IMPROVED DESIGN OF UNBONDED CONCRETE OVERLAYS

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ABSTRACT

An unbonded concrete overlay is an excellent choice for long-lasting rehabilitation of a deteriorated concrete pavement. However, concerns over thickness and joint design of unbonded concrete overlays hinder their more widespread use. This paper reviews the existing approaches to unbonded overlay thickness design, examines actual field behavior and long-term performance of these overlays, and presents a framework for an improved design approach which relates design to performance.

Four approaches to unbonded overlay design are considered: the traditional Corps of Engineers procedure, design of the overlay as a new pavement, and multilayer pavement design using either elastic layer theory or plate theory. These approaches are evaluated with respect to their theoretical bases, inherent assumptions, sensitivity to various design inputs, and compatibility with actual field performance of unbonded overlays.

The major distresses in jointed unbonded overlays are linear cracking and corner breaks due to combined loading and curling; reflection cracking and other distresses are much less significant. Continuously reinforced unbonded overlays exhibit little distress of any kind except reflection cracking over transverse joints. However, the objectives of the existing approaches to unbonded overlay thickness design have little connection to the observed performance of either overlay type.

Finite element analysis holds the most promise for an improved approach to unbonded overlay design. Two-dimensional, plate theory-based multilayer finite element programs (or equations developed from them) are capable of realistically modelling most, but not all, of the complex factors which must be considered. Recommendations are given for further research needed to fully develop improved methods for unbonded overlay analysis and design.

INTRODUCTION

An unbonded concrete overlay is an excellent choice for long-lasting rehabilitation of a deteriorated concrete pavement. However, concerns over thickness and joint design of unbonded concrete overlays hinder their more widespread use. The traditional U. S. Army Corps of Engineers (COE) design procedure generally produces very conservative designs which perform well in the field but are not cost-competitive with other rehabilitation alternatives. At the other extreme, some unbonded overlays of apparently adequate thickness have exhibited surprisingly large amounts of cracking due to factors not considered in the design of the overlay. Clearly the existing unbonded overlay thickness design procedures do not consistently produce designs capable of cost-effective, reliable long-term performance.

This paper reviews the existing approaches to unbonded overlay thickness design, examines the real field behavior and long-term performance of these overlays, and presents a framework for an improved design approach which relates design to performance.

HISTORICAL BACKGROUND OF UNBONDED OVERLAY DESIGN

Traditionally, unbonded overlay thickness design has been done using some form of the familiar "square root" equation shown below:

$$h_{ol} = \sqrt{h_f^2 - h_{eff}^2} \qquad (1)$$

where h_{ol} = unbonded overlay thickness
h_f = required slab thickness for future traffic
h_{eff} = effective thickness of existing slab

The required slab thickness for future traffic loadings is determined by any suitable rigid highway or airfield pavement design procedure. Typically, the support conditions (i.e., k-value) beneath the existing pavement are

assumed in determining h_f, along with the slab properties (i.e., elastic modulus, modulus of rupture, and joint load transfer) of the overlay, not the existing pavement. The existing slab's effective thickness, h_{eff}, is typically the actual thickness multiplied by a condition factor less than 1.0, depending on the extent and severity of slab cracking.

The apparent origin of the "square root" equation, according to Rollings (1), is the report by Older (2) of the results of the Bates Road Test. Older observed that the equation he derived for required concrete pavement thickness to support a given magnitude of corner loading adequately described the performance of one-layer concrete pavements tested, but not two-layer pavements referred to as "monolithic brick" (a brick surface on a concrete base). As Figure 1 shows, a better fit to these data was obtained when the thickness of the two-layer pavement was expressed by the square root of the sum of the squares of the two layer thicknesses.

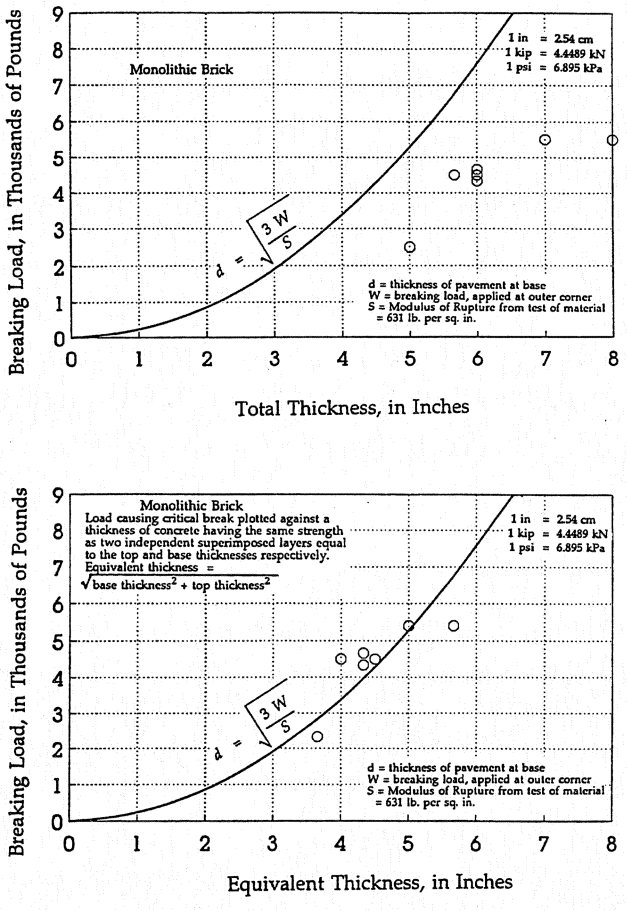


Figure 1. Relation of pavement thickness to load causing corner break. (2)

This adjustment was described in the following manner by Older:

> "At many points along the edges and adjacent to all corners, it was observed that, under load, the brick surfacing became distinctly separated from the concrete base. This seemed to indicate that the pavement was acting as two separate slabs."
>
> "... abscissas were used which represent the thickness of a concrete slab computed as having transverse strength equal to the transverse strength of two superimposed independent slabs..." (2)

Following the Bates Road Test, the square root equation came into general use for unbonded overlay design. Very few unbonded overlays were built on highways prior to 1931; the first airfield unbonded overlays were built around 1943. In the 1940's, the American Concrete Institute and the Corps of Engineers adopted the general form of Equation 1 for design of unbonded concrete overlays.

