

A Review and Discussion of Current Developments Involving Bonded Concrete Overlays of Airfield Pavements

Peter M. Semen^{*} and Raymond S. Rollings[†]

Abstract

Fully-bonded portland cement concrete overlays have been widely used by the U.S. military to rehabilitate rigid airfield pavements that have functional deficiencies – such as roughness, surface profile, poor friction, or foreign object damage (FOD) potential. Significant developments in the concrete industry over the last 15 years – including considerable changes in concrete material additives, construction practices, surface preparation, and computer modeling – have led to changes in traditional practices. A survey of the recent literature in relevant topics led to the synthesis of applicable developments from several areas. New research on failure mechanisms, surface preparation, bonding agent use, and interface texture has provided fresh insight regarding some conventionally-accepted wisdom. Integrating contemporary findings into recommended practice should improve the oft-times variable nature of achieving the best bonding conditions for bonded overlays and ultimately improve their reliable long-term performance.

Introduction

An effort is currently underway to update existing U.S. Air Force practice in placing fully-bonded concrete overlays to rehabilitate portland cement concrete (PCC) airfield pavements. Since developing the basic design criteria over a half century ago, the U.S. military has used overlay techniques extensively to maintain and upgrade airfield pavements worldwide. This experience – coupled with periodic reexamination over the years of design methodology, long-term performance, and contemporary practices (Gillette 1965; Darter and Barenberg 1980; Boyer et al. 1981; Hutchinson 1982; Rollings 1988) – has kept these standards up-to-date and they continue to be widely used throughout the airfield pavement community.

The present effort focuses on adopting the best surface preparation and bonding techniques available today for fully-bonded concrete overlays of rigid airfield pavements. Because the military airfield pavement design concept relies on positive load transfer between slabs (Rollings 1981; Rollings 1988) and no methods to reestablish sufficient load transfer with a bonded concrete overlay (BCO) have

^{*} Research Civil Engineer, U.S. Army Corps of Engineers, Engineer Research & Development Center, Cold Regions Research & Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755, email: peter.m.semen@erdc.usace.army.mil

[†] Research Civil Engineer (Retired), U.S. Army Corps of Engineers, Engineer Research & Development Center, Cold Regions Research & Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755, email: rollingseng@earthlink.net

been successful to-date,[‡] their use is limited to correcting functional surface deficiencies of a structurally adequate pavement in good condition other than the surface problems. The cause for the current reassessment was an extensive BCO failure at Fairchild Air Force Base, WA in 1998 which resulted in widespread corner breaks and cracking, ultimately requiring replacement of a significant percentage of the overlay repairs (Figure 1). An Engineering Technical Letter (ETL) on this topic is currently under development and will be published by the Air Force Civil Engineer Support Agency (AFCESA). The authors' intent here is to provide a discussion of BCO-related issues which will form the basis for updating existing criteria.



Figure 1. Corner break in concrete overlay due to bond failure at Fairchild AFB.

Background

During the 1940s and 1950s the U.S. Army Corps of Engineers conducted an extensive series of full-scale trafficking tests and developed the basic equations to

[‡] In a 1998 highway project on I-40 in Oklahoma City, ODOT successfully demonstrated the placement of dowel bar retrofitting at previously non-doweled joints during a bonded concrete overlay placement (Burwell and Benson 2002). The emplacement of load transfer restoration concurrently with a BCO to achieve simultaneous structural and functional improvement has not been documented in airfield pavement practice.

design rigid overlays of plain concrete pavements. Despite its empirical basis, the method has been used successfully by the U.S. military over the past half century and has been widely adopted by others. Performance of overlays designed by this approach has generally been good, even in the face of widely-varying conditions encountered in airfield operations around the world.

Subsequent to the pavement design efforts by the Corps, the Portland Cement Association (PCA) initiated an overlay testing program (Felt 1956; Felt 1960) focused on procedures to ensure bonding between the new and old concrete. This research established many of the standard placement practices which, for the most part, remain essential to developing a good bond. They include:

- Importance of surface preparation
- Emphasis on maintaining a clean surface prior to overlay placement
- Using high quality materials and first class workmanship
- Employing proper curing and jointing practices
- Achieving proper compaction of the new concrete

These continue to be followed today and have proven to be critical elements in achieving a good long-term result.

However, some of the procedures advocated by this early work, and generally followed ever since, no longer measure up to our present understanding of the material properties, stress distributions, and failure mechanisms in concrete repairs. The following sections will address several of these areas in light of current knowledge.

