Infrared Thermography Revolutionizes Asphalt Paving

Significant Cost Savings for States and Municipalities

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FLIR Systems

CONTENTS

Summary

Highways throughout the United States are typically engineered to last 15 years or more, but some have been failing much earlier due to potholes, cracks, raveling, and other problems. This premature road failure unnecessarily wastes millions of taxpayer dollars every year and threatens the strategically critical National Highway System (NHS), which carries more than 40 percent of all highway traffic, 75 percent of heavy truck traffic, 90 percent of tourist traffic, and virtually all of our military traffic. (See maps on pages 3 and 4, and table of mileage in Appendix 4, page 21.)

> For the first time, a state DOT had a practical field test method and an economical tool—the infrared camera—to conduct quality assessments of asphalt pavement during laydown that could predict potential areas of faliure.

To improve the longevity of these roads—more than 90% of which are paved with hot-mix asphalt (HMA)—the Transportation Research Board (TRB) of the National Academies coordinated a five-year-long $150 million Strategic Highway Research Program (SHRP). This program created a set of optimized design and analysis methods and standards called SuperPave® in 1993. The TRB conservatively projected that if the new SuperPave procedures achieve only a 25% increase in highway service life, state and federal agencies could save $785 million annually in avoided road repair costs, and motorists could save between $1.3 billion and $2.1 billion a year in maintenance-related delays and vehicle wear and tear, plus the value of improved safety conditions.

However, even after SuperPave procedures were adopted, which did not focus on field construction, premature failure persisted. The Washington State Department of Transportation (WSDOT) and the University of Washington, at about that time, conducted a series of detailed thermographic research studies of hot-mix asphalt during road construction using an Inframetrics (now FLIR) ThermaCAM® infrared camera. The camera was provided by

Astec, a major manufacturer of infrastructure equipment. The studies determined that a major cause of premature hot-mix asphalt road failure in Washington State is excessive thermal differentials in the hot-mix caused by surface cooling during truck transport from the batch plant to the construction site.

WSDOT later purchased a ThermaCAM PM-290 infrared camera to continue this research during the 1999 through 2001 construction seasons. The infrared camera is used to accurately locate areas of excessive thermal anomalies in the hot-mix during mat laydown. The density of the anomalously cool imaged pavement areas is then evaluated by nuclear densitometry.

It was found that in areas where thermal differentials in the hot-mix during laydown were 25 Fahrenheit degrees or greater, air voids typically increased by 2% or more after compaction, therefore decreasing the density and lowering the resistance of the affected areas to wear and tear.

Extensive field data previously showed that every 1% increase in air voids over a base threshold of 7% causes a 10% reduction in pavement life from physical and environmental wear and tear. On this basis, the WSDOT carefully correlated the thermographic and nuclear density data. The result—for the first time, a state DOT had a practical field test method and an economical tool, the FLIR infrared camera, to conduct qualitative assessments of asphalt pavement *during laydown* that could predict potential areas of failure.

Remixing the hot-mix in the field prior to loading it into the paver machine could solve the thermal segregation problem, but if so, how would the remixing be achieved? After an exhaustive series of tests of available road-building equipment, the WSDOT concluded that remixing techniques were effective, and that material transfer devices or vehicles (MTO/MTV) that thoroughly reblend the hot-mix just prior to placing it on the roadway effectively eliminate temperature differentials.

"The use of a thermographic protocol to validate density for road building specifications offers important benefits for the paving industry and federal and state specifying agencies."

With the problem identified and a pragmatic and economical test method and solution in hand, WSDOT implemented a systematic density specification on 10 projects in 2002, and is applying the specification to selected hot-mix road construction in 2003 and thereafter—a significant step for reducing premature road failure.

The standardization of density profiling and the use of a thermographic protocol to validate hot-mix density offers important benefits for the paving industry and federal and state specifying agencies. These benefits include the promise of longer lasting and smoother roads; improved return on road construction investment; a wider paving window for contractors; and stimulus for the development of new ways to maintain thermal consistency in batches of hot-mix during transport and laydown.

The National Highway System— A Strategic Resource

America's paved highways and lesser roads compose a 6.4 million kilometer transportation network on which the nation depends for the vast preponderance of its commerce, travel, and security. Surprisingly, only about 4% of this network of roads composes the strategically critical National Highway System (NHS). The NHS was established in 1995 by the U.S. Department of Transportation (DOT), in cooperation with state and local officials under the authority of the National Highway System Designation Act of 1995.

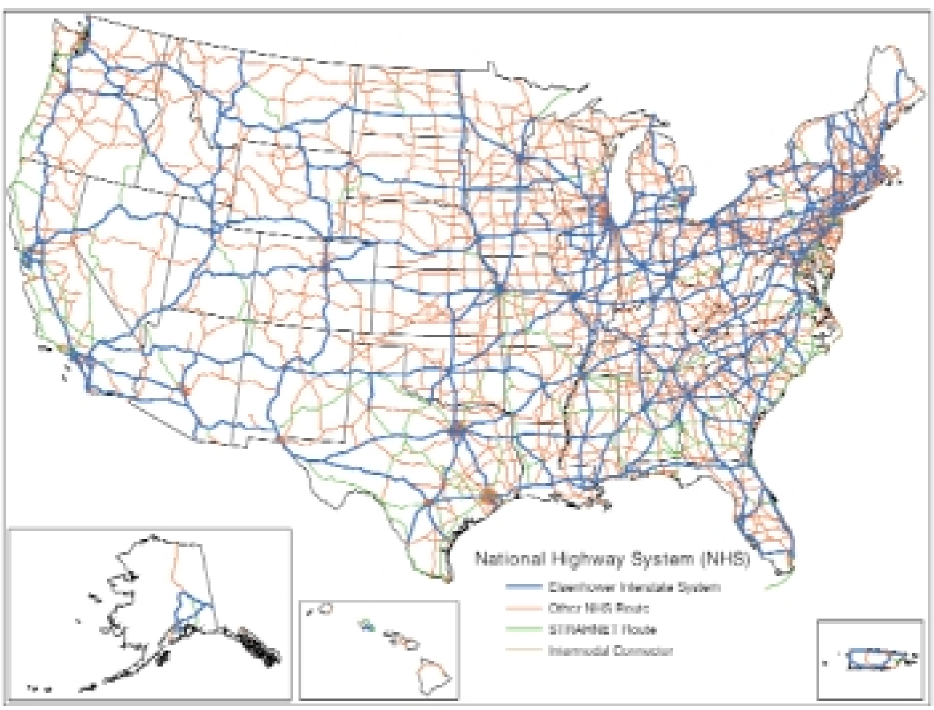
In his commentary as he signed the NHS bill into law on November 28, 1995, President Clinton wrote:

"The designation of the National Highway System makes clear that transportation infrastructure should be viewed as a single system with each mode complementing the others. Manufacturers and shippers rely on several modes of transportation to deliver their products to consumers in the most efficient manner possible. The National Highway System unites these different modes by providing access to major ports, airports, rail stations, and public transit facilities. The National Highway System also provides 53 critical connections to Canada and Mexico so that goods can move across our nation's borders efficiently….