In the 1940's and 1950's, the Corps of Engineers conducted a series of full-scale field tests of concrete overlays at Lockbourne Air Force Base in Ohio and the Corps' Ohio River Division laboratories in Sharonville, Ohio, for the purpose of validating its pavement design and overlay design procedures. (3) Figure 2 illustrates the results of these tests.

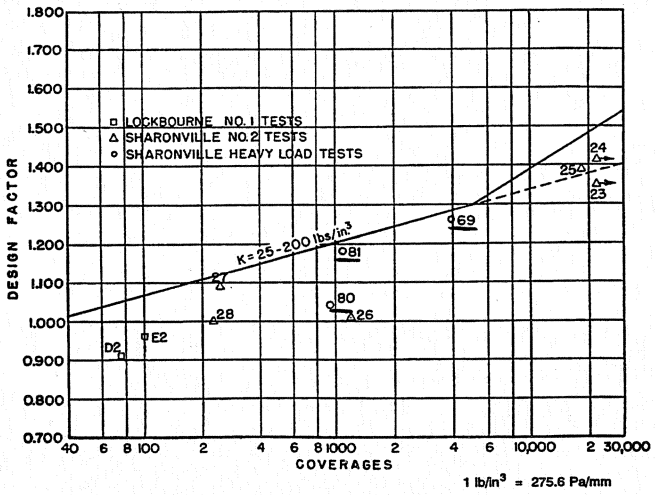


Figure 2. Corps of Engineers' full-scale field tests of concrete overlays. (3)

An "unbonded" overlay was defined as being separated from the existing pavement by a layer such as asphalt concrete. A different thickness equation, shown below, was adopted for design of "partially bonded" overlays, defined as being placed on the existing pavement without any particular effort to either separate or bond the two layers.

$$h_{ol} = \sqrt[1.4]{h_f^{1.4} - h_{eff}^{1.4}} \qquad (2)$$

Equations 1 and 2 were used to compute an equivalent single slab thickness for each test section, and Westergaard's edge stress equation was then used to compute the maximum edge stress for a single slab of this thickness due to a design wheel load. The "design factor" on the vertical axis is the flexural strength of the overlay concrete divided by the maximum edge stress computed for the equivalent single slab. The line drawn on the graph represents the expected performance of a single slab (i.e., h_f).

According to Mellinger, "the distance below the curve that the points fall indicates to what degree the various overlay test items performed better than the design procedure assumes they should." (3) A better interpretation of Figure 2 might be that the distance to the right of the line indicates to what degree an overlay test section performed better, that is, supported more coverages than the design procedure indicates an equivalent single slab could support.

This graph suggests that the full-scale tests validated the Corps' concrete overlay design equations as reasonable and somewhat conservative. However, it is important to note that most of the points shown really represent "partially bonded" overlays rather than unbonded overlays, since no separation layer was placed. According to Mellinger, the Lockbourne test sections and the Sharonville No. 2 test sections were "water cured and carefully cleaned before placement of the overlay slab." (3) Mellinger also reported that the performance of these sections was evaluated using the partially bonded overlay equation.

The Sharonville heavy-load test sections had a membrane curing compound placed on the existing slabs before the overlays were placed. This would not be considered an adequate separation layer by modern standards, although analysis of strain gauge data from the Sharonville heavy-load sections did confirm that the overlays remained unbonded. According to Mellinger only these three sections were evaluated using the unbonded overlay equation. (3) Thus, only the three points labelled 69, 80, and 81 in Figure 2 can properly be considered unbonded overlay performance results.

Furthermore, the unbonded overlay equation is even more conservative than Figure 2 suggests, for three reasons. First, "coverages to failure" was defined as the coverage level at which the first crack or structural break was observed on the surface of the overlay pavement." Mellinger reported that traffic was actually continued on sections 80 and 81 to 3600 coverages. Second, because sections 80 and 81 were reinforced rather than plain concrete, the actual overlay thicknesses were increased 27 percent for the purpose of evaluating them as equivalent single plain concrete slabs. Design factors for the actual overlay thicknesses would have been 0.95 and 1.06 for these two sections, rather than the design factors 1.04 and 1.18 plotted in Figure 2. Third, the joints in the three unbonded overlay test sections were matched to the joints in the base pavements. Current recommended practice in unbonded overlay construction is to mismatch the overlay joints and base pavement joints by at least three feet, so that edge loads on overlay slabs are supported by the interior of the base slab.

THEORETICAL BASIS AND IMPLICATIONS OF COE EQUATION

Although many engineers have the impression that the square root equation for unbonded overlay design is completely empirical, the comments by Older quoted before indicate that the equation has a theoretical basis. Rollings (1) has demonstrated the derivation of this equation using beam theory. Analogous results would be obtained from plate theory, as other researchers have shown. (4, 5, 6, 7)

To briefly summarize Rollings' derivation, an overlay slab and existing pavement (base) slab which are unbonded may be represented by an equivalent single slab, where "equivalence" may be defined by, among other things, equal surface deflection, equal stress in the overlay slab, or equal stress in the base slab, as shown below:

For surface deflection of the overlay equal to surface deflection of the equivalent single slab:

$$E_e h_e^3 = E_{ol} h_{ol}^3 + E_b h_b^3 \qquad (3)$$

where:

E_e = elastic modulus of equivalent single slab
h_e = thickness of equivalent single slab
E_{ol} = elastic modulus of overlay slab
h_{ol} = thickness of overlay slab
E_b = elastic modulus of base slab
h_b = thickness of base slab

