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Determination of Mechanical Properties for Cement-Treated Aggregate Base

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The field construction of CTA was monitored, and samples were collected for laboratory determination of the compressive strength, modulus of elasticity, and modulus of rupture. Tests with the falling weight deflectometer were conducted to back-calculate the CTA modulus of elasticity, and field cores were collected for testing compressive strength and modulus of elasticity. CTA gained strength with increases in cement content, and the increase in strength and the strength level depended on the aggregate properties, such as the resilient modulus of unbound aggregate. All measured properties were highly variable.

VDOT would need to implement a strength-based CTA design to be able to use the required mechanical properties of CTA in the MEPDG system. The study recommends using a target design 7-day compressive strength of 600 to 800 psi. Such strength corresponds well with VDOT's current pavement design practice in accordance with the 1993 AASHTO design guide. CTA mechanical properties were suggested based on this target strength. Most of the default values presented in the MEPDG are considered reasonable. In addition, the values recommended for use in the MEPDG are 1.5 million psi for modulus of elasticity and 200 psi for modulus of rupture.

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FINAL REPORT

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ABSTRACT

The Virginia Department of Transportation (VDOT) currently follows pavement design procedures for all new and rehabilitated pavements based on the 1993 *AASHTO Guide for Design of Pavement Structures*. VDOT's Materials Division is in the process of implementing the Mechanistic-Empirical Pavement Design Guide (MEPDG) procedure via AASHTOWare Pavement ME Design software. The MEPDG uses mechanical properties of pavement materials for pavement structural design. The mechanistic-empirical design process presents a major change in pavement design from the 1993 AASHTO design guide. It calculates pavement responses through mechanistic analysis based on inputs such as traffic, climate, and materials properties to predict the pavement damage or distress over time for both asphalt and concrete pavements. The purpose of this study was to evaluate the mechanical properties of cement-treated aggregate (CTA) and recommend values for use in AASHTOWare Pavement ME Design software.

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INTRODUCTION

Cement treatment of an aggregate base layer is an enhancement to the road foundation support when poor subgrade conditions are encountered. This treated layer usually provides a good working platform for subsequent construction as well as adequate structural support for the pavement structure. Although in-place amendment is possible, the Virginia Department of Transportation (VDOT) follows common practice, which is to use a central-mix plant and haul cement-treated aggregate (CTA) material to the site. CTA could be used in both flexible and rigid pavement structures. CTA consists primarily of base aggregate mixed with a specified percentage of hydraulic cement by weight and field compacted at moisture contents that are slightly greater than the optimum moisture content. Currently, VDOT specifies the preparation of CTA as Aggregate Base Material, Type I, Size No. 21A or 21B pug-mill mixed with 4% hydraulic cement by weight. In addition, Type I is to consist of crushed stone, crushed slag, or crushed gravel, with or without soil mortar or other admixtures.

VDOT currently uses the American Association of State Highway and Transportation Officials (AASHTO) *AASHTO Guide for Design of Pavement Structures* (AASHTO, 1993), hereafter referred to as the 1993 AASHTO design guide. The guide uses structural layer coefficients (empirical values) for CTA as well as other materials present in different layers for the design of pavement structure. VDOT's Materials Division is in the process of implementing (scheduled for January 2018) the procedures outlined in the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) (AASHTO 2015) using AASHTOWare Pavement ME Design software (hereinafter Pavement ME Design) that uses mechanical properties of pavement materials for pavement structural design. The purpose of this study was to establish appropriate pavement design input parameters for statewide use in the MEPDG for CTA base and to develop of a mix design process that considers strength.

Relevant literature shows that the field performance of CTA is variable, and poor performance is often attributed to a variety of factors including fines content, aggregate mineralogy, and chemical deterioration of the cement matrix and variability in construction, cement content, etc. Scullion and Harris (1998) conducted forensic evaluations of three failed cement-treated bases in pavements. They found that the failures of the three sections were related to problems with materials selection, quality control, and pavement design and determined the primary cause to be chemical deterioration that resulted in destruction of the cement matrix. Lim and Zollinger (1998) conducted an experimental study on the development of strength and the modulus of elasticity of CTA base materials and found that for a given aggregate type, the development is mostly governed by the applied cement content. Other mixing variables, such as coarse and fine aggregate contents, compound each other, and their overall effect is less significant compared to the effect of cement content. Burns and Tillman (2006) found that the mineralogy of the base aggregate made a difference in the strength of the CTA. The provision of diabase aggregate showed the highest unconfined compressive strength followed by limestone and mica aggregates. The authors found variable results when granite aggregates were used, but the strengths were generally on the order of those obtained for the diabase aggregate.

VDOT's field evaluations and experience have shown a wide variability of CTA quality in terms of compressive strength. CTA cores from a continuously reinforced concrete pavement (CRCP) project on I-64 at Battlefield Boulevard in Chesapeake, Virginia (constructed in 2008), showed compressive strength values from 1,290 to 2,060 psi. It is important to note that recycled concrete aggregate was used on this project. In another section on U.S. 58 in Southampton, Virginia, 20-year-old CTA was cored and tested for compressive strength, which varied from 890 to 3,310 psi. Historically, there have been reports from VDOT field personnel that some CTA could not be cored intact. It seems obvious that a design method with a strength requirement would be beneficial for producing uniform product.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the mechanical properties of CTA and recommend values for use in Pavement ME Design. In order to achieve this goal, a strength-based CTA design process had to be developed.

The objectives of the study were as follows:

1. Identify the mechanical properties of CTA needed for mechanistic design using Pavement ME Design.

2. Develop a mix design procedure based on strength requirements for CTA.

3. Identify methods or correlations to determine appropriate mechanical properties of CTA.

4. Suggest typical values of mechanical properties of CTA to be used in the MEPDG procedure.

METHODS

Overview

To achieve the study objectives, the following tasks were conducted:

1. Conduct a literature review to assess the state of the research and current findings with regard to CTA in addition to practices followed by VDOT and other highway agencies for specifying their mixture and design criteria.

2. Identify the mechanical properties of CTA needed in Pavement ME Design and the sensitivity of pavement performance (or design) to each property.

3. Monitor field construction of CTA projects, and collect samples for laboratory study of CTA properties.

4. Document the field construction of and lessons learned regarding CTA projects.

5. Conduct a laboratory study of CTA including sample preparation and testing for mechanical properties.

6. Assess the performance of CTA in existing pavement structure(s):

   — Conduct falling weight deflectometer (FWD) testing and back-calculate the modulus of elasticity.

   — Collect cores and measure compressive strength and variability.

7. Provide a recommendation for CTA mix design strength.

8. Provide a recommendation for specific values of the mechanical properties of CTA for use in MEPDG analysis.

Literature Review

The literature regarding CTA and its use in pavement structures was identified by use of the resources of the VDOT Research Library and the University of Virginia Library. Online databases that were searched included TRID, the Engineering Index (EI Compendix), Transport, and WorldCat, among others. In addition to a search of the websites of the select U.S. state departments of transportation (DOTs) for their specifications, a survey of the 50 state DOTs was conducted through e-mail communication with pavement engineers to determine DOT practices with regard to CTA use in pavements.

CTA in MEPDG Analysis

Mechanistic-empirical pavement design has incorporated use of a CTA layer into the analysis for pavement design. The mechanical properties of CTA are required to perform the analysis. The version of the analysis software that VDOT plans to implement, Pavement ME Design (Version 2.2), was considered during this study. In addition, a sensitivity analysis was performed for those properties to study their influence on the predicted distresses for typical flexible and rigid pavement structures.

In Pavement ME Design, CTA may be considered as a layer in both flexible and rigid pavements. When hot-mix asphalt (HMA) is placed over CTA, the pavement system is considered to be semi-rigid. Semi-rigid pavements were not included in the MEPDG's global calibration process. However, semi-rigid pavements were included in VDOT's local MEPDG calibration for flexible pavements (Smith and Nair, 2015). The modulus of elasticity, modulus of rupture, and density of the materials are the main required inputs to Pavement ME Design for CTA materials. The distresses predicted by Pavement ME Design for the anticipated climate and traffic conditions depend on the values of the input parameters that characterize pavement materials, as well as layer thicknesses and other design features.

Study of the sensitivity of predicted performance to the design inputs will help identify the inputs that have most influence on predicted performance by the MEPDG. Therefore, a series of sensitivity analyses was conducted for the input of different CTA properties into Pavement ME Design for representative pavement sections with the local calibration coefficients. The performance limits and other project input parameters in the sensitivity analyses were based on VDOT's *Pavement ME User Manual—Draft* (VDOT, 2017a). The pavement structures that were used for each of the design situations are shown in Table 1 for asphalt, CRCP, and jointed plain concrete pavement (JPCP) sections.

Table 1. Example Pavement Structure for Sensitivity Analysis

Asphalt Design	CRCP Design	JPCP Design
1.5 in SM-12.5E 2.0 in IM-19.0A 7.0 in BM-25A 6.0 in CTA Subgrade: A-6 *Traffic* Two-way AADTT: 3,250 *Climate:* Alexandria	9.0 in CRCP 2.0 in OGDL 6.0 in CTA Subgrade: A-7-6 *Design properties* Steel (%): 0.70 Bar diameter: 0.625in Steel depth: 3.5in Shoulder type: AC shoulder *Traffic* Two-way AADTT: 2,500 *Climate:* Newport News	9.0 in JPCP 2.0 in OGDL 6.0 in CTA Subgrade: A-7-5 *Design properties* Joint spacing: 15 ft Dowel diameter: 1.5 in Dowel spacing: 12 in Shoulder type: tied PCC Load transfer efficiency: 70% PCC-base contact friction: full *Traffic* Two-way AADTT: 2,500 *Climate:* Virtual: Alexandria, Virginia; Herndon, Virginia; Baltimore, Maryland

SM = surface mixture (asphalt); IM = intermediate mixture (asphalt); BM = base mixture (asphalt); CTA = cement-treated aggregate; AADTT = average annual daily truck traffic; CRCP = continuously reinforced concrete pavement; OGDL = open-graded drainage layer; AC = asphalt concrete; JPCP = jointed plain concrete pavement; PCC = portland (hydraulic) cement concrete. Width of the pavement = 12 ft.

Monitoring Field Construction

The site for evaluating CTA construction practices was selected from existing VDOT projects; no separate construction was planned for the evaluation of CTA. Only two projects in VDOT's Hampton Roads District were available for monitoring during construction:

1. *Middle Ground Boulevard in Newport News:* 6 in of CTA overlaid with 11in of HMA

2. *Nimmo Parkway in Virginia Beach:* 8 in of CTA overlaid with 8.5 in of HMA.

Middle Ground Boulevard Project

The Newport News site was located near Oyster Point Mall. The test site was on City Center Boulevard (formerly known as Middle Ground Boulevard) between Jefferson Avenue (Route 143) and Fishing Point Drive. Production and construction of the CTA layer were observed on December 19, 2013, at a location just across from the Newport News Professional Building. The CTA was produced at a nearby plant and hauled to the site. The facility contained aggregate bins, one cement storage silo, and a pugmill, as shown in Figure 1. The plant capacity was 250 tons/hour; a batch consists of 5 to 6 tons of CTA. VDOT 21A aggregate from a local quarry was mixed with 4% by weight cement in the pugmill for CTA production. Quality control testing for cement and moisture content in CTA was conducted at the plant by the producer. A titration test, as shown in Figure 2, was conducted to determine the cement content at the producer's laboratory.

Figure 1. CTA Plant for Middle Ground Boulevard Project: (a) VDOT 21A aggregate pile; (b) pugmill and haul truck; (c) pugmill gate closed; (d) gate open for loading truck. CTA = cement-treated aggregate.

Figure 2. Titration Test for Cement Content: (a) weighing CTA sample for testing; (b) adding ammonium chloride to sample; (c) transferring solution from sample for titration; (d) titration completed. CTA = cement-treated aggregate.

Haul time from the plant to the project was approximately 30 min. CTA was placed using a box spreader onto a subgrade material having a California bearing ratio of 20. The construction steps are shown in Figure 3. Initially, a CTA layer was placed to a thickness of around 9 to 10 in, and then it was compacted using a vibratory roller to a thickness of around 7 in. Density was measured after compaction and was recorded at about 98% to 99% of Proctor maximum dry density in accordance with Virginia Test Method 1 (VDOT, 2017b). The measured moisture was within 2% points above optimum moisture content. This CTA layer was then graded or bladed to the design thickness of 6 in and re-compacted.

Later, the CTA layer was overlaid with multiple layers of asphalt mixture to final grade: 3 in of open-graded drainage layer, 4 in of BM-25.0 (base asphalt mixture), 2 in of IM-19.0D (intermediate asphalt mixture), and 2 in of SM-9.5D (surface asphalt mixture).

Figure 3. Construction of CTA on Middle Ground Boulevard: (a) haul truck dumping to spreader; (b) blading with motor grader and back dump; (c) compaction with vibratory roller; (d) finished CTA surface. CTA = cement-treated aggregate.

During the site visit, CTA mixtures were collected at the plant from four haul trucks, and 6 × 12 in cylinders were prepared using a vibratory hammer as specified in ASTM C1435-08: Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer (ASTM International, 2013). Cement and moisture contents as measured in the plant laboratory by the producer for these four batches are shown in Table 2. Compaction of the sample using a vibratory hammer in the cylindrical mold is shown in Figure 4.

Table 2. Cement and Moisture Contents of CTA Samples

Batch	Cement (%)	Moisture (%)	Comments
1	4.4	7.37	Sample was sticking to vibratory hammer head.
2	4.6	5.93	
3	4.2	5.45	
4	3.6	5.23	
Target	4.0	5.4±2	Based on Proctor results.

CTA = cement-treated aggregate.