"But the National Highway System is also something more. It is a prime example of the strategic investment of federal resources. The National Highway System comprises only 4 percent of our nation's highways, but these roads carry almost half our highway traffic and most of our nation's truck and tourist traffic. The improvements made to these roads will not only support our nation's economic, national defense, and mobility needs, but directly and significantly improve the safety of roadways…." [1]

The Ubiquity of the NHS

The NHS consists of 256,000 kilometers of roads having four or more lanes of pavement that carry more than 40 percent of all highway traffic, 75 percent of heavy truck traffic, and 90 percent of tourist traffic.[2] It includes the legacy Dwight D. Eisenhower Interstate Highway System and other preexisting and planned roads important to the nation's economy, defense, and mobility.[3] Today, about 90 percent of America's population lives within 8 km of an NHS road. All urban areas with a population of more than 50,000 and 93 percent with a population of between 5,000 and 50,000 are within 8 km of an NHS road. Counties that contain NHS highways also host 99 percent of all jobs in our nation, including



The U.S. National Highway System

99 percent of manufacturing jobs, 97 percent of mining jobs, and 93 percent of agricultural jobs.[4, 5]

The establishment of the NHS enabled the federal government to revise and strengthen its management of our highway infrastructure from strategic and fiscal perspectives. Significant economic, demographic, and security developments had occurred since the Dwight D. Eisenhower System of Interstate and Defense Highways and the Highway Trust Fund were established by the Federal-Aid Highway Act of 1956,[6] replacing the older U.S. Highway System[7] that was founded by a similar act in 1925.

The Roads that Comprise the NHS

The NHS includes as a major subset the preexisting 70,000 km Eisenhower System, which accounts for almost 30 percent of all NHS roadways.

A second component consists of 21 congressionally designated High-Priority Corridors (see map), totalling 7,200 km, as identified in the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA).

A third component is the non-interstate portion of the Strategic Highway Corridor Network, or STRAHNET, identified by the Department of Defense in cooperation with DOT, totalling about 25,000 km. These corridors and the interstate highways are critical strategic links. For example, Operation Desert Storm and Enduring Freedom demonstrated that the ability to move troops and equipment via highways to airports, ports, rail terminals, and other bases for rapid deployment is essential to our national defense.

The fourth component consists of major Strategic Highway Corridor Network connectors. These consist of more than 3,000 km of roads linking major military installations and other defense-related facilities to the STRAHNET corridors.

The fifth and final component of the NHS is the rest of the system: about 148,000 km of important arterial highways that serve interstate and interregional travel and that provide connections to major ports, airports, public transportation facilities, and other intermodal facilities.

General Roy Stone, October 17, 1836–August 6, 1905, was a New York-born Civil War hero and civil engineer. An innovator, he designed an elevated railway that was displayed in Philadelphia during the 1876 Centennial Exposition. He subsequently spearheaded railroad tunneling and harbor improvement projects in New York, and invented a suction dredge for harbor work. By 1890, his interests had shifted from mass transit to roads, likely stemming from his battlefield experiences in the Civil War. After years of championing a national effort to improve roads, he held the post of Director of the new federal Office of Road Inquiry from its creation on October 3, 1893 for five years. By then, he had molded the fledgling agency, later to develop into the Federal Highway Administration, into the recognized leader of the good roads movement.

Roads Paved with Good Intentions

In 1893 the Federal Highway Administration (FHWA) was established as the precursor Office of Road Inquiry, headed by infrastructural visionary General Roy Stone (left), a colorful Civil War hero who fought at Gettysburg. "Good roads," said General Stone, "are the highways to wealth." In a tip of the temporal hat to General Stone’s acute foresight, the original Office of Road Inquiry, which had only two employees and a $10,000 budget, has grown into today’s Federal Highway Administration, which employs 3,500 people and has a budget of more than $26 billion, much of which is “passed through” to individual states.

> “Highway agencies could save as much as $785 million…. In addition, the resulting reductions in maintenance-related delays and in vehicle wear and tear could save motorists between $1.3 billion and $2.1 billion a year.”

In recent years, Congress supported the historic FHWA “good roads” mission by creating the Strategic Highway Research Program (SHRP) in 1987 as a 5-year, $150-million research program to improve the performance, durability, and safety of U.S. highways. The research was performed by independent contractors and was targeted in four areas: asphalt, concrete and structures, highway operations, and engineering for long-term pavement performance.

In parallel with that effort, Congress addressed the need to fund the construction and repair of strategic highways by promulgating the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), and in June 1998, the Transportation Equity Act for the 21st Century ("TEA 21"). TEA 21 mandates a 44% increase in federal spending over a six-year period that began in October 1998. TEA 21 includes a special provision which prohibits diversion of the mandated spending for other purposes, and contains matching provisions calculated to produce increased spending at the state and local levels as well.

In October 1987, the U.S. Congress authorized the Strategic Highway Research Program (SHRP)—a five-year, applied research initiative that ended in March 1993— "…to develop and evaluate techniques and technologies to combat the deteriorating conditions of the nation's highways and to improve their performance, durability, safety, and efficiency."[11]

Directed by a committee of senior personnel from state highway agencies, industry, and academia, SHRP operated as a unit of the National Research Council. The states paid for the program by contributing one-quarter of 1 percent of their federal-aid highway funds. Research was conducted under contract with private organizations and universities in four areas: asphalt, concrete and structures, highway operations, and pavement performance.

At the conclusion of the research, the FHWA, the American Association of State Highway and Transportation Officials (AASHTO), and the National Academy of Science Transportation Research Board (TRB) mounted an effort to introduce the highway community to SHRP innovations. The task was to move 100-plus products and procedures developed or evaluated under SHRP out of the laboratory to the state and local agencies responsible for building and maintaining the nation's highway network.[6]

The keystone result of the SHRP asphalt research was Superpave™ an acronym for Superior Performing Asphalt Pavements (and a registered trademark of the National Academy of Sciences). Superpave was a $53 million research effort to develop new ways to specify, test, and design asphalt materials. The resulting Superpave system represents an improved method for specifying the components of asphalt concrete, asphalt mixture design and analysis (see Appendices 1 and 2).

The nation's return on the $150 million investment for SHRP is remarkable. As a conservative hypothetical, a researcher in the SHRP projected that if less than one-quarter of all U.S. road overlays use performance-graded binders specified by SHRP guidelines, and see only a 25% increase in service life, highway agencies could save as much as $785 million (in 1996 dollars) on road repair costs annually. In addition, the resulting reductions in maintenance-related delays and in vehicle wear and tear could save motorists between $1.3 billion and $2.1 billion a year.[8]

"Many new and reconstructed highways throughout the United States…have been failing much earlier than anticipated due to potholes, cracks, raveling, and other problems."

Good Intentions Aren't Always Enough

Notwithstanding the SuperPave methods and adequate funding, many new and reconstructed highways throughout the United States—more than 90% of which are paved with asphalt and engineered to deliver service lives of 15 years and more—have been failing much earlier than anticipated due to potholes, cracks, raveling, and other problems.[9] In addition to the financial toll, the creation of work zones during repair and rehabilitation projects disrupts traffic, and rough pavements can damage vehicle tires and suspension systems and pose serious safety risks.[10]

Using Thermography to Build Longer Lasting Roads

In the United States, we spend about $15 billion annually to maintain and build roads paved with asphalt concrete to meet increasing traffic volumes and loads. The premature failure of roads due to causes traced to construction methods has become a growing problem that is adding significantly to road maintenance budgets.

For four decades prior to the Strategic Highway Research Program (SHRP), the negative effects of low compaction temperatures and aggregate segregation in HMA on road service life had been studied and documented. Standard mix design procedures were developed and adopted by AASHTO, for example the Marshall Mix Design Criteria, which specifies air void minimums (see Appendix 3). Although SHRP research was focused on an improved mix design and analysis system, some well-accepted HMA design principles were kept in mind:

"Lower compaction temperatures are directly related to an increase in air void content, which decreases the strength of the pavement," and the realization that: "Even with a perfect mix design, if the mix is not properly compacted in the field, the final product will not last for its intended length of time." [12]

However, the conventional wisdom until the mid-1990s was that HMA compaction problems were due to overall cool mix temperature, to the segregation of aggregate within the mix, or to incomplete mixing of asphalt binder and aggregate. An entirely new perspective on the factors negatively affecting HMA compaction began in earnest in 1995. In that year a collaboration of researchers in the Department of Civil and Environmental Engineering at the University of Washington noted that "large numbers of dense-graded asphalt concrete paving projects in the U.S. and internationally have experienced a cyclic occurrence of low-density pavement areas, generally called 'cyclic segregation' or 'end-of-load segregation', which prematurely fail by fatigue cracking, raveling, or both." [13] The intervals between problem areas seemed to correspond to the length of mat laid down from one truckload of HMA.