Insights from Recent Research

A survey of the literature related to pavement repair, concrete bonding, and surface preparation was performed, with a particular emphasis on developments over the past 10 to 15 years. Much progress has been made during this period to advance our understanding of concrete overlays. Most notably, considerable research efforts by the Center for Transportation Research at the University of Texas at Austin and the Virginia Transportation Research Council form a large body of new information focused specifically on overlay construction and performance. Also, during the 1990's the Corps of Engineers completed a major research program on Repair, Evaluation, Maintenance, and Rehabilitation (REMR) of waterway structures, with significant work on concrete repair (McCleese 2000). Much of the research deals with concrete repair materials and methods similar to those used by the pavements community.

Debonding Mechanism

Traditionally, shear strength at the interface between the overlay and the substrate has been used to measure the bond quality in pavement overlays. The rationale behind this originally came from comparing the pavement-overlay structure to that of a two-layer composite concrete beam. Flexural testing at PCA established that at shear bond strengths around 200 psi, laminated beams were as strong as comparable monolithic specimens (Felt 1956). Ever since, this value has been cited

in the literature as the baseline for a bond that will provide good long-term performance (Gillette 1965; Hutchinson 1982; ACPA 1990; McGhee 1994).

New research, incorporating finite element analysis and fracture mechanics models, have cast doubt on the conventionally accepted view that debonding occurs by a shear failure at the interface.[§] In a study exploring vertical wheel loads, thermal gradients, and braking forces on a BCO, Lau et al. (1994) used finite element modeling to compute the shear stresses at a fully-bonded interface. Finding that typically-reported shear bond strengths were at least twenty times larger than their calculated stresses, they concluded that overlay failures must have other causes. Independent work by both Granju (2001) and Lange & Shin (2001) using numerical modeling in conjunction with experimental measurements determined that debonding was actually the result of tensile stress acting normal to the bond interface. They discovered that drying and thermal shrinkage in the overlay, when restrained by the relatively stable substrate, led to high tensile stresses at slab edges and corners. This caused the overlay to peel or curl away from the original pavement, resulting in a tensile failure. Thus, the design of concrete overlays should be governed by tensile strength at the bond interface, and not the shear strength. In addition, limiting the potential for volumetric changes in the overlay, especially at early-age when there is a relatively weak bond, is so important that proper curing and minimization of thermal stresses cannot be overemphasized.

Surface Preparation

Many different methods of surface preparation have been used over the years to promote a high bond strength at the overlay-pavement interface. It has been clear since the early years that careful surface preparation is required to achieve the higher bond strengths needed for successful BCO placements.

For a some time it has been suspected that certain methods may actually leave behind a damaged layer in the substrate that reduces the potential bond strength. The petrographic evidence that milling causes microcracking in concrete is now clear (Hindo 1990; Silfwerbrand 1990; Warner et al. 1998). This has led to a growing consensus that blasting-type surface preparation methods, such as shotblasting, hydroblasting, or sandblasting that rely on an impelled medium to remove material and do not leave microcracking, are superior to those based on a tool's direct impact with the surface. With the wider availability of shotblasting machinery and their ability to provide sound, clean, and well-textured concrete, the use of milling is being discouraged (McCullough and Rasmussen 1999; Smith et al. 2002).

In some cases, especially where a significant depth of material must be removed, milling can still be useful as the primary method but it should always be followed by an appropriate secondary technique which is adequate to remove microcracking damage. These would include shotblasting (ACPA 1990; Hunt 1999), two or more passes of heavy sandblasting (Warner et al. 1998; Carter et al. 2002; Silfwerbrand and Paulsson 1998), and waterblasting (Hall et al. 2001).

[§] To his credit, Felt acknowledged at the time he proposed the shear strength criterion that "further experimental and analytical studies [were] needed to determine the maximum bond stresses which must be resisted under various conditions of loading, temperature change, and drying shrinkage (Felt 1956)."

Use of Bonding Agents

Bonding agents, such as neat cement or sand-cement grout, have long been prescribed to improve the bond strength of overlays, but questions whether they are necessary and under what conditions can they be omitted have lingered. Application of grout, with the need to prevent drying before overlay placement and ensure proper consistency, has been identified as a problematic step in the repair process and been regularly reported as the cause of failures. Several researchers have shown that use of bonding agents appears to be unnecessary if the surface preparation of the existing concrete is sufficiently aggressive (Silfwerbrand 1990; Whitney et al. 1992; Wells et al. 1999). Eliminating the need for a bonding agent, especially with its extra logistics and potential for creating new problems, by choosing the right surface preparation method should reduce the complexity and improve the overall reliability of repair placement.

