Design and Quality Control of Concrete Overlays

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16. Abstract

The United States has a significant investment in civil infrastructure, which is deteriorating under heavy use, age, and environmental attack. A large proportion of this infrastructure consists of plain and reinforced concrete pavements and bridge decks. Concrete overlays have been used for pavement and bridge deck rehabilitation for many years. Concrete overlays on pavements or bridge decks can fulfill three design functions – they can strengthen the structure against further deterioration due to fatigue cracking (or rutting, with whitetopping overlays), they can improve smoothness and restore ride quality, and they can add skid resistance.

This research developed and tested a range of plain and fiber reinforced concrete overlay mixes that allow reliable, economic, and durable overlay construction as well as early opening to traffic. This report documents the benefits of using nondestructive testing technologies, including spectral analysis of surface waves, in overlay investigation, planning, construction, and quality control. Analytical modeling using the HIPERBOND module of the program HIPERPAVE was used to investigate behavior and performance prediction for the eight overlay concrete designs investigated in the laboratory testing program. So far, two ultra thin whitetopping overlays have been constructed in Alabama, on heavily traveled asphalt pavements in Selma and Jasper. Both projects were constructed in the outside lanes at intersections, where stopped trucks caused considerable rutting over the years. Performance of the two overlays to date has been very good. Recommendations are made in this report for materials selection, design, and construction controls for overlay construction.

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Executive Summary

The United States has a significant investment in civil infrastructure, which is deteriorating under heavy use, age, and environmental attack. A large proportion of this infrastructure consists of plain and reinforced concrete pavements and bridge decks. Many of these facilities are already well beyond their planned design lives. Selection, design, and quality control of appropriate materials are critical for economical and durable repairs. Appropriate models to evaluate repair materials and strategies are also necessary. Improved economy and reliability of overlays will facilitate management of transportation networks.

Concrete overlays have been used for pavement and bridge deck rehabilitation for many years. For pavements, both unbonded and bonded overlays have been used. Use of bonded overlays is less common, although they offer significant advantages. Plain and fiber reinforced concrete have been used to overlay concrete pavements, concrete bridge decks, and asphalt pavements.

Concrete overlays on pavements or bridge decks can fulfill three design functions – they can strengthen the structure against further deterioration due to fatigue cracking (or rutting, with whitetopping overlays), they can improve smoothness and restore ride quality, and they can add skid resistance.

The main objective of this research was to develop and test a range of plain and fiber reinforced concrete overlay mixes that would allow reliable, economic, and durable overlay construction as well as early opening to traffic (approximately 6 to 12 hours). Other objectives were to investigate a number of nondestructive testing technologies related to overlay planning and construction, and to investigate the effects of design, materials, environment, and construction variables on overlay performance.

This research project encompassed extensive laboratory, field, and analytical work. The laboratory portion involved the fabrication and testing of a large number of specimens for each of eight different overlay concrete designs. Field investigation included observing construction and performance of two ultrathin whitetopping (UTW) sites in Alabama, and evaluation of spectral analysis of surface waves (SASW) nondestructive testing (NDT) equipment for investigation, planning, and quality control of concrete overlays. Analytical modeling used the computer program HIPERPAV to evaluate the behavior and performance of overlay designs.

Concrete used for pavement overlays is a particular category of high performance concrete (HPC). Therefore, this concrete should take advantage of the latest HPC research and technology. As with any HPC, materials selection and mixture proportions are very important for performance. Early age behavior must be considered as well as long-term performance – factors such as shrinkage and thermal contraction must be considered, and in many cases will govern design. These factors are as important as strength, if not more so. Fibers seem to provide benefits, but they have not yet been quantified for this particular application.

Performance of overlays also depends on surface preparation and curing. If these are neglected, even the best designed materials may fail. Management of overlay temperatures at early ages is important. Thus, knowledge of anticipated environmental conditions during construction can help avoid early-age behavior problems.

In this report, the factors that affect the early age behavior and long-term performance of bonded overlays have been reviewed. Laboratory tests on the strength and stiffness development of eight candidate concrete overlay designs showed that high strength concrete was appropriate for opening overlays to traffic in 24 hours or less, but normal strength concrete may be used if traffic loading is delayed for 48 or 72 hours. For larger projects, normal strength concrete may be used for sections that will have 48 to 72 hours or more of curing before traffic loading begins, with high strength concrete used for other sections. Abrasion resistance and durability should also be considered, and may favor the use of high strength concrete with fly ash or slag replacement.

This report also demonstrates the benefits of using NDT technologies, including SASW, in overlay planning, construction, quality control, and investigation. SASW may be used to investigate the existing condition of pavements before overlay construction, to assist in determining design parameters and to identify weak areas that may need additional rehabilitation. During construction, SASW may be used to monitor overlay stiffness development. Another application for SASW is the investigation of overlay performance following construction. This use of SASW was demonstrated during field investigations of the Selma UTW overlay approximately one year after construction.

Analytical modeling using the HIPERBOND module of the program HIPERPAVE was used to investigate behavior and performance prediction for the eight overlay concrete designs investigated in the laboratory testing program. While it was found that all could be used satisfactorily under certain conditions, the most important variable was the time of construction. Morning paving on a sunny day carried a significant risk of overlay failure.

So far, two UTW overlays have been constructed in Alabama, on heavily traveled asphalt pavements in Selma and Jasper. Both projects were constructed in the outside pavement lanes at intersections, where stopped trucks had caused considerable rutting over the years. Performance of the two overlays to date has been very good. Further implementation of this technology can help address rutting due to heavy truck loads. The long-term performance of these overlays should continue to be monitored, in order to learn lessons for future construction.

The research has focused so far on pavement overlays. However, the same principles apply to bridge deck overlays and concrete repairs, since similar material and design parameters govern behavior and performance.

Section 1
Introduction

The United States has a significant investment in civil infrastructure, which is deteriorating under heavy use, age, and environmental attack. A large proportion of this infrastructure consists of plain and reinforced concrete pavements and bridge decks. Many of these facilities are already well beyond their planned design lives. Selection, design, and quality control of appropriate materials are critical for economical and durable repairs. Appropriate models to evaluate repair materials and strategies are also necessary. Safety of concrete bridge decks and pavements can be considerably improved by providing increased skid resistance through thin concrete overlays. Improved economy and reliability of overlays will facilitate management of transportation networks.

In some cases, poorly planned or constructed repairs, inappropriate materials selection, or a combination of factors resulted in early failure. This has happened in several cases for concrete pavement and bridge deck overlays. Such cases lead to even more severe infrastructure problems, with continued impaired use of the facility in addition to a need to remove the original repair before a new repair can be constructed. In addition, other elements of infrastructure may be overloaded during extended repairs of one portion. Rehabilitation of a major bridge may route heavy trucks onto nearby bridges that were not designed for that level of fatigue loading. A thorough laboratory-testing program of overlay and repair materials and methods, coupled with finite element modeling for verification, will lead to important advances in concrete overlay technology.

Concrete overlays have been used for pavement and bridge deck rehabilitation for many years. For pavements, both unbonded and bonded overlays have been used. Unbonded overlays use the existing pavement as high quality subbase support. In contrast, use of bonded overlays is less common, although they offer significant advantages. This report specifically addresses the technology of bonded overlays. Plain and fiber reinforced concrete have been used to overlay concrete pavements, concrete bridge decks, and asphalt pavements.

Currently concrete overlays are perceived to be expensive and difficult to construct. However, properly constructed concrete overlays are durable and can considerably extend the service lives of existing facilities. Concrete overlays on pavements or bridge decks can fulfill three design functions – they can strengthen the structure against further deterioration due to fatigue cracking (or rutting, with whitetopping overlays), they can improve smoothness and restore ride quality, and they can add skid resistance. In current practice the latter two functions are normally met with asphalt overlays. However, this could be changed with faster and more reliable bonded concrete overlay technology, since with proper design all three functions could be served simultaneously.

This research will have applications to all repairs using cementitious materials by helping further define the materials selection, proportioning, and quality control considerations that improve the behavior and performance of repairs and overlays.

Project Objectives

The main objective of this research was to develop and test a range of plain and fiber reinforced concrete overlay mixes that would allow reliable, economic, and durable overlay construction as well as early opening to traffic. Other objectives were to investigate a number of nondestructive testing technologies related to overlay planning and construction, and to investigate the effects of design, materials, environment, and construction variables on overlay performance through analytical modeling. Proper control of these variables is important for overall overlay quality control and quality assurance.

Approach and Work Plan

This research project involved extensive laboratory, field, and analytical work. The laboratory portion involved the fabrication and testing of a large number of specimens for each of eight different overlay concrete designs. Field investigation involved observing construction and performance of two ultrathin whitetopping (UTW) sites in Alabama, and evaluation of spectral analysis of surface waves (SASW) nondestructive testing (NDT) equipment for investigation, planning, and quality control of concrete overlays. Analytical modeling used the computer program HIPERPAV to evaluate the eight overlay concrete designs under a range of environmental conditions.

Organization of This Report

Section 2 of this report presents the literature review and theoretical background of this research. Next, Section 3 provides a detailed discussion of the research plan. The materials testing and results are described in Section 4. Applications of nondestructive testing for overlay technology are evaluated in Section 5. Section 6 reviews the analytical modeling of overlay performance. The field observations for the UTW overlays in Selma and Jasper, Alabama, are discussed in Section 7. Recommendations for future research and the project summary and conclusions are presented in Sections 8 and 9, respectively.

Section 2
Background and Literature Review

Deteriorating asphalt and concrete pavement infrastructure worldwide demands innovative and economical rehabilitation solutions. A properly designed and constructed bonded overlay can add considerable life to an existing pavement, by taking advantage of the remaining structural capacity of the original pavement. Two types of thin concrete pavement overlays rely on bond between the overlay and the existing pavement for performance. Different terminology is used, depending on whether the existing pavement is concrete or asphalt (Delatte, 2001).

Concrete overlays bonded to existing concrete pavements are called Bonded Concrete Overlays (BCO) or Thin Bonded Concrete Overlays (TBCO). In this report, the term BCO will be used because it includes TBCO. These overlays have been constructed for several decades (McGhee, 1994), although their use has mostly been localized to Iowa and Texas. Texas BCO projects have been particularly well documented (Delatte, 1996, Delatte et al., 1996b, Delatte et al., 1997, Huddleston et al., 1995, Lundy et al., 1989, Lundy et al., 1991, Wade et al., 1995, Whitney et al., 1992). Considerable research experience has been developed in this technology, particularly in these states (Delatte and Laird, 1999). Some results were obtained by the Strategic Highway Research Program (SHRP) (Smith and Tayabji, 1998).

Concrete overlays bonded to existing asphalt pavements are called Ultrathin Whitetopping (UTW). This technology developed from the observation that concrete pavements over asphalt often bond to the asphalt, and that some reduction on concrete flexural stresses may be expected from this effect. The technology has been developed mostly in the last ten years. Typically, these overlays are used to address rutting of asphalt pavements. Use of UTW has become increasingly common across the U.S., although Tennessee has constructed more than other states (Delatte and Webb, 2000, ACPA, 1998).

For both BCO and UTW overlays, characteristics of the overlay concrete have important implications for early age behavior and long-term performance. Bond strength and resistance to cracking are important for overlay performance. In many cases these overlays are constructed on heavily traveled pavements, making early opening to traffic important. UTW overlays are now routinely opened to traffic within 24 hours after placement.

Therefore, early strength development without compromising durability is necessary. Satisfactory performance will only occur if the overlay is of sufficient thickness and is well bonded to the original pavement. The design assumption is that the overlay bonds perfectly with the original pavement, producing a monolithic structure. Without bond, there is very little structural benefit from an overlay, and the overlay may break apart rapidly under heavy traffic.

Significant stresses may be caused by the volumetric contraction of the overlay due to shrinkage and thermal effects (Choi, 1992, Delatte, 1999). The tensile stresses developed in the overlay by this contraction may induce cracking in the overlay, as well as loss of bond. Laboratory and field research for a bonded overlay on an interstate highway in El Paso, Texas has provided insight into design of high performance concrete for these applications (Delatte, 1996). Finite element modeling may also be used to predict overlay stresses.

