CONCRETE PAVEMENT DESIGN: IT'S MORE THAN A THICKNESS DESIGN CHART

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ABSTRACT

Many aspects must be considered in developing an adequate concrete pavement design besides the selection of the pavement thickness. This paper examines some of these aspects of design and illustrates them with examples drawn from the author's experience. Among the topics covered are: an understanding of the basis of existing empirical pavement design practices, effect of site conditions, awareness of the basis of design tools and equations, appreciation of the difference between design simplification and actual field complexity, the crucial role of pavement materials, and the impact of construction on pavement performance.

INTRODUCTION

Thickness design of concrete pavements is amenable to theoretical treatment. One may calculate stresses in the pavement using some analytical model that can incorporate modern very complex aircraft landing gears. The calculated stresses are then compared to some fatigue relation based on laboratory beam specimens, full-scale airfield trafficking field tests, road tests, etc. to select a pavement design thickness. This type of analysis is the mainstay of rigid pavement design trends today. The advent of modern computers makes even very sophisticated modeling tools available to any practitioner or researcher who wishes to make use of them.

The author has spent much of his professional career trying to understand and develop improved design analysis for military airfields and similar heavy-load pavements and personally believes sound theoretical analysis is the fundamental foundation upon which all pavement design should be based. During a career now approaching three decades, the author has progressively worked through modeling technology of Westergaard-type models, layered elastic theory, and finite element modeling for a spectrum of pavements.[1-8] Another aspect of the author's professional work has been to investigate field failures and disputes concerning design, materials, or construction associated with predominately military airfield pavements.[9-17] Over time, it has become apparent that our problems in the field are almost never due to a thickness design error, but usually are human errors where we misuse our design tools and fail to deal adequately with the site conditions, materials or construction processes. However, we have increasingly concentrated our research and education on honing our thickness design sophistication to a fine edge but often neglect other aspects that are the source of most of our real problems in the field. In this paper, the author would like to share observations on sources of military airfield rigid pavement design problems that he has encountered in practice.

LEARN AND ASSIMILATE WHAT WE ALREADY KNOW

Modern pavement design and construction is evolutionary rather than revolutionary. This technology has evolved from a mix of theoretical studies, laboratory and model investigations, full-scale tests, and observations and measurement of field performance. It is a pragmatic blend of theory and practice that developed from the efforts of a broad spectrum of people in academia, the construction and materials industry, government agencies, and consulting. This is a rich heritage we inherit from very bright people, and it behooves us to build upon this knowledge rather than through our ignorance of past efforts replow the same fields again and again.

Reinforcing Steel: What It Can and Cannot Do

Military airfield experience has generally found unreinforced concrete pavements with short joint spacing and doweled longitudinal construction joints to be the most cost-effective and best-performing concrete pavement for normal circumstances. Periodically, one hears at professional society meetings and finds papers proposing use of "active" reinforcing steel in pavements. By moving the steel from the approximate middle of the slab where it is conventionally placed when used in pavements to the lower portion of the slab, these proposers envision the steel taking tensile stresses as the slab is bent in flexure by traffic loads. In this manner, the steel handles tension where concrete is weak, and the concrete is relied upon to withstand only compressive stress where it is strongest. Such a concept of behavior is used very effectively by our colleagues in structural design of concrete, and usually this concept is presented as if the pavements community is a dinosaur not to embrace the concept on the spot.

Unfortunately, such proponents have apparently never bothered to study actual pavement behavior or previous tests. The concept of "active" reinforcing was extensively tried in the 1940s and 1950s, but unfortunately, it did not work. Addition of steel did not slow the formation of cracking in the pavement. Since the crack became the focus of further deterioration such as spalling that generated debris that posed a hazard to aircraft, the steel did not provide the structural value for the military airfield designer that it did for our structural engineering colleagues. Consequently, reinforcing's function in pavements shifted from "active" reinforcing to keeping cracks that might form (e.g., in odd-shaped slabs or slabs with inclusion such as refueling hydrants where cracking is geometrically normally unavoidable) closed so that deterioration of the crack is slowed. In this role, it functions best near the middle of the slab, not at the extreme fibers. These experiences were gained in laboratory model tests and full-scale trafficking tests and reported in the readily available professional literature.[1, 18, 19, 20] Similar experience was developed from the highway civil aviation industry. The proponents of "*active*" reinforcing never bothered to learn why the pavements community uses reinforcing differently from structural engineers, and worst of all, they never bothered to validate their concepts through test, experimentation, or theoretical modeling matched to field measurements.

