By Tom Kuennen, Contributing Editor

Building Better Roads from the Ground Up

A strong foundation is the key to a strong pavement structure

A pavement is only as strong as its foundation. Without an adequate base or foundation, a road simply cannot stand up to long-term traffic volumes, increasing vehicle weights and speeds, and the assault of the elements.

Strong subbases bolster the base and pavement layers above.

While the concept of a subbase is simple, the reality is that in today's world of advanced technology, a subbase design and construction can be complex and demanding. Subbase design may require analysis of existing, virgin and reclaimed materials, application and mixing of stabilization chemicals, installation of stabilization fabrics, and measurement of compaction using "smart" technology built into dirt rollers. Subbases must also be drained and protected from frost.

And the new philosophy of mechanistic-empirical design, as articulated by the American Association of State Highway & Transportation Officials (AASHTO) with the National Cooperative Highway Research Program (NCHRP), is bringing a new rigor to the design and construction of subbases.

The result will be better-performing pavement structures.

Damage from Inadequate Subbases

Subbases inadequate for the traffic loads they carry will manifest their shortcomings in a variety of ways.

The most common clue to base failure-related pavement woes in is fatigue cracking. Fatigue, or bottom-up, cracking results when traffic load stresses propagated to asphalt pavement foundations cause foundation cracks to work their way upward through the pavement.

In asphalt pavements, it's manifested as a series of interconnected cracks resembling an alligator hide, hence its popular name *alligator cracking*. It develops into many-sided, sharp-angled pieces, usually less than 12 inches on the longest side.

Low-severity fatigue cracking characterizes an area of cracks with no or only a few connecting cracks. The cracks are not spalled nor sealed, and pumping of base materials out the cracks is not evident. In **moderate fatigue cracking**, the interconnected cracks form a complete pattern, cracks may be slightly spalled and may be sealed, and pumping is not evident. **High-severity fatigue cracking** is an area of moderately or severely spalled interconnected cracks forming a complete pattern, the pieces of which may move when subjected to traffic loads. Cracks may be sealed, and pumping may be evident.

In portland cement concrete pavements (PCC), longitudinal cracking describes cracks that are mostly parallel to the pavement centerline, and are attributed to subgrade heaving that pushes upward against the rigid slab and cracks it.

Base and subbase layers that are composed of expansive soils with an abundance of clay must be stabilized, frequently done with cement. This is particularly true of soils in Louisiana, Texas and the American Southwest. Expansion of these base and subbase layers will cause heaving in the pavement, forcing it upward, causing it to fissure and break. The pavement likely will have to be completely reconstructed.

Layers of Pavement Structure

The pavement structure is composed of layers beginning with the subgrade, topped by the subbase, the base course, and lastly one or more surface courses. On roads with lighter traffic loads, the surface course(s) may rest directly on the subbase.

The surface courses can be a single course of portland cement concrete (PCC), although simultaneous twin lifts of PCC are being studied *(see "Research that Can Change the Way We Work,"* April 2011, pp. 26-39); or one, two or even three courses of hot-mix asphalt or its warm and cold-mix permutations. These will rest on base and subbase layers that can be unbound, bound, or stabilized by a variety of methods, including cement- or lime-slurry, dry cement or lime, asphalt emulsion, or foamed asphalt.

