UNCONVENTIONAL INTERVENTION
SOUTHEAST ATLANTA GREEN INFRASTRUCTURE INITIATIVE COMPLETES LARGEST PERMEABLE PAVER ROADWAY PROJECT IN NORTH AMERICA
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More than four miles of roadways have been renovated with permeable interlocking concrete pavement in Atlanta.

The Southeast Atlanta Green Infrastructure Initiative completes largest permeable paver roadway project in North America.

The differences between pavers and slabs aren’t just about size, especially when it comes to vehicular loads.
ICPI SEeks PARTNERSHIPS TO COLLECT DATA, CALM DRIVERS AND SAVE LIVES

Relaxing Traffic

Just about every urban center in Canada and the U.S. is jammed with traffic, especially during morning and evening rush hour (or rush hours in bigger cities). Regardless of the city size, there consistently seems to be more cars and trucks than pavement to move them. It’s certainly not relaxing traffic for the drivers stuck in it.

Because they are just about the lowest density urban land use, residential areas don’t see many traffic jams. Thanks to spread out land use, residential traffic isn’t quite as hectic. While it’s not relaxing, at least it moves, even during rush hour.

Whether low or high density, residential areas are a rising source of complaints about near misses, car crashes, plus cyclist and pedestrian accidents. Vehicular traffic needs to relax, be calmed and be mindful of non-vehicular users.

There are a variety of tools and designs to calm traffic. They range from the ubiquitous (and cheap) stop sign to more visible designs that extend curbs to narrow intersections and slow traffic. Radical road remedies reduce flows and reclaim space for bus lanes, pedestrian refuge islands, bike lanes, sidewalks, bus shelters, parking or landscaping.

A main motivation for using calming remedies is creating safer streets. The benefits outweigh the costs. According to the National Safety Council, a car accident with an incapacitating injury costs the private and public sectors (medical care, loss of productivity, etc.) about $208,500. The direct and societal costs run over $4 million for each traffic death. In 2013, a motor vehicle injury occurred on average every 14 seconds according to the Rocky Mountain Insurance Information Association. Given these events and costs, an investment in traffic calming can be recovered almost immediately.

When it comes to using pavements to slow drivers, the options are limited: speed humps or the really annoying speed bumps. A forgotten form of relaxation is changing the surface to interlocking concrete pavement. A surface change means a visual and noise change that’s kinesthetically communicated to the driver via the steering wheel. Unfortunately, ICP doesn’t show up regularly in classic traffic-calming references published by the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or the Institute for Traffic Engineers. Why? No experience and no hard before-and-after data.

So let’s start collecting data. The industry seeks a current condition where vehicular and pedestrian traffic conflict is a documented problem as measured by vehicle/pedestrian counts, near-miss reports, accidents and other incidents. For example, we are seeking conditions near schools where traffic calming is essential. We’d like to monitor before and after results via surveys and/or speed/traffic counters. We are seeking a partnership where other stakeholders participate with us financially as well as in the planning, execution and monitoring stages. Potential opportunities include school districts, police/fire/rescue stations, busy residential streets, libraries, parks, business districts and complete street projects. If there is traffic that needs calming, drivers that need to relax and slow down to spare injuries and deaths, we just might have a relaxing solution.

CONTACT US
Interested in a partnership to make roads safer?
Email icpi@icpi.org.

No rat race here: Traffic calming in Delbrück, Germany (called ‘traffic relaxing’ there) extends front yards into the street and narrows it while using pavers to slow drivers.
Resetting the Bar

ASCE UPDATES AND RELEASES DESIGN STANDARD FOR INTERLOCKING CONCRETE PAVEMENTS

The Transportation & Development Institute (T&D) of the American Society of Civil Engineers (ASCE) recently updated and released ASCE 58-16 Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways. According to the ASCE, “The standard provides preparatory information for design, key design elements, design tables for pavement equivalent (to asphalt) structural design, construction considerations, applicable standards, definitions, and best practices.” This new version, which replaces Standard ASCE/T&D/ICPI 58-10, includes updated references to quoted ASTM standards, clarification of subgrade type and drainage characteristics, and the addition of new green infrastructure rating systems. The 42-page design guide provides tables for base thickness using aggregate, asphalt-treated, cement-treated and asphalt bases under interlocking concrete paving units that conform to ASTM C936. The book provides thicknesses for various soil subgrade conditions under traffic up to 45 mph and exerting no more than 10 million lifetime 18,000 lb (80 kN) equivalent single axle loads or ESALs. Transportation engineers, road designers, planners, pavement manufacturers and municipal officials can rely on this comprehensive guide to interlocking concrete pavements.