Assuming $E_e = E_{ol} = E_b$:

$$h_e = \sqrt[3]{h_{ol}^3 + h_b^3} \quad (4)$$

For stress in the base slab equal to stress in the equivalent single slab:

$$E_e\, h_b\, h_e^2 = E_{ol}\, h_{ol}^3 + E_b\, h_b^3 \quad (5)$$

Assuming $E_e = E_{ol} = E_b$:

$$h_e = \sqrt{\frac{h_{ol}^3}{h_b} + h_b^2} \quad (6)$$

For stress in the overlay slab equal to stress in the equivalent single slab:

$$E_e\, h_{ol}\, h_e^2 = E_{ol}\, h_{ol}^3 + E_b\, h_b^3 \quad (7)$$

Assuming $E_e = E_{ol} = E_b$:

$$h_e = \sqrt{\frac{h_b^3}{h_{ol}} + h_{ol}^2} \quad (8)$$

Equations 6 and 8 are equivalent to the COE equation when $h_{ol} = h_b$ and $E_e = E_{ol} = E_b$. This implies that when the COE equation is used for unbonded overlay design, the maximum tensile stress in the base slab and in the overlay slab will be equal to the maximum tensile stress in the equivalent single slab (i.e., the required single slab thickness for future traffic loadings) **only when $h_{ol} = h_b$ and $E_e = E_{ol} = E_b$.** To the extent that the overlay thickness and the existing pavement thickness differ, or to the extent that the elastic modulus of the required slab thickness for future traffic and the elastic modulus of the overlay differ from the elastic modulus of the base slab, the COE equation will not produce an overlay thickness which will experience stresses in either the overlay or the base slab equivalent to stresses in the design single slab.

The practical implication of these restrictions is that the COE equation will in some cases give a reasonable approximation of the overlay thickness required to satisfy stress equivalence, but will not satisfy this requirement in such cases as an overlay much thinner or much thicker than the existing pavement, or an existing pavement with a much different elastic modulus than the elastic modulus of the overlay.

Mellinger and other researchers acknowledged the equal moduli implication and offered adjustment equations for base and overlay layers of different flexural strengths. In fact an adjustment for different flexural strengths of the base and overlay layers was made in the analysis of the Corps' field test data shown in Figure 2. (3) However, since that time a flexural strength adjustment has not been consistently applied in conjunction with the Corps' design equation. The unbonded overlay design procedure used by the U. S. Army and Air Force (8) applies a flexural strength adjustment when the strengths differ by more than 100 psi. Use of a flexural strength adjustment in the Federal Aviation Administration's unbonded overlay design procedure (9) was proposed several years ago in a study done by the Corps of Engineers (10), but has not been adopted.

A second observation to be made concerning these equations is that Equation 4 (based on deflection) is not similar in form to Equations 6 and 8 (based on stress) nor to the COE equation. This means that an overlay thickness which provides an "equivalent single slab thickness" from the standpoint of bending stresses will not be equivalent in terms of deflection.

Finally, it is important to note that any beam theory or plate theory derivation of an "equivalent single slab" for an unbonded overlay/pavement system assumes **full contact** between the overlay and the base pavement. They may bend independently, without shear transfer at their interface, but they must have the same radius of curvature.

The practical implication of this is very significant: if the overlay slab curls or warps up from the base slab in response to a temperature or moisture gradient, **it will experience much different and in some situations much greater stresses under combined load and curling than the equivalent thickness equations imply.** The inability to account for the effect of curling on stresses in an unbonded overlay is a major limitation of the COE equation and any other equivalent thickness equations used for unbonded overlay thickness design.

UNBONDED OVERLAY DISTRESS TYPES AND CAUSES

Any approach to design of unbonded overlays is only adequate to the extent that it considers how unbonded overlays perform, and how they fail. Past surveys of field performance indicate that unbonded overlays generally provide very good long-term performance, sometimes as a result of overdesign. Several major field studies of unbonded overlays conducted in recent years (11, 12, 13, 14), along with some case study reports of unbonded overlay performance (15, 16, 17), have identified the key distress types in jointed and continuously reinforced unbonded overlays.

Distress Types and Causes in Jointed Unbonded Overlays

The major load-related distresses in jointed unbonded overlays are corner cracking and transverse or longitudinal linear cracking. These types of slab cracking are manifestations of fatigue damage due to wheel load stress repetitions. Just as in conventional concrete pavements, slab stresses increase when portions of the slab lose contact with the foundation, because of thermal curling, moisture warping, or erosion of the foundation.

A positive (daytime) temperature gradient will curl the slab downward at the corners, reducing support to the slab's transverse and longitudinal edges and adding to edge stresses induced by traffic wheel loads. A negative (nighttime) temperature gradient will curl the slab upward at the corners, reducing support to the slab's corners and adding to corner stresses induced by traffic wheel loads. The magnitude of curling stress caused by a given temperature gradient is a function of the joint spacing and foundation stiffness, among other things.

The key difference between an unbonded concrete overlay and a conventional concrete pavement is that an unbonded overlay rests on a very stiff and fairly unerodible foundation, so that when an unbonded concrete overlay experiences a given temperature gradient, it will curl much more than a concrete slab on a softer foundation would. Curling is a very important contributor to stress in unbonded overlays, and should be accounted for both in thickness design and joint spacing selection. A fatigue analysis based on flat-slab conditions, without consideration of curling, may lead to underdesign.

In some European countries (Germany and Austria, for example), the existing concrete pavement is fractured before a jointed unbonded overlay is placed. (20) This technique, which deserves further consideration, may improve the performance of the overlay by reducing curling stresses and improving uniformity of support.

Under some conditions moisture warping may also contribute significantly to slab deformation and stress. Some research has shown that in concrete pavements in fairly wet climates, moisture contents remain constant through nearly the full slab thickness. (18) This implies that in these regions moisture warping is probably not a significant factor in slab thickness design. However, in drier climates moisture warping appears to contribute significantly to slab deformations, especially at corners, and thus should be considered in design.

Faulting is a fairly minor problem in jointed unbonded overlays when load transfer and an adequate separation layer are used. Unless the separation layer experiences some erosion under traffic loads, faulting is much slower to develop in unbonded overlays than in conventional concrete pavements. According to a recent survey (14), average joint faulting ranged from 0 to 5.6 mm (0 to 0.22 in) on 28 highway unbonded overlays in the United States which had been in service between 2 and 39 years and carried between 0.1 and 26.5 million 80-kN (18,000-pound) equivalent single-axle loads (ESALs). The highest faulting occurred on a project with no dowels, a sand-asphalt separation layer, and expansion joints at 305-m (1000-ft) intervals.

