WHY DO OUR CONCRETE PAVEMENTS STILL FAIL?

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Abstract

Despite an unprecedented growth in our knowledge and analytical ability, concrete pavements continue to fail more often than we would like. This paper examines a variety of failures encountered by the author in order to try to draw some overall conclusions on why we continue to have such failures. By understanding the types of situations that lead to failure in practice, we may identify how to avoid their reoccurrence in the future.

Introduction

The last century has seen an explosion in research and knowledge of concrete pavements. Today we have analytical tools, modern materials, sophisticated construction equipment, and accumulated knowledge of concrete pavements that are unsurpassed in history. Despite these advances, we continue to have concrete pavement failures far more frequently than we would like. In the following sections, we will examine specific failures to try to learn why concrete pavement failures persist. These examples are drawn from the author's personal experience over the last thirty years primarily with military airfield pavements. These examples are broadly grouped as (1) Design, Analysis, and Detailing (2) Materials, (3) Construction, and (4) Human Failings. In the study of failures, we try to learn from past experiences to avoid repeating the mistakes again in the future. However, every project and case is somewhat different, and many failures often have several contributing factors. From these specific illustrative examples, we shall try to draw conclusions on practices that contribute to concrete pavement failures. As we shall see the cause of failure is shared among government agencies, designers, contractors, and manufacturers and no one group is the sole cause of our problems.

Design, Analysis, and Detailing

Abuse and Misuse of Design Aids. Design aids remove much of the drudgery of engineering work. Modern computer programs allow rapid calculation with precision and include multitudes of parameters in a manner that was incomprehensible before the computer technology blossomed. Yet often these design aids, whether graphical, tabular, or computerized, are based upon specific models, assumptions, default values, and the like that are not obvious to the user who has not trained with the

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specific design aid. Failure to understand our design aid's basis and inherent limitations is a path to gross mistakes. When one contemplates the rapid computerization of our design work, such misuse must be one of our most common errors in practice.

A classic example of a designer failing to understand his design tool occurred during expansion of a US Air Force 30-m (100-ft) diameter circular power check pad (Rollings and Rollings 1991). These pads are used to anchor aircraft while engines are run up for maintenance, and a new aircraft assigned to this airbase required the existing pad to be expanded. The design of this expansion was assigned to a newly arrived junior engineering officer who consulted the appropriate military airfield design manual. Using the modulus of subgrade reaction values from a recent base-wide pavement evaluation report and typical concrete flexural strengths commonly available at this base, the young lieutenant was able to use a design chart in the manual to calculate the required pavement thickness for the pavement to support the new aircraft. The power check pad was expanded with two rings of slabs with this newly calculated design thickness. However, once opened to traffic the new ring of slabs failed rapidly with widespread cracking.

Aircraft seldom traffic unsupported edges of runways, taxiways, and ramps. Air Force concrete pavement design recognizes this and is based on explicitly allowing for 25 percent load transfer between adjacent slabs due to dowels and aggregate interlock. Every design chart in the military manuals and all of the military design computer programs inherently include this assumption. In the case of the power check pad, existing aircraft turn so that the main gear traverses along the outside slab edges where there is no load transfer; hence the outside slabs were being exposed to one-third more load than the design chart actually used in the thickness calculations. In cases such as this where free-edge loading actually occurs, the designer is expected to know to use a thickened edge detail to handle the problem.

The Devil is in the Details. One of the most fundamental tasks a concrete pavement designer must accomplish is the basic layout of the pavement slabs and joints. Essentially one details the pavement to have square slabs (or at least not to deviate from square by more than 25%), and maximum slab dimensions are selected from the slab thickness based on one of several guidelines that have been used for fifty years or so. If slabs are odd-shaped or are too long for their thickness, the slabs will crack. If one must use such slabs, then reinforcing is added to keep the cracks from opening and deteriorating. In addition if the slab has inserts such as for hydrant refueling systems, if the slab shapes are irregular, if joints are mismatched, or if concrete is placed on a surface that is cracked, one generally expects the new concrete to crack in undesirable ways and reinforcing is again used.