Dave Hein, P.Eng., Vice President of T&D and chairman of the technical committee that created and updated the standard, notes that, “ASCE 58-16 continues to provide municipal and consulting engineers with this tool to design and implement interlocking concrete pavements in streets, alleys and parking lots. When properly designed and constructed, these pavements can be more cost-effective over their life than conventional asphalt and concrete. And besides, pavers upgrade the appearance of any street.” WHERE TO BUY Purchase the updated standard at www.asce.org/booksandjournals. The price is $60 for ASCE members and $80 for non-members.

Clarify and Confirm

INDUSTRY DEVELOPING A SECOND ASTM PAVING SLAB STANDARD

Last summer, ASTM approved C1782 Standard Specification for Utility Segmental Concrete Paving Slabs. Needed for decades, the industry now provides a baseline product standard for segmental concrete paving units from 12 x 12 up to 48 x 48 in. (300 x 300 up to 1,200 x 1,200 mm). ASTM C1782, however, was written for paving units that do not require close dimensional tolerances. Such tolerances noted in Table 1 at right are from that standard.

### TABLE 1. DIMENSIONAL TOLERANCES IN ASTM C1782

<table>
<thead>
<tr>
<th>Length and Width, in. [mm]</th>
<th>Thickness, in. [mm]</th>
<th>Concave or Convex Warpage in One Dimension, in. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units up to and including 24 in. [610 mm]:</td>
<td>±0.04 [1.0] and +0.08 [2.0]</td>
<td>±0.12 [3.0]</td>
</tr>
<tr>
<td>Units over 24 in. [610 mm]:</td>
<td>±0.06 [1.5] and +0.12 [3.0]</td>
<td>±0.12 [3.0]</td>
</tr>
<tr>
<td>Up to and including 17.75 in. [450 mm]:</td>
<td>±0.08 [2.0]</td>
<td></td>
</tr>
<tr>
<td>Over 17.75 in. [450 mm]:</td>
<td>±0.12 [3.0]</td>
<td></td>
</tr>
</tbody>
</table>
Utility paving slabs often have architectural finishes and are used in residential and some commercial applications for at-grade and roof ballast applications. Architectural finishes include (but are not limited to) blasted, hammered, tumbled, textured and polished surfaces. The Interlocking Concrete Pavement Institute is proposing a second ASTM standard for slabs with closer (tighter) dimensional tolerances. Like products conforming to C1782, products conforming to the proposed standard typically have architectural finishes. However, the main difference between C1782 and the proposed new standard is that the latter has closer dimensional tolerances required for pedestal-set roof applications, as well as for at-grade bitumen-set and some sand-set applications. The new proposed standard formalizes these dimensional tolerances used with architectural paving units for these applications for over 20 years. This proposed new standard below is very similar to ASTM C1782 except for the closer dimensional tolerances shown in Table 2.

Rather than provide optional closer dimensional tolerances within C1782, a new standard is being proposed that differentiates itself from C1782 with higher dimensional tolerances for architectural paving slabs. Also, two distinct paving slab standards (standard and architectural grade) can help reduce confusion between these two groups of paving products among specifiers, contractors, and other users. Freeze-thaw durability and flexural strength requirements are proposed to remain the same as those in C1782. Acceptance of this new standard is anticipated in 2018, but this depends on the outcome of voting by ASTM members.

TABLE 2. TIGHTER DIMENSIONAL TOLERANCES PROPOSED FOR ARCHITECTURAL PAVING SLABS

<table>
<thead>
<tr>
<th>Length and Width, in. [mm]</th>
<th>Thickness, in. [mm]</th>
<th>Concave or Convex Warpage in One Dimension, in. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units up to and including 24 in. [610 mm]:</td>
<td>Up to and including 17.75 in. [450 mm]:</td>
<td>±0.04 [1.0] and ±0.06 [1.5] ±0.04 [1.0]</td>
</tr>
<tr>
<td>–0.04 [1.0] and +0.04 [1.0]</td>
<td>±0.06 [1.5]</td>
<td>±0.04 [1.0]</td>
</tr>
<tr>
<td>Units over 24 in. [610 mm]</td>
<td>Over 17.75 in. [450 mm]:</td>
<td>±0.08 [2.0]</td>
</tr>
<tr>
<td>–0.06 [1.5] and +0.06 [1.5]</td>
<td>±0.06 [1.5]</td>
<td>±0.08 [2.0]</td>
</tr>
</tbody>
</table>

