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Secrets of Perpetual Pavement Revealed

Page 16

Thin-Lift Warm Mix Smoothes I-280,

Page 26

New Life-Cycle CO_2e Estimator,

Page 40

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Buried Instruments Reveal Secrets of Perpetual Pavements

Perpetual Pavements may be performing even better than anticipated by designs

By Tom Kuennen

As data from instruments buried in roadways and test sites across the nation is collected and analyzed, researchers are developing a better notion of what it takes to build an asphalt pavement that can last indefinitely.

Ongoing analyses of these data are finding that Perpetual Pavements — an asphalt pavement designed to provide a service life of 75 years or longer with only routine maintenance — can withstand higher levels of strain than suggested by empirical designs or lab tests without accumulating fatigue damage. This means thinner sections for Perpetual Pavements may be in the offing.

Perpetual Pavements are designed with several layers of asphalt pavement of different mix designs topped with a renewable surface course. Distresses in the top layer will occur eventually, necessitating periodic surface renewal, but they will not penetrate deep into the pavement's structure. Instead, they can be managed through routine

On I-94 in Wisconsin, screened asphalt is placed atop gauges and carefully compacted by hand.

maintenance, such as simply cold milling the top layer and placing a new asphalt surface course.

Properly designed Perpetual Pavements should last for more than half a century without major structural rehabilitation or reconstruction, shortening construction delays and saving costs.

Fatigue Cracking

The bottom layer of a Perpetual Pavement provides resistance to fatigue cracking, while its intermediate and upper layers resist top-down cracking and rutting caused by traffic.

The fatigue-resistant bottom layer is the defining element of Perpetual Pavement design. This may consist of a "rich" layer typically containing more liquid asphalt binder content with lower air voids, making it more flexible. Such a base can be designed so that the commonly accepted endurance limit of 70 microstrains (με) or more is never exceeded. The higher asphalt content also bolsters the bottom layer's resistance to moisture.

Atop this base, a middle layer is created with an asphalt mix designed to support anticipated traffic loads and minimize deflections, while the top layer can use any asphalt pavement mix design that is both durable and rut-resistant.

Ideally, scheduled preventive maintenance and periodic renewal of the driving course would be all the work that will be required on a Perpetual Pavement. Such work could be done in a classic mill-and-fill operation at night, with reopening of roadway in the morning, with minimal impact or delays for the driving public.

Perpetual Pavements are designed using mechanistic/empirical (M/E) procedures, contrasted with long-standing conventional empirical design. In an M/E-designed pavement, engineers analyze how anticipated traffic stresses will induce strain that will affect the pavement's performance, taking into account material qualities and thickness.

On I-5 in Oregon, a small roller carefully compacts HMA over strain gauges without vibration.

By contrast, conventional empirical design takes the results of existing experience — in the industry's case, the AASHO Road Test (1956–60) — and then constructs a design that conforms to a test design that successfully withstood loadings anticipated for the new construction.

The thickest asphalt pavement in the AASHO experiment was only 6 inches thick. Pavement designs in the modern era are based on an extrapolation of results from these relatively thin pavements, which can result in overdesigned pavements.

"One of our big areas of study is mechanistic response, and proving the Perpetual Pavement concept by combining results from laboratory testing at multiple strain levels, with actual strain measurements and field observations from the Test Track," said Buzz Powell, P.E., Ph.D., assistant director of the National Center for Asphalt Technology (NCAT) in Auburn, Ala.

While full-depth asphalt pavements have performed well for decades, the Perpetual Pavement concept was first articulated in 2000 through the Asphalt Pavement Alliance. Soon afterward, researchers began studying these structures and instrumenting newly placed pavements to see if their theoretical resistance to fatigue cracking translated to real-world roadways.

Careful field testing is needed to ensure that in-service Perpetual Pavements are performing according to design expectations, said James Crovetti, Ph.D., civil engineering professor and director of the Transportation Research Center at Marquette University in Milwaukee. "Valuable performance data can be gathered through instrumentation, placing sensors in and around the pavement to directly monitor the live responses of pavements to traffic and the environment," he said.

