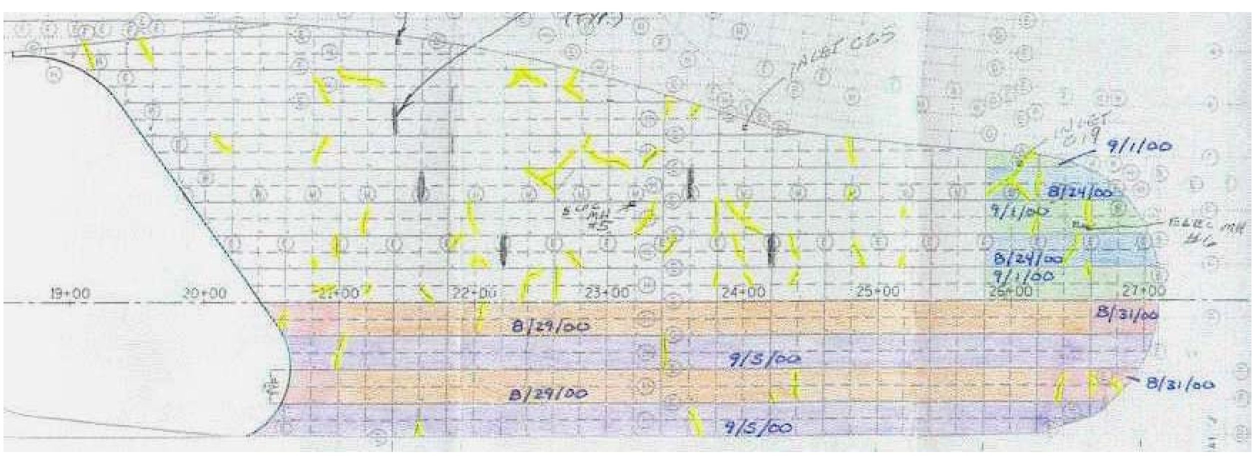


Figure 36. Stage I paving plan and observed cracking during the construction of the Air Carrier Apron expansion project (2000) at the Austin Straubel International Airport.

Figure 37. Stage II paving plan and observed cracking during the construction of the Air Carrier Apron expansion project (2000) at the Austin Straubel International Airport.

An evaluation of the data presented in table 20 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC and the design, materials, and construction variants:

- Figure 38 provides the hourly air temperature and wind speed during the weeks of PCC placement. Large temperature swings (> 25°F [-4°C]) were observed on several days during the paving. Wind speeds were high during most of the construction. Relative humidities were low during Stage II construction. One hot day (> 90°F [32°C]) and one cold day (< 40°F [4°C]) were noted during the paving operation. Generally, the conditions for paving were more severe for Stage II than for Stage I (and consequently there is more incidence of cracking here).
- The aspect ratio of the slab length to width is out of the recommended specification of 1.25. This could lead to a biased stress concentration in one of the axes during bending.

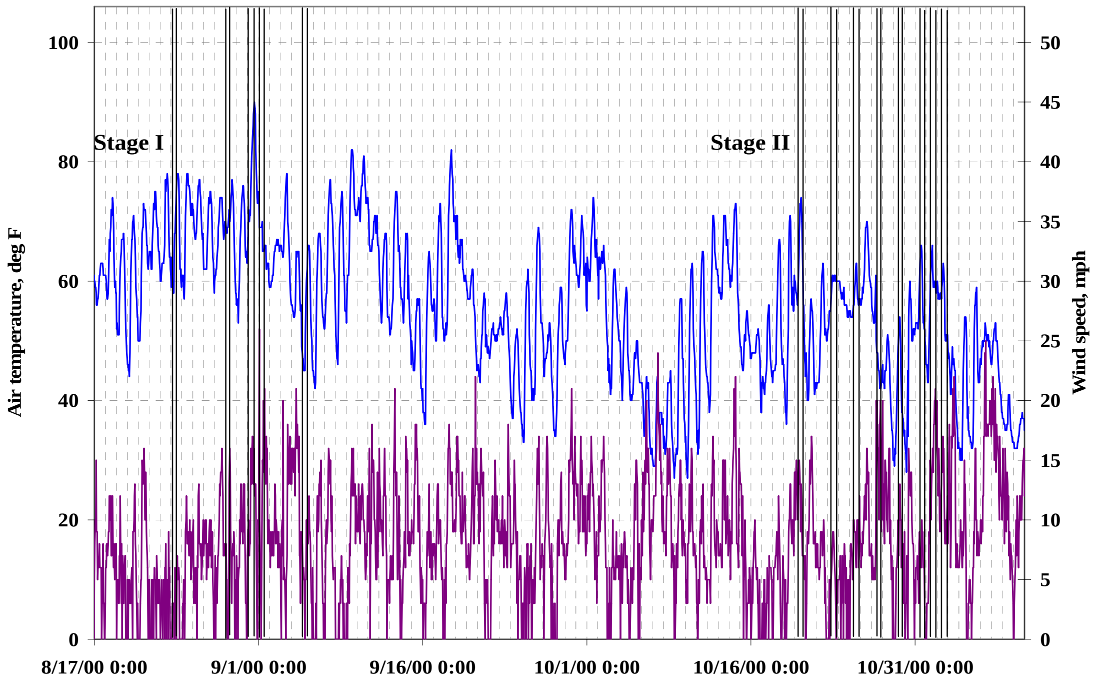


Figure 38. Ambient temperatures and wind speed during 2001 Stage I and II paving of the Air Carrier Apron at the Austin Straubel International Airport.

- The joint design is essentially 40 ft by 25 ft (12.2 m by 7.625 m) with control contraction joints spaced at 20 ft by 12.5 ft (6.1 m by 3.81 m). The contraction joints between panels include dowel bars and the construction joints have tie bars. Dowels are not required at contraction joints when a stabilized base is used. Such a system can lead to excessive restraint to slab movement and can increase slab stresses.
- The asphalt contents used for the ATB were typical of high-quality HMA mixtures. Furthermore, considering the relatively high densities achieved, it can be conjectured that the base will be strong.
- An analysis of the PCC mix design revealed the following mixture-related issues:
  - A high cement factor concrete was used.
  - The FM and percent passing No. 50 (300 µm) sieve indicate that fine sand was used.
  - The combined aggregate gradation factors indicate that the mix is possibly gap-graded.
  - Records indicate that the coarse aggregate used in the P-501 mixes was crushed dolomite. This aggregate is of sedimentary origin and could potentially have a very high CTE. When combined with a high aspect ratio panels, this factor can lead to significant tensile stresses in the slab.
- Although specifications call for moistening the pavement just prior to PCC placement to avoid placing concrete over a very warm base, it is not clear whether this was done. Furthermore, there is no record of the ATB being whitewashed prior to placing the PCC. The dark asphalt surface has a potential to be at a temperature several degrees greater than the ambient temperatures in the presence of direct sunlight. This causes even a

moderate change to the concrete surface temperature right after placement (e.g., absence of direct sunlight or a passing cold front) to show up as an exaggerated thermal gradient through the slab resulting in significant stresses.

- Some of the stakeholders interviewed suggested that the ATB could have been milled to establish grade without following up with a leveling course. However, this could not be confirmed from records review.
- Early entry saws were employed and skip sawing was done (every two to three joints at 2.75- to 3-in [70- to 76-mm] depths [D/5.3]). When available, standard, diamond-bladed saws were also employed to sawcut to D/4. It is conceivable that on some days of paving, the PCC bottom reached cure prior to the top due to the presence of a warm base, and the skip sawing of joints using an early entry saw was not adequate to relieve the resultant stresses.

Conclusions

In reviewing the factors listed above and the data presented in table 20, it is possible that there are several trigger factors that could have led to the uncontrolled cracking. However, high temperature gradients through the slab at an early age are believed to interact with the following variants to cause the EAD:

- Slabs with high aspect ratios.
- Excessive restraint to slab movement cause by load transfer and tie devices.
- Rough ATB/PCC interface.
- Inadequate sawcut depth.

5.4.3 Austin Straubel International Airport Air Carrier Apron Construction (2001)—Non-EAD Companion Project

In continuation of the project described in section 5.4.2, the Austin Straubel International Airport Air Carrier Apron was expanded in 2001 by paving the area bordered by taxiways D2, J, F, and A. Stage IV of the project experienced no early cracking following construction. Because of the early cracking in the Stage I and II projects and the lack of cracks in the Stage IV project, it was selected for review and comparison. Approximately 20,000 yd^2 (16,745 m^2) of pavement were placed in this construction operation.

Construction of the Stage IV Air Carrier Apron expansion began on April 18, 2001 and was completed on September 4, 2001. Paving of the main portion of the Stage IV expansion extended from approximately station 28+00 to 34+50 with a width of approximately 275 ft (84 m). Schedules for PCC paving with stationing and offset for the Stage IV construction are shown in table 24.

Based on the records review and a comparison of the data presented for this project and the Stages I and II section described earlier, it appears that practically everything between the projects was similar including the typical section, joint layout, ATB properties, PCC properties, ATB/PCC interface properties, and other construction factors. The only significant difference is

Table 24. PCC paving schedule for stage IV expansion of the Air Carrier Apron at the Austin Straubel International Airport (2001).

Date	Layer	Begin Station	End Station	Offset
8/17/01	P-501	28+40, TW J	East edge	50R-75R, 0-25R
8/20/01	P-501	TW J, 28+80	East edge25	25L-50L, 75L-100L
8/21/01	P-501	32+00, TW J	East edge, 28+40	125L-150L, 50R-75R
8/22/01	P-501	33+00	East edge	75R-100R
8/23/01	P-501	33+63	37+00	25R-50R
8/24/01	P-501	32+75,36+70,34+10	33+20,37+20,34+40	175-200L,25-50R,225-250L
8/28/01	P-501	28+00, 28+00	33+00, East edge	75R-100R, 25R-50R
8/29/01	P-501	TW J	East edge	0-25L, 50-75L
8/30/01	P-501	28+40, 32+80	East edge	100L-125L, 150L-175L
8/31/01	P-501	-	-	Northeast triangle

that the placement season was Summer as opposed to Fall and the trigger conditions that contributed to the cracking in the former case were not present during the construction of Stage IV. Air temperatures and rainfall for the days of PCC paving are shown in table 25. These indicate a Stage IV paving average air temperature of 68.2°F (20.1°C) and an average range (low to high) of 22.5°F (-5.3°C) for the 11 days of PCC paving. Figure 39 provides the hourly air temperature and wind speed during the weeks of PCC placement. Rainfall occurred on August 22, 2001 between 4:00 and 9:00 AM, on August 30, 2001 between 4:00 and 6:00 AM.

Conclusion

Favorable ambient placement conditions helped avoid early cracking during this stage of the apron construction despite the presence of several variants that have exceeded their threshold values.

Table 25. Daily air temperatures and rainfall amounts during stage IV construction of the Air Carrier Apron at the Austin Straubel International Airport.

Date	Air Temperature, °F				Rainfall, in
	Maximum	Minimum	Range	Average	
8/17/01	79	58	21	69	0.00
8/20/01	80	52	28	66	0.00
8/21/01	80	54	26	67	0.00
8/22/01	82	63	19	73	0.14
8/23/01	79	63	16	71	0.00
8/24/01	77	61	16	69	0.00
8/28/01	79	50	29	65	0.00
8/29/01	80	55	25	68	0.00
8/30/01	81	60	21	71	0.03
8/31/01	68	47	21	58	0.00
Average	**79**	**56**	**22**	**68**	**0.02**

°C = (°F – 32)*5/9 1 in = 25.4 mm

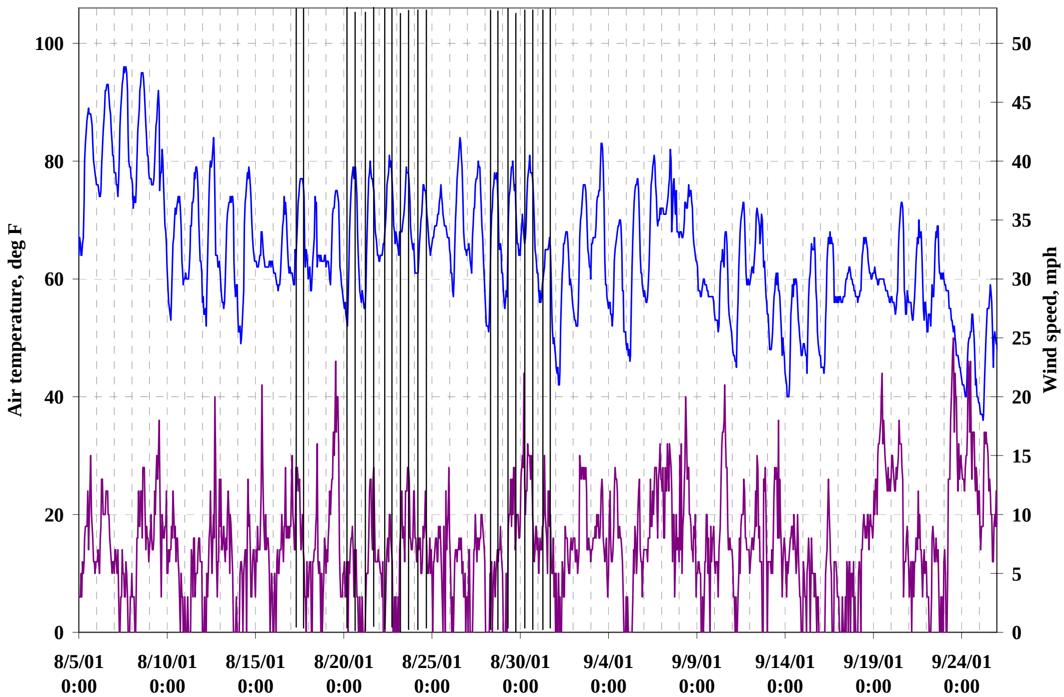


Figure 39. Paving temperatures and wind speeds during stage IV construction of the Air Carrier Apron at the Austin Straubel International Airport

5.4.4 Southern Wisconsin Regional Airport Runway 13-31 and Taxiway B Extension (2003)—Non-EAD Companion Project

The Southern Wisconsin Regional Airport Authority reconstructed the original Runway 13-31 and parallel Taxiway B structures. They also extended these structures about 3,400 ft (1,037 m) to the northwest. No early cracking was reported for this paving project. As a control section for comparison with similar pavements containing early cracking, the extension of Runway 13-31 and Taxiway B (area 6) was selected for review under this study. Approximately 120,000 yd^2 (100,467 m^2) of pavement was placed in the two features. Figure 40 presents a sketch of the typical section and joint layout of all the features constructed.

The paving reconstruction and extension area began at approximately station 127+00 and progressed to Taxiway B station 177+00 and Runway 13-31 station 174+00. Dimensions of the mainline paving extension are approximately 5,000 ft (1,525 m) by 60 ft (18.3 m) for Taxiway B and 4,700 ft (1,434 m) by 150 ft (45.75 m) for Runway 13-31. Schedules for PCC paving of the extension with stationing and offset are shown in table 26.

An evaluation of the data presented in table 21 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC, as well as the design, materials, and construction variants:

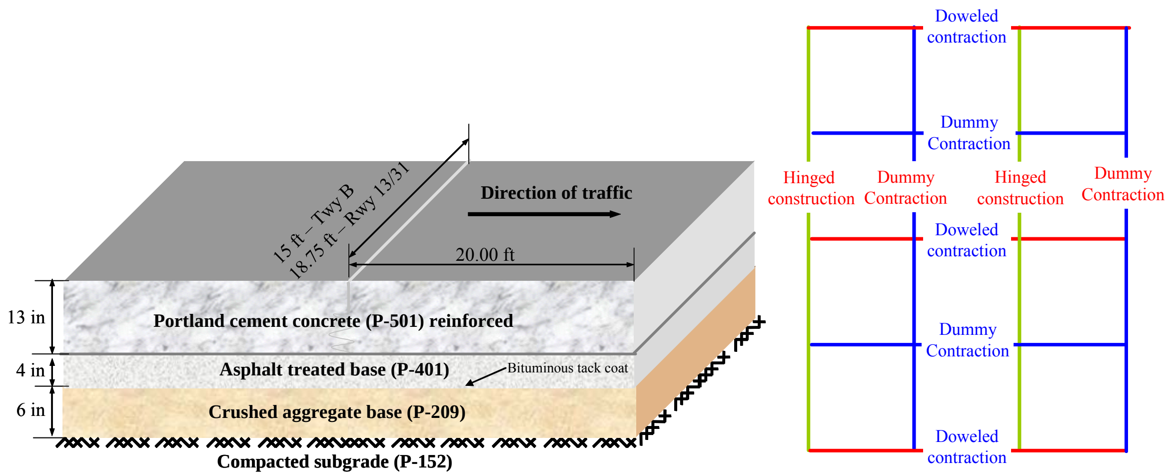


Figure 40. Typical section and joint layout for Runway 13-31 and Taxiway B at Southern Wisconsin Regional Airport (2003).

Table 26. ATB and PCC paving schedule for Southern Wisconsin Regional Airport Runway 13-31 and Taxiway B projects.

Feature	Date	Layer Type	Lane	Begin Station	End Station	Offset
Runway 13-31	04/15/03	P-501	2	127+00	174+00	37.5’ Lt to 56.25’ Lt
	04/17/03	P-501	4	174+00	126+80	0’ to 18.75’ Lt
	04/18/03	P-501	6	127+00	174+00	18.75’ Rt to 37.5’ Rt
	04/21/03	P-501	8	174+00	127+00	56.25 Rt to 75.0’ Rt
	04/22/03	P-501	1	126+80	174+00	56.25’ Lt to 75.0’ Lt
	04/23/03	P-501	3	174+00	126+80	18.75’ Lt to 37.5’ Lt
	04/24/03	P-501	5	126+80	174+00	0’ to 18.75’ Rt
	04/25/03	P-501	7	174+00	126+80	37.5’ Rt to 56.25 Rt
	07/26/02	P-401 Base	Lot 5			
	07/30/02 08/01/02	P-401 Base	Lot 7			
	08/01/02	P-401 Surface	Lot 8			
	08/02/02	P-401 Surface	Lot 9			
Taxiway B	05/05/03	P-501	1 & 2	172+00	135+00	0’ to 30.0’ Lt
	05/06/03	P-501	1 & 2	135+00	126+80	0’ to 30.0’ Lt
	05/06/03	P-501	2	172+00	176+00	0’ to 15.0’ Lt
	05/07/03	P-501	3 & 4	172+00	147+60	0’ to 30.0’ Rt
	05/08/03	P-501	3 & 4	147+60	126+80	0’ to 30.0’ Rt
	05/08/03	P-501	4	172+00	176+00	15.0’ Rt to 30.0’ Rt.
	05/12/03	P-501	1	172+00	176+00	15.0’ Lt to 30.0’ Lt
	05/12/03	P-501	3	172+00	176+22	0’ to 15.0’ Rt
	05/12/03	P-501	5	170+80	176+22	30.0’ Rt to 45’ Rt
	07/26/02 07/29/02	P-401 Base	Lot 6			
	07/30/02 08/01/02	P-401 Base	Lot 7			
	10/05/02	P-401 Surface	Lot 10			

- Figures 41 and 42 provide the hourly air temperature and wind speed during the paving of Runway 13-31 and Taxiway B, respectively. It can be noted from these figures that large temperature swings (> 25°F [-4°C]) and cold temperatures persisted throughout the paving season; the fluctuations were more dramatic during the paving of the runway section. Wind speeds were also high on several days. Generally speaking, the paving conditions were fairly severe and given the right variants could trigger early distress in the pavement slabs.

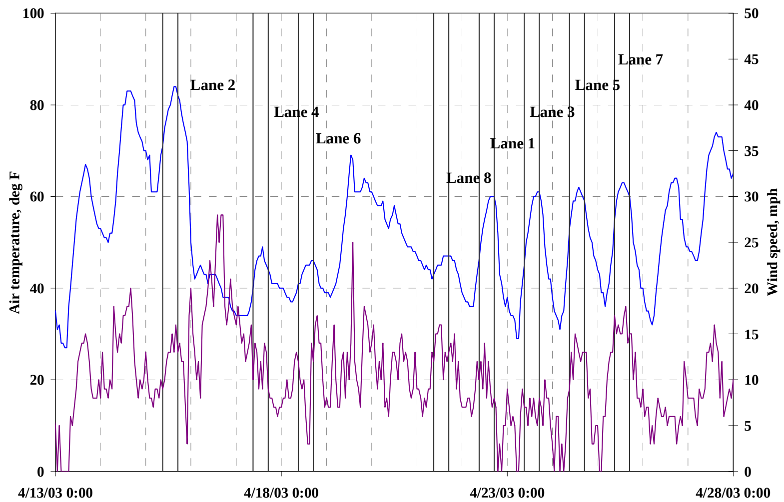


Figure 41. Ambient temperatures and wind speed during the paving of Runway 13-31 at the Southern Wisconsin Regional Airport (2003).

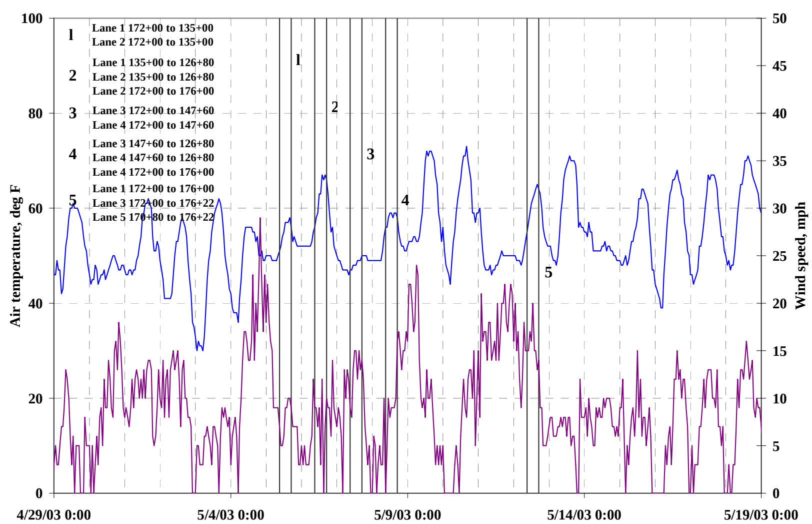


Figure 42. Ambient temperatures and wind speed during the paving of Taxiway B at the Southern Wisconsin Regional Airport (2003).

- The aspect ratio of the slab length to width is out of the recommended value of 1.25 for the runway. However, the maximum slab dimension was within the recommended value.
- The asphalt contents used for the ATB were typical high-quality HMA mixtures.
- An analysis of the PCC mix design revealed the following mixture-related issues:
  - Approximately, 29 percent flyash was added to the PCC mix. The rate of initial strength gain will be slower for PCC mixes with flyash, particularly in the presence of cold weather.
  - The FM and percent passing No. 50 (300 µm) sieve indicate that fine sand was used.
  - The combined aggregate gradation factors are indicative of a well-graded aggregate mixture that should not be prone to uncontrolled cracking due to segregation during placement.
  - Records indicate that the coarse aggregate used in the P-501 mixes was crushed dolomite. This rock is of sedimentary origin and could potentially have a very high coefficient of thermal expansion.
- It appears that the ATB was whitewashed prior to the placement of the PCC. This is in accordance with the recommended practice for ATBs.
- Diamond blade saws were used for initial transverse joint sawing to a design depth of 3 in (76 mm) (D/4). The specifications (P-501-4.10) required consecutive transverse joint sawing to commence when the concrete had hardened sufficiently to permit cutting without damage to the concrete surface. There is no indication of any deviations.

Conclusions

In reviewing the factors listed above and the data presented in table 21, it is surprising that early cracking did not develop on this project. There were significant trigger factors present and several design and material variants exceed their recommended threshold levels. However, some of the construction variants which are directly related to the possible modes of cracking were under control. These include whitewashing the base layer and the seemingly adequate joint sawing. Perhaps the biggest design variant that was favorably aligned is that the pavement was constructed on a base whose characteristics are a low slab/base interface friction coefficient and low stiffness. Furthermore, the base thickness was only 4 in (102 mm), which further helps reduce the flexural rigidity of this layer and decrease the curling/warping stresses.

5.5 REVIEW OF CEMENT-TREATED PERMEABLE BASE (CTPB) PROJECTS

A total of four pavement projects with a CTPB layer were short-listed for extensive data collection and evaluation in this study. Two of these projects had exhibited EAD, as defined in this study. The remaining two projects did not experience EAD. Table 27 lists the selected projects along with key project details. On the Wichita projects, the CTPB layer was constructed in accordance with the FAA AC 150/5370-10A, Item P-204, *Cement Treated Drainage Layer*, with some modifications to suit local practices. The Syracuse CTPB layer was constructed using the US Army Corps of Engineers specification 02714. Only the Wichita EAD project had an on-site companion project affording a more direct comparison of factors leading to the development of early cracking.

Table 27. List of projects with a CTPB layer selected for detailed study.

Section Location	Feature of Interest	Year Built	Early Cracking Present?	Design
Mid-Continent Airport (ICT) Wichita, KS	• Taxiway E	1998	Yes	15 in PCC 4 in CTPB Filter Fabric 6 in Lime treated subgrade Sandy, lean clay subgrade
Mid-Continent Airport (ICT) Wichita, KS	• North Cargo Apron	1995	No	15 in PCC 6 in CTPB Filter Fabric 8 in Lime treated subgrade Brown lean clay with sand subgrade
Hancock International Airport (SYR) Syracuse, NY	• 174th ANG Apron and Taxiway D	1999	Yes	10 in PCC 8 in CTPB Filter Fabric 17 in CTB GL, ML subgrade
Kansas City International Airport (MCI) Kansas City, MO	• Terminal Apron	2000 and 2001	No	16 in PCC 7 in CTPB Filter fabric 12 in Lime treated subgrade CL subgrade

1 in = 25.4 mm

5.5.1 Summary of Key Variables

Summaries of the parameter values/descriptions of the key trigger factors and variants for each of the projects discussed are presented in this section. Table 28 presents the information from the Mid-Continent Airport taxiway E constructed in 1998 (experienced EAD) and the apron section constructed in 1995 (did not experience EAD). Data for the EAD section in Hancock International Airport (1999) are presented in table 29, whereas, table 30 presents that from non-EAD section in Kansas City International Airport built in 2000/2001. Also provided in these tables are the recommended threshold values for the various trigger and variant factors for rigid pavements built on CTPB, with appropriate comments as to how the as-built properties compare with them.

Table 28. Summary and comparison of data from Wichita Mid-Continent Airport EAD (1998) and on-site non-EAD companion (1995) sections with recommended practice.

	Key Data Item	ICT EAD Project (Taxiway E - 1998)	ICT non-EAD Project (North Cargo Apron - 1995)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes	No			Approximately 5 percent of the panels placed on the first three days of paving showed cracks. The cracks were transverse in nature and some of them were partial depth, while others were full-depth working cracks.
	Ambient PCC Paving Conditions	Max. Temp – 102°F Min. Temp – 61°F	Max. Temp – NA Min. Temp – NA	Good hot- and cold-weather management plan and execution.	NA	Hot temperatures increase shrinkage potential. This was certainly a trigger factor for the EAD section. The presence of very large temperature swings due to unexpected rain showers was the most likely trigger factor for the EAD section since they cause steep gradients in PCC slabs.
		Hot weather present during PCC paving with temperature > 90°F on all PCC paving days. Temp. swing > 30°F also occurred due to freak rain events on two days of PCC paving.	Normal paving weather is assumed.			
	PCC Placement Season	Summer	Fall			
Design Variants	Thickness	PCC Design – 15 in Actual – 15.3 in (avg.) Actual – 0.3 in (SD)	PCC Design – 15 in Actual – 15.2 in (avg.) Actual – 0.2 in (SD)			The as-built PCC thickness agrees with the as-designed value.
		CTPB Design – 4 in Actual – NA (avg.) Actual – NA (SD)	CTPB Design – 4 in Actual – NA (avg.) Actual – NA (SD)	CTPB thickness: 4 to 6 in	No	OK, 4 in is adequate for a drainage layer.
	Joint Spacing	Trans. Spacing (L) – 25 ft Long. Spacing (W) – 25 ft	Trans. Spacing (L) – 25 ft Long. Spacing (W) – 25 ft	Max. dimension ≤ 20 ft.	Yes	The maximum panel dimension is 25 percent higher than the maximum recommended length but the other two length criteria are satisfied.
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 964 lb/in²	Mix Design – 750 lb/in² (estimated)	650 lb/in² (28-day)		
		Actual – 887 lb/in² (avg.) Actual – 111 lb/in² (SD)	Actual – 879 lb/in² (avg.) Actual – 46.8 lb/in² (SD)			As designed strengths are very high for the EAD section. High strengths are accompanied by high moduli which increases stresses.
	28-day CTPB Comp. Str.	Design – 1,140 lb/in²	Design – 1,140 lb/in²	500 lb/in² approx.	Yes	The as-built strength value for the EAD section was much higher than designed increasing the probability of cracking. In contrast, the non-EAD section had a lower strength value.
		Actual – 1,875 lb/in² (avg.) Actual – 49 lb/in² (SD)	Actual – 879 lb/in² (avg.) Actual – 46.8 lb/in² (SD)			
	CTPB Cement Content	282 lb/yd³	282 lb/yd³	190 to 235 lb/yd³	Yes	Cement content higher than recommended. Explains the high strengths achieved.
	CTPB Gradation Factors	Design D_{10} – 0.035 in Actual D_{10} – 0.026 in (avg.) Actual D_{10} – 0.003 in (SD)	Design D_{10} – 0.035 in Actual D_{10} – 0.028 in (avg.) ActualD_{10} – NA (SD)			Design permeability higher than recommended practice but no measured values were available from the field to verify if they were achieved. This is itself is not detrimental unless the very open-texture of the base promotes PCC paste penetration and subsequent bonding.
	CTPB Permeability	Design permeability – 2,430 ft/day Actual permeability – NA (avg.) Actual permeability – NA (SD)	Design – 2,430 ft/day	500 to 1,000 ft/day	No	

1 in = 25.4 mm   1 ft = 0.305 m   1 lb/in² = 6.895 kPa   1 lb/yd³ = 0.59 kg/m³   1 lb = 0.452 kg   °C = (°F-32)*5/9

Table 28. Summary and comparison of data from Wichita Mid-Continent Airport EAD (1998) and on-site non-EAD companion (1995) sections with recommended practice (continued).