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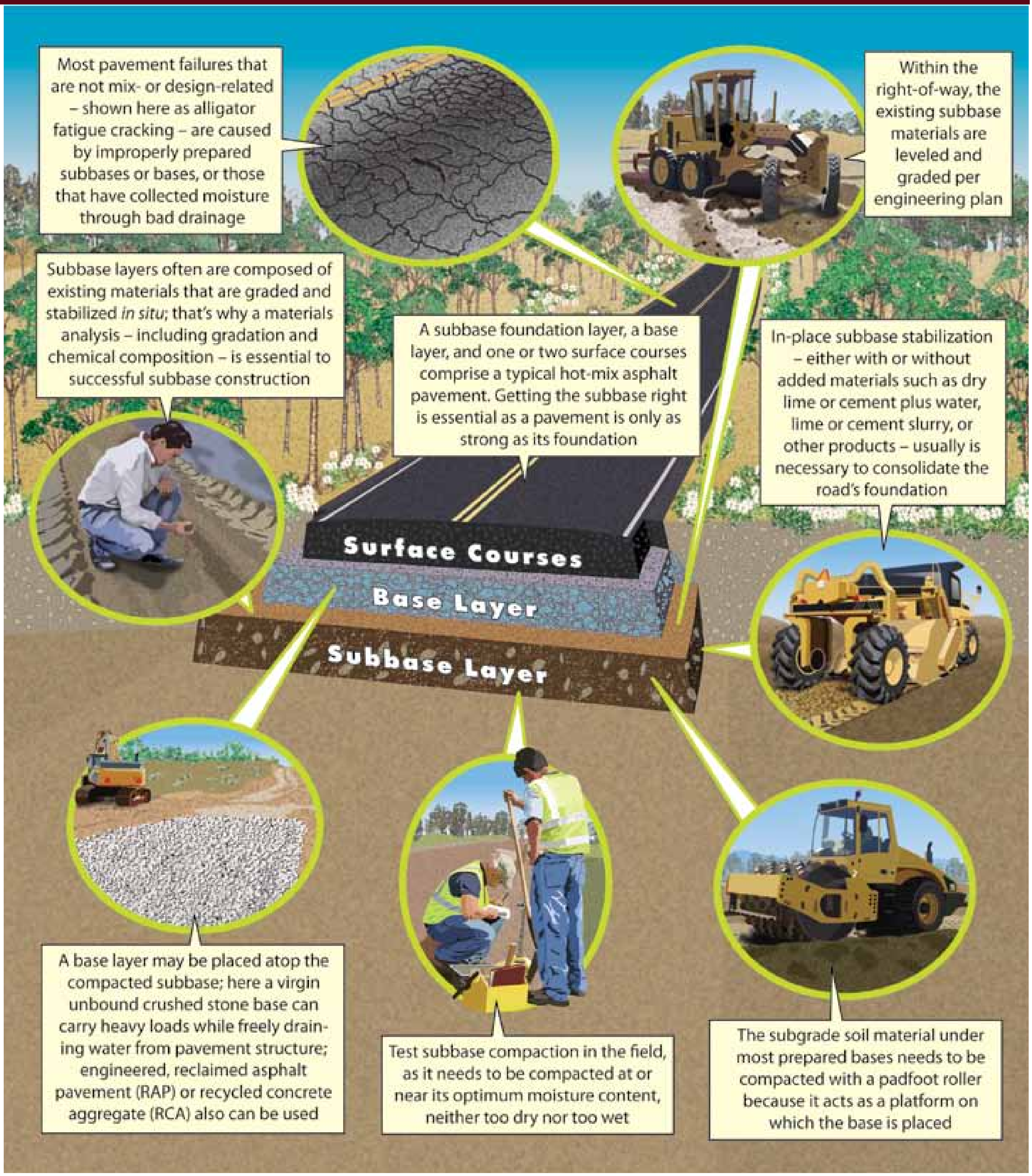
Illustration by Edd Hickingbottom

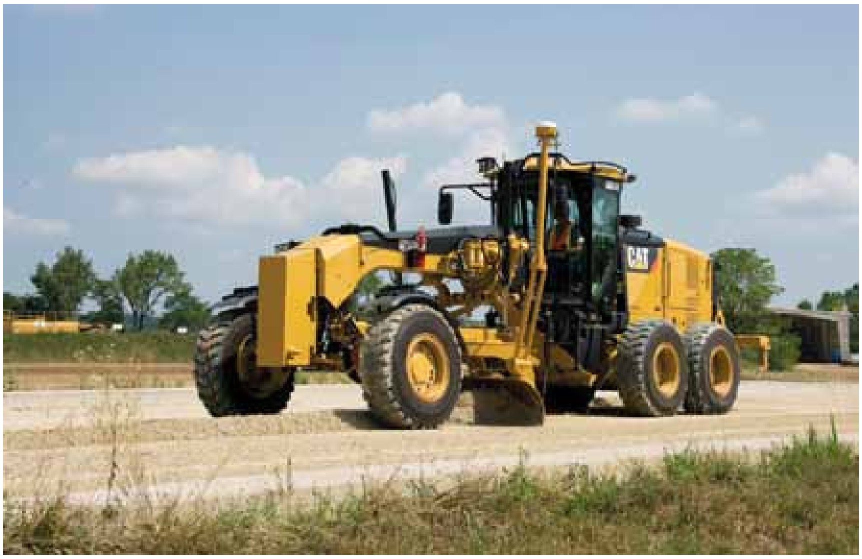
Start Strong, Finish Strong

Weak bases are surface failures waiting to happen



For new alignments, stabilize subgrade prior to work on subbase, base and pavement layers.