Although these are all fundamental basics of concrete pavement design, errors occur every year with detailing of concrete pavements. On a runway in Texas 200-mm (8-in) thick concrete pavement was placed in 4.6 by 5.7m (15 by 18.75 ft) slabs. Slabs of this thickness are limited to a maximum joint spacing of 4.6 m (15 ft) by Air Force practice. Almost every slab in this project quickly cracked to bisect the 5.7 m (18.75 ft) length. Similarly, since the 1950s, we have been aware that slabs that are crowned in the middle without a joint tend to crack down the crowned axis of the slab. During the 1990s three Air Force runways and taxi lanes were designed with unjointed crowned slabs by a government design agency. In every case, the slabs cracked. One of these examples is a concrete runway that developed a continuous 3,048-m (10,000-ft) long centerline crack much to the disgust of the Air Force owner. These are mistakes we should not make, but they continue to occur.

Understand the Site Conditions. In one of the Corps and Air Force's first uses of the design-build approach for an airfield pavement, a concrete runway was to be extended. The bidders were provided borings in the project vicinity with gradations, Atterberg limits, and soil classifications plus a tabulated collection of design CBR values for various compaction and moisture conditions from past pavement projects at the airbase. Soils in this tabulation were CL or CH clays, and some of these projects included values for lime-stabilized soils. Also, included were results for modulus of subgrade reaction plate load tests on an older lime-stabilized project.

The winning bid by a major U.S. firm used a design CBR of 7 which was estimated to provide a design modulus of subgrade reaction of 33.9 kPa/mm (125 psi/in). This value had been selected from an older project in the provided tabulation for a CL clay compacted to 95 percent density at 1 percent above optimum moisture content. The winning bid was $2 million lower then the next nearest bid. Shortly after award of the contract, the winner requested a $2 million increase in the contract award based on changed site conditions. The basis of the claim was worse soil subgrade conditions than anticipated in design; specifically the actual subgrade design values should have been a CBR of 5 and a modulus of subgrade reaction of 14.9 kPa/mm (55 psi/in.).

The claim was without basis as the same information had been provided all bidders, and only the winner had used such optimistic initial subgrade design values. The local soils are fine-grained residual soils formed on prairie uplands that are predominately CL clays with lesser amounts of CH, ML, CL-ML soils. CH soils, some of which showed potentially expansive characteristics, have been encountered on the base before as was shown in the bid document data, and stabilization had been used to mitigate this in some past projects. The project borings revealed a 1.5-m (5-ft) thick CH clay layer at the surface in one part of the project area, and CH clays at shallow depth in several other borings. Data in the bid documents on CH clays were limited to two projects which provided design CBR values of 4 and 5. If all unstabilized soil data in the bid document for CL and CH clays were analyzed to determine the 85 percentile value as required in military manuals, the design CBR value would be 5. The winner's selection of 7 for design CBR was based on a single value on one project. Even that answer was not a conservative solution as other moisture conditions for that soil on the same project had provided CBR values of 5 and 6.

Low subgrade strengths were to be expected on this project, and the bid documents provided the necessary data to arrive at such a conclusion. The winner's selection of a design value higher than the government and other bidders appears to require almost purposeful selection to achieve an optimistic value (which leads to thinner pavements and lower bid price). One is left to draw the conclusion that either the designer working on this specific project was inexperienced and working without adequate professional oversight or this was a planned stratagem to win the bid and then raise the profit with change orders. The military is ill-served to leave it to such "professional" judgment to design their pavements in the competitive world of design-build and low-bid awards.

Don't Out-Smart Yourself. Theoretical analysis of a concrete pavement is a surprisingly daunting task: geometric and joint issues, material shrinkage factors, environmental effects on the structure, uncertain in-situ material properties and strengths, complex nonlinear material response, perplexing fatigue behavior, moving loads, etc. Consequently, pavement design has tended to evolve with relatively simple analytical and material models and a number of empirical and experience-based guidelines on joints, spacing, etc. that tend to work and keep us out of trouble. The venerable late Professor Yoder aptly stated the case (Yoder and Witczak 1975) as: "*the philosophy that governs the design, simply stated, is, joints and steel are used to relieve and/or take care of warping stresses, and the design, then, is based upon load alone when considering thickness. This principle is so important that it must be clearly understood by the designer.*" Consequently, we should be wary then of forgetting why we have some of these "simple" guidelines and rules-of-thumb. We want to make certain that our new theoretical considerations do not lead us into trouble by forgetting why some of these old guides were put in place.

During the 1970s there was considerable interest in the Federal Aviation Administration and the military airfield community for using steel-fiber reinforced concrete in airfield pavements. Several studies were conducted leading to a comprehensive design methodology that included post-cracking behavior of the slab, new design fatigue relationships for steel-fiber reinforced concrete, and deflection checks to assure subgrade adequacy.