Subsequently, in 1995, as part of Master's Degree thesis research, and working under commission from the Washington State Department of Transportation (WSDOT), then UW graduate student Steven A. Read began his investigation into the end-of-load segregation phenomenon by closely observing night-time construction operations on Interstate 5 near Seattle. Read had been a paving crew operator for 15 years and was intimately familiar with paving equipment. Following a paver closely, he observed that masses of asphalt crust, which had formed on the surface of the hot-mix load as it was trucked from the mixing plant to the paver, were dumped from the truck into the paver hopper and, clearly discernible with the naked eye, were extruded from the paving machine along with the great bulk of the loose HMA mass.

The next day he discussed his observations with thesis advisor Prof. Joe P. Mahoney, and returned to the worksite armed with an asphalt thermometer. Through direct measurement, he confirmed his intuitive speculation that the masses of relatively cool, stiff, and therefore compaction-resistant, crust went through the paving machine without substantial remixing during end-dump operations.

The Shuttle Buggy material transfer vehicle, manufactured by Roadtec.

Read also noted that most of the WSDOT paving projects identified as having "cyclic segregation" occurred either during night paving operations or near the beginning or end of the normal paving season. These are periods when ambient temperatures are likely to be cooler than optimal and accelerate the cooling of mix during transport to the work site.[14]

A "Eureka" Finding

Read had made a "eureka" finding that ultimately led to the conclusion at WSDOT that: "…placement of this cooler hot-mix can create pavement areas near or below cessation temperature [175°F],[15] which tend to resist adequate compaction."[16] Even after aggressive rolling, these isolated coolareas have lower densities (and more air voids) than the surrounding hotter material.

"Truly, it is hard to describe the positive effect that FLIR's impact has had for us and the paving industry," said Prof. Joe Mahoney of the University of Washington. "I hope you sell hundreds of cameras to the paving industry!"

As a result, these areas are relatively porous and less resistant than the denser matrix around them to wear and degradation from traffic and the environment.

Read's observation had set in motion a process of discovery that had profound ramifications for the paving industry. The physical segregation of relatively coarse and fine aggregate stone in HMA, caused by frictional drag against conveyors and hopper boundaries, and of aggregate segregation from the asphalt binder had previously been identified as a cause of longitudinally dispersed low-density regions in the HMA mat. Indeed, a new class of paving vehicle, the material transfer vehicle (MTV), had been developed and introduced in 1988 by Roadtec, a Chattanooga, Tennessee-based subsidiary of Astec Industries—a leading manufacturer of infrastructure construction equipment, specifically to control aggregate segregation. At that time, thermal segregation was not even on the industry's radar screen. This new evidence from WSDOT now identified thermal segregation as the primary perpetrator of premature mat failure.

FLIR ThermaCAM® PM-280 infrared camera similar to that loaned by Astec to the University of Washington and WSDOT in 1998. The original unit is still in service at Astec.

Unexpected Assistance

At the time of his initial observations, Read did not have access to sophisticated thermal imaging equipment. That limitation was removed from subsequent investigations unexpectedly in 1998 by a major corporate player in the infrastructure industry.

When Dr. Don Brock, CEO of Astec Industries, saw Read's thesis identifying thermal segregation as a new factor that could affect asphalt mix density, he had his own "eureka" moment and without fanfare telephoned Read's thesis adviser Prof. Joe Mahoney at UW with a remarkable offer.

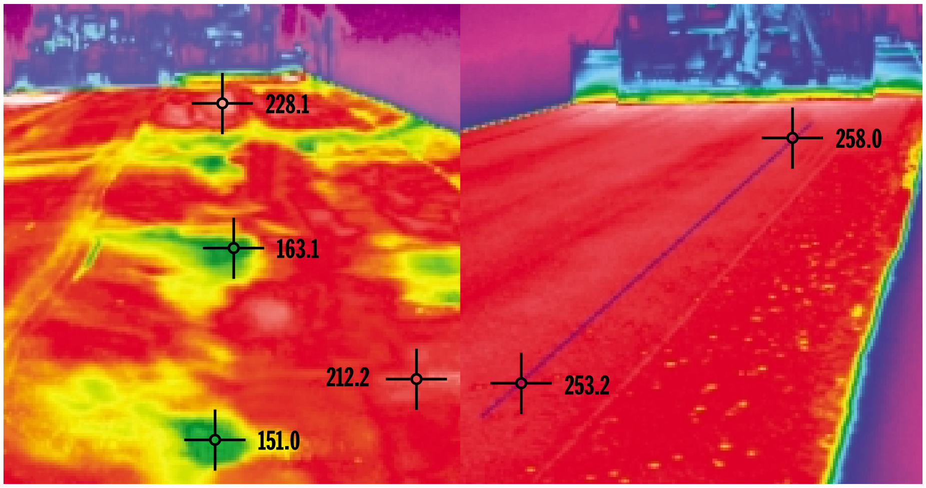
"I was stunned," recalls Mahoney. "Out of the blue he called and said that he would loan us his [infrared imaging] camera and send Herb Jakob, a senior engineer, to operate it. That enabled us to pursue a reasonably thorough study.

"Truly, it is hard to describe the positive effect that FLIR's impact has had for us and the paving industry," said Prof. Joe Mahoney of the University of Washington."I hope you sell hundreds of cameras to the paving industry!"[18]

Read's thesis provided Brock with the promise of a major, unheralded performance benefit that was already built into the Shuttle Buggy. By virtue of its thorough remixing of HMA, Brock had realized that the Shuttle Buggy not only controlled aggregate segregation, but also controlled thermal segregation. Iron-clad validation of the effect of thermal segregation on asphalt pavement density could be a marketing bombshell for the Shuttle Buggy, Roadtec and Astec Industries.

On June 23, 1998 Brock dispatched Herb Jakob, Astec's Manager of Market Development, and his recently purchased Inframetrics ThermaCAM PM-280 infrared camera (still in service today at Astec Industries[19]) to Washington. The resulting collaboration in a multi-year series of studies supervised by the WSDOT was to provide critical detailed thermal profiling of HMA laydown operations leading to at least four revolutionary accomplishments:

1. Validation of the direct relationship between thermal segregation and lower mat density.
2. Provision of a quantitative basis for developing a standardized HMA density profiling procedure.
3. Addition of a new and extremely important sales benefit to the Shuttle Buggy's performance.
4. Establishment of a new market for high-resolution thermography.



Left: Thermogram showing serious cyclic thermal differentials in a hot-mix asphalt mat.
Right: Thermogram showing minimal thermal differentials in a hot-mix asphalt mat. Temperatures are in degrees Fahrenheit (see Gallery section on page 16 for details).

The WSDOT Study Series

1998. The 1998 study team included personnel from the WSDOT, plus Prof. Mahoney and graduate student Stephen Muench from the University of Washington, and Herb Jakob from Astec. Four projects were chosen on several different construction areas on Interstate 5 in Everett, Washington, and also state highway construction in Seattle. Early and late season paving and night operations were studied to maximize the occurrence of temperature differentials.

> The team concluded that these isolated areas of premature failure were related to temperature differentials and not to aggregate segregation.