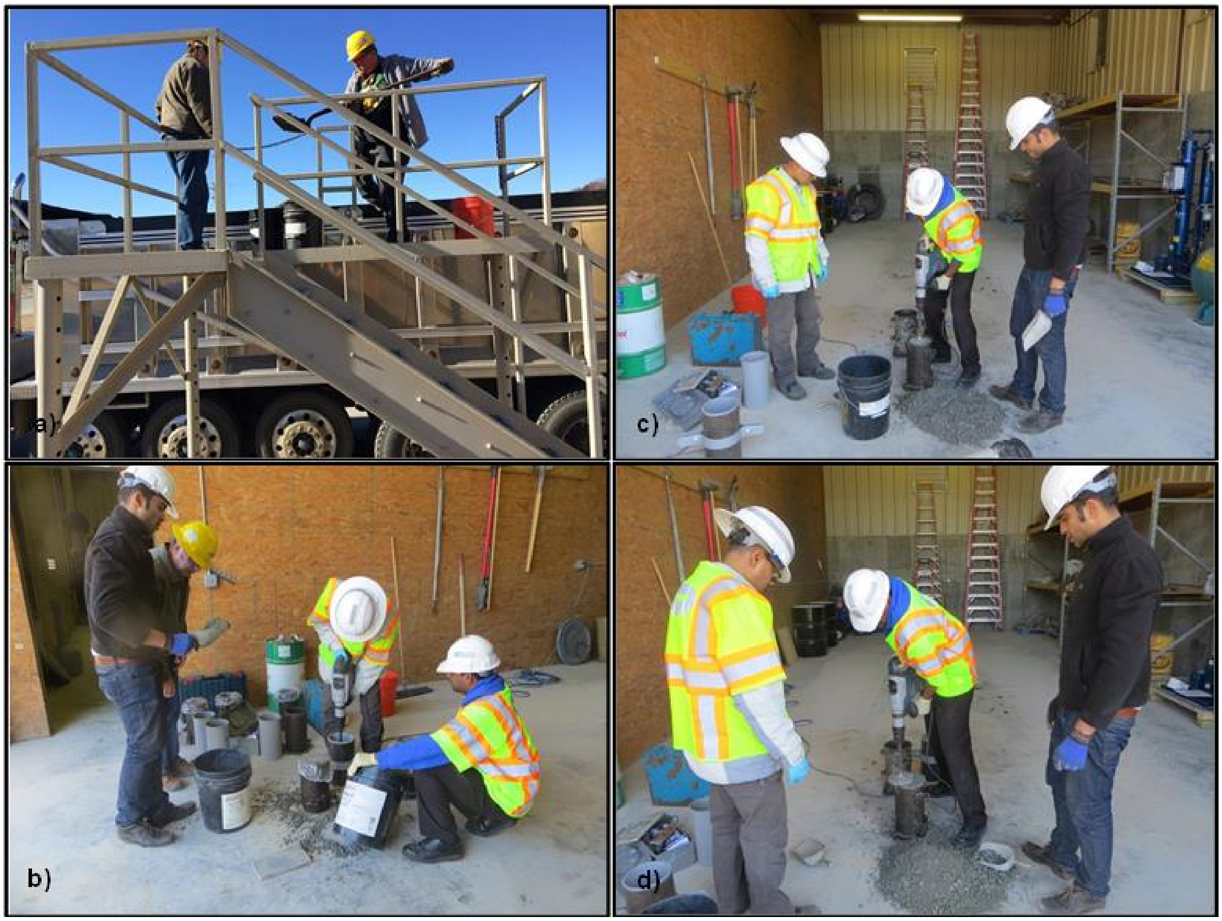

Figure 4. Preparation of CTA Cylinder Using Vibratory Hammer: (a) sampling from haul truck at plant; (b) compacting cylinder in plastic mold with steel sleeve; (c) sample compaction in steel mold; (d) leveling off samples in mold. CTA = cement-treated aggregate.

Nimmo Parkway Project

The second project site was located near Virginia Beach in VDOT's Hampton Roads District. It consisted of the realignment of Nimmo Parkway on a fill area. The site was visited on April 17, 2014, to observe the production and construction of the CTA layer. CTA was produced using VDOT 21A aggregate from a local quarry and 4% cement in a portable pugmill. The construction steps are shown in Figure 5. The haul truck directly dumped the CTA on prepared subgrade, and a motor grader was used to spread it to a uniform thickness. A roller was used in both vibratory and static mode to compact CTA initially to the desired density. Then the compacted CTA layer was graded to the design thickness of 8 in using a motor grader blade as shown in Figure 5 and re-compacted. A roller pattern of six vibratory and one static passes was used to achieve final density.

Figure 5. CTA Construction at Nimmo Parkway: (a) back dumping CTA; (b) spreading CTA with motor grader; (c) compaction with roller; (d) grading to 8-in thickness using blade and re-compacting. CTA = cement-treated aggregate.

At some locations, it was necessary to use a water truck to re-wet the CTA mixture for proper compaction because of the dried surface; at times, the water spray was too heavy and water ponding was also observed. Water spray, blading, and re-compaction are shown in Figure 6. Thicknesses were checked after the compaction and found to be deficient at several locations, so this section was reworked and watered heavily before re-compaction. Standing water was observed while the section was reworked with a motor grader as shown in Figure 6. In many locations, the base looked very wet and soft after final compaction. Later, the CTA layer was overlaid with multiple layers of asphalt mixture to final grade: 4 in of BM-25.0 (base asphalt mixture), 2 in of IM-19.0D (intermediate asphalt mixture), and 2.5 in of surface mixture 9.5D (surface asphalt mixture).

CTA samples were also collected from this project for laboratory study. As opposed to plant-sourced sampling, samples were obtained from two trucks in the field as they were delivering the materials. A few cylindrical (6 × 12 in) specimens and one beam (6 × 6 × 21 in) were prepared from each truck using vibratory hammer compaction. All specimens were brought to the Virginia Transportation Research Council (VTRC) laboratory for curing and strength testing at specified ages.

Figure 6. Water Spray, Grading, and Re-compaction of CTA on Nimmo Parkway: (a) dry CTA surface; (b) water truck to wet surface for more compaction; (c) blading to achieve proper grade and standing water; (d) heavy water spray. CTA = cement-treated aggregate.

Laboratory Study of CTA

CTA was produced in the VTRC laboratory using four sources of aggregate: (1) Middle Ground Boulevard project, (2) Nimmo Parkway project, (3) Route 208 project, and (4) a quarry in Staunton. As mentioned, the first two sources of aggregate are the same as the sites visited for construction monitoring. The third source of aggregate was a source used in a recently completed CTA project on Route 208 in Fredericksburg, and the fourth source of aggregate was an aggregate with good unbound base properties (high resilient modulus). Each aggregate was used to produce CTA at three cement contents: 3%, 6%, and 9%. Cylindrical (6 × 12 in) and beam (6 × 6 × 21 in) samples were prepared in the laboratory using a vibratory hammer in accordance with ASTM C1435-08. This was a hand-held electric vibrating hammer with a 6 in-diameter round head attachment for compaction. Cylinders were compacted in four equal lifts, whereas beams were compacted in only two layers. Proctor results obtained from respective projects/quarries were used for compaction moisture content. Both cylinders and beams were cured in a moist room (100% relative humidity and approximately 70 °F) at the VTRC laboratory and tested at specified ages in accordance with the following ASTM standards for compressive strength (f_c), splitting tensile strength (f_{st}), modulus of elasticity (E_c), and flexural strength of beams (f_r) (ASTM International, 2013).

- ASTM D1633-00: Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders (2014) (sample size and preparation was different than standard)

- ASTM C496-11: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (2011) (sample was soaked for 4 hours as in ASTM D1633)

- ASTM C469-14: Standard Test Method for Static Modulus of Elasticity and Poisson's ratio of Concrete in Compression (2014) (sample was soaked for 4 hours as in ASTM D1633)

- ASTM C78-10: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (2010) (sample was soaked for 4 hours as in ASTM D1633).

Field Evaluation of CTA

Field performance of CTA is not readily measurable since many factors such as properties of other layers and traffic and environmental loading affect the performance of the pavement system. Characterization of in-place CTA was carried out using FWD tests. A back-calculation algorithm was used to analyze the FWD data to estimate the elastic modulus of CTA at three sites (one site was tested at two different ages) with different service lives. Multiple 4-in-diameter core samples were also collected from the same locations as the FWD test drops from three of those sites. These cores were used to measure compressive strength in accordance with a procedure similar to that in ASTM D1633 and the modulus of elasticity in accordance with ASTM C469; in both cases samples were soaked in water for 4 hours before testing unlike the respective standards. Unfortunately, the limitation in the core length did not allow for direct modulus measurement in most cases; the current laboratory setup at VTRC requires that specimens be at least 7 in long, whereas most core samples were 6 in or less in length. In addition to FWD testing and determination of core strengths, a limited visual observation of crack reflection through the flexible pavement system was used as a performance measure for some of these sites. Table 3 outlines the sites used for FWD testing and coring.

Table 3. Field Sites for FWD Testing and Coring

Project/Site Location[a]	Year Constructed	FWD Testing	Coring	Visual Observation
Middle Ground Blvd.	2013	4 and 20 months	4 and 20 months	2016
Nimmo Parkway	2014	None	None	2016
Route 208	2011-2013	2 to 4 years (2015)	2 to 4 years (2015)	2016
U.S. 460E in Salem	2001	none	15 years	2015
U.S. 60W in Elko (rigid pavement)	1979	2015	2015 (after 36 years)	2015

FWD = falling weight deflectometer.
[a]All pavements were flexible except for U.S. 60.

As mentioned previously, the Middle Ground Boulevard and Nimmo Parkway sites were visited during construction and relevant construction information was collected. FWD testing involves VDOT regular basin testing with four load levels.

Back-Calculation of CTA Layer Modulus

FWD data are used to back-calculate the CTA layer modulus. In FWD testing, because of the application of an impulse load, the pavement surface deflects vertically downward and forms a deflection basin. Nine sensors were used at different radial offset distances from the point of load for the measurement of vertical deflections. The distances of the sensors from the center of the loading plate were 0, 8, 12, 18, 24, 36, 48, 60 and 72 in. The magnitudes of the load were varied at four load levels: 6,000, 9,000, 12,000, and 16,000 lbf. For each load level, four replicate tests were performed at a single test point.

A software program, Evercalc (developed by the Washington State DOT), was used for back-calculation of the layer modulus. Evercalc uses WESLEA (provided by the Waterways Experimental Station, U.S. Army Corps of Engineers) as the layered elastic solution to compute the theoretical deflections and a modified augmented Gauss-Newton algorithm for optimization. Evercalc is capable of evaluating a flexible pavement structure that contains up to five layers. Back-calculation requires inputs such as number of layers, layer thickness, Poisson's ratio of material in each layer, temperature, and the presence of any rigid layer underneath the subgrade. Prior to the analysis, a value for the layer modulus is assumed, which is often called the seed modulus. Surface deflections at radial offset distances are calculated using the seed modulus and layer thickness. From an initial seed modulus, Evercalc iteratively searches for the final modulus for each pavement layer. The deflections calculated using WESLEA are compared with the measured ones (from FWD testing) at each iteration. The process is repeated by changing the seed modulus each time until the difference between calculated and measured deflections is within a selected tolerance. When the root mean square (RMS) error falls within the allowable tolerance or the number of iterations has reached a limit, the algorithm terminates. When multiple deflection data sets from a given location are analyzed, the final moduli from the previous deflection data are used as seed moduli for analyzing the next data set in order to improve the performance of the program (Washington State DOT, 2005).

Detailed information about the layer thickness was selected from core thickness measurements and construction history. The initially assumed layer moduli of asphalt were based on limited laboratory testing of cores (dynamic modulus testing using different temperatures and frequencies). The FWD records the pavement surface temperature at each station during the testing. All the different asphalt layers are combined to one layer for the purpose of back-calculation. Generally, one should evaluate no more than three or four layers with unknown moduli in the back-calculation process and should attempt to obtain matches between the calculated and measured deflection basins, as indicated by RMS error of 2% or less. If a pavement structure consists of a stiff layer such as CTA, it is usually difficult to obtain low RMS error values. High convergence errors do not necessarily mean that the back-calculated layer moduli are not good.

CTA Mix Design

VDOT uses prescriptive mixture proportioning to produce CTA. Usually, 4% cement by weight is mixed with VDOT 21A or 21B aggregate, irrespective of source or mineralogy or gradation (although within specification limit). These can produce a wide range of strengths in the field depending on the aggregate. In order to specify a mechanistic design parameter for the MEPDG procedure, a specified strength is needed. Therefore, a mix design procedure is recommended based on achieving an average compressive strength similar to that of concrete pavement construction. The selection of design strength was facilitated by a review of existing specifications from other highway agencies, current pavement design steps as outlined in the 1993 AASHTO design guide, and the laboratory study conducted during this research.

Mechanical Properties of CTA for MEPDG

The pavement design procedure according to the MEPDG requires input values for the mechanical properties of every layer of the system. Such values for CTA were recommended for VDOT use based on the design strength, laboratory study, field performance, and a MEPDG sensitivity analysis. Modulus values that corresponded to the design compressive strength in the laboratory study and the modulus values from the back-calculation of FWD data were considered. The sensitivity of the performance of a typical pavement structure using the MEPDG program to changes in CTA modulus values was also investigated in the selection process.

RESULTS AND DISCUSSION

Literature Review

The literature review was focused on the following:

- typical strengths and mechanical properties of CTAs used by different agencies
- CTA mechanical property values
- mix design, e.g., target property value, sample preparation and testing, % cement selection, limits on cement, compaction process
- aggregate gradation, percent passing the No. 200 sieve, liquid limit (LL), plastic limit (PL)
- durability tests and requirements
- field construction and quality control / quality assurance practices by other agencies

- minimum and maximum strength requirements
- use of CTA in pavement design using the AASHTO and MEPDG methods.

CTA is widely used as a base course for flexible and rigid pavement. CTA provides a stiffer and stronger base than unbound aggregate base. A stiff base reduces deflections attributable to traffic loads, which results in lower strains in the asphalt surface. This delays the onset of surface distress, such as fatigue cracking, and extends pavement life (Halsted et al., 2006).

The literature review revealed that shrinkage, fatigue, durability, erosion, strength, and stiffness are properties that greatly affect pavement performance. Performance issues associated with the use of CTA in asphalt pavements include block cracking, transverse cracking, longitudinal cracking, and bottom-up cracking. Cracking and faulting are the primary distress types found in concrete pavement. Wen et al. (2014) conducted a detailed literature review regarding the distresses of asphalt and concrete pavements built with CTA and the properties of CTA that contribute to these distresses.

