Design Considerations Associated with the Rehabilitation of R/W 9-27 at IAH

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Introduction

Runway 9-27 was originally constructed in 1987, by AEO (PDC) Contract 265, as a 10,000 ft x 150 ft pavement on the south side of the Houston International Airport (IAH) airport. The center 9,400 ft portion of the runway consisted of a 3 inch asphalt surface course on a 28" Lime/Cement/Fly-ash (LCF) base course and a 28 inch stabilized subbase course. The first 300 ft on each end of the runway consisted of 14 inch Portland Cement Concrete (PCC) over a 3 inch asphalt concrete (AC) bond breaker on a 14 inch LCF base course and a 28 inch stabilized subbase course.

Existing Pavement Structure and Condition

The 28 inch LCF layer consists of an engineered combination of lime/cement/flyash materials with sand and aggregate. The LCF layer varied in thickness from 20 to 28 inches was essentially a roller compacted pozzolanic concrete, which gains considerable strength as it ages. The as-constructed compressive strength in 1987 was approximately 1,500 psi. However, core samples taken at random locations tended to indicate the strength of the LCF layer in 1998 was 3,400 psi (1).

The original AC surface layer was placed using FAA P-401 specification. The pavement generally performed well although "rutting and shoving" became evident in 1990-1991 when a seal coat was placed on the runway. In 1998, the runway was milled 1 inch and overlaid with ½ inch of a stress absorbing membrane interlayer (SAMI) and a 5 inch layer of Novophalt (resin modified asphalt).

However, a forensic analysis, as part of the project design effort, on the existing pavement structure found shoving to still be prevalent in selected areas of the pavement surface (Figure 1). The forensic evaluation determined that this distress was likely due to high shear stresses resulting from the braking and cornering action of aircraft in conjunction with the stiff nature of the Novophalt material. In effect, the synergistic effects of a stiff, polyethylene binder; oxidative aging over 10 years of service life in the top inch of the asphalt concrete; and the high, near surface shear stresses resulted in shoving and crazing (closely spaced top-down cracking).

Figure 1 Shoving of Wearing Course on Runway 9-27 (1).

Based on analysis of the field performance from the forensic, laboratory testing, and back-calculated HWD data for the existing runway pavement structure indicated that the overall "slab" stiffness may have been reduced due to the cumulative effect of shrinkage cracks and

smaller, load associated cracks in the LCF layer. Furthermore, these cracks most likely contributed to a lack of bonding between the different compaction planes. This was thought to be a possibility because the LCF layer was constructed in approximately seven individual sublayers. Even though the combined stiffness of several partially bonded or unbonded stiff sublayers could be substantially less than the stiffness of a monolithic layer of the same thickness and stiffness, there was great concern that the overall effective k value immediately below unbonded concrete overlay rehabilitation options could lead to substantial curling and warping stresses (1).

Design Options and Analysis

A LEDFAA analysis was performed to develop paving alternatives using the material properties for specific pavement areas, with results for a PCC overlay ranging from 8.5 to 14.5 inches. Following the LEDFAA analysis, the finite element based ISLAB2000 computer model was used to further evaluate the PCC overlay thicknesses predicted by LEDFAA. The following process was involved (1):

- Determine the critical location and critical stresses imparted by the design aircraft (which was determined to be B-777)
- Assess the fatigue life consumption of the rehabilitated (i.e. overlaid) pavement due to the design traffic
- Evaluate the impact of overlay thickness on damage of the LCF layer