The camera was able to clearly discern cool areas in the uncompacted mat, as well as to determine the temperatures of loose mix in trucks, pavers, and other equipment.[20] Follow-up in-place density testing was performed on finished pavement in areas identified as "normal" and "cool," and samples from these areas were taken to the WSDOT laboratory and tested for mix properties, including aggregate segregation, asphalt/aggregate segregation, and density differentials.

The relatively cooler areas were found to have lower densities than the hotter areas, with an overall air void range of 1.6 to 7.8%. No significant aggregate segregation was found. The team concluded that these isolated areas of premature failure were related to temperature differentials and not to aggregate segregation.[21]

1999. In its follow-up study in 1999 the WSDOT/UW team investigated 36 projects throughout the paving season with the camera and in-place nuclear density testing to determine "patterns between different operations," including any measurable effects of a variety of material transfer devices or vehicles, pavers, rollers, air and ground temperatures, and other factors on final mat properties.

The study fine-tuned the relationship between temperature differentials within the hot-mix and its final density. The observed temperature differential range on all the jobs was from 5 to 68 Fahrenheit degrees. As expected, higher differentials resulted when there was no remixing prior to placement of the hot-mix and typically after longer haul times. The pivotal finding was that localized air voids typically increased by 2 percent or more when the temperature differential was 25 Fahrenheit degrees or larger.

The study also confirmed quantitatively that air voids decreased when the hot mix was reblended prior to placement and with higher overall mix temperatures and air temperature. It reached the general conclusion that no one single piece of equipment or operation will guarantee that temperature differentials will not occur, but that techniques can be utilized to offset the effects of the temperature differentials. Indeed, when the mix was reblended prior to laydown, temperature differentials could be reduced significantly, in some cases to less than 10 Fahrenheit degrees.[22]

2000. The WSDOT focused its 2000 study on establishing a standardized longitudinal density profile procedure by combining thermography and nuclear density evaluations on 17 paving projects. The goal was to develop a reliable field method to accurately determine the density of the finished product as a function of its thermal properties during laydown. Anecdotal field data provided some measurement of the effectiveness of truck bed insulation and the tight/insulated tarping of loads during haul to ameliorate the cooling of HMA in transit, although the systematic analysis of these effects was not included in the scope of the study.

The pivotal finding was that localized air voids typically increased by 2 percent or more when the temperature differential was 25 Fahrenheit degrees or larger.

The study found that "Although temperature differentials can frequently occur on hot-mix construction projects, they may be minimized or eliminated by remixing, shorter haul distances, warmer environmental conditions, good rolling practices, etc." However, the landmark quantitative finding was the determination of a critical thermal differential threshold within the hot-mix as it was extruded from the paver, above which the density of the resultant cured mat was significantly compromised.

On 69 profiles taken on the 17 projects, temperature differentials greater than 25 Fahrenheit degrees resulted in failing density profiles 89.3% of the time. With differentials less than 25 Fahrenheit degrees, 80.5 percent of the profiles passed. These results include all variables associated with the paving operation.

The 2000 study verified the 1999 finding that when thermal differentials were greater than 25 Fahrenheit degrees in the mat, air voids increased by approximately 2%. This determination was extendible to forecast pavement life, because it was known from previous field data and analysis that for every 1% increase in air voids over 7%, there is an approximate 10% reduction in pavement life.[23]

Now the WSDOT researchers had a quantitative relationship connecting temperature differentials, density differentials, and the life of the pavement."[24] In addition, the team had a practical method based on thermography to determine the location of density tests, which in turn could be used to project road maintenance costs that could be avoided. Using this rule-of-thumb, and adding the minimum 2% air voids that typically result from a temperature differential area to WSDOT's long-term in-place density average of 93% (or 7% air voids) would result in a 20% decrease in pavement life from that implicit in the specifications.[25]

The research team also found that: "If temperature differentials [greater than 25 Fahrenheit degrees] exist, but the finished pavement has a uniform density of 93 percent or greater for dense-graded mixes, then the pavement should serve its intended purpose for its intended length of time."

The team had a practical method based on thermography to determine the location of density tests, which in turn could be used to project road maintenance costs that could be avoided.

In response to these determinations, WSDOT implemented a systematic density specification on 10 projects in 2002, and to selected HMA road construction projects in 2003 and thereafter. The specification includes carrot-and-stick provisions: a cost disincentive if density differentials are located and a bonus for work that is consistently in-spec. Further work to standardize a test protocol is ongoing.

Challenges and Opportunities for the Paving Industry

The standardization of density profiling and the embedding of a thermographic protocol in road-building specifications to validate density may offer important benefits for the paving industry and federal and state specifying agencies:

- Smoother, longer lasting roads.
- Improved return on road construction investment.
- Maximization of the value of Superpave procedures.
- Wider paving window for contractors.
- Stimulus for the development of new technology to maintain thermal consistency in truckloads of HMA during transport and laydown.

"Simply put, roads that are built to meet density specifications last longer than roads that fail to meet them."

Longer Lasting Roads

Simply put, roads that are built to meet density specifications last longer than roads that fail to meet them because they have a higher than allowable proportion of air voids. The value of density profiling in projecting road service life for dense-graded HMA can be calculated from quantitative research, which has demonstrated that: "…an approximately one-percent increase in air voids (above a baseline value of seven percent) results in a minimum 10 percent decrease in pavement life. Thus, areas of higher air voids will likely suffer from accelerated pavement distress when compared to the mat as a whole." [26, 27, 28, 29]

Improved Return on Road Construction Investment

The arithmetic that can be applied to project dollar savings from extensions to pavement life is a straightforward tabulation of the expense that is avoided by not having to resurface or reconstruct a given length and value of road. For budget-strapped transportation agencies trying to squeeze the maximum value from their road-building investment, the proven effectiveness of combining thermographic analysis, density measurement, and off-the-shelf material transfer equipment to counter the premature road failure problem is welcome news. As noted earlier, even with a perfect mix design, if the mix is not properly compacted in the field, the final product will not last for its intended length of time." [30]

On the other hand, a density profiling specification linked to disincentives may be interpreted as a challenge by some contractors. For example, in 2000, the Transportation Research Board (TRB) published a member recommendation that: "Payment for any [HMA] lot with evidence of segregation should be paid on the basis of the segregated areas only because these areas control the life of the entire lot." (Typical practice when segregation leads to a loss of pavement life, is that localized maintenance strategies are typically not used within state agencies; pavements are overlaid or reconstructed.) The specific TRB recommendation: "If low levels of segregation are present within a lot, the pay factor should be 90 percent (consistent with a pay factor for a pavement with a 2 percent increase in air voids). Medium levels of segregation equate to a pay factor of 80 percent (consistent with pay factors for an increase in air voids of 4 percent) and lots with high levels of segregation should be removed and replaced." [31]

Washington State, by virtue of a its multi-year study effort, has created a specification for road construction that addresses the effect of temperature differentials during construction to determine potential low-density areas. These areas can be located with an infrared camera and are tested with a nuclear density gauge and must meet the minimum density specification. Testing (and penalty) continues until density differentials do not exist.

The WSDOT publishes a periodic report called the "Gray Notebook" that tracks a variety of performance and accountability measures for routine review by the Washington State Transportation Commission and others. The theory is: "What gets measured, gets managed." The Gray Notebook is a concept brought to WSDOT by its new Secretary of Transportation, Doug McDonald.[32]

The Good News for Contractors

By utilizing material transfer devices and vehicles and validating results with the accurate temperature profiling provided by field-proven IR cameras such as the FLIR E-series and P-series, contractors can pave under cooler conditions with virtual assurance of meeting specifications. The promise for contractors includes better results during nighttime paving and beyond the traditional paving season and of reaping the rewards of job bonuses when offered.