FOLLOW DEVELOPMENTS
For the latest news and information about the interlocking concrete pavement industry, visit icpi.org.
CROSS SECTION:
— Machine-installed permeable pavers
— 2 in. No. 89 stone
— 4 in. No. 57 stone, open-graded base
— 2 to 4 ft. No. 4 stone, open-graded subbase

THE SOUTHEAST ATLANTA GREEN INFRASTRUCTURE INITIATIVE COMPLETES LARGEST PERMEABLE PAVER ROADWAY PROJECT IN NORTH AMERICA

In July 2012, a series of storms caused combined sanitary and storm sewer overflows in parts of southeast Atlanta, flooding homes and streets. After visiting the flood-prone neighborhoods, Mayor Kasim Reed committed to finding a long-term solution. Thus began the Southeast Atlanta Green Infrastructure Initiative, which led to the largest permeable interlocking concrete roadway project in North America, more than four miles.

Crews maintained an average pace of 5,000 sf per day with machine installation.
The flooding occurred at the nexus of piped natural drainage systems that transfer much of the runoff from downtown Atlanta, a highly impervious area, to Peoplestown, Mechanicsville and Summerhill. Located at a natural drainage point of a 1,500-acre watershed, these downstream neighborhoods finally found relief from the city’s unconventional intervention.

**IMMEDIATE RESPONSE**

With a mandate from the mayor’s office to solve flooding problems, the Department of Watershed Management rose to the challenge. “We went out into the field with our contractors to do assessments and came back with several projects that could be completed quickly to start providing immediate capacity relief,” said Todd Hill, Director of Environmental Management for the Department of Watershed Management. “We developed a phased approach.”

The bottom line, comprehensive solution meant managing about 24 million gallons of runoff. Phase one, a 30-day immediate response, began with cleaning up all inlets, raising curbs and installing bioswales and rain gardens on city property. These efforts resulted in 350,000 gallons of capacity relief. “Not a lot, but a start,” Mr. Hill said.

Phase two involved constructing a 5.8 million gallon combined sewer storage vault underneath a parking lot at Turner Field during the Atlanta Braves’ four-month offseason. In March 2015, work began on the permeable interlocking concrete roadway renovations that took nearly a year and a half to complete.

Phase three is currently in development and will mitigate eight million gallons through the construction of a combined sewer vault, capacity relief ponds and a community park to be constructed in Peoplestown on the lots that saw some of the worst flooding in 2012. The city is working with homeowners to acquire these properties at fair market value plus an additional percentage to compensate for relocation.

**BIGGEST BANG FOR THE BUCK**

At the outset of planning their roadway renovations, Mr. Hill and his team asked, “What will get us the biggest bang for our buck?” Considering permeable interlocking concrete pavement they agreed, “If we’re going to do a paver project, we want to have the greatest impact possible,” Mr. Hill said. Looking back, the aggregate capacity relief storage provided by the paver system was less expensive than the water storage vaults.

With a budget of $15.8 million that initially included $1.1 million in allowances for restoring utility lines, the Department of Watershed Management began excavation and installation of permeable interlocking concrete pavers on the first of many streets upstream from the flood-prone areas. The goal was to use permeable pavers and the water storage capacity of deep aggregate reservoirs beneath them to provide downpipe capacity relief. “We picked residential streets that contributed to the flooding of our combined sewer system,” said Mr. Hill. Collectively, the four miles of permeable paver roads provided four million gallons of capacity relief.

Though the original plan had six miles of roadways slated to receive permeable pavers, once crews started peeling back the streets, they unearthed some unforeseen and unfortunate complications. On some of the larger stretches of roads, crews uncovered old streetcar lines alongside utility lines encased in two feet of concrete. “The timeline to even do a few feet at a time was going to be so outrageous that it...
HOW URBANIZATION CAUSES FLOODING

LOW DENSITY RESIDENTIAL (RURAL)
10–20% Impervious Surface

- 38% Evapotranspiration
- 20% Runoff
- 42% Infiltration

Medium Density Residential (Subdivision)
30–50% Impervious Surface

- 35% Evapotranspiration
- 30% Runoff
- 35% Infiltration

High Density Residential/Industrial/Commercial
75–100% Impervious Surface

- 30% Evapotranspiration
- 55% Runoff
- 15% Infiltration

During excavation, crews discovered utilities that “shouldn’t have been there” and at different depths than plans indicated.

would blow our schedule, increase cost and make it impossible for residents to access their homes, so we had to make a decision to eliminate that portion,” Mr. Hill said.