	Key Data Item	ICT EAD Project (Taxiway E - 1998)	ICT non-EAD Project (North Cargo Apron - 1995)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I/II	Cement Type – Type I/II			
		Cem. Factor – 565 lbs/yd^3 Pozz. Cont. – 15% FA "C"	Cem. Factor – 565 lbs/yd^3 Pozz. Cont. – 15% FA "C"	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3
		w/c ratio – 0.4	w/c ratio – NA			
		Total Water – 226 lbs	Total Water – NA	Less than 250 lb	No	OK
		Mortar Volume – 77%	Mortar Volume – NA	Less than 60%	Yes	Mortar volume greater then recommended for EAD section. High amount of paste can penetrate the open CTPB.
	PCC Fine Aggregate Gradation	Type – Intermediate (River Sand)	Type – Fine	Coarse sand	No – EAD Yes – non-EAD	Fine sand increases water demand and shrinkage. Non-EAD section has more bulking potential.
		Passing No. 50 sieve – 10%	Passing No. 50 sieve – 20.8%	Lower limit of ASTM C33 5 to 30 % band preferred	No – EAD Yes – non-EAD	
		Fineness Mod.– 2.9	Fineness Mod.– 2.5	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Limestone	Limestone			Moderate CTE.
	PCC Combined Aggregate Gradation— Design	WF – 47.2	WF – 47.4	WF > 29 & CF < 75	No	EAD mixture is outside the workability box. Non-EAD mixture is just within it. This factor is critical when PCC is placed on CTPB since it can govern paste penetration.
		CF – 80.1	CF – 74.6		Yes – EAD No – non-EAD	
		Nom. Max. Agg. – 1.5 in	Nom. Max. Agg. – 1 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
		CTPB Curing – LMFCC (water-base) 8 hr curing using fog and spray. Rate – NA	CTPB Curing – LMFCC (wax-base) 12 hr curing Rate >1 gal/90 ft^2	None recommended. Fog spraying if ambient temperatures are hot.		
	Initial Sawcut	Equipment – Mostly traditional	Equipment – Traditional	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/4	Depth – D/4	D/3	Yes	Maybe insufficient depth if a high degree of paste penetration occurred.
	Separation Layer	Present; Filter Fabric (P-154)	Present; Filter Fabric (P-154)	Geotextile or aggregate separation layer.	No	According to recommended practice.
	Bond Breaker	Asphalt emulsion at 1 gal/90 ft^2	Asphalt emulsion at 1 gal/45 to 90 ft^2	Choke stone layer	Yes	Asphalt emulsion can decrease the permeability of the CTPB layer. A choke stone layer is placed between the PCC and CTPB to reduce paste penetration and bond.
	CTPB QA Program	Thickness, smoothness, permeability	Compressive strength, gradations.	Thickness, gradation, permeability, grade, smoothness.		QA variables not in accordance with recommended practice.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 29. Summary and comparison of data from Hancock International Airport EAD section (1999) with recommended practice.

	Key Data Item	SYR EAD Project (174th ANG Apron - 1999)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	Yes			Mostly longitudinal cracking in addition to some random shrinkage cracking.
	Ambient PCC Paving Conditions	Max. Temp – 75°F Min. Temp – 65°F	Good hot- and cold-weather management plan and execution.	NA	Excess evaporation loss was a trigger factor.
		No hot or cold-weather issues, or high temperature swings. Excess evaporation loss was a possibility.			
	PCC Placement Season	Summer			
Design Variants	Thickness	PCC Design – 10 in Actual – NA (avg.) Actual – NA (SD)			
		CTPB Design – 8 in Actual – NA (avg.) Actual – NA (SD)	CTPB thickness: 4 to 6 in	Yes	The CTPB layer is thicker than recommended. If the stiffness of this layer is high, this higher thickness can lead to higher curling/warping stresses in the PCC slab.
	Joint Spacing	Trans. Spacing (L) – 12.5 ft Long. Spacing (W) – 12.5 ft	Max. dimension ≤ 20 ft.	No	OK
			L/W < 1.25	No	
			Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 643 lb/in^2	650 lb/in^2 (28-day)		
		Actual – NA (avg.) Actual – NA (SD)			
	28-day CTPB Comp. Str.	Design – 770 lb/in^2	500 lb/in^2 approx.	No	The design strength value is not excessive but no strength values were measured for verification purposes.
		Actual – NA (avg.) Actual – NA (SD)			
	CTPB Cement Content	200 lb/yd^3	190 to 235 lb/yd^3	Yes	OK
	CTPB Gradation Factors	Design D_{10} – 0.2117 in Actual D_{10} – 0.2114 in (avg.) Actual D_{10} – 0.003 in (SD)			A high D_{10} value suggests that this is a very open graded mixture. Very open graded permeable bases promote excess paste penetration. Paste penetration in the range of 1 to 2 in were noted on this project.
	CTPB Permeability	Design permeability – NA Actual permeability – NA (avg.) Actual permeability – NA (SD)	500 to 1,000 ft/day	NA	Permeability values were not recommended in design or measured in the field.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 29. Summary and comparison of data from Hancock International Airport EAD section (1999) with recommended practice (continued).

	Key Data Item	SYR EAD Project (174th ANG Apron - 1999)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type II			
		Cem. Factor – 611 lbs/yd^3 Pozz. Cont. – None	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3. Extremely high cement factor. If this mixture is placed in the day time with the maximum heat of hydration occurring
		w/c ratio – 0.44			
		Total Water – 220 lbs	Less than 250 lb	No	OK
		Mortar Volume – 60%	Less than 60%	No but at the limit.	OK but it is the upper limit.. High paste content concrete when placed on open-graded bases can promote bond.
	PCC Fine Aggregate Gradation	Type – Intermediate (Coarse Sand)	Coarse sand	No	Fine sand; increased shrinkage potential.
		Passing No. 50 sieve – 15%	Lower limit of ASTM C33 5 to 30% band preferred	No	
		Fineness Mod.– 2.93	3.1 to 3.4 for cem.. fac. > 400 lb/yd^3	Yes	
	PCC Coarse Agg. Type	Limestone			Moderate CTE aggregate.
	PCC Combined Aggregate Gradation— Design	WF – 30	WF > 29 & CF < 75	No	OK
		CF – 73		No	
		Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
		CTPB Curing – LMFCC (water-base) Rate – NA	None recommended. Fog spraying if ambient temperatures are hot.		
	Initial Sawcut	Equipment – Early entry	Early entry or traditional wet saws.	No	
	Sawcut Depth	Depth – D/4	D/3	Yes	Maybe insufficient depth particularly if the paste has penetrated the CTPB.
	Separation Layer	Present; Geotextile Filter Fabric (P-154)	Geotextile or aggregate separation layer between permeable base and the layer below it.	No	Separation layer according to recommended practice.
	Bond Breaker	None	Choke stone layer	Yes	For very open-graded mixes it is recommended that a choke stone layer is placed between the PCC and CTPB to reduce paste penetration and bond.
	CTPB QA Program	Thickness, smoothness, permeability	Thickness, gradation, permeability, grade, smoothness.		OK.

1 in = 25.4 mm   1 ft^2 = 0.093 m^2 1 gal = 3.785 L   1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

Table 30. Summary and comparison of data from Kansas City International Airport non-EAD section (2000/2001) with recommended practice.

	Key Data Item	MCI Non-EAD Project (Terminal Apron – 2000/2001)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	No			
	Ambient PCC Paving Conditions	Max. Temp – NA Min. Temp – NA	Good hot- and cold-weather management plan and execution.	NA	Since the projects reviewed were placed over several seasons, a variety of trigger factors could have been encountered during construction. However, these were not quantified.
		As the section was paved over all seasons, several cold- and hot-weather days were encountered.			
	PCC Placement Season	Summer/Fall/Winter/Spring			
Design Variants	Thickness	PCC Design – 16 in Actual – NA (avg.) Actual – NA (SD)			
		CTPB Design – 7 in Actual – NA (avg.) Actual – NA (SD)	4 to 6 in	Yes	The CTPB layer is thicker than recommended. If the stiffness of this layer is high, this higher thickness can lead to higher curling/warping stresses in the PCC slab.
	Joint Spacing	Trans. Spacing (L) – 15 to 25 ft Long. Spacing (W) – 20 ft	Max. dimension $\leq$ 20 ft.	Yes in some instances.	In some instances the maximum dimension was 25 percent higher than the maximum recommended length but the other two length criteria are always satisfied.
			L/W < 1.25	No	
			Max. L < 21*PCC Thk.	No	
Materials Variants	14-day PCC Flexural Strength	Mix Design – 710 lb/in^2	650 lb/in^2 (28-day)		
		Actual – 734 lb/in^2 (avg.) Actual – 71 lb/in^2 (SD)			The as-built flexural strength is similar to the design value. The as-built strength variability is typical.
	28-day CTPB Comp. Str.	Design – 620 lb/in^2	500 lb/in^2 approx.	No	The design strength value is similar to recommended strength indicating an adequate base layer stiffness to support construction traffic.
		Actual – NA (avg.) Actual – NA (SD)			
	CTPB Cement Content	155 lb/yd^3	190 to 235 lb/yd^3	No	OK, although cement factor is lower than recommended if long-term durability is assured.
	CTPB Gradation Factors	Design D_{10} – 0.19 in Actual D_{10} – NA (avg.) Actual D_{10} – NA (SD)			The D_{10} value suggests that this base is fairly permeable or open graded. Very open graded permeable bases promote excess paste penetration.
	CTPB Permeability	Design permeability – NA Actual permeability – 5,278 ft/day (avg.) Actual permeability – 10,710 ft/day (SD)	500 to 1,000 ft/day	No	Design permeability higher than recommended practice. This is itself is not detrimental unless the very open-texture of the base promotes PCC paste penetration and subsequent bonding.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

Table 30. Summary and comparison of data from Kansas City International Airport non-EAD section (2000/2001) with recommended practice (continued).

	Key Data Item	MCI Non-EAD Project (Terminal Apron – 2000/2001)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Mixture Properties	Cement Type – Type I/II			
		Cem. Factor – 637 lbs/yd^3 Pozz. Cont. – 20 % FA "C"	Lowest cement content to achieve optimum strength, durability, and shrinkage characteristics.	Yes	Cement factor > 400 lb/yd^3
		w/c ratio – 0.31			
		Total Water – 193 lbs	Less than 250 lb	No	OK
		Mortar Volume – 77%	Less than 60%	Yes	Mortar value higher the recommended. This is of concern when PCC is being placed on the fairly open-graded CTPB.
	PCC Fine Aggregate Gradation	Type – Intermediate	Coarse sand	No	Fine sand increases water demand and shrinkage. This non-EAD section complies with current recommendations regarding fine aggregate gradation.
		Passing No. 50 sieve – 10%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 2.9	3.1 to 3.4 for cem. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Limestone			Moderate CTE aggregate.
	PCC Combined Aggregate Gradation— Design	WF – 38.2	WF > 29 & CF < 75	No	OK, although field control of the mix is crucial to avoid segregation.
		CF – 75.8		Yes	
		Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing – Polyethylene sheeting	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
		CTPB Curing – LMFCC (water-base) 8hr curing time. Rate – NA	None recommended. Fog spraying if ambient temperatures are hot.		
	Initial Sawcut	Equipment – Traditional	Early entry or traditional wet saws.	No	Recommended equipment used to saw the joints.
	Sawcut Depth	Depth – D/3	D/3	No	OK
	Separation Layer	Present; Filter Fabric (P-154)	Geotextile or aggregate separation layer.	No	Separation layer according to recommended practice.
	Bond Breaker	Asphalt emulsion at 1 gal/90 ft^2	Choke stone layer	No	For very open-graded bases it is recommended that a choke stone layer is placed between the PCC and CTPB to reduce paste penetration and bond. Asphalt emulsion decreases the base drainability.
	CTPB QA Program	Thickness, smoothness, permeability	Thickness, gradation, permeability, grade, smoothness.		Gradation and grade are recommended for QA programs but they were not controlled in the field.

1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg

5.5.2 Wichita Mid-Continent Airport Taxiway E Reconstruction (1998)--EAD Project

In the late summer of 1998, Wichita Mid-continent Airport reconstructed taxiway E and associated taxiway segments. Reconstruction of the 75-ft (23-m) wide taxiway extended about 1,750 ft (534 m) between RW 32 and TW B. Design layers and thicknesses for this pavement included a 15-in (381-mm) thick PCC surface course placed on a 4-in (102-mm) CTPB layer. The P-204 CTPB layer was constructed over a P-155 lime stabilized sandy, lean clay subgrade. Construction and contraction joints for the pavement surface are spaced at 25-ft (7.625-m) intervals, resulting in three primary paving lanes. Figure 43 presents a sketch of the typical section and the typical joint layout for the feature of interest.

Paving of the CTPB was completed between August 6 and September 1, 1998. Moist curing of the base was applied every 2 hours for a total of 8 hours. Prior to the PCC placement, the surface was sprayed with a thin layer of P-601 asphalt emulsion to provide a separation layer for thickness determination. Immediately prior to PCC placement, the CTPB surface was moistened due to the hot weather.

Placement of the PCC layer was primarily completed on August 25, 27, and September 10, 1998. On both August 25th and August 27th, unexpected thunderstorms stopped the paving operation and reduced the air temperatures by 18 and 22°F (-8 and -6°C) within 4 hours and the maximum air temperatures reached 99 and 102°F (37 and 39°C), respectively. Transverse cracks (7.9 and 7.5 percent of slabs) in the PCC surface were noticed the day following the placement. Wind screens and water misting following placement were not used on the project. Some surface

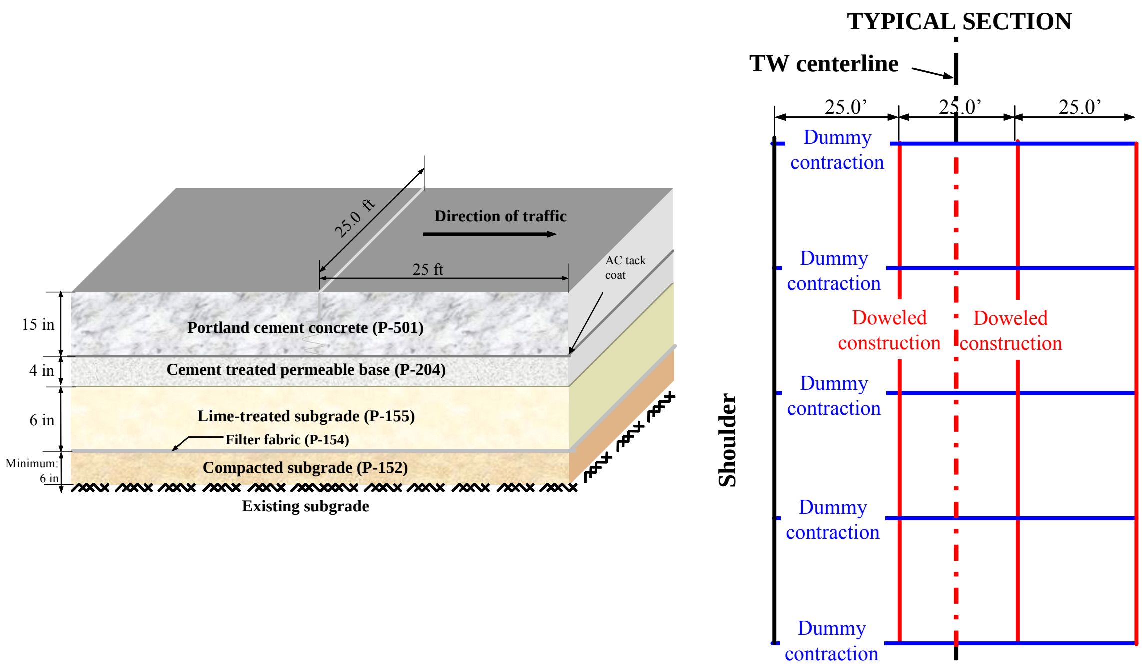


Figure 43. Typical section and joint layout for Taxiway E reconstruction (1998) at the Wichita Mid-Continent Airport.

shrinkage was noted on May 25th, 2004, as shown in figure 44. Thunderstorms were not encountered during paving of the center lane on September 10, 1998, and no cracking was observed in the surface. Several of the stakeholders indicated that the rapid cooling of the PCC surface, in conjunction with the stabilized base, could have been factors in the cracking.

Figure 44. Shrinkage cracks in Taxiway E at Wichita Mid-Continent Airport.

An evaluation of the data presented in table 28 for this project suggests the following with regard to the various ambient trigger conditions present during the paving of the PCC, and the design, materials, and construction variants:

- The placement was primarily completed between August 25 and September 10, 1998. Large temperature swings of about 20°F (-7°C) and high air temperature of about 100°F (38°C) were recorded during the paving operations, as shown in figure 45. The combination of hot weather and rapid thunderstorm-related temperature drops may have been a significant contributing factor to the early cracking. The rates of evaporation were also noted as being on the rise.
- Surface shrinkage cracks are evident in several locations of the 1998 project, indicating the effects of high temperatures.
- The panel dimensions are above the industry-recognized practical maximum of 20 ft (6.1 m), although the slab/width criterion and thickness criterion are satisfied.

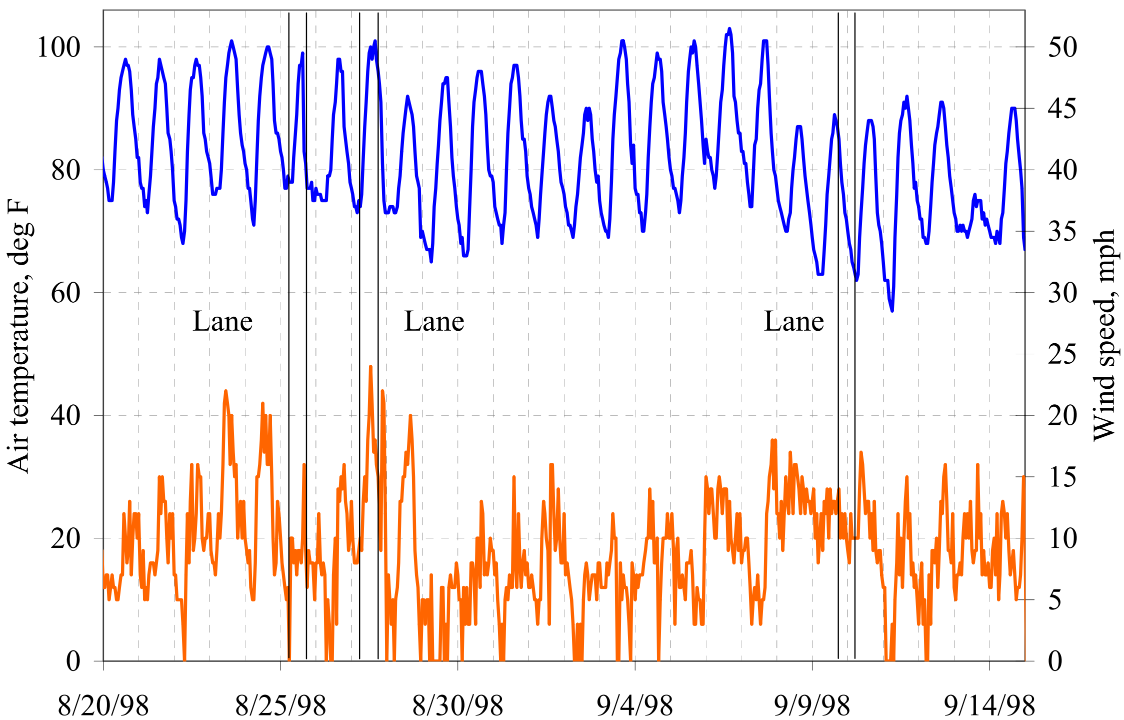


Figure 45. Paving temperatures and wind speeds during reconstruction of Taxiway E reconstruction (1998) at the Wichita Mid-Continent Airport.

- The long slab dimensions could be an aggravating factor causing cracking under unfavorable ambient conditions (excessive curl and warp stresses).
- CTPB compressive strength data were available from coring. These data indicated a 28-day compressive strength of about 1,900 lb/in^2 (13,100 kPa). This base therefore qualifies as an excessively stiff base. Furthermore, the base appears to be very open-graded. Open-graded bases under PCC pavements are conducive to paste penetration and can cause excessive restraint stresses if their stiffnesses are also excessive.
- An analysis of the PCC mix design revealed the following P-501 mixture-related issues:
  - The cement factor of 565 lb/in^2 (3,896 kPa) is a high value. There is a possibility of generating excessive heat of hydration which when combined with the prevalent hot temperatures and high wind speeds leading to excessive shrinkage in the mix.
  - The FM computed of 2.9 and percent passing the No. 50 (300 µm) sieve of 10 percent for the fine aggregate indicate that the mixture does not have excess fines and has a reduced shrinkage potential.
  - The workability and coarseness factors derived from the combined aggregate gradation were around 47 and 75, respectively. The coarseness factor is good, whereas the workability is near unrealistic. The potential for segregation and uncontrolled cracking exists if the mixture is not well controlled in the field.

- Records indicate that mist curing (surface fogging) was performed for 8 hours starting 3 hours after compaction to cure the CTPB. An asphalt emulsion applied at a rate of 1 gal (3.785 L) per 90 ft^2 (8.4 m^2) was used prior to paving to serve as a bond breaker. The impact of this application on lowering the degree of restraint at the slab-base interface is not considered adequate. In addition, this application can decrease the permeability of the CTPB.
- Conventional diamond blade saws were used for initial joint sawing. The depth of the initial sawcut was D/4. The recommended sawcut depth was one-third of the slab thickness. A deeper sawcut could have avoided the random shrinkage cracking, particularly in light of the fact that the PCC could have penetrated the CTPB, thereby increasing the effective section thickness.

Conclusions

In reviewing the factors listed above, it can be seen that the most likely trigger factor which led to the movements in the slab was the high temperature swing, combined with the high air temperatures and high wind speeds during the paving operations. However, the contributing factors that aggravated the situation include the following:

- Large panel dimensions.
- Presence of a stiff base.
- Shrinkage susceptible PCC mix.
- Excessive restraint at the slab/base interface.
- Inadequate sawcut depth.

5.5.3 Wichita Mid-Continent Airport North Aircargo Apron (1995)—Non-EAD Companion Project

In early Fall 1995, the Wichita Mid-Continent Airport North Air Cargo Apron and associated taxiway segments were extended. Construction of the 330-ft (101-m) wide by 700-ft (213.5-m) long pavement was completed using design layers and thicknesses of 15-in (381-mm) thick PCC, 4-in (102-mm) CTPB, 8-in (203-mm) P-155 lime treated subgrade, placed over a compacted sandy, lean clay subgrade. Construction and contraction joints for the pavement surface are spaced at 25-ft (7.625-m) intervals. This project had similar design cross-section, materials, construction factors as the Taxiway E project discussed in section 5.5.2. However, no early-age cracking was observed on this pavement. Therefore, it was selected as a companion section for detailed comparisons.

Table 28 presents a detailed one-to-one comparison of the various design, materials, and construction factors between this project and the Taxiway E project constructed in 1998. A few key observations from the comparison are presented as follows:

- PCC paving took place in the last 2 weeks of October, 1995. The weather conditions at the time of paving were assumed to be milder than those prevalent during the reconstruction Taxiway E at the same airport.

- The large panel dimensions (25 ft [7.625 m]) used on this project were outside the recommended guidance of 20 ft (6.1 m).
- Seven CTPB strength records were available in the project files. The average 7-day compressive strength for this section was about 860 (5,930 kPa). This value is far below the average value obtained for the Taxiway E.
- An analysis of the PCC mix design revealed the following P-501 mixture-related issues:
  - The PCC mixture design seems to be very similar for the two projects.
  - The cement factor (15% fly ash) used in both P-501 mixture is typical for paving work.
  - Fine aggregate gradations for the P-501 design mix fall evenly within the ASTM C 33 limits. The amount of fine aggregates passing the No. 50 (300 µm) sieve was 10 percent, which is about half of the companion EAD section. However, the fineness modulus value was below the minimum recommended level of 3.1 (same as for the EAD section).
  - The workability and coarseness factors derived from the combined aggregate gradation are 47 and 75, respectively. These are deemed to produce, on average, a workable mixture that may reduce the potential for uncontrolled cracking.
- Records indicate that the initial sawcut was made with a traditional diamond-bladed, wet saw to a depth of D/4 similar to the EAD section.

Conclusions

Although the design features and construction process were similar to the companion EAD section, early cracking did not occur probably due to the non-existence of trigger factors, such as large temperature swing, high air temperature, and low relative humidity. A low base stiffness and a more optimized PCC mix may have also contributed to the absence of cracking.

5.5.4 Syracuse Hancock International Airport 174th ANG Apron (2000)—EAD Project

In August 2000, the a new concrete Apron was constructed at the 174th Air National Guard Apron collocated at the Hancock International Airport in Syracuse, New York. Figure 46 presents a sketch of the typical section and the typical joint layout for this project.

The specifications used for the construction were based on the USAF Specification 02515, *Rigid Concrete Pavement for Airfields*, and the USACE Specification CEGS-02174, *Drainage Layer*.

PCC paving operations started in July and ended on August 11, 2000. After 30 to 60 days following the end of the construction, random shrinkage cracks appeared in the outside east row of panels, which is tied to the next row of slabs with tie deformed bars. The cracks were located near the end point of the tie bars. In addition, random cracks appeared in another 10 slabs located toward the aircraft shelter. These cracks occurred roughly after 30 to 60 days after the end of the construction. Figure 47 highlights the areas on the apron where the cracks were located.

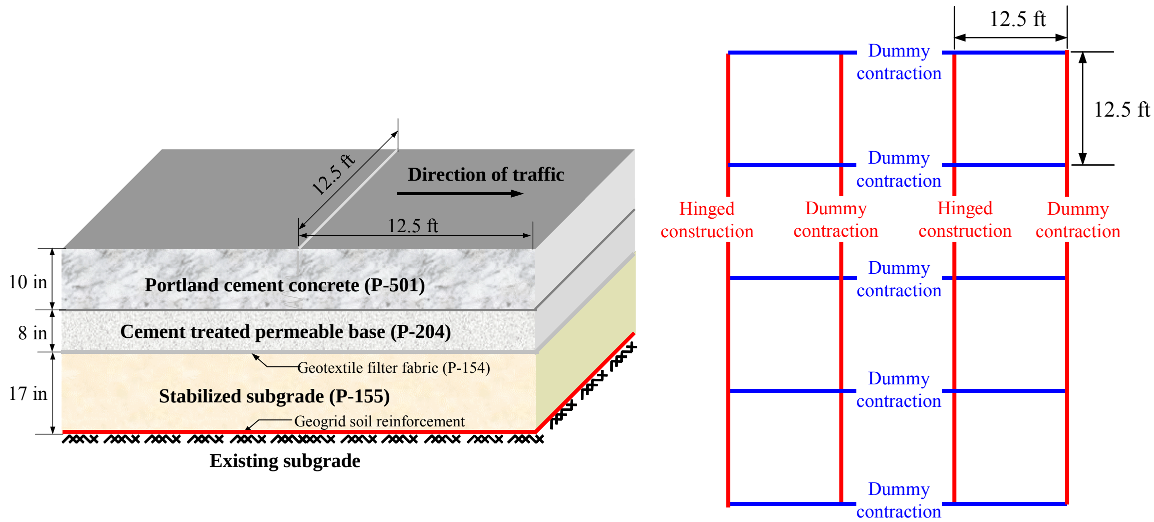


Figure 46. Typical section and joint layout of the 174th ANG Apron Upgrade at the Syracuse Hancock International Airport.

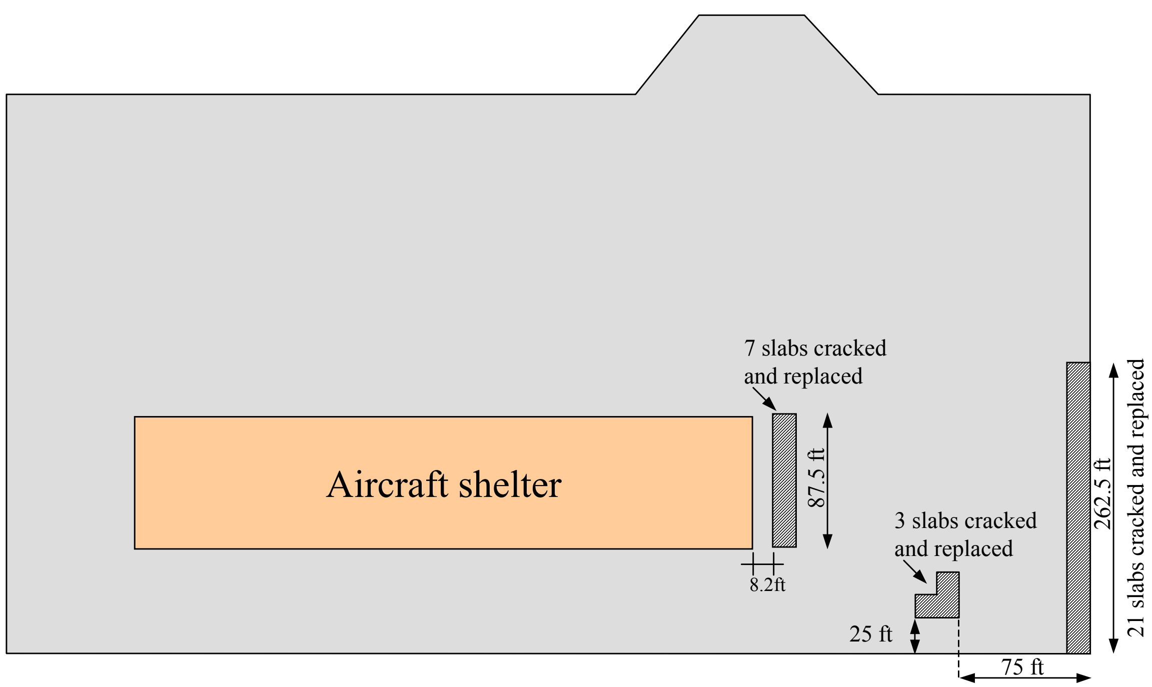


Figure 47. Location of random shrinkage cracks at Syracuse Hancock International Airport.

An evaluation of the data presented in table 29 for this project suggests the following with regard to the environmental conditions during concrete paving operations and design features, material characterization, and construction process:

- The maximum reported temperature during the PCC placement was 75°F (24°C) and no extreme weather issue was reported. However, modeling of the prevalent conditions around the time of PCC placement indicate that excess evaporation losses could have been a potential trigger factor.
- A forensic study revealed that a strong bond developed between slab and base. Cores extracted from this project indicated that plastic concrete penetrated the CTPB layer between 1 and 2 in (25 and 51 mm). The separation line between slab and base could not even be detected. The very open-graded nature of the CTPB resulted in penetration of the PCC paste into it, thereby increasing the slab/base interface restraint.
- Excessive restraint caused by the use of tie bars at contraction joints appears to be one of the design variants that contributed to the appearance of random cracking. Since the tie bars hold the slabs together, the pavement slabs behave as if they are 25-ft (7.625-m) long instead of 12.5 ft (3.81 m). This violates the maximum panel length recommendation of 20 ft (6.1 m).
- The design CTPB 28-day compressive strength was 770 lb/in^2 (5,309 kPa). No actual measured strength data were available to verify these values. If the as-built values were close to as-designed, the base would only be moderately stiff.
- An analysis of the PCC mix design revealed the following P-501 mixture-related issues:
  - The cement factor of 611 lb/yd^3 (361 kg/m^3) is high, increasing the possibility of excessive heat of hydration at the time of set. Flyash was not used on this project.
  - The FM computed for the fine aggregate gradation was 2.9, which is only slightly less than the recommended lower FM limit. The percent passing the No. 50 (300 μm) sieve, a good indicator of bulking potential of the fine aggregate and excess water demand, was 15 percent. This indicates that the mixture does not have excessive fines and has a reduced shrinkage potential.
  - The combined aggregate gradation appears to be representative of a well-graded and workable mixture. The workability and coarseness factors derived from the combined aggregate gradation were 30 and 73, respectively. Both workability and coarseness factors are within recommended values; however, field control of the mixture is vital to avoid early cracking problems.
- No bond breaker was placed between the PCC pavement and the CTPB.
- Early entry equipment was used to saw the PCC joints. However, a depth of D/4 may not have been adequate, considering the bond between the PCC and CTPB layers.