Dowel bars have been the topic of extensive research and discussion by the pavements community for well over a half-century because they provide a crucial structural purpose (particularly important in airfield pavement design) and have repeatedly been shown to improve pavement performance. The existing round, smooth dowel bar has survived out of literally hundreds of proprietary load transfer devices that were marketed and evaluated by the Bureau of Public Roads/Federal Highway Administration during the 1930s to the 1960s. During these investigations, dowel looseness has been repeatedly shown to be highly detrimental to load transfer which is a crucial dowel function, particularly in military airfield design. Today, there is at least one new proposed dowel shape and a variety of plastic sleeves to go around conventional and the proprietary dowels that are actively being promoted. The author has yet to see one piece of factual data assessing whether these will have an adverse effect on the dowel structural capacity. The concern is that looseness at the plastic sheath/dowel interface or simply the mismatch of material stiffness with their modulus values of 200,000 MPa, 28,000 to 41,000 MPa, and 6,900 to 13,800 MPa (29 million, 4 to 6 million, and 1 to 2 million psi) for steel, concrete, and plastic respectively will cause a drastic reduction in load transfer. Such products cannot be accepted for use until factual data is developed showing their effective performance envelopes so that the designer can know how and where to use them. Less marketing and more well-designed experimentation are needed before these new products can be used intelligently. It is simply a fact of life that no statement about a product by a manufacturer or proponent with a financial stake in the product can be accepted at face value without independent testing. Ignore this at your own risk.

Simple Geometry Can Trip You Up

Concrete slabs have very specific "*preferences*" for how they wish to exist in the field. Generally, the slab will crack unless it is essentially square and if the dimensions between joints are excessive for the slab thickness. One may write equations incorporating the effects of factors such as thermal changes and subgrade restraint friction, but these neglect other significant factors. Consequently, in practice, slab dimensions are selected by rules of thumb not theory. The traditional Air Force and Army military airfield rules for slab length and width were 4.6 m (15 ft.) maximum for slabs less than 225-mm (9-in.) thick, 6.1 m (20 ft.) for slabs 225- to 300-mm (9- to 12-in.) thick, and 7.6 m (25 ft.) for slabs 300-mm (12-in.) or more thick. Failure to adhere to these rules, which date back over a half-century, generally results in slab cracking soon after placement. On a recent project at Reese AFB, almost every slab cracked shortly after placement simply because the designer had specified a slab length that was excessive for the slab thickness.

In the early 1980s, the Air Force Major Command Pavement Engineers felt they were seeing too many cracked 7.6 m (25 ft) slabs and made a policy decision to limit the maximum size of slabs to 6.1 m (20 ft). This pragmatic exercise of observation and engineering judgement would later be validated by a formal FAA study that verified that cracking was more prevalent in larger airfield slabs. A common detailing error that arises periodically occurs when the designer dimensions a partially-bonded rigid overlay to match the underlying slab joints without considering the overlay thickness. Often the overlay is thinner than the original pavement and too thin for the original slab dimensions. If placed to match the underlying joints anyway, the overlay soon suffers from *"unexplained"* cracking that is really simply caused by excessive slab dimensions for the overlay thickness. With the Air Force's new policy on maximum slab dimensions, the designer is often faced with the problem of how to detail joints for a partially bonded overlay for an old pavement with 7.6 m (25 ft) slabs. The choices are essentially to quarter the old slab with 3.8 m (12.5 ft) joints in the overlay or reinforce the slab to slow the deterioration of the cracks that otherwise will form.

A series of unfortunate experiences with cracked airfield pavements in the 1940s and 1950s convinced the Corps of Engineers that slabs that were crowned in the center, although often convenient for achieving the desired pavement crown, had an unfortunate tendency to crack down the axis of the crown. Such detailing was abandoned, but in the 1980s a new concrete runway at Travis AFB was crowned in the center to conveniently accommodate the slab size, runway width, and runway transverse slope. The crown occurred in the middle of the center row of slabs, and we now have a 3,048-m (10,000-ft) long runway centerline crack from what is still sometimes ascribed to an "*act of God*" rather than poor slab geometry that is the actual cause.