Joint spalling occurs occasionally in unbonded concrete overlays for the same reasons that it occurs in conventional concrete pavements. Joint spalling may be prevented to a large extent by selection of durable aggregates, proper joint sawing procedures, and proper joint sealing and maintenance.

Field surveys indicate that reflection cracking is very uncommon in jointed concrete overlays. Only high-severity distresses such as a badly shattered slab, severe corner break, or large full-depth asphalt patch have much chance of reflecting through a jointed unbonded overlay. An interlayer of an inch or more of hot-mix asphalt concrete, independent slab bending action, and mismatched joints combine to make jointed unbonded overlays much less sensitive to underlying slab condition than asphalt or bonded concrete overlays.

Distress Types and Causes in Continuously Reinforced Unbonded Overlays

The major load-related distresses in continuously reinforced unbonded overlays are transverse crack deterioration and punchouts. In CRC overlays just as in conventional CRC pavements, breakdown of two or more closely spaced transverse cracks must occur before a punchout can occur. Only two of eleven unbonded CRC overlays surveyed in a recent study had any punchouts, while seven had some medium-severity transverse cracks. (14)

The primary cause of these two distresses is excessive deflection due to unrepaired distress or poor joint load transfer in the underlying slab. Due to close spacing of transverse shrinkage cracks, continuously reinforced unbonded overlays are more sensitive to existing slab conditions (specifically, unrepaired distress and poor load transfer) than jointed unbonded overlays. As a result, in many cases CRC overlays require thicker separation layers and more preoverlay repair than jointed overlays. Adequate preoverlay repair includes full-depth concrete patching; field studies have shown that full-depth asphalt patching is not sufficient preoverlay repair to prevent reflection cracking in unbonded CRC overlays. (16)

Some studies have suggested that faulted joints in an overlaid pavement may cause reflection cracking in an unbonded CRC overlay when an inadequate separation layer (e.g., curing compound only) is used, since horizontal expansion and contraction of the overlay may be restrained by the faulted joints. (15, 19) However, transverse crack breakdown has occurred in some CRC overlays at regular intervals matching the underlying joint spacing, even when a separation layer of an inch or more of asphalt was used. (17) This suggests that poor load transfer at the underlying joints, rather than faulting, is the primary cause of the CRC overlay crack deterioration.

Is curling a significant problem in CRC overlays? It seems reasonable to suppose that temperature gradients could cause the slab to curl up, which would increase tensile stress at the top of the slab when loads were applied to the edge. This phenomenon could not, however, create a punchout until two adjacent transverse cracks had broken down and lost load transfer. It also seems reasonable to suppose that curling could contribute to higher deflections and thus to breakdown of transverse cracks.

However, as yet no field studies have demonstrated that punchouts occur in CRC overlays at locations other than at known locations of unrepaired distress or working joints in the underlying pavement. When conventional CRC pavements are placed on strong, unerodible foundations, very little, if any, transverse crack deterioration occurs and thus punchouts generally do not develop, even after many years of heavy truck traffic. An excellent example of this is Belgium's experience: in more than 100 km of CRC pavements built on strong, unerodible foundations more than 20 years ago and subjected to heavy truck traffic, no punchouts have yet developed.

Belgium's CRC pavements are actually comparable to unbonded CRC overlays, since the layers beneath the CRCP are an asphalt concrete separation layer, a lean concrete base, and a granular subbase. Belgium and some other European countries also fracture the existing pavement prior to placement of a CRC overlay, which improves the uniformity of support. (20)

Numerous other examples of excellent long-term performance of CRCP on strong foundations exist in the United States and Europe. Evidently curling does not contribute significantly to crack deterioration or punchouts in continuously reinforced concrete placed on a uniformly strong and durable foundation.

DESIGNING UNBONDED OVERLAYS FOR PERFORMANCE

The preceding review of major distress types suggests a clear direction for design of jointed unbonded overlays and another for continuously reinforced unbonded overlays. The focus of design for jointed unbonded overlays should be designing for the combined effects of load and curling. This requires coordinated selection of the overlay slab thickness and the joints spacing. Reflection cracking has not been shown to be a significant factor in jointed unbonded overlay performance and thus should not be a major concern in thickness design.

Unbonded CRC overlays, on the other hand, experience practically no distress except reflection cracking due to unrepaired distress and poor load transfer in the underlying slab. The focus of thickness design for CRC overlays should be on foundation preparation (preoverlay repair or slab fracturing, and an adequate separation layer) to provide uniform support, and to the extent that this is not done, providing sufficient slab thickness and sufficiently large crack spacing to resist breakdown of cracks above weak areas.

LIMITATIONS OF APPROACHES TO UNBONDED OVERLAY DESIGN

Currently four different approaches to unbonded PCC overlay thickness design exist. The first approach is the Corps of Engineers equation described before, which uses an empirical relationship between unbonded overlay thickness and structural deficiency. The second approach is essentially new design of a PCC pavement, in which the existing pavement structure is characterized as a foundation for the new slab. The third and fourth approaches are to model the overlay and existing slab as either two elastic layers or two plates on a foundation. Each of these approaches has some significant limitations which must be recognized in order to define an improved approach to unbonded overlay design.

Corps of Engineers Design Procedure

The Corps of Engineers method is based on the "square root" equation presented earlier. One of the major limitations of this method is the structural deficiency concept itself; namely, the assumption that an overlay satisfies a structural deficiency between a required single slab thickness and an existing thickness, which implies that

the overlaid pavement will perform the same as the equivalent single slab. Although the structural deficiency approach to overlay design is quite popular, in most cases it represents a considerable extrapolation beyond the performance data which produced the design procedure for the required future slab thickness. The Corps of Engineers field tests were actually among the few cases in which the structural deficiency concept has been tested against overlay performance data. However, as described previously, very few of the pavement sections in the Corps' field tests were truly unbonded overlays, and their actual performance was much better than the square root equation indicates.