The steel-fiber reinforced concrete was quite expensive, but the new design methodology resulted in much thinner pavements. In addition, field studies had shown that the higher strength of the steel-fiber reinforced concrete resulted in contraction cracking at much wider spacing than conventional concrete. Consequently, contraction joints could be much further apart and the cost of constructing and maintaining the joint s could be reduced allowing a further economic advantage for steel-fiber reinforced pavements.

During the 1980s several steel-fiber reinforced concrete airfield pavements were built at civil and Navy airfields using the new methodology. These tended to be relatively thin and large (sometimes only 100- to 150-mm (4- to 6-in.) thick and 15 or even 30 m (50 and even 100 ft) between contraction joints). There were soon reports of widespread corner breaks at these airfields . A Federal Aviation Administration and Army Corps of Engineers investigation of the corner breaks found that the relatively thin and large steel-fiber reinforced concrete slabs were curling and rapidly developed corner breaks under traffic (Rollings 1993). Curling is a very complex phenomena with many contributing factors: autogenous concrete shrinkage, adverse thermal gradients at setting, drying shrinkage, seasonal moisture and thermal effects, diurnal temperature effects, carbonation, etc. Regardless of what mechanisms may be involved, the large plan dimension of the slabs relative to their thin cross section required very little differential shrinkage between the top and bottom of the slab to get curling in the field. Curling appeared rapidly after construction and was permanent. Once opened to traffic, these curled slabs developed widespread corner breaks.

In developing a new design methodology for steel fiber concrete airfield pavements, we addressed the classical design issues of calculating stresses and performing a fatigue analysis. However, in aggressively allowing relatively thin but large in-plan slabs, we ignored the impact of curling forces. These forces we had traditionally kept under control by relatively short slab dimensions which we violated by allowing large joint spacing in the steel-fiber reinforced concrete. In the end, field performance was dominated by curling behavior and not load fatigue stresses. Our improved design methodology failed to address the curling mechanisms when we started pushing slab dimensions beyond past practice, and widespread failure resulted. Today, we obviously no longer allow such large slab dimensions.

Materials

The materials we use in our pavements must have the necessary engineering properties, possess the necessary workability so that they can be handled, placed, consolidated, and finished, be durable under the exposure conditions, and be as economical as possible. Too often our focus is on concrete strength alone, and we forget the many other aspects of material technology that may lead to unsatisfactory performance. We also make no attempt to measure the in-situ properties of our concrete slabs. Instead we rely on samples taken of the as-delivered concrete (e.g., air content or beam samples to be cured in the laboratory), and rely on our construction specifications to get the concrete, that is satisfactory as delivered, placed, consolidated, finished, and cured in an acceptable manner. Other than perhaps cores taken for thickness determination, the concrete pavement slab is never tested to verify that it meets the engineer's design assumptions and specifications. This is unique in pavements as asphalt concrete, base courses, subgrades, etc. routinely undergo a variety of density measurements, gradation checks, asphalt content measurements, etc. from samples taken from the in-situ pavement to assure specification compliance. In contrast, the concrete pavement community has no actual knowledge of the in-situ concrete characteristics.

Specification Limits. In the 1959, Selfridge AFB had a massive problem with popouts from unsound aggregates that led to reconstruction in 1964. This failure received considerable press and triggered a Congressional investigation. The popouts posed a potential foreign object damage (FOD) hazard to the then new Air Force jet aircraft, and the whole affair was quite embarrassing for the US Army Corps of Engineers and the Air Force. As a result, military engineers developed a consensus specification that strictly limited the deleterious material in aggregates to be used in military airfield concrete pavements to avoid future popout and FOD hazard potential. This was much tighter than conventional limits such as in ASTM C-33, and the requirements remain in military guide specifications. Meeting these military deleterious material requirements can significantly increase construction costs.