<u>Conclusions</u>

In reviewing the factors listed above and presented in table 29, it can be seen that the most likely trigger factor leading to early cracking was the evaporation losses that occurred at the time of construction. The resulting shrinkage was not uniform through the slab thickness, partly due to a variety of factors, including slab/base friction, tie bars at contraction joints, and the weight of the slab.

5.5.5 Kansas City International Airport North Terminal Apron (2000/2001)—Non-EAD Companion Project

The construction of the North Terminal Airport of Kansas City International Airport was finalized in September 2001. The preparation of the subgrade started in June, 2000 and after 1 month, the placement of the PCC surface began. The total paved area was about 114,000 yd^2. The design layers and thickness for this pavement included a 16-in (406-mm) PCC slab placed over a 7-in (178-mm) CTPB and a 12-in (305-mm) lime treated subgrade. The joint layout included 20-ft (6.1-m) wide slabs with length varying from 15 to 25 ft (4.575 to 7.625 m). The joint design included mostly dummy contraction and doweled construction joints. Figure 48 shows a sketch of the typical section and joint layout for this project.

Table 30 presents a detailed description of the various design features, materials, and construction factors for this project. A few key observations are presented as follows:

- The project was paved during all seasons—Summer, Fall, Winter, and Spring. Hence, a variety of trigger factors are expected to have been present at various times of paving.
- The longitudinal joints for this project varied between 15 and 25 ft (4.575 and 7.625 m), whereas a transverse joint width of 20 ft (6.1 m) was kept constant. The panel length of 25 ft (7.625 m) is above the recommended maximum value of 20 ft (6.1 m).
- The design 28-day CTPB compressive strength was 620 lb/in^2 (4,275 kPa), which is not a very stiff base.
- The CTPB layer appears to be fairly permeable and open in texture (permeability values measured in the laboratory exceeding 5,000 ft/day [1,525 m/day]). PCC Paste penetration and subsequent bonding the PCC slab will be of concern with this base type.

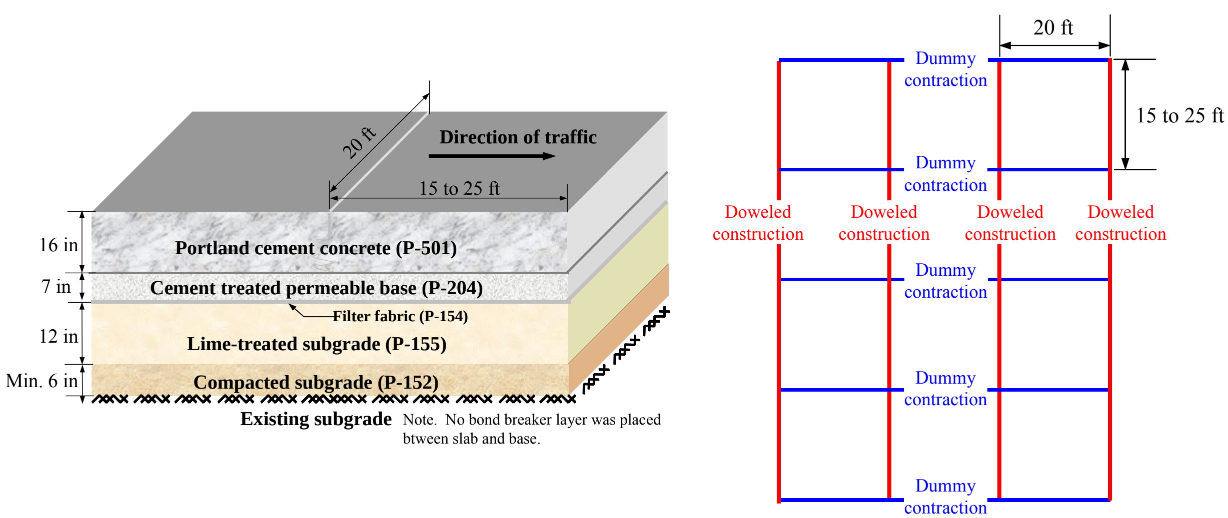


Figure 48. Typical section and joint layout for North Terminal Apron of Kansas City International Airport constructed in 2000 and 2001.

- An analysis of the PCC mix design revealed the following:
  - The cement content (>400 lb/yd^3 [236 kg/m^3] and the mortar volume were high.
  - Fine aggregate gradations for the P-501 design mix fall evenly within the ASTM C 33 limits. The amount of fine aggregates passing the No. 50 (300 µm) sieve was 10 percent, which is within the preferred ASTM C33 band, but the fineness modulus value (2.9) was below the minimum recommended level of 3.1.
  - The workability and coarseness factors derived from the combined aggregate gradation were 38 and 76, respectively. These are deemed to produce, on average, a workable mixture that may be resistant to uncontrolled cracking.
- A polyethylene film was used to cure the PCC slab for at least 7 days and no traffic was allowed during that time.
- An asphalt emulsion at a rate of 1 gal (3.785 L) per 90 ft^2 (8.4 m^2) was used prior to paving to serve as a bond breaker. The impact of this application on lowering the degree of restraint at the slab-base interface is not considered inadequate. Such an application can decrease the permeability of the CTPB.
- Sawcutting to a depth of D/3 of the slab thickness was employed.

<u>Conclusions</u>

Although some of the design features were more favorable to the appearance of random cracks, such as the existence of some long slab panels, high air temperature and high cement content, no early cracks were reported. This is attributed, in part, to the low CTPB stiffness and adequate sawing.

5.6 REVIEW OF ASPHALT-TREATED PERMEABLE BASE (ATPB) PROJECTS

A total of four pavement projects with ATPB layers were short-listed for extensive data collection and evaluation in this study. These sections were located at the Memphis International Airport, Tinker Air Force Base, and Fort Sill Army Airfield. None of these projects exhibited EAD, as defined in this study.

The ATPB projects at the Memphis airport were constructed in accordance with modified versions of the FAA AC 150/5370-10A, Item P-402, *Porous Bituminous Base Course*. The ATPB sections at Tinker Air Force Base and Fort Army Airfield were constructed in accordance with the US Army Corps of Engineers specification 02714. Only the Memphis International Airport projects are discussed in this report, as a means of documenting good practice when using ATPB under rigid airfield pavements. The other projects do not have the detail necessary to be useful for this discussion. Table 31 presents a listing of the selected projects along with key project details.

Table 31. List of projects with an ATPB layer selected for detailed study.

Section Location	Feature of Interest	Year Built	Early Cracking Present?	Design
Memphis International Airport (MEM) Memphis, TN	• Runway 18R-36L (2002)	2002	No	19 in PCC 4 in ATPB 8 in CTB 6 in Soil cement Lime-treated subgrade
Memphis International Airport (MEM) Memphis, TN	• Taxiway Mike (2000/01)	2000/01	No	19 in PCC 4 in ATPB 8 in CTB 6 in Soil cement Lime-treated subgrade

1 in = 25.4 mm

5.6.1 Summary of Key Variables

Table 32 presents the parameter values/descriptions of the key trigger factors and variants for the selected projects. Also provided in this table are the recommended threshold values for the various trigger and variant factors which, if exceeded, increase the likelihood of EAD.

5.6.2 Memphis International Airport Runway 18R-36L (2002) and Taxiway Mike (2000/2001)—Non-EAD Projects

Runway 18R-36L is located on the west end of the Memphis International airport. The entire length of the runway was reconstructed in 2002. The runway is approximately 9,300 ft (2,837 m) long and 150 ft (46 m) wide. Taxiway Mike is located parallel to and just east of Runway 18R-36L. The construction of the Taxiway Mike began in 2000 and was finalized in 2001. Taxiway Mike is 10,100 ft (3,080 m) long and 150 ft (46 m) wide. The typical section and jointing detail for both the taxiway and runway were similar, with the exception that the outer lanes of the taxiway are a full-depth asphalt pavement.

Figure 49 provides a sketch of the typical section and jointing details for these two features. No evidence of EAD of consequence to this report was found during or immediately following the construction of these features.

Table 32. Summary and comparison of data from Memphis International Airport Runway airport non-EAD sections (2002 and 2000/2001) with recommended practice.

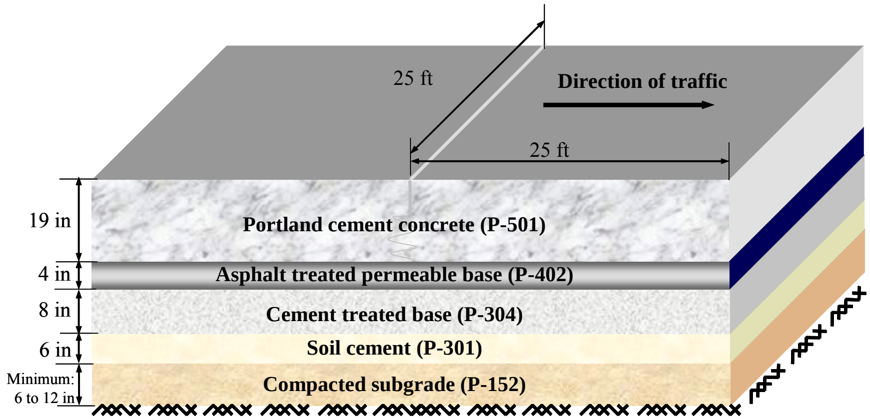
	Key Data Item	MEM Non-EAD Project (Runway 18R-36L – 2002)	MEM Non-EAD Project (Taxiway Mike – 2000/2001)	Recommended Practice	Threshold Exceeded?	Comment
Trigger Conditions	EAD Present?	No	No			
	Ambient PCC Paving Conditions	Max. Temp – 85°F (median). Min. Temp – 50°F (median).	Max. Temp – Varied by season. Min. Temp – Varied by season.	Good hot- and cold-weather management plan and execution.	No	• Hot temperatures increase shrinkage potential. This could have been a trigger factor for these non-EAD sections. • Large temperature swings cause steep gradients in PCC slabs. This could also have been a trigger factor for these non-EAD sections.
		Hot weather (temperature > 90°F) present on several days during PCC paving but no large temperature swings.	Hot and cold weather present But adequate precautions taken.			
	PCC Placement Season	Spring/Summer	Winter but mostly Spring/Summer			
Design Variants	Thickness	PCC Design – 19 in Actual – 19.8 in (avg.) Actual– 0.5 in (SD)	PCC Design – 19 in Actual – 19.4 in (avg.) Actual– 0.7 in (SD)			The as-built PCC thickness was greater than as-designed. If grade tolerances are met, this implies a high variability in the underlying layer thicknesses.
		ATPB Design – 4 in Actual – NA (avg.) Actual– NA (SD)	ATPB Design – 4 in Actual – NA (avg.) Actual– NA (SD)	4 to 6 in	No	OK
	Joint Spacing	Trans. Spacing (L) – 25 ft Long. Spacing (W) – 25 ft	Trans. Spacing (L) – 25 ft Long. Spacing (W) – 25 ft	Max. dimension ≤ 20 ft.	Yes	The maximum dimension is 25 percent higher than the maximum recommended length but the other two length criteria are satisfied.
				L/W < 1.25	No	
				Max. L < 21*PCC Thk.	No	
Materials Variants	28-day PCC Flexural Strength	Mix Design – 870 lb/in^2	Mix Design – 750 lb/in^2 (4 mix designs approved)	650 lb/in^2 (28-day)		The mix design strength is higher than typical values. It may increase the probability of cracking due to increase in modulus.
		Actual – 790 lb/in^2 (avg.) Actual – 40 lb/in^2 (SD)	Actual – 799 lb/in^2 (avg.) Actual – 44 lb/in^2 (SD)			The as-built flexural strength is less than 10 percent higher than design values. The as-built strength variability is typical.
	As-Designed ATPB Mix Properties	AC Content – 2.8% (by wt.) AC Grade – PG 64-22 Anti-strip agent used D_{10} – 0.13 in	AC Content – 2.8% (by wt.) AC Grade – PG 64-22 Anti-strip agent used D_{10} – 0.07 in	2 to 3.5% AC Stiffer AC grades Anti-strip	No	• The mixture properties seem adequate to produce a good quality durable material. • Higher the D10, higher the permeability. The D_{10} of AASHTO #57 stone is 0.22. New Jersey perm. bases has a D_{10} is 0.07 in. • Good quality control on gradation in field.
	As-Built ATPB Mix Properties	D_{10} – 0.08 in (avg.) D_{10} – 0.03 in (SD)	D_{10} – 0.1 in (avg.) D_{10} – 0.05 in (SD)			
	PCC Mixture Properties	Cement Type – Type I	Cement Type – Type I			
		Cem. Factor – 500 lbs/yd^3 Pozz. Cont. – 17.6% FA "C"	Cem. Factor – 500 or 547 lbs/yd^3 Pozz. Cont. – 18.6% FA "C"	Lowest cement content to achieve opt. str., dur., and shrinkage characteristics	Yes	Cement factor > 400 lb/yd^3 (used in 4 mixes) (used in 2 out of 4 mixes)
		w/c ratio – 0.45	w/c ratio – 0.45			
		Total Water – 225 lbs.	Total Water – 228 to 223 lbs. (lower water for FA mixes)	Less than 250 lb	No	OK
		Mortar Volume – 63%	Mortar Volume – 65%	Less than 60%	Yes	The mortar volume is slightly higher than recommended.

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg °C = (°F-32)*5/9

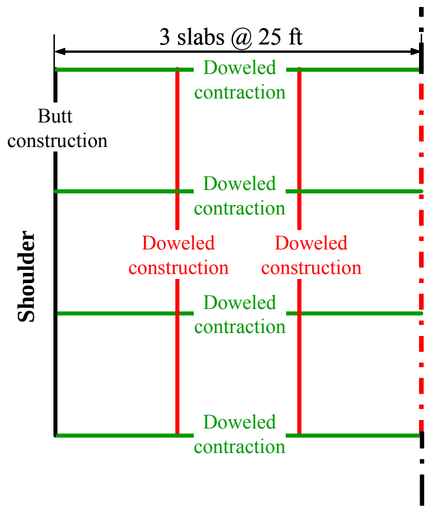
Table 32. Summary and comparison of data from Memphis International Airport Runway airport non-EAD sections (2002 and 2000/2001) with recommended practice (continued).

	Key Data Item	MEM Non-EAD Project (Runway 18R-36L – 2002)	MEM Non-EAD Project (Taxiway Mike – 2000/2001)	Recommended Practice	Threshold Exceeded?	Comment
Materials Variants	PCC Fine Aggregate Gradation	Type – Intermediate (Natural Sand)	Type – Intermediate (Natural Sand)	Coarse sand	Yes	Fine sand increases water demand and shrinkage but intermediate gradation seems to be appropriate since cracking was not observed.
		Passing No. 50 sieve – 13%	Passing No. 50 sieve – 16%	Lower limit of ASTM C33 5 to 30 % band preferred	No	
		Fineness Mod.– 2.6	Fineness Mod.– 2.6	3.1 to 3.4 for cem. fac. > 400 lb/yd^3	Yes	Increased shrinkage potential.
	PCC Coarse Agg. Type	Limestone	Limestone			Moderate coefficient of thermal expansion.
	PCC Combined Aggregate Gradation— Design	WF – 37.1	WF – 37.1	WF > 29 & CF < 75	No	Outside the workability box.
		CF – 79.8	CF – 79.8 (typical mix)		Yes	
		Nom. Max. Agg. – 1.5 in	Nom. Max. Agg. – 1.5 in			
Construction Variants	Curing type & process	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	PCC Curing – White-pigmented LMFCC (resin-base) Rate >1 gal/150 ft^2	Fog spraying and white pigmented CC preferred in hot weather.	No	OK
		ATPB Curing – None.	ATPB Curing – None.			
	Initial Sawcut	Equipment – Traditional.	Equipment – Traditional.	Early entry or traditional wet saws.	No	Recommended equipment used to saw the joints.
	Sawcut Depth	Depth – D/3	Depth – D/3	D/3	No	OK
	Separation layer	CTB primed with asphalt tack coat.	CTB primed with asphalt tack coat.	Geotextile or Aggregate separation layer between permeable base and the layer below it.	Yes	A separation layer is vital for the long-term performance of a drainable base.
	Bond Breaker	None	None	None recommended	No	OK
	Whitewashing/Fog Spraying During Hot Paving Conditions?	The ATB surface was whitewashed and mist sprayed water prior to the placement of the PCC.	NA	Use lime-water solution reflect solar radiation or moisten ATPB without saturation just prior to paving.	No	This is good practice particular when paving under hot conditions.
	ATPB Surface Condition Prior to Paving	Surface mist spaying with water ahead of PCC paving. Whitewashing ATPB or night paving used when hot temperatures persisted.	No record			Milled surface increases base restraint but no record was available to verify if milling occurred prior to PCC placement.
	ATPB QA Program	Thickness, bituminous content, gradation, visual condition, grade, surface evenness	Thickness, bituminous content, gradation, visual condition, grade, surface evenness	Thickness, gradation, permeability, visual condition, grade, surface evenness.		Excellent control over the product to ensure uniformity, constructability, and quality in terms of permeability and stability.

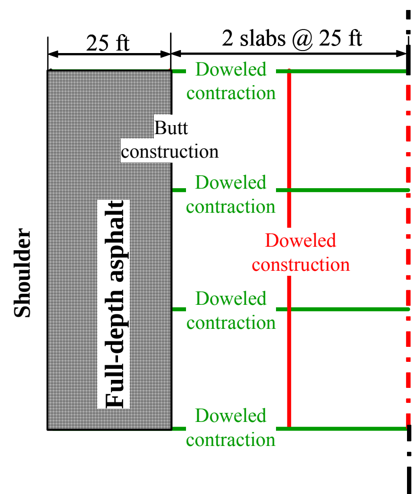
1 in = 25.4 mm 1 ft^2 = 0.093 m^2 1 gal = 3.785 L 1 lb/yd^3 = 0.59 kg/m^3 1 lb = 0.452 kg



(a) Typical section Runway 18R-36L & Taxiway Mike.



(b) Runway 18R-36L joint layout.



(c) Taxiway Mike joint layout.

Figure 49. Typical section and joint layout for Runway 18R-36L (construction in 2002) and Taxiway Mike (constructed in 2000/001 located at the Memphis International Airport.

The reconstruction of Runway 18R-36L was a carefully planned and executed exercise to ensure minimum down time to airport operations. The entire reconstruction effort took place between February and September of 2002 (circa Polk and Mitchell, 2003). The following is an approximate breakdown of the construction schedule for the CTB layer and the layers above it.

- CTB construction commenced on March 8, 2002 and ended April 24, 2002. The following ambient conditions were noted from project records:
  - Temperatures cool until 1st week of April and warmed up after that.
  - Median temperature range was 65°F (18°C) (max) and 35°F (2°C) (min).
  - Only 1 day with 90°F (32°C) was encountered.
- ATPB construction commenced on March 29, 2002 and ended June 5, 2002, during which time the following ambient conditions were noted:
  - Temperatures cooler until 1st week of April and warmed up after that.
  - Median temperature range was 85°F (29°C) (max) to 45°F (7°C) (min).

- P-501 construction began on April 16, 2002 and ended July 1, 2002, during which time the following ambient conditions were noted:
  - Earlier parts were cooler than latter parts.
  - Median temperature range was 85°F (29°C) (max) to 50°F (10°C) (min).
  - Several hot days (> 90°F [32°C]) in June.
  - Some rain days.

The construction of Taxiway Mike spanned over several seasons and progressed in two stages (2001 and 2002). The following is an approximate breakdown of the construction schedule for the CTB layer and the layers above it:

- The first stage of CTB paving commenced on September 27, 2000 and ended on November 28, 2000. The second stage commenced on February 5, 2001 and ended on August 2, 2001.
- The first stage of ATPB paving commenced October 7, 2000 and ended on December 1, 2000. The second stage paving began on February 19, 2001 and ended August 14, 2001. This layer was placed mostly in July, 2001.
- Initial PCC paving took place in October 2000 when the first nine lots were placed. The second stage paving commenced on January 23, 2001 and continued until August 22, 2001. The north and south full-width concrete sections were paved first, followed by the center four-lane sections.

The following were the ambient conditions encountered during the paving of Taxiway Mike:

- The beginning of the October 2001 had a few hot days, but for most part the median temperatures stayed between 85°F (29°C) and 60°F (16°C).
- November started off warm with temperatures in the upper 60's °F (10's °C), but cooled off rapidly. The median range of ambient temperatures was between mid-50°F (10°C) and mid-30°F (-1°C). The number of actual paving days was minimal (2 to 3 days when either CTB or ATPB were placed).
- January was cold and very little paving was actually done.
- Conditions in February warmed up but had significant number of rain days (approximately half the days). Very little paving was done; however, all three items were place in some quantity.
- Temperatures in March ranged from the 50's to 30°F (10's to -1°C). One significant cold-weather paving day was encountered when heating blankets were used for protecting the PCC. Next day's paving started only after the cylinders were broken.
- Temperatures significantly warmed up in April through August and significant placement of paving items occurred. The temperature ranges in April and May were in between 85°F (29°C) to 50°F (10°C).
- Conditions were good rest of the way with several hot days (>90°F [32°C] but below 100°F [38°C]).

It was noted during the stakeholder interview process that adequate precautions were taken during the placement of the PCC layer for both runway and taxiway jobs to handle adverse weather conditions.

Table 32 presents a detailed one-to-one comparison of the various design, materials, and construction factors between the two projects, as well as the recommended practice. It can be noted from the table that most of the design, materials, and construction factors between the two projects were identical. A few key observations from the comparison are:

- Since the PCC placement on both the runway and taxiway took place over several seasons, significant trigger factors (notably hot-weather conditions) were prevalent, which could cause excessive deformations in the slab leading to EAD.
- The maximum panel length is above the recommended maximum of 20 ft (6.1 m). However, interviews with the stakeholders revealed that this panel length has a history of success at the airfield, owing to the type of base it is placed on.
- The ATPB seems like a well designed mixture. The specifications ensure that the mixture is well coated and that the gradation is controlled in the field. An anti-strip agent is also used to ensure long-term durability—a major concern with this base type. The D_{10} value—a good indicator of permeability—suggests that the mixture is fairly, but not overly, drainable. A very open-graded aggregate promotes penetration of the PCC paste and, hence, offers more restraint to slab movements.
- An analysis of the PCC mix design revealed the following mixture-related issues:
    - The cement factor used on both the runway and taxiway mixes is moderate. Issues regarding excessive heat of hydration are moderated by the amount of flyash used. Rate of strength gain was not an issue consideration the prevalent ambient conditions when the PCC was paved.
    - The FM and percent passing the No. 50 (300 μm) sieve indicate that the sand was on the finer side. There is a potential for EAD developing if evaporation losses are not controlled through adequate and timely curing.
    - The combined aggregate gradation factors indicate that mixture segregation issues are a possibility, but are not encountered in the field.
    - Records indicate that the coarse aggregate used in the P-501 mixes was crushed limestone. Limestone has a moderate CTE. However, combined with the large panel spacings and hot ambient conditions, EAD could develop if the frictional restraint is excessive.
- Extra effort was expended on the job to ensure that the asphalt coating on the ATPB layer was uniform. For this purposes, a remixing spreader was utilized in the field to prevent truck-to-truck segregation of ATPB caused by asphalt draindown. It is noted that having this piece of equipment on-site helped achieve 100 percent uniformity of the mixture.
- The ATPB layer was whitewashed to mitigate heat absorption into the asphalt and was also mist sprayed immediately prior to the PCC placement.
- The CTB layer served as a separation layer between the ATPB and the underlying soil. Cement or pozzolan stabilized layers are not usually recommended since they develop shrinkage cracks through which, given the right conditions, moisture and fines from the subgrade can flow into the base layer rendering it ineffective over time.
- The production control of the ATPB mixture included checking consistency of asphalt content and gradations. In the absence of actual field permeability testing, this is very necessary to ensure that the design permeability and stability are being achieved in the field.

- PCC paste penetration in the ATPB was noted on prior jobs; however, it was deemed that it was not significant enough to cause yield loss.
- Traditional sawcutting equipment (diamond blade, walk-behind, wet saws) was used to perform the initial sawcuts. The sawcut depth was D/3.
- Records review and stakeholder interviews indicated that adequate hot- and cold-weather precautions were taken during the construction of the pavement layers.

Conclusions

In reviewing the factors listed above and the data presented in table 33, it is noted that no EAD was found on the projects reviewed, despite the significant trigger factors present and some of the design and material variants exceeding their recommended threshold levels (joint spacing, PCC mix properties). Even though the PCC paste penetrates the ATPB system and bonds to it, the relative stiffness of this layer compared to the PCC, helps mitigate the restraint stresses that can develop in the PCC layer. Other construction variants that helped mitigate the occurrence of EAD include whitewashing of the base layer, the seemingly adequate joint sawing, and also a well designed and execute plan to manage environmental trigger factors during construction.

5.7 SUMMARY AND CONCLUSIONS

5.7.1 Summary

An extensive review of select airfield projects was conducted under the empirical analysis task of this study to gain a better understanding of the how various base types and other climatic, design, materials, and construction factors affect the early-age distresses in rigid airfield pavements. The base types evaluated were CTB, econocrete, ATB, CTPB, and ATPB.

It became evident at the outset that climatic factors are the *trigger* conditions that drive slab movements, which result in early-age cracking. There are three classes of trigger conditions that can exist during PCC paving:

- Large ambient temperature drops or swings (drops greater than 25°F [14°C]).
- Hot ambient temperatures.
- Excessive surface evaporation.

The deformations in the slabs caused by the triggers are axial and bending in nature. When these movements are restrained, tensile and bending stresses build-up in the slabs resulting in the formation of early distress in the form of cracking. Several varieties of early cracking were witnessed in the field including, random, corner, diagonal, transverse, and longitudinal. However, on any given project, only one or two types of cracking were observed. The following is a summary of the types of cracking observed and the number of projects on which it was witnessed:

- Transverse cracking: 4 of 9 projects with EAD.
- Longitudinal cracking: 2 of 9 projects with EAD.
- Transverse and longitudinal cracking: 1 of 9 projects with EAD.

- Transverse and diagonal cracking: 1 of 9 projects with EAD.
- All type of cracking: 1 of 9 projects with EAD.

Therefore, it can be concluded that a majority of the early cracking (approximately 78 percent) witnessed was transverse, longitudinal, or both.

The magnitude of stress build-up and early-age cracking on any given project is a function of the interaction of the trigger-induced deformations with various design, materials, and construction factors. These factors are termed as *variants* in this study, since they are under the direct control of engineer, designer, or constructor of the pavement and can be varied as needed to suit the job requirements. Threshold or desirable parameter values or ranges were established for each of these variants to help analyze the data gathered. When the as-designed or as-built parameter estimates of the variants exceeded their individual threshold values, they were noted and their possible consequences on EAD were discussed in the detailed summaries created for each project evaluated.

Table 34 presents a summary of the triggers (mentioned previously) and eleven key design, construction, and materials variants for each of the twenty projects evaluated in this study. Also presented is the base type and an indication of whether EAD was present or not for each given project. Note that the base type is treated as a category variable and not as a variant because the effect of the base type is characterized adequately by variants, such as base stiffness and PCC slab/base friction. Also, for the purposes of this table, the column "Poorly Graded PCC Mix" represents the combined aggregate grading characteristics of the PCC mix. The column "Shrinkage Susceptibility of the Mix" was assessed based on an evaluation of three factors: fine aggregate bulking potential and fineness modulus, total mortar content of the PCC mix, and total water in the PCC mix.

5.7.2 Conclusions

The following conclusions can be drawn from this table:

- Based on the climatic data gathered, it was observed that the most common trigger situation leading to EAD in rigid pavements built over stabilized or drainable bases is a large ambient temperature drops caused by an approaching cold front or a sudden rain shower. This is followed by hot-weather paving associated with high evaporation losses.

Table 33. Summary of the dominant triggers and variants observed for the airfield projects reviewed.

Airfield Project	EAD Present?	Trigger Condition Presence			Design Variants			Material Variants					Construction Variants			
		Hot Temp. (> 90 °F)	Temp. Swing (>25 °F)	Excess Evap. Loss?	Base Type	Panel Size Guidance Exceeded?	High Base Thick.?	Excess Base Strength/ Stiffness?	High PCC Cement Factor?	Poorly-Graded PCC Mix?	High CTE Coarse Agg.?	Shrinkage Susceptible PCC Mix?	Initial Sawing Inadequate?	Bond Breaker Inadequate?	Shrinkage Cracks Present in Base?	Base Milled or Open-Textured?
BTR - Rwy 4L/22 R (2003)	Yes	Yes		Yes	CTB			Yes			Yes	Yes	Yes		Yes	Yes
XNA - Rwy 16/34, Twy B&F, Apron (1997/98)	Yes	Yes		Yes	CTB			Yes		Yes			Yes	Yes	Yes	Yes
XNA - Terminal Apron (2003)			Yes*		CTB			Yes							Yes	
OMA - Taxiway A (1998)	Yes		Yes		CTB	Yes		Yes	Yes				Yes		NA	
OMA - Runway 14L/32R (2002)			Yes*		CTB				Yes			Yes			NA	
BRL - Taxiway A, Phase I (2001)	Yes	Yes			CTB		Yes	Yes	Yes	NA		NA	Yes	Yes	Yes	Yes
BRL - Taxiway A, Phase IV (2002)		NA	NA	NA	CTB		Yes		Yes	Yes		Yes		Yes	NA	
GRB - Taxiway M (2001)	Yes		Yes		LCB	Yes		Yes	Yes			Yes	Yes	Yes		NA
GRB - Taxiway D (2001)	Yes				LCB	Yes		Yes	Yes			Yes	Yes	Yes		NA
MSO - Air Carrier Apron, Phase I (2001)	Yes		Yes		LCB		Yes	Yes	Yes		NA		Yes		NA	NA
MSO - Air Carrier Apron, Phase IV (2002)			Yes*		LCB		Yes				NA		Yes		NA	NA
GRB - Air Carier Apron Expansion (2000)	Yes		Yes		ATB	Yes							Yes		NA	Yes
GRB - Air Carier Apron Expansion (2001)					ATB	Yes							Yes		NA	Yes
JVL - Runway 13/31 Extension (2002)			Yes	Yes	ATB	Yes					Yes	Yes			NA	NA
ICT - Taxiway E (1998)	Yes		Yes		CTPB	Yes		Yes				Yes	Yes		NA	Yes
ICT - North Air Crago Apron (1995)					CTPB	Yes							Yes		NA	Yes
SYR - 174th ANG Apron (1999)	Yes			Yes	CTPB		Yes							Yes	NA	Yes
KCI - Teminal Apron (2000/01)		Yes	NA		CTPB	Yes	Yes			Yes		Yes			NA	Yes
MEM - Runway 18R-36L (2002)		Yes*		Yes*	ATPB	Yes				Yes		Yes		Yes	NA	Yes
MEM - Taxiway M (2000/01)		Yes*		Yes*	ATPB	Yes				Yes		Yes		Yes	NA	Yes

Note: The (*) indicates that positive steps were taken as part of construction to mitigate adverse climatic effects on these projects.