A second major limitation of the COE method is the derivation of an equivalent single slab thickness based on bending stresses only, without consideration for overlay slab curling. The COE method is unconservative in this respect, which coupled with its conservatism in other respects makes for unreliable design and somewhat unpredictable performance. If a jointed unbonded overlay is constructed with too long a joint spacing with respect to its slab thickness, it will experience high curling stresses and will develop linear cracks and/or corner breaks prematurely. On the other hand, a jointed unbonded overlay with a sufficiently short joint spacing to minimize curling stresses may be overdesigned using the COE equation, so that it will provide long life and good performance, but may not be cost-competitive with other overlay alternatives.

A third major limitation of the COE approach may be seen by examining Equation 1: for a given required future slab thickness, a thick existing pavement will require a thinner unbonded overlay than a thinner existing pavement in the same condition. This implies that a given thickness of unbonded overlay will perform better on a thicker existing pavement than on a thinner existing pavement. Field performance studies do not support the implication that unbonded overlay performance is affected by existing pavement thickness as the equation suggests.

An example of this is the runway at Grand Forks Air Force Base in North Dakota. (21, 22) The runway was constructed in 1958 and had carried B-52 bomber aircraft traffic for 30 years when it was evaluated for rehabilitation in 1988. The existing pavement was jointed plain concrete, ranging in thickness from 38 to 61 cm (15 to 24 in) in different sections of the runway, and the sections ranged in condition from very poor (PCI of 18) to good (PCI of 57). Based on the extent of load-related distress, it was estimated that 40 percent of the pavement's fatigue life had been consumed. Rehabilitation of the runway was needed to support a significant increase in aircraft loadings, particularly by the heavy B-1 bomber, which has a weight of approximately 100 metric tons (225,000 pounds) on each main gear. A fatigue analysis indicated that a new concrete slab thickness of approximately 51 cm (20 in) was needed to support the expected future traffic loadings.

However, the Corps of Engineers' design approach indicated that little or no unbonded overlay thickness was needed for the runway. According to this procedure, as outlined in Air Force Manual 88-6 (8), no unbonded overlay thickness was obtained for four of the eight sections of the runway, and the overlay thicknesses obtained for the remaining four sections were less than 17.8 cm (7 in). (22) These obviously inadequate designs were obtained because the existing pavement was about as thick as the required future thickness, so that even after application of appropriate condition factors, little or no structural deficiency was indicated using the Corps of Engineers' square root equation.

Design of Unbonded Overlay as New Pavement

This approach involves designing an unbonded overlay as a new PCC pavement. The elastic modulus, modulus of rupture, and load transfer coefficient inputs to the design model are typically the anticipated values for the overlay slab.

In conventional concrete pavement design by plate theory, load-induced interior, free edge, and corner stresses may be computed from Westergaard's equations (23), and curling stresses may be computed in jointed slabs of finite dimensions using the equations developed by Westergaard and Bradbury. (24, 25) However, these equations have some limitations, including:

1. Inability to account for stress reduction due to joint/crack load transfer,
2. Inability to compute responses due to multiple-wheel loads (e.g., dual or dual-tandem gears),
3. Inability to consider the effects of a base layer between the slab and the foundation on deflections and stresses,
4. Inability to accurately compute curling stresses when the slab curls sufficiently to lose contact with the foundation, and
5. Inability to compute correct responses for finite slab sizes for which infinite or semi-infinite slab assumptions do not apply.

Two-dimensional finite element computer analysis programs may be used to overcome these limitations. These programs have been used with great success in conventional concrete pavement design. Among the most powerful capabilities of these programs is the ability to analyze the complex behavior of a slab subjected to both traffic loading and temperature curling.

The most popular of the two-dimensional finite element codes used for concrete pavement analysis (namely, ILLI-SLAB, JSLAB, and FEACONS) were all originally coded to model traffic loadings only. In later modifications, curling analysis subroutines were added to compute deformations and stresses in a slab due to a linear temperature gradient. When combined with stress due to traffic wheel loads, temperature curling stress may result in an increase or decrease in total stress. For example, upward curling of a slab's edges and corners due to a negative (nighttime) temperature gradient produces tensile stress at the top of the slab and compressive stress at the bottom of the slab. This results in an increase in total stress due to a corner load but a decrease in total stress due to an edge load.

Simple superposition of the curling stresses and load stresses either predicted from theory or computed separately by finite element analysis do not match the total combined stresses computed by finite element analysis. The reason that theoretical curling stresses do not match curling stresses computed by finite element analysis is that the Westergaard and Bradbury equations for curling stress assume that even when curled, the slab is in full contact with the foundation. The finite element programs more accurately compute curling stresses by taking into account loss of contact between the slab and foundation.

However, superposition of curling stresses and loading stresses obtained separately from finite element analysis also does not produce total stresses in agreement with finite element analysis of combined load and curling. The reason for this is that load stresses are computed assuming full contact with the subgrade, and are not subsequently modified when the deformations due to temperature curling are computed. This problem may be circumvented using correction equations developed by Darter (26), Salsilli (6), and Lee (27).

As an alternative to finite element analysis, various researchers have developed equations to compute slab stresses and deflections by Westergaard's equations, and also take into account the factors listed above. For example, Foxworthy (28) and Ioannides and Korovesis (29) used ILLI-SLAB to develop equations for the effect of load transfer on edge stress and deflection. Seiler (30) used the H51 computer program (computerized influence charts) to develop equations for edge stress, taking into account degree of joint load transfer, for a variety of multi-wheel aircraft gear. The equivalent slab equations developed by Tabatabaie and others (4, 5, 6, 7) may be used to compute stress and deflection in a slab with a bonded or unbonded base.

These equations may be used to design an unbonded overlay as a new slab with the existing pavement as its foundation. The advantage to this approach is that it does not require access to the type of computer hardware (i.e., mainframe, workstation, or personal computer with 80486 processor) necessary to run any one of the currently available finite element programs. A disadvantage is the problem of selecting an appropriate design k-value to characterize the existing pavement, as described later.