According to Mr. Hill, their desire was to place as many concrete pavers as possible and not deplete the budget on extra labor costs. This pragmatic approach was applied throughout the construction phase and brought the project to completion on time and under budget. But there were still many challenges that had to be overcome during the construction phase.

WHAT LIES BENEATH

With some street sections nearly 100 years old, the first surprise encountered by construction crews was a layer of old concrete below the asphalt roads that required additional time to remove. Once the roadways were opened up, a new set of challenges emerged. “We had utilities showing up that shouldn’t have been there, and some at depths that weren’t shown on any plans,” Mr. Hill said. Brick manholes were especially difficult to work around and many were replaced. Water mains and old pipes ruptured during excavation and required repair. Of the $1.1 million originally earmarked to address utilities, adjustments brought the total closer to $3 million by project completion.

Another main concern during construction dealt with the close proximity of older homes along some streets. Crews excavated two to four feet for the permeable pavement aggregate subbase layer and installed impermeable liners along the sidewalks to prevent lateral migration of stormwater toward these homes and their basements.

Due to their layout and age, street widths varied as much as a foot from one block to the next, adding a substantial amount of cutting time for the edge pavers. Despite this challenge, machine installation maintained an average rate of about 5,000 sf per day with no time required for concrete to cure.

Managing road closures and rerouting traffic, including public transit buses, also posed a significant challenge. “During the construction phase, there was a bit of inconvenience, to put it mildly,” said Cameo Garrett, External Communications Manager for the Department of Watershed Management. “It was very important that, as things

Continued on page 10
CHECK DAM CROSS SECTION

PHASES OF DEVELOPMENT

PHASE ONE (0.34 MG)
- Catch basin and inlet cleaning
- Raise curbs
- Green infrastructure projects: bioswales, rain gardens, revegetation

PHASE TWO (13 MG)
- Turner Field media lot CSS storage vault
- Permeable interlocking concrete paver roads

PHASE THREE (9.65 – 10.85+ MG)
- Connally Trunks CSS storage vaults
- Capacity relief projects and ponds

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Since most streets are on sloped terrain, check dams made of perforated impermeable liners slow flowing water and allow some of it to infiltrate into the soil subgrade.
changed during construction, we continuously provided information and updates to the affected communities.”

The original construction time estimates anticipated residents would lose access to their driveways for only a few days. But with all the utility issues encountered, the average road closures stretched to one and a half weeks. “Community outreach and engagement really needs to be taken into account,” said Cory Rayburn, Construction Project Manager for the Department of Watershed Management. “It’s very important for the contractor to have a public information officer onsite at all times during construction. We wrote that into our contract documents, and that’s something we recommend on all future projects.”

SUCCESSFUL RESULTS

“Permeable pavers are a very good solution for stormwater management, especially in highly urban areas with combined sewers that need capacity relief,” Mr. Hill said. “We have been surprised by and pleased with the amount of infiltration into the ground. We were estimating much less.” Many of the sloped streets included check dam systems to encourage infiltration. The paver streets store runoff from a four-hour, 25-year storm yielding 3.68 inches of rainfall.

While achieving capacity relief was the main goal accomplished by this project, the decision to use permeable interlocking concrete pavement also contributed to increased property values for some communities and led to new development investments. “We know the houses that are on the...
Permeable pavers are a very good solution for stormwater management, especially in highly urban areas with combined sewers that need capacity relief."
—Todd Hill, Director of Environmental Management, Department of Watershed Management, City of Atlanta

```
COLORIST
- BLENDING OF UP TO 6 COLOURS
- MODULAR DESIGN ALLOWS INTEGRATION TO ANY PAVER/BLOCK MACHINE
- SYSTEM IS EQUIPPED WITH OWN CONTROL UNIT TO ALLOW AN EASY IMPLEMENTATION OF A SIMPLE SIGNAL HAND SHAKE
- NO REPROGRAMMING OF EXISTING PAVER/BLOCK MACHINE PLC NECESSARY
- HIGH REPRODUCIBILITY OF A ONCE DEFINED BLEND
- BLENDING PARAMETERS CAN BE STORED IN A RECIPE FUNCTION
```

Homes along paver streets are more sought after than those on surrounding neighborhood streets.
Permeable paver streets are more sought after than on other streets in these neighborhoods," Mr. Hill said. "The residents who live in those areas really love the pavers and think they're very beautiful," Ms. Garrett said.