Stimulus for New Technology

Thermography systems built for the asphalt paving industry with standardized measurement protocols and palettes, software optimization, visible laser targeting capability, and field-tested ergonomics will assure accurate measurement of mat temperatures under the most challenging conditions. The WSDOT research has led to many other research efforts to mitigate temperature differentials, including potential improvements to road-building equipment; for example, insulated, covered, or heated truck beds to minimize thermal differentials during transport of HMA from the batch plant.

The promise for contractors includes better results during nighttime paving and beyond the traditional paving season and of reaping the rewards of job bonuses when offered.

Better Tools for Better Roads

The return on roadbuilding investments promises to be far more certain than it has ever been before, thanks to extensive research, advances in performance and ergonomics in thermographic cameras, and construction equipment innovations that help achieve higher consistent HMA density than ever before.

State-of-the-Art Material Transfer Vehicle (MTV)

A very readable extract from a Roadtec brochure about the Shuttle Buggy MTV summarizes the practical implications of the HMA research findings produced by the teamwork of WSDOT, UW, and Astec Industries:[33]

"When you have a long haul on a cold day, you're going to get truck ends, those big clumps and chunks of cooled-down material. Run them through the Shuttle Buggy. It will break up the big stuff and remix all of it, resulting in a smooth mix with an even temperature throughout.

"The expected life of a segregated pavement could be half of its expected 12 to 15 years."

"Pavement smoothness is affected by temperature and aggregate segregation. This type of segregation causes non-uniform densities. The newly laid mix will not be compacted evenly, resulting in excess air voids. You end up with a substandard pavement that will be short-lived. Identifying the segregation problem has typically been done by visual observation as the mix is placed. Where large aggregate is used for base and binder materials, the segregated spots can be easily identified. On finer surface mixes, however, segregation spots are not as noticeable and may not show up until six to twelve months after placement. The Washington State Department of Transportation determined that the expected life of a segregated pavement could be half of its expected 12 to 15 years.

"Recently, the proven technology of the highly accurate FLIR infrared camera has been used to evaluate asphalt pavement for possible aggregate segregation. As the infrared camera was used to look at the mix being discharged from the truck bed, it became obvious that the temperature differential was significantly greater than ever anticipated. Temperature differentials as much as 80 Fahrenheit degrees occurred on mixes that had been hauled as little as 10–15 miles at mix temperatures of 290°F. Some areas of the truck bed were as low as 210°F.

"Through using the infrared testing, the segregation problem turned out to be related to a differential in temperature in the asphalt as it was hauled from the plant to the job site. Temperature differential damage occurs when a truck load of HMA is dumped into the paver. If the load is exhibiting temperature differentials, the very cool material that is along the sides of the load is extruded out towards the sides of the paver's hopper. When the truck is emptied and the pile in the hopper is run down, this cool material falls inward to lay on top of the material over the slat conveyors. When the next truck arrives and dumps into the paver, this cool mix is conveyed back to the auger chamber and screeded out. The screed is unable to consolidate the colder mix and open, segregated appearing areas (temperature differential damage) show in the mat. As this can work for each load placed, the segregation cyclic becomes apparent.

"Even when mix is produced correctly at the plant, properly stored in a silo and correctly loaded into a truck, a poor quality pavement can be produced because of temperature segregation. This leads to the conclusion that some type of remixing must be performed immediately prior to placing the mix to achieve a uniform temperature. Various transfer devices were studied [by WSDOT] to determine their effect on temperature differential damage. In most cases, the mat was improved; however the temperature segregation was not eliminated.

"The Roadtec Shuttle Buggy® material transfer vehicle was the only machine tested that eliminated the temperature segregation. Remixing augers in the bottom of the storage hopper remix the material before being discharged from the machine. On an auger assembly, the distance between the flights is called the pitch. When the auger is buried in material, and the pitch on the auger is the same, all of the material will fill the flights and tunnel through the mass. By changing the pitch of the auger, new material can enter the flights as the flights spread out. In the Shuttle Buggy, the pitch changes twice on each side of the hopper, allowing mix from six different areas across the hopper to remix or reblend. This process allows the cold coarse, hot fine materials to be thoroughly reblended.

"It is apparent that temperature variations of mix discharged from the truck have been much greater than previously thought and have been a significant problem for many years. While HMA can be produced uniformly at an asphalt plant, with every step of the process performed correctly, heat loss in the truck is inevitable. Infrared thermography test results prove that remixing is necessary to insure a uniform temperature of the mix directly in front of the screed, which is essential to achieve mat quality and pavement smoothness."

Thermography Advances

A new generation of temperature imaging equipment makes asphalt thermography as easy as taking a photograph. The ThermaCAM E-Series and P-Series IR cameras from FLIR are the smallest, smartest infrared inspection cameras ever developed. Four models are available, each equipped with different features to address varying inspection requirements and budget requirements. They weigh only 1.5 pounds with batteries, and fit easily in the palm of the hand or on a toolbelt. They offer state-of-the-art features including:

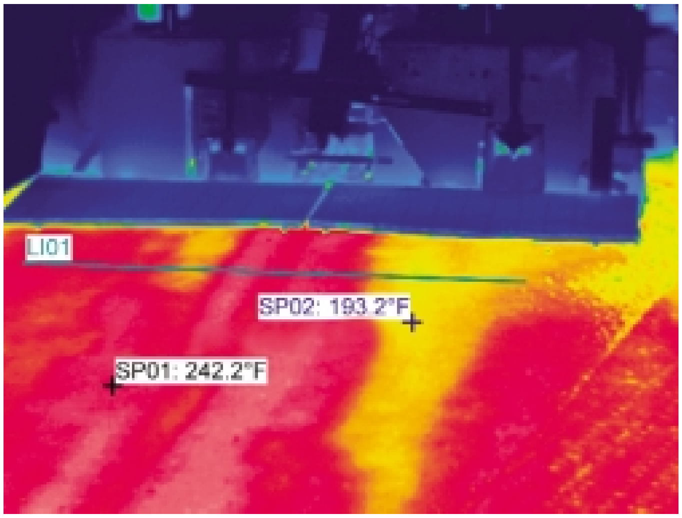
- Extremely crisp thermal imaging.
- Precision temperature measurement of up to 19,000 points on a single image.
- On-board JPEG image storage at the press of a button.
- Download images images quickly via USB or RS232.
- Bright LCD and optimizable, easy-to-interpret temperature color palette facilitate recognition and interpretation of thermal values.
- Exclusive Laser LocatIR®, which projects a bright red spot enabling the operator to target readings precisely where desired, day or night.
- 60 Hz image refresh time enables real-time imaging for continuous surveying.
- A family of interchangeable optics with different fields of view.
- Rechargeable Li-ion batteries can be recharged in trucks and cars or from a two-bay battery charger.
- Exclusive Wearable Optics accessory, combining safety glasses and a high-resolution state-of-the-art Heads-Up-Display (HUD) that presents the image directly to the eye, improving worker safety and productivity in challenging environments.