NCAT: Redefining 'Perpetual'

Perpetual Pavements have a long history at the NCAT Test Track, and each research cycle reveals new data about what designs can yield perpetual performance. Using accelerated loading, each test cycle delivers about 9 million to 10 million ESALs (equivalent single-axle loads), or about 10 to 12 years of traffic on a rural interstate highway.

"When the track was originally built [in 2000], our Perpetual Pavement sections were several feet thick, so we could be confident no deep distresses would confound our performance comparisons of different surface mixes," said Powell. "The 1993 AASHTO Design Guide that was used to design the foundation for our track required a really thick, robust foundation, due to the conservative nature of the empirical design process."

continued on page 19

The next two-year cycle tried pavements much thinner, and they revealed a surprise.

"When we rebuilt in 2003 we ripped out eight of the original perpetual sections and built pavements of different thicknesses," said Powell. "The thickest two pavements were 9 inches thick, and the computer said 9 inches should fail near the end of the research cycle [in 2005]. But it turned out that those 9-inch pavements are perpetual. So now we are working to find out what defines 'perpetual.'"

Powell said that NCAT is looking at lab testing, mix characterization, instrumented pavements in the field, and surface performance observations to determine just what thickness can provide Perpetual Pavement results.

"We are finding here that a 9-inch pavement is giving us the same performance of a 24-inch pavement," he said. "Now the question is not whether or not Perpetual Pavements work, but how thin can we build them and have them still be perpetual?"

Traffic continued on some of those sections in the following cycle and the sections continued to perform. "These [2003 sections] should have failed at 9 million to 10 million ESALs, but now have survived 30 million ESALs and are still going," said Powell. "We will continue traffic on at least one of those sections in the next research cycle [2012–2014], and they will be 12 years old by its conclusion." Twelve years on the test track is equivalent to more than 120 years of normal traffic.

Currently, three of the thinner instrumented pavements at the NCAT Test Track are confirmed perpetual sections: two 9-inch pavements built in 2003 on a good base and subgrade and one 14-inch pavement built in 2006 on a soft, plastic-clay subgrade.

Instrumentation of the perpetual sections is placed at multiple depths and includes temperature gauges for environmental conditions, pressure plates to indicate load divided by area, and strain gauges to detect how much bending is occurring in the layer as a result of the traffic.

In the middle of the wheel path are two longitudinal and two transverse strain gauges on 2-foot centers. "Move 2 feet to the edge of the wheel path on both sides and we have the same configuration," said Powell. "The data points for each axle load are transmitted wirelessly. That's important because it keeps personnel away from the track while the trucks are running."

The NCAT findings should prompt a serious rethinking of just how thick a Perpetual Pavement must be.

"The first takeaway is the striking difference in what we perceive the thickness of a Perpetual Pavement

continued on page 20

In 2009, a strain gauge array is overlaid with asphalt base layer in advance of two years of Perpetual Pavement testing at NCAT.

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needs to be. When the track was designed in the late 1990s using the '93 AASHTO Design Guide and layer coefficients, theoretically an extremely thick pavement was needed to survive for numerous research cycles," said Powell.

"We found we don't need 24 inches to be perpetual. We can get perpetual performance from 9 inches, and we only know this because we built that 9-inch pavement on the same base and subgrade using very similar mixes," he said. "That's a significant finding and demonstrates why we need mechanistic design, and why we have to do things differently. The old design methodology was giving us thicknesses that were off the scale."

Wisconsin: Affirming Principles

In Wisconsin, the I-94, I-43 and I-794 expressways all converge in downtown Milwaukee. When the interchange was reconstructed in 2005–06, Marquette University Transportation Research Center decided to instrument a Perpetual Pavement section in the project.

"We instrumented an asphalt Perpetual Pavement on the north leg of the project, to provide us data to validate suppositions of 40 or more years of fatigue life built into it," said Marquette's Crovetti. "We put in an array of strain gauges, weigh-in-motion and environmental sensors, and collected data for 18 months. We analyzed the results and the projections validated that it will have at least 40 to 50 years of fatigue life in the lower levels of the pavement, assuming we have periodic resurfacing of the surface."