- Large ambient temperature drops typically occurred in northern climates when paving was performed in early Spring or late Fall. The magnitudes of the swing that led to the development of distresses were in the order of 30°F (17°C). It was also observed that, during this temperature drop, if the lowest temperature reached was below 40°F (4°C), the risk of EAD was greater than when the ambient temperatures remained warmer.
- Another key observation was that at least one trigger condition should be present on any given project to cause EAD.
- It was noted that if 50 percent or more of the key variants are unfavorably aligned with a trigger condition, the likelihood of EAD is certain. However, EAD can also occur even if as few as two to three variants are unfavorably aligned.
- The ranking of the key variants that had the most influence on the development of EAD is as follows (ranked in decreasing order of importance):
  - Excess base strength/ stiffness.
  - Sawing (initial and final).
  - Panel sizes and aspect ratios.
  - PCC/base interface friction.
  - PCC cement factor.
  - Presence or absence of bond breaker.
  - Shrinkage susceptibility of PCC mixes.
  - Presence of shrinkage cracking in base.
  - Base thickness.
- In general high-strength cement stabilized bases such as CTB and LCB are more sensitive to combinations of triggers and variants. On the other hand, it was noted from the data collected that despite the presence of significant trigger conditions and above threshold variant parameter values, ATB and ATPB did not develop EAD as evidenced by the Janesville Runway 13/31 project and the Memphis Taxiway M and Runway 18R/36L projects.
- Proper planning and execution of the construction to account for adverse climate conditions is a key to good performance, as evidenced by the successes achieved in EAD mitigation on the Omaha Eppley Runway 14L-32R and Missoula International Air Carrier Phase IV projects. It was noted that most construction specifications include provisions to deal with potential trigger conditions, but to achieve consistent success, an understanding of the trigger factors and enforcement of the provision is imperative.

CHAPTER 6. THEORETICAL ANALYSIS

6.1 INTRODUCTION

This chapter presents the results of theoretical analysis performed to verify and extend the observations documented in chapter 5 regarding the primary factors contributing to EAD risk in PCC airfield pavements constructed over stabilized and drainable bases. The objective is to further quantify the impact of the key variants identified as contributing to EAD.

As with any other analysis, in order to develop guidance to mitigate risk of EAD in rigid pavements, it is imperative to understand the modes of early distresses and the critical responses driving them. This was done empirically and has been reported in chapter 5. Table 34 presents a summary of the major triggers and variants identified through empirical analysis as being chiefly responsible for the development of EAD. Also presented are the "cause and effect" relationships between the identified key triggers and aggravating variants. An understanding of the cause and effect relationship between triggers, variants, and EAD, will lead to developing effective solutions. The information presented in this table form the basis for theoretical analysis and modeling presented in this chapter. The goal of the theoretical analysis was to identify the most sensitive variants or combination of variants for a given trigger condition. Obviously, for any given situation, some variants are more sensitive than others and certain combinations of key variants poses a much higher EAD risk than if each variant were to be looked at individually.

6.2 THEORETICAL MODELING OF EAD RISK

Modeling the risk of early cracking involves four components:

- Climatic effects modeling—determining the temperature and moisture regimes in the PCC slab based on ambient conditions and material properties of the concrete.
- Materials modeling—determining concrete's early-age behavior including heat of hydration, shrinkage, strength gain, creep, etc.
- Structural response modeling—calculating critical structural responses in the slab-foundation system due to the imposed environmental loading conditions.
- Construction effects modeling—determining the changes in pavement behavior as a function of key construction activities (e.g., curing, sawcutting).

In this study, theoretical modeling of PCC pavements over stabilized and permeable bases was accomplished using HIPERPAV II version 3.0 (Ruiz et al., 2005) (referred to hereinafter as HIPERPAV) and ISLAB2000 (Khazanovich at al., 2000). Key highlights and capabilities of each of these programs vis-à-vis the objectives of this analysis are given below.

Table 34. Effect of triggers and variants on pavement responses and early-age distress modes.

Trigger Factor	Effect on Pavement Response & Potential Distress Modes	Aggravating Variants and Interactions
Large Temperature Drop-Induced Thermal Shock caused by an approaching cold front or a significant rain/snow event.	• Imposes a negative thermal gradient though the slab (top cooler than bottom). • If the slab is sufficiently hardened, this can lead to tensile stresses at the top of the slab and a potential for top-down cracking.	• Late sawing or inadequate sawcut depth. • Long PCC slab panels or high slab aspect ratios. • Very thick or stiff base. • Improper timing of PCC placement with respect to the timing of thermal shock (e.g., placing it when the heat of hydration is maximum at the time of steepest temp. drop). • Excessive restraint at the slab/base interface. • Inadequate planning or execution of cold weather paving plans.
Hot weather paving conditions caused by high ambient temperatures, high solar radiation, low relative humidity, and high wind speeds.	• Causes excessive drying shrinkage through the slab leading to warping and axial deformations. • The effect of drying shrinkage is similar to that of a negative thermal gradient. Axial deformations cause stress build-up at locations of restraint (e.g., slab/base interface, tie bars). Cracking can be of any orientation depending on variants present.	• Hot concrete temperatures (> 85°F). • Inadequate or late curing. • Late sawing or inadequate sawcut depth. • Excessive restraint at the slab/base interface. • High cement factor concrete without supplementary admixtures. • Shrinkage susceptible PCC mixture. • Certain types of chemical admixtures (e.g., high-range water reducers). • Placing PCC in a way that the maximum heat from hydration occurs during the hottest part of the day. • Placing PCC on a hot base layer. • Inadequate planning or execution of hot weather paving plans.

6.2.1 HIPERPAV II

Developed based on a decade of Federal Highway Administration (FHWA) sponsored research, HIPERPAV is a computer program that can predict the early-age behavior of both Jointed Plain Concrete Pavements (JPCP) and Continuously Reinforced Concrete Pavements (CRCP). HIPERPAV incorporates pavement design, mix design, environmental, and construction factors in predicting the early-age behavior. HIPERPAV uses a series of the models in predicting pavement performance including (Ruiz et al., 2005):

- Concrete heat of hydration.
- Heat transport within concrete.
- Concrete strength and modulus gain.
- Concrete shrinkage.
- Creep relaxation of concrete at an early age.
- Curling and warping stress calculation.
- Slab-base friction.
- Prediction of the critical early-age cracking tensile stresses.

The inputs to HIPERPAV may be divided into the five basic categories: pavement design inputs, material and mix design inputs, climatic inputs, construction inputs, and traffic loading (these are not needed for early-age pavement analysis). Using these inputs, HIPERPAV calculates load and curling stresses using the Bradbury-enhanced Westergaard model. A one-dimensional model is used to calculate restraint stresses imposed by the layer immediately underneath the slab (Ruiz et al., 2005). Critical pavement responses are then computed as a combination of these solutions.

In the early-age analysis module of HIPERPAV (one of three main analysis modules and of primary interest to this study), the main outputs are plots of tensile strength and critical stresses over the first 72 hours of a pavement's life. From these results one can estimate the likelihood of cracking and the most likely time for crack formation. The main limitation of HIPERPAV is that program employs a simplified analytical model for stress calculation; however, this is not considered to be limiting for the purposes of this study.

6.2.2 ISLAB2000

ISLAB2000 (Khazanovich et al., 2000) is an enhanced version of the ILLI-SLAB two-dimensional finite element program developed at the University of Illinois (Tabatabaie, 1977; Tabatabaie et al., 1979; Ioannides, 1985; Korovesis, 1988; Khazanovich, 1994) to perform structural response calculations of concrete pavements using real world jointing, load transfer, and base support conditions. The program has the ability to analyze separation between the pavement layers, model slab/base friction, analyze slabs with mismatched joints/cracking, and handle non-linear temperature gradients. A new version of the ISLAB2000 (to be released) allows coupled tension and bending analysis of plates through the use of a finite element with five degrees of freedom and the Coulomb interlayer friction model—a key improvement in friction modeling. Also, the new version has the ability to model stress concentrations in the slab arising from a partial depth crack. In this study, ISLAB2000 was specially used to determine the impact of base thickness and stiffness on EAD risk.

6.2.3 Theoretical Modeling Approach

The theoretical modeling exercise comprised of the following activities:

- Selection and Preparation of Case Studies—This activity included selecting representative projects for detailed modeling. The criteria for selection included: (1) availability of detailed information required for theoretical analysis, (2) availability of accurate field notes describe the type and exact timing of EAD occurrence, and (3) a broad representation of commonly encountered EAD trigger conditions and variants. As part of this activity several interesting scenarios within projects with and without early cracking obtained during the empirical records review process in chapter 5 were selected to be simulated.
- Evaluation of Selected Case Studies—This activity primarily included modeling EAD risk for the selected projects using HIPERPAV. Modeling consisted of computing the stresses developed during the early life of these pavements (the first 72 hours) and comparing them with the corresponding PCC strength gain. EAD risk was established in this manner and compared with the field observations of distress documented in chapter 5. The goal here was to verify that theoretical analysis can capture real world observations. If successful, the benefit would be to ability to extend the analysis beyond the immediate inference space of the empirical observations.

- Performing Sensitivity Analyses—This activity included performing several “what if” simulations for some of the projects to quantify the EAD risk as function of each of the key variants and their combinations using HIPERPAV and ISLAB2000.

For the selected projects, data for theoretical analysis were obtained from the following sources:

- Pavement design inputs
  - Slab geometry information was obtained from project plans.
  - Slab and base thickness information was obtained from project QC records (as-built thicknesses used).
  - Base modulus was estimated from project QC compressive strength information for LCB, and CTB and approximated for ATB.
  - Modulus of subgrade reaction was estimated from subgrade layer information type and subbase layer information provided in the project plans.
- PCC materials inputs
  - Information regarding chemical admixtures, aggregate type, flyash type, and batch proportions was obtained from approved project mix design submittals.
  - PCC flexural strength was obtained from project QC records.
- Climatic inputs
  - Placement time was estimated from inspector field notes.
  - Hourly temperatures, wind speeds, and relative humidity information for the specific paving day of interest and following two days (as required by HIPERPAV) were obtained from NCDC’s climatic databases. HIPERPAV defaults were used for solar radiation for these days.
- Construction inputs
  - The PCC mix temperature information was obtained from batch tickets where available or from inspector field notes.
  - Initial support layer temperatures were assumed based on the prevalent ambient temperatures at the time of placement.
  - Curing method was obtained from project specifications. The time at which curing was applied was approximated based on the length of each paving run.
  - Sawing information was obtained from interviews conducted with stakeholders and documented in project records.

6.3 CASE STUDIES AND SENSITIVITY ANALYSES

Specific scenarios from the following projects were modeled using HIPERPAV:

- Omaha-Eppley Field Taxiway A extension (1998) and Runway 14L-32R (2001) construction.
- Baton Rouge Metropolitan Airport Runway 14L-22R Reconstruction (2003)—daytime and nighttime paving.
- Missoula International Airport Air Carrier Apron Construction, Phase I (2001) and Phase IV (2002) projects.
- Southern Wisconsin Regional Airport Runway 13-31 and Taxiway B Extension (2003).

Each of these projects contains several unique circumstances of interest to this study. Complete project details are available in chapter 5. Descriptions of the key aspects of the scenarios modeled within each of these projects and the simulation results are documented herein.

6.3.1 Case Study 1: Omaha-Eppley Airfield Taxiway A Extension (1998) and Runway 14L-32R Construction (2001)

This case study demonstrates the impact of panel size, base stiffness, and sawcut timing on EAD risk in the presence of large ambient temperature swings. Early cracking was observed on a portion of the Omaha-Eppley Airfield Taxiway A constructed in 1998. The cracking was attributed to a single climatic trigger event—a large temperature swing. Variants that exceeded their threshold limits on this project were—a high strength and stiffness CTB base, long PCC slab lengths, a high cement factor concrete, and a potentially rough PCC slab/base interface.

In contrast, the Runway 14L-32R project built using the same design as Taxiway A but under milder ambient conditions and with conscientious control over some of the key variants such as panel sizes, base stiffness, and sawcut timing exhibited no EAD. This runway was built over several months; however, only the portion of the project constructed at the same as the Taxiway A portion, which experienced EAD, was chosen for comparison purposes.

<u>HIPERPAV Inputs</u>

Table 35 presents a summary of the key inputs used for theoretical analysis of the selected sections of the Taxiway A and Runway 14L-32R using HIPERPAV. Differences between the two sets of inputs are highlighted in *italicized* text. The ambient conditions at the time of construction of both these projects are shown in figure 50.

<u>Results and Discussion</u>

Figure 51 presents HIPERPAV-computed tensile strength versus tensile stress development for Taxiway A, while figure 52 presents the same information for Runway 14L-32R. The critical stress output in HIPERPAV is the greater of the bottom-up or top-down stress at any given time. If the computed strength is always greater than the stress, the likelihood of EAD occurrence is minimal. However, if stresses exceed strength, the risk of EAD is greater at time of this occurrence.

For both Taxiway A and Runway 14L-32R, that the critical stresses were developed at the top of the slab. This is as expected and is due to the negative thermal gradient applied through the slab thickness due the temperature drop. However, it can be noted from figure 52 that the critical tensile stresses exceed the tensile strength on the 1st, 2nd, and even the 3rd day after PCC placement on Taxiway A. This would therefore suggest an elevated risk for EAD development unless positive steps are taken to mitigate it. By comparison, for the Runway 14L-32R, the risk of EAD is smaller (smaller area bound between the critical strength and critical stress curves) and occurs on the first day of paving as shown in figure 52. However, as the PCC placement time is varied, the risk gets even smaller as shown in figure 53.

Table 35. Summary of HIPERPAV inputs for the Omaha Eppley Field case studies.

Input Category	EAD Project Strategy—Taxiway D	Non-EAD Project Strategy—Runway 14L-32R
PCC thickness	17 in	17 in
Slab dimensions	*25 ft x 25 ft*	*20 x 18.75 ft*
CTB thickness	6 in	6 in
CTB modulus	*2,000,000 lb/in²*	*1,400,000 lb/in²*
Frictional characteristics of the base	*Critical axial restraint stress: 15 lb/in² (HIPERPAV default for CTB)* *Movement at sliding: 0.001 in*	*Critical axial restraint stress: 10 lb/in² (HIPERPAV default for CTB)* *Movement at sliding: 0.01 in*
PCC cement type	IP	IP
Aggregate type	Limestone	Limestone
Mix design information	• Coarse aggregate: 1,515 lb/yd³ • Fine aggregate: 1,492 lb/yd³ • Water: 250 lb/yd³ • Cement: 625 lb/yd³	Same as for EAD project.
PCC 28-day flexural strength	*800 lb/in²*	*828 lb/in²*
Construction date	*10/9/1998 (thermal shock on this day induced cracking)*	*10/1/2002 (comparable ambient conditions but did not have as large of a temperature swing)*
PCC placement time:	*8 AM*	*11 AM*
Initial PCC mix temperature	73°F	75°F
Initial base temperature	68°F	70°F
Curing method	Single coat LMFCC	Single coat LMFCC
Age curing applied	0.5 hr (assumed)	0.5 hr (assumed)
Sawing age	*8 hrs*	*Optimum time (Early Entry)*
Strategy Reliability Level	90 percent	90 percent

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in² = 6.895 kPa 1 lb/yd³ = 0.59 kg/m³ °C = (°F-32)*5/9

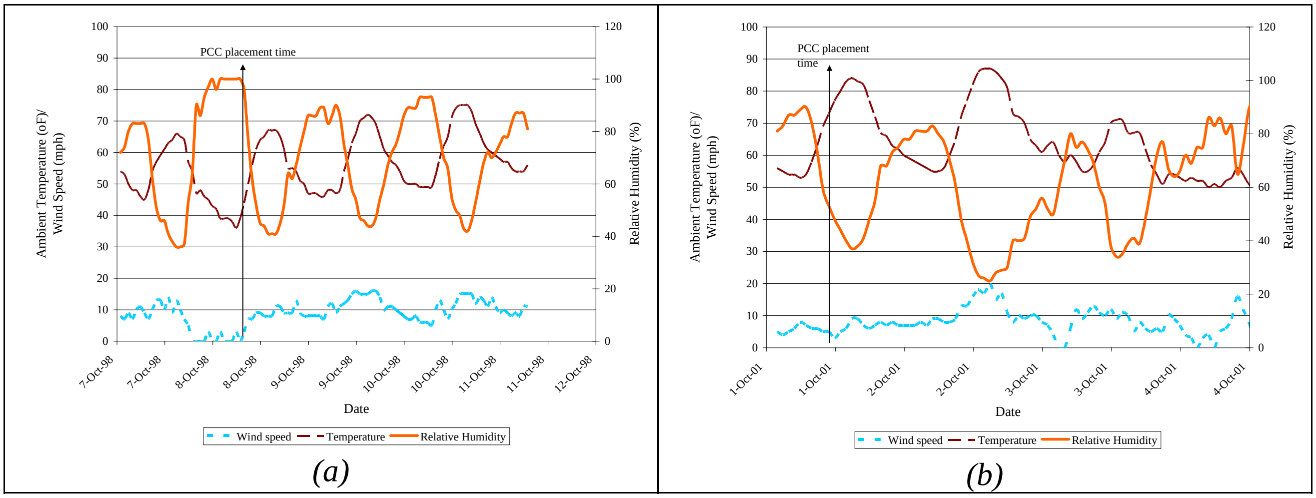


Figure 50. Ambient conditions at the time of paving for the (a) OMA Taxiway A and (b) OMA Runway 14L-32R sections.

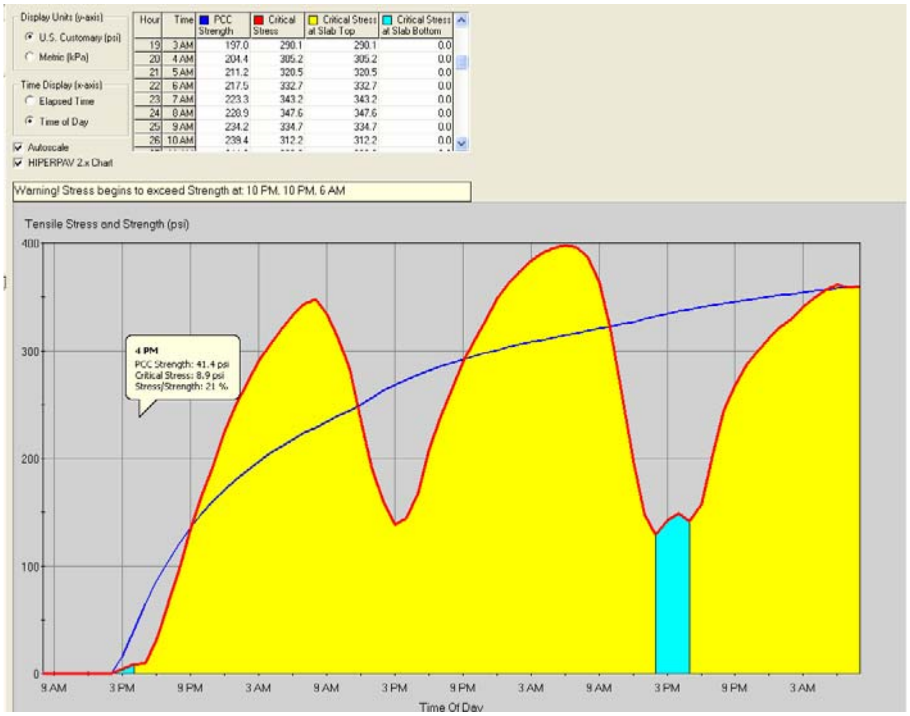


Figure 51. Strength gain versus critical stresses in the young concrete for OMA Taxiway A.

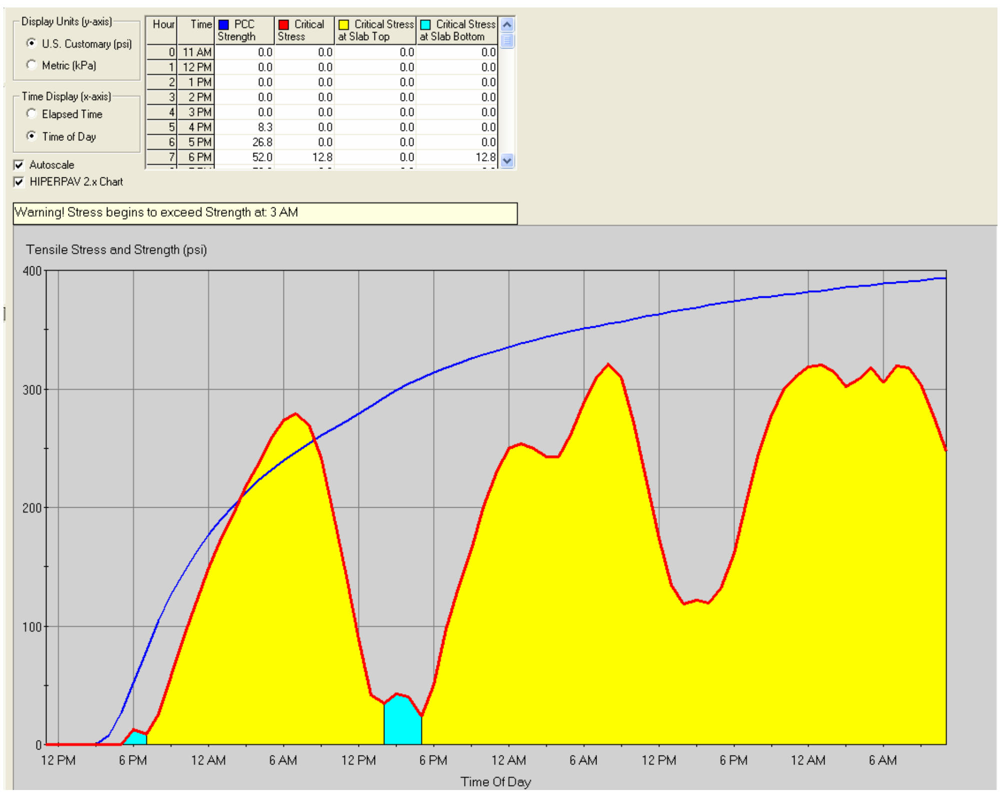


Figure 52. Strength gain versus critical stresses in the concrete layer for the OMA Runway 14L-32R section.

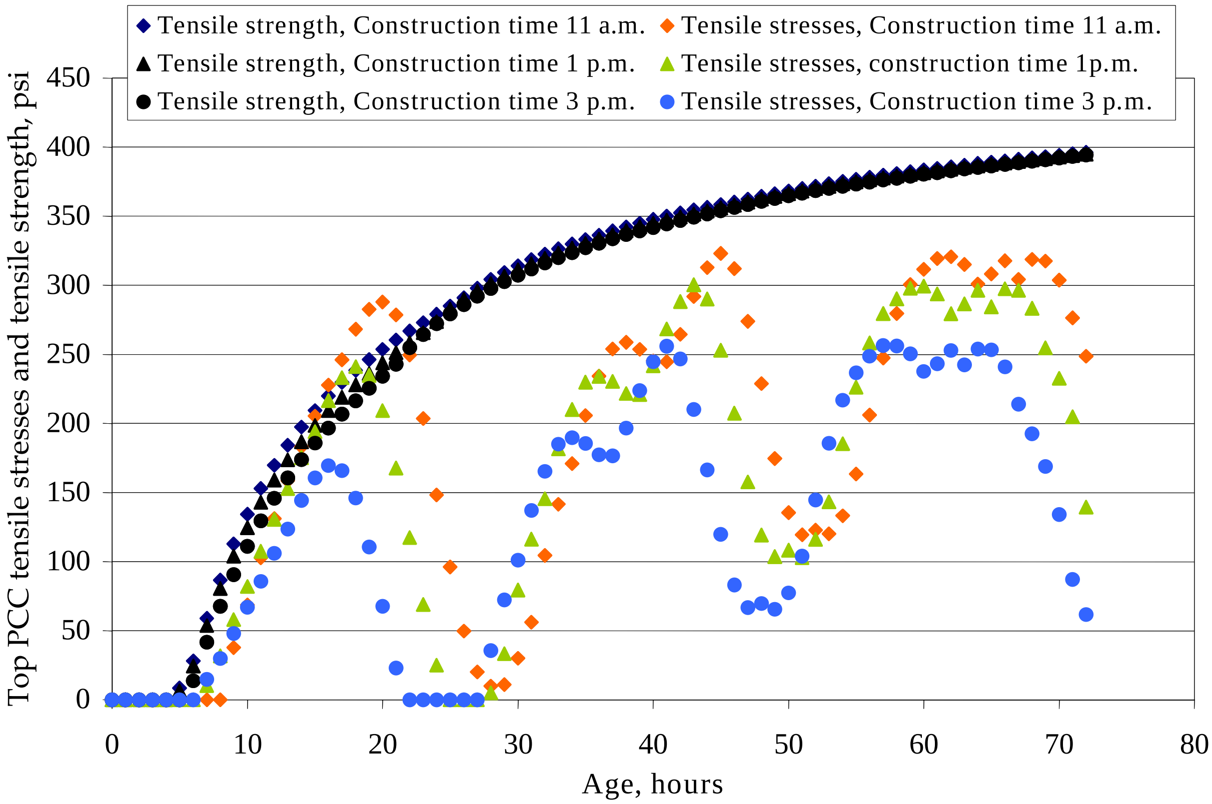


Figure 53. Effect of construction time on tensile stresses at the top of the PCC layer for the Runway 14L-32R section.

These observations regarding EAD risk for the Omaha-Eppley taxiway and runway projects from the analysis above agree with the findings reported in chapter 5. The taxiway project developed cracking and the runway project did not. To reiterate, the EAD risk mitigation on the runway was aided by favorable climatic conditions and ensuring that some of the key variants were below their threshold levels. Other positive steps that can contribute to EAD risk mitigation were identified by performing a sensitivity analysis. The results of this analysis are presented in the following section.

Sensitivity Analysis

The impact of other design, materials, and construction variants (slab size, base stiffness, PCC slab/base interface friction) on EAD potential for this trigger factor (large ambient temperature drop) was evaluated as explained below. The effect of base thickness, important in the consideration of curling stresses, was determined using the ISLAB2000 program. The results are presented later in this chapter.

- Slab size – this parameter was varied at 6 levels to encompass all the possible airfield pavement slab dimensions as noted below.
  - 25 ft by 25 ft (7.625 m by 7.625 m).
  - 20 ft by 20 ft (6.1 m by 6.1 m).

- 15 ft x 15 ft (4.575 m by 4.575 m).
- 12.5 ft x 12.5 ft (3.81 m by 3.81 m).
- 20 ft x 18.75 ft (6.1 m by 5.72 m).
- 20 ft x 12.5 ft (6.1 m by 3.81 m).

- Base type – this parameter was varied to cover the five base types of interest to this study. For ATB, two cases were evaluated—a rough textured surface as in a milled surface and a smooth surface. The inputs required for a base in the HIPERPAV program are the modulus of elasticity, restraint stress, and movement at restraint. These were assumed as follows for the various base types considered:
  - LCB/CTB: Modulus (E) = 2,000,000 lb/in^2 (13,790 kPa); Restraint stress = 15 lb/in^2 (103 kPa); Movement at sliding: 0.001 in (0.025 mm).
  - ATB with rough interface: E = 500,000 lb/in^2 (3,447,500 kPa); Restraint stress = 10 lb/in^2 (69 kPa); Movement at sliding: 0.01 in (0.25 mm).
  - ATB with smooth interface: E = 500,000 lb/in^2 (3,447,500 kPa); Restraint stress = 5 lb/in^2 (35 kPa); Movement at sliding: 0.02 in (0.50 mm).
  - ATPB: E = 75,000 lb/in^2 (517,125 kPa); Restraint stress = 5 lb/in^2 (35 kPa); Movement at sliding = 0.01 in (0.25 mm).
    - Note: For the purposes of this study, and for lack of better information, the ATPB was assumed to have the same frictional restraint stress as a smooth ATB surface and movement at sliding as a rough ATB surface.
  - CTPB: E = 1,000,000 lb/in^2 (6,895,000 kPa); Restraint stress = 15 lb/in^2 (103 kPa); Movement at sliding = 0.01 in (0.25 mm).
    - Note: For the purposes of this study, and for lack of better information, the CTPB was assumed to have the same frictional restraint stress and movement at sliding as a CTB layer.

All other factors including climatic conditions, materials and mix design, foundation inputs, construction time, etc., remained the same as for the Taxiway A project (see table 35) making it the baseline reference for comparison purposes.

Effect of Slab Size

The impact of slab size on the tensile stresses at the top of the PCC layer is shown in figure 54. As expected, the longest slab panels (25 ft [7.625 m]) result is much higher stresses compared to the shortest slab panels (12.5 ft [3.81 m]). It is also observed that the longer slab dimension controls the generated stress level since slabs with a length of 20 ft (6.1 m) but different slab widths (20, 18.75, and 12.5 ft [6.1, 5.72, and 3.81 m]) resulted in similar stress levels.

Effect of Base Type

Figure 55 shows the effect of base type (i.e., combined effect of base stiffness and slab/base interface friction) on top PCC tensile stresses. It is observed that stiffer and rougher bases (CTB/LCB) result in more tensile stress than softer and smoother bases ATB. This is expected because stiff bases increase the curling stresses imposed by a thermal gradient and rough bases increase the tensile stresses developed from axial restraint for a given amount of deformation. Even with a given base type (e.g., ATB), a smoother interface resulted in lower stress generation than a rougher one. However, it appears that the HIPERPAV model is more sensitive to interface friction than to base stiffness as evidenced by the results for the CTPB and CTB and ATPB and ATB (rough) cases.

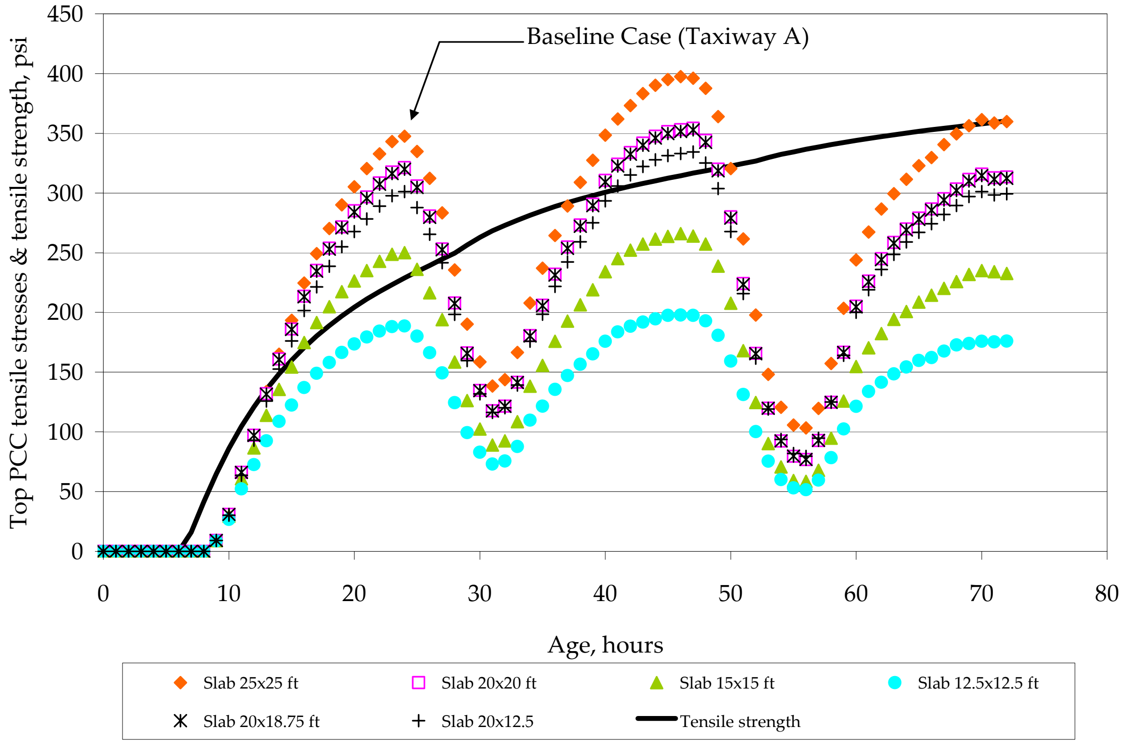


Figure 54. Effect of slab size on the PCC tensile stresses for the Taxiway A section.