Bonded overlays may serve one or more of three purposes:

- Structural overlays increase pavement thickness and reduce flexural stresses, thus increasing fatigue life.
- Functional overlays restore ride quality (smoothness)
- Functional overlays may provide skid resistance (texture).

Traditionally, concrete overlays have been used for structural purposes, but they can, of course, simultaneously solve functional problems. Where the pavement structure is sufficient and only functional problems need to be addressed, asphalt overlays are generally used in the U.S., due in large part to lower initial cost.

Overlays which bond to an existing pavement (UTW and BCO) should be distinguished from more conventional overlays that do not rely on bond to reduce flexural stresses. More conventional overlays are typically much thicker and are designed using conventional pavement design procedures. When constructed over existing asphalt pavement, they are termed "whitetopping" and use the existing asphalt as a high quality base. When constructed over existing concrete pavement, they are termed unbonded or separated overlays and use a crack relief or separation layer of asphalt between the old and new pavement to prevent reflective cracking. Bond is not a consideration for these overlay designs, and they are beyond the scope of this report.

Structural Behavior and Performance

The long-term performance of bonded overlays is highly dependent on early age behavior – if debonding or excessive cracking occurs at early ages and leads to failure, long-term performance will obviously be poor. A number of failures of BCO at early age have occurred (Delatte et al., 1996a). These include:

- California IH-10, 1981 (Delatte et al., 1996a, Neal, 1983)
- Louisiana US-61, 1981 (Delatte et al., 1996a, Temple and Cumbaa, 1985)
- Texas IH-610 North Loop in Houston, 1985 (Delatte et al., 1996a, Teo et al., 1989)
- Texas IH-10 in El Paso, 1996 (Delatte et al., 1996b)

These are well documented in state department of transportation reports and other sources. Generally debonding occurred at a very early age, within the first 48 hours following placement. The overlays were removed or repaired by bonding them to the original pavement with epoxy, so how they would have performed if left unbonded is not known. Small debonded areas have been found in some other overlays. These overlays generally have not failed. Early age debonding of UTW in service has not been reported.

High Performance Concrete (HPC)

For BCO and UTW overlays, early opening to traffic is often important, and early age behavior determines whether bond is achieved. Therefore, the use of high performance concrete (HPC) should be considered for these applications.

The American Concrete Institute defines HPC as "Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices (Russell, 1999)." The commentary states, "A high-performance concrete is a concrete in which certain characteristics are developed for a particular application and environment (Russell, 1999)." Examples of characteristics that may be considered critical for an application are:

- Ease of placement
- Compaction without segregation
- Early age strength
- Long-term mechanical properties
- Permeability
- Density
- Heat of hydration
- Toughness
- Volume stability
- Long life in severe environments (Russell, 1999)

Some of these characteristics are particularly important for concrete for overlays bonded to existing pavements. These include early-age strength (for early traffic applications), long-term mechanical properties, heat of hydration, toughness, volume stability, and long life in severe environments. Although compressive strength is often specified as a condition for opening overlays to traffic (Delatte et al., 1997), it is less important than these other characteristics. Thus, concrete for BCO and UTW is clearly a category of HPC, and materials selection and mixture proportioning should be based on desired early-age behavior and long-term performance.

Early Age Behavior

At early ages, it is important to reduce stresses within the overlay and at the interface to less than the tensile and bond strength of the concrete. The overlay contracts due to concrete shrinkage and thermal contraction. This leads to tensile stresses within the overlay, which can lead to cracking, as well as shear and tensile stresses between the overlay and existing pavement, which can lead to debonding. Debonding may lead to thin concrete slabs that will fail quickly in fatigue, with failure manifested as corner breaks.

Therefore, desirable characteristics at early ages for BCO and UTW concrete include:

- High bond strength
- Low shrinkage
- Low thermal contraction
- Low modulus of elasticity
- High creep (stress relaxation)

These characteristics may not be easily achieved together. For example, high bond strength is associated with high compressive strength, which is also generally associated with high modulus of elasticity and low creep. Some materials that develop high early strength also develop very high shrinkage, which can lead to early failure (Delatte, 1999). Thus, all characteristics of the concrete at an early age must be considered to design an appropriate HPC overlay. There are many similarities between the requirements for overlay concrete and the requirements for repair materials (Smoak and Husbands, 1997).

Early age behavior also depends on factors other than the concrete properties. The prepared existing pavement surface must be rough and clean enough to facilitate bond. Proper surface preparation improves the shear and tensile bond strength at the interface. Adequate concrete curing improves concrete strength gain, while minimizing the shrinkage and thermal contraction of the concrete. Inadequacy in surface preparation, materials, or curing can lead to overlay failure (Delatte, 1996, Delatte, 2001). Properly engineered overlay concrete is a necessary but not a sufficient condition for proper performance of BCO or UTW.

Finite Element Modeling

Finite element modeling has been used to determine overlay tensile stresses and interface tensile and shear stresses. The stresses can be compared to relevant concrete strength properties to determine a factor of safety. If the factor of safety becomes less than one, failure is predicted. In a previous study, the factor of safety for El Paso BCO concrete and a number of other repair materials was evaluated. Results correlated well with laboratory observations of crack development (Delatte, 1999). The HIPERBOND module of the computer program HIPERPAV may also be used to predict whether BCO failure is likely for a given concrete under certain environmental conditions (Rasmussen et al., 1999).

It is important to verify finite element predictions with field observations. BCO temperatures, moisture gradients, and strains were measured following construction of a test section in El Paso, Texas in June 1995 (Delatte et al., 1996a, Delatte et al., 1996c, Delatte, 2001). A large number of cracks were observed in the overlay, although there was little debonding (Delatte et al., 1996a, Delatte et al., 1996c).

Long Term Performance

For long-term performance, the overlay must continue to provide smoothness and skid resistance with minimal deterioration. Desirable characteristics for long-term overlay concrete include:

- High durability, including resistance to freeze-thaw, alkali-aggregate, and sulfate attack

- High flexural and fatigue strength
- High abrasion resistance

As noted earlier, the long-term properties do not matter if early age properties are not satisfactory. However, once early age failure is prevented, environmental attack, fatigue, and tire abrasion are the most important factors affecting long-term performance. Therefore, long-term performance as well as early-age behavior should be considered in the design of overlay HPC.

BCO and UTW High Performance Concrete

Two important aspects of BCO HPC are selection of the appropriate materials, and determination of proper mixture proportions. Materials should be selected before mixture proportions are determined, due to the fact that some mixture parameters will depend upon the materials selected.

Materials Selection

Materials selection should address cement and other cementitious materials, aggregates, admixtures, and fibers. Once materials have been selected, they should also be evaluated for compatibility.

Even when high early strength is desired, it is not necessary to use high early strength cements (e.g. Type III). Type II/V cement was used for El Paso test sections and overlay construction (Delatte et al., 1996a). Use of lower heat cements, such as Type II/V, as well as replacement with fly ash or slag, can reduce heat buildup in the overlay, and thus reduce thermal stresses. They may also provide additional resistance against environmental attack, and the higher ultimate strength may lead to longer fatigue life of the overlay. It is common in HPC to use supplementary cementitious materials such as fly ash, slag, or silica fume. Use of these materials should be considered for bonded overlays. In addition to improving performance, these materials can reduce the cost of the overlay concrete.

Aggregates should be selected for the lowest possible coefficient of thermal expansion in order to minimize thermal stresses. Overlay aggregates should also have low absorption – shrinkage due to aggregate absorption was suggested as a possible cause of the failure of the California I-80 BCO (Neal, 1983). A dense aggregate gradation can reduce paste requirements and shrinkage, as can use of the largest possible maximum size aggregate. Maximum size of coarse aggregate should not be more than a third of the overlay thickness, and preferably a fourth. However, the overlay concrete must be workable enough for proposed placement methods.

It is also necessary that aggregates be sufficiently resistant to tire abrasion to prevent loss of skid resistance. The abrasion resistance of the overlay concrete is improved by using durable, angular fine aggregate.

Available aggregates should be evaluated carefully to determine which best meet early age and long term performance requirements. Performance requirements may justify purchase of more expensive aggregates, or careful aggregate blending.

Typical admixtures include air entrainment, high range water reducers, and retarders. Enough air must be entrained for durability. High range water reducers (HRWR) can make concrete with a low water-cementitious ratio workable enough for placement. Retarders delay set in hot weather, and may be combined with HRWR in a single admixture. Although shrinkage reducing admixtures (SRA) are not in common use yet for BCO and UTW, they offer considerable potential for reducing overlay stresses and thus providing additional safety against cracking and debonding. The use of SRA in overlay HPC is deserving of further research.

BCO and UTW concrete designs have made considerable use of fibers for concrete reinforcement. These have included steel, synthetic or polypropylene, and nonmetallic or polyolefin fibers (Delatte et al., 1996a). Synthetic fibers are often used for UTW. Possible benefits of fibers include:

- Increased resistance to shrinkage cracking,
- Improved bond strength, and
- Increase fatigue life.

So far, however, the benefits of fibers in overlay concrete have not been quantified. Fiber reinforced concrete has been shown in several studies to be more resistant to shrinkage cracking (Padron and Zollo, 1990, Gryzbowski and Shah, 1990). An increase in flexural toughness, particularly under high strain rate or impact loading, has been demonstrated (Bindiganavile and Banthia, 2001). Steel fibers have also been used, although they are not as common (Chanvillard et al., 1989).

Mixture Proportioning

Typical mixture proportions for BCO and UTW have had rather high contents of cementitious materials, as shown in Table 2-1. Although research may show that cement contents may be lowered without harming long-term performance, it is important at early ages to have enough paste at the interface for bond.

Unless the surface of the existing pavement is saturated surface dry when the overlay is placed, it will draw moisture from the overlay, possibly interfering with hydration. The low water-cement ratio of the El Paso BCO concrete, coupled with a very dry surface, is thought to have contributed to overlay debonding (Delatte et al., 1996b). Therefore, a higher water-cementitious materials ratio (w/cm) of 0.35 to 0.40 is probably appropriate.

Table 2-1. Typical BCO and UTW Mixture Proportions (Delatte et al., 1996a, ACPA 2000)

Mixture proportions (per cubic yard)	El Paso BCO (Delatte et al., 1996a)	UTW (ACPA 2000)
Cement (lbs.)	570	800
Fly ash (lbs.)	307	-
Water (lbs.)	255	280
Coarse aggregate (lbs.)	1,789	1,700
Fine aggregate (lbs.)	1,099	1,230
Air content (percent)	4.5	-
Water/cementitious materials ratio	0.29	0.35
Synthetic fibers (lbs.)	3	3

Some minimum amount of cementitious material is also necessary to provide enough paste for bond – probably 650 to 700 pounds. A 30 % replacement of cement with fly ash will improve workability, reduce heat of hydration, increase long-term strength, and enhance resistance to environmental attack.

Coarse and fine aggregate proportions should be developed using the volumetric mix design procedures of American Concrete Institute (ACI) committee 211 (ACI, 1991). Proper air content should be 4 to 6 %. Admixture dosages should be adjusted through trial batches, and the interactions between admixtures should be considered. Typical amounts of synthetic fibers used are 3 pounds per cubic yard. For the El Paso test section steel fiber reinforced concrete, 75 pounds per cubic yard of hooked-ended steel fibers were used (Delatte et al., 1996a).

Nondestructive Testing

Nondestructive testing may be used to evaluate existing pavement structures, or to evaluate the performance of bonded overlays (Delatte 1996, Delatte et al., 1998). Available NDT technologies include impact-echo (Sansalone and Streett, 1997), impulse-response, SASW, the falling weight deflectometer, and others (Delatte 1996, Delatte et al., 1998, Pessiki and Olson, 1997). The maturity method may be used to predict overlay strength development (Delatte et al., 2000a).