This analysis demonstrated an unusual trend as the bending stresses actually decreased when the PCC overlay thickness is less than about 10-inches. However, an overlay thickness below 12-inches induced high bending stresses at the bottom of the LCF layer which represented a potential for excessive damage in that layer. The optimum PCC design was determined to be 14 inches, which provided adequate thickness for the PCC and the LCF layer design stresses. This determination also satisfied the design thickness developed using the LEDFAA software. However, the design should reflect the effects of climatically induced gradients in the PCC overlay, which can play a major role in determining the magnitude and effect of curling and warping stresses that often are the cause of early, random cracking. Early aged curling (a temperature-based stress) and warping (a shrinkage-based stress) were a major concern during paving of R/W 9-27 because of the stiff support conditions that exist due to the LCF base layer. The design effort resulted in the development of three alternative PCC overlay methods for the proposed pavement rehabilitation (1):

- **Alternative 1** - Jointed Concrete Overlay
  14 inch PCC; 1 inch to 2 inch AC Leveling Course; Mill Existing AC Surface to 3 inch Depth; Existing 28 inch LCF Base

- **Alternative 2** - Jointed Concrete Overlay
  14 inch PCC; 2 inch AC Separation Layer; Mill Existing AC Surface to Top of LCF (5inch to 7 inch); Existing 28 inch LCF

- **Alternative 3** - Continuously Reinforced Concrete Overlay (Mill 3 inches of existing AC) 14 inch Continuously Reinforced PCC;1 inch to 2 inch AC Leveling Course; Mill Existing AC Surface to 3 inch Depth; Existing 28 inch LCF

Alternative Selection

Table 1 itemizes key decision factors associated with the pavement type selection for the R/W 9-27 rehabilitation. The repair alternatives listed in the table consisted of only unbonded concrete overlay options where the categories of key factors affecting the selection are itemized in the first column which can be delineated into performance, design, and construction components.

Table 1 Alternative: R/W 9-27 Pavement Types.

Design/Construction Issue	**UBOL-Jointed**	**UBOL-CRC**
Random cracking in base layer	Address wide, low LTE crack	Address wide, low LTE crack
200 ft expansion joints	Retro-fit and match	Retro-fit and match
Milling of ACOL	No	No
Design thickness/WLS	High	Moderate
Stiff subbase support	High risk of damage due to environmental stress	Low risk
Complexity of construction	Mod – slab replacements due to crack control issues	Low
Ranking	2	1

Area of concern
Desirable feature

A key aspect of long term concrete pavement performance (particularly those of the unbonded jointed concrete options) is the quality and the nature of the curing effort relative to keeping the set temperature gradient to a minimum during and shortly after the construction phase. The set gradient plays a major part of the magnitude and effect of the resulting curling and warping stresses that often are the cause of early, random cracking that are mainly dictated by the prevailing weather and curing conditions at the time the construction takes place. Tensile stresses and cracking in a concrete pavement often result from temperature and shrinkage effects during the early stages of hydration while the concrete is developing stiffness. Due to exposure to ambient conditions, a concrete pavement may cool to a minimum temperature as well as shrinkage due to moisture loss after cycling through a maximum temperature such that tensile stresses can be induced in the concrete slab. Stress development may become significant very soon after placement, perhaps even before the concrete has attained a certain degree of strength. Crack development in concrete pavement has been noted to be sensitive to diurnal temperature and wind effects. The tendency to curl and warp is restrained by concrete slab weight in which the resulting level of stress development is a function of the stiffness of the subbase layer as reflected in the radius of relative stiffness (ℓ- subsequently defined). When the slab curls and warps in an upward

configuration at the corners, tensile stresses are induced in the upper mid-slab area. Analysis of stress induced by a linear temperature gradient in rigid pavements was developed by Westergaard and others (1).