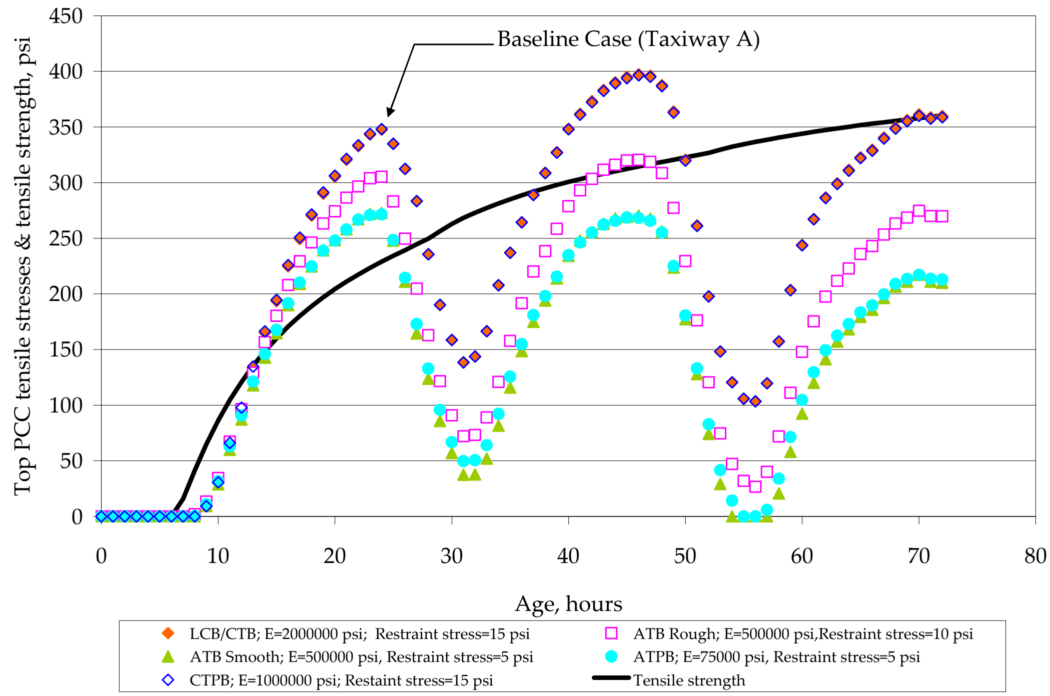


Figure 55. Effect of base type on PCC tensile stresses for the Taxiway A section.

Effect of Slab Size and Base Type Interaction

Based on figures 54 and 55, it can be concluded that by themselves, slab dimensions (within the practical range of airfield pavement construction) or base type cannot control the occurrence of EAD on Taxiway A. Therefore, another analysis showing an interaction of slab size and base type was performed. The results of this analysis are presented in figure 56. Clearly, the combined effect of these variants on reducing EAD risk is greater than the individual effect each variant. This is in line with one of the observations in Chapter 5 which noted that in order to completely minimize the risk of EAD, more than 50 percent of the variants should be have favorable parameter values.

6.3.2 Case Study 2: Baton Rouge Metropolitan Airport Runway 4L-22R Reconstruction (2003)

This case study was illustrates the impact of hot weather paving conditions on EAD. The specific variants that aggravated EAD risk included the use of a shrinkage susceptible PCC mix, presence of a high strength/stiffness base offering a high degree of restraint, inadequate sawcut depth, and shrinkage cracks in the base. An interesting aspect of this project is the observation by the stakeholders that changing PCC placement time from daytime to nighttime, the contractor was able to prevent EAD. The impacts of the variants that relate to this trigger factor are illustrated in this example.

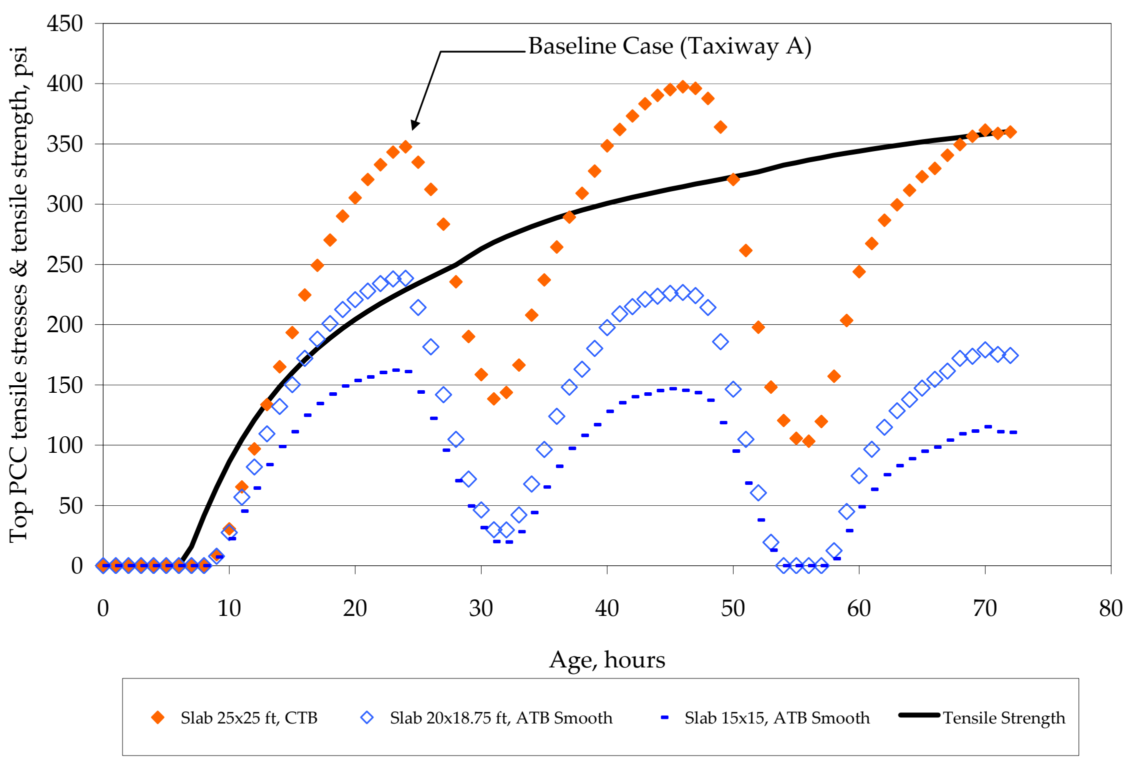


Figure 56. Effect of base type and panel size interaction on PCC tensile stresses for the Taxiway A section.

HIPERPAV Inputs

Table 36 presents the key inputs required for theoretical analysis of selected portions of Runway 4L-22R placed on May 23 and June 2, 2003 using HIPERPAV. The differences between the two sets of inputs are highlighted in *italicized* text. The biggest difference is the time of PCC placement. The ambient conditions at the of PCC placement of these two projects are shown in figure 57. Notice that the temperature regimes and wind speeds for these two projects at PCC placement time are quite similar. The average ambient relative humidities were slightly greater for the night paving project.

Table 36. Summary of HIPERPAV inputs for the Baton Rouge case studies.

Input Category	**Project Runway 4L-22R—Daytime Paving Strategy**	**Project Runway 4L-22R—Nighttime Paving Strategy**
PCC thickness	15 in	15 in
Slab dimensions	20 ft x 18.75 ft	20 ft x 18.75 ft
CTB thickness	6 in	6 in
CTB modulus	2,000,000 lb/in^2	2,000,000 lb/in^2
Frictional characteristics of the base	Critical axial restraint stress: 15 lb/in^2 (HIPERPAV default for CTB) Movement at sliding: 0.001 in	Critical axial restraint stress: 15 lb/in^2 (HIPERPAV default for CTB) Movement at sliding: 0.001 in
PCC cement type	I	I
Aggregate type	Siliceous Gravel	Siliceous Gravel
Mix design information	• Coarse aggregate: 1869 lb/yd^3 • Fine aggregate: 1290 lb/yd^3 • Water: 217 lb/yd^3 • Cement: 439 lb/yd^3 • Flyash (Type F [CaO<7%]): 78 lb/yd^3	• Coarse aggregate: 1869 lb/yd^3 • Fine aggregate: 1290 lb/yd^3 • Water: 217 lb/yd^3 • Cement: 439 lb/yd^3 • Flyash (Type F [CaO<7%]): 78 lb/yd^3
PCC 28-day flexural str.	770 lb/in^2	770 lb/in^2
Construction date	*5/23/2003 (hot weather paving conditions)*	*6/2/2003 (hot weather paving conditions)*
PCC placement time:	*7 AM*	*12 AM (midnight)*
Initial PCC mix temperature	*82°F*	*84°F*
Initial base temperature	75°F	75°F
Curing method	Single coat LMFCC	Single coat LMFCC
Age curing applied	8 hrs	8 hrs
Sawing age	*8 hrs*	

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 °C = (°F-32)*5/9

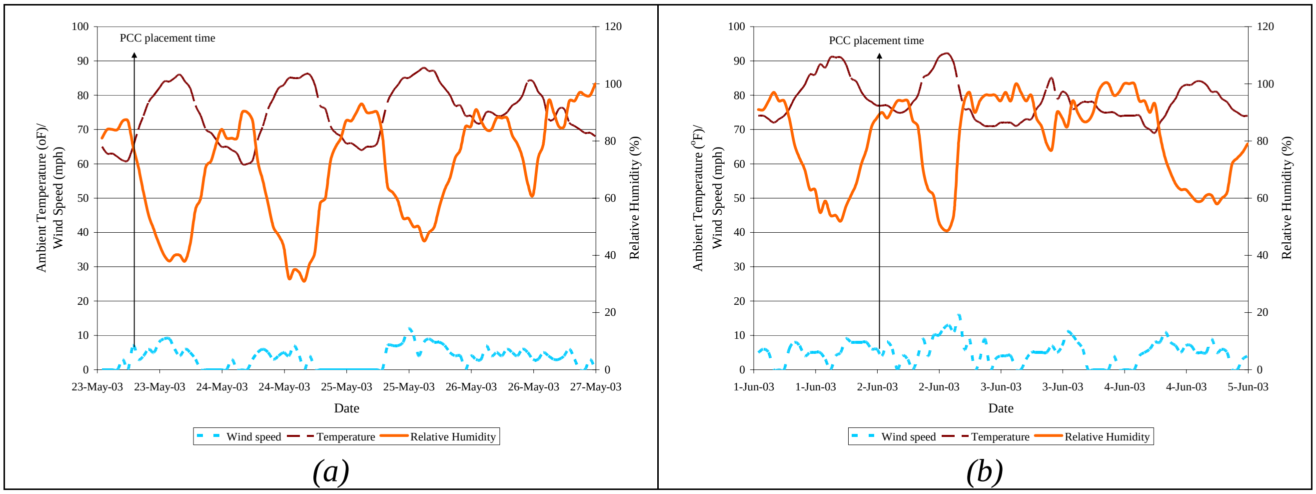


Figure 57. Ambient conditions at the time of paving BTR Runway 4l-22R for (a) daytime and (b) nighttime paving strategies.

Results and Discussion

Figures 58 and 59 present the HIPERPAV computed tensile strength versus tensile stress development for the daytime and nighttime paving strategies, respectively. Clearly, the risk of EAD is higher for the former case which resulted in cracking in the field. This case study therefore demonstrates the importance of proper planning of construction activities to mitigate the EAD risk. In the example discussed, proper planning included shifting PCC placement time from day to nighttime to mitigate the adverse impacts related hot weather paving.

It can also be noted from figures 58 and 59 that in addition to tensile stress development at the top of the slab, more substantial stresses also develop at the bottom of the slab (particularly within the first few hours of placement) for this trigger condition. As explained in table 35, this can be attributed to the bending as well as axial deformations caused by this trigger condition.

<u>Sensitivity Analysis</u>

Recall that in chapter 5, the CTB surface on this project was noted as being milled and was believed to offer excessive restraint at the PCC slab/interface. Also, from table 36, it is noted that the concrete mix temperature at placement was very high. Both these factors increase stresses in the slab and contribute to EAD risk. In the sensitivity analysis undertaken for this project, the impact of using different base types on the responses of the original daytime strategy was evaluated. Further, the effect of lowering the PCC mix temperature, a recommended practice for hot weather paving, was also evaluated.

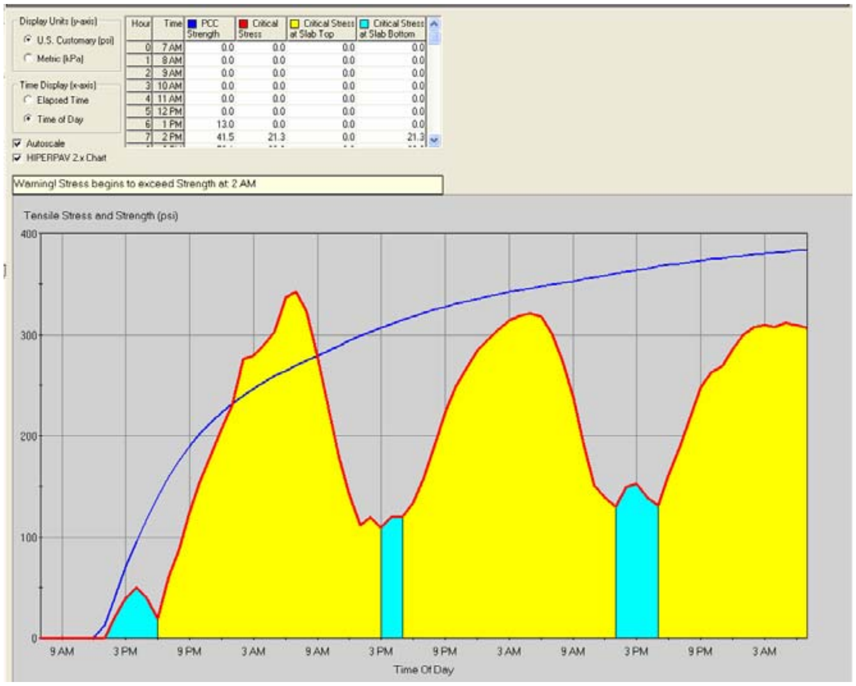


Figure 58. Strength gain versus critical stresses in the concrete layer for the BTR Runway 4L-22R daytime paving strategy.

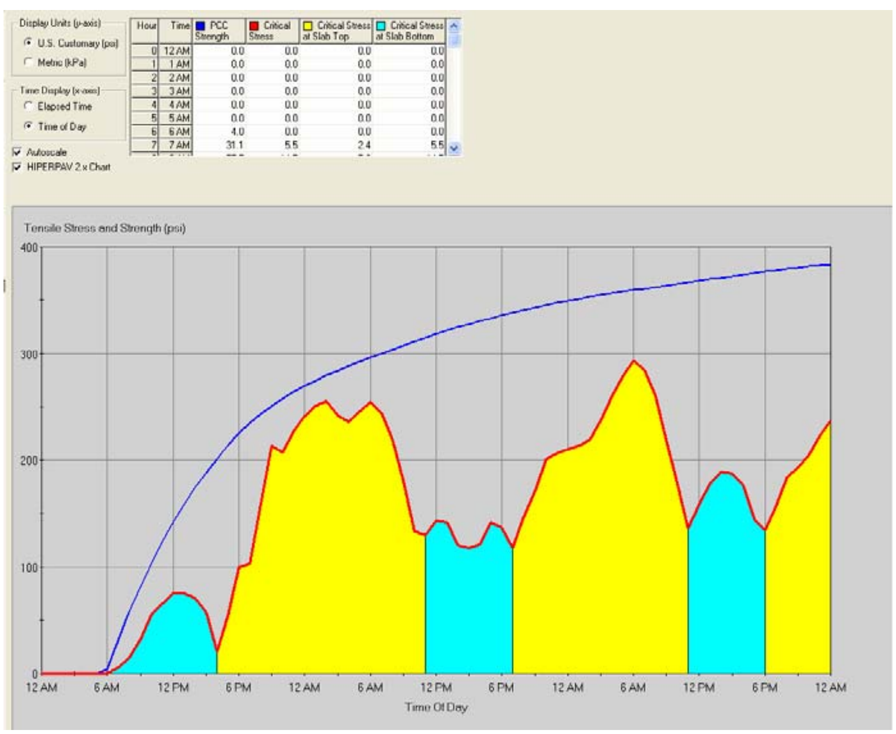


Figure 59. Strength gain versus critical stresses in the concrete layer for the BTR Runway 4L-22R nighttime paving strategy.

The following parameter values were assumed for these two factors in the sensitivity analysis:

- Base type – this parameter was varied to include three additional base types: ATB with a smooth surface, ATB with a rough surface, and ATPB. The base stiffnesses and friction properties were as defined earlier for the Omaha Eppley case study.
- PCC mix temperature—60°F and 70°F (16°C and 21°C).

All other inputs to HIPERPAV remained the same as for the original daytime strategy presented in table 36.

Effect of Base Type

Figure 60 presents the results of the effect of varying the base type on the computed critical tensile stresses. It is readily apparent from the results that using a base type with a lower stiffness and restraint would have mitigated the EAD risk.

Effect of PCC Mix Temperature

Figure 61 presents the results of the effect of decreasing the PCC mix temperature on the computed critical tensile stresses and strength development. Two important observations can be noted from this figure:

- As PCC mix temperature reduces, the tensile strength development slows down owing the reduced heat available for hydration.
- Also, the stresses developed decrease due to lower shrinkage rates and the reduced PCC modulus.

However, it can be noted from the figure 61 that lowering the PCC mix temperatures alone will not be sufficient to eliminate EAD risk. Other hot weather paving precautions including fog spraying the PCC surface or the use of wet cotton or burlap mats to assist in moist curing would be additionally required for this purpose.

Other variants including reducing joint spacing, early entry sawing, deeper sawcuts, etc., as noted in table 34, could have been considered to manage the EAD risk. In light of these findings, the nighttime paving option the contractor chose was perhaps the most economical solution for this situation.

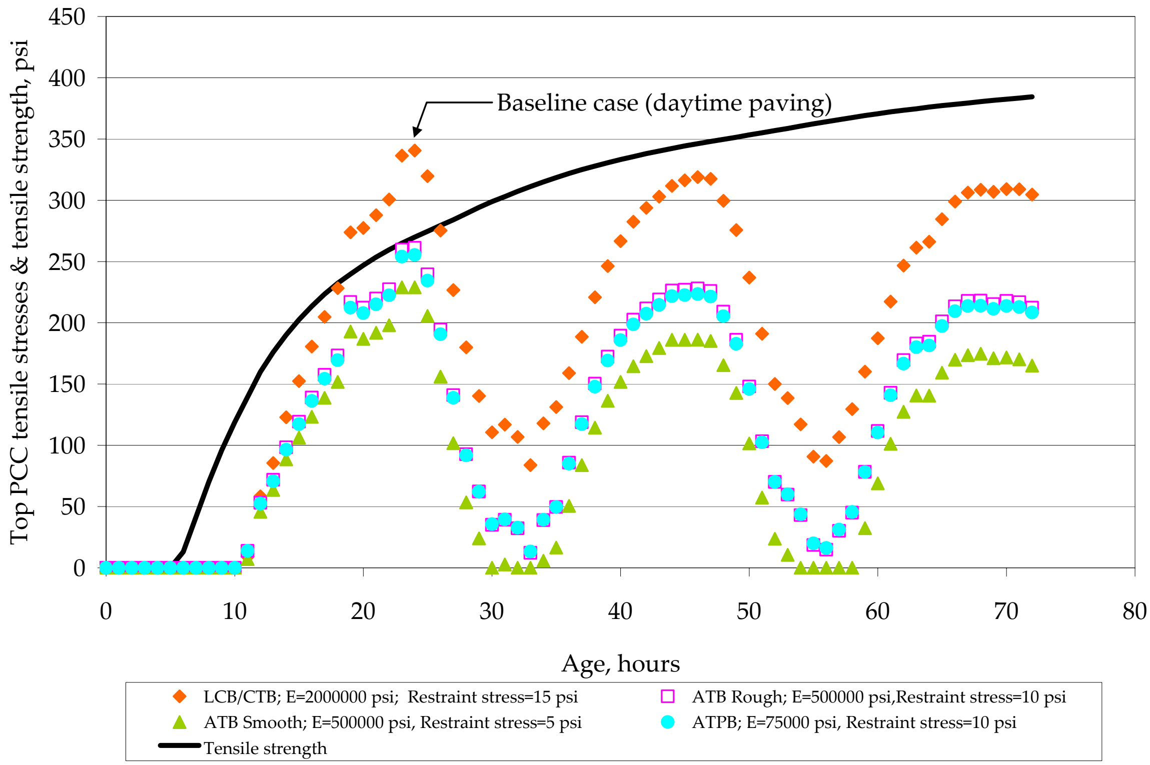


Figure 60. Effect of base type on tensile stress development for the BTR Runway 4L-22R nighttime paving strategy.

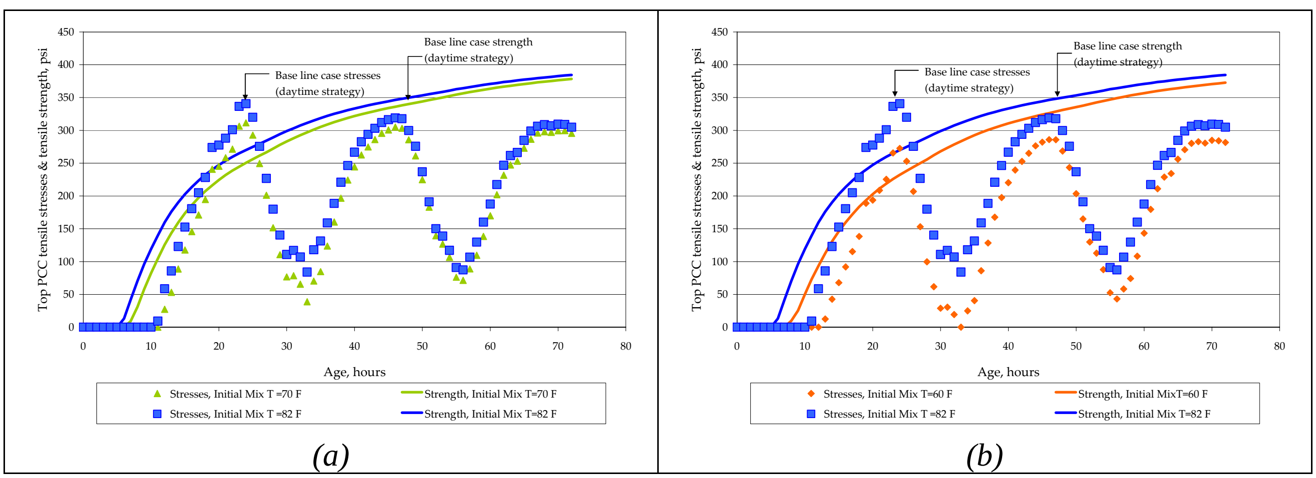


Figure 61. Effect of changing PCC mix temperature on tensile stress and strength development for the BTR Runway 4L-22R daytime paving strategy
(a) PCC mix temperature = 70°F (21°C) and (b) PCC mix temperature = 60°F (16°C).

6.3.3 Case Study 3: Missoula International Airport Air Carrier Apron Construction, Phase I (2001) and Phase V (2002)

This case study demonstrates the impact of anticipating and planning for adverse weather conditions on EAD risk.

As reported in chapter 5, a portion of the Phase I apron constructed in 2001 developed early cracking that was attributed to a single climatic trigger event—a large temperature swing. This trigger factor is similar to the one considered in Case Study 1 but has one important difference—the temperature swing had the characteristic signature of a cold front and was followed by a more prolonged spell of cold weather. This trigger condition therefore not only imposes a large negative thermal gradient through the slab but also retards strength gain. The aggravating variants that contributed to the development of the EAD included presence of a thick and very stiff base (LCB) and late sawing.

In contrast, Phase IV construction of this apron did not experience EAD. Cold weather was also present during this phase of paving. As noted in chapter 5, the adverse impact of the cold weather was countered by having a more responsive construction crew with an effective temperature management plan (including suspending paving during cold snaps, the use of heaters and insulation blankets to protect the pavement, etc.) and a less stiff base. Only the portion of the Phase IV construction project where the ambient temperature regime was comparable to that of the Phase I construction was chosen for evaluation in this case study.

<u>HIPERPAV Inputs</u>

Table 37 presents a summary of the key inputs used to simulate the early-age behavior of selected sections of the Missoula Airport Apron using HIPERPAV. The differences between the two sets of inputs are highlighted in *italicized* text. The ambient conditions at the time of construction of the two strategies presented in the table are shown in figure 62.

<u>Results and Discussion</u>

Figure 63 presents HIPERPAV computed tensile strength versus tensile stress development for the Phase I project, while figure 64 presents the same information for the Phase IV project. It is evident from the figures that the Phase I project has a substantial EAD risk which explains the cracking that appeared on this project soon after construction. The critical stresses occur at the top of the slab suggesting a top-down cracking mode.

From the theoretical analysis (see figure 64), the Phase IV project also shows potential for EAD risk. The risk appears to be greater on the second day after PCC placement. However, no EAD was observed on this project due to the positive actions of the construction crews and inspection staff in anticipating and planning for the cold front to minimize the thermal gradient and ensure adequate curing of the PCC. This prevented the excessive stress build-up in the young concrete slab leading to cracking. Some of the positive measures taken to mitigate the adverse impact of cold weather according to field inspector's notes for this time period included the use of heaters to maintain the PCC surface temperatures at or above 48°F (9°C).

Table 37. Summary of HIPERPAV inputs for the Missoula International Airport Carrier Apron case studies.

Input Category	EAD Project Strategy—Phase I	Non-EAD Project Strategy—Phase IV
PCC thickness	16.5 in	16.5 in
Slab dimensions	20 ft x 20 ft	20 x 20 ft
CTB thickness	6 in	6 in
CTB modulus	*2,000,000 lb/in^2*	*1,800,000 lb/in^2*
Frictional characteristics of the base	*Critical axial restraint stress: 15 lb/in^2 (HIPERPAV default for CTB) Movement at sliding: 0.001 in*	*Critical axial restraint stress: 10 lb/in^2 (HIPERPAV default for CTB) Movement at sliding: 0.01 in*
PCC cement type	I	I
Aggregate type	Limestone	Limestone
Mix design information	• Coarse aggregate: 1,700 lb/yd^3 • Fine aggregate: 1,350 lb/yd^3 • Water: 225 lb/yd^3 • Cement: 500 lb/yd^3 • Fly Ash: 100 lb/yd^3	Same as for EAD project.
PCC 28-day flexural strength	*812 lb/in^2*	*749 lb/in^2*
Construction date	*6/2/2001*	*10/1/2002*
PCC placement time:	*8 AM*	*2 PM*
Initial PCC mix temperature	65°F	65°F
Initial base temperature	60°F	60°F
Curing method	Single coat LMFCC	Single coat LMFCC
Age curing applied	0.5 hr (assumed)	0.5 hr (assumed)
Sawing age	*24 hrs*	*Optimum time (Early Entry)*

1 in = 25.4 mm 1 ft = 0.305 m 1 lb/in^2 = 6.895 kPa 1 lb/yd^3 = 0.59 kg/m^3 °C = (°F-32)*5/9

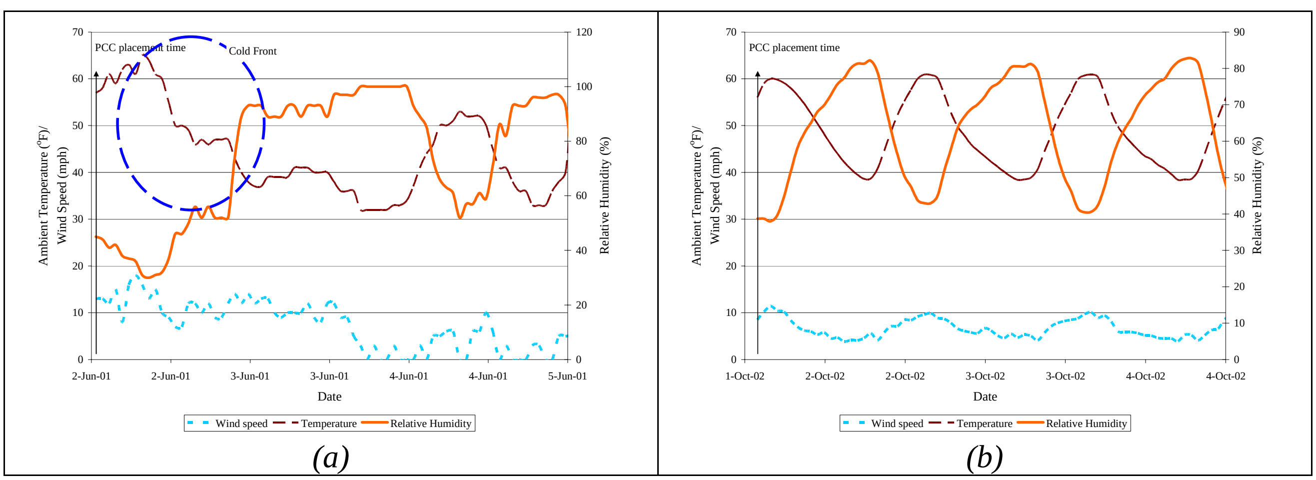


Figure 62. Ambient conditions at the time of paving Missoula International Airport Apron (a) Phase I and (b) Phase IV.