There are periodic calls to drop these restrictive aggregate quality requirements. However, they address a major failure we had in the past, and the user (US Air Force) continues to demand pavements with low potential foreign object damage hazard. Recently, the Corps of Engineers rejected a contractor's submitted aggregate for a ramp at an Air National Guard Facility because of excessive deleterious material. The aggregate was then used on a civil airport feature on the other side of the runway. Problems with popouts rapidly appeared, and the local authorities are tightening aggregate requirements for future projects. In another case, a US Air Force military engineering unit was building a large airfield ramp at an important base in the Middle East. Time was critical so many of the conventional material quality tests were ignored for expediency to get the job done. Soon after placement, aggregate popouts became widespread (over 100 per slab in some cases, Figure 1) and intense sweeping and maintenance efforts were required to reduce the FOD hazard and allow aircraft operation. As investigation afterwards would find, the local aggregates are unsound and unsuitable for concrete. Even in a military emergency where time is crucial, their use proved highly unsatisfactory and military operations were seriously impeded because of the simple mistake of using a bad aggregate in the concrete mixture. Even on a wartime footing, blindly casting away "overly restrictive" conventional peacetime requirements may prove unwise.

The engineering community struggles constantly to balance quality requirements and costs, and the task is not easy. We need to assess the durability of aggregate in service; yet, our existing tests simply do a poor job (e.g., Rollings and Rollings 1996, Marek 1991, Dolar-Mantuani 1978). As aggregate sources become more constrained the importance of this durability testing and qualifying of aggregates becomes even more important; yet we continue to rely on methods and requirements that simply are not up to the task.

Figure 1. Example of severe popouts, Middle East Airbase

Changes That Go Unnoticed. Alkali-silica reaction in concrete is a well-documented phenomena that is extensively discussed in many textbooks. Essentially some, but not all, forms of silica in coarse or fine aggregate in concrete can react to form a gel that imbibes water. This results in swelling with possible consequent concrete cracking, aggregate popouts, and expansion of affected structures (Figure 2). In the early 1960s, the military mandated aggregate testing and low-alkali cements if reactive aggregates were to be used. During this period, the military conducted extensive aggregate and concrete testing, often controlled the concrete mixtures and ingredients used on military airfield pavements, and had extensive on-site inspection.

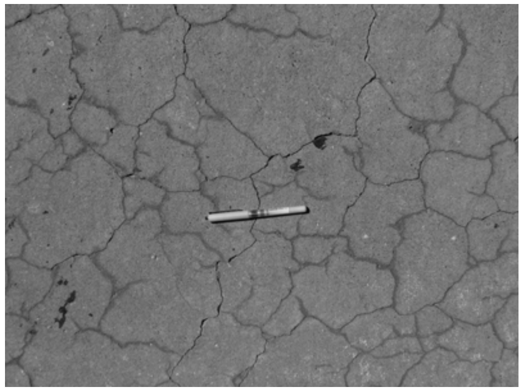

Figure 2. Example of ASR cracking on a Kirtland AFB taxiway

By the late 1990s, the US Air Force had nineteen airbases with alkali-silica reaction problems; on one 1995 project symptoms of attack appeared in less than 5 years and extensive patching was required within eight years. Similar reports were coming in from Navy and Army airfields. Obviously existing guidance and practices that were working in the 1960s were not working in the 1990s.

Several things had changed since the initial military guidelines on dealing with alkali-silica reaction were established. During the ensuing decades, policy changes and declining government manpower and laboratory resources led to a shift to the contractor for responsibility for materials used in military pavements. Government control, oversight, and review declined significantly. Contractors had little incentive to worry about relatively long-term alkali-silica reaction issues, and testing and countermeasures were routinely ignored. Changes in cement manufacture brought on by energy considerations and emission controls had also led the average alkali content of U.S. portland cement to increase from 0.4 to 1.2%. The concrete mixtures were more complex as new sources of alkali came from common additions of pozzolans and admixtures. Also, aggregate sources simply were becoming more limited from depletion and restricted development of new sources. The potential for alkali-silica reaction had increased during this period at the same time that government testing and oversight declined.

Guidelines were put into place by the military in one era, but as policy, concrete technology, and aggregate resources changed and evolved, the guidelines remained static and unchanging. They eventually proved unworkable and widespread damage occurred to military pavements because of the military pavement community's inertia and stagnation. Today the military has renewed emphasis on testing for aggregate reactivity and mandates use of active countermeasures using fly ash, slag, or lithium admixtures if reactive aggregates are used.

Unexpected Consequences. Sulfate attack is another form of chemical attack on portland-cement concrete that is well documented in standard texts and professional publications. Essentially, calcium and alumina in the portland-cement concrete react with sulfate and water to form the expansive sulfo-aluminate mineral ettringite. Protection against sulfate attack of concrete is provided by using sulfate-resistant cements (Type II or V). These cements are manufactured to have low alumina contents thereby limiting one of the needed ingredients for ettringite formation.