Some transverse cracking in HMA surface layers result from the shrinkage of the stabilized base (Chen, 2007). The HMA surface layer of an asphalt pavement with a high-stiffness cement-stabilized layer as the base is prone to top-down fatigue cracking in the wheel path (ARA, Inc., 2004). Block cracking often is reported in HMA pavements that are constructed with cement-stabilized layers. This cracking is caused by shrinkage of the underlying stabilized base (Scullion, 2002) that results from the loss of moisture and temperature variations. In addition, block cracking occurs in cement-stabilized layers that have high unconfined compressive strength. The structural properties of CTA depend on the aggregate material, quantity of cement, curing conditions, and age; the compressive strength of CTA varies from 300 to 800 psi, and modulus of rupture varies from 100 to 200 psi (Halsted et al., 2006). A CTA layer may be susceptible to shrinkage attributable to moisture loss, cement hydration, and other environmental factors. This shrinkage results in transverse cracking of the stabilized base, which could reflect to an HMA surface. Shrinkage and fatigue cracking are important distresses when cement-stabilized materials are used as base or subbase layers. It has been reported that these distresses are affected by cement content, material type and gradation, fines content, density, moisture content, curing time, freeze-thaw cycles, wet-dry cycles, and time to traffic opening (Gaspard, 2002; Khoury and Zaman, 2007; Sebesta and Scullion, 2004).

Increases in cement content led to significant shrinkage cracking problems. With increased cement contents, cracking became so prevalent that several state DOTs banned the use of cement stabilization in their roadways (Guthrie et al., 2002). CTA needs to remain hard and durable and be able to resist volume changes or hydraulic pressures caused by freezing and thawing or moisture changes that could gradually break down the cementitious bonds (Halsted et al., 2006). In general, cement content that will provide a 7-day unconfined compressive strength of 300 to 400 psi is satisfactory for most mixed-in-place CTA applications. Because there is usually a greater volume of coarse aggregate involved, strengths for plant-mixed CTA can be as high as 800 psi. However, the main reason for limiting strength is to minimize shrinkage cracking that is caused by higher cement and water contents. Experience has shown that high strengths can cause additional cracks to reflect through the pavement surface. The objective is to have a balanced design, where enough cement is used so that the resulting stabilized base is strong, durable, and relatively impermeable but not so strong that it results in other types of distress in the pavement (Halsted et al., 2006).

Erosion of cement-stabilized layers also contributes to cracking and joint faulting in concrete pavements. Pumping of fines leads to voids underneath the concrete slab under repeated traffic loads, which results in stress concentrations and cracking. The movement of the loosened material from one joint side to the other may cause joint faulting (ARA, Inc., 2004). George (1968) reported that cement-treated bases should be compacted to a density as high as possible to minimize shrinkage; addition of fly has the most beneficial effect in minimizing shrinkage cracking because it provides enhanced workability and facilitates compaction. The Portland Cement Association (PCA) provides guidelines for addressing shrinkage cracking through design and construction practices (George, 2002). For a given aggregate type, the development of strength and the modulus of CTA mixtures are mostly governed by the applied cement content. Corley-Lay (1997) undertook a study to determine the advantage of plant-mixed over road-mixed (in situ) CTA base course. Road-mixed sites had higher compressive strength than did plant-mixed sites. However, it was noted that obtaining intact cores of CTA was difficult. The average compressive strength for the road-mixed cores was 2,762 psi; the average for the plant-mixed cores was 1,182 psi. The American Concrete Institute (ACI) equation proposed for the estimation of the modulus of elasticity of normal concrete was found to overestimate the modulus of CTA (Lim and Zollinger, 1998).

Most of the current design practices are based only on strength, without consideration of long-term durability or performance. Many state DOTs require sufficient cement to achieve a minimum unconfined strength as high as 750 psi after 7 days. Although this content of cement results in a very stiff layer, it does not necessarily guarantee acceptable long-term pavement performance (Scullion et al., 2000). PCA and the U.S. Army Corps of Engineers developed their individual design criteria for CTA in accordance with both strength and durability requirements, whereas most state DOTs have historically focused on compressive strength alone (ACI, 1990; PCA, 1971). The Texas DOT constructed thousands of highway miles with cement-stabilized base layers that were designed to meet a 700 psi compressive strength requirement and had unsatisfactory performance in many instances because of shrinkage cracking (Scullion et al., 2000).

Durability tests such as the wet-dry test (ASTM D559: Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures) and the freeze-thaw test (ASTM D560: Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) are the most common tests used for CTA (Wen et al., 2014). With these tests, the weight loss of a cement-treated material under wire brushing is determined through 12 cycles of wetting and drying or freezing and thawing. Research performed by PCA (1971) found that about 20% of the samples with a 7-day compressive strength of 300 psi; 70% with a compressive strength of 500 psi; and 97% with a compressive strength of 750 psi would pass the freeze-thaw test. A tube suction test has also been developed for investigating moisture susceptibility of aggregate base material (Scullion and Saarenketo, 1997). This test helps to identify base material that may be particularly sensitive to moisture degradation in the field and to determine the correct amount of cement to use for stabilization. The concept behind the tube suction test is to measure the movement of water in a sample of cement-stabilized material. Dempsey and Thompson (1973) conducted research on the feasibility of vacuum-saturation procedures as a rapid method for predicting the durability of cement-stabilized material. They found a good correlation for residual strength and moisture content between specimens exposed to vacuum saturation and to five freeze-thaw cycles. Guthrie et al. (2008) found a strong correlation between unconfined compressive strength after freeze-thaw cycling and unconfined compressive strength after the vacuum-saturation test.

As part of the literature review, several state DOTs were contacted regarding their CTA specification and use. CTA specifications were also obtained from state DOT websites. 4 shows a summary of the findings; the details are provided in the Appendix.

Table 4. Summary of State DOT Specifications and Practices

	Design 7-Day Compressive Strength, psi		Aggregate Properties			
Agency/DOT	**Minimum**	**Maximum**	**LL**	**PI**	**% Passing No. 200 Sieve**	**Comments**
California DOT	750				3-15%	
Colorado (City of Thornton)	650	1,000	<30		3-15%	Cement: >5%
Federal Aviation Administration	400	800	<25	<6		28-day strength < 1,000 psi; minimum 98% compaction; sliding pay scale with 98% to 95% compaction; freeze-thaw and wet-dry durability < 14% mass loss as an option
Georgia DOT	300	450				
Kansas DOT	650	1600				Pay based on percent within limit; reference SD: 260 psi
Maryland DOT	750			<6	0-8%	Cement: 3.25- 4.75%
Michigan DOT	750			<6		0-25% passing No. 80 sieve; sliding pay scale with 98% to 95% compaction; freeze-thaw and wet-dry durability < 14% mass loss
Montana DOT	500	1500	<30	<7	4-12%	Minimum 95% compaction; sliding pay scale with 400-2,000 psi compressive strength
Oklahoma DOT	600	1200			1-15%	Target strength: 800-1,000 psi Cement: 3-5%
South Carolina DOT	600				0-20%	Cement: 2.5-5%
Tennessee DOT	500					

DOT = department of transportation; LL = liquid limit; PI = plasticity index; SD = standard deviation.
Note: The information provided was obtained from the websites of the various entities or through e-mail communication. Details are available from the authors upon request.

State DOTs use CTA as a base course for several reasons such as (1) a poor subgrade; (2) enhancement of the pavement structure; (3) use of drainage layer; (4) economics; and (5) personal choice. Several states do not use CTA in their pavement structure and thus specifications are not available. Some of the states have strength-based specifications for CTA with specified minimum and maximum strength criteria. A few states limit the cement content, up to 5% by weight, which is usually helpful in limiting shrinkage cracks.

The requirements for design method, placement, compaction, and quality control/quality assurance for CTA vary widely among state DOTs. Only the Georgia DOT determines the in situ compressive strength by testing 6-in-diameter cores drilled from the constructed CTA base. Specified minimum and maximum compressive strengths range from 300 to 1,600 psi among different DOT specifications, wherein many DOTs require a minimum of 750 psi. In a NCHRP study, Wen et al. (2014) recommended the following 28-day compressive strengths of CTA to be used in MEPDG: minimum, 392 psi; maximum, 1,296 psi; and typical, 763 psi. In general, a plasticity index less than 6 is specified for aggregates used in CTA. Many states also have aggregate gradation requirements that limit the percent passing the No. 200 sieve. Except for a few states, detailed sample preparation, compaction, and quality assurance requirements were not shown in the CTA specifications. The Michigan DOT, the Montana DOT, and the Federal Aviation Administration specified freeze-thaw durability requirements as less than 14% mass loss when tested in accordance with ASTM D560. VDOT requires contractors to verify the actual cement content used in CTA by the titration method as specified in Virginia Test Method 40, Determining Cement Content of Freshly Mixed Cement-Aggregate Mixtures (VDOT, 2017c). Most states specify that compaction be done within 2 to 2.5 hours of mixing and require more than 95% of specified density (mostly by the Proctor method). The use of fly ash up to 25% by weight of cementitious materials is allowed by several states.

CTA in MEPDG Analysis

Many properties of CTA were identified as required input for MEPDG analysis. Table 5 summarizes the required inputs for Pavement ME Design (Version 2.2). The specific values of these properties suitable for VDOT use are recommended based on the selected CTA design strength, properties of field CTA, and sensitivity analyses of predicted distresses by the MEPDG. The results for sensitivity analysis are discussed here.

As mentioned previously, the typical pavement layer information for VDOT was used for the analysis. Other input parameters used in the analysis were CTA base crack (full-width transverse) spacing of 25 ft and modulus of rupture of 107 psi.

Table 6 provides a summary of predicted distresses for asphalt pavement with varying CTA moduli of elasticity from 200,000 to 2 million psi. It can be seen from this limited sensitivity analysis that CTA's modulus of elasticity has a minor effect on any type of distresses considered by the MEPDG.

Table 5. CTA Inputs Properties for Flexible and Rigid Pavements in Pavement ME Design

Type of Pavement	Input Required	
Flexible pavement (semi-rigid)	General	Layer thickness (in) Unit weight (pcf) Poisson's ratio
	Strength	Modulus of elasticity (psi) Modulus of rupture (psi) Minimum elastic modulus (psi)
	Cracking	Chemically stabilized base crack spacing (ft) Chemically stabilized base crack LTE (%) Chemically stabilized base crack fatigue LTE (%)
	Thermal	Thermal conductivity (BTU/hr-ft-degree F) Heat capacity (BTU/lb-degree F)
Rigid pavement (CRCP, JPCP)	General	Layer thickness (in) Unit weight (pcf) Poisson's ratio
	Strength	Elastic modulus (psi)
	Thermal	Thermal conductivity (BTU/hr-ft-degree F) Heat capacity (BTU/lb-degree F)

CTA = cement-treated aggregate; LTE = load transfer efficiency; CRCP = continuously reinforced concrete pavement; JPCP = jointed plain concrete pavement.

Table 6. Distress Prediction Summary for Different CTA Elastic Moduli

Distress Type	CTA Elastic Modulus (psi)				
	200,000	**500,000**	**1,000,000**	**1,500,000**	**2,000,000**
Terminal IRI (in/mi)	151	150	149	149	149
Permanent deformation: total pavement (in)	0.27	0.27	0.27	0.27	0.27
AC total fatigue cracking: bottom up + reflective (% lane area)	7.09	5.44	4.12	3.49	3.09
AC total transverse cracking: thermal + reflective (ft/mi)	2414	2414	2414	2414	2414
AC bottom-up fatigue cracking (% lane area)	3.08	1.92	1.07	0.71	0.51
AC thermal cracking (ft/mi)	1	1	1	1	1
AC top-down fatigue cracking (ft/mi)	330	334	348	329	329
Chemically stabilized layer: fatigue fracture (% lane area)	0.13	0.06	0.03	0.02	0.01

CTA = cement-treated aggregate; IRI = International Roughness Index; AC = asphalt concrete.

Although asphalt concrete (AC) bottom-up fatigue cracking and AC total fatigue cracking (bottom-up + reflected CTA fatigue cracks) show some decrease with increasing modulus, they are below the allowed limit by a large margin; when the modulus of elasticity varies from 1 to 2 million psi, total distressed area varies from 4% to 3%. The other predicted distress types, such as rutting or transverse cracks, are insensitive to variations of the CTA modulus of elasticity. There will be around 210 full-width transverse cracks if the seed (assumed) crack spacing in the CTA layer is 25 ft, which will add up to 2,520 ft of linear cracking per mile for a 12-ft-wide lane, whereas the predicted transverse cracks on AC are around 2,414 ft per mile (more than 95% of initial seed crack) for all CTA moduli in Table 6.

In order to verify the insensitivity of the CTA elastic modulus to predicted transverse cracks, further analysis was done with varying seed (initial input) transverse crack spacing in CTA: 6 ft, 10 ft, 15 ft, 20 ft, and 25 ft, which would amount to 10,548 ft [(5,280/6-1)*12]; 6,324 ft; 4,212 ft; 3,156 ft; and 2,520 ft of initial linear cracks per mile for a 12-ft lane, respectively. Results indicated that the pavement performance as determined by Pavement ME Design did not show much sensitivity to either elastic modulus or the crack spacing of CTA layer. The summary of predicted distresses for CTA with different transverse crack spacings using CTA elastic modulus values of 1 million psi and 2 million psi is provided in Tables 7 and 8, respectively. There is no effect of seed transverse crack spacing on any other predicted distresses except for transverse reflective cracks irrespective of CTA modulus. Pavement ME Design predicts that more than 90% of cracks would reflect through the AC surface in a 30-year analysis period regardless of input crack spacing; a 6-ft spacing added a few more extra cracks, whereas a 25-ft spacing led to a few less cracks than the initial cracks.

Figure 7 compares transverse cracking on the AC surface as a function of pavement age for different seed crack spacing and they are identical for both CTA moduli. The rate of reflection is about 50% to 90% in 10 to 25 years for all seed cracks. So it is apparent that controlling the crack development in CTA itself is the most important phenomenon during construction.

The sensitivity of pavement performance to the values of the CTA modulus of rupture and thickness was also investigated, and the results are presented in Tables 9 and 10. There are some minor variations of the predicted distresses by Pavement ME Design for the selected input properties of all other pavement layers. Table 10 shows the sensitivity of different distresses to CTA thickness. It can be seen that as thickness increases, AC bottom-up cracking decreases.