As previously noted, early aged curling and warping stress were a major concern during paving of R/W 9-27 because of the stiff support conditions that exist due to the 28 inch LCF base layer justifying calls for special measures to be taken to assure the quality of curing during construction and the long term performance of an unbonded, jointed systems. Of course, concerns of excessive curling and warping stresses were mainly associated with the jointed design alternatives. One option to limit these types of stresses is through proper selection of the spacing between the sawcut joints. It is noted in Section 337 under Item (b) of the FAA Advisory Circular 150-5320-6D (chg 2 dated 06/03/2002) the design spacing for jointed concrete construction is elaborated. The text of this discussion is in the form of guidelines for concrete pavement sections containing both stabilized and unstabilized bases. Quoting directly from the circular:

> **"With Stabilized Subbase.** Rigid pavements supported on stabilized subbase are subject to higher warping and curling stresses than those supported on unstabilized foundations. When designing a rigid pavement supported on a stabilized subbase a different procedure is recommended to determine joint spacing. Joint spacing should be a function of the radius of relative stiffness of the slab. The joint spacing should be selected such that the ratio of the joint spacing, in inches, to the radius of relative stiffness is 5.0 or less to control transverse cracking. In the absence of conclusive local experience, a maximum joint spacing of 20 feet (6.1 m) is recommended. The radius of relative stiffness is defined by Westergaard as the stiffness of the slab relative to the stiffness of the foundation. It is determined by the following formula:
> *:*
>
> $$\ell = \left(\frac{Eh^3}{12\left(1-\upsilon^2\right)k} \right)^{\frac{1}{4}}$$
>
> *where:*
>
> *E = modulus of elasticity of the concrete, usually 4 million psi*
> *h = slab thickness, in.*
> *v = Poisson's ratio for concrete, usually 0.15*
> *k = modulus of subgrade reaction, pci*
>
> *The radius of relative stiffness has the dimension of length and when calculated in accordance with the above, the units of ℓ are inches."*

The basis for the FAA advisory circular guidance is imbedded in the fundamental considerations originally elaborated by Westergaard (5) which are only be briefly elaborated here. Westergaard presented solutions which considered curling stresses in a slab of infinite and semi-infinite dimensions based on the following governing equations (5):

$$\ell^4 \frac{d^4 w}{dy^4} + kw = 0$$

where w = vertical displacement in the y direction. Although the slab weight restrains the curling, the weight is not included in the equation. However, the displacement (w) caused by curling can be considered only part of the slab displacement. There are two boundary conditions that Westergaard addressed to solve the above expression which defined relative to an infinitely long slab of a finite width and for a semi-infinite slab. A pavement slab is considered to be of infinite extent with respect to the length of the slab when the tendency to curl in longitudinal direction is fully restrained or $w = 0$ at the longitudinal center. With a positive Δt (temperature at the top higher than the temperature at the bottom), the maximum tensile stress is at the bottom surface of the slab in longitudinal direction, whose value is:

$$\sigma_x = \frac{E\alpha\Delta t}{2(1-\nu)}$$

where α = thermal coefficient of expansion in the concrete. The tensile stress pattern in concrete slab is shown in Figure 2. For a slab of finite dimensions, Bradbury (2) suggested an approximate formula to estimate the maximum stress, where two coefficients were given based on the Westergaard analysis. Bradbury developed a chart to determine the correction factors that were applied to the Westergaard equation to determine the curling stress in the slab. The Bradbury coefficient depends on radius relative stiffness of the slab, length of the slab, modulus of elasticity of concrete, thickness of the slab, Poisson ratio of concrete, and modulus of subgrade reaction as indicated in Figure 3.

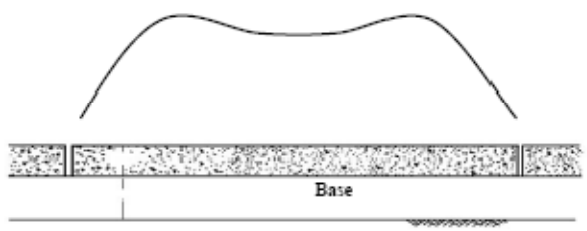

Figure 2 Tensile stress pattern in slabs (4).