Section 3
Research Plan

The research tasks were addressed through laboratory and field-testing, including nondestructive testing, as well as through computer modeling. Descriptions of the research tasks follow.

First, a thorough literature review was carried out on bonded concrete overlay projects on pavements and bridge decks, with particular attention to high early strength and fast-track projects. This has been documented in Section 2 of this report.

A thorough materials testing program of concrete overlay mixes was developed to evaluate strength and stiffness development, bond development, and shrinkage at early ages. Traditional concrete quality control through slump and compressive strength testing may have little meaning for concrete overlays. Research at the U.S. Army Corps of Engineers Waterways Experiment Station (WES) (Smoak and Husbands, 1997) and at the University of Texas (Delatte et al., 2000a, Delatte et al., 2000b) has indicated that other parameters such as tensile strength, bond strength, coefficient of thermal expansion, and drying shrinkage are much more important than compressive strength. Some mixes involving polypropylene fibers were investigated. The effects of surface preparation and the condition of base concrete on overlay performance were also considered in this phase of the investigation. The materials properties investigated were compressive and splitting tensile strength, modulus of elasticity, bond to concrete (with three different surface roughness characteristics), and durability. Eight different overlay concrete designs were tested.

Available nondestructive testing methods such as impact-echo, impulse-response, ultrasound, spectral analysis of surface waves, and falling weight deflectometer were investigated for monitoring behavior and performance of overlays. Spectral analysis of surface waves (SASW), was evaluated in the field.

Overlay behavior and performance were investigated using the HIPERBOND module of the HIPERPAV computer program and the material parameters determined earlier. In an earlier study, the material behavior predicted by modeling correlated well with that observed during testing by WES (Delatte, 1999).

Section 4
Materials Testing and Results

Eight different concrete overlay mix designs were investigated. These are summarized in table 4-1. Four of these were high early strength (designated with H), with 800 pounds per cubic yard of cementitious material, and a water/cementitious materials ratio of 0.35. Four of these were normal strength (designated with N) with 625 pounds per cubic yard of cementitious material, and a water/cementitious materials ratio of 0.45. Although the normal strength (N) specimens were more conventional concrete, they can still be classified as HPC.

Of each type, one was plain (HP or NP) and three were reinforced with synthetic polypropylene fibers. The fiber reinforced overlay designs have an F as the second letter of the designation. Half of the mixes used a 30 % replacement of cement with either fly ash (HFFA and NFFA) or ground granulated blast furnace slag (HFS and NFS). Constituents in table 4-1 are in pounds per cubic yard.

Table 4-1. Overlay Mix Designs Investigated

Mix	Cement	Fly ash	Slag	Water	Coarse Aggregate	Fine Aggregate	Fibers	Air	Slump	w/cm ratio
	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	Percent	Inches	
1 – HP	800			280	1700	1230		6%	1 – 3	0.35
2 – HF	800			280	1700	1230	3	6%	1 – 3	0.35
3 – HFFA	560	240		280	1700	1230	3	6%	1 – 3	0.35
4 – HFS	560		240	280	1740	1190	3	6%	1 – 3	0.35
5 – NP	625			280	1700	1380		6%	1 – 3	0.45
6 – NF	625			280	1700	1380	3	6%	1 – 3	0.45
7 – NFFA	437.5	187.5		280	1700	1380	3	6%	1 – 3	0.45
8 – NFS	437.5		187.5	280	1740	1340	3	6%	1 – 3	0.45

Materials Used

For the concrete mixtures in this testing plan the cement used was Type I-II Portland cement, which is commonly used for concrete overlays as well as structural and paving concrete. Depending on the mix design, the cement content ranged from 437.5 to 800 pounds per cubic yard. Natural sand was used as fine aggregate, and #67 stone (with a maximum nominal size of 3/4 inch) was used as coarse aggregate. The coarse aggregate was limestone with some stone pieces of approximately 1- 1/4 inch size. Potable tap water at normal temperature was used in the mix.

Pozzolanic materials such as fly ash and ground granulated blast furnace slag were used as a partial substitute for some part of the Portland cement. The fly ash was class C (high calcium fly ash). These materials were added to improve the workability of the mix and to increase its durability. These materials are known to provide high long-term strength and durability but may reduce initial strength gain compared to plain cement mixtures.

Some of the concrete mixtures were reinforced with synthetic polypropylene fibers. The fibers were 2 inches long and were fibrillated so that tiny branches were formed to increase the bonding between the fibers and concrete. These fibers do not absorb water, and therefore do not affect the mixing requirements. Polypropylene fibers are effective in controlling plastic shrinkage cracking, which can be a governing factor in pavement performance. Polypropylene fibers were used in this study because their recent increased use in concrete overlay applications, particularly UTW.

Two types of admixtures were used in this study. Air entrainment was used to protect the concrete from freeze-thaw damage and deicer scaling. Air entrainment was done with the commercially available product Air 30 (Monex Resources Inc.). A high range water reducer , Pozzolith 400 manufactured by Master Builders Technologies, was added to reduce the amount of water required to obtain desired consistency of the mix. The dosages of water reducer were 10 to 25 ounces per 100 pounds of cement. Table 4-1 shows the different mix designs tested in this study.

Materials Testing Plan

The number of tests and ages at testing for the eight overlay designs are shown in table 4-2. For each mix design, 24 cylinders and 3 freeze-thaw prisms were fabricated. Three pull-off specimens were fabricated by casting overlays on top of previously cast base concrete specimens (figures 4-1 to 4-3).

Table 4-2. Number of Tests and Age at Testing

Days	Pull-off	Splitting tensile	Compressive	Modulus	Freeze-thaw
1	3	2	2	2	
3	3	2	2	2	
7	3	2	2	2	
14	3	2	2	2	3

Each pull-off specimen had a surface prepared to a different degree of roughness, as illustrated in figures 4-1 through 4-3.   The three surface roughness characteristics were smooth, roughened with a broom, and roughened by stamping a broken concrete specimen on the surface. For each of the pull-off specimens, it was possible to perform a total of 19 tests. Five pull-off tests each were performed at 1, 3, and 7 days, and four at 14 days. To prepare the specimens for pull-off testing, a two-inch diameter core barrel was used to core through the overlay into the base concrete. Then, an aluminum disk was attached to the top of the overlay using a high strength epoxy, as shown in figure 4-4.

Next, a Dyna pull-off tester with 3,600-pound capacity was used to apply tension to the disks until failure. This tester was capable of applying over 1,100 psi in tensile stress. The tester is illustrated in figure 4-5, and a number of failed specimens are shown in figure 4-6. The specimens shown in figure 4-6 failed where the overlay attached to the interface, but this was not the case for all specimens.

Figure 4-1. Base slab smooth surface

Figure 4-2. Base slab broom surface

Figure 4-3. Base slab rough surface

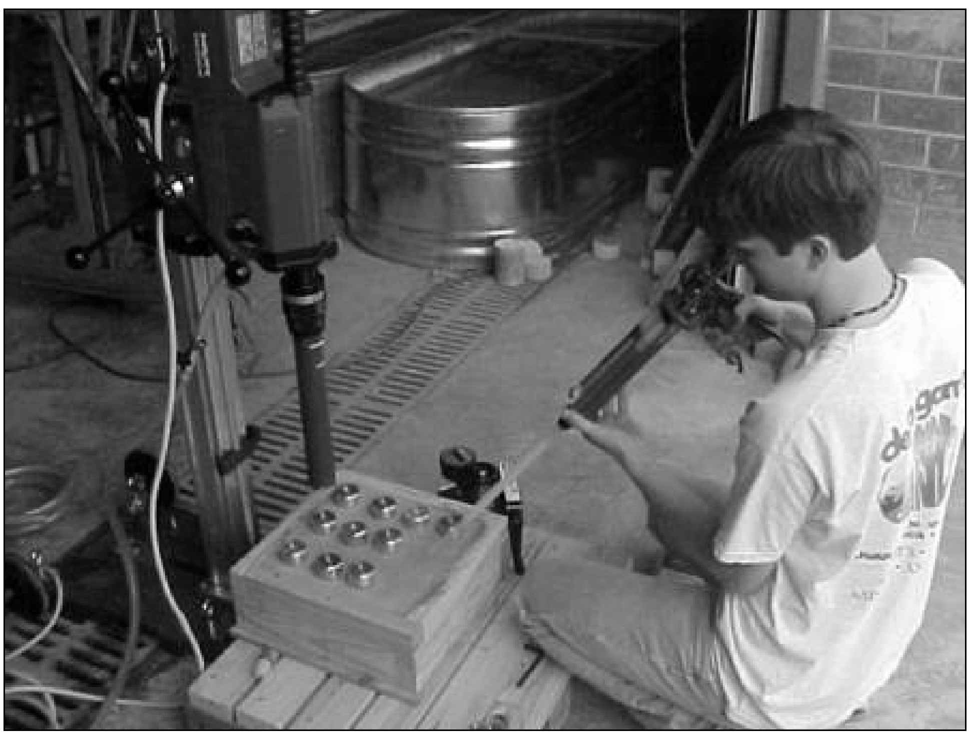

Figure 4-4. Coring and attaching pull-off disks

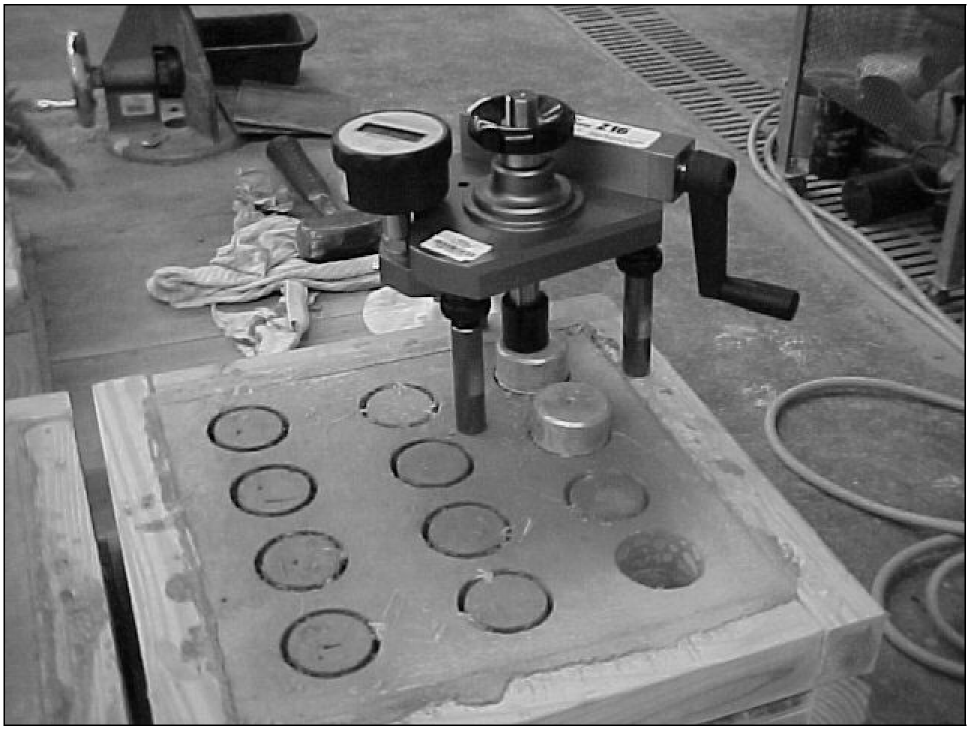

Figure 4-5. Pull-off testing

Figure 4-6. Specimens after pull-off testing

A number of bond test methods have been developed (Wade et al., 1995, Whitney et al., 1992, Giessert et al., 1999, Delatte et al., 2000a). The most commonly used are shear and tension tests. For this research, tension tests were used, with commercially available testing equipment (Dyna).

Actual Concrete Proportions

Actual proportions of the freshly mixed concrete constituents including cement, water, coarse and fine aggregate, fibers, cement substitutes such as fly ash or slag are in pounds per cubic yards (tables 4-3 to 4-10). Slump is measured in inches and unit weight is in pounds per cubic foot. Air entraining and high range water reducing admixture content is in pounds.