Table 7. Distress Prediction Summary for Different CTA Crack Spacings

	CTA Modulus of Elasticity (1 million psi)				
	Crack Spacing (ft)				
Distress Type	**6 ft**	**10 ft**	**15 ft**	**20 ft**	**25 ft**
Terminal IRI (in/mi)	204	173	160	153	149
Permanent deformation: total pavement (in)	0.27	0.27	0.27	0.27	0.27
AC total fatigue cracking: bottom up + reflective (% lane area)	4.12	4.12	4.12	4.12	4.12
AC total transverse cracking: thermal + reflective (ft/mi)	11218	6133	3897	2939	2414
AC bottom-up fatigue cracking (% lane area)	1.07	1.07	1.07	1.07	1.07
AC thermal cracking (ft/mi)	1	1	1	1	1
AC top-down fatigue cracking (ft/mi)	347	347	347	347	347
Chemically stabilized layer: fatigue fracture (% lane area)	0.03	0.03	0.03	0.03	0.03

CTA = cement-treated aggregate; IRI = International Roughness Index; AC = asphalt concrete.

Table 8. Distress Prediction Summary for Different CTA Crack Spacings

	CTA Modulus of Elasticity (2 million psi)				
	Crack Spacing (ft)				
Distress Type	**6 ft**	**10 ft**	**15 ft**	**20 ft**	**25 ft**
Terminal IRI (in/mi)	205	171	159	153	148
Permanent deformation: total pavement (in)	0.27	0.27	0.27	0.27	0.27
AC total fatigue cracking: bottom up + reflective (% lane area)	3.09	3.09	3.09	3.09	3.09
AC total transverse cracking: thermal + reflective (ft/mi)	11218	6133	3897	2939	2414
AC bottom-up fatigue cracking (% lane area)	0.51	0.51	0.51	0.51	0.51
AC thermal cracking (ft/mi)	1	1	1	1	1
AC top-down fatigue cracking (ft/mi)	329	329	329	329	329
Chemically stabilized layer: fatigue fracture (% lane area)	0.01	0.01	0.01	0.01	0.01

CTA = cement-treated aggregate; IRI = International Roughness Index; AC = asphalt concrete.

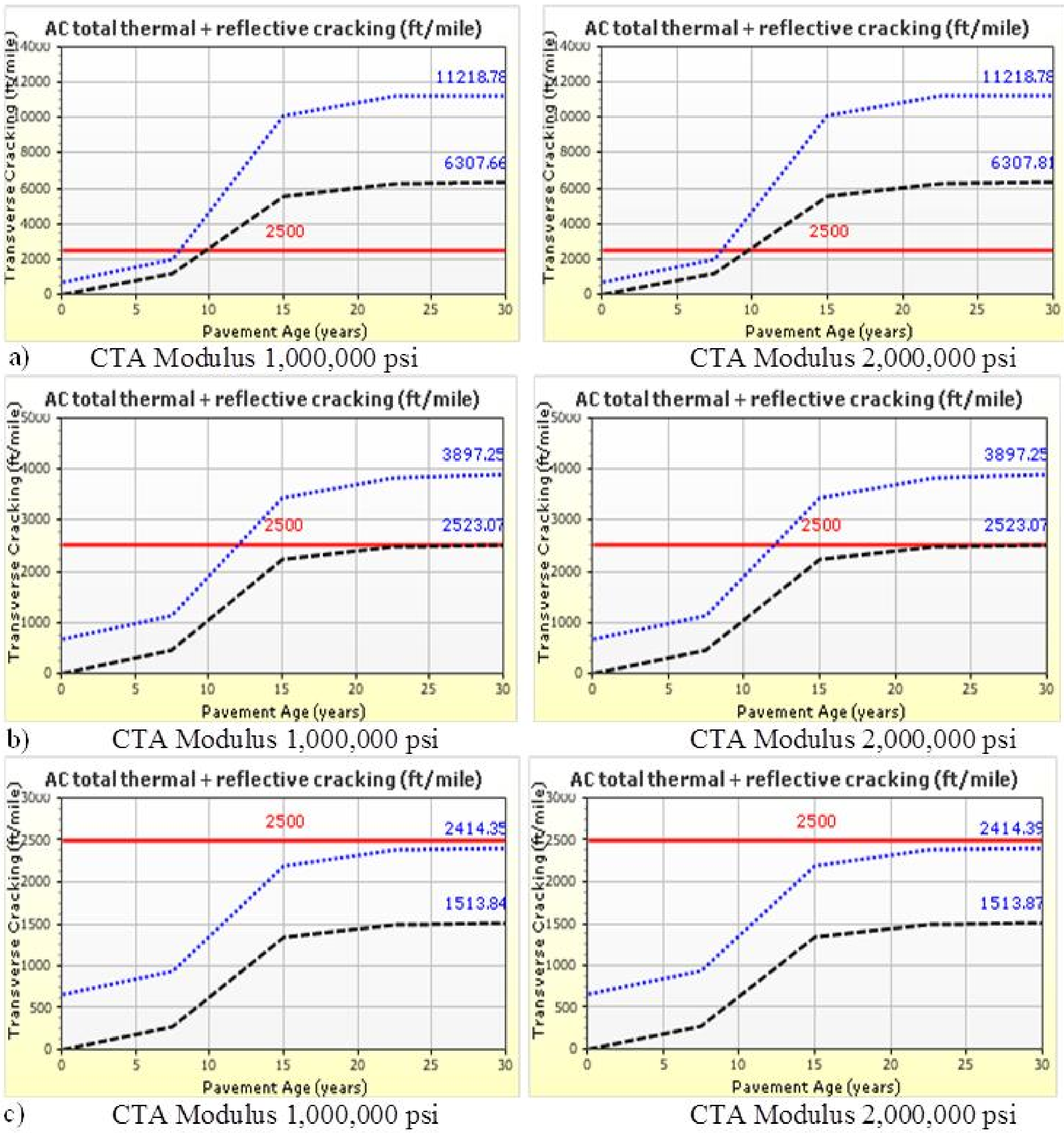

Figure 7. Transverse Crack Reflection at Different Pavement Ages With Seed Crack Spacing: (a) 6 ft; (b) 15 ft; (c) 25 ft. Red line = threshold value; blue line = specified reliability; black line = 50% reliability. CTA = cement-treated aggregate; AC = asphalt concrete; modulus = elastic modulus.

Table 9. Distress Prediction Summary for Different CTA Moduli of Rupture

Distress Type	CTA Modulus of Rupture 1 million psi and Crack Spacing 25 ft			
	CTA Modulus of Rupture (psi)			
	50	**100**	**200**	**300**
Terminal IRI (in/mi)	149	149	149	149
Permanent deformation: total pavement (in)	0.27	0.27	0.27	0.27
AC total fatigue cracking: bottom up + reflective (% lane area)	4.02	4.1	4.54	5.1
AC total transverse cracking: thermal + reflective (ft/mi)	2414	2414	2414	2414
AC bottom-up fatigue cracking (% lane area)	1.02	1.06	1.3	1.64
AC thermal cracking (ft/mi)	1	1	1	1
AC top-down fatigue cracking (ft/mi)	348	347	344	342
Chemically stabilized layer: fatigue fracture (% lane area)	0	0.02	0.07	0.12

CTA = cement-treated aggregate; IRI = International Roughness Index; AC = Asphalt Concrete.

Table 10. Distress Prediction Summary for Different CTA Thicknesses

Distress Type	CTA Modulus of Elasticity 1 million psi and Crack Spacing 25 ft			
	CTA Thickness			
	4 in	**6 in**	**8 in**	**10 in**
Terminal IRI (in/mi)		149	148	149
Permanent deformation: total pavement (in)	0.27	0.27	0.27	0.27
AC total fatigue cracking: bottom up + reflective (% lane area)	4.89	4.12	3.67	3.38
AC total transverse cracking: thermal + reflective (ft/mi)	2415	2414	2415	2417
AC bottom-up fatigue cracking (% lane area)	1.56	1.07	0.80	0.65
AC thermal cracking (ft/mi)	1	1	1	1
AC top-down fatigue cracking (ft/mi)	333	347	359	337
Chemically stabilized layer: fatigue fracture (% lane area)	0.03	0.03	0.03	0.03

CTA = cement-treated aggregate; IRI = International Roughness Index; AC = Asphalt Concrete.

Although CTA's modulus of elasticity is important in the analysis of pavement performance, the most critical influence is the (seed or initial) transverse crack spacing in the CTA. In general, a higher modulus stems from a high cement content, which may cause high drying shrinkage. Therefore, limiting CTA's strength and modulus of elasticity for semi-rigid pavement is desirable to limit reflective cracking. Based on the survey by Wen et al. (2014), state agencies consider transverse and block cracking to be the most severe distress types in pavements constructed with cement-stabilized layers. George (2002) reported that a low strength or low modulus/strength ratio is beneficial in mitigating shrinkage cracking.

The sensitivity analysis of CTA properties was also conducted on the performance of rigid pavement. Irrespective of CTA's modulus of elasticity, which varied from 200,000 to 2 million psi, punchouts, which is the main distress type for CRCP, were predicted to have a frequency of two per mile in 30 years of design (analysis) life. VDOT's *Pavement ME User Manual—Draft* (VDOT, 2017a) recommends a distress limit of six punchouts per mile. For JPCP, the main distress types in Pavement ME Design are mean joint faulting and transverse cracking (% slabs). These distresses, with values around 0.07 in to 0.08 in and 9% (% slabs) for mean joint faulting and transverse cracking, respectively, were found not to be sensitive to the variation of CTA's modulus of elasticity from 200,000 to 2,000,000 psi.

Sensitivity analyses were also conducted for other CTA input parameters shown in Table 5; the predicted distresses were not sensitive to these parameters. The change in load transfer efficiency (LTE) from the default value of 50% to 90% did not produce any difference in predicted distresses using Pavement ME Design. It is recommended that default input values be used for CTA properties such as LTE, thermal conductivity, and heat capacity.

Monitoring Field Construction

Two field construction sites were monitored to understand the steps and challenges for CTA construction. CTA could easily dry out when a motor grader is used to spread the material because of the time needed to manipulate the materials. In addition, subsequent blading to achieve the desired thickness can contribute to poor construction such as dry and loose CTA. The time between mixture production and final compaction should be monitored carefully; many state DOTs and the ACI limit it to 2 to 2.5 hours. Use of additional moisture for compaction should be avoided or kept to a minimum. The use of an asphalt paver to place the CTA may be beneficial and would result in a high-quality production. It would eliminate blading or grading, reduce construction time, prevent moisture loss, and require only a few passes of a roller to achieve sufficient compaction.

The cylinders and beams prepared at both sites were brought into the VTRC laboratory for curing and strength testing at different ages. Tables 11 and 12 summarize the test results for Middle Ground Boulevard and Nimmo Parkway, respectively. Although Nimmo Parkway samples were tested at 7, 28, and 90 days, Middle Ground Boulevard samples were tested at 20 and 28 days.

A second field visit was done during the construction of CTA on subsequent sections of Nimmo Parkway. Again, CTA samples were collected from the trucks at the field site and specimen cylinders and beams were prepared as before. Unfortunately, all of these samples fell apart during curing for an unknown reason and could not be tested.

Table 11. Strength and Elastic Modulus Values for Middle Ground Boulevard Field Specimens

Field Specimen	20-day Compressive Strength, psi	28-day Compressive Strength, psi	28-day Splitting Tensile Strength, psi	28-day Elastic Modulus, psi ($\times 10^6$)	
				Compressive Specimen	Splitting Specimen
Batch/truck 1	235	210	55	0.51	0.59
Batch/truck 2	250	270	45	0.74	0.68
Batch/truck 3	160	240	55	0.63	0.74
Batch/truck 4		260	50	0.61	0.61
Average, psi	215	245	51	0.64	
Standard Deviation	48.2	26.5	4.8	0.078	
COV (%)	22.4	10.8	9.3	12.3	

COV = coefficient of variation.

Table 12. Strength Values for Nimmo Parkway Field Specimens

Field Specimen	Compressive Strength, psi			Splitting Tensile Strength, psi		Beam Flexural Strength, psi (90 days)
	7 days	28 days	90 days	28 days	90 days	
Truck 1	230	300	330	100	-	70
Truck 2	460	580	520	110	140	220
	-	550	810	150	-	-
Average, psi	345	477	554	120	140	145
Standard Deviation	-	154	242	26	-	-
COV (%)	-	32	44	22	-	-

Despite the same design of 4% cement content, there is a clear difference in average strengths for all ages between the two projects as evident in Tables 11 and 12. Since these samples were prepared using the same vibratory hammer, the difference could be attributed to the properties of the aggregate and the consistency of the mixture (e.g., cement distribution, aggregate segregation). Although the Middle Ground Boulevard samples showed lower strength, the corresponding coefficient of variation (COV) was also lower than that for the Nimmo Parkway samples. The 28-day average compressive strengths were 245 psi with a COV of 11% for Middle Ground Boulevard samples, and 477 psi with a COV of 32% for Nimmo Parkway samples.

Laboratory Study of CTA

Samples of cylinders and beams were prepared in the VTRC laboratory with the aggregates collected from four sources, including three CTA sites. They were tested for strengths at different ages after curing in the moist room. The results are summarized in Tables 13 through 16 for samples prepared with a vibratory hammer.