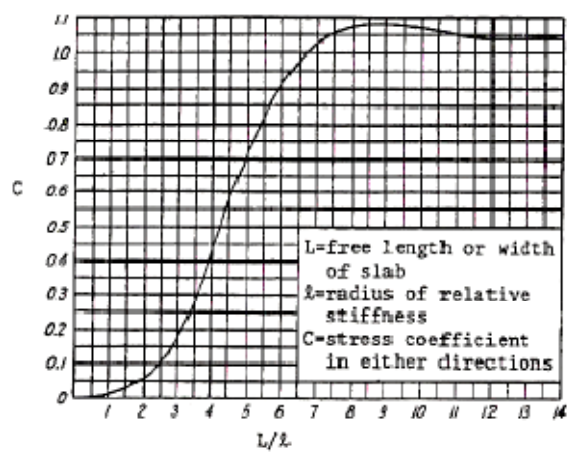

Figure 3 Coefficients for maximum stress in curled slab (2).

When a slab with a finite length (L_x) and a finite width (L_y) is curled (or warped) as subjected to a temperature gradient, stress distributions can be found analytically. For estimating the maximum σ in a finite slab, Bradbury proposed an approximate fomula as follows (2,3, 5):

$$\sigma_x = \frac{E\alpha\Delta t}{2}\left(\frac{C_1 + \nu C_2}{(1-\nu^2)}\right)$$

where C = the Bradbury Coefficient = $= 1 - \left(\frac{2cos\lambda cosh\lambda}{sin2\lambda + sinh2\lambda}\right)\left[(tan\lambda + tanh\lambda)cos\frac{y}{\sqrt{2}\ell}cosh\frac{y}{\sqrt{2}\ell} + (tan\lambda - tanh\lambda)sin\frac{y}{\sqrt{2}\ell}sinh\frac{y}{\sqrt{2}\ell}\right]$ and $\lambda = \frac{x}{\sqrt{8}\ell}$. The coefficient C_1 is typically in the longitudinal direction, whereas C_2 is for the perpendicular direction. Coefficient C_1 increases as the ratio L/ℓ increases, having a value of C = 1.0 for L = 6.7ℓ, reaching a maximum value of 1.084 for L=8.88ℓ. In summary, the magnitude of the restraint stress is affected by slab dimensions and support stiffness. When the coefficient C has a maximum value of 1.084, the maximum tensile stress due to curling is 0.638 $E\varepsilon^t$ (where $E\varepsilon^t = E\alpha\Delta t$ and $\nu = 0.15$) which implies that the maximum curling stress cannot exceed 63.8% of total possible restrained tensile stress. Any additional contributors to the tensile stress in the slab such as those induced by reinforced steel bar and friction between subgrade and slab may add to the balance of stresses, but the total tensile stress should not exceed $E\varepsilon^t$

Following the guidelines in Section 330, a composite k value between 325 and 400 psi/in (assuming a subgrade k of 100 psi/in) is estimated (to account for the effect of the LCF layer on the slab supporting conditions however the FAA design charts only extend to a 12 inch subbase thickness). For the recommended value for E, an ℓ value of 39.1 inches results which suggest a design pavement jointing for this project between 13.0 and 19.6 feet. According to Westergaard Theory, the idea location is actually 4.44 ℓ which yields a spacing of 14.5 feet.

Using ISLAB2000 (6) results, it is evident from the data shown in Figure 4a and b that relative to pavement type a CRC design has a definite advantage over a jointed or a contraction design although the curing behavior is a concern for both pavement types. Curing stresses are shown as a function of slab thickness, temperature gradient, base thickness, and stiffness of the LCF layer. Curing stresses for the contraction design are shown in the longitudinal direction while the curling stresses for the CRC are in the transverse direction.