New parking areas for the C-17 aircraft at Charleston AFB began showing centerline cracking in the middle slabs of the parking lane for each aircraft. The nose gear of the airplane travels directly along the slab centerline where the crack forms. These are slow taxiing aircraft approaching and leaving their designated parking spot on the ramp so traffic is very concentrated with negligible wander. Because of the particular slab dimensions at this site and the C-17 gear configuration, two of the 6 tires on each main gear traffic both outside edges of the center slab with the cracks. Initially, we thought the problem arose because of a rapid and large stress reversal from a positive moment (tension on the bottom of slab) at the centerline under the passage of the relatively light nose wheel to a larger negative moment (tension on the top of the slab) at the centerline caused by the trailing heavily loaded main gear tires on the outside slab edge. While it was an interesting theory, a finite element analysis of the problem found the stresses involved were well below what we would anticipate causing cracking at such an early age. A more careful examination of the site and plans found that each parking slot was crowned in the center so the center slab ended up crowned in the center. Once again this simple geometric detail was probably the cause of our mysterious cracks.

APPRECIATE THE INDIVIDUAL SITE CONDITIONS

We must build on sites created by nature and modified over time by man, and we must build with materials largely shaped by the whimsical forces of nature. Failure to appreciate the complexity this adds to our job provides us with the opportunity to participate in a variety of interesting but embarrassing debacles.

We are Slaves of Geology

In the early 1980s the author participated in the construction of a military airfield in a very arid portion of the Middle East. Twice during construction, flooding disrupted the work. A senior engineer from the engineering design firm was flown to the site. After touring the fiasco of the flooded site, he reiterated that the minimal drainage provisions in his firm's original design were correct, and the floods were a rare act of God in this remote arid site.

Recently, the author returned to the site to participate in the redesign investigation for the facility as the primary runway and taxiway flooded under water every few years and despite relatively light traffic, the runway and taxiway had major shear failures that had closed them to heavy military aircraft. The runway and taxiway had been built in a playa - a dry desert lake bed - within a closed basin. While the region is arid, the limited rainfall, averaging only 75 mm (3-in.) per year, comes rapidly in a few violent storms. As is common in closed basin desert geomorphology, the run-off is high, and it all collects in the playa. There it sits until removed by slow infiltration into the fine-grained playa soils or evaporation. We now face the daunting challenge of installing massive pumps to remove this playa lake when it forms and drowns the runway or building up the pavements several meters to get out of the intermittent lake waters. The only reason we face this issue is the original design firm from the Midwestern U.S. failed to appreciate the problems inherent in building in a desert playa. One also wonders, if the engineer's avowal that their original design was correct in the face of floods during construction represented a poor professional judgement or was it simply insuring that the firm was not held accountable for its error and ignorance in the design.

During placement of the concrete end of a runway at Travis AFB, placement proceeded with great difficulty. The concrete workability was poor, finishing was difficult, and the contractor was forced to repeatedly make adjustments to the mix proportions and placed the concrete only with great difficulty. With so much handwork and placement difficulty, it was not surprising when the pavement began spalling and showing similar durability problems soon after construction. An investigation found that the concrete coarse aggregate came from an igneous quarry in the nearby mountains. The quarry is in a confined working area and is very complex geologically with portions being partially metamorphosed. The aggregates from the quarry were tested and passed the required tests prior to construction. Some months after this testing when actual production of aggregates for the Travis project was underway, quarrying had shifted to a different portion of the quarry where the rock had been partially metamorphosed. The difference would be apparent visually only to a geologist or very experienced materials person. It turned out that aggregates from this portion of the quarry have the unfortunate characteristic of releasing smectite clay when exposed to water. This very plastic clay mineral was found throughout the concrete matrix and was the source of the peculiar mix characteristics that caused the construction problems that led ultimately to the spalling and unsatisfactory performance of the pavement.