Table 13. Strength Results for Laboratory-Prepared Samples for Middle Ground Boulevard

Sample	Age, days	3% Cement		6% Cement		9% Cement	
		Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi
Compressive Strength Samples (6×12 in cylinder)	7	292	-	459	-	1412	-
		254	-	-	-	-	-
	28	353	-	726	1.99	1773	-
		258	-	768	2.02	-	-
	90+	-	-	-	-	2181	2.61
Tensile Strength Samples (6 ×12 in cylinder)	7	59	-	-	-	-	-
	28	53	-	130	-	-	-
	90+	-	-	-	-	338	2.97
Beam Flexure (6 × 6 × 21 in beam) Modulus of Rupture	7	-	-	-	-	-	-
	28	104	-	200	-	-	-
	90	-	-	-	-	422	-

Table 14. Strength Results for Laboratory-Prepared Samples for Nimmo Parkway

Sample	Age, days	3% Cement		6% Cement		9% Cement	
		Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi
Compressive Strength Samples (6 × 12 in cylinder)	7	913	-	1,655	-	3,371	-
	28	735	-	2,210	2.64	-	-
	90+	1,441 (287 days)	-	2,301	-	4,960 (287 days)	4.61
Tensile Strength Samples (6 × 12 in cylinder)	7	-	-	-	-	-	-
	28	-	-	-	-	450	-
	90+	243 (287 days)		251		501 (287 days)	4.35
Beam Flexure (6 × 6 × 21 in beam) Modulus of Rupture	7	-	-	-	-	-	-
	28	-	-	519	-	-	-
	90+	270 (287 days)	-	-	-	593	-

Table 15. Strength Results for Laboratory-Prepared Samples for Route 208 (Fredericksburg)

Sample	Age, days	3% Cement		6% Cement		9% Cement	
		Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi	Strength, psi	Elastic Modulus, $\times 10^6$ psi
Compressive Strength Samples (6 ×12 in cylinder)	7	317	-	463	-	559	-
	28	377	-	337	0.4	954	1.31
	90+	441	-	782	1.02	1340	1.65
Tensile Strength Samples (6 × 12 in cylinder)	7	-	-	-	-	-	-
	28	72	-	-	-	-	-
	90+	64	-	113	-	186	-
Beam Flexure (6 × 6 × 21 in beam) Modulus of Rupture	7	-	-	-	-	-	-
	28	-	-	-	-	-	-
	90	123	-	151	-	274	-

Table 16. Strength Results for Laboratory-Prepared Samples for Staunton Base Aggregate

Sample	Age, days	3% Cement		6% Cement		9% Cement	
		Strength, psi	Elastic Modulus, $\times10^6$ psi	Strength, psi	Elastic Modulus, $\times10^6$ psi	Strength, psi	Elastic Modulus, $\times10^6$ psi
Compressive Strength Samples (6 ×12 in cylinder)	7	-	-	-	-	-	-
	28	937	0.87	2997	4.21	5266	5.26
	90+	807	-	3549	-	6003	-
Tensile Strength Samples (6 ×12 in cylinder)	7	-	-	-	-	-	-
	28	-	-	-	-	-	-
	90+	147	-	398	-	644	-
Beam Flexure (6 × 6 × 21 in beam) Modulus of Rupture	7	-	-	-	-	-	-
	28	-	-	-	-	-	-
	90	-	-	-	-	-	-

Cylindrical samples were tested for compressive and splitting tensile strength, and beams were used for flexural strength. Some of the cylinders were tested for modulus of elasticity before testing for compression or indirect tension. The additional limestone aggregate (fourth source) with VDOT 21A/B gradation was collected from Staunton, Virginia; this base aggregate showed a very high resilient modulus (when tested unbound in a separate study) as compared to the Middle Ground Boulevard aggregate (Hossain, 2015).

An increase in cement content shows a corresponding increase in strength for all four sources of aggregate. Compressive strengths at 7 and 28 days for different cement contents are compared in Figures 8 and 9. The variation in cement content from 3% to 9% produced compressive strengths at 7 and 28 days of approximately 600 psi and above 600 psi, respectively, for all four sources of aggregate. Therefore, it is practical to achieve around 600 psi compressive strength in 7 days using similar aggregates. Figure 9 clearly indicates that the Staunton aggregate with the higher resilient modulus results in higher compressive strength as compared to the Middle Ground Boulevard aggregate, which has a lower resilient modulus. It also indicates that the aggregate with the higher resilient modulus may also provide higher strength with lower cement contents than an aggregate with a low resilient modulus. So the achieved strength depends on not only the cement content but also the aggregate itself.

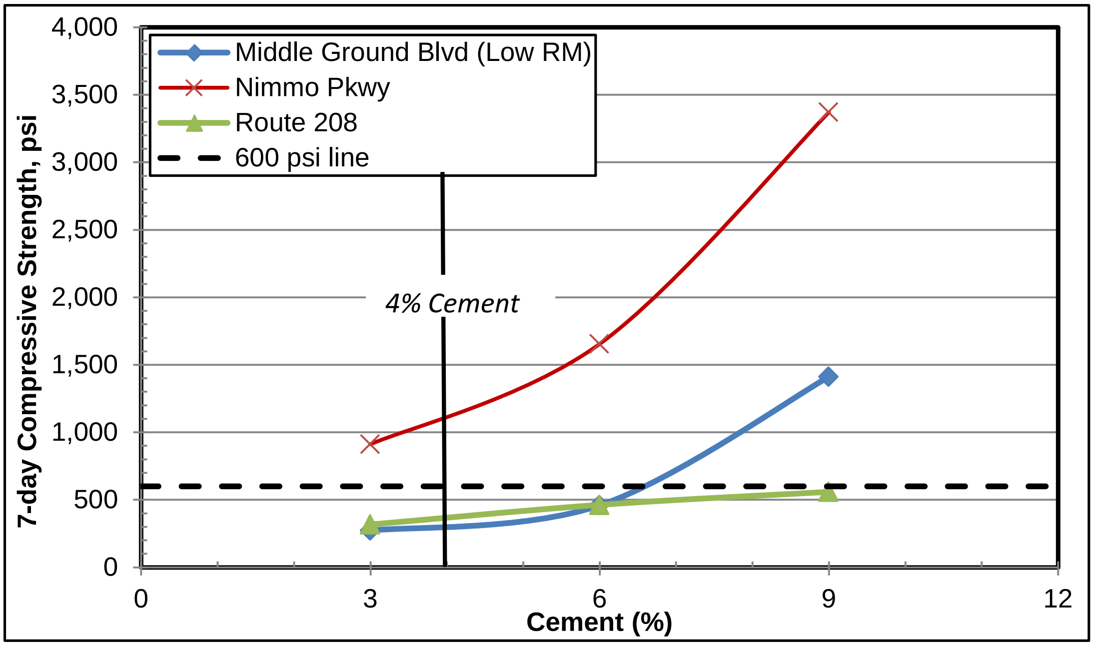

Figure 8. 7-Day Compressive Strength of CTA Produced With Vibratory Hammer. CTA = cement-treated aggregate; RM = resilient modulus.

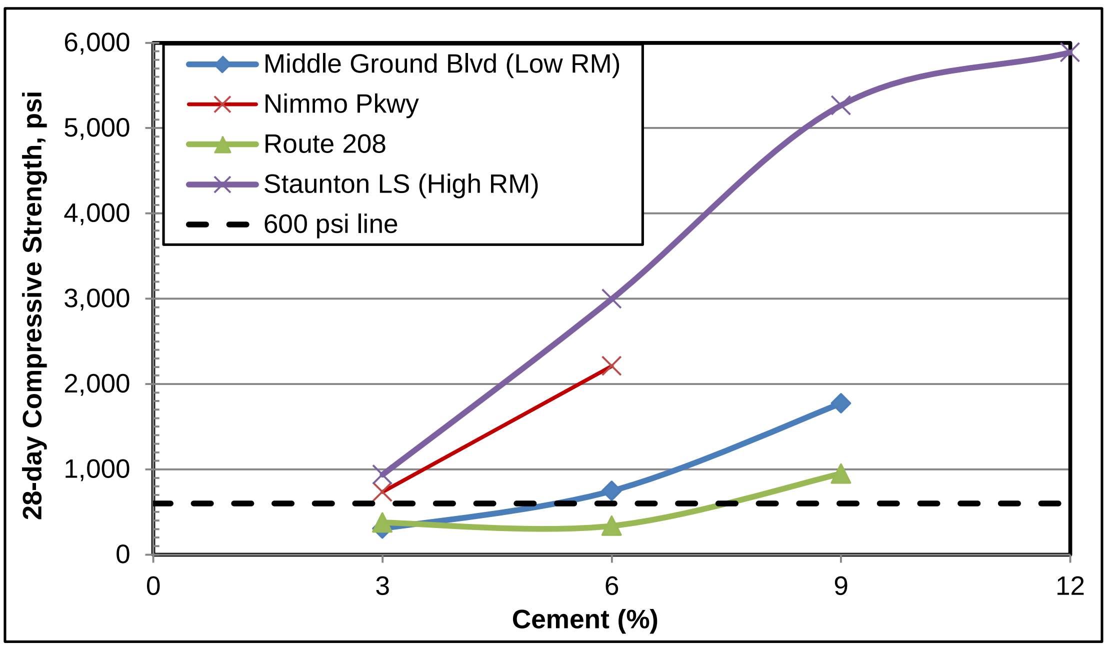

Figure 9. 28-Day Compressive Strength of CTA Produced With Vibratory Hammer. CTA = cement-treated aggregate; RM = resilient modulus.

All four sources of aggregate showed strength gain over time in Figure 10, as expected, but the observation was limited to the first 90 days after mixing and some mixtures have only two data points (7 and 28 days, or 28 and 90 days). The CTA prepared in the laboratory has continued to gain strength up to 90 days, but long-term projection was not possible from this study.

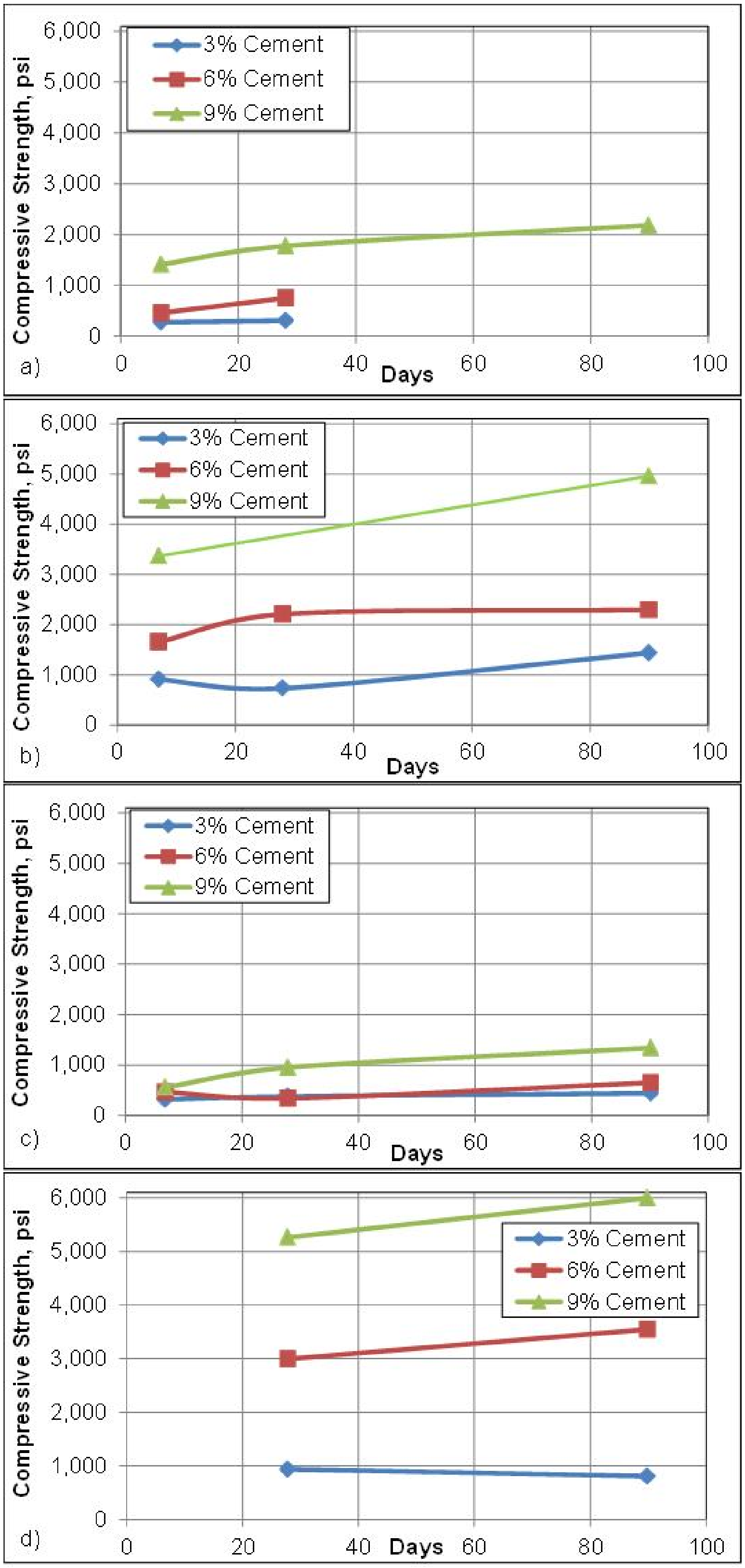

Figure 10. Compressive Strength Gain With Age in Laboratory-Prepared CTA: (a) Middle Ground Boulevard; (b) Nimmo Parkway; (c) Fredericksburg, Route 208; (d) Staunton limestone. CTA = cement-treated aggregate.

Field Evaluation of CTA

Field evaluation involved characterizing existing CTA using back-calculation analysis of non-destructive FWD test data, measuring actual field CTA cores for strength, and visually observing the performance of the pavement section for possible distresses related to the CTA properties.

FWD Back-Calculation Results

FWD testing was possible at only two sites: Middle Ground Boulevard, and Route 208. The CTA modulus of elasticity values were back-calculated using Evercalc and are presented here. The deflection data from 9,000 lbf were used for back-calculation.

Middle Ground Boulevard (Newport News)

FWD testing on Middle Ground Boulevard was conducted at 4 and 20 months after construction. Field cores showed average layer thicknesses of 10 in and 6 in for asphalt and CTA, respectively. Back-calculation of CTA layer moduli is shown in Figures 11 and 12. The average CTA modulus after 3 months was 325,000 psi, with a COV of 68% (minimum 126,000 psi; maximum 1,074,000 psi; SD of 221 psi), whereas the average CTA layer modulus after 20 months increased to 1,520,000 psi, with a COV of 42% (minimum 195,000 psi; maximum 2,000,000 psi; SD of 640 psi). This indicates that the CTA layer modulus increases over time in the field.