Elaborating further on the Figure 4 illustrated behavior, the Bradbury and Westergaard characterization is limited a single slab on grade configuration and converting a multi-layer configuration to a single slab configuration allows a way to illustrate the exceptional dominance of the stiffness of the 28 inch LCF layer on curling stress. As indicated in Figure 5, the single layer k value used for curl stress analysis where a stiff subbase is involved may be much greater than that indicated from Section 330 in the FAA design charts. The k value on top of the LCF layer that effectively creates the curling stress as back calculated using the Westergaard formulation for the Bradbury C and equating the curling stress from the ISLAB2000 analysis (taking the multiple layer into account) to $\sigma = C^*\sigma_0$ (where $\sigma_0 = E_c\alpha\Delta t$) a single layer composite k value can be back calculated. This effect of course becomes less dominant in pavement sections of lower LCF base thicknesses. Nonetheless, high composite k values can be the source of damage that could ultimately shorten the fatigue life particularly of a contraction design.

Conclusions

Clearly climatically induced stresses should be a key consideration in the pavement design and type selection particularly in the cases where an exceptionally stiff support platform exists.

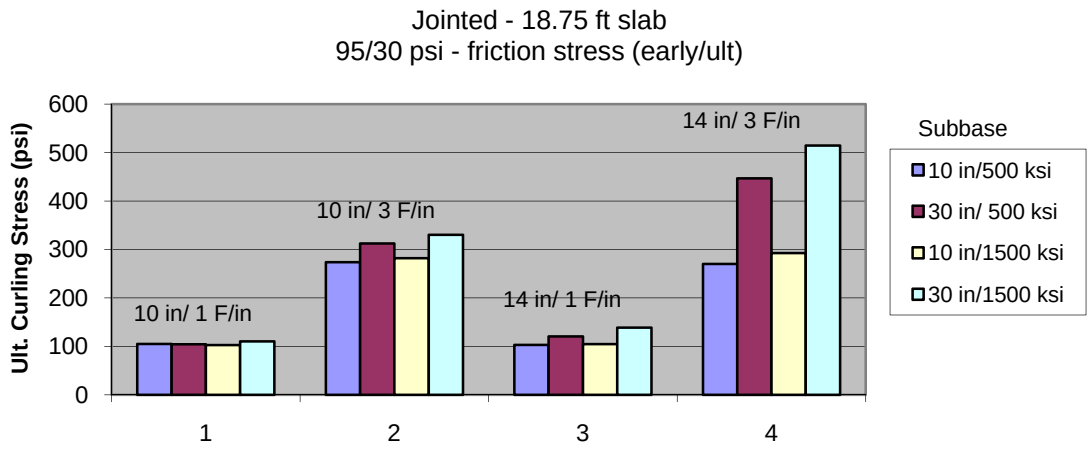

Figure 4a Curling Stresses for a Jointed 18.75 ft Slab - Longitudinal.

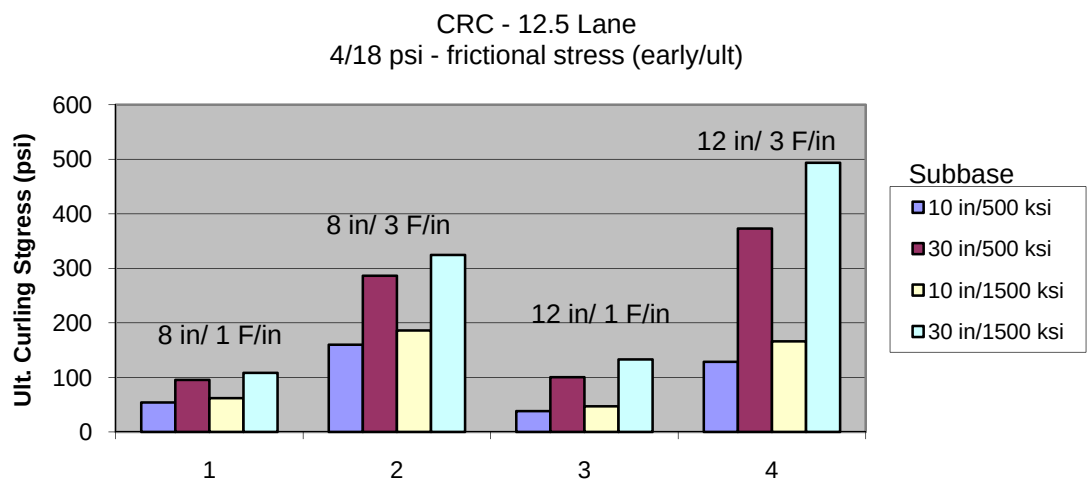

Figure 4b Curling Stresses for a CRC Pavement - Transverse.