Strength Testing Results

As shown in table 4-2, compressive and splitting tensile strength tests were performed at 1, 3, 7, and 14 days. At each time, two specimens of each type were tested. The record of strength development with time as well as the actual mix proportions and properties are shown for the eight overlay designs in tables 4-3 to 4-10. Concrete strength test results are in pounds per square inch. Most of the high strength overlay specimens (except HFFA) achieved a 14-day compressive strength of approximately 8,000 psi, and a one-day strength of approximately 4,000 psi. In contrast, the normal strength specimens achieved one-day strength of approximately 2,000 to 3,000 psi, and 14-day strength of 4,000 to 5,500 (except NFFA). In both cases, the 14-day strength developed by the specimens with fly ash was considerably lower. Typical state DOT specifications require 3,000 psi for opening overlays to traffic at 24 hours (Delatte et al., 1997). Only the normal strength overlay designs with fly ash or slag replacement would have failed to meet that criterion.

The splitting tensile strengths followed similar trends, but there was more scatter. With the exception of the normal strength overlay designs with fly ash or slag replacement, all had splitting tensile strengths between 300 and 600 psi at one day, and between 450 and 850 psi at 14 days.

Bond Testing Results

Tables 4-3 to 4-10 also show all pull-off test results. There was considerable variability in the measured bond strength. Bond strength increased between one and three days, although the increase (if any) at 7 and 14 days was less obvious.

Bond testing was subject to considerable scatter. In part this was due to the variable nature of bond, and in part due to testing. A pull-off specimen might have failed in five different ways. The disk might fail where it is attached to the overlay with epoxy, either in the epoxy or in weak concrete at the surface. The overlay might fracture, or the base concrete might fracture. Finally, the desired failure mode, separation of the overlay from the base concrete, might occur.

The last failure mode was the only one that provides an actual measurement of the bond strength between the overlay and the base concrete. The others all provided a lower bond measurement, because in those failure modes the bond did not fail, but remained intact.

Table 4-3. Actual Proportions and Concrete Strength Test Results of Mix 1 HP

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	4800	590	2.42	82	118	153
3	6,595	660	3.04	146	151	144
7	7,398	770	3.22	197	267	124
14	8139.5	715	3.77	237	324	121

Actual proportions of fresh concrete					
Cement	800	W/cm ratio	0.35	Slump, in	1
Water	280	Water reducer	0.6	Unit weight	151
Coarse aggregate	1700			Air admixture	0.20
Fine aggregate	1230			Air content, %	4.50

Table 4-4. Actual Proportions and Concrete Strength Test Results of Mix 2 HF

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	4225	455	2.36	130	145	102
3	7185	730	2.42	253	219	158
7	7780	680	2.37	172	343	201
14	8583.5	820	3.64	195	375	190

Actual proportions of fresh concrete					
Cement	800	W/cm ratio	0.35	Slump, in	3
Water	280	Water reducer	1.10	Unit weight	152
Coarse aggregate	1700	Fibers	3	Air admixture	0.20
Fine aggregate	1230			Air content, %	5.00

Table 4-5. Actual Proportions and Concrete Strength Test Results of Mix 3 HFFA

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	2930	400	2.68	147	218	227
3	3859	480	2.70	210	261	216
7	5346	610	3.14	122	214	148
14	5698	590	3.04	219	307	278

Actual proportions of fresh concrete					
Cement	560	W/cm ratio	0.35	Slump, in	1.5
Water	280	Water reducer	-	Unit weight	150
Coarse aggregate	1700	Fibers	3	Air admixture	0.20
Fine aggregate	1230	Fly ash	240	Air content, %	5.80

Table 4-6. Actual Proportions and Concrete Strength Test Results of Mix 4 HFS

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	3825	410	2.12	0	0	0
3	7046	550	2.53	84	143	179
7	7509	760	3.03	144	160	236
14	8109	795	3.31	236	292	192

Actual proportions of fresh concrete					
Cement	560	W/cm ratio	0.35	Slump, in	1.25
Water	280	Water reducer	-	Unit weight	150.1
Coarse aggregate	1740	Fibers	3	Air admixture	0.25
Fine aggregate	1190	Slag	240	Air content, %	4.50

Table 4-7. Actual Proportions and Concrete Strength Test Results of Mix 5 NP

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	3900	480	2.67	133	137	90
3	6524	650	3.33	147	235	173
7	7306	640	3.63	205	222	176
14	7836.5	650	4.15	245	235	206

Actual proportions of fresh concrete					
Cement	625	W/cm ratio	0.45	Slump, in	1.5
Water	280	Water reducer	0.60	Unit weight	154
Coarse aggregate	1700			Air admixture	0.25
Fine aggregate	1380			Air content, %	6.00

Table 4-8. Actual Proportions and Concrete Strength Test Results of Mix 6 NF

Concrete age	Concrete Strength test results, psi					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	2241	325	1.85	77	96	56
3	3669	430	2.44	210	218	181
7	4192	525	2.75	206	228	185
14	3712	450	2.67	216	296	196

Actual proportions of fresh concrete					
Cement	625	W/cm ratio	0.45	Slump, in	2
Water	280	Water reducer	0.50	Unit weight	145
Coarse aggregate	1700	Fibers	3	Air admixture	0.20
Fine aggregate	1380			Air content, %	4.90

Table 4-9. Actual Proportions and Concrete Strength Test Results of Mix 7 NFFA

Concrete age	**Concrete Strength test results, psi**					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	1422	-	-	102	91	96
3	2808	360	2.35	192	195	142
7	3028	410	2.52	213	240	211
14	-	-	-	212	285	302

Actual proportions of fresh concrete

Cement	437.5	W/cm ratio	0.45	Slump, in	1.35
Water	280	Water reducer	-	Unit weight	137.5
Coarse aggregate	1700	Fibers	3	Air admixture	0.25
Fine aggregate	1380	Fly ash	187.5	Air content, %	5.50

Table 4-10. Actual Proportions and Concrete Strength Test Results of Mix 8 NFS

Concrete age	**Concrete Strength test results, psi**					
days	Compressive	Splitting tensile	Modulus	Tensile Bond strength		
			million	Smooth base	Broom base	Rough base
1	1368	190	1.82	0	0	0
3	2082	310	2.39	95	158	202
7	5661	410	2.69	182	164	232
14	-	-	-	190	193	259

Actual proportions of fresh concrete

Cement	437.5	W/cm ratio	0.45	Slump, in	2
Water	280	Water reducer	0.20	Unit weight	151
Coarse aggregate	1740	Fibers	3	Air admixture	0.60
Fine aggregate	1340	Slag	187.5	Air content, %	5.50

Bond strengths for the broom finish surface are higher than for the smooth surface. However, the bond strengths for the rough surface are the lowest for many of the designs.

Some of the overlay specimens had not developed enough strength at one day to be cored without damage. These are shown as having no bond strength at one day, and testing began with three-day specimens.

Stiffness Development

For each overlay design, two cylinders were tested for modulus of elasticity at 1, 3, 7, and 14 days. The normal strength specimens with fly ash (NFFA) could not be tested at one day. Other specimens developed a one-day modulus of 1.8 to 2.7 million psi, and a 14-day modulus of 2.6 to 4.1 million psi.

Durability

The resistance of concrete to freezing and thawing cycles is an important measure of durability (Polivka et al., 1975, Powers, 1975, Toutanji et al., 2001). Freeze-thaw tests were performed to determine the durability of the concrete mixtures used in this test plan. The concrete specimens were exposed to rapidly repeated cycles of freezing and thawing in accordance with ASTM C666 (1997). Procedure A, rapid freezing and thawing in water, was followed in the laboratory to carry out the tests. This procedure does not provide any quantitative measure of the service life that can be expected of a particular mix type, but can be used to indicate the variation in both properties and conditioning of concrete samples.

The freeze–thaw tests were carried out on beam samples made from the same concrete mixed for the overlay specimens. After curing these samples for 14 days in a water tank, they were transferred to a freezer. The beams were kept in the freezer until sufficient samples of each mix type were available to run the freeze-thaw machine. This was done to maintain the consistency of the test. The beam prism samples used in this test were 3 by 4 by 16 inches long.

The freeze-thaw testing equipment was model HM–120 of Gilson Company, Inc. This machine has 18 stainless steel containers for concrete specimens with a of 1/8 inch water on all sides of the specimens. These containers are placed side by side with a heating element inserted between them. To keep the specimen from direct exposure it was kept off the bottom of the container by using 1/8-inch brass rods. The center specimen was used as the pilot specimen to control the test and had a thermometer inserted to measure the temperature increase and decrease from 40 to zero degrees Fahrenheit. The cycle started by alternately lowering the temperature of the freezing plate to zero degrees Fahrenheit and then increasing the temperature to 40 degrees Fahrenheit. The cycle length was kept at 4 hours in accordance with ASTM C666 (1997). Initial measurements of length, cross section, weight and fundamental transverse frequency were made for each specimen, as per the standards given in ASTM C215 (1997).

During the test, beam specimens were removed from the freeze-thaw machine at intervals not exceeding 36 cycles of exposure. At the end of each interval the machine was stopped while it was in the thawing cycle. To ensure that the specimens were completely thawed and maintained at the specified temperature, they were kept in the freeze-thaw apparatus for a day. The beam specimens were then taken out and water was used to wash them free of scale, then they were put into a water tank for 4 to 5 hours. Measurements of length change, cross sectional dimensions, weight loss and fundamental transverse frequency were made after wiping the specimen surface free of excess water. The stainless steel containers were also washed free of the scale with water, and returned to the freeze-thaw machine along with the specimens.

The specimens were returned to the container based on a predetermined rotation and orientation scheme so that each specimen was subjected to same conditions on all sides and in all parts of the machine. The containers were then filled with fresh water and the test was resumed. This whole procedure was continued for 300 cycles after which the test was stopped and final measurements were taken to calculate the percentage mass loss and durability factor to indicate the relative durability. Durability factor results are shown in table 4-11 and percent mass loss is shown in table 4-12.

Table 4-11. Durability Factors After 300 Freeze-Thaw Cycles

Mix type	Durability factor results			Average
	1	2	3	DF
HP	0.938	-	-	0.938
HF	0.908	-	-	0.908
HFFA	0.983	0.991	-	0.987
HFS	-	-	-	-
NP	0.778	-	-	0.778
NF	0.955	0.956	0.956	0.956
NFFA	0.964	0.928	-	0.946
NFS	0.885	-	-	0.885
Jasper	0.942	0.959	0.951	0.950
Overlay base	0.824	0.894	0.895	0.871

Table 4-12. Mass Loss After 300 Freeze-Thaw Cycles

Mix type	Percentage mass loss			Average value
	1	2	3	
HP	4	-	-	4
HF	4	-	-	4
HFFA	0	0	-	0
HFS	-	-	-	-
NP	2	-	-	2
NF	0	0	1	0
NFFA	1	1	-	1
NFS	0	-	-	0
Jasper	5	0	0	2
Overlay base	3	3	2	3

The lowest durability factor was 0.778. ASTM C 666 specifies ending the test when the durability factor is less than 0.6, so all specimens passed 300 freeze-thaw cycles. For one design (HFS) the results were not complete at the time this report was written.

Discussion of Materials Testing Results

All of the designs tested appear to have satisfactory strength, stiffness, bond properties, and durability for use in bonded overlay construction. Most of the high strength mixtures can receive traffic at 24 hours or less, while some of the normal strength mixtures will require 48 or 72 hours. The high strength mixtures may also have higher durability and abrasion resistance due to the lower water/cementitious materials ratio.

All beam specimens of each mix type tested performed very well and were in good condition at the end of 300 cycles of rapid freezing and thawing. The beam specimens after 300 cycles had only minor scaling along the surface, edges and corners, and no cracking or any other deterioration. The good condition and performance of the specimens can be largely attributed to the use of air entrainment of up to 6 percent, use of pozzolanic materials such as fly ash and ground granulated blast furnace slag and proper curing of the concrete specimens under laboratory controled conditions.