Photo courtesy of Wirtgen America



New Cat 160M2 motor grader preps subbase prior to base placement.

Photo courtesy of Caterpillar

The subgrade is the graded, prepared ground beneath the subbase layer. It's been described as the point at which excavation ceases and construction starts, and supports the entire pavement structure and traffic loads.

In practice the subbase becomes the main load-bearing layer of the pavement, evenly spreading the traffic loads across the subgrade. The materials used may be soil-aggregates, unbound granular material, or bound granular material.

Soil-aggregate subbases consist of soil from the subgrade, combined with mineral aggregate present on the road surface, with or without additional aggregate. ASTM D1241-07, *Standard Specification for Materials for Soil-Aggregate Subbase, Base and Surface Courses* describes soil-aggregate as sand-clay mixtures; gravel; stone or slag screenings; sand; crusher-run coarse aggregate consisting of gravel, crushed stone, or slag combined with soil mortar; or any combination of these materials. These subbase materials are spread, shaped and compacted in accordance with DOT contract documents.

They differ from granular subbases, which are composed of granular material that may be present on the roadbed, plus a specified quantity of virgin aggregates – with or without recycled materials – that meet strength, abrasion and gradation specs. The granular mixture is placed on a subgrade, uniformly moistened, shaped and compacted to spec.

Aggregates used in granular base and subbase applications generally consist of sand and gravel, crushed stone or quarry rock, slag, or other hard, durable material of mineral origin, according to the Federal Highway Administration (FHWA). The gradation requirements vary with type base or subbase.

"Granular base materials typically contain a crushed stone content in excess of 50 percent of the coarse aggregate particles," according to the FHWA. "Cubical particles are desirable, with a limited amount of flat or thin and elongated particles. The granular base is typically dense-graded, with the amount of fines limited to promote drainage."

Granular subbase is also dense-graded, but tends to be somewhat coarser than granular base, FHWA says. The requirement for crushed content for granular subbase is not required by many agencies, FHWA says, although provision of 100 percent crushed aggregates for base and subbase use is increasing in premium pavement structures to promote rutting resistance.

"A granular subbase course is that part of the pavement structure constructed to provide a foundation for the base course, to distribute the superimposed loading to the subgrade and to provide drainage beneath the base and surface courses," states the Wisconsin DOT in its *Construction and Materials Manual.* "It usually consists of natural sand or a mixture of sand with gravel, excavated and constructed with grading equipment as an item under a grading contract."

Before placing the subbase material, the subgrade or foundation must be properly prepared, the Wisconsin DOT says. "It should be smooth, shaped to conform to required crown and grade, and be compacted to the required density."

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Where travel of the placing equipment ruts or disturbs the foundation, means must be employed to correct these conditions ahead of placing the subbase material, the Wisconsin DOT warns. "If the subbase is constructed on a rutted foundation, the roadbed will not drain properly and areas of weakness may develop in the pavement structure. Placing, shaping and compacting the subbase material to conform for its full width to the required grade, section and density is necessary for satisfactory construction of the proposed base course. The inspector should frequently check the subbase course for correct depth and spread."

Draining the Subbase

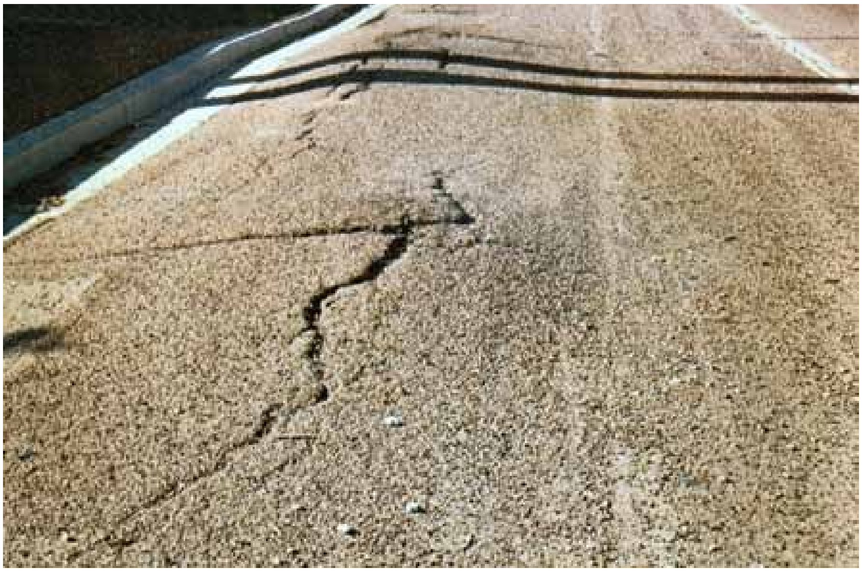
Wisconsin DOT warns of the danger of water in pavement structures. It's commonly said that "water is the enemy of pavements." Therefore whatever can be done to keep water out of the pavement structure is effort well spent.