Another disadvantage is that not all of the necessary equations to make this a complete design approach have yet been developed. For example, the equations for edge stress reduction for load transfer for a variety of multi-wheel aircraft gear have only been developed for transverse joint loading conditions. Additional work is needed to develop similar equations for longitudinal joint loading and corner loading. The equations for curling stress calculation (the correction factor for superposition results) have been developed for both positive and negative temperature gradients, but only for edge loading. More work is needed to develop accurate curling stress adjustment equations for corner loading.

Two key differences exist between this approach and the Corps of Engineers approach. The first difference is that the existing pavement is not considered to contribute any structural capacity to the total structural capacity of the overlaid pavement. The existing pavement is instead considered a foundation for the new slab. This leads to the second major difference between the two methods. The k-value of the foundation beneath the existing pavement is used to determine the required future slab thickness in the Corps of Engineers method, whereas the new pavement design method requires a k-value beneath the overlay. The major difficulty in application of the new design approach thus lies in selection of an appropriate design k-value.

Conventional practice in concrete pavement design for many years has been to assign a k-value to a granular or stabilized base which was considerably higher than the k-value of the subgrade, and which was a function of the thickness and stiffness of the base layer. This convention is still employed in the 1986 AASHTO Guide (31) and in the Portland Cement Association design procedure (32). Following this logic, an existing concrete pavement with an asphalt concrete surfacing for a separation layer would be assigned a very high k-value, such as 500 psi/in (138 kPa/mm) or more for unbonded overlay design.

Concrete pavement backcalculation results from field studies have demonstrated that this method for assigning k-values to high-strength bases for PCC pavements yields unrealistically high values for design. (33) It appears that more appropriate design k-values may be selected on the basis of backcalculation results from in-service PCC pavements, and reduced as needed to maintain consistency with a design model derived for static plate-load tests. Specifically, dynamic k-values backcalculated from deflections measured on a concrete slab are typically about two times larger than static k-values obtained from plate load tests on the base.

To assess whether these findings apply to unbonded overlays as well, destructive and nondestructive test data from unbonded overlays were obtained from several sources and analyzed to backcalculate overlay slab elastic moduli and foundation k-values. (34, 35, 36, 37, 38) The backcalculated dynamic k-values were not unusually high, but instead were generally consistent with the k-values which would be assigned to the foundation beneath the existing pavement. In addition, the elastic moduli backcalculated for the overlays were not unusually high, but instead were within the normal range of about 3 to 9 million psi (20,685 to 62,055 MPa), and were generally consistent with strength tests on cores. In a few cases an unusually high backcalculated modulus was obtained for the overlay slab, which indicates that the overlay thickness alone is not the appropriate thickness to use for backcalculation. This may be due to construction variability, or to some degree of bonding between the overlay and the base slab. These results are consistent with other studies which have shown that bonding between a concrete slab and a base layer tends to increase the backcalculated modulus of the slab, but does not appreciably affect the backcalculated k-value.

These backcalculation results indicate that when an unbonded overlay is designed as a new pavement with the existing pavement as its foundation, it is neither necessary nor appropriate to use an extremely high design k-value such as 500 psi/in (138 kPa/mm) or more. A design static k-value in the range of 200 to 400 psi/in (55 to 110 kPa/mm) is probably appropriate in most cases. Whenever possible, deflections should be measured on the existing pavement prior to overlay to backcalculate a dynamic k-value for the existing foundation and to estimate from this a reasonable static k-value for design of the overlay.

Another issue which should be considered is the effect of curling on predicted performance. If a jointed overlay slab is designed as a new pavement with the existing pavement serving as its foundation, it will experience much higher curling stresses than a conventional concrete pavement on a weak foundation. These higher curling stresses may be accurately computed using finite element analysis or available equations. However, if the performance model used to determine the required slab thickness was developed for concrete pavements on weak foundations, the detrimental effect of high curling stresses may not be adequately reflected in the predicted performance of the overlay. This would be true if, for example, the AASHTO or FAA design procedure were used to determine the required future slab thickness, rather than a fatigue analysis which directly considered combined load and curling effects. Either increased slab thickness or reduced joint spacing may be necessary to achieve the performance from the unbonded overlay that is predicted by the model.

Unbonded Overlay Design by Multilayer Elastic or Plate Theory

A third approach to unbonded overlay design is to use either elastic layer theory or plate theory/finite element analysis to model the overlay and the base slab on the existing foundation. This is arguably the most appropriate, but also the most difficult, of the three main unbonded overlay design methodologies described here. The basic approach is the same as for design of the overlay as a new pavement, except that the existing pavement structure is characterized more realistically not as a uniform foundation but as a multilayered system.

Although similar in concept, the actual application of this methodology in unbonded overlay design is considerably more difficult than in new pavement design. Among the difficulties associated with this approach are:

1. Characterizing the existing slab, including deciding how (if at all) to account for existing deterioration,

2. Identifying the important structural responses (e.g., overlay stress, overlay deflection, base slab stress, etc.), and

3. Identifying the important performance criteria (e.g., cracking in the overlay and/or cracking in the base slab).

Unbonded Overlay Design by Elastic Layer Theory

Several researchers have proposed methods for designing multilayer pavement structures, including unbonded concrete overlays, using elastic layer theory. (39, 40, 41, 42, 43, 44) The most complete development of an unbonded overlay design procedure based on elastic theory was done by Rollings of the Corps of Engineers Waterways Experiment Station. (1) This research, which included a thorough review of the available performance data from the Corps of Engineers full-scale field tests, is briefly summarized below.

The existing pavement is characterized by an effective elastic modulus which reflects the extent of cracking present. This is an alternative to the approach used with the empirical Corps of Engineers method, in which the effective slab thickness is reduced in accordance with the extent of cracking. The structural condition of the existing pavement is described by the Structural Condition Index (SCI), which is the load-related distress component of the Pavement Condition Index (PCI) rating developed by Shahin, Darter, and Kohn. (45) An empirical relationship between SCI and backcalculated PCC modulus of cracked slabs is used to determine the effective PCC modulus as a function of slab fragment size.