The durability factor was calculated, per ASTM C666 (1997), for the three beam specimens of each mix type as shown in the table. Except for mix type NP, which had a durability factor of 78 %, all other mixtures showed demonstrated high durability factors. These results are supported by the visual appearance of the beam specimens, which also indicated good performance. The change in lengths of specimens was not observed to be significant in comparison to other variables and is thus not reported here.

The loss in weight of the specimens was also calculated and the results are tabulated in table. The specimens performed very well with the maximum percentage weight loss of four percent for mix types HP and HF. As shown in table 4-4, mix type HF had one of the higher slump values of three inches in comparison to other mixtures. Since higher slump increased the tendency of segregation and bleeding in the fresh mix and resulted in lower quality paste on the top surface, this might have caused the higher weight loss (Polivka, et al., 1975). These results also match well with the good performance indicated by visual inspection and durability factor results.

On large projects, where paving continues over several days, normal strength mixtures may be used when two or more days will elapse before traffic is returned to the pavement, with high strength mixtures used for the last day's construction. This will maximize economy while permitting early traffic on the pavement.

Section 5
Applications of Nondestructive Testing

Nondestructive testing has a number of potential applications for overlays. First, since the new overlay is bonded to existing pavement, and will use that pavement as part of the new composite pavement structure, it is important to assess the structural capacity of the existing pavement. Weak spots in the existing pavement may lead to premature failure of the overlay. Therefore, structural deficiencies of the existing pavement may need to be addressed. This is true for concrete and asphalt layers, as well as base, subbase, and subgrade materials.

A second application is to monitor the stiffness development of the overlay concrete after paving. The SASW method has been used to monitor the stiffness development of a BCO (Delatte, 1996). The maturity method provides an additional means of monitoring strength gain (Delatte et al., 2000a, Delatte et al., 2000b).

Finally, NDT may be used to evaluate overlay performance in cases of possible or actual overlay failure (Delatte et al., 1998). Figure 5-1 illustrates the use of impulse-response to find debonding in a BCO test strip.

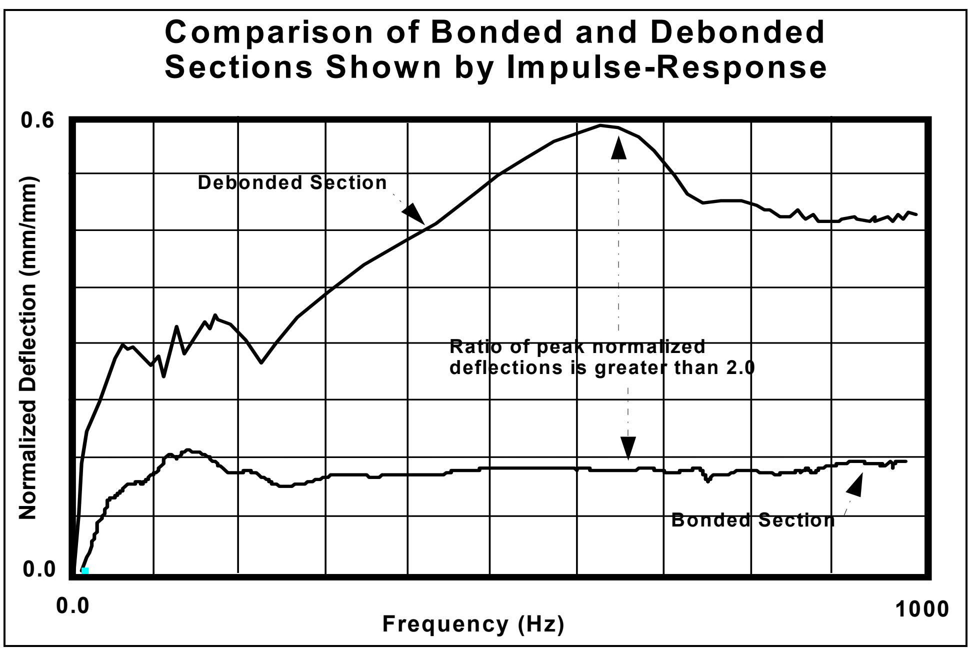

Figure 5-1. Detection of debonding by impulse-response (Delatte, 1996).

Available NDT Technologies

A number of NDT technologies are available. Previous research at the University of Texas (Delatte et al., 1998) and at the University of Alabama at Birmingham has indicated how some of these may be used. Available NDT technologies reviewed during this research include SASW, impulse-response, impact-echo, falling weight deflectometer, and Hilti Ferroscan. Characteristics of these systems are briefly discussed below.

SASW

SASW was developed at the University of Texas and has been used extensively at the University of Alabama at Birmingham. Olson Instruments manufactures two systems – one is used for geotechnical analysis, and one is used for pavement analysis. Each system uses a hammer and a pair of geophones. The spacing of the impact source (hammer) and geophones is gradually increased to measure longer surface wavelengths, which penetrate deeper into the surface of the ground.

The SASW data is used to develop a plot of wavelength versus velocity, which can in turn be used to estimate pavement and soil engineering properties as a function of depth. SASW technology was evaluated during this research, primarily at a one-year-old UTW overlay in Selma, Alabama.

Impulse-response

Impulse-response uses a single impact source (hammer) and geophone to measure the mobility of a system. This technology has often been used to measure integrity of piles, piers, and other foundation systems. No impulse-response equipment was available during this research.

Impact-echo

Impact-echo has often been used to evaluate defects within a concrete structure. This technology generally uses a smaller source than an impulse-response system, and an accelerometer rather than a geophone. It has been used to accurately measure the thickness of concrete pavement. No impact-echo equipment was available during this research.

Falling weight deflectometer (FWD)

Many state highway agencies and consultants use the falling weight deflectometer (FWD) to evaluate pavements. The FWD may be used with backcalculation software to estimate the engineering properties of pavement layers. However, the thickness of each layer must be known or assumed in order to estimate material properties. The FWD was not used during this research.

Hilti Ferroscan

A number of reinforcement locating devices are available. These devices may typically be used to locate reinforcing bars. The Hilti FS-10 Ferroscan is a device that analyzes a 2-foot square portion of a concrete structure and provides a picture of the reinforcing steel. In addition to providing the reinforcement pattern, the bar diameter and depth of cover may be obtained under favorable conditions. This equipment was available during this research and was evaluated in the laboratory, but no suitable field demonstration site was found.

SASW Testing and Results

A UTW overlay was constructed in Selma, Alabama, in July 2000. This project is described in Section 7. SASW testing was carried out approximately one year after construction. The equipment setup is shown in figure 5-2. The two small accelerometers used for pavement testing are shown, as well as the data acquisition and analysis computer.

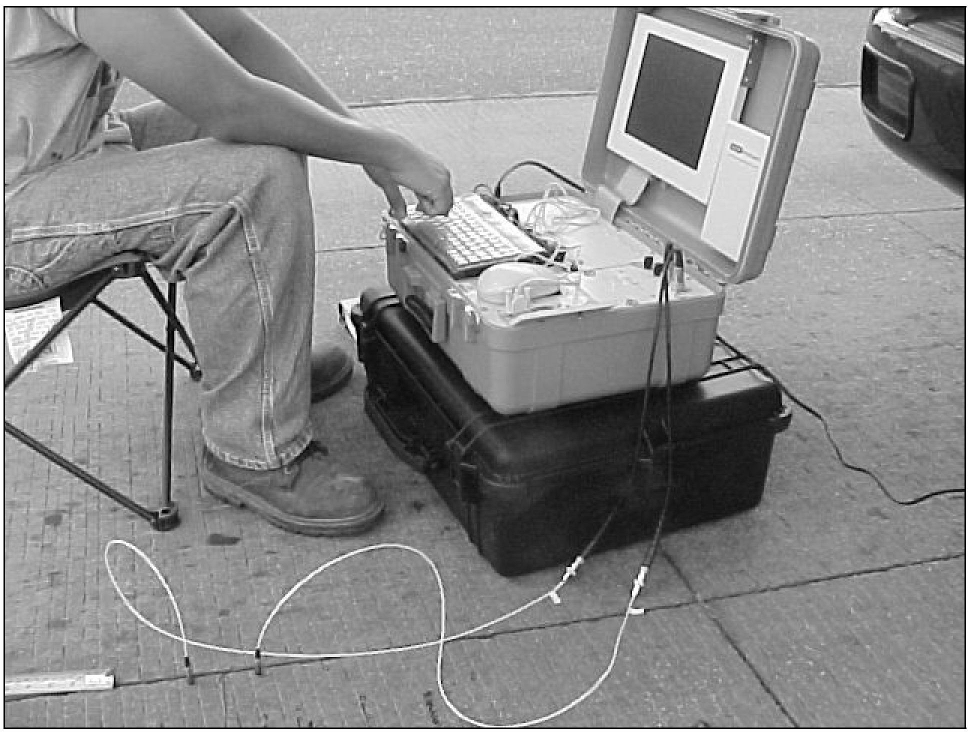

Figure 5-2. Selma UTW SASW testing.

Testing was carried out at several locations. One asphalt pavement location was tested away from the overlay, in order to demonstrate how SASW may be used to evaluate an existing asphalt pavement before construction. Results are shown in figure 5-3. Wavelengths are shown in inches, and shear wave velocities in inches per second. Three separate layers may be observed. The top layer is indicated by the shortest wavelength (up to 10 inches) and represents asphalt with a shear wave velocity of approximately 45,000 inches per second. Next, the other pavement layers show velocity decreasing to approximately 16,000 inches per second. Finally, the subgrade has a shear wave velocity of approximately 10,000 inches per second. A second location, on UTW, is shown in figure 5-4. This is one of two locations for UTW.

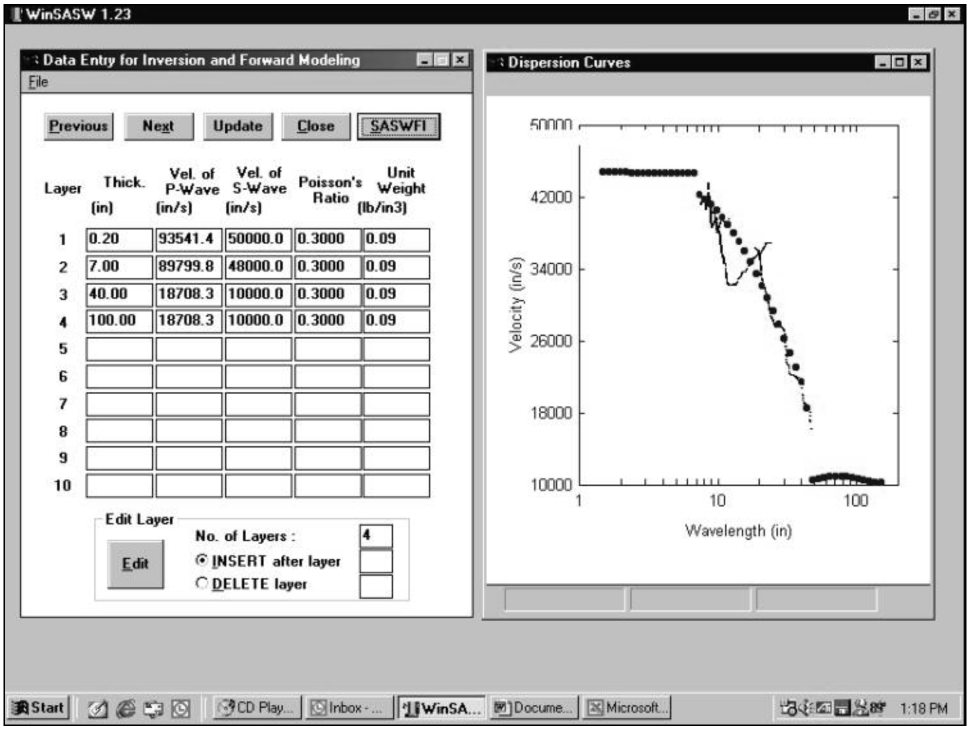

Figure 5-3. SASW testing results on asphalt pavement, Selma, Alabama.