Know the Site History and Its Significance

A newly placed runway porous friction course at Spangdahlem Airbase performed poorly and was removed along with a small amount of the underlying dense-graded asphaltic concrete one year after placement. This was to be replaced by a layer of dense-graded asphaltic concrete and then a new porous friction course. As the dense-graded asphaltic concrete layer was being placed, severe blistering developed in the newly placed material, and construction was brought to a halt. The resulting intense investigation of the problem found that the original pavement was portland cement concrete placed in the 1950s and then periodically overlayed to considerable thickness over the next 30 years as missions changed and the surface aged. Sometime in the 1960s, the side drains were reworked so that a concrete drainage box extended from the original concrete up to the surface on the edges of the runway. At this point, the thick asphaltic concrete on the runway was trapped in an impermeable bathtub formed by the original portland cement concrete at the bottom and the portland cement concrete drains on the edges. Contrary to popular opinion, asphaltic concrete is not impermeable. Its field permeability is strongly influenced by placement density and the quality of the longitudinal construction joints. In old pavements such as this, cracking exists which aids water infiltration. Coring found extensive water deposits in the asphaltic concrete distributed in an erratic three-dimensional pattern that could not be drained. This water had caused stripping in some layers and provided the reservoir of water to cause blistering when the hot asphaltic concrete was placed on the surface. A redesign of the overlay included an initial porous layer that was able to bleed the vapor off during paving and prevent blistering during placement of the overlying dense graded overlay.. The overlay was successfully placed before the onset of winter, but it was a very close run. This critical airbase was almost closed to operations over a winter when international tensions in this region were at a crisis level. All of this occurred because we had built a bathtub and trapped water. This geometry of portland cement concrete overlaid with asphaltic concrete between impermeable sides is not uncommon on some of our older military facilities.

UNDERSTAND OUR DESIGN TOOLS

Design methods for pavements have evolved to meet specific requirements of various agencies. Design aids such as computer programs, nomographs, design charts, etc. have also been developed that ease the tedium of design and speed the necessary calculations. Inherent in all such systems are basic assumptions and premises upon which they are built. To use these tools effectively one must remember their fundamental assumptions and limitations.

Misuse of a Design Aid

A power check pad at Tyndall AFB had to be expanded because a new mission aircraft required a larger pad to allow it to taxi onto the pad, operate engines for maintenance, and then turn and taxi back off the pad. A newly assigned lieutenant fresh from college was given the task of designing the expansion of the pad by several rows of slabs to accommodate the new aircraft.

Not long after the project construction was complete, the outer ring of slabs began cracking and rapidly the cracking grew progressively worse. Upon investigation, it was learned that the thickness for the new slabs had been selected from the design charts in the Air Force airfield design manual. These concrete pavement design charts are based on the premise that a portion of the load at the slab edge will be carried through load transfer from dowels, keys, aggregate interlock, etc. by the adjacent slab. Such conditions are routinely met on airfield pavements where aircraft gear do not normally go near the edge of runways, taxiways, ramps, etc. In the case of the power check pad, the turning aircraft’s main gear does traffic next to the edge of the pavement creating a true free-edge condition. The actual stress state in this condition is thirty-three percent greater than the condition for which the design chart is intended. The rapid deterioration was simply due to over loading and could have been prevented by providing a standard thickened-edge detail at the outside slab edge.

Errors like this by a new engineering graduate who is using a specific design tool for the first time are not unexpected. The real failure here was not the young engineer's mistake, but rather was the management of the engineer which failed to provide proper technical oversight, review of his design products, and training in how to use a specific design tool which he probably never had seen before even in a college pavements course had he had one.

Know the Basis of the Equation

In the 1950s the military had to radically increase the structural capacity of many existing airfield pavements to accommodate the new very heavy B-47 and B-52 strategic jet bombers. An accelerated program of testing developed the Corps of Engineers rigid and flexible overlay equations for rigid pavements. These equations are of the form

$$h_o^n = h_r^n - C_1 h_e^n \quad \text{and} \quad t = 2.5\,(F\,h_r - C_2 h_e)$$

where h_o is the rigid overlay thickness, t is the flexible overlay thickness, h_r is the total required concrete thickness if no pavement existed, h_e is the thickness of actual existing pavement to be overlaid, the C factors reflect the structural condition of the existing pavement, n is a power whose value varies depending on the bond between the rigid overlay and the base pavement, and F is an adjustment factor to be discussed further in a minute.