“We have councilmembers pleased, and other councilmembers asking if they can have pavers in their districts," Mr. Hill said. And the project has drawn not only the attention of some jealous neighbors, but national attention as well. The Department has received calls from other cities including Philadelphia, Washington D.C., San Francisco and Portland, Oregon, and has presented the project at numerous industry conferences throughout the country.

AN OUNCE OF PREVENTION IS WORTH A POUND OF CURE

The Atlanta Department of Watershed Management is now focusing efforts on educating contractors who will be working on or around their permeable pavement to prevent damage before it occurs. Nonetheless, some accidents happen from uninformed workers. In one instance, a concrete truck was washed out while parked on a permeable paver street. The runoff clogged the paver joints as well as the aggregate subbase, resulting in a $6,000 repair bill. In other instances, construction sites adjacent to the permeable paver roads needed to carefully manage sediment so it didn’t run into the street.

"It's going to take education to ensure that anyone digging into these paver roadways has either gone through training or read the maintenance manual," Mr. Rayburn said. So far, the Department has held an in-depth ‘Train the Trainer’ course for Watershed and Public Works employees based on the maintenance manual that was developed by the contractor, and will follow up with additional guidance and resources. "As of now, the protocol is to call our construction inspectors, the ones who were onsite during the paver installations, to monitor any tie-in construction involving water or sewer lines," Mr. Rayburn said.

The city has a three-year contract with the project’s design-build contractor to provide service and maintenance for the permeable paver streets. “But after that, we will need a coordinated effort to help ensure the permeable paver streets are maintained,” Mr. Rayburn said.

REFLECTIONS IN HINDSIGHT

For any municipality contemplating permeable interlocking concrete pavement streets, Mr. Hill advises, “Spend a lot of time planning the process, thoroughly locate all utilities and determine if they will need rehab in the near future. Particularly with older urban streets, there may be layers upon layers of unknown mysteries beneath the surface. “Have a full-blown SUE [Subsurface Utility Exploration] performed for every road to identify some of the harder-to-locate utilities before you actually start work,” Mr. Rayburn said. The SUE helps the design-builder come up with a more comprehensive design prior to excavation or construction, saving time and minimizing surprises.

"We are very grateful that our administration was so farsighted with regard to sustainability and making this a very green city," Mr. Hill said. "They provided the necessary support to make these things happen."

“Green Infrastructure and Low Impact Development practices are not new. However, the regional application by municipalities to solve flooding and capacity relief is a developing industry,” Mr. Rayburn said. “The social
and economic development that can occur when these practices are done right is definitely an added benefit."

In Atlanta’s case, the green infrastructure initiative has had a direct impact on new investment. "The Historic Fourth Ward stormwater pond adjacent to the Atlanta Beltline created a miniature ecosystem within the heart of Atlanta which reconnected surrounding residents to nature. The main function of the facility is combined sewer capacity relief, but we have seen over $500 million in private redevelopment in the surrounding area," Mr. Rayburn said.

"We always look for opportunities to utilize green infrastructure where our historical response would have been a bigger pipe or vault," Mr. Rayburn said. "That way, you can solve the problem while creating a real benefit for the community."

GOING GREEN
For more information on Atlanta’s green infrastructure initiatives, visit www.AtlantaWatershed.org/GreenInfrastructure.

PROJECT CREDITS:
30% Design: City of Atlanta Engineering Services Division led by Nolton Johnson
Design-Build Contractor: Southeastern Site Development and CNG Concrete Construction, Joint Venture
Final Design: AMEC Foster Wheeler, James L. Studer
Subcontractor: Four Seasons Landscape Management, Inc.
Manufacturer: Belgard

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The differences between pavers and slabs aren’t just about size. When it comes to vehicular loads, thickness really matters.