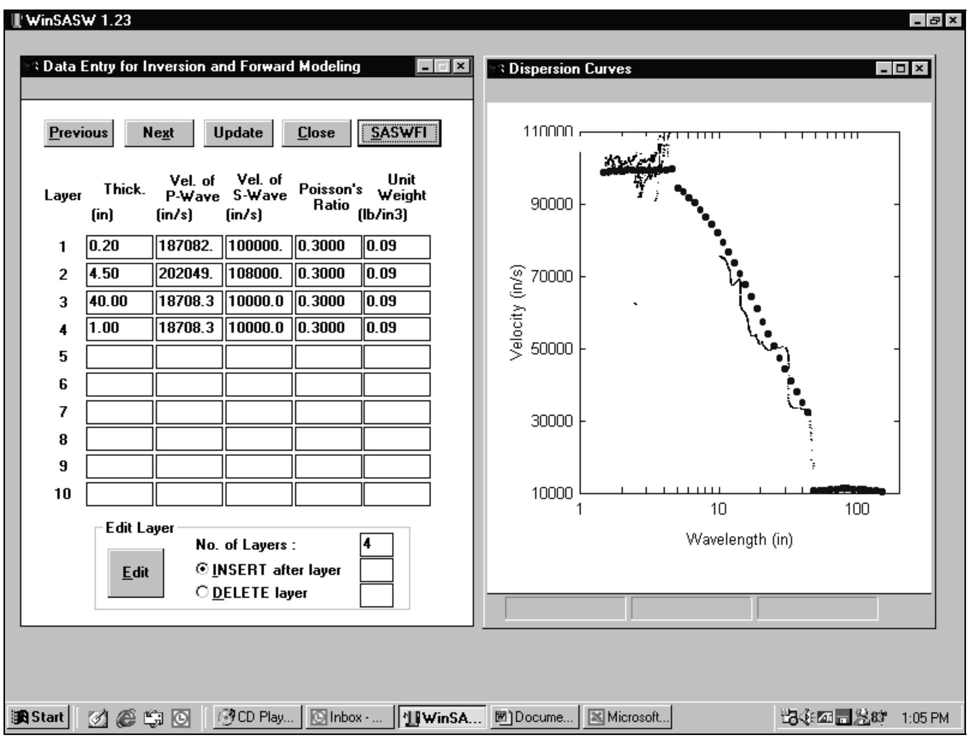

Figure 5-4 SASW testing results on UTW, Selma, Alabama.

The concrete overlay has a much higher shear wave velocity, approximately 100,000 to 120,000 inches per second. Beneath the concrete, the asphalt and other flexible pavement layers observed in figure 5-3 may also be seen.

Following overlay construction, a large shrinkage crack was observed crossing several panels. SASW testing was carried out at this location. Compared with figure 5-4, there did not seem to be any significant loss of structural integrity near the crack. The crack has not deteriorated in the year since construction.

Section 6
Performance Prediction Modeling

Finite element modeling may be used to predict early age behavior and performance of bonded overlays (Choi 1992, Delatte, 1996, Delatte, 1999, Lundy et a.l., 1989, Lundy et al., 1991, Rasmussen et al., 1999). Recently, the program HIPERPAV developed under a Federal Highway Administration contract (Rasmussen et al., 1999) has been used to evaluate early age behavior and performance of pavements. Within HIPERPAV, the module HIPERBOND may be used to evaluate BCO behavior and performance.

Review of HIPERPAV Software

HIPERPAV requires inputs for design, mix design, environmental variables, and construction (Figure 6-1). Either the HIPERPAV module (for new Jointed Concrete Pavement) or the HIPERBOND module (for BCO) may be selected.

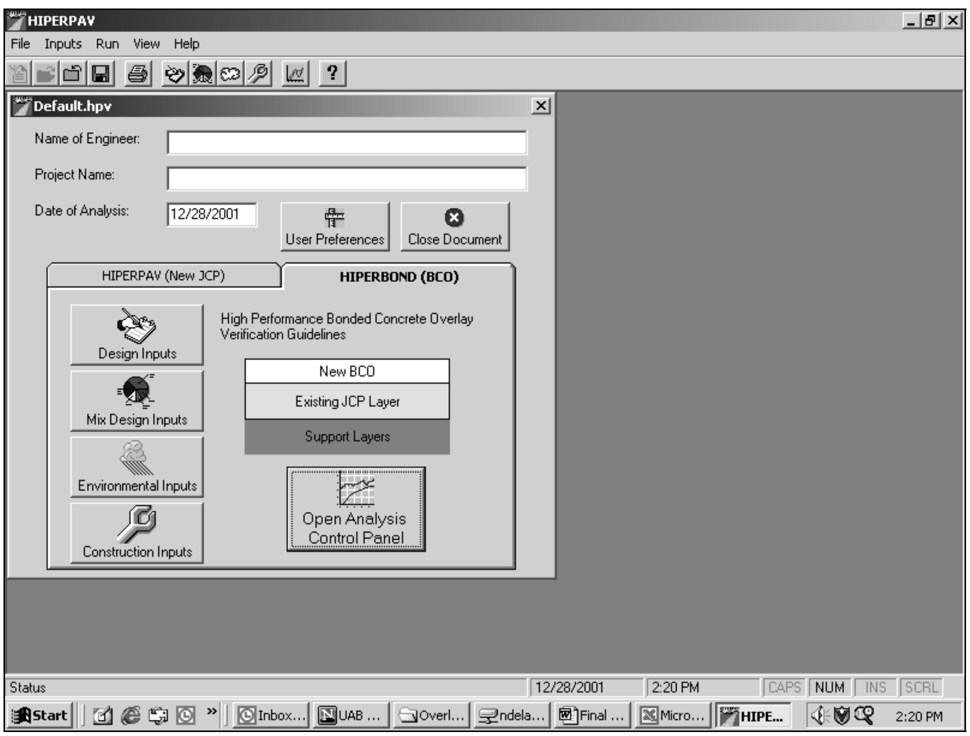

Figure 6-1. HIPERBOND Inputs.

Once the inputs are selected, the Analysis Control Panel is selected. When selecting the HIPERBOND module or opening the Analysis Control Panel, the user is cautioned several times with the statement "The HIPERBOND Module has not been extensively calibrated or validated and is still considered to be preliminary in nature."

After starting the analysis, tensile and shear stresses are calculated and compared to strength, as a function of time since construction. If at any time either stress exceeds the available strength, the overlay is predicted to fail (figure 6-2).

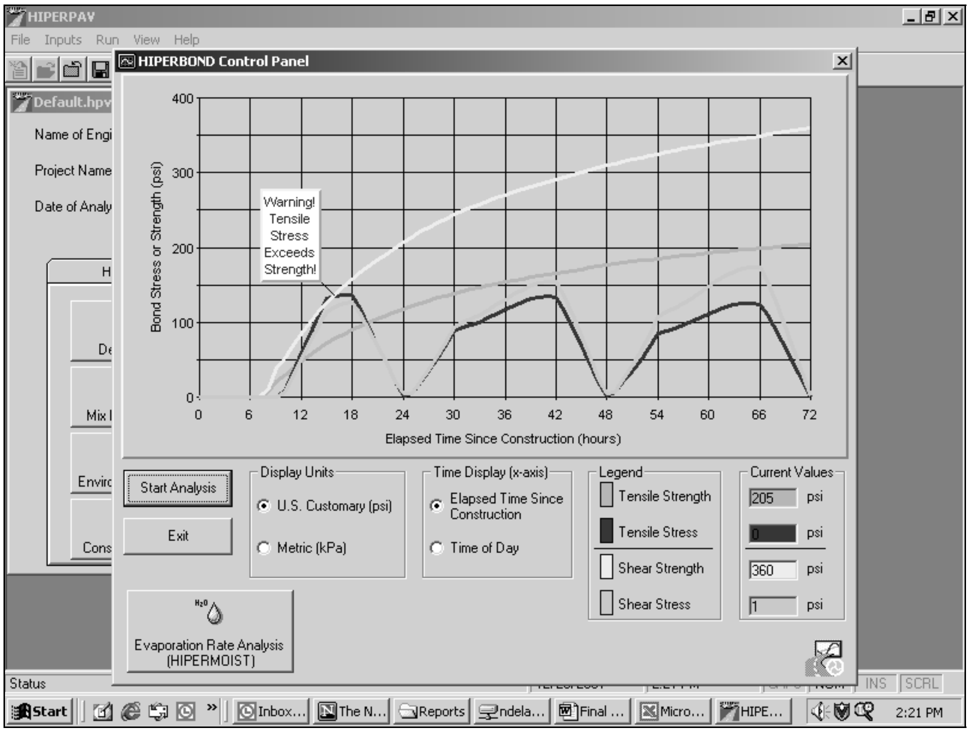

Figure 6-2. Typical analysis results with cracking predicted.

It is well known that the evaporation of moisture from concrete affects the early age behavior and performance of bonded overlays. Often, the ACI evaporation limit of 0.2 pounds of water per square foot per hour is used as a projected failure criterion (Wade et al., 1995, Delatte, 1996, Delatte et al., 1996b, Delatte et al., 1998, Rasmussen et al., 1999). The Evaporation Rate Analysis (HIPERMOIST) Module calculates evaporation as a function of wind speed for winds of 0 to 30 miles per hour. An example is shown in figure 6-3. In this case, the limit is exceeded if winds exceed 15 miles per hour.

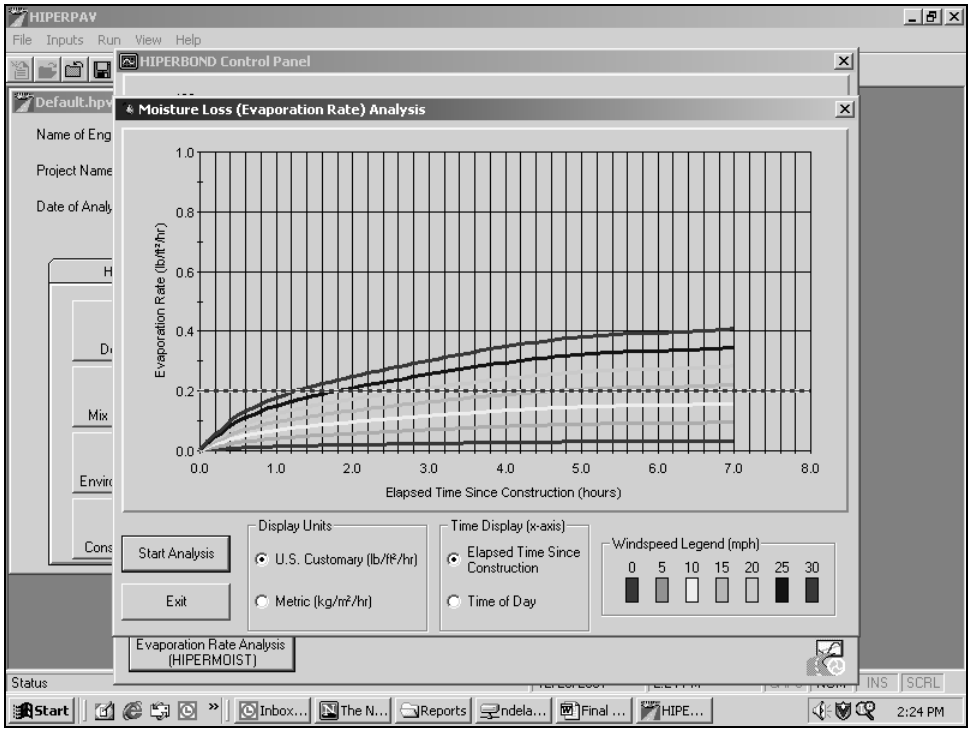

Figure 6-3. Cracking predicted if wind exceeds 15 mph.

Analysis and Results

The overlay concrete designs investigated in Section 4 were evaluated using HIPERBOND. Some of the input parameters were kept constant, and some were varied. The parameters that were kept constant are shown in table 6-1.