The section was a four-lift, 13-inch asphalt pavement, Crovetti said. The bottom lift was a 4-inch asphalt layer, followed by 3- and 4-inch intermediate layers, all finished off with a 2-inch stone-matrix asphalt (SMA) surface.

To enable a comprehensive mechanistic-empirical pavement appraisal, researchers also documented the materials characteristics of the pavement section.

The outer wheel path of the outside lane was instrumented with asphalt strain sensors, base and subgrade pressure sensors, subgrade moisture and temperature sensors, asphalt layer temperature sensors, traffic wander strips and a weigh-in-motion system.

Quartz piezoelectric strips were used to collect rolling weights of traffic. (The NCAT Test Track does not collect in-pavement weight data as the weights of the rolling test trucks are already known.)

"We instrumented one wheel path of one lane, so we targeted our weigh-in-motion devices to measure the wheel loadings traveling over our strain gauges," Crovetti said, noting

that a single wheel path was used as researchers wanted wheel loads, not axle loads.

Weather sensors and a video camera were also installed to monitor real-time traffic and environmental conditions. The data from all the sensors was collected and transmitted wirelessly, in real time, to a server at Marquette.

The instrumentation delivered remarkable results. "We saw that the strain results at the bottom of the pavement were markedly lower than we anticipated," said Crovetti. "In this project, we instrumented a small piece of the world. But from what we measured, we are confident that this pavement will perform structurally for its anticipated life."

At the Marquette Interchange project in Wisconsin, unscreened asphalt is tamped over gauge arrays with a plate compactor just as paving crew approaches.

Oregon: Calibrating the Model

In the Pacific Northwest, as the Oregon Department of Transportation (ODOT) moved toward adoption of the Mechanistic-Empirical Pavement Design Guide (MEPDG) procedures, it wished to calibrate its model for fatigue cracking against Oregon-specific conditions.

In 2005, ODOT installed instruments in two adjacent pavement structures along I-5 north of Albany, Ore. — one asphalt pavement on an aggregate base, the other asphalt pavement over rubblized portland cement concrete. ODOT later expanded the study to include a site along US 97 in Redmond in 2008 and another in 2009 along I-5 in southwestern Oregon where there was a different traffic mix and pavement characteristics.

At all three sites, transverse and longitudinal strain gauges were installed, coupled with weigh-in-motion and axle sensors. Pressure plates were not used. Researchers were able to monitor temperature down to the base course.

"We wanted to collect that data to see if it had a significant bearing on the predicted strains that we got from the MEPDG," said Todd Scholz, Ph.D., assistant professor in the School of Civil and Construction Engineering at Oregon State University.

"Axle sensors were used to determine the lateral position of the traffic in the lane. We needed that information to verify the predicted strains from the mechanistic model, and to get an appreciation of wheel wander," he said.

In Redmond, the structure was similar to I-5, except 12 inches total of asphalt pavement was used on I-5 compared to 11 inches in Redmond.

"The northern I-5 site had different asphalt mixes, dense-graded for the main structure, capped with an open-graded friction course, whereas the Redmond and southern I-5 sites all had dense-graded mixes," Scholz said.

Scholz received quality information regarding traffic weights and position of trucks in the lanes. "We now have an appreciation of wheel wander at all three installations for inclusion into the MEPDG software, for both interstates and primary arterials," he said.

The bottom layers of the pavements are withstanding the loads better than expected, said Scholz.

"For Perpetual Pavements, we're getting strains in the 50- to 55-microstrain magnitude as a maximum," said Scholz. "On I-5, we are typically between 35 and 40 microstrains, which is roughly half the criterion for design of Perpetual Pavements."

New York State: 9 Inches Works

In New York State, an instrumented Perpetual Pavement section has been performing as designed for more than three years.

A section of I-86 at Angelica, N.Y., was constructed as a perpetual test section in September 2008. "This section is subjected to weather variations and heavy loading," said Julian Bendaña, Ph.D., P.E., an engineering research specialist at the New York State Department of Transportation, in a December 2011 report.