Under circumstances such as these, load stresses are rarely the issue but environmental stresses are - raising the potential for shortened fatigue life and several instances of randomly cracked slabs prior to a single load being applied to the pavement. Ideally, bonded overlays are the best option for thick, stiff support layers because many of the construction related issues described above are eliminated.

There are areas of needed research that would help to facilitate and streamline the consideration of curling and warping stresses in design:

- The validation of the Bradbury coefficients relative to capturing key design stresses
- The validation of the correct k value to use of load and curling stress analysis
- The validation of the effect of curling and warping behavior on fatigue life

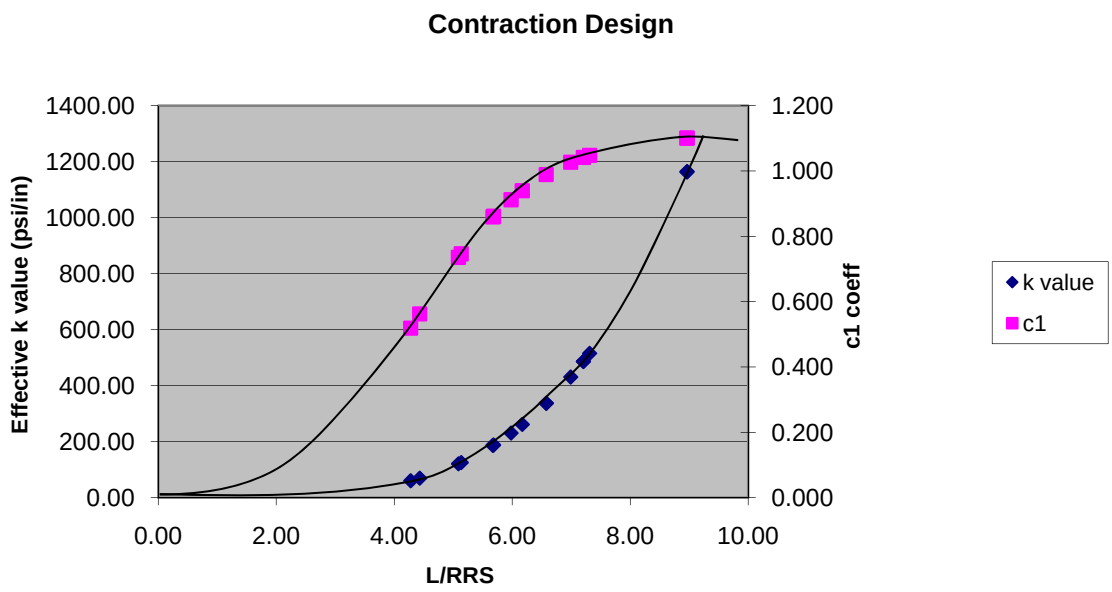

Figure 5 Relationship between the Effective k value and the Bradbury C Factor.

- The validation of design and construction measures to reduce the effect of curling and warping behavior

Certainly, these are all key areas to consider particularly when weighing the use of a bonded versus an unbonded design. Using an AC interlayer under a concrete slab will moderate the frictional interface yet it reduces the structural restraint of the slab to carry load through a partial bond between the surface and the subbase. It also allows for the inducement of slab pumping action under which erosion can take place possibly causing joint related performance issues. Several important options, including those related to the use of the CRC, need elaboration in order for the FAA design methodology to completely address the use of a jointed option in both design and rehabilitation.

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