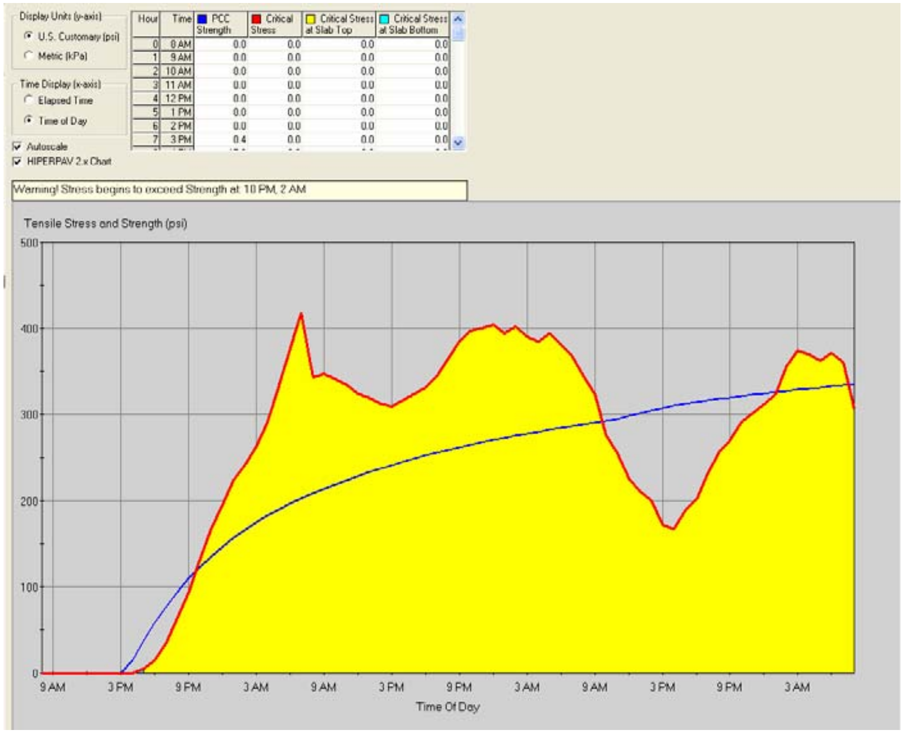


Figure 63. Strength gain versus critical stresses in the concrete layer for the Missoula Air Carrier Apron Phase I strategy.

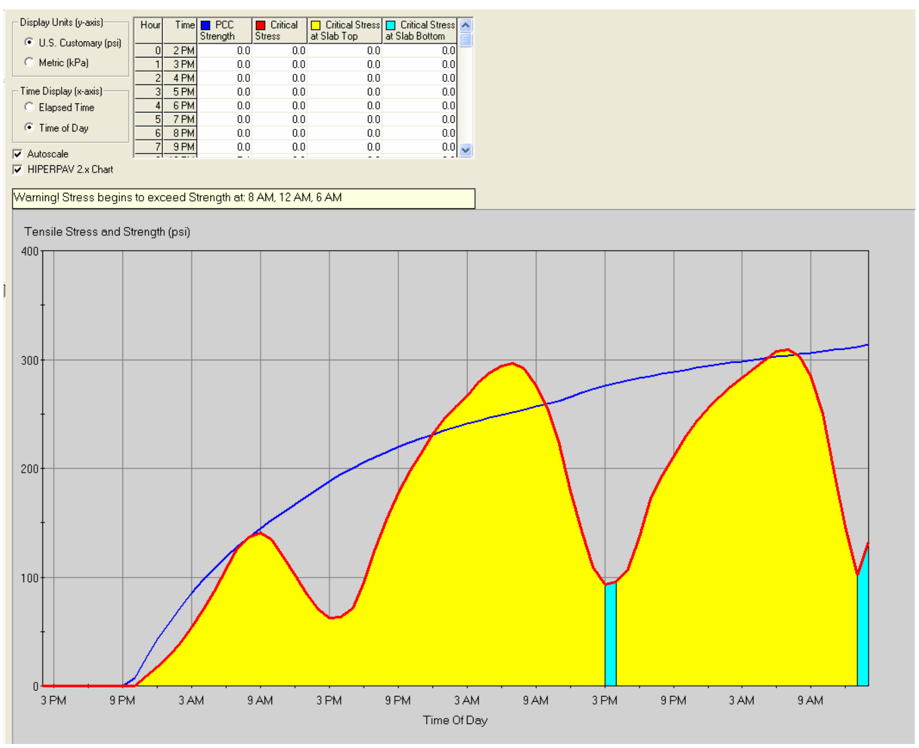


Figure 64. Strength gain versus critical stresses in the concrete layer for the Missoula Air Carrier Apron Phase IV strategy without artificial heating.

Figure 65 presents the results of a reevaluated Phase IV scenario where the ambient low temperatures were modified in HIPERPAV to reflect the actual field conditions after the application of the heaters; all other inputs were kept the same. It shows that the computed tensile stresses were lower than those shown in figure 64, due to the reduced thermal gradients through the slab. The temperature management plan, when taken along with the other positive measures (early sawing and less stiff base) to lower the EAD risk on the Phase IV project, was successful in preventing early cracking problems.

6.3.4 Case Study 4: Southern Wisconsin Regional Airport Runway 13-31 (2002)

The final case study is drawn from the Southern Wisconsin Regional Airport Runway construction project located in Janesville, Wisconsin. As discussed in chapter 5, this project presented a very interesting scenario where a seemingly detrimental combination of trigger conditions and design variants, which had caused cracking in other instances evaluated in this study, did not result in the development of EAD. The trigger conditions for the selected portion of this construction project were somewhat different in nature than the case studies discussed so far. PCC placement occurred under cool temperatures (at or below 40°F [4°C]) after which there was significant temperature increase of nearly 25°F (14°C) followed by a 30°F (15°C) drop in temperature causing severe stress reversals in the young concrete. It was conjectured that perhaps the largest single factor that explains the lack of distress in this case is the presence of a relatively less stiff and less restraining base layer. This hypothesis will be tested in this example.

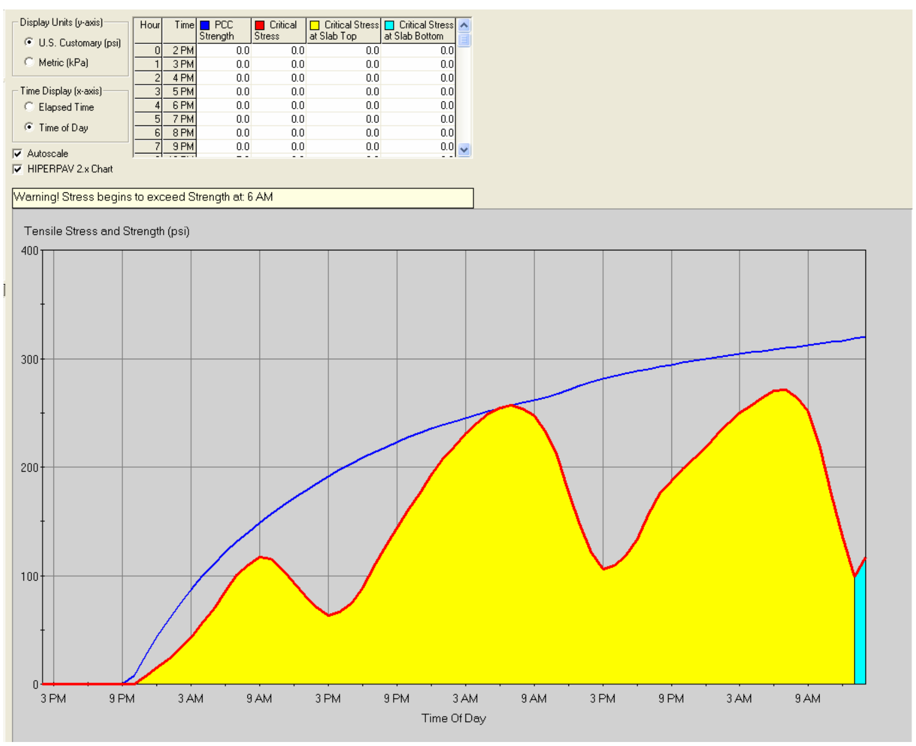


Figure 65. Strength gain versus critical stresses in the concrete layer for the Missoula Air Carrier Apron Phase IV strategy after artificial heating was applied.

HIPERPAV Inputs

Table 38 presents a summary of the key inputs required to perform the theoretical analysis of selected portions of the Runway 13-31 project. The ambient conditions at the time of PCC placement on lane 8 of this runway—the portion of interest—are shown in figure 66.

Results and Discussion

Figure 67 presents HIPERPAV computed tensile strength versus tensile stress development for the runway project evaluated. It is evident from the figure that the critical stresses were below the strength at all times during the first 72 hours. Besides, the magnitudes of stresses were the lowest of all the cases analyzed so far in this study. The strength developed was also lower due to the cool ambient temperatures. The results presented clearly demonstrate that the EAD risk was low on this project and therefore no cracking was observed.

Figure 68 presents the sensitivity of the slab stresses to base type for this scenario. Clearly, the risk of EAD occurrence increases with increase in base stiffness and base restraint. This finding confirms the hypothesis regarding the ability of a smooth asphalt base in mitigating the EAD risk.

Table 38. Summary of HIPERPAV inputs for the Southern Wisconsin Regional Airport Runway 13-31 construction project.

Input Category	EAD Project Strategy—Lane 8 Runway 13-31
PCC thickness	13
Slab dimensions	20 ft x 15 ft
ATB thickness	4 in
ATB modulus	500,000 lb/in^2
Frictional characteristics of the base	Critical axial restraint stress: 5 lb/in^2 (HIPERPAV default for ATB) Movement at sliding: 0.02 in
PCC cement type	I
Aggregate type	Limestone
Mix design information	• Coarse aggregate: 1,991 lb/yd^3 • Fine aggregate: 1,220 lb/yd^3 • Water: 196 lb/yd^3 • Cement: 400 lb/yd^3 • Fly Ash: 110 lb/yd^3
PCC 28-day flexural strength	665 lb/in^2
Construction date	4/21/2003
PCC placement time:	10 AM
Initial PCC mix temperature	56°F
Initial base temperature	56°F
Curing method	Single coat LMFCC
Age curing applied	0.5 hr (assumed)
Sawing age	Optimum time (Early Entry)

1 in = 25.4 mm   1 ft = 0.305 m   1 lb/in^2 = 6.895 kPa   1 lb/yd^3 = 0.59 kg/m^3 °C = (°F-32)*5/9

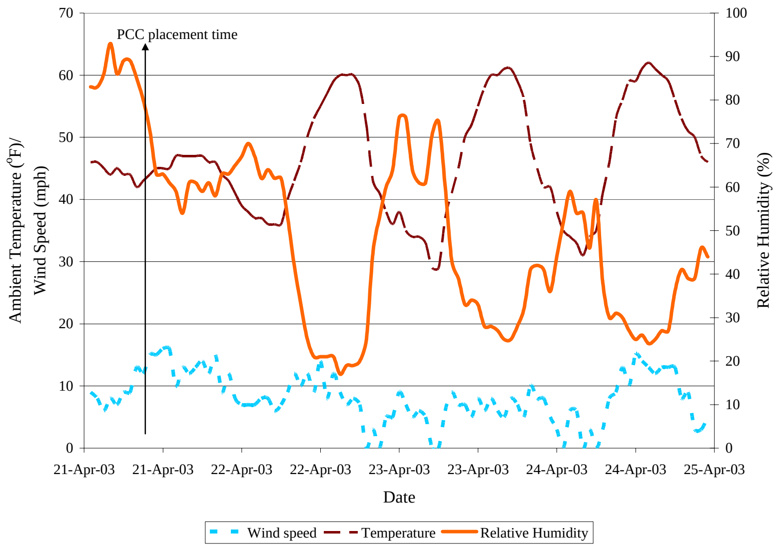


Figure 66. Ambient conditions at the time of paving Southern Wisconsin Regional Airport Runway 13-31.

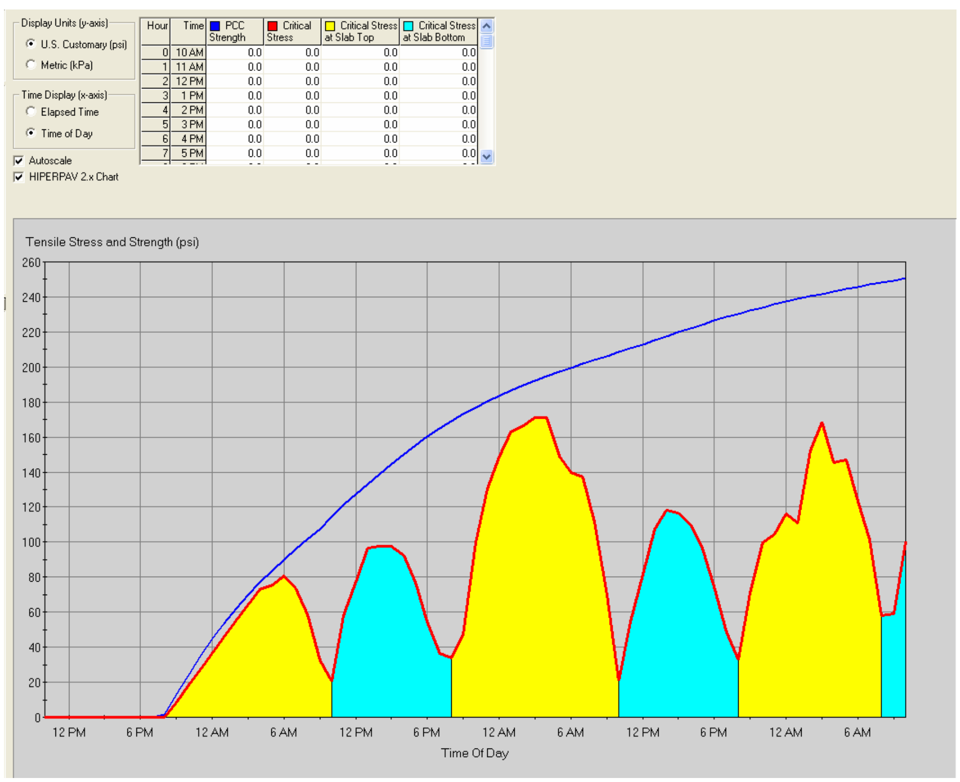


Figure 67. Strength gain versus critical stresses in the concrete layer for the Southern Wisconsin Regional Airport Runway 13-31.

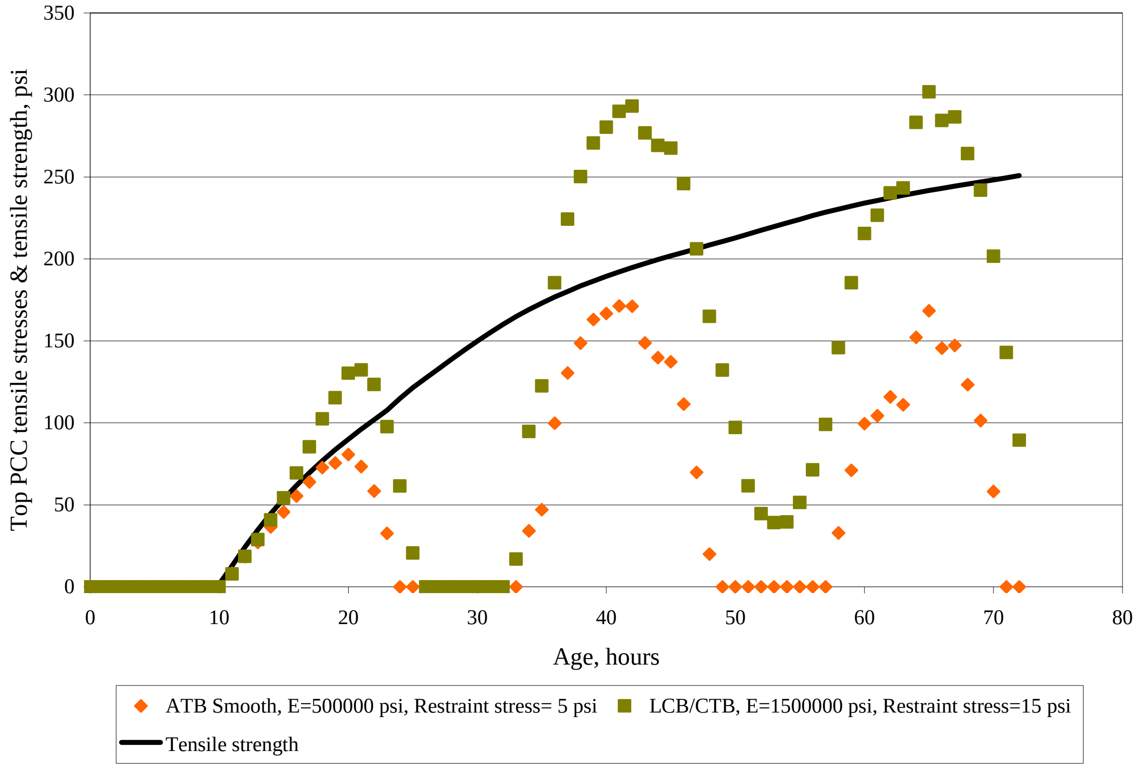


Figure 68. Effect of base type on tensile stress development for the Southern Wisconsin Regional Airport Runway 13-31 paving strategy.

6.4 ISLAB2000 ANALYSIS

This section presents results of theoretical evaluations performed using the ISLAB2000 finite element program to evaluate the interacting effects of key PCC slab and stabilized base parameters on critical slab stresses. The factors evaluated in this analysis include PCC slab sizes, base thicknesses, slab-base friction, and base stiffness. For simplicity, time-based climatic effects modeling and materials modeling was not considered here.

<u>Inputs</u>

The case study of interest for this analysis is the Omaha-Eppley Taxiway A project described in chapter 5 and in section 6.3.1. This project was modeled as a system of six, 17-in (432-mm) PCC slabs over a CTB placed on top of a subgrade with a k-value of 200 lb/in^2/in (54 kPa/mm).

The loading is assumed to be in the form of a nighttime temperature gradient with the PCC surface at 35°F (1°C) and the PCC bottom at 85°F (29°C), simulating a thermal shock soon after PCC placement (the higher bottom temperatures are from the heat of hydration).

The PCC modulus of elasticity, E_{PCC}, was estimated at different ages based on the compressive strength. The compressive strength of the PCC was varied from 70 lb/in^2 (483 kPa) to 4,300 lb/in^2 (29,649 kPa) to simulate aging of the concrete over the first 3 days of its life (from 0 days to up to 72 hours). From the following equation, this results in a PCC modulus range of 0.5 $*10^6$ to $4*10^6$ lb/in^2. ($34.5*10^6$ to $27.6*10^6$ kPa).

$$E_{PCC}= 33\rho^{1.5}(f_c)^{0.5} \qquad \text{Eq. 3}$$

where: ρ = unit weight of PCC slab.
f_c = compressive strength of concrete lb/in^2.

The PCC and CTB CTE were assumed to be $6.0*10^{-6}$ in/in/°F.

Sensitivity Analysis Parameters

The following combinations of slab dimensions, CTB thicknesses, PCC slab/base interface conditions, and CTB modulus were simulated using ISLAB2000 for the basic set of parameters explained above:

- Case 1
  - Slab dimensions – 25 ft by 25 ft (7.625 m by 7.625 m).
  - PCC slab interface bond – Full friction (simulates a very rough base surface)
  - CTB thickness – 4, 6, and 8 in (102, 152, and 203 mm).
  - CTB modulus – 2,000,000 lb/in^2 (13,790,000 kPa).
- Case 2
  - Slab dimensions – 20 ft x 18.75 ft (6.1 m by 5.72 m).
  - PCC slab interface bond – Full friction (simulates a very rough base surface)
  - CTB thickness – 4, 6, and 8 in (102, 152, and 203 mm).
  - CTB modulus – 2,000,000 lb/in^2 (13,790,000 kPa).
- Case 3
  - Slab dimensions – 20 ft x 18.75 ft (6.1 m by 5.72 m).
  - PCC slab interface bond – Full slip (simulates an smooth base surface)
  - CTB thickness – 4, 6, and 8 in (102, 152, and 203 mm).
  - CTB modulus – 2,000,000 lb/in^2 (13,790,000 kPa).
- Case 4
  - Slab dimensions – 20 ft x 18.75 ft (6.1 m by 5.72 m).
  - PCC slab interface bond – Full slip (simulates an smooth base surface)
  - CTB thickness – 4, 6, and 8 in (102, 152, and 203 mm).
  - CTB modulus – 1,000,000 lb/in^2 (6,895,000 kPa).

Results and Discussion

Figures 69 through 71 present comparisons of calculated stresses at PCC top surface (critical location for negative temperature gradient loading) with PCC tensile strength at different ages. Prior to analyzing the results, it should be noted here that direct comparisons between the results presented in this section with those presented in section 6.3 are not encouraged. This is because friction modeling in ISLAB2000 is different from that in HIPERPAV. No attempt was made here to calibrate the responses from these two programs since the primary idea was to draw relative comparisons from the sensitivity analyses conducted with each of them.

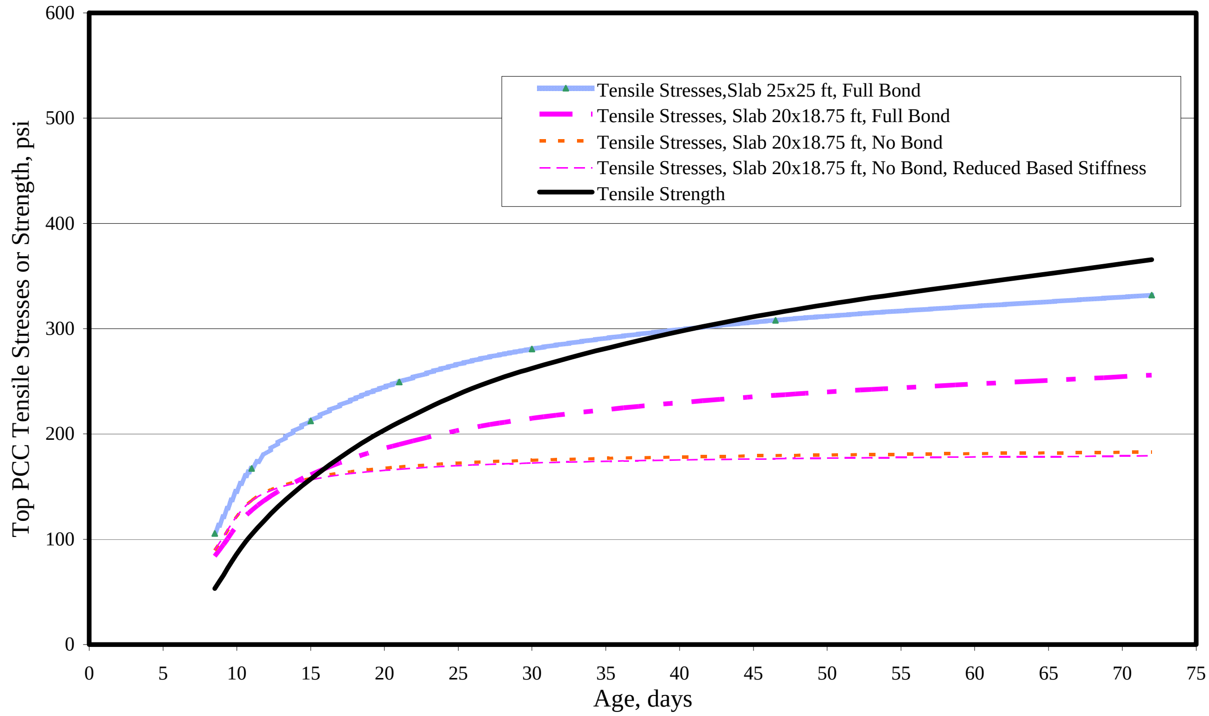


Figure 69. Top stresses and tensile strength versus flexural stresses at Omaha Eppley Airfield, assuming a CTB thickness of 4 in (102 mm).

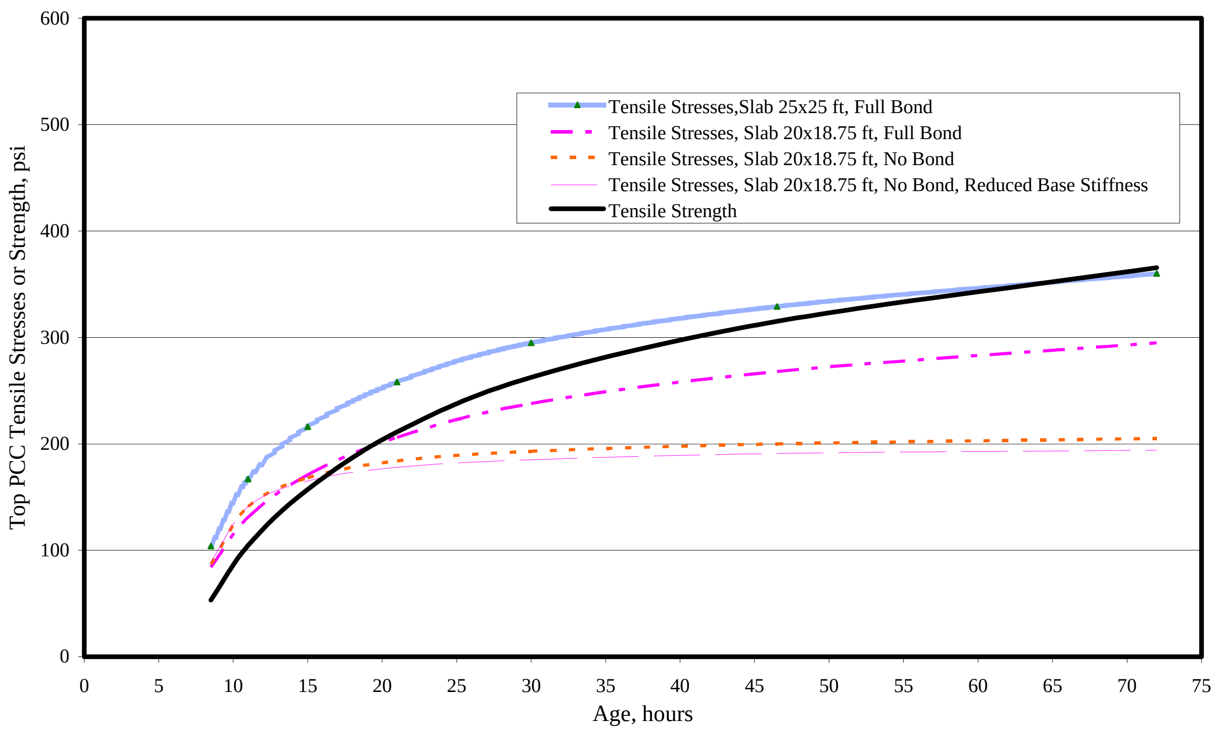


Figure 70. Top stresses and tensile strength versus flexural stresses at Omaha Eppley Airfield, assuming a CTB thickness of 6 in (152 mm).

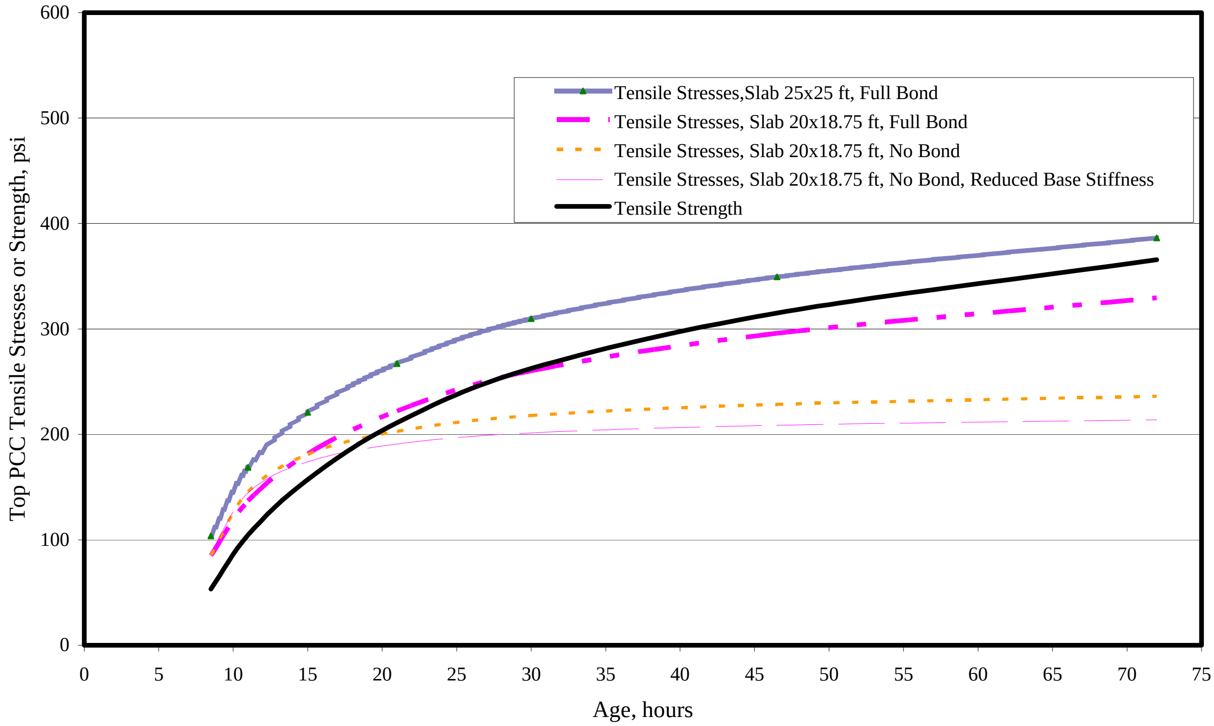


Figure 71. Top stresses and tensile strength versus flexural stresses at Omaha Eppley Airfield, assuming a CTB thickness of 8 in (203 mm).

The following important observations can be made from this multi-parameter interaction analysis regarding the impact of the various parameters on maximum PCC tensile stresses:

- Regardless of the panel size, slab/base interface friction, or base stiffness, a thick CTB layer leads to an increase in the PCC tensile stresses at the top of the slab for the applied negative temperature gradient. This is because thick bases increase the foundation support values and hence the curling stresses in slabs.
- For the case of high restraint (full bond), longer panel sizes lead to higher PCC tensile stresses.
- Impact of base stiffness on PCC tensile stresses is lower for an unbonded condition. Although not shown, the opposite is true when a high friction exists between the slab and base layers.
- Impact of base thickness is greater than base modulus.

6.5 SUMMARY AND CONCLUSIONS

A detailed theoretical analysis of the early-age behavior of PCC pavements placed over stabilized and drainable bases was performed. The analysis considered the combined effect of the two key triggers and key design, materials, and construction variants that influences EAD risk on four selected projects. EAD risk was quantified by comparing computed critical tensile stresses in the PCC slabs with predicted PCC tensile strength during the first 72 hours of the pavement's life. Sensitivity analyses were also conducted to further quantify the EAD risk as a function of key variants. The HIPERPAV and ISLAB2000 programs were used in performing the theoretical analysis.

The results of the analysis demonstrate the following:

- The available analysis tools are flexible, accurate, and are capable of producing results that can be used to assess EAD risk. However, the accuracy of the analysis is dependent on the accuracy of the inputs.
- Theoretical analysis results agree well with field observations of early cracking.
- PCC slab/base interface friction and base stiffness were among the most sensitive variants that affect EAD risk. Stiffer and rougher bases produce higher risk.
- PCC slab size in combination with the base parameters was also found to influence EAD risk substantially.
- Presence or absence of trigger conditions is another key element determining EAD risk. However, it was shown that the adverse effects of these trigger conditions can be mitigated through conscientious construction planning and execution.
- Finally, theoretical analysis tools can be used effectively to quantify the EAD risk that various triggers and variants present for any given scenario. They can also be used to model the effects of measures commonly applied to mitigate these risks.

CHAPTER 7. DEVELOPMENT AND TESTING OF SPECIFICATIONS

7.1 OVERVIEW

As stated in chapter 1, one of the key goals of this study was the development of specifications for the six material types of interest—CTB, econocrete, ATB, UPB, ATPB, and CTPB. Depending on the material, specification development involved either updating existing FAA specifications or preparing totally new ones, as shown below.