Rollings suggests that after an unbonded overlay is placed, the base slab continues to deteriorate and that its elastic modulus continues to decline. He further suggests that this decline in base slab modulus results in a progressive lessening of support to the overlay slab. This hypothesis is illustrated schematically in Figure 3, from Reference 1.

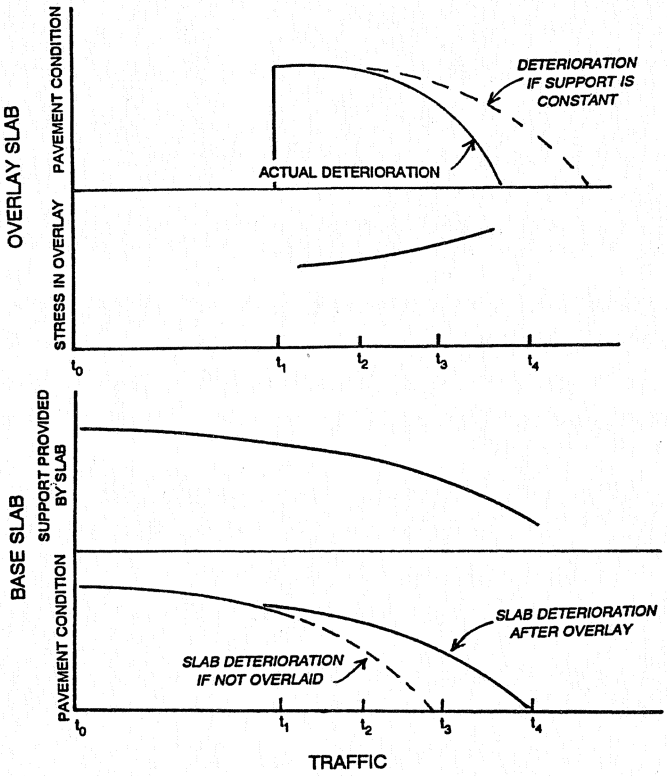


Figure 3. Rollings' model for deterioration of PCC pavement and unbonded PCC overlay. (1)

The future design life of the overlay is divided into time intervals, and the traffic loadings anticipated over the design life are divided according to these time intervals. For each interval, the modulus of the base slab is predicted, and bending stresses in the base pavement and in the overlay are computed. Adjustment factors are used to convert stresses computed by elastic layer theory to edge stresses at joints and cracks in the base slab and overlay slab. According to Rollings, a load transfer adjustment need only be applied to stress in the base slab if the measured deflection load transfer is less than 25 percent, and no load transfer adjustment is needed for stress in the overlay. The adjusted stresses in the base and overlay slabs are then used to predict the loss of SCI over the time interval. If the total loss of SCI over the design life is excessive, a greater trial overlay thickness is selected and the analysis is repeated.

A major limitation of this approach to unbonded overlay design is the reliance on an empirical relationship between existing slab cracking and existing slab elastic modulus, coupled with reliance on the hypothesis that the elastic modulus of the base slab declines over time after overlay and thus offers progressively less support to the overlay. It has not been demonstrated by field studies that unbonded overlay performance is as sensitive to either existing slab modulus or existing slab cracking as this procedure suggests.

The other major limitations of the elastic layer theory approach are the inability to compute curling stresses in the overlay slab and the inability to directly compute edge and corner stresses in the overlay.

Unbonded Overlay Design by Multislab Finite Element Analysis

The fourth approach to unbonded overlay design is to use finite element analysis to model the existing pavement and the overlay as slabs resting on the existing pavement's foundation. This permits direct consideration of factors such as load transfer efficiency and multi-wheel gear, just as for single-slab finite element analysis. The difference is that the existing slab is more realistically modelled as a layer, characterized by a thickness and elastic modulus, than as a dense liquid foundation. This approach permits reasonably accurate computation of stresses in both the overlay and the base slab, at least for traffic loading only. An example of this approach using the JSLAB finite element program has been documented by Tayabji and Okamoto. (46) A comparison of the results of this method (for traffic loading only) with those obtained from the Corps of Engineers equation is shown in Figure 4. JSLAB was used to compute stresses in unbonded overlays systems and slabs on grade under an 80-kN (18-kip) single-axle load. The overlay design thicknesses obtained were those which produced free edge stress in the overlay slab equal to the stress computed in the single slab. The overlay thicknesses are similar to those obtained from the COE equation. Curling stresses, however, are not considered.

It is important for designers who take this approach to be aware that none of the two-dimensional finite element programs commonly used for concrete pavement analysis can correctly model curling for two slabs above the foundation. In ILLI-SLAB, for example, a user may enter two bonded or unbonded layers above the subgrade, with a different linear temperature gradient for each layer. However, ILLI-SLAB actually converts these gradients to one single linear temperature gradient through both layers, with the result that both layers curl together and remain in full contact. This is not so much a specific flaw of ILLI-SLAB or the similar programs as a fundamental inability of two-dimensional finite element analysis to model separation between two layers above the foundation.

The only evident solution to this dilemma when using two-dimensional finite element analysis to design an unbonded overlay is to model two slabs above the foundation only for analysis of traffic loading effects, and to model only one slab above the foundation for analysis of temperature curling effects. A relatively high k-value should

Resurfacing Thickness Determined Using JSLAB:

Required Thickness, in	Existing Thickness, in	Resurfacing Thickness, in		
		Case 1	Case 2	Case 3
8	8	6.8	min 6.0	min 6.0
	7	7.2	6.0	6.0
	6	7.6	6.8	6.0
10	9	9.0	7.0	min 6.0
	8	9.2	7.8	6.0
	7	9.4	8.8	8.0
12	9	11.5	10.4	9.0
	8	11.7	10.8	10.0
	7	11.8	11.2	10.8

Resurfacing Thickness Determined Using Corps of Engineers' Equation:

Required Thickness, in	Existing Thickness, in	Resurfacing Thickness, in		
		c = 0.35	c = 0.60	c = 0.80
8	8	6.5	min 6.0	min 6.0
	7	6.8	min 6.0	min 6.0
	6	7.2	6.5	6.0
10	9	8.5	7.2	6.0
	8	8.5	7.9	7.0
	7	9.1	8.4	7.8
12	9	10.8	9.8	8.9
	8	11.0	10.3	9.6
	7	11.3	10.7	10.2

Note: Case 1, Case 2, and Case 3 correspond to levels of cracking in existing slab corresponding to COE condition factor (c) levels of 0.35, 0.60, and 0.80, respectively.