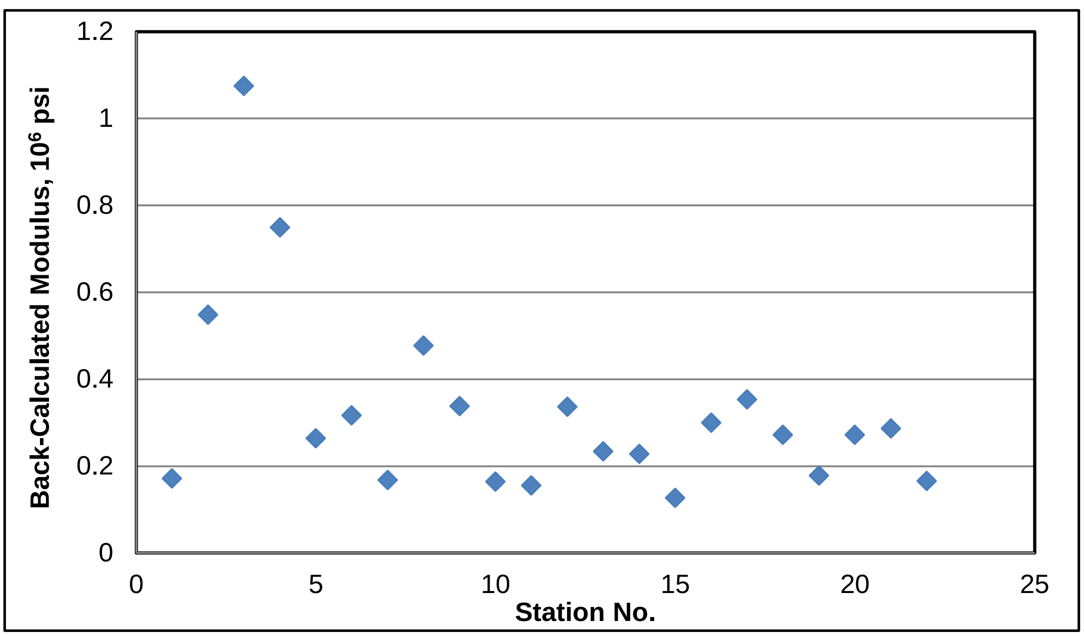

Figure 11. CTA Back-Calculated Layer Modulus at 4 Months After Construction (Middle Ground Boulevard). CTA = cement-treated aggregate.

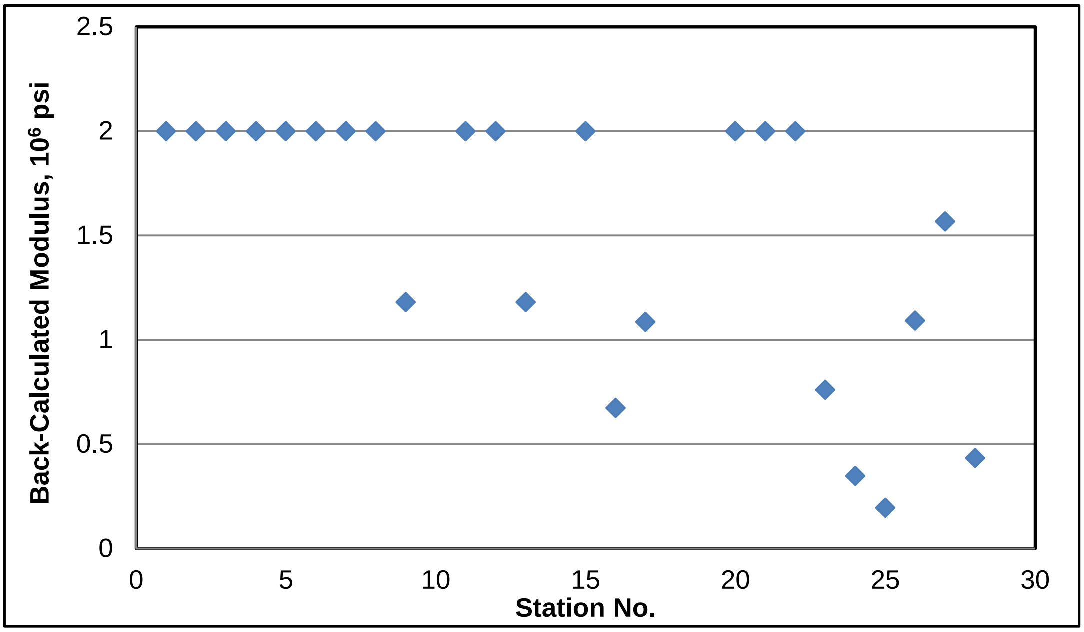

Figure 12. CTA Back-Calculated Layer Modulus at 20 Months After Construction (Middle Ground Boulevard). CTA = cement-treated aggregate.

Route 208, Fredericksburg District

In 2015, FWD testing was done on Route 208 on three sections that were constructed in 2011, 2012, and 2013, respectively. Back-calculation results are shown in Figure 13 for all three sections. Average back-calculated CTA layer elastic moduli were 2,078,000 psi; 1,514,000 psi; and 959,000 psi for construction years 2011, 2012, and 2013, respectively. The CTA layer elastic modulus increases over time similar to the trend observed for Middle Ground Boulevard.

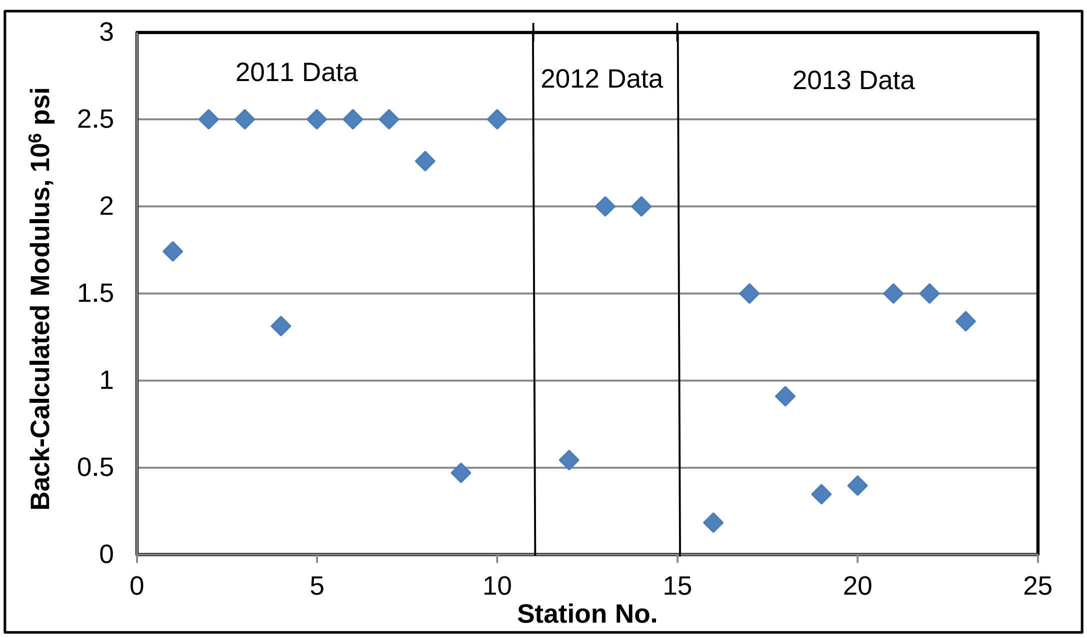

Figure 13. CTA Back-Calculated Layer Modulus (Route 208). CTA = cement-treated aggregate.

Table 17 summarizes the statistics for the back-calculated elastic moduli for Middle Ground Boulevard and Route 208. There is a trend of strength and stiffness gain over the life of these sections, in this case up to 4 years.

It is obvious from these two field projects that the back-calculated CTA modulus of elasticity increases with age. One year after construction, the modulus varied from 1 to 2 million psi with the current CTA construction practice. The CTA strength and stiffness results in these projects are highly variable, with a COV as high as 60%.

Table 17. Statistics of Back-Calculated CTA Modulus of elasticity From Field FWD Measurements

Site (Year Built)	Pavement Structure	Age Tested	Data Points	Back-Calculated Modulus of elasticity $\times 10^6$ psi				COV (%)
				Average	Standard Deviation	Minimum	Maximum	
Middle Ground Boulevard (2013)	10 in AC + 6 in CTA	3 months	22	0.326	0.223	0.127	1.075	68
		20 months	24	1.522	0.640	0.195	2.000	42
Route 208 (2013)	11 in AC + 6 in CTA	2 years	8	0.959	0.576	0.183	1.500	60
(2012)		3 years	3	1.514	0.841	0.543	2.000	56
(2011)		4 years	10	2.078	0.698	0.470	2.500	34

CTA = cement-treated aggregate; COV = coefficient of variation.

Strength of Field CTA Cores

As mentioned, multiple cores were collected from each site. All cores were 4-in cores with variable lengths. Most of the cores were tested for compressive strength, and a few of those with sufficient height were tested for modulus of elasticity beforehand. Densities of large pieces of broken cores from the strength test were measured using the water displacement method. Table 18 summarizes the test results for compressive strength of the 4-in cores from all sites. A few cores were also tested for splitting tensile strength.

The average compressive strength from field cores shows a wide variation, from 600 to 1,100 psi with the exception of one 36-year-old project for which it was about 2,150 psi. Their standard deviations (SDs) are also very high, with a range of 300 to 470 psi; these variabilities reflect both materials and construction practice. (The SD from two recent field projects was around 300 psi, and it seems the process control with such variability is achievable.) On the other hand, the variation in the unit weight was small, with a COV ranging from 1% to 4% except for the samples used for the modulus of elasticity test from U.S. 460, for which the COV was 20%.

Table 18. Statistics for Field CTA Core Strengths and Unit Weights

Site	Age	Unit Weight, lb/ft^3 (as-received or SSD)						Strength, psi (or Elastic Modulus, x 106 psi)					
		N	Avg.	SD	Min.	Max.	COV (%)	N	Avg.	SD	Min.	Max.	COV (%)
Compressive Strength for 4-in Cores													
Middle Ground Blvd.	4 months	4	144.0	2	143	147	1.3	4	519	295	110	739	57
Middle Ground Blvd.	20 months	5	143.0	3	141	148	2.1	7	850	302	614	1377	36
Route 208 (2011-13)	2-4 years	6	148.5	4.5	140.6	152.8	3.0	6	622	313	324	1168	50
U.S. 60W (CRCP, 1979)	36 years	5	147.7	2.2	144.9	150.5	1.5	5	2151	674	820	2233	31
U.S. 460E (Salem)	15 years	7	144.1	5.3	134.3	148.5	3.7	7	1079	467	710	1983	43
Splitting Tensile Strength for 4-in Cores													
Route 208 (2011-13)	2-4 years	7	145.0	3.9	139.7	150.4	2.7	7	101.7	42.5	65.2	172.8	41.8
Elastic Modulus for 4-in Cores													
U.S. 460E (Salem)	15 years	5	146.5	2.9	141.5	148.5	20.0	5	1.85	0.98	0.93	3.08	53

CTA = cement-treated aggregate; SSD = Saturated Surface Dry; Avg. = average; SD = standard deviation; Min. = minimum; Max. = maximum; COV = coefficient of variation.

Visual Observation

The five sites were visually observed for distress in 2015 and 2016. None of the recently constructed sites showed any cracks or other distresses. Figure 14 shows the pavement surfaces during recent visits to the Middle Ground Boulevard and Nimmo Parkway sites; only Nimmo Parkway has a minor longitudinal crack. U.S. 60 is a 36-year-old concrete pavement in poor condition that needs reconstruction.

U.S. 460 in Salem, a 15-year-old asphalt pavement, has moderate to severe block cracking throughout the section. Some cores were taken on top of cracks, but none of the cracks extended to the CTA layer, as would be the case with reflective cracks. The cracks extended only to a maximum 2.25-in depth, as shown in Figure 15.

Figure 14. Surface Condition in 2016: (a) Middle Ground Boulevard; (b) Nimmo Parkway

Figure 15. U.S. 460 in Salem, Top-Down Transverse Crack

CTA Mix Design

VDOT's current practice for CTA mix design does not provide a fixed strength; rather, cement content is fixed. With this approach, the strength and stiffness vary with the source of aggregate, as discussed previously. The main objective of this study was to recommend a reasonable value for CTA's modulus of elasticity for the design of pavement structures using the MEPDG approach. In order to ensure the achievement of the design modulus, the CTA mixture has to be designed with a target for strength instead of a constant (4%) cement content for all mixtures. The target value was based on the literature, the practices of other highway agencies, and VDOT field experience.

Selection of Strength

VDOT currently uses the 1993 AASHTO design guide and a layer coefficient of 0.2 for CTA. The guide provides a relative comparison of the layer coefficient for CTA with 7-day compressive strength and elastic modulus values as shown in Figure 16.

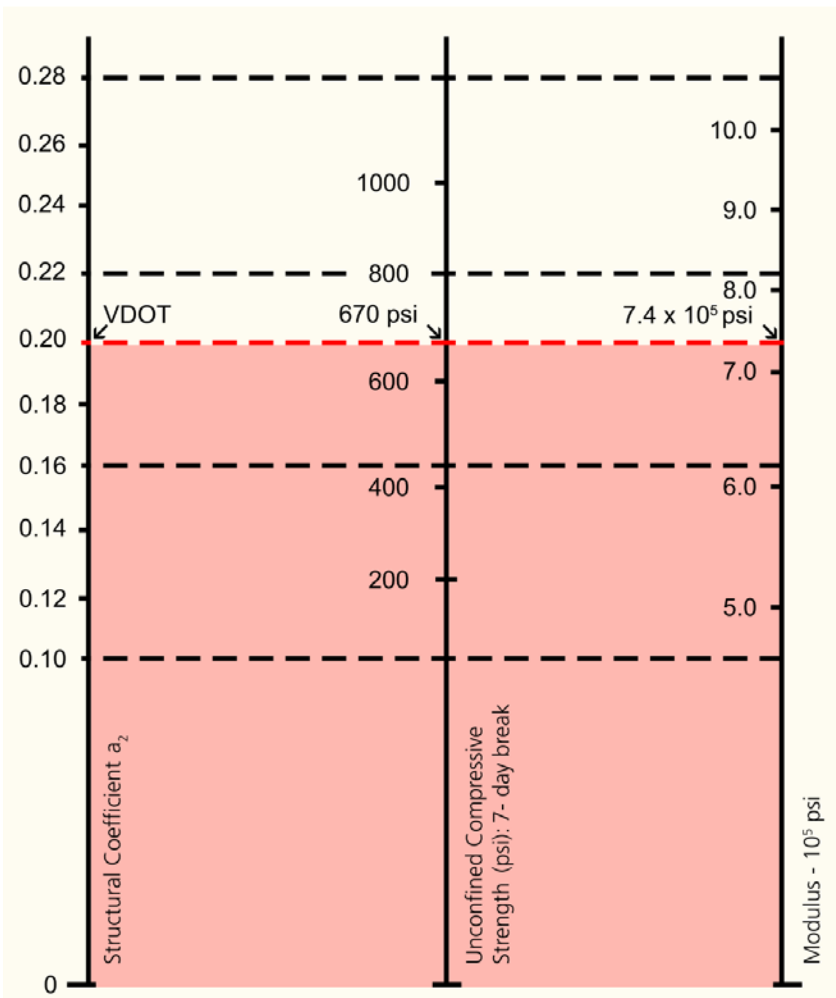

Figure 16. 7-Day Compressive Strength and Elastic Modulus of CTA Corresponding to Layer Coefficients (AASHTO, 1993). CTA = cement-treated aggregate; VDOT = Virginia Department of Transportation.