<u>Updated FAA Specifications</u>
- Item P-304—CTB.
- Item P-306—Econocrete.
- Item P-403—ATB.

<u>New FAA Specifications</u>
- UPB.
- CTPB.
- ATPB.

7.2 PRELIMINARY SPECIFICATION DEVELOPMENT WORK

Following the completion of the airport project reviews and the empirical and theoretical data analyses, a preliminary set of six specifications was prepared for review and consideration by the project panel. This work was largely guided by the results of the comprehensive data analyses, all kinds of useful information contained in the collected literature (reports, manuals, other agencies' specifications), and various insights provided by pavement practitioners and expert consultants.

While a substantial effort was made in addressing the technical issues within each specification, an equally significant effort was put forth in establishing consistency among the specifications in terms of their arrangement of content, level of detail, use of Engineer's notes, and other items. Each specification was given the following format:

- Description—Description of the subject base material.
- Materials—Presentation of the requirements associated with each material used in the production, placement, and finishing of the subject base material.
- Composition of Mixture—General description of the subject base material and presentation of the base material mix design requirements and certification submittal requirements.
- Equipment—Sequential presentation of the specific types of equipment to be used in producing, placing, and finishing the subject base material.
- Construction Methods—Sequential presentation of the specific construction methods to be used in producing, placing, and finishing the subject base material.

- Material Acceptance—Description of the field sampling and testing procedures to be used for base material acceptance and the corresponding acceptance criteria for each test.
- Method of Measurement—Description of the method of measuring the constructed and accepted quantity of the subject base material.
- Basis of Payment—Description of the basis for payment for furnishing and placement of the subject base material.
- Testing Requirements—List of ASTM or other applicable standards containing established procedures for testing material properties.
- Material Requirements—List of ASTM or other applicable standards containing test criteria for material acceptance.

7.3 CONSTRUCTION DEMONSTRATION

To evaluate the constructability of the stabilized and permeable base materials undergoing specification development, a field demonstration was performed in Columbus, Mississippi in March 2005. The demonstration involved the construction of seven base layer test sections, complete with laboratory mix designs, laboratory and field testing of base material engineering properties, and field examination of base layer response to construction traffic, water, and concrete placement.

Base materials placed in the demonstration included CTPB, UPB with two different gradations, CTB with two different cement contents (5 and 8 percent), and ATPB with two different gradations. Econocrete and ATB test sections were not placed due to the predominance of interest in evaluating the constructability of the other materials.

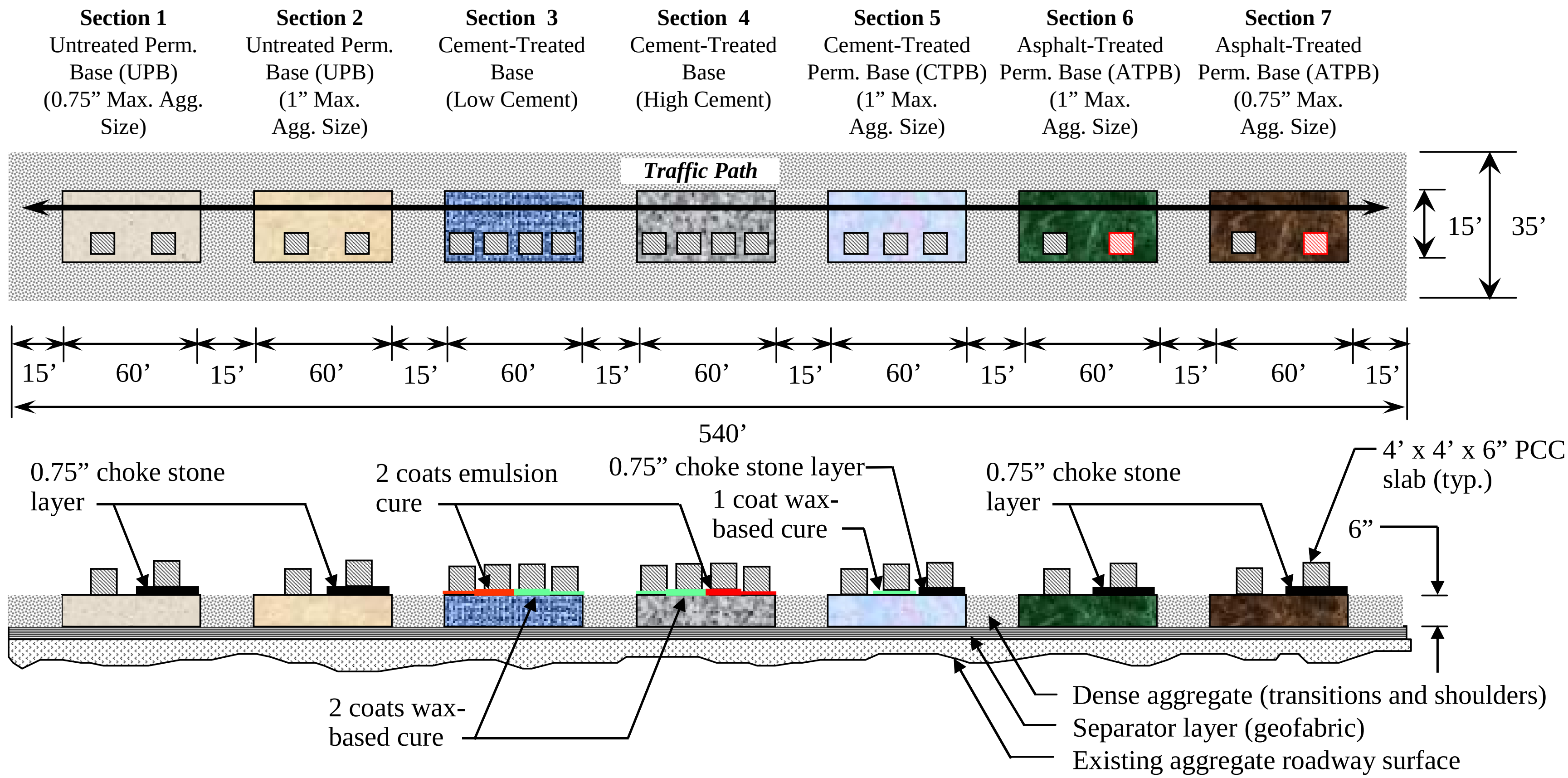
This section discusses in detail the layout, construction, and evaluation/testing of the demonstration base layers, and summarizes the key findings and results of the field investigation.

7.3.1 Test Site Description and Layout

The location of the demonstration test site was at the APAC-Mississippi paving material production facility in Columbus, Mississippi. The site is situated on an unpaved road owned by APAC leading back to abandoned gravel pits. The site is flat and includes a slight horizontal curve at one end. A 15-ft (4.6-m) wide by 300-ft (91.5-m) long strip of geotextile fabric (Beltech 883, AASHTO class I woven) was laid out and pinned down on the existing aggregate road to serve as a separation layer for the base materials.

The final layout (plan and profile views) of the test site is shown in figure 72. With the following exceptions, the test site was constructed as originally specified:

- 1-in (25.4-mm) top-size aggregate gradations were used for the permeable base materials (sections 2, 5, and 6) instead of 1.5-in (38.1-mm), because larger-sized aggregate were not locally available.
- In section 4, the emulsion and wax-based curing compounds were inadvertently placed in opposite order.



Note: In sections 3 and 4, the PCC slabs at the ends were preceded with only 1 coat of curing material (i.e., emulsion, wax-based compound)

Figure 72. Test site layout.

7.3.2 Equipment

Table 39 lists the various pieces of equipment used to produce, haul, place, and compact the test materials.

7.3.3 Construction

Test site construction took place March 14-16, 2005. UPB, CTB, and CTPB test sections were constructed on the first day (Monday, March 14), while the two ATPB test sections were constructed on the second day (Tuesday, March 15). Choke stone layers, bond-breaker materials, and PCC slabs were all placed on the third and final day (Wednesday, March 16). The test sections were constructed in the order shown in figure 72 (section 1, section 2, section 3, etc.). Transitions and shoulders were installed at the end of each day, never exceeding the last test section placed that day.

Table 39. Construction demonstration equipment.

Material	Production/Mixing	Hauling	Placement	Compaction
0.75-in Top-Size UPB	Astec Inc. drum-mix asphalt plant	Tandem and semi-trailer dump trucks	Cedarapids CR461 track-type asphalt paver	DynaPac CC421 static steel-wheel roller (12.5 tons)
1-in Top-Size UPB	Astec Inc. drum-mix asphalt plant	Tandem and semi-trailer dump trucks	Cedarapids CR461 track-type asphalt paver	DynaPac CC421 static steel-wheel roller (12.5 tons)
Low cement CTB	On-site using John Deere 3100 loader/backhoe, John Deere 624G end-loader, and Caterpillar SS250 pulvi-mixer	John Deere 624G end loader	Cedarapids CR461 track-type asphalt paver	Caterpillar 634C vibratory steel-wheel roller (12.9 tons) and Caterpillar PS-150B pneumatic tire roller (5.4 tons)
High cement CTB	On-site using John Deere 3100 loader/backhoe and John Deere 624G end-loader	John Deere 624G end loader	Cedarapids CR461 track-type asphalt paver	Caterpillar 634C vibratory steel-wheel roller (12.9 tons) and Caterpillar PS-150B pneumatic tire roller (5.4 tons)
1-in Top-Size CTPB	Astec Inc. drum-mix asphalt plant	Tandem and semi-trailer dump trucks	Cedarapids CR461 track-type asphalt paver	DynaPac CC421 static steel-wheel roller (12.5 tons)
1-in Top-Size ATPB	Astec Inc. drum-mix asphalt plant	Tandem and semi-trailer dump trucks	Cedarapids CR461 track-type asphalt paver	DynaPac CC421 static steel-wheel roller (12.5 tons)
0.75-in Top-Size ATPB	Astec Inc. drum-mix asphalt plant	Tandem and semi-trailer dump trucks	Cedarapids CR461 track-type asphalt paver	DynaPac CC421 static steel-wheel roller (12.5 tons)
Choke stone	—	Tandem truck	Manual	DynaPac CC421 static steel-wheel roller (12.5 tons)
Emulsion curing compound	—	Asphalt Distributor	Asphalt Distributor	—
Wax-based curing compound	—	—	3-gal manual sprayer	—

1 in = 25.4 mm
1 gal = 3.785 L
1 ton = 0.0.91 metric tons

Weather conditions during the construction demonstration were as follows:

- Day 1, Monday March 14—Partly sunny, cool (45 to 55°F [7 to 13°C] morning, 55 to 65°F [13 to 18°C] afternoon), 5- to 10-mi/hr (8- to 16-km/hr) winds.
- Day 2, Tuesday March 15—Cloudy, cool (48 to 58°F [9 to 14°C] morning, 58 to 64°F [14 to 18°C] afternoon), calm winds, light rain late afternoon.
- Day 3, Wednesday March 16—Cloudy, cold (35 to 45°F [2 to 7°C] morning, 45 to 55°F [7 to 13°C] afternoon), 10- to 15-mi/hr (16- to 24-km/hr) winds.

Details surrounding the construction of each test section are presented below.

<u>Section 1—Unbound Permeable Base (UPB) with 0.75-in (19-mm) Top-Size Aggregate</u>

Aggregate blending began around 9:30 am on Day 1. The crushed limestone materials were blended in the following percentages, by weight:

- No. 57: 29%.
- No. 78: 30%.
- No. 89: 24%.
- No. 8910: 17%

No water was added in the blending process; the stockpile moisture content of 3 percent was utilized.

Approximately 28 tons (25.4 metric tons) of the UPB mixture was transported to the jobsite and loaded into the asphalt paver (figure 75, left) beginning at 11:15 am. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7.5 in (190.5 mm) (figure 73 right). Placement was completed at 11:30 am.

Compaction of the UPB began immediately after its placement. A total of three passes of the static steel-wheel roller were made according to the sequence shown in figure 74. Total roll-down was estimated to be 1.25 in (32 mm). Nuclear density measurements were taken after each roller pass.

Placement of the choke stone layer on half of the test section took place around 8 am on Day 3. The ASTM No. 89 material used as the choke stone was spread manually with rakes and lutes and then compacted with two passes of the static steel-wheel roller to a depth of about 0.75 in (19 mm).

Figure 73. 0.75-in (19-mm) top-size UPB loaded into asphalt paver (left) and then spread and placed in one uniform lift (right).

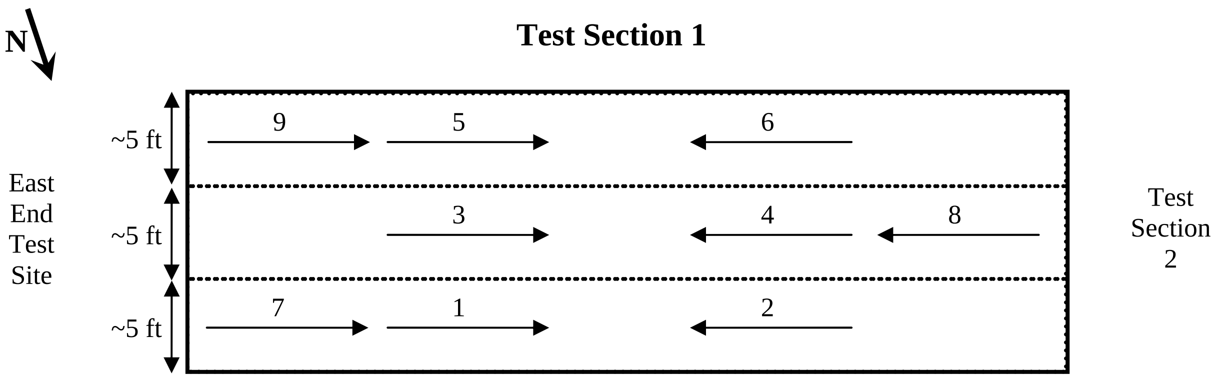


Figure 74. Rolling pattern for 0.75-in (19-mm) top-size UPB.

Between 10:45 and 11:05 am on Day 3, the two PCC slabs were constructed; one on the choke stone area and the other directly on the UPB. The slabs, like all other slabs placed in the test site, were cast using 4-ft by 4-ft (1.2-m by 1.2-m) wooden forms, steel reinforcement, ready-mix concrete with 4-in (102-mm) slump, a spud vibrator, and various strike-off and finishing tools (figure 75).

Section 2—Unbound Permeable Base (UPB) with 1-in (25-mm) Top-Size Aggregate

Aggregate blending began around 11:50 am on Day 1. The crushed limestone materials were blended as follows:

Figure 75. Pouring of concrete slab on 0.75-in (19-mm) top-size UPB (left) followed by insertion of reinforcing steel and concrete consolidation (right).

- No. 57: 33%.
- No. 78: 20%.
- No. 89: 30%.
- No. 8910: 17%.

No water was added in the blending process; the stockpile moisture content of 3 percent was utilized.

Approximately 28 tons (25.4 metric tons) of the UPB mixture was transported to the jobsite and loaded into the asphalt paver beginning at 12:50 pm. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7.25 in (184 mm). Placement was completed at 1:05 pm.

Compaction of the UPB began immediately after its placement. A total of three passes of the static steel-wheel roller were made according to the sequence shown in figure 76. Total roll-down was estimated to be 1.25 in (32 mm). After each roller pass (figure 77, left), nuclear density measurements were taken (figure 77, right).

Placement of the choke stone layer on half of the test section took place around 8:15 am on Day 3. As with test section 1, the choke stone material was spread manually with rakes and lutes and then compacted with two passes of the static steel-wheel roller to a depth of about 0.75 in (19 mm).

The PCC slabs for this test section were placed between 11:00 and 11:20 am on Day 3. As with test section 1, one slab was placed on the choke stone area and the other directly on the UPB.

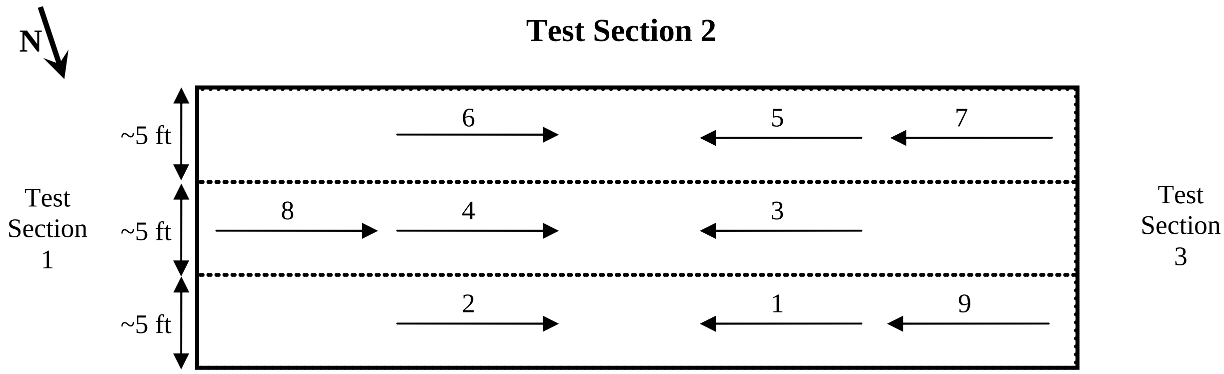


Figure 76. Rolling pattern for 1-in (25-mm) top-size UPB.

Figure 77. Static steel-wheel rolling of 1-in (25-mm) top-size UPB (left) followed by nuclear density testing (right).

Section 3—Cement-Treated Base (CTB) with Low-Cement Content

Aggregate blending began around 12:30 pm on Day 1, with local pit-run materials loaded onto dump trucks in the following percentages, by weight:

- No. 57: 72%.
- No. 78: 14%.
- No. 89: 14%.

No water was added in the blending process, as the stockpile moisture content was deemed sufficiently close to the mix design amount.

Mixing of the blended and moistened aggregate with 5 percent cement (by weight) took place between 1:15 and 2:00 pm on Day 1. The process involved spreading the aggregate and cement into a windrow at the side of the test site, mixing the materials with two passes of the pulvi-mixer, and performing additional mixing in a stockpile format using the loader/backhoe and end-loader (figure 78, left).

The final stockpiled CTB mixture was loaded into the asphalt paver around 2:10 pm using the end-loader. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7 in (figure 78, right). Placement was completed at 2:25 pm.

Compaction of the CTB began immediately after its placement. Three to four passes of the vibratory steel-wheel roller were made according to the sequence shown in figure 79, followed by three passes of the pneumatic roller. Total roll-down was estimated to be 1 in (25 mm). After each roller pass (figure 80, left), nuclear density test measurements were taken (figure 80, right).

Figure 78. On-site mixing of low-cement CTB (left) and placement of material into uniform layer (right).

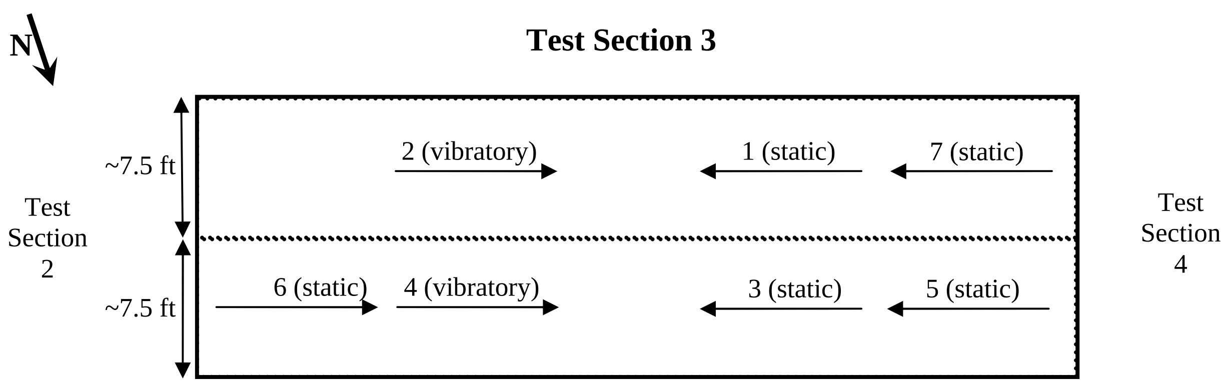


Figure 79. Rolling pattern for low-cement CTB.

Figure 80. Vibratory steel-wheel rolling of low-cement CTB (left) followed by nuclear density testing (right).

Emulsion (SS-1) curing material was sprayed on a 30-ft by 7.5-ft (9.2-m by 2.3-m) portion of the test section at 4:30 pm. A first application from the asphalt distributor truck fully covered the surface. A second, lighter coat was applied immediately thereafter.

Wax-based curing compound (ChemRex Master Cure 200W) was applied full-width (15 ft [4.6 m]) to the other end (30 ft [9.2 m]) of the test section at 4:50 pm. The material was applied at the rate of about 0.045 gal/yd^2 (0.203 L/m^2).

A second coat of the wax-based curing compound was applied around 7:30 am on Day 3. This application, intended to serve as a bond-breaker between the CTB and PCC, covered only half of the area (15 ft by 15 ft [4.6-m by 4.6 m]) treated on Day 1 with wax-based compound.

The PCC slabs for the low-cement CTB test section were placed between 11:10 and 11:35 am on Day 3. A total of four slabs were constructed; two on the emulsion-treated portion of the test section, one on the double-coated wax-based compound area, and one on the single-coated wax-based compound area.

<u>Section 4—Cement-Treated Base (CTB) with High-Cement Content</u>

Aggregate blending began around 1:30 pm on Day 1, with local pit-run materials loaded onto dump trucks in the following percentages, by weight:

- No. 57: 72%.
- No. 78: 14%.
- No. 89: 14%.

No water was added in the blending process, as the stockpile moisture content was deemed sufficiently close to the mix design amount.

Mixing of the blended and moistened aggregate with 8 percent cement (by weight) took place between 2:15 and 3:00 pm on Day 1. Unlike the low-cement CTB placed in section 3, the mixing was done solely in a stockpile format using the loader/backhoe and end-loader. The final stockpiled CTB mixture was loaded into the asphalt paver around 3:05 pm using the end-loader. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7 in (178 mm). Placement was completed at 3:20 pm.

Compaction of the CTB began immediately after its placement. A total of three passes of the vibratory steel-wheel roller were made according to the sequence shown in figure 81. Total roll-down was estimated to be 1 in (25 mm). Nuclear density test measurements were taken after each roller pass.

Emulsion (SS-1) curing material was sprayed on a 30-ft by 7.5-ft (9.2-m by 2.3-m) portion of the test section at 4:40 pm (bottom part of figure 82). A first application from the asphalt distributor truck fully covered the surface. A second, lighter coat was applied immediately thereafter.

Wax-based curing compound (ChemRex Master Cure 200W) was applied full-width (15 ft [4.6 m]) to the other end (30 ft [9.2 m]) of the test section at 4:50 pm (figure 82). The material was applied at the rate of about 0.045 gal/yd^2 (0.203 L/m^2).

A second coat of the wax-based curing compound was applied around 7:45 am on Day 3. This application, intended to serve as a bond-breaker between the CTB and PCC, covered only half of the area (15 ft by 15 ft [4.6 m by 4.6 m]) treated on Day 1 with wax-based compound.

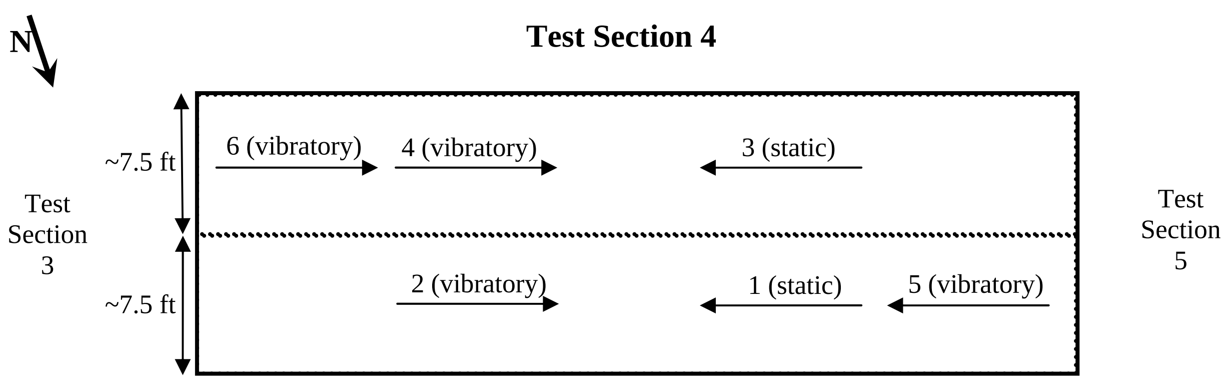


Figure 81. Rolling pattern for high-cement CTB.

Figure 82. Application of wax-based curing compound to high-cement CTB (asphalt emulsion-treated area at bottom).

The PCC slabs for the high-cement CTB test section were placed between 11:25 and 11:45 am on Day 3. As with section 3, a total of four slabs were constructed; two on the emulsion-treated portion of the test section, one on the double-coated wax-based compound area, and one on the single-coated wax-based compound area.

<u>Section 5—Cement-Treated Permeable Base (CTPB) with 1-in (25-mm) Top-Size Aggregate</u>

Aggregate blending began around 3:00 pm on Day 1. The crushed limestone materials were blended in the following percentages, by weight:

- No. 57: 33%.
- No. 78: 20%.
- No. 89: 30%.
- No. 8910: 17%.

The blended aggregate materials were mixed with 6.5 percent cement, by weight, in the asphalt plant. No water was added in the blending process; the stockpile moisture content of 3 percent was utilized.

Approximately 30 tons (27.2 metric tons) of the CTPB mixture was transported to the jobsite and loaded into the asphalt paver beginning at 4:15 pm. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7.25 in (184 mm). Placement was completed at 4:30 pm.

Because it was noticed that the in-place mix had dried some between mixing and placement, water was sprayed on the surface to help reactivate the cement and improve compactability (figure 83). Water application was heavier than desired and was subsequently stopped for concern that the cement paste at the surface was being washed down into the middle and bottom of the CTPB.

Compaction of the CTPB began at 4:40 pm and was completed at 4:55 pm. A total of three to four passes of the static steel-wheel roller were made according to the sequence shown in figure 84. Total roll-down was estimated to be 1.25 in (32 mm). Nuclear density measurements were taken after each roller pass.

Figure 83. Application of water to in-place CTPB.

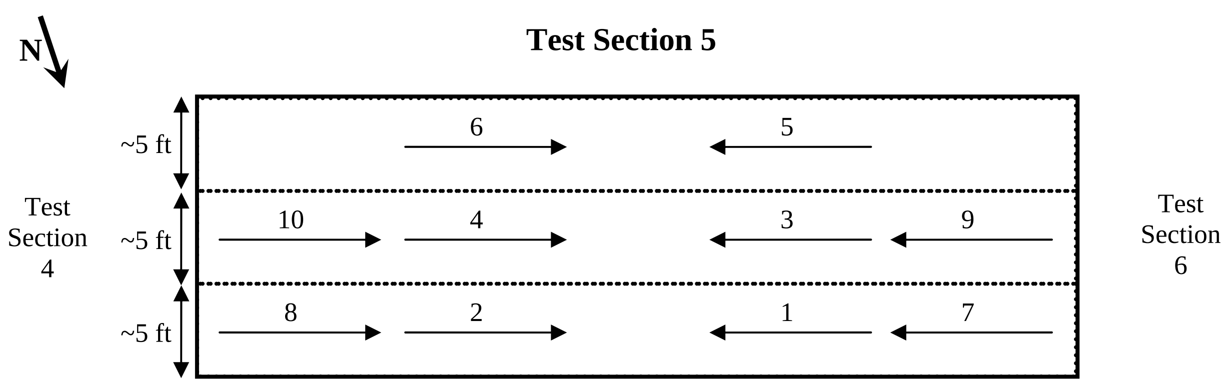


Figure 84. Rolling pattern for 1-in (25-mm) top-size CTPB.

Wax-based curing compound (ChemRex Master Cure 200W) was applied full-width (15 ft [4.6 m]) to the middle third (20 ft [6.1 m]) of the test section at 5:10 pm. The material was applied at the rate of about 0.045 gal/yd^2 (0.203 L/m^2). A second coat of the wax-based curing compound was applied around 7:50 am on Day 3.

Placement of the choke stone layer on the final third of the test section took place around 8:30 am on Day 3 (note: the first one-third of the test section received no curing compound or choke stone). The choke stone material was spread manually with rakes and lutes and then compacted with two passes of the static steel-wheel roller to a depth of about 0.75 in (19 mm).

PCC slab placement for the CTPB occurred between 11:45 am and 12 noon on Day 3. A total of three slabs were constructed; one on the untreated portion of the test section, one on the double-coated wax-based compound area, and one on the choke stone-treated area.

Section 6—Asphalt-Treated Permeable Base (ATPB) with 1-in (25-mm) Top-Size Aggregate

Aggregate blending began around 9:40 am on Day 2. The crushed limestone materials were blended in the following percentages, by weight:

- No. 57: 33%.
- No. 78: 20%.
- No. 89: 30%.
- No. 8910: 17%.

The blended aggregate materials were mixed with 2.7 percent asphalt cement (PG 67-22), by weight, in the asphalt plant.

Approximately 28 tons (25.4 metric tons) of the ATPB mixture was transported to the jobsite and loaded into the asphalt paver beginning at 11:05 am. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7 in (178 mm) (figure 85, left). The temperature of the ATPB mix at laydown was approximately 270°F (132°C) at mid-depth and 230°F (110°C) at the surface. Placement was completed at 11:20 am.

Compaction of the ATPB (figure 85, right) began at 2:25 pm, the time at which the mix temperature had dropped to below 150°F (66°C) (145°F [63°C] mid-depth, 115°F [46°C] surface) as required by the specification. Two to three passes of the static steel-wheel roller were made according to the sequence shown in figure 86. The first full pass was completed by 2:35 pm. Because the mixture tended to push considerably, subsequent rolling was delayed until the mix temperature decreased to more acceptable levels. The second full pass took place between 3:30 and 3:40 pm. Total roll-down was estimated to be 1 in (25 mm). Nuclear density measurements were taken after each roller pass.

Figure 85. Laydown of 1-in (25-mm) ATPB using asphalt paver (left) and compaction using static steel-wheel roller (right).

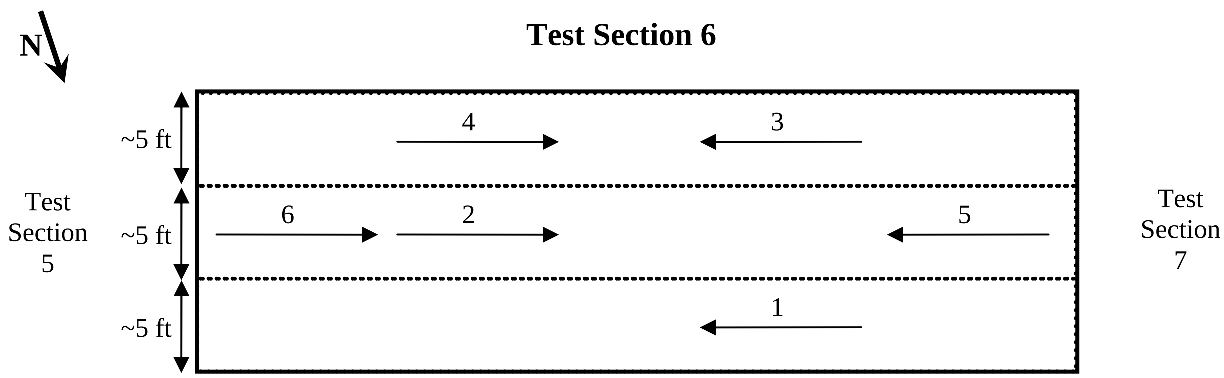


Figure 86. Rolling pattern for 1-in (25-mm) top-size ATPB.