Scanning electron microscope research on the interface between repair materials and a concrete substrate have yielded new insights (Wells et al. 1999; Lange 2000). It appears that aggressive surface preparation exposes the open pore structure of the existing concrete, allowing the plastic concrete to penetrate and create a mechanical interlock at the bond interface. Bonding agents can interfere with this capillary action in a very porous surface, but appear to help with less aggressive surface preparation. The lower viscosity and more fluid nature of grout allows penetration of tighter pore structures and thus improves bond strengths when paired with more moderate surface removal.

The same mechanism may also explain the long-running debate over the moisture condition required at the interface during overlay placement. Both dry and saturated surface dry have been recommended, but results have not been consistently good with either. Perhaps the more aggressively prepared surfaces with open pores are best left dry to encourage capillary action in absorbing the fresh concrete paste. On the other hand, the less porous substrates require water in the pores to aid in thinning the fresh paste to a thinner consistency that can penetrate the tighter pore structure. Another dimension to the wet vs. dry question may actually be how the water affects the temperature of the interface. Evaporative cooling may serve to lower thermal stresses and the potential for flash setting, particularly in hot, windy conditions that have been problematic for overlay placement. This cooling effect has not been studied or tested yet.

Degree of Texture Needed

In light of the research on bonding agents, it appears that their use is unnecessary if the surface preparation of the existing concrete is sufficiently aggressive to expose an open pore structure. However, parameters to categorize the degree of texture necessary before bonding agent use can be discontinued are not clear. Some have promoted the idea that more texture is better and will lead to greater bonding (Hindo 1990; Delatte et al. 1998). Others have found that some degree of texture is necessary, but extremely rough surfaces are not required beyond some threshold value (Felt 1960; Silfwerbrand 1990).

Taking a closer look at surface preparation methods that have been successful in the past and today perhaps can shed some light on this question. Acid etching was used very successfully for many years, though it has fallen out of favor today due

to increasing environmental scrutiny. The aggressive blasting techniques – shotblasting, waterblasting, and heavy sandblasting – are also proving to be reliable contemporary techniques. It is very interesting that old and new methods result in very different surface textures but both have proven successful in promoting bond. The International Concrete Repair Institute produces a set of nine surface profile chips of increasing roughness that are used as a qualitative standard in the repair industry (ICRI 1997). In fact, the smoothest specimen corresponds to a surface prepared with acid etching, while the roughest reflects heavy scarification. Clearly the degree of macrotexture cannot be used to decide whether a surface will be good for bonding. Rather, it is the microtexture that directly reflects the degree of surface porosity which promotes the capillary action necessary for bonding.

Texture measurement techniques have advanced recently with the use of non-contact laser profilometry that are proving to be much faster and more accurate than the traditional sand patch method in ASTM E 965 (Kuemmel et al. 2000; Maerz et al. 2001). It seems possible to reliably measure the average texture depth in the field with this method, reflecting the degree of macrotexture present in a pavement surface. However, as illustrated above with the acid etching vs. shotblasting example, macrotexture measurements are insensitive to pavement microtexture characteristics (ASTM 2001). Unfortunately, this new technology has not advanced to the point where measurements of microtexture can be made. The pavement friction community has found the direct measurement of microtexture is difficult, though one method has been developed using the energy loss in a pendulum slipping across the surface (Brown et al. 2001). Due to the high degree of macrotexture produced by modern surface preparation methods that would limit the contact area for this method, it does not seem promising for repair work. The continuing refinement of optical texture measurement technology, to the point where microtexture can be accurately quantified, promises to provide superior field QA/QC for surface preparation in the future.

The Road Ahead

Overlay Bonding – A Holistic Approach

The realization has been growing in the repair community that a systems approach must be taken in addressing the problem (Emmons et al. 1994). The overlay, the substrate, and the interface that join them must work together as a composite system – compatible with each other and the conditions they are exposed to. The choice of repair material properties, the selection of a surface preparation method, the design geometry, and choice of curing methods are just some of the many interrelated factors which can be controlled that will ultimately affect the long-term performance of the overlay. With the infinite variety of conditions, materials, construction techniques, and designs there is no “magic bullet” panacea repair material that will work best for all situations. Best practices, material property recommendations, and specifications can give general guidelines to follow in avoiding many common problems, but each situation presents unique challenges and a different combination of intricately linked factors.

Modeling Efforts

The ultimate answer to the problem at hand with interrelated environmental, material, design, and construction variables is the use of a model that can incorporate these and predict performance based on changes in these different inputs. Successful use of a model would allow the designer or builder to evaluate different combinations of the inputs and see the effect on performance. Also, the sensitivity of a particular job to changes in weather or material properties could be anticipated and measures taken during design or construction to prevent overlay debonding failure.