According to Figure 16, a layer coefficient of 0.2 for CTA would correspond to a 7-day compressive strength and modulus of 670 psi and 740,000 psi, respectively. Therefore, a target 7-day compressive strength for a mix design could be around 670 psi, but variability would have to be considered. No historical data are available to estimate the variability, but the field core strength values of existing CTA presented previously suggest very high variability. Therefore, a target design strength of 600 to 800 psi or even wider target seems reasonable until more data are available to assess the variability.

The design strength values used by different highway agencies are summarized in Table 4 and vary from 300 to 1,600 psi; many agencies use minimum and maximum limits to incorporate the variability. Some of these values are plotted in Figure 17 along with values of average strength from field projects and the 1993 AASHTO extrapolated value. It is important to point out that field core strengths are not 7-day compressive strengths but rather are more than 1 year old.

To remain consistent with current VDOT pavement design practice (AASHTO, 1993), a 7-day compressive strength of around 670 psi, which corresponds to a layer coefficient of 0.2, would be a reasonable target value for mix design. Findings in the literature (PCA, 1971) suggest that a 7-day compressive strength of more than 750 psi usually ensures freeze-thaw durability of CTA.

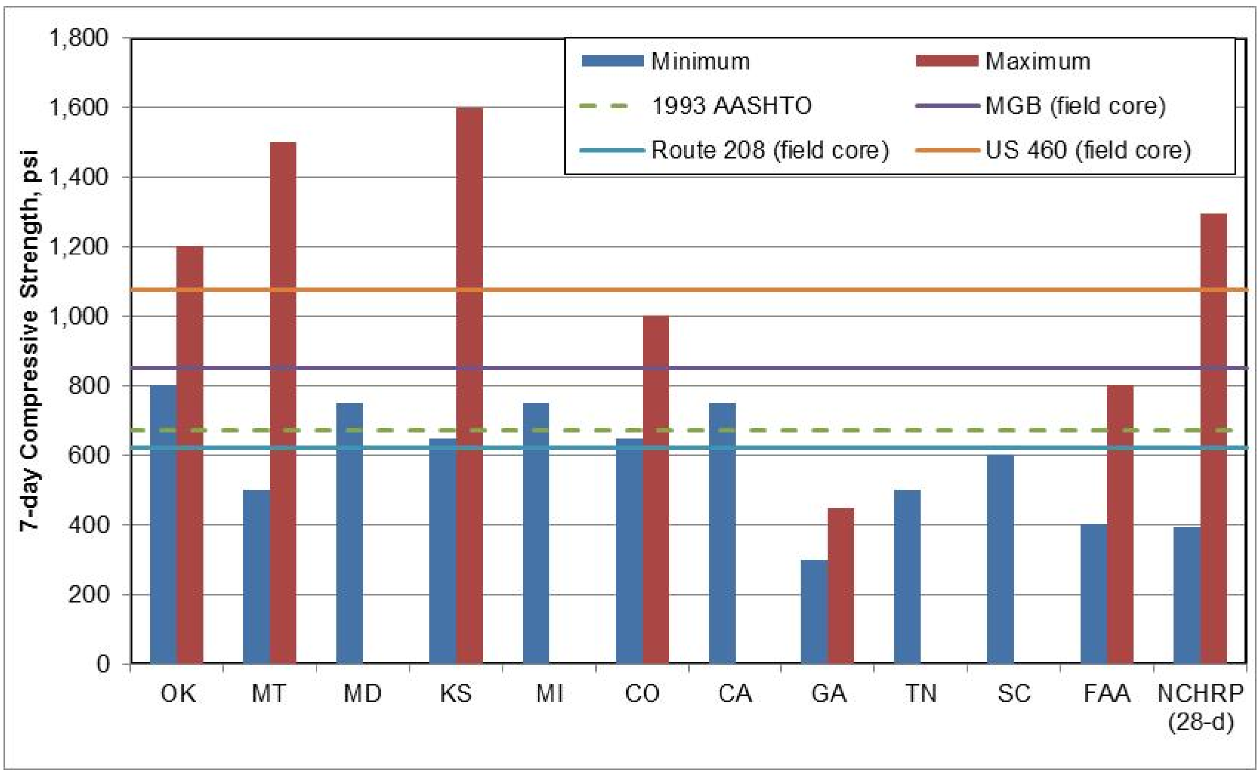

Figure 17. CTA Design Compressive Strengths From Perspectives of Different Entities. CTA = cement-treated aggregate; MGB = Middle Ground Boulevard; MGB, Route 208, and US 460 are field core strengths for more than a 1-year-old pavement; NCHRP (Wen et al., 2014) values are average 28-day strengths; 1993 AASHTO is the 7-day strength corresponding to a 0.2 layer coefficient; FAA = Federal Aviation Administration. Note: The information provided was obtained from the websites of the various entities or through e-mail communication. Details are available from the authors upon request.

A limited study in the laboratory also suggested a similar trend. CTAs produced with two sources of aggregate were tested for freeze-thaw durability in accordance with AASHTO T 136: Standard Method of Test for Freezing-and-Thawing Test of Compacted Soil-Cement Mixtures (AASHTO, 2010). After 12 freeze-thaw cycles, the source with the 7-day CTA compressive strength of 550 psi showed a mass loss of more than 50% whereas the source with a 7-day CTA compressive strength of 1,050 psi had less than 2% mass loss. A set of cylindrical samples (6 × 6 in) prepared with the modified Proctor hammer was used for this freeze-thaw test. Similarly, a wet-dry test in accordance with AASHTO T 135: Standard Method of Test for Wetting-and-Drying Test of Compacted Soil-Cement Mixtures (AASHTO, 2010) showed a mass loss of less than 4% and 8%, respectively, for CTAs prepared with those aggregates. The results for the CTA samples at the end of 12 cycles of both freeze-thaw and wet-dry testing are shown in Figure 18.

Figure 18. Freeze-Thaw and Wet-Dry Test Samples After 12 Cycles of Testing: (a) Source A freeze-thaw; (b) Source A wet-dry; (c) Source B freeze-thaw; (d) Source B wet-dry. Source A with 7-day compressive strength of 550 psi, and Source B with 7-day compressive strength of 1,050 psi. CTA = cement-treated aggregate.

Sample Preparation

Different highway agencies and researchers have mentioned using different size samples, including 4 in × 4.5 in, 6 in × 6 in, and 6 in × 12 in cylinders. Available compaction methods are Proctor hammer, modified Proctor hammer, vibratory hammer, and gyratory compactor. During this study, a vibratory hammer as specified in ASTM C1435 was mainly used to prepare 6 in × 12 in cylinders. Only a few 6 in × 6 in samples were prepared with the modified Proctor method. The effect of sample size on the strength was not examined during this study. Since all the samples had the minimum dimension of 6 in, no scalping (i.e., removal of coarser particles) was needed as the nominal maximum aggregate size was less than 1.5 in, which is one-fourth the diameter (6 in) of the sample. The practicality of sample preparation with different sizes such as 4 in × 8 in cylinders with a vibratory hammer, 6 in × 6 in cylinders with a modified Proctor hammer, or 6 in × 12 in cylinders with a vibratory hammer, and so forth, could be further explored. In order to gain the best benefit from compaction, samples will have to be prepared at optimum moisture content and compacted to maximum dry density in accordance with either Proctor or modified Proctor standards.

Mechanical Properties of CTA for MEPDG Analysis

The pavement design procedure according to the MEPDG concept requires input values for the mechanical properties of every layer in the system. Such values for CTA were recommended for VDOT's use based on the design strength, laboratory study, field performance, and MEPDG sensitivity analysis. The elastic modulus values corresponding to the design compressive strength in the laboratory study and the modulus values from the back-calculation of FWD data were considered. The sensitivity of the performance of a typical pavement structure to CTA modulus values using Pavement ME Design was also investigated.

The required input properties of CTA in Pavement ME Design were discussed previously. Selection of some specific values of such properties based on the design compressive strength of 600 to 800 psi, as mentioned previously, is discussed here. The general properties for both flexible and rigid pavements are layer thickness, unit weight, and Poisson's ratio. Layer thickness is the design thickness, and default values for unit weight and Poisson's ratio could be assumed as 150 pcf and 0.2, respectively. Although unit weight was not measured in most cases in this study, there are some reference values for unit weight from field cores provided in Table 18. A value of 145 pcf is a reasonable estimate as compared to the default value of 150 pcf in Pavement ME Design.

The two properties related to the strength of CTA are the modulus of elasticity and the modulus of rupture. Once design compressive strength is fixed between 600 and 800 psi, other values should be consistent with it. A reliable measured value of either is lacking because of difficulty in preparing proper size samples and challenges of instrumentation of low strength material. Despite such difficulties, some values were measured on 6 in × 12 in laboratory-prepared cylinders and some on field cores, as presented in Tables 13 through 16 and Table 18.

These values are plotted in Figure 19 and compared to the conventional concrete relationship, which was also recommended in the MEPDG manual of practice (AASHTO, 2015) to be used for CTA. It is obvious that at the lower strength range this relation over-predicts the modulus of elasticity. So the estimate of the modulus from the conventional relationship would be slightly less than 1.4 to 1.6 million psi for a compressive strength of 600 to 800 psi. On the other hand, the modulus of elasticity varies from 700,000 to 800,000 psi, from Figure 16 (AASHTO, 1993). But this 600 to 800 psi compressive strength would increase in the field over time. The average back-calculated elastic modulus of elasticity, shown in Table 18, varies from 1 to 2 million psi. Although the predicted distresses did not show much sensitivity to the modulus of elasticity in the current version (Version 2.2) of Pavement ME Design, a value from

1 to 2 million psi will be a reasonable estimate. With such a high degree of variability of the back-calculated modulus and measured compressive strength, a lower bound value of 1.5 million psi would be reasonable until more measured values can be gathered. Since it is not practical to collect a sample from the field to measure the residual (minimum) modulus of elasticity, the default value of 100,000 psi is recommended.

Again, the number of measured values of the modulus of rupture available from this study is limited and the values represent only laboratory-prepared beam samples (6 in × 6 in × 21 in). These values are plotted in Figure 20 against the average compressive strength from the same batches of mixture. These beam samples were prepared in two layers using a vibratory compactor as specified in ASTM C1435. There is a clear trend of increasing modulus of rupture with increases in compressive strength, and a 600 to 800 psi compressive strength would correspond to 160 to 200 psi. The typical value of the modulus of rupture suggested by Wen et al. (2014) is 107 psi, which seems low compared to the values observed during this study. Pavement ME Design requires a minimum value of 300 psi and a maximum value of 1,000 psi for the modulus of rupture, which seems to be high compared to the test results in this study. The 7-day compressive strength of 600 to 800 psi would increase over time; therefore, a value of 200 psi for the modulus of rupture would be reasonable for design purposes with consideration of the high variability in the field-measured strength and stiffness. As seen in Table 9, distresses predicted by Pavement ME Design are not sensitive to modulus of rupture values ranging from 50 to 300 psi.

Thermal properties of CTA and LTE at the cracks in CTA were not examined in this study. The use of Pavement ME Design default values is recommended for these properties for design purposes.

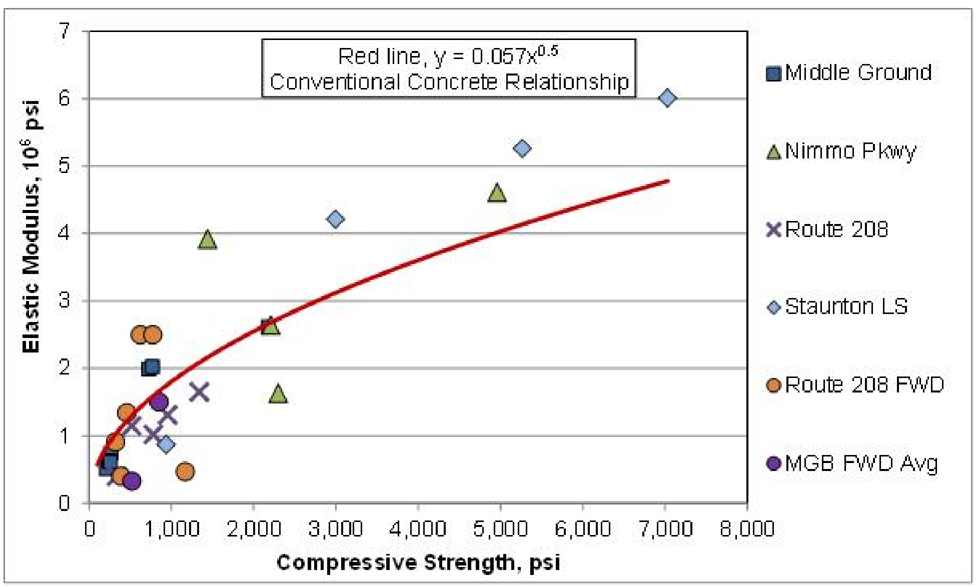

Figure 19. Relationship Between Compressive Strength and Elastic Modulus. Middle Ground = Middle Ground Boulevard; LS = limestone; FWD = falling weight deflectometer.