FLIR ThermaCAM P60

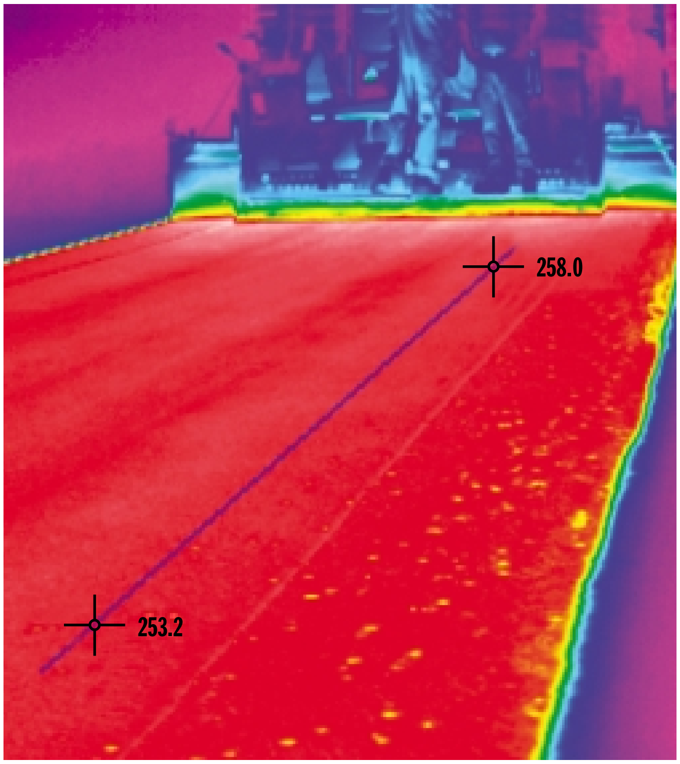
FLIR ThermaCAM E2

FLIR IR Heads-Up-Display (Wearable Optics)

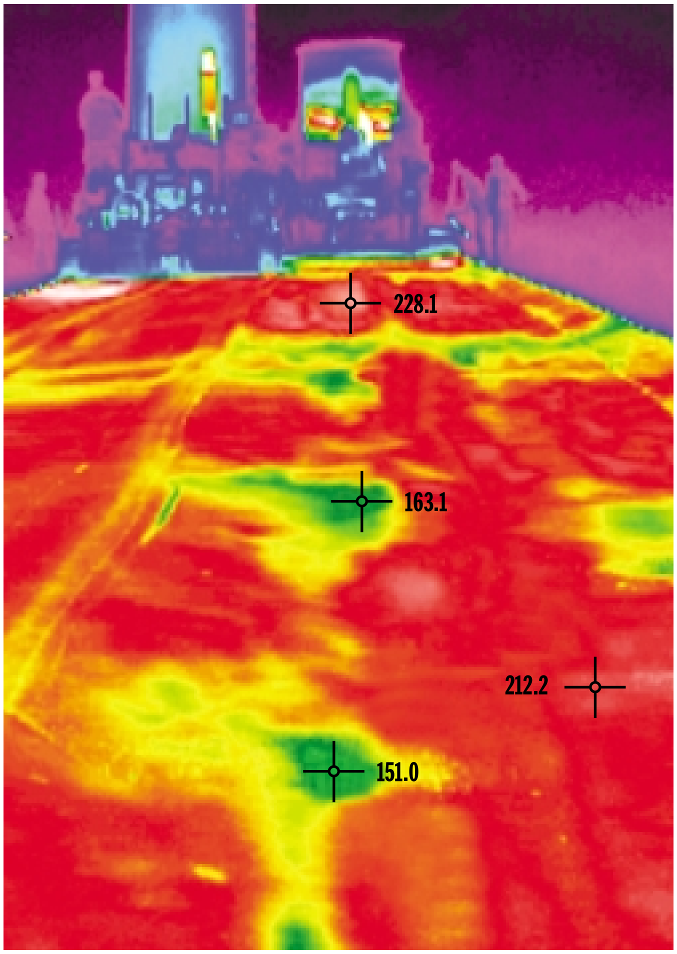
Gallery



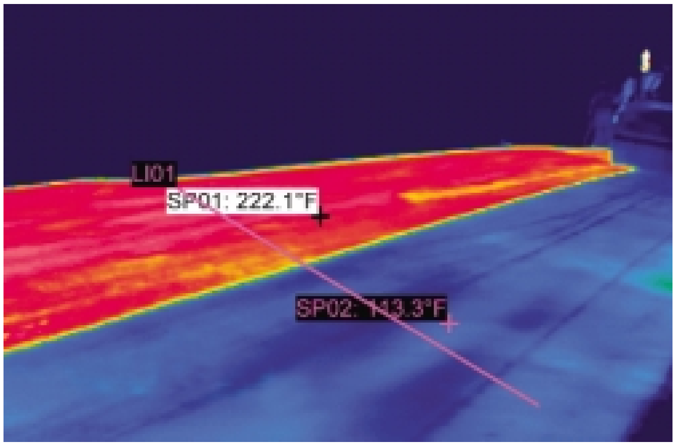
The thermograph reveals a temperature differential of about 50 Fahrenheit degrees in this mat directly behind the paver. The cooler areas will be more difficult to compact (cessation temperature is approximately 175°F) and probably will result in lower density. Final densities could be out-of-spec for state highways in some states.



With only a 5 Fahrenheit degree differential, the longitudinal section shown in the thermograph indicates that this cooling asphalt mat exhibits exceptional thermal uniformity. The final mat density was uniform (less than 2.8% air voids). The visual photo of the road taken a year later shows no evidence of wear or degradation.



Asphalt that is cooler than about 175°F is relatively stiff, and resists rolling, which typically results in a lower density than hotter areas, and is therefore prone to premature failure. Note the low-temperature spots in the thermograph, which are as cool as 151°F and correlate with the visibly worn dark spots in the visual photo of the same section of roadway.



The thermograph shows the contrast in temperatures between the cool, curing lane to the right (113.3°F) and the hot mat being laid down on the left (222.1°F).

First and last image pairs were taken by David Shahon, FLIR; the second and third pairs are used courtesy of Kim Willoughby, Washington State Department of Transportation.

Appendix 1: Superpave™ ROI[34]

The Superpave system enables designers to select materials and design a mix to meet specific weather and traffic conditions at the project site. The system relies on an innovative array of equipment that tests and evaluates asphalt binders and mixes. All state highway agencies currently have five of the six pieces of binder testing equipment, and all have at least one Superpave gyratory compactor, which simulates the effects of construction and traffic on an asphalt mix.

FHWA established the National Asphalt Training Center in Lexington, KY, to educate engineers and technicians about the Superpave system. To augment this system, state departments of transportation teamed with universities to establish regional Superpave centers in Alabama, Indiana, Nevada, Pennsylvania, and Texas. In addition to training engineers, technicians, and other highway workers, the five centers conduct ruggedness, precision, and bias testing of new procedures and equipment. The National Highway Institute also sponsors courses on the Superpave system.

Case Studies

Highway agencies nationwide report that Superpave pavements are holding up well to heavy traffic and extreme climates. For example:

- The Alabama Department of Transportation (DOT) reported that an 8-km resurfaced section of badly rutted Route 165 showed virtually no rutting after two years, despite heavy truck traffic and extremely hot weather.
- A 1995 Superpave overlay on a section of Interstate 10 near Phoenix, Ariz., successfully withstood heavy truck traffic and 17 consecutive days of temperatures above 43 degrees Celsius (110 degrees Fahrenheit). It continues to resist permanent deformation.
- After four years of cold weather and heavy traffic, early Superpave test sections on Interstate 43 in Waukesha County and on Interstate 94 in Monroe County, Wis., are faring considerably better than adjacent sections constructed with Wisconsin's conventional mix.
- Minnesota reported similar success with a 1995 Superpave overlay mix on a rural road in Blue Earth County.

Benefits

The Texas Transportation Institute (TTI) was contracted to conduct a macroeconomic analysis of the benefits of SHRP products and the cost of their implementation. Based on case studies, a team of TTI economists and engineers evaluated the total nationwide costs and benefits of researching, developing, and implementing technologies.

The TTI economic assessment of the Superpave system focused exclusively on the role of the asphalt binder in mix performance. Binder properties significantly affect the performance of an asphalt mix and its ability to resist permanent deformation and low-temperature cracking. Correct selection of binders, as provided by Superpave procedures, result in longer lasting pavements. In addition to benefits, the TTI analysis in all cases considered costs, such as the increased cost of Superpave binders over other grades of binders and the state’s costs to purchase and maintain equipment and to train employees.