The Federal Highway Administration funded development of a model in this area during the mid 1990's for use with the growing implementation of fast-track construction methods that were leading to thermal cracking issues at early-age. One component of this HIPERPAV (high performance paving) model dealing with fast-track paving operations, was a module called HIPERBOND that dealt specifically with bonded concrete overlay behavior in the first 72 hours after placement (McCullough and Rasmussen 1999). Using material, environmental, construction, and design variables as inputs, the HIPERBOND model predicts the development of stresses and bonding strength over time. It incorporates components to approximate heat of hydration, volumetric movements, slab curling, creep, and both strength and modulus development. Unfortunately, it seems that this model has not been fully calibrated and validated yet, with only limited highway testing with state DOT's (McCullough and Rasmussen 1999; Delatte et al. 2001). As such, it is no longer available as part of the current HIPERPAV software releases, though its development is very well documented (McCullough and Rasmussen 1999). Collaboration with military and civilian airfield pavement authorities would be useful in determining its usefulness for airfield pavement overlays. If validated, incorporation within relevant design software – such as PCASE the pavement-transportation computer assisted structural engineering program (USACE, 2004) – could help in avoiding future failures.

Without test data for calibration, models are useless in making confident predictions of the system behavior. As stated earlier, the original overlay design standards developed by the Corps of Engineers are based on empirical observations collected more than 50 years ago. Since then, tremendous improvements in data collection and in-situ measurement technologies have taken place, allowing more sophisticated characterization of pavement properties under traffic loads. Fortunately, the Federal Aviation Administration is beginning some new accelerated trafficking tests of overlaid airfield pavements at its National Airfield Pavement Test Facility in Atlantic City, NJ (Khazanovich 2001). Although only unbonded and partially-bonded PCC overlays are planned at this time, they may yield some results applicable to calibrating a bonded overlay model for airfields. And hopefully a well-instrumented fully-bonded test section might be studied in the future that could provide reliable data for model validation.

New Testing Methods

New test methods and research are undoubtedly needed before bonded overlay construction can be consistently specified and objective QA/QC testing can measure if specifications are being met. Unfortunately, the curling nature of the

debonding mechanism does not lend itself to accurate measurement in terms of the actual failure mode with methods currently available (Granju 2001). The brittle nature of a concrete overlay does not allow the use of conventional peeling tests applied to the characterization of more flexible layered composites. Until a convenient test is developed that can more appropriately measure the fracture mechanics at work, Granju (2001) suggests that measuring the mean tensile bond strength at the interface should be sufficient to predict debonding propagation. In this regard, it is fortunate that better adhesives have become widely available that simplify the rapid pull-off tensile testing of concrete in the field.

The need for a method to measure the microtexture of a prepared surface to ensure proper bonding is also evident from the previous discussions. Hopefully the laser techniques coming into wider use to measure the roughness index and texture depth of pavements will continue refinement until microtexture can be measured reliably in the field. Advances in this area may also be driven by other needs in the airfield pavement community, especially friction measurement.

Another remaining parameter that is hard to quantify, but critically important to proper bonding of overlays is cleanliness. Just as the “How rough is rough?” question is hard to answer, so is the matter of “How clean is clean?” Even though there is great concern over FOD and a whole industry is built on sweeping and vacuuming airfield pavements, there is no standard method to directly measure surface cleanliness. The sweeping community relies on frictional measurements to indirectly measure whether a surface is clean or not. Unfortunately this method is not compatible with a surface ready for a repair, nor would it necessarily measure if a rough surface was clean or not. The development of an objective way to specify cleanliness for a repair surface would help in controlling debonding problems caused by loose dirt. Though, its usefulness in situations where the particles have become wet and formed a paste that clogs the open pores would be limited.

Conclusions

The use of fully-bonded concrete overlays to rehabilitate functional deficiencies in airfield pavements have a long history of successful use, but problems with debonding failures still occur. New insights into the failure mechanics of BCOs, acceptable surface preparation methods, the use of bonding agents, and critical texture parameters will help in updating Air Force guidance. Avoiding failures in overlays requires proper surface preparation, appropriate material selection, adequate consolidation, and proper curing practices. Because deficiencies in any one of these areas can lead to debonding, all these conditions must be met simultaneously in order to achieve acceptable performance. Due to the complicated nature of the overlay repair problem and the interrelated variables that determine successful performance, a properly-calibrated model is the best way to evaluate the effects of changing any of the multiple inputs. The development of better test methods to characterize important bonding parameters are needed to more reliably specify surface preparation for repair work.

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