As noted below, saturated pavement structures will actually pump water and base fines out of HMA fatigue cracks or along the sides of PCC slabs, indicating subbase and base layers in dire straits.

Pavement structures will contain water in its free state, as capillary water between the granular material, bound moisture, or water vapor. Free water is the form of most concern, engineers say, because it can do the most harm and is the only form of water that can be significantly removed by gravity drainage.

The subgrade, granular subbase and other pavement layers always are constructed with cross slope to facilitate drainage. Rain or melt water will enter pavement through cracks and joints in the driving surface. A properly designed pavement will use gravity to encourage water to find its way through voids in the granular base and subbase following the slope, to either exit the structure into side ditches, or into a built-in pavement drain that will take it to ditches and ultimately to a creek, wetland or bioswale.

Permeable road bases are made of an open-graded granular material that allows free flow of water through the subbase or base layer, and then out to a drainage appurtenance. The permeable base may be unbound or bound, as in the case of the cement-treated permeable base – which adds structural strength – and may be separated from the subgrade by an impermeable drainage fabric that keeps fines from migrating from the subgrade into the subbase.



If not stabilized, expansive subbase and base layers will heave and destroy pavement.

Photo courtesy of Crafco

"Daylighted" permeable base – exposed here at the shoulder – is a lower-cost PCC pavement drainable design that doesn't require separation fabric or drainage systems.

Photo courtesy of FHWA after Gisi, Brennan and Luedders

'Daylighted' Permeable Bases

Optimal use of fabric requires a drainage system, but a lower-cost design for PCC pavements -- the "daylighted permeable base" -- allows free draining of water to roadside.

"Daylighted permeable bases are well-suited for roadways with flat grades (1 percent or less) and shallow ditches, where it is difficult to outlet drainage pipes at an adequate height above the ditch," says the FHWA in its 2009 *Tech Brief* publication, *Daylighted Permeable Bases*.

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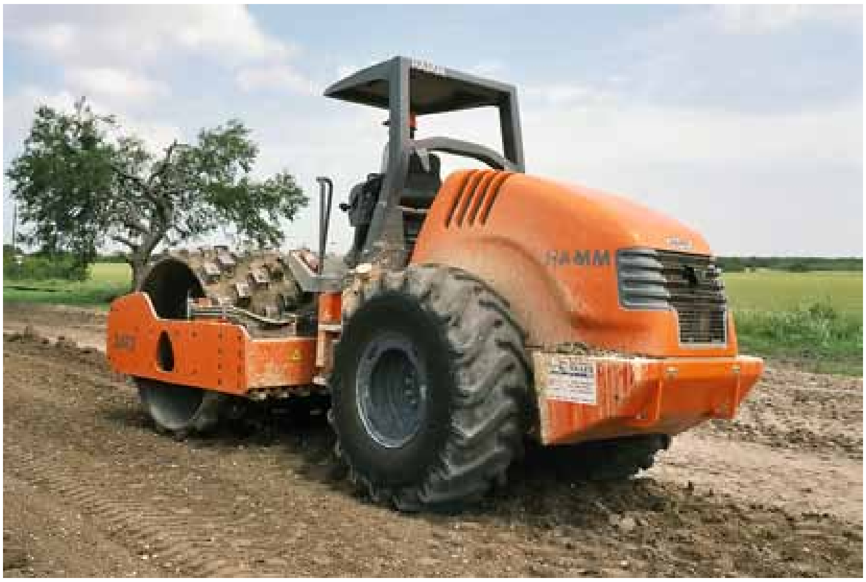

Photo courtesy of Hamm Compaction Division

For subgrade and subbase compaction, padfoot or "sheep's foot" soil compactors provide more compactive effort per square inch than smooth-drum rollers.

"Daylighted permeable bases have been used for more than 20 years in the United States to remove infiltrated water from pavement structures," FHWA writes. "[W]hen appropriately used, designed, constructed and maintained, daylighted permeable bases have the potential to perform just as well as edge-drained permeable bases, for about the same or even lower cost."