However, simply using sulfate-resistant cements will not confer protection in all cases. Figure 3 shows heaving of cement-stabilized base course made with Type V cement. In such cases, the alumina needed for formation of ettringite is provided from clay minerals in the stabilized base, and the low-alumina Type V cement provides no protection (Rollings et al 1999). In 1995, a 40-year old concrete apron made with Type V cement was recycled as fill and base course under two buildings and airfield pavements at an Air Force base. Within a few years, this nominally sulfate-resistant recycled concrete was undergoing sulfate attack with resulting heaving of pavements and building foundations (Rollings et al 2005). The recycled concrete was far more pervious and existed under wetter conditions with more extreme sulfate exposure than when it had been a concrete apron. These factors along with possibly exposing more alumina reaction sites when the concrete was crushed are thought to be the main reasons why the normal protective measure of using Type V cement failed in this instance. Even though we have effective methods of resisting sulfate attack of concrete for conventional paving applications, if we change how or where we use this technology, we may find it ineffective. Because a protective measure works under one condition does not mean it will work in all other situations.

Figure 3. Heaving from sulfate attack on Type V cement-stabilized base, Holloman AFB, NM

Construction

Most pavement work is awarded to the lowest bid submitted by a contractor. This immediately pits the owner/engineer into conflict with the contractor. The owner and engineer want the best pavement possible and are keenly interested in long-term quality and performance. The contractor, on the other hand, has to provide only the minimum possible to meet the specification. To try to provide more quality or a better product increases the contractor's cost and to obtain the winning bid all such extras had to be pared. Hence, our construction system establishes an atmosphere of very different aspirations and expectations between the owner and engineer on one side and the contractor on the other.

The importance of skilled personnel and independent inspection of construction remain fundamental. The distinguished late New York engineer Jacob Feld noted in his pioneering text on failures (Feld 1968) that a 1903 editorial in *Engineering News Record* noted the need for concrete work to *be under the constant supervision by skilled foreman, architects or engineers* and a 1918 editorial published by the American Railway Association concluded that

> *The one thing which these failures conclusively point to is that all good concrete construction should be subjected to rigid inspection. It should be insisted upon that the Inspector shall force the Contractor to follow out the specifications to the minutest details ... It is believed that only by this kind of inspection is it possible to guard against the failure of concrete structures.*

Feld (1968) observed *so the 1903 editorial advice still held in 1918, and the lesson was not learned and is still not learned.* We may simply extend Feld's observation that the lesson remains unlearned in 2005.

The Contractor Must Have the Experience To Do the Job. A 45.7 m by 304 m (150 ft by 1,000 ft) end of runway at an airbase in the Southeastern U.S. was to be removed and replaced. This was a small-business set aside contract. The contractor that won the award had no airfield experience, and their experience appeared to be limited to small industrial and residential concrete pavement placements. The contractor attempted to place the runway using wooden forms, a vibrating screed, manual consolidation, and formed joints. The scope of the work was beyond this contractor's experience and equipment: over 90 percent of the surface failed smoothness tolerances, pavement thickness varied widely and was significantly thin in places, joint sealant reservoirs failed all relevant requirements, and poor concrete consolidation was widespread. All placed concrete was removed, the contractor was bankrupted, and the work was reprocured and redone.

It was obvious from the beginning of the work that the contractor was not up to this size and scale of job. However, on-site government personnel were similarly inexperienced. It was not until all but the last two slabs were in place that the government seriously examined this work and found that it was not going to be acceptable. It is common to blame small business and minority set asides for problems like this. Such is not the case. The reprocured work went to a small business, minority-owned firm who did an excellent job (with antiquated but adequate equipment) and who went on to successfully win the subsequent removal and replacement of the other end of the runway. The key is the contractor has to be experienced and adequately equipped for the job. Airfield work is more demanding than most other paving work and those experienced on highway and light industrial pavements may not be up to dealing with airfields.

Workmanship and Good Practices. During the 1980s and early 1990s, the U. S. Air Force had a number of new concrete pavements that developed early-age spalling with resulting complaints of the resulting FOD hazard from the flying units. This spalling occurred anywhere from during construction to within the first year of use. This led to considerable consternation within the Air Force, and the situation reached the point that one major command was on the verge of banning all slipform paving on its bases believing that to be the cause of the problem.