Placement of the choke stone layer on half of the test section took place around 8:40 am on Day 3. As with test sections 1, 2, and 5, the choke stone material was spread manually with rakes and lutes and then compacted with two passes of the static steel-wheel roller to a depth of about 0.75 in.

The PCC slabs for this test section were placed between 12 noon and 12:30 pm on Day 3. One slab was placed on the choke stone-treated area and the other directly on the ATPB.

Section 7—Asphalt-Treated Permeable Base (ATPB) with 0.75-in (19-mm) Top-Size Aggregate

Aggregate blending began around 11:30 am on Day 2. The crushed limestone materials were blended in the following percentages, by weight:

- No. 57: 50%.
- No. 78: 20%.
- No. 89: 30%.

The blended aggregate materials were mixed with 3.0 percent asphalt cement (PG 67-22), by weight, in the asphalt plant.

Approximately 28 tons (25.4 metric tons) of the ATPB mixture was transported to the jobsite and loaded into the asphalt paver beginning at 12:55 pm. The material was spread and placed on the geotextile fabric in one lift to a depth of about 7 in (178 mm). The temperature of the ATPB mix at laydown was approximately 240°F (116°C) at mid-depth and 212°F (100°C) at the surface. Placement was completed at 1:10 pm.

Because of the lower production temperature of the section 7 ATPB material, as compared with the section 6 ATPB, its compaction took place simultaneously with the compaction of the section 6 ATPB (i.e., 2:25 to 2:35 pm for the first full pass, 3:30 to 3:40 pm for the second full pass). A total of two passes of the static steel-wheel roller were made according to the sequence shown in figure 87. Total roll-down was estimated to be 1 in (25 mm). Nuclear density measurements were taken after each roller pass.

Placement of the choke stone layer (figure 88) on half of the test section took place around 8:50 am on Day 3. As with test sections 1, 2, and 5, the choke stone material was spread manually with rakes and lutes and then compacted with two passes of the static steel-wheel roller to a depth of about 0.75 in (19 mm).

The PCC slabs for this test section were placed between 12:20 and 12:45 pm on Day 3. As with section 6, one slab was placed on the choke stone-treated area and the other directly on the ATPB.

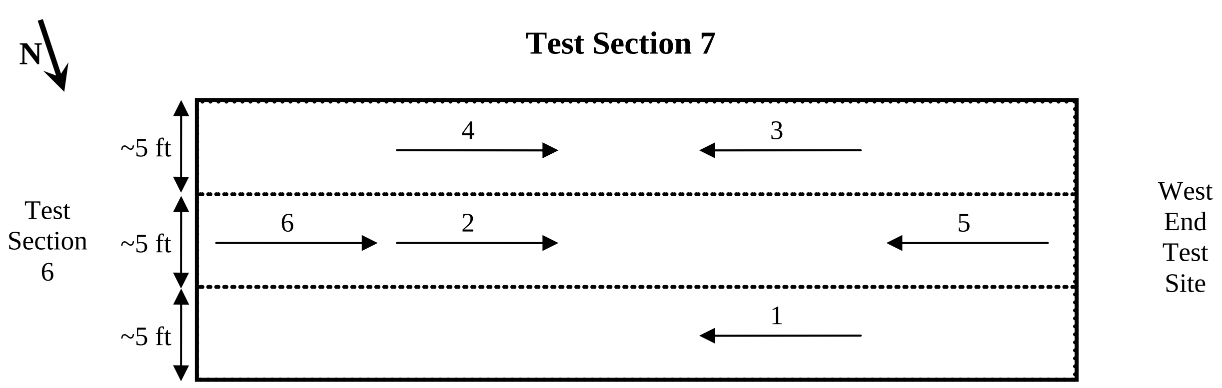


Figure 87. Rolling pattern for 0.75-in top-size ATPB.

Figure 88. Compaction of choke stone layer on 0.75-in (19-mm) top-size ATPB.

7.3.4 Testing and Evaluation Results

Several different base material properties were evaluated as part of the construction demonstration. These included aggregate gradation, mix density, compressive strength, permeability, and stability under construction traffic. Also examined was the potential for bonding and infiltration of PCC, with and without different bond-breaker materials and choke stone. This section presents the material property requirements used in the demonstration and provides the results of tests and visual observations made concerning the various properties.

Aggregate Gradation

Table 40 shows the gradation requirements for each material and presents the gradation test results from field samples. With the exception of a few individual sieve sizes (highlighted values in column 5), each material conformed to the gradation specified.

Density

Table 41 lists the density requirements for each material. It also shows the laboratory-determined maximum dry densities and the field dry densities, as determined using a nuclear density gauge (backscatter method for UPB, CTPB, and ATPB; direct transmission method for CTB). For the CTB materials, density was achieved after just two passes of the roller. Moreover, after two passes, density began to decrease due to the material's tendency to push/shove under the weight of the roller.

Table 40. Aggregate gradation requirements and test results.

Test Section	Mixture Type	Sieve Size	Required Percent Passing	Actual Percent Passing (Field Samples)
1	0.75-in Top-Size UPB	1.0 in	100	100
		0.75 in	95-100	96.0
		0.5 in	73-88	85.2
		0.375 in	58-75	69.7
		No. 4	37-55	**30.2**
		No. 8	5-25	13.2
		No. 16	0-8	7.9
		No. 50	0-5	4.7
2	1-in Top-Size UPB	1.5 in	100	100
		1.0 in	95-100	100
		0.75 in	80-95	95.2
		0.5 in	60-80	81.3
		0.375 in	50-68	66.5
		No. 4	40-55	39.7
		No. 8	5-25	13.8
		No. 16	0-8	8.1
		No. 50	0-5	4.5
3 & 4	Low- & High-Cement CTB	2.0 in	100	100
		No. 4	45-100	73.6
		No. 10	37-80	70.2
		No. 40	15-50	**61.0**
		No. 80	0-25	**35.0**
5	1-in Top-Size CTPB	1.5 in	100	100
		1.0 in	95-100	99.2
		0.75 in	77-87	89.9
		0.5 in	53-63	54.7
		0.375 in	41-51	**30.2**
		No. 4	15-25	**5.9**
		No. 8	0-6	2.7
6	1-in Top-Size ATPB	1.5 in	100	100
		1.0 in	95-100	97.4
		0.75 in	77-87	87.5
		0.5 in	53-63	57.8
		0.375 in	41-51	42.0
		No. 4	15-25	13.3
		No. 8	0-6	4.9
7	0.75-in Top-Size ATPB	1.0 in	100	100
		0.75 in	95-100	**89.3**
		0.5 in	67-77	72.3
		0.375 in	50-60	59.8
		No. 4	19-29	20.3
		No. 8	0-6	5.7

1 in = 25.4 mm

Table 41. Density requirements and test results.

Test Section	Mixture Type	Density Requirement	Max. Dry Density (Lab)	Field Density (Nuclear Gauge)
1	0.75-in Top-Size UPB	None (minimum 2 roller passes; continue rolling until aggregate is seated with no crushing)	NA	1 static pass 109.0 lb/ft^3 2 static passes 112.3 lb/ft^3 3 static passes 114.3 lb/ft^3
2	1-in Top-Size UPB	None (minimum 2 roller passes; continue rolling until aggregate is seated with no crushing)	NA	1 static pass 108.0 lb/ft^3 2 static passes 111.0 lb/ft^3 3 static passes 114.8 lb/ft^3
3	Low-Cement CTB	98% of maximum theoretical density determined in lab	119.9 lb/ft^3	1 vibratory & 1 static pass 118.6 lb/ft^3 (98.9%) 13.9% moisture 1 vibratory & 2 static passes 117.1 lb/ft^3 (97.7%) 14.3% moisture
4	High-Cement CTB	98% of maximum theoretical density determined in lab	121.7 lb/ft^3	1 vibratory pass 115.6 lb/ft^3 (95.0%) 13.3% moisture 2 vibratory passes 119.9 lb/ft^3 (98.5%) 12.9% moisture
5	1-in Top-Size CTPB	None (minimum 2 roller passes; continue rolling until aggregate is seated with no crushing)	NA	2 static passes 120.2 lb/ft^3 4 static passes 124.8 lb/ft^3
6	1-in Top-Size ATPB	None (minimum 2 roller passes; continue rolling until aggregate is seated with no crushing)	NA	1 static pass 103.0 lb/ft^3 3 static passes [a] 105.1 lb/ft^3
7	0.75-in Top-Size ATPB	None (minimum 2 roller passes; continue rolling until aggregate is seated with no crushing)	NA	1 static pass 102.9 lb/ft^3 3 static passes 106.5 lb/ft^3

[a] Lab density of a core taken from field: 106.6 lb/ft^3
1 in = 25.4 mm
1 lb/ft^3 = 15.95 kg/m^3

Permeability

Permeability requirements for the three permeable base types (UPB, CTPB, and ATPB) were as follows:

- Laboratory (ASTM D 2434 constant head test)—Between 500 and 1,500 ft/day (152.5 and 457.5 m/day).
- Field (gallon of water test)—Base should allow 1 gal (3.785 L) of water to pass through it within 1 minute.

Laboratory permeability tests conducted on CTPB and ATPB cores taken from the field gave the following results:

- CTPB with 1-in (25-mm) top-size aggregate: 63 ft/day (19.2 m/day).
- ATPB with 1-in (25-mm) top-size aggregate: 1,800 ft/day (549.0 m/day).
- ATPB with 0.75-in (19-mm) top-size aggregate: 1,300 ft/day (396.5 m/day).

The low permeability value for CTPB is believed to be the result of the heavier-than-desired application of water to the CTPB surface immediately following placement. As mentioned previously, the cement paste at the surface was partially washed down into the middle and bottom of the CTPB layer, which likely filled voids and adversely impacted permeability.

Field permeability tests on all five permeable base test sections showed highly drainable materials. Water poured onto the surface of each base drained immediately through the base without any ponding.

Compressive Strength

The 7-day compressive strength requirement for CTB was 500 to 1,000 lb/in^2 (3,447.5 to 6,895 kPa). Seven- and 14-day tests on moist-cured laboratory specimens yielded the following results:

<u>7-Day</u>

- Low-cement CTB: 135 lb/in^2 (930.8 kPa)
- High-cement CTB: 405 lb/in^2 (2,792.5 kPa).

<u>14-Day</u>

- Low-cement CTB: 175 lb/in^2 (1,206.6 kPa)
- High-cement CTB: 520 lb/in^2 (3,585.4 kPa).

Twenty-eight-day compressive strength tests performed on cores extracted from the field gave the following results:

- Low-cement CTB: 590 lb/in^2 (4,068.1 kPa)
- High-cement CTB (emulsion cure): 665 lb/in^2 (4,585.2 kPa).
- High-cement CTB (light wax cure): 1,200 lb/in^2 (8,274.0 kPa).

- High-cement CTB (heavy wax cure): 1,010 lb/in^2 (6,964.0 kPa).

Stability

To test each base material's ability to withstand the effects of construction traffic, three different pieces of construction equipment were operated across the seven test sections following their completion. The first piece of equipment, the track-type asphalt paver used to place the various base materials, was driven across the test sections on Day 3 of the demonstration. With the exception of some slight scuffing of the UPB materials under turning movements by the paver, all of the sections held up well under the paver.

Application of a fully loaded (with sand) semi-trailer dump truck on Day 3 produced only slight deformations in the CTB, CTPB, and ATPB materials. However, similar application in the UPB sections created 1-in (25-mm) deep ruts (figure 89) in both the choke-stone and non-choke-stone areas. Such rutting in a real construction scenario would not be acceptable.

Figure 89. Rutting in 1-in (25-mm) top-size UPB produced by loaded dump truck.

Finally, application of an end-loader a week after construction resulted in only minor scuffing of the UPB material under turning movements.

Bonding to PCC and Cement Infiltration

A week after placing 4-ft by 4-ft (1.2-m by 1.2-m) concrete slabs on the various base layers, the slabs were pulled off using an end loader and chain. Cement infiltration into the CTB was minimal, whereas penetration into the permeable bases (and choke stone) varied from 0.5 to 1 in (12.7 and 25.4 mm).

The degree of bonding between PCC and bound/treated base types (CTB, CTPB, and ATPB) was mostly affected by the presence of choke stone. Where choke stone was used on top of CTPB or ATPB, no bonding occurred (figure 90). However, where PCC was placed directly on the CTPB or ATPB, the entire thickness of the base layer was pulled up with the PCC slab (figure 91), signifying a strong bond between the two materials.

For CTB, the use of emulsion and wax-based curing compound as bond-breakers had no to little affect. With the exception of the double application of wax-based curing compound, which gave debonding for a small portion of the PCC–base interface, the entire thickness of CTB was pulled up with the PCC slab.

Figure 90. Slab pull-off from ATPB with choke stone.

Figure 91. Slab pull-off from ATPB without choke stone (left) and CTPB without choke stone (right).

7.3.5 Summary of Key Findings

The following list summarizes the key findings of the construction demonstration:

- Placement—Successful laydown achieved with all four materials (UPB, CTB, CTPB, and ATPB) using conventional asphalt paver.
- Compaction—Sufficient density of ATPB and CTPB materials achieved with two to three passes of 12-ton (10.9-metric ton) static steel-wheel roller. Sufficient density of CTB materials achieved with two to three combined passes of 12-ton (10.9-metric ton) vibratory and static steel wheel rollers.
- Stability under construction traffic—Both the 0.75-in (19-mm) and 1-in (25-mm) top-size UPB materials exhibited problems, raising concern as to the acceptability of UPB for use under rigid airfield pavements. CTB, CTPB, and ATPB materials all held up well under heavy loads and turning movements.
- Base permeability—UPB, ATPB, and CTPB materials were all quite drainable in the field. Low laboratory permeability values for field-extracted CTPB cores were the result of cement paste inadvertently washed down from the surface.
- Bond-breaking—Choke stone layer provided the best means of breaking the bond between PCC and bound/treated base. Single and double applications of wax-based curing compound and asphalt emulsion were largely ineffective as bond-breakers.
- Strength—CTB with lower cement content yielded very low early-age strength.

7.4 FINAL MODIFICATIONS TO SPECIFICATIONS

Based on the key observations and findings from the construction demonstration and following a detailed review and discussion of the preliminary specifications by the project panel and the research team, final modifications were made to the CTB (P-304), Econocrete (P-306), ATPB, and CTPB specifications. Appendixes A through D contain the final recommended specifications.

Two minor changes were proposed to the draft P-403 specification for ATB. These changes pertained to (a) the need for whitewashing the ATB immediately prior to concrete paving if excessively high surface temperatures are encountered and (b) the need for a smooth ATB surface texture when placed under concrete pavement.

No changes were made to the UPB specification, as this material was deemed unsuitable for use as a base type under rigid airfield pavements.

CHAPTER 8. SUMMARY OF FINDINGS

There is adequate empirical evidence available to prove that the phenomenon of premature cracking of concrete airfield pavements is real. Several factors, including the pavement base, affect the early-age performance of the concrete. Some safeguards can be built into pavement design, materials selection, and construction to prevent uncontrolled cracking by addressing issues of base thickness and strength. However, an approach to resolving the premature cracking problems involves much more than simply specifying base thickness and strength.

The research reported herein has studied the issues related to the design and construction of stabilized and permeable bases under concrete airfield pavements and the factors that contribute to EAD. The research findings should help designers and constructors in future design and construction projects. Products from the reported research, in addition to this report, include a Design Guide and five specifications for stabilized and permeable bases.

The important findings from each significant phase of the research are provided below.

8.1 LITERATURE REVIEW

A thorough review of published information, as described in chapter 2, produced the following findings:

- There is broad consensus among airfield pavement engineers that a uniform and durable base is essential for ensuring long-term performance of a rigid pavement.

- Stiff base layers, such as CTB and econocrete, add to the flexural stiffness of rigid pavement structures and help transmit loads across discontinuities (joints and cracks) in the pavement slabs. However, they also increase the stresses due to curling and warping in the pavement slabs leading to (1) premature cracking if adequate strength is not developed early in the pavement's life, and (2) fatigue cracking over the pavement's life.

- An upper limit of 500 $lb/in^2/in$ (136 kPa/mm) is placed on the subgrade modulus (k-value) to prevent designers from incorporating extremely stiff base layers in the design.

- The amount of premature cracking that may result on any given project ranges from 1 to 5 percent of the total project.

- Factors considered as major causes of premature cracking are:
  - High strength or thick stabilized bases.
  - Degree of restraint between PCC slabs and base.
  - PCC slab jointing (panel size dimensions and sawing operations).
  - Texture of the base.
  - Concrete mixture design in the PCC slab.
  - Weather and ambient conditions prevalent during the construction of the PCC slab.

- If temperature and moisture curling/warping stresses were considered in the thickness design, an increase in k-value could actually require a thicker slab for a given slab geometry.

- Higher-strength base materials are more likely to produce cracks that can reflect into the PCC surface layer. Some contractors tend to achieve strengths of CTB materials greater than the minimum specified in order to expedite construction; however, these may produce higher curling stresses with a more damaging impact particularly when the concrete is relatively young.

- FAA sponsored research (Grogan, 1999) measured strength/stiffness values at major civil airports indicating that PCC layers were behaving more as a bonded overlay on the stabilized layer rather than a PCC layer resting on a separate stabilized layer.

- Current methods (Grogan, 1999) of constructing a bond-breaker using asphalt emulsion do not perform adequately. In general, the stabilized base layer is bonded to the PCC and a slippage plane or horizontal crack develops below the PCC-stabilized base interface.

- Rough slab-base interfaces promote a higher degree of friction, which causes excessive axial restraint to volumetric shrinkage and to thermal expansion and contraction.

- Analysis of data from the instrumented runway at the Denver International Airport indicated that the loaded pavement behaved unbonded at times and bonded at other times, even in the presence of a bond-breaker between the slab and base layer (Rufino, 2003). Therefore, it is possible to have a bonding action without physical vertical bond or adhesion.

- Frictional restraint can develop in concrete pavements placed over ATPB and CTPB (Voigt 2002), while concrete is in plastic state under the extrusion pressure of the slip form paver. Concrete penetration into the open-textured permeable base layer can be as much as 1 to 2 in (25 to 51 mm) (ACPA, 2002b) and causes restraint to slab movements during thermal and moisture driven contraction and expansion.

- The most common bond-breakers for CTB and LCB are a double-coat of wax-based curing membrane or a geotextile fabric (Kohn and Tayabji, 2003). An asphalt emulsion coat, used as a curing compound for CTB, can also serve as a bond-breaker. However, according to Grogan et al. (1999), a fresh application of emulsion 8 to 12 hours prior to paving may be most effective.

- One way to limit paste intrusion into drainable bases is to not require a high degree of voids in the permeable base (i.e., reduced permeability requirements). The current UFC criteria on permeable bases suggests that a permeability of 1,000 ft/day (305 m/day) is adequate for permeable bases.

- Joint spacing has an impact on early-age stresses. The degree of movement is greatly controlled by the coefficient of thermal expansion of the aggregate and also the prevalent ambient conditions soon after placement. The problem translates to uncontrolled cracking if the concrete is not strong enough to resist these early stresses.

- Longer joint spacings also cause increased curling stresses in bending. This is further exacerbated by the presence of stiff stabilized bases, which cannot accommodate themselves to the curled or warped shape.

- The optimum window of opportunity to sawcut joints typically occurs a few hours after the concrete placement, when concrete strength is acceptable to operate saw equipment without excessive raveling at the joints. The window ends when the concrete's volume reduces significantly (from drying shrinkage or temperature contraction) and restraint of the reduction induces tensile stresses greater than the tensile strength.

- Early-entry sawing methods provide better crack control over conventional methods of sawing joints.

- A poor concrete mix design can aggravate the problem of premature cracking. Mixtures with higher water demand and total mortar volume have an increased potential for volumetric shrinkage, which can lead to uncontrolled cracking. Factors that increase water demand include higher cement factor concrete (>500 lb/yd^3 [>295 kg/m^3]) and concrete made with fine sand. The type of coarse aggregate can influence the temperature sensitivity of concrete. The gradation of the combined aggregates affects the workability of concrete mixtures and, therefore, its early-age performance.

- Considerations for early-age cracking need to be balanced with requirements of strength and durability.

- FAA specifications, as implemented on several projects, require that the sand for the PCC meet the ASTM C 33 specification. No more than 45 percent of material is retained on any one sieve. Fineness modulus between 2.3 and 3.1. The presence of fine sand (excessive minus No. 50 [300 µm] sieve material) increases the bulking potential dramatically and thereby the potential for volumetric shrinkage and early cracking. Mixtures prone to segregation are also prone to early distress.

- Most commonly cited factor affecting premature cracking is weather. Air temperature, wind speed, relative humidity, precipitation, and solar radiation all have an impact on the early-age performance of concrete since they either heat or cool and dry or wet-up the concrete (ACPA, 2002b). They also influence the temperature of the base layer, which in turn influences the heat flow into and out of the concrete layer during hydration.

8.2 REVIEW OF AIRPORT CONSTRUCTION PROJECTS

An extensive review of selected airfield projects, described in chapters 3, 4, and 5, was conducted to gain a better understanding of the how various base types along with climatic, design, materials, and construction factors affect the early-age distresses in rigid airfield pavements.

Of the more than 200 airfield projects examined, 119 were found to have pavements with cement-treated, asphalt-treated, econocrete, or permeable base layers. These airfields were spread across 38 states and represented diverse climatic zones. Important conclusions from a review of those projects exhibiting EAD and those that did not are summarized below for each base type.

Three climatic conditions or “trigger” factors that contribute to EAD during PCC paving are:

- Large ambient temperature drops or swings (drops greater than 25°F [14°C]).
- Hot ambient temperatures.
- Excessive surface evaporation.

However, it was found that the large temperature swings and hot-weather conditions accompanied by factors that increase surface evaporation (high wind speeds and low ambient relative humidities) were found to be the most common causes.

The findings of the airfield project reviews are summarized below by base type.

8.2.1 Cement-Treated Base (CTB) and Econocrete Base Projects

Cracking in PCC placed over CTB may result from shrinkage-related volumetric reduction due to hot-temperatures and low-relative humidity, and can be aggravated by the following design, materials, or construction “variants”:

- Shrinkage-susceptible PCC mixture.
- Coarse, gap-graded PCC mixture vulnerable to segregation.
- Inadequate sawcut depth or late sawing.
- High strength/stiffness base.
- Base layer offering a and high degree of restraint.
- Presence of shrinkage cracks in the CTB.
- Inadequate bond breaker.

Large temperature swings may produce cracking, particularly when aggravated by other factors such as:

- High cement factor concrete.
- Large panel dimensions.
- Presence of a stiff base.
- Inadequate sawcut depth.

The high cement factor generates a large heat of hydration that heats the mass concrete. However, a sudden variation of temperatures in the top "skin" of the slab can lead to an internal thermal gradient that can cause the concrete to curl upward (just as if a large negative temperature gradient is being applied). This upward curl is resisted by the friction at the slab-base interface and self-weight of the slab leading to tensile stresses at the top of the slab. If these tensile stresses cannot be accommodated by the strength gain in the material, cracks may form. When large cold fronts are anticipated, it is advisable to look out for factors that could lead to such situations.

Shrinkage-related deformations due to hot-temperatures is believed to interact with the following variants to cause the EAD:

- Presence of a very thick base.
- Presence of a very strong/stiff base.
- Absence of a bond breaker.
- Rough CTB/PCC interface.
- Inadequate sawcut depth.
- Presence of shrinkage cracks in CTB.

Based on a review of the data from the airfield projects, those with EAD and those without, it appears that by having an effective temperature management plan, a responsive construction crew, low stiffness base, low friction on base surface, and proper sawing of joints, the problem of early cracking can be greatly reduced. Small changes to the design and construction process that reduce the potential for early EAD include reducing the joint spacing, decreasing the stiffness of the CTB, and use of early entry saw.

8.2.2 Asphalt-Treated Base (ATB) Projects

Not many asphalt treated bases with early-age cracking were found during the search conducted in this study. For the one project that experienced early-age cracking, several trigger factors lead to the uncontrolled cracking problem in the PCC layer. High temperature gradients through the slab at an early age are believed to interact with the following variants to cause the EAD:

- Slabs with high aspect ratios.
- Excessive restraint to slab movement cause by load transfer and tie devices.
- Rough ATB/PCC interface due to milling of the ATB surface.
- Inadequate sawcut depth.

Whitewashing of the base layer prior to PCC placement when hot ambient conditions are present, placing a leveling course if milling is needed, and proper selection of PCC panel dimensions can provide insurance against EAD. Construction of PCC over a base whose characteristics provide low slab/base interface friction coefficient and low stiffness can also ensure success. Further, thin base thickness, no more than 4 in (102 mm), can help reduce the flexural rigidity and decrease the curling/warping stresses.

8.2.3 Cement-Treated Permeable Base (CTPB) Projects

Trigger factors that have caused problems with PCC constructed over CTPB are similar to those with CTB construction. High temperature swings combined with high air temperatures and high wind speeds during the paving operations have contributed to EAD. Factors that aggravate the PCC construction over CTB include:

- Large panel dimensions.
- Presence of a stiff base.
- Shrinkage susceptible PCC mix.
- Excessive restraint at the slab/base interface.
- Inadequate sawcut depth.

On similar designs, where there have not been any EAD, the trigger factors (large temperature swings, high air temperature, and low relative humidity) were not issues. Also, low base stiffness and improved PCC mix have contributed to the absence of early-age cracking.

8.2.4 Asphalt-Treated Permeable Base (ATPB) Projects

As with asphalt-treated bases, even for asphalt-treated permeable bases, it was difficult to locate projects where the PCC placed over this base has experienced early-age cracking. No EAD was noted on the ATPB projects reviewed even when significant trigger factors were present and some design and material variants exceeded recommended levels (joint spacing, PCC mix properties). Perhaps one of the biggest factors contributing to the lack of EAD was the selection of the base type itself. Even though the PCC paste penetrates the ATPB system and bonds to it, the relative stiffness of this layer compared to the PCC is low and helps mitigate the restraint stresses that can develop in the PCC layer. Other construction variants that helped mitigate the occurrence of EAD include whitewashing of the base layer, the seemingly adequate joint sawing, and also a well designed and execute plan to manage environmental trigger factors during construction.

8.3 THEORETICAL ANALYSES

Chapter 6 discusses the analyses performed to theoretically verify and extend the observations documented in chapter 5. The main objective was to quantify the impact each key variant has on EAD risk.

The analysis considered the combined effect of key trigger factors and key design, materials, and construction variants that influences EAD risk on four selected projects.

Theoretical analysis results agree well with field observations of early cracking. It was found that thicker, stiffer, and rougher bases also produce higher EAD risk. The interaction between PCC slab and base type produced the greatest risk of EAD. Presence or absence of trigger conditions is another key element determining EAD risk. It was concluded that theoretical analysis tools can be used effectively to quantify the EAD risk that various triggers and variants present for any given pavement design and construction scenario.

8.4 CONSTRUCTION DEMONSTRATION

To evaluate the constructability of the stabilized and permeable base materials, a field demonstration was performed as described in chapter 7. The demonstration involved the construction of seven base layer test sections, complete with laboratory mix designs, laboratory and field-testing of base material engineering properties, and field examination of base layer response to construction traffic, water, and concrete placement.

Base materials placed in the demonstration included CTPB, UPB with two different gradations, CTB with two different cement contents, and ATPB with two different gradations. Econocrete and ATB test sections were not placed due to the predominance of interest in evaluating the constructability of the other materials.

Key findings from the test section are:

- Placement—Successful laydown achieved with all materials (UPB, CTB, CTPB, and ATPB) using conventional asphalt paver.
- Compaction—Sufficient density of ATPB and CTPB materials achieved with two to three passes of 12-ton (10.9-metric ton) static steel-wheel roller. Sufficient density of CTB materials achieved with two to three combined passes of 12-ton (10.9-metric ton) vibratory and static steel wheel rollers.
- Stability under construction traffic—Both the 0.75-in (19-mm) and 1-in (25-mm) top-size UPB materials exhibited rutting problems, raising concern as to the acceptability of UPB for use under rigid airfield pavements. CTB, CTPB, and ATPB materials all held up well under heavy loads and turning movements.
- Base permeability—UPB, ATPB, and CTPB materials were all quite drainable in the field. Low laboratory permeability values for field-extracted CTPB cores were the result of cement paste inadvertently washed down from the surface.
- Bond breaking—Choke stone layer provided the best means of breaking the bond between PCC and bound/treated base. Single and double applications of wax-based curing compound and asphalt emulsion were largely ineffective as bond-breakers.

8.5 SPECIFICATIONS

Based on the findings of the research study, a set of five new and/or revised specifications have been drafted. These specifications are:

- CTB.
- Econocrete.
- ATB.
- CTPB.
- ATPB.

The new specifications address technical issues and were prepared to provide consistency among the specifications in terms of format, level of detail, test methods specified, and use of Engineer's notes.

8.6 CONCLUSIONS

Three major trigger conditions and up to a dozen key variants have been found to be responsible for the development of EAD in PCC pavements placed over stabilized and drainable bases. EAD occurs in the form cracking that includes longitudinal, transverse, diagonal, corner, and random with the first two being more common.

Specific conclusions from the research are:

- EAD in rigid pavements built over stabilized or drainable bases can be caused by a large ambient temperature drop due to an approaching cold front or a sudden rain shower followed by hot weather paving associated with high evaporation losses.
- Large ambient temperature drops typically occur in northern climates when paving is performed in early spring or late fall.
- At least one trigger condition must be present on any given project to cause EAD.
- When 50 percent or more of the key variants are unfavorably aligned with a trigger condition, the likelihood of EAD is certain. However, EAD can also occur even if as few as two to three variants are unfavorably aligned.
- Major trigger conditions are:
  - Large ambient temperature swings.
  - Hot weather.
  - High surface evaporation.
- Key variants that most influence the development of EAD are (ranked in decreasing order of importance):
  - Excess base strength/ stiffness.
  - Sawing (initial and final).
  - Panel sizes and aspect ratios.
  - PCC/Base interface friction.
  - PCC cement factor.
  - Presence or absence of bond-breaker.
  - Shrinkage susceptibility of PCC mixes.
  - Presence of shrinkage cracking in base.
  - Base thickness.
- In general, high-strength cement stabilized bases, such as CTB and econocrete, are more sensitive to combinations of triggers and variants. Despite the presence of significant trigger conditions and variants above threshold values, ATB and ATPB did not develop EAD.
- Proper planning and execution of the construction to account for adverse climate conditions is a key to a quality pavement.

This research has developed new information and guidance on the design and construction of stabilized and drainable base layers for PCC airfield pavements. The companion Guide will provide a useful handbook for both designers and constructors. Implementation of the findings from this study should greatly improve the quality of PCC airfield pavements and eliminate the early-age distresses that have so frequently plagued past projects.

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