Two types of materials have been used for daylighted permeable bases, FHWA says. The first is an unstabilized large-sized stone, also called a rock base, typically constructed about 18 to 24 inches thick. The second type of material is a permeable base gradation such as would be used for an edge-drain system, either untreated or treated with asphalt or portland cement, and typically constructed about 4 to 6 inches thick. The permeability requirements and asphalt or cement content required to maintain long-term stability are the same for daylighted permeable bases as for edge-drained permeable bases, FHWA says.

A permeable daylighted base needs a suitable separator layer beneath it to prevent subgrade fines from migrating up into and clogging the base, but not necessarily a fabric, FHWA reports. "This may be an appropriately graded untreated aggregate subbase, an appropriate geotextile fabric, or a layer of subgrade soil treated with sufficient lime or cement to achieve good long-term stability and resist erosion," the agency says.

Download the complete report at *fhwa.dot.gov/pavement/concrete/pubs/hif09009/hif09009.pdf*

Impact of New Design Guide

Part of the new complexity of subbase design, and ultimately construction, derives from the ongoing adoption of new highway pavement design procedures set forth in the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Final Report* (NCHRP, 2004), now referred to as the *Mechanistic-Empirical Pavement Design Guide* (MEPDG), and in the process of adoption by DOTs from coast-to-coast.

Mechanistic-empirical are big words that describe a very simple concept. Mechanistic refers to the interaction between the materials and structure of a pavement, and how it stresses and strains under load deflection. The *MEPDG* paradigm relates these pavement mechanics to empirical or experimental performance data obtained in field or lab.

The guide uses mathematical models to describe this relationship, and the primary basis for all mechanistic-based pavement performance predictions methods is cumulative axle load applications.

"The benefit of a mechanistic-empirical approach is its ability to accurately characterize *in situ* material (including subgrade and existing pavement structures)," says the Washington State DOT in its online tutorial. "This is typically done by using a portable device to make actual field deflection measurements on a pavement structure to be overlaid. These measurements can then be input into equations to determine existing pavement structural support (often called backcalculation) and the approximate remaining pavement life. This allows for a more realistic design for the given conditions."

The existing 1993 edition of the AASHTO *Guide for Design of Pavement Structures* is based on empirical equations derived from the well-known, but outdated, *AASHO Road Test*. This program conducted performance testing between 1958 and 1960 of a limited number of structural sections at one location, Ottawa, Ill., and based on much-reduced traffic levels compared those of the 21st century.

Under the new design guide, a designer of any pavement must first consider site conditions such as traffic, climate, subgrade, existing pavement condition for rehabilitation and construction conditions in proposing a trial design for a new pavement or rehab. Then, using the software, the trial design will be evaluated through prediction of key distresses and smoothness. If the trial does not meet the demanded performance criteria, the pavement design must be revised until it does.

The new guide also incorporates procedures for performing traffic analyses, includes options for calibrating to local conditions, and incorporates measures for design reliability. Engineers can use the guide to analyze common causes of pavement distress, including fatigue, rutting and thermal cracking in asphalt pavements, and cracking and faulting in concrete pavements.

Reclaimed Materials in Bases

There is no question that recycled concrete aggregate (RCA) also may be used in road subbases and bases, so

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long as it is treated as an engineered material, that is, crushed, screened, processed and tested as though it were a virgin aggregate. *See Better Roads, Two for the Price of One,* April 2010, pp. 16–29.

In that *Road Science Tutorial,* we reported that TxDOT has researched and used RCA with good success for about 17 years. In the years 2006-2008, TxDOT saved approximately 1.8 million tons of virgin aggregates by incorporating RCA in cement treated base, flexible base, continuously reinforced concrete pavement (CRCP), filter dams, gabion walls, concrete traffic barriers, flowable fill and select backfill for mechanically stabilized earth walls. "This equates to an estimated savings of $12.6 million from reduced or eliminated landfill and virgin aggregate associated costs," TxDOT reports. "Savings from using RCA has the potential to increase tenfold based on current availability of RCA."

But recycled aggregate from structures may perform just as well as RCA from demolished highways, say Dana V. Martin and Gregory W. Halsey, undergraduate research assistants, and Jeffrey S. Melton, research assistant professor, Department of Civil Engineering, University of New Hampshire-Durham, in their 2011 Transportation Research Board paper, *Comparison of Building Derived Aggregate in Comparison to Crushed Stone*.