An investigation of this problem at twelve bases found that the most common cause of this early-age spalling was poor construction practices and problems existed with both slipform and formed construction (Rollings 1998). Some of the spalling arose from well known poor practices such as adding water to the surface to aid in finishing and overworking the surface that then leads to a weak nondurable layer of paste on the surface. Some were specific to a construction technique such as use of hand-placed mortar to correct excessive edge-slump of slipformed pavements. Such mortared edge repairs typically developed massive spalling problems. In some cases, there were contributing factors from poor mixture proportions, poor curing, and special operational issues, but the heart of this issue was poor construction practices. This is particularly hard to rectify. The government inspection effort is greatly reduced today so the success or failure of reducing these poor practices depends primarily on the professionalism and training of the field superintendent and construction crew. The U.S. Air Force and Corps of Engineers have made a concentrated effort in the last decade to expand educational efforts with both government project personnel and contractor personnel to alert all parties to these problems. In addition, the U.S. Air Force has mandated use of well-graded aggregates for concrete as pioneered by Mr. Jim Shiltstone in the hope that concrete mixtures that are easier to place, consolidate, and finish will reduce problems with edge slump and other field difficulties that encourage use of poor practices. These educational efforts and adoption of more careful aggregate grading controls have helped reduce the early-age spalling problem but have not solved it.

Late Sawing of Joints. Every year somewhere, we have at least one case of uncontrolled cracking because joints were not sawn soon enough. For example, in 1993 at an airbase in Texas, an apron was slipformed in warm, dry summer weather. It was wet-cured with burlap for 1 day and then membrane cured. The contractor waited until the burlap was removed to begin sawing transverse contraction joints. Before the pavement could be turned over to the Air Force over 25 percent of the slabs had cracked. These were typical cracks from late sawing: some parallel and near the intended joint, some meandering back and forth across the joint (Figure 4). Coring found these were full-depth working cracks, and the adjacent saw cuts had not cracked. Concrete generally has to be sawed the day it is placed. Delays until the next day or later almost invariably lead to cracks starting to develop on their own and leave the saw cuts uncracked.

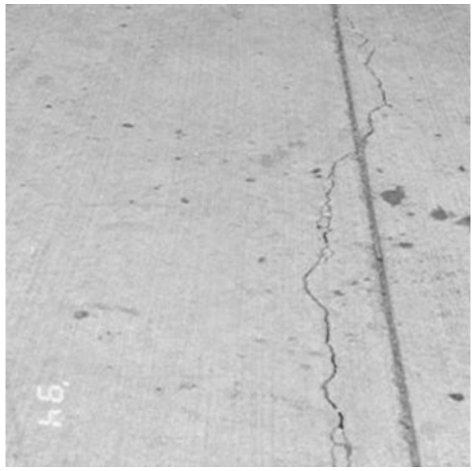

Figure 4. Uncontrolled contraction cracking from late sawing Reese AFB, TX

Small Changes and Their Unexpected Consequences. Military concrete airfield pavements must be consolidated with internal vibrators. These normally must be mounted, on equipment and manual insertion of vibrators is not allowed except for small hand placements. This has generally worked very well except at three bases where we have gotten longitudinal cracking in the vibrator paths. Investigations have found there is a mortar-rich zone in the vibrator path where the crack occurs, and this has been ascribed to over or excessive vibration. Cracking of this nature began appearing during paving at a New England airbase. Concrete placement was proceeding slowly and erratically because of delays of the concrete trucks coming on base from an off-site plant. In addition, a cool front had dropped temperatures significantly and concrete strength gain was slowed making cracking more likely. The contractor improved delivery process of the concrete to minimize delays and speed placement, automatic cutoffs were installed on the paver to stop vibration whenever the paver stopped, and curing was improved. With these steps, the cracking ended.

Human Failings

Animosity Between the Parties. Karl Terzaghi (1958) wrote a classic paper discussing the competing views and inherent discord between the owners, design engineers, field construction engineers, and contractors. His biting observations ring as true today as they did 47 years ago, and current examples illustrating this incompatibility between the views of the parties abound. At one military facility in the Great Plains, the government construction department forbade the design department to even come on the construction site. In another case, the government design engineer adamantly refused to agree to a base course under a rigid airfield pavement because the manual did not require a base on this subgrade. The owner pointed out that two years before on similar soils at a nearby base, construction had bogged down in the fine sands because of poor trafficability. The design engineer remained unswayed. If the contractor needed a base course to build the pavement he could provide it at his own expense, it wasn't going in his design since the manual did not require it. Fortunately, this would be overruled by the owner, but too often there is an atmosphere of open warfare between the disparate parties involved in concrete pavement design and construction.