These equations are empirical since the analytical tools of the period were inadequate for treating the complex situation of overlays explicitly. The details of their origin and use are described elsewhere,[4,5] and the equations are widely used around the world for design of overlays. Because these are empirical equations, their range of validity is limited to that covered in the original tests, and this sometimes leads to anomalies such as calculating negative numbers for flexible overlays. This invariably causes consternation, but actually reflects the historical premise used to develop these equations.

At the time of the development of these equations, the Air Force was concerned that spalling on concrete pavements could lead to damage by debris being ingested in their newly deployed jet engines. Hence failure for the rigid overlay test items which formed the basis for the empirical equation was defined to be initial cracking in the slab. No such concern existed with asphaltic concrete so failure for the flexible overlays was defined to be the onset of structural failure of the subgrade (large visible surface deflection indicating imminent catastrophic shear failure). The F factor in the flexible overlay equation essentially adjusts the required concrete pavement thickness to a point where the slab is shattered into approximately 35 pieces at the end of the design traffic, and major structural failure of the subgrade is impending. It is this failure definition that results in the negative numbers as the flexible overlay equation drastically reduces the required concrete thickness to allow this shattering of the rigid pavement and subgrade failure to develop. The flexible and rigid overlay equations are based on vastly different levels of performance: initial cracking for rigid and borderline massive subgrade failure for flexible. Obviously, designs based on these equations should never be compared directly to one another for cost as they provide grossly different levels of performance. Nevertheless, such comparisons are routine.

Grasp the Implications of the Assumptions

Many texts on pavement design make a comment to the effect that the strength of the subgrade is relatively unimportant in rigid pavement design. The genesis of this type of statement is readily seen in Westergaard-type formulas where the subgrade strength in terms of the modulus of subgrade reaction only appears in the terms containing the radius of relative stiffness. The radius of relative stiffness is within a logarithmic expression, and the modulus of subgrade reaction only affects the radius of relative stiffness as the fourth root of its location in the denominator. Even relatively large changes in the numerical value of subgrade strength will be greatly reduced by the time one takes a fourth root and then a logarithm. Consequently, these theoretical formulations show the subgrade strength to have a relatively minor effect upon the pavement stress calculations. And indeed if one looks at instrumentation data from pavements, the bulk of the load is carried by slab bending, and the stresses applied to the subgrade are quite low. Hence, the subgrade is not normally even checked nor seriously considered in rigid pavement design calculations.

This counterintuitive statement that subgrade strength is relatively unimportant in rigid pavement holds up to the point where cracking begins. As cracking begins, the stiffness of the slab is reduced and loading on the subgrade increases. If one carries this to the extreme where the slab is broken into brick size units, the result is essentially a concrete paver surfaced pavement which are conventionally designed as flexible pavements not rigid ones. Now the subgrade strength has become the dominant factor. Many design methods use the onset of cracking to be the design failure condition. This is reasonable as this is the point where accelerated deterioration is likely to start, and it is also the point where the “infinite” slab assumption of Westergaard and layered elastic models begins to break down. Up to the point where cracking begins, the impact of subgrade strength on rigid pavements is minor, but after cracking begins, subgrade strength assumes an increasingly important role. The military allows a pavement thickness reduction for what it rates as high-strength subgrades to try to take advantage of this superior post-cracking behavior.[1]

Today we are increasingly likely to be asked to evaluate an existing pavement or to estimate its remaining life rather than simply develop a new design. Normally, we carry out such evaluations by simply reversing our design calculation methodology. If I am dealing with a rigid pavement that has cracks, my conventional Westergaard and layered elastic models really do not apply well, and my conventional analysis ignores any potential adverse effect of subgrade soils in this post-cracking zone where their impact is increasing in importance. This is routinely ignored in pavement structural evaluations.