Now passing 100 million sf sold in 2015, paving slabs are seeing increasing use in residential and commercial applications.
Project owners and designers specify segmental concrete paving slabs due to their unique visual appeal and finishes. Their large format often fits a particular dimensional module for the design of the project, complements the architectural character of adjacent buildings, or enhances the landscape architecture of the site. Some designers understake segmental pavement patterns by using paving slabs with fewer joints. In other situations, designers may mix smaller and larger slab units to create strong visual effects. While most applications are for at-grade or roof deck pedestrian uses, paving slabs are seeing increased use in areas with vehicular traffic. ICPI is engaged in field-testing research to assess the performance of slabs under vehicular loads (see page 20).

When properly designed and constructed, paving slabs can withstand a limited amount of automobile and truck traffic. Unlike interlocking concrete pavements, slabs offer little to no vertical, horizontal or rotational interlock. Each unit bears applied loads and does not transfer applied loads to neighboring ones. Hence, their application to areas with limited vehicular traffic.

The load-carrying capacity of paving slabs and interlocking concrete pavements is put into perspective by reading ICPI Tech Spec 4 Structural Design of Interlocking Concrete Pavements and ASCE 58-16 Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways. Both publications provide base thickness tables for pavements receiving up to 10 million 18,000 lb (80 kN) equivalent single axle loads or ESALs. Now underway, an emerging ICPI Tech Spec on structural design of paving slabs provides designs for up to 75,000 ESALs. This suggests that the structural capacity of paving slabs is less than 1% of that offered by interlocking concrete pavement. This further suggests that paving slabs should be exposed to limited vehicular traffic, and very few trucks per day.

Paving slabs are sometimes mistakenly called pavers. This misnomer has led to applying slabs under inappropriate vehicular applications in a few instances. To reduce confusion, the segmental concrete pavement industry is following other countries where product nomenclature and product standards specifically differentiate pavers from slabs. Figure 2 illustrates the difference.

A practical construction-related difference between concrete pavers and paving slabs is the former generally requires one hand to install a unit and the latter requires at least two hands to lift and place. In reality, most slab installations use clamps or vacuum equipment shown in Figure 3. Most commercial slab applications subject to trucks will be installed on a concrete base. Asphalt is generally not used as a base because it can’t be easily formed into an even surface.

**PRODUCT STANDARDS**

In the U.S., ASTM C1782 Standard Specification for Utility Segmental Concrete Paving Slabs defines them as having an exposed face area greater than 101 in.² (0.065 m²) and a length...
Paving slabs are sometimes mistakenly called pavers. This misnomer has led to applying slabs under inappropriate vehicular applications in a few instances.
In the CSA test, the top of the paving slab is enclosed with a leak-proof compartment and the interior receives a 3% saline solution. See Figure 4. After completing 28 freeze-thaw cycles, the paving slabs pass the CSA requirement if the surface yields no more than an average loss of 300 grams per square meter of the inundated surface area or 500 grams lost for specimens with an architectural finish.

Continued on page 18
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An architectural finish is wearing surface amended with face mix, ground (polished) or shot blasted treatments, formed (to look like stone per Figure 5), hammered and/or flame-treated to provide a more stone-like appearance. If the architectural paving units do not meet the mass lost requirement at 28 cycles, the freeze-thaw cycles continue until 49 cycles are completed. The paving slabs meet the durability requirements in CSA A231.1 when the average loss after 49 cycles does not exceed 800 grams per square meter or 1,200 grams for units with an architectural finish. The lowest temperature in this test method is more severe than C1782, i.e., 5° F or -15° C.

Dimensional tolerances are similar in ASTM and CSA paving slab standards. Dimensional tolerances are determined from unit dimensions provided by the manufacturer for specific products. Tolerances for length, width and height and for convex and concave warpage are as follows:

- Length and width: -0.04 and +0.08 in. (-1.0 and +2.0 mm)
- For units over 24 in. (610 mm), ASTM C1782 allows -0.06 and +0.12 in. (-1.5 and +3 mm)
- Height: ±0.12 in (±3.0 mm)
- Concave/convex warpage for units up to and including 18 in. (450 mm) in length or width: ±2.0 mm; units over 18 in. (450 mm): ±3.0 mm

Paving slabs meeting these dimensional tolerances are loosely laid, or can be installed on a sand setting bed (i.e., sand-set) if tolerances are consistent. However, these tolerances are generally not suitable for precision sand-set, bitumen-set or pedestal-set (typically roof) applications. These installation methods require length, width, thickness and warpage tolerances not exceeding 0.06 in. (1.5 mm) than the specified dimensions. In some cases, paving units may require post-production grinding to achieve these tolerances. This treatment is sometimes called gauging. For additional information of bitumen-set applications, read ICPI Tech Spec 20 - Construction of Bituminous-Sand Set Interlocking Concrete Pavement.