Fraud and Corruption. These are not a new problems in construction. McCullough (1972) describes the well-documented corruption and fraudulent substitution of below-strength steel cable in the Brooklyn Bridge in 1878. Fraud and corruption in construction continue today. For example, the American Society of Civil Engineers is launching a massive initiative to reduce corruption in the construction industry, and Peters (2001) noted at an American Association of Highway and Transport Officials (AASHTO) Subcommittee on Construction meeting, there is an increasing need to be aware of fraud potential and there is a rise in problems like core substitution, false weight tickets, bid rigging, and collusion . The U.S. military mandates every lot of joint sealant used on military airfield concrete pavements has to be individually tested by an independent laboratory because certificates of conformance to specification by the manufacturer were found to be totally unreliable. In some cases, over 80 percent of the samples of manufacturer-certified materials failed to meet the specification tests. In a similar vein, Emmons et al (1994) noted that only 15 percent of 46 concrete repair materials that were advertised by their manufacturers as expansive, non-shrinking, or shrinkage- compensating actually tested as low-shrinkage materials.

Fraud exists and is a real problem in construction, but this is not news to anyone. We must be aware of its possibility and take steps to prevent it. However, current trends in procurement of military airfield pavements, in the author's personal opinion, has made fraud more possible and not less. For example:

(1) independent military inspection is greatly curtailed over previous times.

(2) experience levels among military inspectors and engineers is lower than in the past.

(3) certification that pavement materials meet specification is now routinely accepted by the military without any independent testing. Historically, these certifications have been found to be unreliable.

(4) Independent military quality-assurance testing of airfield pavements is becoming increasingly less common. In a number of cases, contractor quality control tests have become the sole basis for accepting and paying for military pavement work. This puts a terrible temptation upon the honest contractor, and for the dishonest, it is simply putting the fox into the chicken house.

Conclusion

The preceding sections have presented a variety of examples of concrete pavement failures encountered on military airfields over the last few decades. Human failings run throughout many of these examples. Some of these are a matter of training and education: proper use of design aids, proper detailing, proper selection of subgrade design strength, proper construction methods, and proper timing of sawing are all amenable to improvement in this manner. Actually making this happen is easier said than done, however. We have the knowledge to avoid these problems, and such failures reflect particularly poorly upon our profession.

In other cases, we actually have the knowledge to avoid the problem, but it is buried in details or old history that is easily overlooked. This would include failures such as the curling failures of the steel-fiber reinforced slabs, the aggregate popout failures, the unnoticed industry changes that led to a resurgence of alkali-silica damage on our airbases, and the longitudinal vibrator cracks. These we should avoid, but in-depth knowledge of the field is needed to be certain that innocuous seeming practices, changes, or specification requirements are properly interpreted for specific project conditions. Avoiding such failures puts a premium on the experience and in-depth technical knowledge of the engineer.

There are also cases where our conventional technical knowledge is weak and can let us down. The inadequacy of conventional durability tests for aggregate and the unusual sulfate attack modes for cement-stabilized soils and recycled concrete containing Type V cement would fall into this category. Improved research is needed to deal with these issues.

Some of our troubles are caused by our inherent failings as human beings. This might include the examples such as the possible purposeful underbidding of the runway extension by optimistic selection of subgrade strength, an unqualified contractor tackling a job beyond his or her abilities, animosity and lack of cooperation between parties involved in the work, and fraud. Many of these human failings can be addressed by better organizational practices: tighter review of designer and contractor qualifications and work, having experienced reviewers who can actually judge adequacy of the design or construction proposals, more imaginative contracting methods to find alternatives to the low-bid approach so that quality can be included in the methodology, meaningful in-situ testing of the concrete pavement to see what was actually provided, improved teamwork and incentives for teamwork, and conscientious inspection and quality assurance testing that is independent of the contractor and manufacturer.

In the end, the bulk of the types of failures presented in this paper are avoidable and should never have occurred. These are failures of our practice of civil engineering; they are not failures of the technical state-of-knowledge of civil engineering.

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