Even with conservative estimates, TTI forecasts tremendous potential savings from Superpave. Using a conservative projection that fewer than one-quarter of all overlays will benefit from the use of performance-graded binders and that those overlays would see only a 25-percent increase in service life, TTI projected that highway agencies could save between $484 million and $785 million annually, depending on how quickly they adopt the new specification. Motorists could save between $1.3 billion and $2.1 billion a year in user costs thanks to reductions in maintenance-related delays and in vehicle wear and tear.

At a cost of $53 million, Superpave research was the most expensive item in the SHRP budget. Additional costs to research,develop, and implement the Superpave binder specification were estimated at $230 million over 20 years.

Yet, these figures pale when compared to the expected benefits. If highway agencies take 10 years to implement the Superpave binder specification, they will save more than twice the total implementation cost annually for the next 20 years.

Appendix 2: Superpave Mix Design[35]

Superpave mix design is a structured approach consisting of four steps:

1. Selection of materials.
2. Selection of design aggregate structure.
3. Selection of design asphalt binder content.
4. Evaluation of moisture susceptibility.

Selection of Materials

This step is accomplished by first selecting a *Performance Grade asphalt binder* for the project climate and traffic conditions. Superpave binders are designated with a high and low temperature grade, such as PG 64-22. For this binder, "64" is the high temperature grade and is the 7-day maximum pavement design temperature in degrees centigrade for the project. The low temperature grade, "-22," is the minimum pavement design temperature in degrees centigrade. Both high and low temperature grades are established in 6-degree increments. Thus, the binder grade is an indication of the project-specific temperature extremes for which the asphalt mixture is being designed.

Selection of Design Aggregate Structure

Five asphalt mixture types are specified in Superpave according to nominal maximum aggregate size: 9.5 mm, 12.5 mm, 19 mm, 25 mm, and 37.5 mm. To specify mineral aggregate, Superpave uses two approaches. First, it places restrictions on aggregate gradation by means of broad *control points and a restricted zone*. Second, it places *consensus requirements* on coarse and fine aggregate angularity, flat and elongated particles, and clay content.

Once binder and aggregate materials have been selected, various combinations of these materials are evaluated using the Superpave gyratory compactor. Three, and sometimes more, trial blends of aggregate, and natural and manufactured sand are evaluated.

Once the trial blends are established, a trial asphalt binder content is selected for each blend. The trial asphalt binder content is selected using an estimation procedure contained in Superpave or on the basis of the designer's experience.

Two specimens of each trial blend are batched and compacted in the *Superpave gyratory compactor*. In addition, two loose specimens of each trial blend are produced and used to measure maximum theoretical specific gravity. The volumetric and densification characteristics of the trial blends are analyzed and compared with *Superpave mix design criteria*. Any trial blend that meets these criteria can be selected as the design aggregate structure.

Selection of Design Asphalt Binder Content

The next step involves selection of the design asphalt binder content for the design aggregate. This step is necessary to verify the approximate binder content used in the preceding step. The Superpave gyratory compactor is used to fabricate test specimens composed of the selected design aggregate structure, but at four different asphalt contents. The asphalt content that results in 4 percent air voids at the design number of gyrations is the design asphalt binder content. The design aggregate structure containing the design asphalt binder content becomes the design asphalt mixture.

Evaluation of Moisture Susceptibility

This final step requires that the design asphalt mixture be evaluated using a test procedure called AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage." This test method was already in wide use prior to the development of Superpave.

Appendix 3: Asphalt Concrete Mix Design[36]

Asphalt concrete mixes should be designed to meet the necessary criteria based on type of roadway, traffic volumes, intended use, i.e., overlay on rigid or flexible pavements, and the season of the year the construction would be performed. Mix designs include Marshall, Hveem and SuperPave criteria. Marshall mix design criteria are as follows.

Marshall Mix Design Criteria

	Light Traffic[1] Surface & Base		**Medium Traffic**[2] Surface & Base		**Heavy Traffic**[3] Surface & Base	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
Compaction, number of blows each end of specimen	35	35	50	50	75	75
Stability, N	3336		5338		8006	
(lb.)	(750)	-	(1200)	-	(1800)	-
Flow, 0.25 mm (0.01 in.)	8	18	8	16	8	14
Percent Air Voids	3	5	3	5	3	5
Percent Voids in Mineral Aggregate (VMA)	Based on Nominal Maximum Particle Size					
Percent Voids Filled With Asphalt (VFA)	70	80	65	78	65	75

Traffic Classifications:

[1] Light - Traffic conditions resulting in a Design EAL <104

[2] Medium - Traffic conditions resulting in a Design EAL between 104 and 106

[3] Heavy - Traffic conditions resulting in a Design EAL >106

Minimum Percent Voids in Mineral Aggregate (VMA)

Nominal Maximum Particle Size U.S.A. Standard Sieve Designation	**Minimum Void in Mineral Aggregate (Percent)**
No. 16 (1.18 mm)	22.5
No. 8 (2.36 mm)	20.0
No. 4 (4.75 mm)	17.0
3/8 in. (9.5 mm)	15.0
1/2 in. (12.5 mm)	14.0
3/4 in. (19.0 mm)	13.0
1 in. (25.0 mm)	12.0
1-1/2 in. (37.5 mm)	11.0
2 in. (50 mm)	10.5
2-1/2 in. (63 mm)	10.0

Standard mix design procedures (Marshall, Hveem) have been developed and adopted by AASHTO; however, some States have modified these procedures for their own use. Any modification from the standard procedure should be supported by correlation testing for reasonable conformity to the design values obtained using the standard mix design procedures.

Appendix 4: National Highway System State and Component Mileage

This table from the Federal Highway Administration of the U.S. Department of Transportation shows the NHS mileage for each state, and a breakdown of each component, including proposed NHS Route mileage.

State	Total NHS Mileage	Eisenhower Interstate System	Congressional High Priority Corridor	Strategic Highway Network	Other NHS	Intermodal Connector
Alabama	3,754	906	491	1,827	1,704	43
Alaska	2,119	1,084	505	1,379	174	62
Arizona	2,806	1,168	244	1,471	1,273	25
Arkansas	2,747	543	569	1,100	1,362	33
California	7,511	2,474	222	4,463	2,789	74
Colorado	3,390	952	-	1,002	2,366	22
Connecticut	961	345	4	350	605	3
Delaware	325	41	-	149	168	7
District of Columbia	79	14	-	14	65	1
Florida	4,330	1,473	-	1,953	2,236	141
Georgia	4,670	1,237	155	1,984	2,562	57
Hawaii	362	54	-	143	205	14
Idaho	2,380	611	-	673	1,702	5
Illinois	5,737	2,158	6	2,167	3,414	150
Indiana	2,910	1,171	253	1,238	1,391	28
Iowa	3,231	782	179	786	2,237	28
Kansas	3,786	872	379	905	2,492	10
Kentucky	2,914	761	637	791	1,443	43
Louisiana	2,719	892	39	1,124	1,553	41
Maine	1,283	366	-	375	891	18
Maryland	1,455	471	-	649	717	88
Massachusetts	1,927	564	-	582	1,299	47
Michigan	4,781	1,241	286	1,339	3,116	40
Minnesota	3,968	912	-	1,117	2,848	3
Mississippi	2,797	684	212	1,175	1,455	82
Missouri	4,563	1,176	642	1,693	2,466	30
Montana	3,892	1,194	221	1,416	2,475	-

(Table continues on next page)