Soon to move through the ASTM balloting process is a second paving slab standard. This one is called Standard Specification for Architectural Segmental Concrete Paving Units. The draft has flexural strength and freeze-thaw de-icer durability requirements identical to C1272. This new standard, however, has much closer dimensional tolerances not exceeding 0.06 in. (1.5 mm), making the units suitable for tightly-fitted sand-set applications, bitumen-set applications, and roof installations supported by pedestals. When this product standard is eventually approved by ASTM, there will be two paving slab product standards; one for mostly residential applications and selected commercial applications, and almost exclusively for high-end commercial applications.
A SNEAK PEEK AT PAVING SLAB STRUCTURAL DESIGN

Thanks to a grant from the ICPI Foundation for Education and Research, design tables were developed earlier this year that provide technically conservative base solutions for paving slabs subject to vehicles. The tables were developed using finite element modeling that simulated pressures from truck tires on paving slabs of various sizes and flexural strengths. The modeling included a 1-inch (25 mm) thick sand bed under the slabs, three base materials, and three soil subgrade conditions. This article previews the design approach for pedestrian and vehicular applications derived from that modeling.

**TABLE 1. TRAFFIC CATEGORIES AND LIMITS**

<table>
<thead>
<tr>
<th>Traffic Limits</th>
<th>Category Symbol</th>
<th>20 yr ESALs (TI)</th>
<th>Equivalent Heavy Vehicles/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do Not Subject to Vehicles</td>
<td>No</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Primarily Pedestrian</td>
<td>P</td>
<td>1,000 (4)</td>
<td>0.1</td>
</tr>
<tr>
<td>Cars only (&lt; 4,500 lbs or 2,000 kg)</td>
<td>LT</td>
<td>30,000 (6)</td>
<td>2.0</td>
</tr>
<tr>
<td>Cars and Occasional Heavy Vehicles (&gt;10,000 lb or 4,500 kg)</td>
<td>OHV</td>
<td>75,000 (6.6)</td>
<td>5.0</td>
</tr>
</tbody>
</table>

For pedestrian applications, 12 x 12 in. (300 x 300 mm) units can be placed on a minimum 6 in. (150 mm) thickness of compacted aggregate base. Thicker bases (generally 8 to 12 in. or 200 to 300 mm thick) should be used in freezing climates and/or on weak clay soils (CBR < 3%). Designers should consider using a lean concrete or concrete base for larger paving units because achieving a very smooth base surface can be difficult with compacted aggregate base.

Design options become a bit more complex for vehicular applications. The first step is determining the maximum number of lifetime 18,000 lb equivalent single axle load or ESAL repetitions. (Caltrans Traffic Indexes are provided in parentheses.) Determining ESALs or TIs can be done using Table 1. It divides them into five categories. Higher ESAL categories generally require thicker units and concrete bases. Applications exceeding 75,000 lifetime ESALs should use interlocking concrete pavers.
The next step is determining the soil strength. The minimum values for designs is a resilient modulus of 5,100 psi (35 MPa), 3% California Bearing Ratio, or an R-value = 7. The maximum values are 11,600 psi (80 MPa), 10% and 18, respectively. Soils with higher values use the latter set for determining the unit size and thickness. After laboratory tests determine the soil strength, that points to specific slab sizes and bases that will work given the anticipated design ESALs in Table 2. Square paving units are recommended over rectangular ones for vehicular traffic with placement in a running bond pattern.

The ICPI design method offers three base options described below in ascending order of supporting stiffness. Construction should include compacting the soil subgrade and bases/subbases to at least 95% of standard Proctor density per ASTM D698 Standard Test Methods for Laboratory Compaction of Soil Standard Effort.

(a) A 12 in. (300 mm) thick compacted aggregate base with gradation conforming to provincial, state or municipal specifications for road base used under asphalt pavement. If there are no guidelines, use the gradations in ASTM D2940 Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports and as described in ICPI Tech Spec 2 Construction of Interlocking Concrete Pavements.