DO NOT MISTAKE SOPHISTICATED ANALYSIS FOR THE TRUTH

Classical concrete pavement thickness design calculates a thickness to resist traffic load and neglects all other contributions to the stress conditions. These additional stresses are recognized as important and have been the topic of considerable analysis and discussion. In fact, soon after Professor Westergaard first developed his pioneering analytical solution to an infinite pavement slab on a spring foundation in the 1926, he returned the following year to the pavement issue and developed solutions for effects of temperature gradients on pavement slabs as the next pressing issue.[21, 22] These temperature effect solutions were popularized by Bradbury in the 1930s,[23] and these solutions are reproduced in all of the standard pavement texts. Students taking a college pavement course often grind through the calculations for daytime and nighttime temperature changes and upward and downward curled slabs. However, such calculations have not penetrated from academia into practice, and environmental effects are lumped into the slab size limitations discussed earlier in actual design practice. Today's analytical technology allows very sophisticated consideration of these effects, and these calculations of temperature induced daytime and nighttime curling are beginning to appear in consultant's reports although I am unaware of any agency embracing these calculations for design yet.

On a recent design project for a new mission at an airbase in the Southeast, the consultant submitted a design that was based on a comprehensive finite element analysis with consideration of daily temperature gradients at the site. The only problem with the analysis was the result was 20 percent thicker than the Air Force's standard design procedure provided for this aircraft for these site conditions. The consultant adamantly insisted his answer was the correct one, and environmental stresses alone would crack the pavement if the agency's design was used. Unfortunately for the consultant, the Air Force had designed numerous pavements for this particular aircraft under even more severe environmental conditions with never a problem like he postulated. The project with the agency's design has now been down for several without any of the supposed environmental cracking problems. The consultant had solved an interesting problem in cyberspace, but his client needed an answer that dealt with airplanes, concrete, and dirt.

We can calculate effects of daily variation in temperature and its effect upon the pavement slab with great sophistication today. Because we can calculate this factor we concentrate on it to the exclusion of other sources of curling problems in pavements. If we examine the potential sources of curling in our pavement we find these include at least

(1) Early-age curling from adverse thermal gradients at the time of setting. This is a permanent curl occurring soon after placement and tending to curl the pavement upwards. Some classical experimental work by the Michigan Highway Department in the 1940s[24] clearly shows the importance of this factor, but one seldom sees it discussed in technical literature today.

(2) Drying shrinkage that begins at the cessation of curing and approaches some asymptotic value dependent on local climatic conditions. Part of this shrinkage is irreversible. Modern concrete mixtures are using ever larger volumes and types of admixtures that often increase shrinkage. Hence current mixture practices may adversely influence curling in the field, but this topic has received little attention to date. Pavement slabs tend to dry readily from the surface and remain moist on the underside so the general trend will be upward curling.

(3) Cyclic temperature and moisture gradients from varying environmental conditions. These fluctuating gradients are caused by moment to moment variations in environmental heating and cooling of the slab that occurs on an hourly and seasonal basis and periodic wetting followed by drying from rains, snow melt and other environmental sources of moisture. These may cause

upward or downward curling of the slab and are superimposed on the previous curling sources. Only the cyclic temperature gradient is included in analytical modeling efforts.

(4) Autogenous shrinkage is small and can probably be neglected except perhaps for some of the lowest water-cement ratio mixes that are placed using heavy dosages of modern water-reducing admixtures. This source of shrinkage encourages upward curling because of base frictional restraint.

(5) Carbonation shrinkage develops from reactions with atmospheric carbon dioxide that cause surface shrinkage and also influences drying shrinkage. This effect promotes upward curl.

A quick review of this list shows our sophisticated modeling only addresses one of the two aspects of the cyclic temperature and moisture factor and neglects all of the other impacts. We are ignoring real issues and concentrating on only the one issue for which we have readily available analytical solutions.

The preceding list of curling factors also suggests most effects are to curl the slab upwards which is quite different from the common discussions centering on upward nighttime curling and downward daytime curling. An analysis of profile data from the SHRP long term monitoring program found a predominance of upward curling in the field.[25]

Although we have been able to calculate stresses caused by temperature gradients in slabs for over 70 years now, it is not clear what to do with the stresses once they are calculated. Most researchers have followed Professor Westergaard's original 1927 assumption of linear superposition of load and thermal gradient stresses. However, researchers are increasingly questioning the appropriateness of this assumption, but no consensus has emerged. As an example, it is well established that the fatigue relationship for concrete is a function of the ratio of at-rest stress and the applied load stress used to generate the fatigue fracture. If the environmental stresses are treated as the at-rest stress state rather than simply adding them to the load stresses, then the thermal effect is to adjust the fatigue relation such that high thermal stresses cause fatigue failure at fewer repetitions for a given load stress.