State	Total NHS Mileage	Eisenhower Interstate System	Congressional High Priority Corridor	Strategic Highway Network	Other NHS	Intermodal Connector
Nebraska	3,007	482	180	545	2,278	4
Nevada	2,165	541	44	847	1,312	6
New Hampshire	810	224	-	224	574	12
New Jersey	2,100	428	-	541	1,450	110
New Mexico	2,976	1,000	53	1,459	1,463	1
New York	5,148	1,498	65	1,622	3,379	94
North Carolina	4,192	1,032	479	1,951	1,663	190
North Dakota	2,750	572	-	710	2,037	3
Ohio	4,543	1,580	393	1,780	2,307	141
Oklahoma	3,325	930	127	1,062	2,128	9
Oregon	3,755	729	363	1,321	2,046	25
Pennsylvania	5,476	1,761	123	1,927	3,414	76
Puerto Rico	448	245	-	284	149	15
Rhode Island	272	71	-	99	165	9
South Carolina	2,668	830	222	1,110	1,433	10
South Dakota	2,943	679	84	778	2,104	30
Tennessee	3,384	1,074	233	1,185	1,947	39
Texas	13,704	3,240	925	5,903	7,165	198
Utah	2,192	934	-	1,234	948	10
Vermont	718	320	-	320	388	9
Virginia	3,486	1,101	702	1,639	1,329	38
Washington	3,384	762	193	1,010	2,041	139
West Virginia	1,767	544	294	621	830	22
Wisconsin	4,215	741	-	908	3,208	99
Wyoming	2,907	915	-	1,015	1,892	-
Total	**163,734**	**46,380**	**9,525**	**61,964**	**92,658**	**2,383**

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[1] Statement of the President Of the United States, Nov. 28, 1995.

[2] Bureau of Transportation Statistics, Washington, DC.

[3] Future Interstate procedures for system actions on the Interstate System for new Federal Aid Highways are addressed by: 23 CFR 470A, "Federal-Aid Policy Guide," December 19, 1997.

[4] United States Department of Transportation, Federal Highway Administration, February 12, 2003.

[5] From: Rodney E. Slater, "The National Highway System: A Commitment to America's Future," Public Roads, Spring 1996. Former Federal Highway Administrator Slater also noted that the NHS "…serves 198 ports, 207 airports, 67 Amtrak stations, 190 rail/truck terminals, 82 intercity bus terminals, 307 public transit stations, 37 ferry terminals, 58 pipeline terminals, and 20 multipurpose passenger terminals. By providing these essential linkages to other modes, NHS creates a seamless transportation system for the rapid movement of people and products.."

[6] On June 29, 1956, President Dwight D. Eisenhower signed the landmark Federal-Aid Highway Act of 1956, which established the modern interstate highway system, which was formally renamed the "Dwight D. Eisenhower System of Interstate and Defense Highways" in October 1990. In his memoir "Mandate for Change 1953-1956", President Eisenhower wrote: "More than any single action by the government since the end of the war, this one would change the face of America. ... Its impact on the American economy—the jobs it would produce in manufacturing and construction, the rural areas it would open up—was beyond calculation." Sinclair Weeks, Eisenhower's Secretary of Commerce, called the resulting highway construction effort: "the greatest public works program in the history of the world."

[7] Slater, op. cit. — "Before the Interstate Highway system brought fast, limited access highways to the United States, there was, and still remains, another nationwide system of highways that enabled travelers to follow standardized routes to any part of the nation. This system, known as the United States Highway System or simply as "US" highways, was the first time in history that a national standard was set for roads and highways. This system was created by the Federal Aid Highway Act of 1925 as a response to the confusion created by the 250 or so named many named highways, such as the Lincoln Highway or the National Old Trails Highway. Instead of using names and colored bands on telephone poles, this new system would use uniform numbers for inter-state highways and a standardized shield that would be universally recognizable. The most important change was that this new system would be administered by the states, not by for-profit private road clubs. The history of US highways is a reflection of the history of 20th Century America. In the 19th Century, the railroads shaped the country, enabling people to travel to and settle in distant places. However, in the invention of the automobile gave everyone unprecedented mobility. The US highway system, itself a reflection of the Progressive Era, shaped the nation by allowing easy access through standardized routes to all parts of the nation."

[8] Dr. Yetkin Yildirim, Superpave Asphalt Research Program, The University of Texas, 1996.

[9] Astec Industries, May 2003.

[10] Michael Halladay, "The Strategic Highway Research Program: An Investment That Has Paid Off", Public Roads, U.S. Dept. of Transportation, Vol 61, No. 5, March/April 1998.

[11] Michael Halladay, op. cit.

[12] Kim A. Willoughby, Joe P. Mahoney, Stephen T. Muench, Steven A. Read et al., "Construction-Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials," Research Project Agreement T9903, Task A3 Cyclic Segregation, prepared for Washington State Transportation Commission, Department of Transportation and in cooperation with U.S. Department of Transportation, Federal Highway Administration, July 2001.

[13] This observation is noted in a paper from private industry written by J. Don Brock and Herb Jakob, "Temperature Segregation/Temperature Differential Damage," Technical Paper T-134, Astec Industries, Chattanooga TN, 1997.

[14] Steven A. Read, "Construction Related Temperature Differential Damage in Asphalt Concrete Pavements," Master's Thesis, University of Washington, Seattle WA, 1996.

[15] U.S. Department of Transportation, Federal Highway Administration, "Materials Notebook: Asphalt Concrete Mix Design and Field Control," FHWA Technical Advisory T 5040.27, March 10, 1988. "Inadequate compaction leads to lower density due to entrapment of air in the mat. Industry guidelines are for density requirements that result in an air void system in the mat of 6-8 percent immediately after construction. Subsequent densification under traffic then typically can lead to an ultimate air void content of about 3-5 percent, as determined by AASHTO T209. A percentage of test strip density or Marshall laboratory density can be used provided each is related to the maximum density (see Appendix 3, above). The specified density should be attained before the mat temperature drops below 175°F."

[16] Kim A. Willoughby, Joe P. Mahoney, Stephen T. Muench, Steven A. Read et al., July 2001 op. cit.

[17] Jeff Richmond, Roadtec Inc., Chattanooga TN, personal communication, April 2, 2003.

[18] Joe P. Mahoney, University of Washington, Seattle WA, personal communication, March 27, 2003.

[19] Scott Lee, Roadtec Inc., Chattanooga TN, personal communication, April 2, 2003.

[20] Herb Jakob, Astec Industries, personal communication, April 2, 2003.

[21] Kim Willoughby, "Construction-Related Variability in Mat Density Due to Temperature Differentials, Washington State Department of Transportation, February 2003,

[22] Kim A. Willoughby, Joe P. Mahoney, Stephen T. Muench, Steven A. Read et al., op. cit.

[23] Kim Willoughby, February 2003, op. cit.

[24] Kim Willoughby, February 2003, op. cit.

[25] Kim A. Willoughby, personal communication, May 28, 2003; and Kim A. Willoughby, Joe P. Mahoney, Stephen T. Muench, Steven A. Read et al., July 2001, op. cit.

[26] Kim Willoughby, February 2003, op. cit.

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[28] Kim A. Willoughby, "Temperature Differentials and the Related Density Differentials in Asphalt Concrete Pavement Construction," Washington State Department of Transportation, Sept. 2001.

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[31] Mary Stroup-Gardiner and E.R. Brown, "Segregation in Hot Mix Asphalt Pavements," Interim Report, National Cooperative Highway Research Program Project 9-11, Transportation Research Board, National Research Council, Washington, D.C., 1998; and "Segregation in Hot Mix Asphalt Pavements," National Cooperative Highway Research Program Report 441, Transportation Research Board, National Research Council, Washington, D.C., 2000.

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[33] Brochure: "Shuttle Buggy® Material Transfer Vehicle," Roadtec, Chattanooga TN, 2003.

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[35] Dr. Yetkin Yildirim, op. cit.

[36] U.S. Department of Transportation, Federal Highway Administration, "Materials Notebook: Asphalt Concrete Mix Design and Field Control," FHWA Technical Advisory T 5040.27, March 10, 1988.

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