Figure 4. Comparison of unbonded overlay design thicknesses from JSLAB and from Corps of Engineers equation. (46)

be used for the subgrade in this single-slab curling analysis. If a low k-value is used, the finite element program will compute a larger settlement of the slab (due to its own weight) into the subgrade, thus underestimating the size of the unsupported region of the slab and underestimating the curling stress.

In unbonded overlay design by multislab finite element analysis, the major question the designer must answer is what to select as the critical structural response: bending stress in the overlay, or bending stress in the slab. Seiler has shown that for free edge loading without curling, the ratio of maximum tensile stresses in the overlay and base slab is equal to the ratio of modulus times thickness ($E_{ol}\ h_{ol}$) of the overlay to modulus times thickness ($E_b\ h_b$) of the base slab. (22) This finding is useful in identifying not only which layer will have the higher stress, but which layer will suffer the greater fatigue damage (assuming the elastic moduli differ) from a given number of traffic loadings, as shown below:

$$\frac{\sigma_{ol}}{\sigma_b} = \frac{E_{ol}\ h_{ol}}{E_b\ h_b} \tag{9}$$

$$\frac{E_{ol}}{E_b} = \frac{MR_{ol}}{MR_b} \tag{10}$$

$$\frac{\log_{10} N_{ol}}{\log_{10} N_b} = \frac{2.13 \left[\frac{MR_{ol}}{\sigma_{ol}}\right]^{1.2}}{2.13 \left[\frac{MR_b}{\sigma_b}\right]^{1.2}} \tag{11}$$

$$\left[\frac{\log_{10} N_{ol}}{\log_{10} N_b}\right]^{0.83} = \frac{\left[\frac{MR_{ol}}{\sigma_{ol}}\right]}{\left[\frac{MR_b}{\sigma_b}\right]} \tag{12}$$

$$= \frac{MR_{ol}}{MR_b}\ \frac{\sigma_b}{\sigma_{ol}} \tag{13}$$

$$= \frac{E_{ol}}{E_b}\ \frac{\sigma_b}{\sigma_{ol}} \tag{14}$$

$$= \frac{E_{ol}}{E_b} \left[\frac{E_b\ h_b}{E_{ol}\ h_{ol}}\right] \tag{15}$$

$$= \frac{h_b}{h_{ol}} \tag{16}$$

where σ = maximum tensile stress
E = concrete modulus of elasticity
h = slab thickness
MR = concrete modulus of rupture
N = allowable coverages to failure

These equations indicate that the ratio of overlay fatigue to base slab fatigue is proportional to the ratio of base thickness to overlay thickness. Thus, for a given trial thickness of the overlay and known thickness of the base slab, the designer may determine which layer will experience the greater fatigue damage from a given number of load repetitions.

It then becomes a matter of the designer's judgement whether to design the unbonded overlay considering (a) fatigue in the overlay only, (b) fatigue in the base slab only, or (c) fatigue in both layers. Engineers who do a great deal of unbonded overlay analysis and design would probably choose the first or third option, since consumption of the base slab's fatigue life will not necessarily cause failure of the overlay. If the third option is chosen, a higher fatigue limit for the base slab (e.g., a Miner's damage ratio, applied coverages versus allowable coverages, of two or more) is often used.

CONCLUSIONS AND RECOMMENDATIONS FOR IMPROVED DESIGN OF UNBONDED OVERLAYS

The traditional method used to design unbonded concrete overlays is unreliable, often unduly conservative, constrained by unreasonable assumptions, weakly validated by field testing, and unresponsive to the performance characteristics of jointed and continuously reinforced unbonded overlays.

The findings of numerous performance reviews indicate that jointed unbonded overlays should be designed for combined load and curling effects, while CRC overlays should be designed for loading only. Jointed unbonded overlay design requires special consideration of the effect of a stiff foundation on high curling stresses in the overlay. CRC overlays should be designed with special consideration to preoverlay repair requirements and overlay crack spacing in order to prevent reflective cracking.

Unbonded concrete overlay design must consider several important factors, including:

- Number, magnitude, geometry, and placement of traffic loadings;
- Overlay strength and stiffness;
- Overlay joint spacing;
- Overlay joint load transfer (for JCP overlays);
- Base pavement joint/crack load transfer (for CRC overlays);
- Stiffness and uniformity of support to overlay, especially for CRC overlays;
- Curling stresses due to temperature gradients; and
- Edge loading and corner loading conditions.

Four different unbonded overlay design approaches were reviewed in this paper: the traditional Corps of Engineers equation, multilayer design by elastic layer theory, new pavement design by plate theory, and multilayer design by plate theory/finite element analysis. The first two approaches are shown to be severely limited in several respects. The other two approaches have fewer limitations and are well suited to considering the effects of complex loading geometries, support conditions, curling, joint spacing, and load transfer.

However, selection of either the new pavement approach or the multislab finite element approach raises specific questions the designer must answer. A major concern with the new pavement approach is how to characterize the support conditions (i.e., selection of a design k-value). A major concern with the multislab finite element approach is how to correctly compute curling stresses.

In order to make either of these two approaches complete, additional research is needed to develop equations for corner curling stresses, and equations for stress reduction by partial load transfer for longitudinal joint loading and corner loading conditions. In the short term, two-dimensional finite element analysis may be used for these purposes.

In the longer term, however, three-dimensional finite element analysis will be needed to correctly model curling in unbonded overlays, as well as to validate the various design equations for slab size effects, curling, load transfer, etc., which have been developed from two-dimensional finite element analysis. This long-term direction does not require developing a new pavement analysis code from scratch: very powerful three-dimensional finite element software packages, possessing all of the capabilities needed to analyze the factors mentioned here, are available and could be employed. Ideally, new design equations and design curves should be developed from 3-D finite element analysis to reduce reliance on this computationally demanding tool.

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