Table 6-1. Parameters kept constant during analysis

Parameter	Constant values
Design inputs	Subbase type: flexible (unbound aggregate), default slab-subbase friction Existing pavement 10 inches thick, 520 psi splitting tension strength, 5 million psi modulus, 15 foot joint spacing BCO 4 inches thick, 4.5 million psi modulus
Mix design inputs	Type I (normal) cement, default strength gain and heat of hydration Limestone/dolomite aggregate for existing pavement and overlay, default coefficient of thermal expansion
Environmental inputs	Maximum humidity 80 %, minimum humidity 40 % Average wind speed 5 mph
BCO construction parameters	Triple coat liquid curing compound Initial PCC mix temperature 65 ° F Heavy shotblasting with no bonding agent Default overlay bond strength – shear strength of 400 psi and tensile strength of 200 psi

Different overlay designs were considered, with hot and cool environmental conditions, sunny and cloudy (overcast) conditions, and paving at 9 a.m. and 6 p.m. Since HIPERBOND does not account for the effect of fibers, the plain and fiber concretes (HP and HF, NP and NF, respectively) were considered to be identical. Therefore, six different concrete designs were considered, for a total of 48 analysis runs. The analysis variables are shown in table 6-2.

Table 6-2. Analysis variables

Parameter	Values considered
Mix design inputs	Mixes 1 through 8, splitting tension strength 800 psi (high strength) or 650 psi (normal strength)
Daily maximum (high) and minimum (low) temperature	Hot high 90, low 70; cool high 70, low 50, both use default temperature distribution
Overcast condition	Sunny, cloudy (overcast)
Paving time	9 a.m., 6 p.m.

Inputs for BCO General Design Parameters are shown in figure 6-4. This information was identical for the high strength designs (HP/HF, HFFA, HFS). For the normal strength designs (NP/NF, NFFA, NFS), the 28-day splitting tensile strength was set at 650 psi.

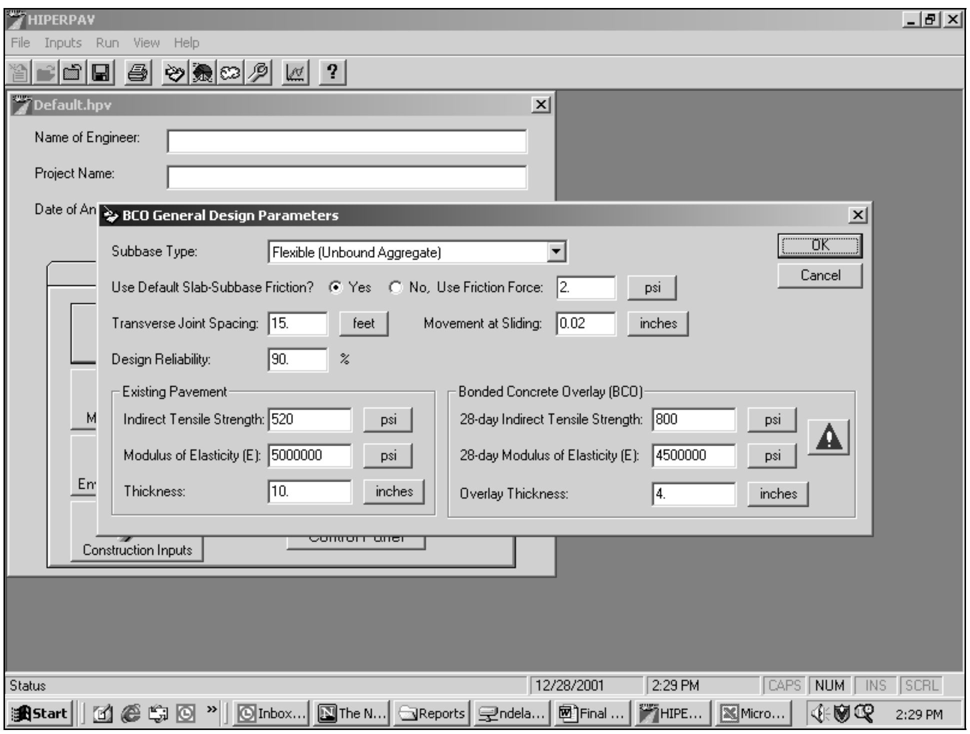

Figure 6-4. BCO general design parameters, high strength concrete.

Inputs for BCO Mix Design Parameters are shown in figure 6-5. This information varied for each of the six designs considered. The type of cement (Type I) and type of aggregate (Limestone/Dolomite) were kept constant, but the weights of the constituent materials were taken from table 4-1.

The inputs for Environmental Parameters are illustrated in figure 6-6. Temperatures and overcast conditions were varied. Figure 6-7 shows the BCO Construction Parameters. The assumed tensile bond strength of 200 psi is consistent with the laboratory test results reported in Section 4.

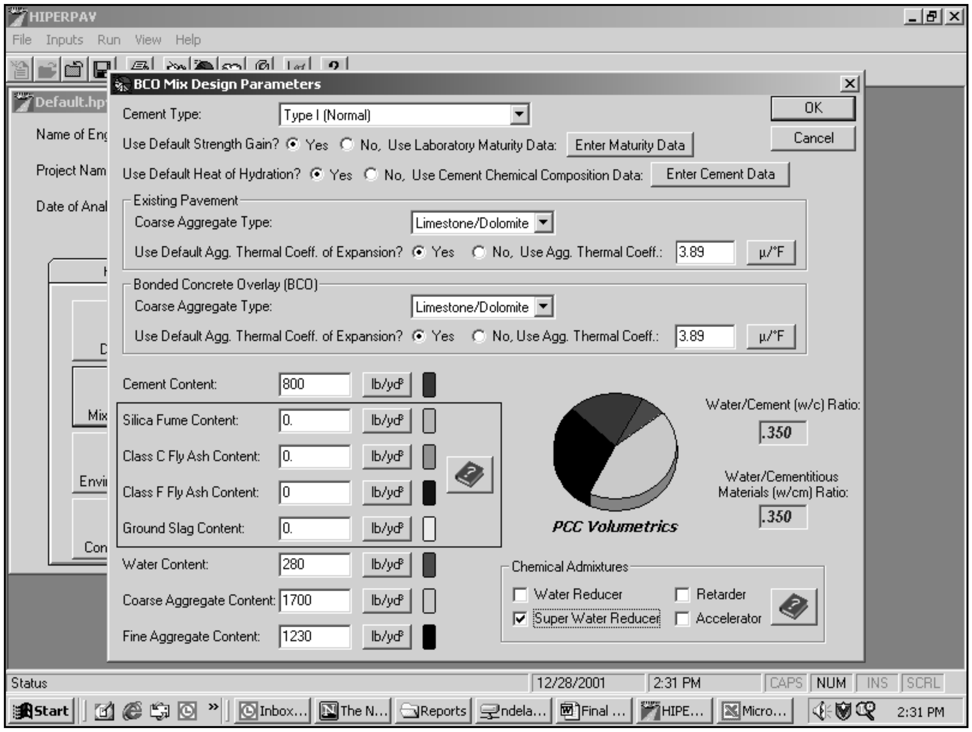

Figure 6-5. BCO mix design parameters, high strength plain concrete.

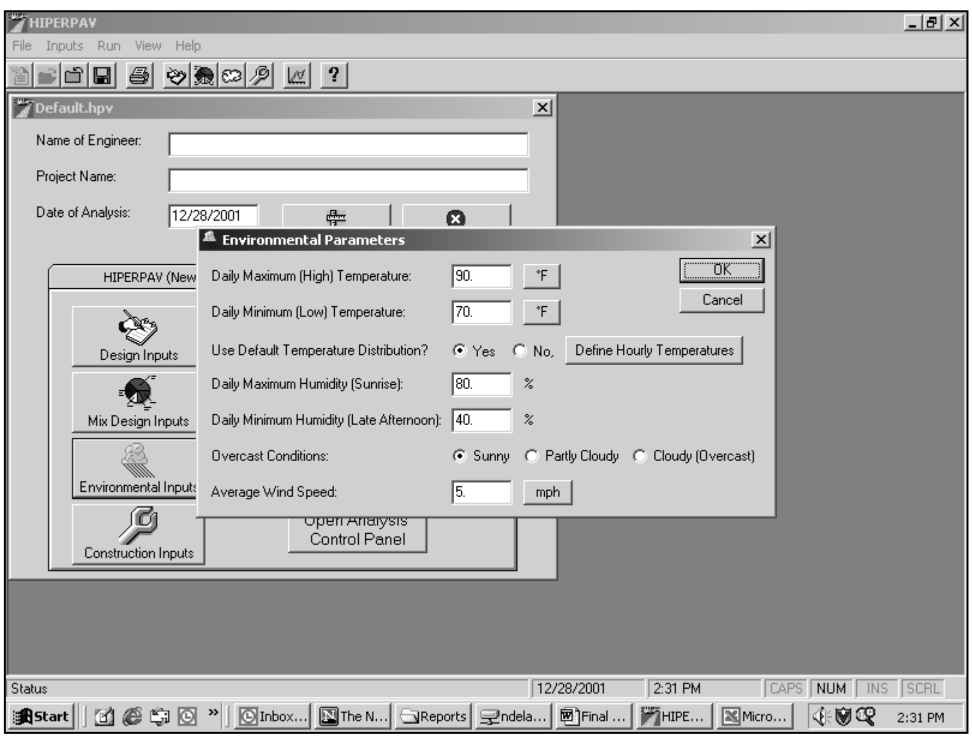

Figure 6-6. Environmental parameters, high temperature, sunny.

Figure 6-7. BCO construction parameters, triple coat of curing compound, morning.

Results for the 48 analyses are shown in tables 6-3 and 6-4. It is possible to control the type of concrete used and the time of paving. The overall weather conditions (hot or cool) may be controlled to some degree by scheduling the date of construction, although actual high and low temperatures may be difficult to predict. However, it is difficult to predict whether sunny or cloudy conditions will prevail during construction, and conditions may change rapidly.

Table 6-3. Analysis results, hot weather

Concrete type	Sunny conditions		Cloudy (overcast) conditions	
	Morning	Late afternoon	Morning	Late afternoon
1 – HP, 2 – HF	**FAIL**	OK	OK	OK
3 – HFFA	**FAIL**	OK	**FAIL**	OK
4 – HFS	**FAIL**	OK	OK	OK
5 – NP, 6 – NF	**FAIL**	OK	**FAIL**	OK
7 – NFFA	**FAIL**	OK	OK	OK
8 – NFS	**FAIL**	OK	OK	OK

Table 6-4. Analysis results, cool weather

Concrete type	Sunny conditions		Cloudy (overcast) conditions	
	Morning	**Late afternoon**	**Morning**	**Late afternoon**
1 – HP, 2 – HF	**FAIL**	OK	OK	OK
3 – HFFA	**FAIL**	OK	OK	OK
4 – HFS	**FAIL**	OK	OK	OK
5 – NP, 6 – NF	**FAIL**	OK	OK	OK
7 – NFFA	**FAIL**	OK	**FAIL**	OK
8 – NFS	**FAIL**	**FAIL**	OK	OK

In all cases, unsatisfactory performance is predicted with morning paving on sunny days. Nearly all of the designs will perform well with afternoon paving whether conditions are sunny or overcast, with the exception of NFS on sunny days in cool weather. These results were developed using a triple coat of curing compound. With only a single or double application of curing compound, more combinations would probably show unsatisfactory performance.

Of the variables investigated, the most important is clearly the time of paving. Late afternoon paving leads to the best predicted performance.

Section 7
Alabama Case Studies and Field Observations

So far two UTW overlays and no BCO overlays have been constructed in Alabama. The first was constructed on July 8, 2000, on the US 80 bypass around Selma, Alabama. The second was constructed on US 78 in Jasper, Alabama, on October 27, 2001. Both are discussed in this section.