(b) A 4 in. (100 mm) thick lean concrete base over a 6 in. (150 mm) thick compacted aggregate base. The lean concrete should have a minimum 725 psi (5 MPa) compressive strength after 7 days per ASTM D1633 Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. Lean concrete is typically a lower strength concrete or a cement-treated base of similar stiffness and strength where an aggregate base is charged with cement (typically 3% to 6% by weight) to bind the aggregates when the cement cures.

(c) A 4 in. (100 mm) thick concrete base over a 6 in. (150 mm) compacted aggregate base. The concrete should have a minimum compressive strength is 3,000 psi (20 MPa) per ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

Table 2 presents a sample of the design tables using a concrete base. The designer finds the paving slab length and width that corresponds to the soil subgrade strength and slab flexural strength. Paving slab length and widths start at 12 x 12 in. and go up to 48 x 48 in. As an illustrative example, Table 2 only goes to 24 in. slabs and not up to 48 in. due to space limitations. Slab thicknesses are 2, 3, 4 and 5 in. If the exact paving slab length and width are not on the table, slabs can take a modest amount of trucks but using thicker units. The ICPI guide tells designers and contractors how thick.
table, the designer finds the closest size paving slab, using a smaller and/or thicker unit as a conservative design measure. The design tables cover square and rectangular slabs only.

An example follows on how a design table works. The highlighted 24 x 24 x 3 in. thick slab is selected by the designer. This will be a concrete base and aggregate subbase over a 5% CBR subgrade with a minimum 750 psi flexural strength for the slabs. The intersection of the highlighted horizontal and vertical columns is marked OHV which means the maximum lifetime load is 75,000 ESALs per Table 1. If the designer wants to use a 24 x 24 x 3 in. slab on a weaker soil subgrade, then the maximum allowed ESALs would be 30,000.

Designs using a concrete base include a 1 in. (25 mm) thick sand setting bed under the slabs. This design solution also applies to paving slabs in a bitumen-sand bed (typically 1 in. or 25 mm thick) since bitumen-set applications require a concrete base. This introduces an additional measure of conservative design since bitumen-sand materials provide a modest increase in stiffness and increased stability resisting repeated turning, accelerating, and braking tire lateral loads.

This article was intended to sample how structural design is done with paving slabs. Similar, additional design tables have been developed for planks and an ICPI Tech Spec is expected later in 2017. As partial validation, the ICPI Foundation for Education and Research is funding the construction of a full-scale load testing area at a paver manufacturing facility in Maryland. The area will receive trucks loaded with paving products where each truck pass will exert several ESALs. The condition of the slabs and planks set on aggregate and concrete bases will be monitored to see how quickly or slowly the slabs will crack, as that defines failure. The testing will likely begin in spring 2017 and run for a few years.

### TABLE 2. DESIGN TABLE FOR 18 X 18 X 3 IN. PAVING SLABS ON A CONCRETE BASE

<table>
<thead>
<tr>
<th>Paving Slab Length in. (mm)</th>
<th>Paving Slab Width in. (mm)</th>
<th>Paving Slab Thickness in. (mm)</th>
<th>Subgrade Modulus, PSI (MPa, CBR, R-Value)</th>
<th>Paving Slab Minimum Flexural Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 (300)</td>
<td>12 (300)</td>
<td>2 (50)</td>
<td>5,100 (35) 3%, 7</td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>12 (300)</td>
<td>12 (300)</td>
<td>3 (75)</td>
<td>7,200 (50) 5%, 10</td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>12 (300)</td>
<td>12 (300)</td>
<td>4 (100)</td>
<td>8,700 (60) 6.8%, 13</td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>16 (400)</td>
<td>16 (400)</td>
<td>2 (50)</td>
<td>11,600 (80) 10%, 18</td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>16 (400)</td>
<td>16 (400)</td>
<td>3 (75)</td>
<td></td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>16 (400)</td>
<td>16 (400)</td>
<td>4 (100)</td>
<td></td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>18 (450)</td>
<td>12 (300)</td>
<td>2 (50)</td>
<td></td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>18 (450)</td>
<td>12 (300)</td>
<td>3 (75)</td>
<td></td>
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<td>18 (450)</td>
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<td>18 (450)</td>
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<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
<tr>
<td>18 (450)</td>
<td>18 (450)</td>
<td>4 (100)</td>
<td></td>
<td>LT OHV OHV OHV OHV OHV OHV OHV OHV</td>
</tr>
</tbody>
</table>
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