Curling is complex with many poorly understood factors. Because we can make sophisticated calculations on some aspects of this problem, does not mean that we understand it or even that we can intelligently incorporate these calculations in today's design methods. It is an important area for serious research, but we do not know enough to use it effectively in design.

PAVEMENT MATERIALS - ITS MORE THAN JUST STRENGTH

Because strength is often taken to be synonymous with quality, it gets much of our attention. Often, I have been on projects where there is some problem, and invariably the discussions, usually quite heated discussions, will turn to the topic that maybe the pavement should be accepted regardless of the defect because the specified pavement strength tests have been met and usually exceeded. Strength in the pavement is an important issue, but we need to be aware of the limitations of what we are considering.

Pavements are designed on the basis of flexural strength. All of our fundamental fatigue relationships, whether from full-scale tests or from laboratory beams, that we use in the design are based on flexural strength. All concrete strength tests - compressive, third-point flexural beam, splitting-tensile, etc. - are index tests and are not fundamental material properties. Consequently, it is not surprising that even tests that purport to measure the same property (e.g., tensile strength) give numerically different results, and there is no unique relation that interrelates these test results. This means I cannot accurately take a core from a pavement and test its compressive or splitting-tensile strength and calculate its in-situ flexural strength. This is unfortunately true no matter how desperately I want this piece of information on flexural strength to evaluate this pavement's structural capacity. The many widely published relationships between different tests (e.g., compressive strength or splitting-tensile strength and third-point flexural strength) have considerable scatter in the data upon which they are based. Rigid pavement fatigue calculations are very sensitive to the specific strength value used in the calculation. The possible variation in estimated flexural strength values with these published relations interrelating different strength tests has a very large impact on any structural evaluation of a rigid pavement. Often, there is no viable alternative other than taking cores and estimating in-situ flexural strength based on some relationship to a test we can run on the core. However, we must realize this is only an estimated strength, and we should consider the possible ranges of strength on our evaluation calculations. I have never known this to be done in practice. It is possible to get a very good and accurate relationship between different strength tests for a single concrete mixture, but any change in the mixture's constituents changes the relationship. Such relationships are almost never available for evaluations but can be developed for quality control programs to allow use of simple concrete cylinders rather than cumbersome beams for testing.

The strength that we specify and evaluate in our quality-control/assurance programs is not the in-situ strength. The actual strength we specify is of the concrete mixture delivered to the site and cured under ideal laboratory conditions. What we really control is the strength of the delivered concrete with the implicit expectation that our specifications for placement, consolidation, finishing, and curing will eventually give us a strength commensurate with the laboratory value. Consequently, errors in consolidation, curing, etc. of the concrete in the real pavement are extremely serious and may severely impact the structural capacity of the pavement. The strength tests from the quality-control program tell us nothing about the impact of these factors on our pavement and are not even germane beyond establishing the potential strength of the concrete mixture delivered to the work site. It is sobering to consider that unlike any other layer of a rigid or flexible pavement, there is normally no evaluation of any in-situ property of the portland cement concrete other than thickness if the pavement is cored.

Over the last thirty years, the military has been progressively shifting responsibility for materials evaluation and concrete mixture proportioning from the government to the contractor. This reflects public policy to reduce government personnel and shift responsibility for the paving product from the government to the contractor. Not all contractors or material producers have been prepared for this change nor has the government's policy of always selecting the lowest bidder recognized the difference in quality of concrete materials and mixtures different contractors may use. Air Force frustration with repeated poor performance of new concrete airfield pavements in the 1980s and 1990s [17] led them to require a well-graded aggregate and control of workability factors in their concrete airfield pavements. The performance problems were largely linked to poor construction practices, and the Air Force is trying to combat the use of concrete mixtures that were difficult to place and encouraged poor practices. This whole issue of how to proportion concrete mixtures for pavement requirements of strength, durability, difficult and sometimes unique airfield exposure conditions, and different placement techniques (e.g., slipform, formed, slab replacement, etc.) deserves greater attention and care from our whole industry.