Selma US 80 Bypass

The first UTW construction in Selma was on heavily rutted asphalt pavement in the truck lane of the US 80 bypass at an intersection. Rutting approached 3 inches (figure 7-1). A 4-inch thick overlay was designed to rehabilitate the pavement. The concrete used was high strength synthetic fiber reinforced concrete with fly ash replacement, similar to the HFFA design investigated in Section 3.

Figure 7-1. Heavy rutting on Selma US 80 bypass.

Only the outer lanes were rehabilitated. The pavement was prepared by cold milling out 4 inches of asphalt (figure 7-2). This made it possible to cast the UTW as an inlay, using the existing asphalt pavement as formwork (figure 7-3). This, in turn, made it easy to match the existing pavement grade and achieve excellent longitudinal smoothness.

Figure 7-2. Cold milling surface preparation

Figure 7-3. Placing UTW as an inlay.

UTW is cut into squares using early entry saws (figure 7-4). Typical spacing is one foot for every inch of UTW thickness. Thus, the 4-inch UTW was cut into 4-foot squares.

Figure 7-4. Early sawcutting of UTW into 4-foot squares

This project was constructed over a weekend, and traffic was allowed on the UTW on Monday morning when the overlay was less than 48 hours old. The early traffic loading did not appear to cause any distress.

Weather conditions were hot and sunny during construction. Following construction, a large shrinkage crack crossing several panels was observed in one section of the UTW. Over the next year, this crack did not show any additional deterioration.

SASW testing was carried out on this project approximately one year after construction. Results have been previously discussed in Section 5. This pavement continues to receive heavy traffic. The UTW appears so far to have solved the chronic rutting previously observed in this area.

Jasper US 78

The second Alabama UTW project was constructed on US 78 in Jasper over the weekend of October 27, 2001. Prior to overlay construction, this section also had heavy rutting in the outer lanes (figure 7-5). Due to heaver traffic than Selma, a 6-inch thick overlay was constructed. This project was also milled and cast as an inlay (figure 7-6).

Figure 7-5. Heavy rutting on US 78 in Jasper.

Figure 7-6. Casting 6 inch thick UTW inlay in Jasper

Due to the greater thickness of the Jasper overlay, the UTW was cut into 6-foot squares (figure 7-7). Cuts were made between the overlay and the asphalt, as well as in the interior of the UTW. Since it is almost impossible to make this cut exactly on the boundary between the two materials, this practice risks creating a weak section subject to deterioration and spalling. Therefore, the performance of the edge cut in Selma and Jasper should be monitored to determine whether this practice enhances or detracts from performance.

Figure 7-7. Cutting along edge of UTW in Jasper.

Samples of the UTW concrete were collected from the Jasper project for subsequent laboratory analysis. Development of compressive and splitting tensile strengths for the Jasper UTW concrete was measured in the laboratory, as well as stiffness development. For all three parameters, the Jasper field concrete results compare well with the HF laboratory design. This is to be expected, since the HF and HFFA designs represent current UTW practice. In addition, the Jasper UTW concrete had a high durability factor after 300 freeze-thaw cycles as shown in table 4-11.

Section 8
Recommended Future Work

This report has documented the first year's work on a projected two-year research project. Due to the construction project in Jasper, it was possible to conduct some of the field investigation that had been proposed for the second year effort.

Research Needs

Many research needs still exist for BCO and UTW. Because of the similarities in the factors affecting early age behavior and long-term performance, the same research approaches can yield useful information for both types of overlays. Questions to be answered include:

- What are the benefits of fibers for BCO and UTW? Research has investigated the effects of fibers in reducing shrinkage cracking and improving fatigue resistance of concrete, but the effect on bond strength (if any) has not been quantified. Moreover, there is a need to determine how to select fibers and to determine optimum fiber quantities for overlay construction. The research so far has not shown any significant strength or bond differences between the HP/NP and HF/NF designs that may be attributed to fibers.
- How can admixtures improve early age behavior and long-term performance of bonded overlays? High range water reducers may improve bond, and shrinkage reducing admixtures may reduce debonding stresses. Although high range water reducers were used in this study, shrinkage reducing admixtures were not.
- What are proper minimum surface preparation specifications for bonded overlays? The specification recommendations for the El Paso BCO were for shotblasting or hydrocleaning to a minimum average texture depth of 0.06 inches (Delatte et al., 1996a).
- What are the curing requirements for BCO and UTW? Curing is known to be important for developing strength as well as reducing stresses due to volumetric contraction. However, the need to open concrete overlays to traffic quickly may make traditional curing methods impractical. The benefits of using double and triple curing compound applications should be investigated further.
- What is the actual strength requirement for BCO and UTW? Current mixtures have very high cementitious material contents, which contributes to early heat buildup. The strength requirement should be reduced to that which is needed for proper overlay performance – however; this is a difficult problem to address because concrete strengths as well as stresses change continually as the concrete cures.

In addition, most work so far has been on overlays for structural improvements. How can concrete overlays be used to address functional problems – to improve smoothness and skid resistance? Although the initial cost may be higher than asphalt overlays, concrete overlays to address functional problems may be considerably more durable. Thus, life cycle costs may be lower, particularly if traffic control and user costs are considered.

Proposed Second Year Work Plan

The research approach for a proposed second year of work encompasses five elements. Important work has been done in four of these areas, including laboratory testing, field-testing, and computer modeling. These results are reported above.

Materials Testing

The materials testing from the first year of work should be continued. In addition to the concrete mixes investigated earlier, the mix designs and materials used by the contractor for Selma and Jasper construction should be evaluated. Additional designs to address some of the topics raised under the Research Needs section above would be tested in the laboratory.

Finite Element Modeling

Finite element modeling using the computer program HIPERPAV (and the HIPERBOND module) developed by the FHWA should be continued. Materials may be analyzed under projected environmental conditions for future projects to develop recommendations for timing concrete placement and joint cutting to avoid cracking. It is possible to investigate project parameters in depth using the HIPERPAVE software to develop project-specific construction recommendations for a state highway agency.

Another important use of finite element modeling is to investigate the strength requirements for opening overlays to traffic. Using the material properties developed during the laboratory investigation documented in Section 4, overlay stresses may be calculated and compared to tensile and bond strengths.

Model Testing

An excellent way to observe the behavior and performance of overlay designs is to construct half-scale bridge deck and overlay models in the laboratory and load them in fatigue at early ages. Previous research at the University of Texas (Huddleston et al., 1995) demonstrated that high early strength overlays could be loaded very early, but more economical concretes were not investigated. This testing may be performed at UAH since fatigue testing equipment is already available there. A typical test setup for overlay fatigue testing is shown in figure 8-1. These results will allow prediction of the concrete strength requirements for opening overlays to traffic, and provide validation of the performance of different overlay designs.

Field Testing

In the final phase arrangements should be made with the Alabama Department of Transportation and/or other agencies for demonstrations, field construction of test sections, and monitoring of behavior and performance to verify this research. It is important to have thorough documentation of the construction of experimental pavement sections, to be able to analyze performance later, and to disseminate lessons learned.

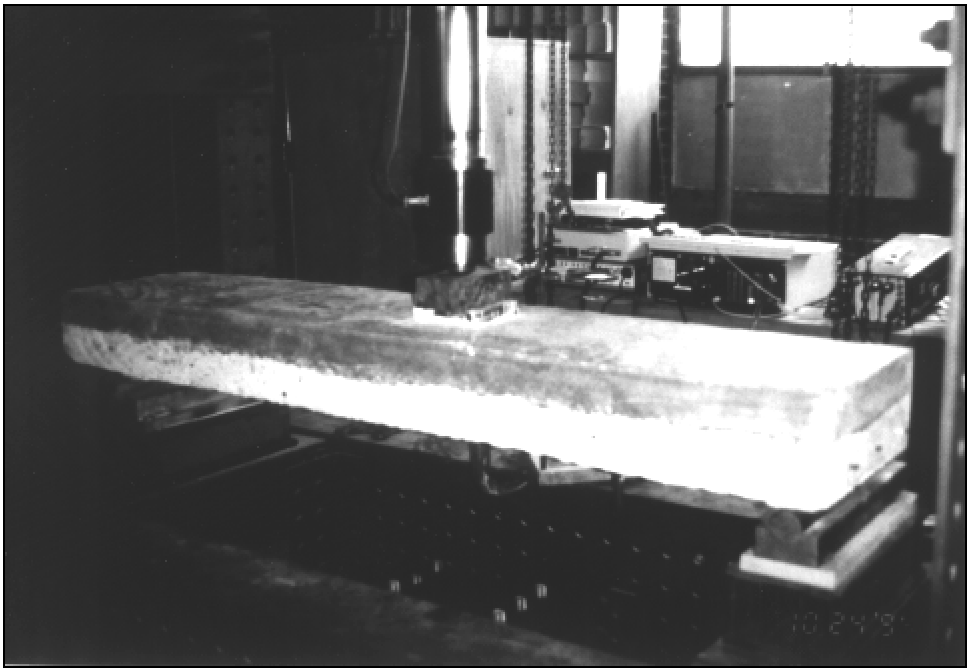

Figure 8-1: Half scale overlay model test

Section 9
Summary and Conclusions

Concrete used for pavement overlays (BCO and UTW) is a particular category of HPC. Therefore, this concrete should take advantage of the latest HPC research and technology. As with any HPC, materials selection and mixture proportions are very important for performance.

Early age behavior must be considered as well as long-term performance – factors such as shrinkage and thermal contraction must be considered, and in many cases will govern design. These factors are as important as strength, if not more so. Fibers seem to provide benefits, but they have not yet been quantified for this particular application.

Performance of overlays also depends on surface preparation and curing. If these are neglected, even the best-designed materials may fail. Management of overlay temperatures at early ages is important. Thus, knowledge of anticipated environmental conditions during construction can help avoid early-age behavior problems.

In this report, the factors that affect the early age behavior and long-term performance of bonded overlays have been reviewed. Laboratory tests on the strength and stiffness development of eight candidate concrete overlay designs showed that high strength concrete was appropriate for opening overlays to traffic in 24 hours or less, but normal strength concrete may be used if traffic loading may be delayed for 48 or 72 hours. For larger projects, normal strength concrete may be used for sections that will have 48 to 72 hours or more of curing before traffic loading begins, with high strength concrete used for other sections. Abrasion resistance and durability should also be considered, and may favor the use of high strength concrete with fly ash or slag replacement.

All of the overlay concrete designs tested have satisfactory mechanical properties, bond strength, and durability. The normal strength concrete is more economical than the high strength concrete, but develops these properties more slowly. The HIPERPAV analysis suggests that the HP, HF, HFS, and NFFA designs will perform well under most environmental conditions, although all designs would risk debonding for morning paving under sunny conditions.

This report has also demonstrated the benefits of using NDT technologies, including SASW, in overlay planning, construction, quality control, and investigation. SASW may be used to investigate the existing condition of pavements before overlay construction, to assist in determining design parameters and identify weak areas that may need additional rehabilitation. During construction, SASW may be used to monitor overlay stiffness development. Another application for SASW is the investigation of overlay performance following construction. This use of SASW was demonstrated during field investigations of the Selma UTW overlay approximately one year after construction.

Analytical modeling using the HIPERBOND module of the program HIPERPAVE was used to investigate behavior and performance prediction for the eight overlay concrete designs investigated in the laboratory testing program. While it was found that all could be used satisfactorily under certain conditions, the most important variable was the time of construction. Morning paving on a sunny day carried a significant risk of overlay failure.

So far, two UTW overlays have been constructed in Alabama, on heavily traveled asphalt pavements in Selma and Jasper. Both projects were constructed in the outside pavement lanes at intersections, where stopped trucks had caused considerable rutting over the years. Performance of the two overlays to date has been very good. Further implementation of this technology can help address rutting due to heavy truck loads. The long-term performance of these overlays should continue to be monitored, in order to learn lessons for future construction.

The research so far has focused on pavement overlays. However, the same principles apply to bridge deck overlays and concrete repairs, since similar material and design parameters govern behavior and performance.

Section 10
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Section 11
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