The new structure is composed of three layers of asphalt pavement with a total thickness of 9 inches. The base layer, placed on rubblized concrete, is 3.5 inches deep, using a 25-mm mix with an asphalt content of 4.4 percent. The middle layer was built with two 2-inch lifts for a total thickness of 4 inches using a 19-mm mix with an asphalt content of 4.7 percent. Finally, the surface course is 1.5 inches thick using a 9.5-mm mix with an asphalt content of 6.1 percent. All four lifts used a PG 64-22 polymer-modified binder.

Four linear variable differential transducers (LVDTs), two pressure cells, four thermocouples and 16 strain gauges were placed in the instrumented section. The reference points for the deep LVDTs are located 11 feet below the surface

continued on page 23

In Oregon, HMA is placed over strain gauges by hand.

course; the two shallow LVDTs have their reference point just below the rubblized concrete. In the base layer, eight strain gauges were installed above the rubblized concrete placed 2 feet apart from each other. There are two thermocouples above the rubblized concrete.

"As of August [2011] the strain measured at the bottom of the asphalt is within the design limits for Perpetual Pavements," said Bendaña. "In addition, the strain gauges installed have a limited fatigue life, and usually are nonfunctioning within a year of installation, but on this pavement these gauges are still intact after more than three years of service, indicating they have not reached their fatigue limit."

Ohio: New Tests This Summer

In Ohio, an instrumented 16-inch-deep Perpetual Pavement built from scratch in 2005 is experiencing stresses at the bottom of the pavement structure much less than anticipated in the design.

"The Perpetual Pavement concept works," said Shad Sargand, Ph.D., professor at the Russ College of Engineering and Technology at Ohio University and assistant director of the Ohio Research Institute for Transportation and the Environment's (ORITE) Accelerated Pavement Load Facility (APLF) in Lancaster, Ohio. "Based on the instrumentation and performance so far, everything is working very well."

It works so well that a new instrumented pavement will be constructed in Ohio in summer 2012. This year, four asphalt Perpetual Pavement test sections of varying thicknesses will be constructed on the State Highway Research Program (SHRP) Test Road on US 23 in Delaware County.

All new sections will have a 6-inch dense-graded base layer; however, the total thickness of asphalt layers will vary. On low-volume access roads, 11- and 13-inch pavements will be constructed, while 13- and 15-inch sections will be built on the main line.

ORITE will develop a detailed instrumentation plan for monitoring the test sections once the specific design buildups for construction are developed by Ohio DOT.

In 2005, the US 30 bypass of Wooster, Ohio, in Wayne County (WAY-30) was constructed exceptionally thick at more than 16 inches. At the surface, a 1.5-inch lift of SMA was placed atop a 1.75-inch Superpave lift, a 9-inch asphalt-treated base, and a 4-inch fatigue-resistant layer. Beneath the pavement was a 6-inch deep-graded aggregate base; and prepared in-situ subgrade soil.

"Back then we used the deep thickness to make sure it behaved like a Perpetual Pavement," said Sargand. "Afterward we built Perpetual Pavements at our APLF in Lancaster with different thicknesses: 16, 15, 14 and 13 inches deep. All of them have performed very well, and the microstrains were well below the design limit of 70 microstrains. Now we want to validate these findings under actual traffic, and will build those sections this coming summer."

On WAY-30, sections were instrumented with pressure cells to monitor subgrade pressures, and deep and shallow LVDTs to record pavement deflections. The asphalt test section also had transverse and longitudinal strain gauges, and a weather station was used to monitor environmental conditions.

During winter controlled-vehicle load (CVL) tests found that longitudinal strain on the bottom fatigue-resistant layer remained less than or equal to 35 microstrains, even at the slowest speeds. Then, during summer tests at highway speeds of 45 and 55 mph, the strain in the fatigue-resistant layer remained close to the design value under even the heaviest loads.

"In everyday use, such high-load strains will be rare," said Sargand. "High-load strains at slower speeds will be even more rare [during traffic stoppages or slowdowns], though these did exceed design strain." Strains at the bottom of the intermediate layer were lower than at bottom of the fatigue-resistant layer, as expected.

Thanks to results like these from instrumented pavements, engineers are learning just how long-lasting and thin Perpetual Pavements can be. AP