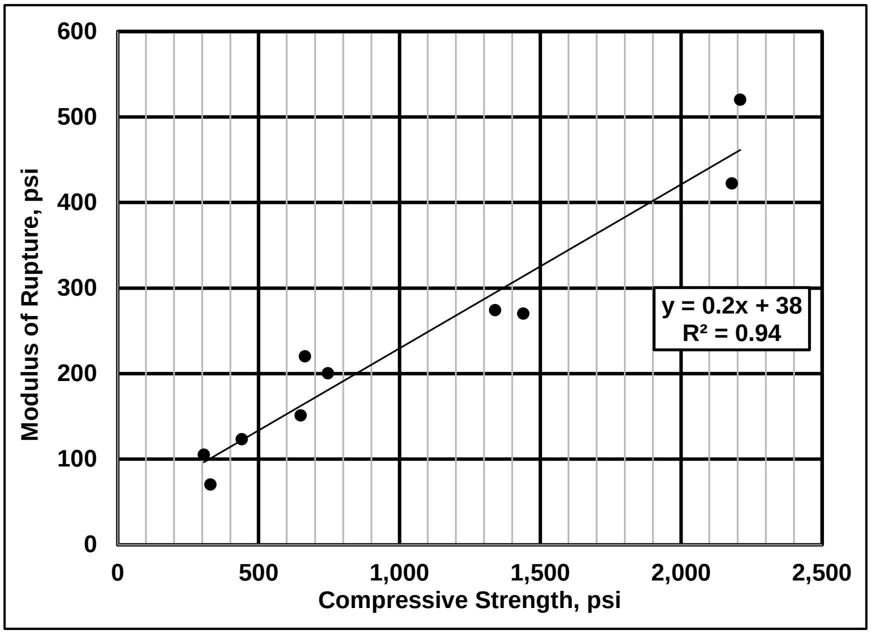

Figure 20. Relationship Between CTA Compressive Strength and Modulus of Rupture. CTA = cement-treated aggregate.

SUMMARY OF FINDINGS

- Many highway agencies use CTA as a pavement layer; most have some sort of 7-day compressive strength requirement for their mix design, which varies from 300 to 1,600 psi; often there is a minimum and maximum strength specified to account for the variability. Some states have restrictions on the amount of cement content, generally less than 5%. There are requirements for aggregate properties, such as percent passing the No. 200 sieve, Atterberg limits, and nominal maximum size. Two states use freeze-thaw durability as a design requirement. A sliding pay scale is also used by two states, one using compressive strength and the other using field density as the basis for payment. Required field compaction among the states varies from 95% to 98% of Proctor density. Many states allow the use of fly ash in CTA up to 25% of cementitious materials.

- The CTA properties required as input to Pavement ME Design are unit weight, Poisson's ratio, modulus of elasticity, modulus of rupture, transverse crack spacing, load transfer efficiency, thermal conductivity, and heat capacity. The predicted distresses were not found to be sensitive to any of these properties, but in all cases transverse cracks were predicted to reflect through the asphalt overlay within a design life of 30 years. Therefore, it will be useful to keep transverse cracks to a minimum in the CTA, possibly by controlling the amount of cement (or maximum compressive strength) to reduce drying shrinkage cracks.

- When loose CTA samples were collected from two field projects and tested for hardened strengths, they showed differences in average strengths (28-day compressive strength, 245 versus 477 psi) and variability (COV, 11% versus 32%), as shown in Tables 11 and 12. Since the cylinders and beams were prepared using a vibratory hammer and cured in the laboratory, the difference in strength is attributed to aggregate source, plant production, cement content, and sampling error.

- When CTAs are spread, handled, and manipulated in the field with a motor grader and/or box spreader, they can easily get dry and may need rewetting for compaction. The blading to achieve thickness can also result in loss of compaction and drying. These operations are time-consuming and sometimes make finishing the compaction within 2 hours of mixing a challenge. All of these factors contribute to the high variability of core strengths observed in the field, as shown in Table 18, where the COV is as high as 60%.

- In the laboratory study, for all aggregates, CTA strength increased with an increase in cement content (Figure 9), but there were differences in strength among the aggregates when the cement content is the same. One source of aggregate with a high resilient modulus achieved higher strength than another aggregate with a lower modulus for the same cement content. This difference is attributed to aggregate properties such as mineralogy; gradation; particle shape, texture, and angularity; Atterberg limits; and percent passing the No. 200 sieve.

- A 7-day compressive strength of 600 to 800 psi is achievable for aggregate sources from Virginia with varying amounts of cement.

- It was often difficult to measure the CTA modulus of elasticity because of the challenges in instrumenting CTA cylinders or cores related to low strength and surface irregularities. In addition, the length of field cores was mostly less than 7 in, which is the length required to be able to mount the deflection-measuring jig. Despite these difficulties, some measurements of modulus of elasticity were performed on both cylinders and cores. Their relationship with compressive strength is shown in Figure 18 and is compared to the conventional concrete relationship. It is obvious that at the lower strength range, such as with CTAs, this conventional concrete relationship over-predicts the CTA modulus of elasticity. Considering the high variability of the back-calculated CTA modulus of elasticity and core compressive strength in the field, a modulus of elasticity value of 1.5 million psi is recommended.

- The modulus of rupture showed a good relationship with compressive strength in laboratory-prepared samples, as shown in Figure 20. This relation could be used to estimate the Pavement ME Design input corresponding to the design compressive strength. A value of 600 to 800 psi compressive strength would indicate a modulus of rupture of 160 to 200 psi. If the design 7-day compressive strength is 600 to 800 psi, it would increase over time in the field, but at the same time there is an indication of very high variability in field strength, so a value of 200 psi as an input should be reasonable.

- Although a limited study on durability was conducted, a CTA sample with a 7-day compressive strength of around 550 psi had a greater than 50% mass loss compared to less than a 2% loss for a CTA with a 7-day compressive strength of 1,050 psi after 12 freeze-thaw cycles in accordance with AASHTO T 36. When similar samples were exposed to 12 wet-dry cycles in accordance with AASHTO T 135, the mass losses were less than 4% and 8% for samples with a 7-day compressive strength of 1,050 psi and 550 psi, respectively. This finding of freeze-thaw durability is in line with observations in the literature of good durability for CTA when the 7-day compressive strength is more than 750 psi.

CONCLUSIONS

- *Aggregate properties affect the strength of CTA.* An aggregate with a higher resilient modulus showed a higher compressive strength with the same amount of cement.

- *CTA design based on a fixed cement content would be difficult to use in mechanistic pavement analysis where a modulus value is required as input.* A fixed amount of cement (say 4%) could generate a range of compressive strengths in CTA, depending on the aggregate source.

- *VDOT's current CTA production and construction process generates a very high variability in the compressive strength of field cores.*

- *A 7-day compressive strength of more than 600 psi is required for an equivalent layer coefficient of 0.2,* which represents current VDOT practice under the 1993 AASHTO design guide procedures.

- *The CTA compressive strength of field cores varies from 600 to 1,100 psi for recent VDOT projects, with a variability of 300 to 470 psi.* These CTAs were in service from 1 to 15 years.

- *The FWD back-calculated modulus of elasticity varies from 1 to 2.5 million psi for a few VDOT field projects.*

- *The modulus of rupture for laboratory-prepared CTA samples shows a strong relation with compressive strength.* The modulus of rupture would vary from 160 to 200 psi for a corresponding compressive strength of 600 to 800 psi.

- *The predicted distresses for both flexible and rigid pavements using Pavement ME Design (Version 2.2) are insensitive to the mechanical properties of CTA.*

RECOMMENDATIONS

1. *VDOT's Materials Division should use the following mechanical properties of CTA in Pavement ME Design.*

    - *Unit weight (pcf):* 145 pcf or the default value of 150 pcf
    - *Modulus of elasticity:* 1,500,000 psi
    - *Minimum modulus of elasticity:* 100,000 psi
    - *Modulus of rupture:* 200 psi
    - *All other inputs:* default values.

2. *VDOT's Materials Division in collaboration with VTRC should develop a specification to incorporate CTA mix design for a target strength of 600 to 800 psi and also incorporate high variability (considering a standard deviation of 300 psi or so) until more data are available to assess variability.*

BENEFITS AND IMPLEMENTATION

Benefits

This study was conducted to develop reference mechanical properties of CTA for the design input parameters of the MEPDG method. The mechanical properties values recommended in this study will be implemented by VDOT's Materials Division by incorporating them into VDOT's *Pavement ME User Manual*. VDOT's State Materials Engineer will implement such CTA design based on strength through changes in the specifications. Once such specifications implementing CTA based on target strength are accepted in the VDOT system, the mechanical property values presented in this study can be referenced for pavement designs that follow the new MEPDG method and be incorporated with the MEPDG protocol as it is adopted by VDOT.

The benefits of implementing Recommendation 1 will be the facilitation of statewide implementation of Pavement ME Design software. Since the suggested mechanical properties of CTA in Recommendation 1 are specific to the materials used by VDOT, they will provide better performance predictions compared to default values.

The benefits of implementing Recommendation 2 will be the assurance of achieving the specified mechanical properties of CTA (in Recommendation 1) in the field.

Implementation

With regard to Recommendation 1, VDOT's Materials Division has already incorporated the suggested values in VDOT's Pavement ME User Manual—Draft (VDOT, 2017a).

With regard to Recommendation 2, VDOT's Materials Division has developed a draft special provision to implement strength-based CTA design. A task group was formed with representatives from VDOT's Materials Division, VDOT's Construction Division, VTRC, the VDOT districts, and the aggregate industry (through the Virginia Transportation Construction Alliance). The group decided to implement a strength-based design in two phases: (1) approval of CTA mix design based on strength, and (2) acceptance of CTA based on measured strength.

During Phase I, contractors and/or producers will submit their CTA mix design only to satisfy the target strength. The job-mix formula will be approved by VDOT. Acceptance of CTA in the field will be based on the existing protocol, including the titration test. Since the variability in strength measurements from this study was based on a limited observation, the task group decided that more strength data would be gathered during Phase I. VDOT's Materials

Division, in collaboration with VTRC, will collect raw CTA samples during production and prepare samples for strength testing. Data will be gathered over a period of 1 to 2 years depending on the availability of an adequate number of projects to estimate the variability. VDOT's Materials Division and VTRC will also investigate the sample preparation issues such as size and compaction techniques.

Based on the findings from Phase I, an acceptance plan will be developed whereby CTA strength could be the basis for payment and will be implemented during Phase II.

The entire implementation is expected to be complete in 5 years.

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APPENDIX

SUMMARY OF STATE SURVEY RESPONSES FOR CTA SPECIFICATION AND USE

DOT	Spec.	Strength Criteria	Aggregate Gradation/Cement Content	QC/QA	No. Samples/ Size	Compaction	Layer Coefficient	Other Comments
Oklahoma (section 317)	Yes	7-day compressive strength Min:600 psi Max:1,200 psi	3-5% cement and fly ash 1-15% No. 200		Split cylindrical molds (6 in x 6 in)	Sleeveless hammer/Standard Proctor rammer	MEPDG; 50-75k psi	More than 95% Proctor in 2 hr
Montana (section 304)	Yes	7-day compressive strength Min:500 psi Max:1,500 psi	Fly ash, LL<30, PI<7, F/T<14% mass loss, cement>4.5% 4-12% No. 200	Sliding pay factor: 400-2,000 psi (pay adjustment)	Standard Proctor (4 in x 4.5 in)	98% of maximum dry density within 2 hr of mixing	0.2	Minimum compaction 95%
Maryland (section 500/ MSMT 321)	Yes	7-day compressive strength Min:750 psi	Cement 3.25-4.75%, PI<6, 0-8% No. 200		Cylindrical molds (6 in x 8.5 in)	Compact each layer using 122 uniformly distributed blows of the compaction rammer	0.25	Stabilized GAB projects have not been done for a long time
Kansas	Yes	7-day compressive strength Min:650 psi Max:1,600 psi	Fly ash	PWL (ref. SD 260 psi)		Compact each lift of CTB to a minimum of 95% of the standard density in 2 hr		
Michigan	Yes	7-day compressive strength Min:750 psi	PI<6, 0-25% No. 80	Sliding pay scale: 100% pay when >98% compaction Reject <95% compaction		The laboratory specimens shall be compacted and tested in accordance with ASTM D558.		The freeze-thaw weight loss shall not exceed 14% in accordance with ASTM D560.
Colorado (City of Thornton)	Yes	7-day compressive strength Min:650 psi Max:1,000 psi	Cement >5% LL<30, 3-15% No. 200				0.23	
California	Yes	7-day compressive strength Min:750 psi	3-15% No. 200	Minimum 750 psi, 0-19% No. 200			Does not use AASHTO Guide; employs Gravel Factor of 1.2 to 1.7	95% compaction in 2.5 hr (trimming within 2 hr)

Georgia	No	300 psi (+150 psi buffer to account for differences in lab and field conditions)		As per special provision, tests are conducted, after 7 days of curing, every 1,000 ft by extracting 6-in cores from in-situ base.	-	.	0.20- 0.28	Rarely uses CTB construction because of ready availability of excellent building materials
Tennessee	Yes	500 psi			-		0.23 for CTB; 0.15 for soil cement	-
Arizona		-						Mix design based on strength
South Carolina	Yes	Compressive strength of 600 psi	LL<25, PI<6 No. 200: 0-20% Cement content 2.5% and 5.0% by weight of the surface dry aggregate		Three test cylinders in accordance with SC-T-142	Molding roller-compacted concrete in cylinder molds using a vibrating hammer		Place CSAB with a high-density asphalt-type paver subject to approval
Missouri	No	-			-	-	-	Use depends on functional class
Ohio	No	-			-	-	-	-
Nebraska	No	-			-	-	-	Does not use CTA
Washington State	No	-			-	-	-	Does not use CTA
Colorado	No	-			-	-	-	Does not use CTA
New Jersey	-	-			-	-	-	Have not used CTA for some time
South Dakota	No	-			-	-	-	-
Indiana	No	-			-	-	-	Does not use CTA
Florida	No	-			-	-	-	-
Connecticut	No	-			-	-	-	Does not use CTA
New Mexico	No	-			-	-	-	-

Louisiana	-	-			-	-	-	-
Federal Aviation Administration		7-day compressive strength Min:400 psi Max:800 psi	F/T<14% loss in 12 cycles, MNS 1 in, 0-25% or 10-35% No. 80, LL<25, PI<6					Maximum 28-day compressive strength 1,000 psi
Wen et al. (2014) NCHRP Report 789 (level 3)	392	28-day compressive strength Min:392 psi Max:1,296 psi		763 psi avg.				