NO PAVEMENT IS ANY BETTER THAN ITS CONSTRUCTION

A well-built but poorly-designed pavement is likely to outperform a poorly-built but well-designed pavement. Consequently, the impact of a capable contractor with skilled and experienced superintendents and laborers on achieving good pavement performance cannot be over-emphasized. Unfortunately, pavements are usually procured by government agencies who by law must select the low-bidder for a job. Despite occasional agency wording that the bidders must demonstrate their qualifications to do the job, the consideration of low-bid cost is the overwhelming factor in selecting successful bids. Construction quality never even enters into bid consideration. Low initial bid costs may be deceptive as the agency's final project costs that include claims, user-costs from delayed project delivery, legal costs for disputes, early maintenance costs springing from poor construction, or pavement replacement earlier than originally intended may make those initial savings from the low-cost bid very illusory.

Today, we are doing more design-build pavement contracts in the military, and we still are locked into the low-bid mentality of procurement. This greatly compounds the potential adverse effects of any contractor inexperience or ignorance. I still recall a bid design on an overseas project that converted the design Boeing 747 aircraft traffic into equivalent 18 kip single-axle loads. There was no prospect that this bidder could develop a viable design-build project simply due to inexperience and unfamiliarity with airport traffic. We still are a long way away from developing viable public policies for procurement of pavement construction or design-build pavement projects that intelligently balance cost and quality.

The designer can make construction easier or harder with his or her design requirements, and the difficulty of construction invariably impacts the quality of construction. Providing a base upon which a contractor can run construction traffic, anchor forms, operate slipform equipment, and avoid delays of adverse weather effects on subgrade soils speeds construction and pays many dividends besides its positive value as part of the pavement structure. During a meeting on a design for a large proposed airfield ramp, the design engineer strongly stated that a base course was unneeded for this particular project as the subgrade soils were granular, drained moderately well, and the environment was mild. The designer adamantly resisted including a base to improve site conditions as not required by the design manual and adding unnecessary cost to the project. Essentially his stated view was that if contractors wanted a base course, they could build it at their own expense. The subgrade soils were fine silty sands which do not support construction traffic. The pavement owner had just a few years previously had an inexperienced contractor working on similar soils at another airbase with a similar design of portland cement concrete placed directly on the subgrade. Rutting by construction traffic and operations caused highly variable concrete pavement thickness (thick in the rut and thin in the adjacent upheaved zone). These and other problems associated with the contractor's inexperience resulted in contractor termination when the project was over ninety percent surfaced, demolition and removal of the existing concrete, reprocurement of the work, a nine-month runway closure extension, the owner's continued expense of maintaining the base's flying units elsewhere during the construction extension, and a two-year legal battle with the contractor's bonding company. The owner overruled the still protesting designer and mandated a base course under the proposed airfield ramp with the observation that a 100-mm (4-in.) thick base course under the pavement and extending the base far enough outside the concrete placement to accommodate slipform paver tracks was cheap insurance to avoid problems. The designer's attitude reflected a adversarial view of contractors that did no one justice and failed to recognize that part of the design process is to insure constructability of the final product. Ease of constructability will, in my opinion, lower construction bids and improve final project quality.

As part of the general government policy to reduce manpower and shift responsibility to the contractor for his or her paving product, the military uses mandates a contractor quality control program to control the paving with a separate more limited government quality assurance program to verify the government actually obtains the specified pavement. As financial pressures developed over the last decades, the numbers of government inspectors have been cut drastically, they are spread more thinly over more projects, their training and experience levels have declined, independent testing by the government or its contract laboratories has declined, and in some cases, the contractor's quality control tests are accepted for quality assurance. There is no substitute for independent inspectors and independent laboratory testing separate from the contractor to insure quality construction. Reliance on the contractor to provide this is foolhardy.

CONCLUSION

This paper has attempted to illustrate areas that we often neglect when designing, specifying, and evaluating concrete pavements. Today, we have increasingly powerful analytical tools to help us numerically calculate pavement design parameters. However, in the author's experience much of this sophistication addresses issues that really do not cause many of our field problems. In the field, people problems, knowledge, attitudes, and mistakes are the predominant causes of problems. These we need to address just as carefully as the more sophisticated analytical issues.

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