Use of recycled concrete aggregate (RCA) for road construction has become a widely accepted practice throughout the United States, and has proven to be an excellent substitute for crushed stone in road base applications. More than 45 states allow its use in highway construction, they write, adding the most common source of RCA is from the demolition of highway infrastructure. "While the use of RCA has become commonplace," they say, "the use of building-derived aggregate (BDA) in roadway construction has not."

BDA derives from the construction and demolition industry, which generates millions of tons per year throughout the United States, the researchers say. An inherent trait of BDA is that there are a variety of other materials present such as brick, porcelain, cement-based masonry units and other inorganic materials, they write.

"The presence of these other materials has created a barrier in the use of BDA for roadway construction," say Martin, Halsey and Melton. "The AASHTO standard for the use of crushed concrete in road base applications, M 319, allows only 5 percent brick by mass to be used." But it's common for BDA to have up to 10 percent brick by mass present, they write, which has precluded its use. The presence of nonconcrete materials in BDA has created a perception that it does not perform as well as RCA or crushed stone.

Their research, performed at the University of New Hampshire and funded by FHWA through the Recycled Materials Research Center there, has shown that BDA is a usable substitute for crushed stone. As it is also important to understand the long-term effects of using BDA, their study quantifies the longer-term performance and associated effects of using BDA in road construction.

In many ways, their results are similar to experiences with crushed concrete, they write. Field projects showed that the RCA worked in base layers, yet it would fail the L.A. Abrasion test and sodium sulfate soundness testing.

"Realistically, those tests were not appropriate for crushed concrete aggregates, and testing procedures were modified," Martin, Halsey and Melton write. "With this perspective, results of this work are promising. The abrasion losses for the BDA were slightly above the allowable limit, but needed to be compared to straight crushed concrete tested under the same conditions to better understand how high the losses really are."

On the other hand, the stiffness increase was almost 50 percent more than that of the crushed rock, and did not decrease with time, they say. "If this trend continues," they report, "it would suggest that the presence of so-called deleterious materials like brick and tile is not significant, and that the BDA can be used as base course aggregate."

Reclaimed asphalt pavement (RAP) is useful as an additive to crushed angular aggregate or pit run granular soils for road subbases and bases in Montana, according to research from Montana State University.

In research prepared for the Montana DOT, *Evaluation of the Engineering Characteristics of RAP/Aggregate Blends*, by Robert L. Mokwa and Cole S. Peebles, Department of Civil Engineering, Montana State University-Bozeman, research and tests were conducted to evaluate the suitability of such RAP blends.

The study examined changes that occur in the engineering properties of aggregate materials when mixed with RAP. In addition to a thorough evaluation of published literature on the subject, an extensive suite of laboratory tests were conducted using four different aggregates blended with asphalt millings over a broad range of mix percentages.

Laboratory investigations suggest that the engineering properties of RAP-blended soils are comparable with those of virgin aggregates, they say.

"Gradation analyses indicate that the addition of RAP to virgin materials does not significantly change the particle size distribution," Mokwa and Peebles say. "The outlook for the continued implementation of RAP as an additive to granular base and subbase materials for use in highway construction looks promising. Results from the extensive suite of laboratory tests indicate that blending asphalt millings with granular cohesionless material, like crushed aggregate or pit run cohesionless soil, results in only minor changes to the engineering properties of the virgin material."

Also, steel slag – the byproduct of steel making – can be used as aggregates for base and subbase road construction. In addition to applications requiring graded aggregates, pit run steel slag is extensively used for subbase construction in some areas, especially where weak subgrade conditions exist.

Steel slag is a crushed product having hard, dense, angular and roughly cubical particles. "Steel slag meets the requirements of ASTM D 694 and D 1241, of national agencies, and of local highway departments for macadam and crushed aggregate bases," reports supplier Phoenix Services, Uniontown, Pa. "Local highway department standards or the producer's recommendations are applicable for both base and subbase courses."

Steel slag for use in bases and structural fills -- where very high stabilities are required -- may require proper selection, processing and aging (weathering) before use, Phoenix says. "Steel slag may contain free lime (CaO or MgO) that may cause the slag to be expansive or cause differential movement when used as a base," Phoenix reports. "Steel slag is not recommended for use in rigid, confined applications such as concrete aggregate, base or fill under structures or floor slabs, or backfill against structures or bridge abutments." ❖