Construction QA/QC Testing versus Selection of Design Values for PCC Pavement Foundation Layers

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ABSTRACT

Traditional quality assurance/quality control (QA/QC) practices for construction of embankment, subgrade, and aggregate base layers in Portland cement concrete (PCC) pavement foundation systems generally rely on a soil classification scheme, percent relative compaction, and moisture content. These parameters are measured periodically during construction from a small volume of material to quantify acceptance. Pavement analysis and design, on the other hand, is based on selection of mechanistic-input parameters, such as layer thickness and elastic modulus values. Although indirect, the parameter values measured during QA/QC testing are often assumed to be surrogates to mechanistic parameters, but the relationships are complex, nonunique, and highly variable. A disconnect therefore exists between what is selected for design and the parameter values chosen to "ensure" quality during the construction process. Further, the spatial nonuniformity of the pavement foundation layers, although often recognized as "key" to pavement performance, is not addressed by construction QA/QC or pavement design and rarely in pavement analysis. This paper highlights some of the assumptions with selecting pavement design values and the methods used for construction QA/QC testing, focusing specifically on geotechnical parameters. Weaknesses with traditional approaches are identified, and new ideas are highlighted that might better link construction quality to the selection of pavement design inputs.

Key words: construction—foundation—pavement—quality control—subgrade

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PROBLEM STATEMENT

Quality pavement foundation layers are essential to achieving excellent pavement performance. In recent years, as truck traffic has greatly increased, the foundation layers have become even more critical to successful pavement performance. Unfortunately, there are still many pavement failures in the United States related to inadequate subbase, natural subgrade, and embankment, which are commonly referred to as foundation layers or roadbed. Recent accelerated pavement testing of concrete pavements has reiterated how the supporting foundation layers and stiffness affect the concrete pavement performance (Cervantes 2009). Factors that contribute to pavement foundation problems are poor construction practices, ineffective Quality Assurance/Quality Control (QA/QC) testing methods and sampling plans, material variability and nonuniformity, unpredictable long-term material behavior, poor verification of material properties during construction, insufficient development of performance-related specifications, and lowcapital investment in the foundation layers. This paper compares some of the assumptions used to select pavement design inputs and the methods used for construction QA/QC testing, focusing specifically on the geotechnical parameters.

Pavement designs are typically completed during the project design phase and are based on the data gathered from the geotechnical site investigation. The designer is required to develop foundation layer parameters based on limited information contained in the soil boring logs. Additionally, the designer has to estimate the material properties of any future fill materials based on the proposed project specifications. The pavement designer is commonly not involved in the construction QA/QC team. The QA/QC testing completed during construction is often insufficient to provide an acceptable level of reliability with regard to uniformity of the pavement foundation layer. A disconnect therefore exists between what is selected for design and what is ultimately constructed. In this paper, QA/QC testing methods that have the potential to bridge the gap between field measurements during construction and the original design inputs are highlighted.

FOUNDATION LAYERS FOR LONG LASTING PAVEMENTS

All pavements are ultimately supported by foundation layer soils. The three essential components to a high-performing pavement structure are illustrated in Figure 1 (Texas DOT 2008). If any one of the three is deficient, a poor performing pavement is likely to result. Pavement design procedures and some of the current deficiencies with the QA/QC system will be briefly introduced in subsequent sections. Although quality materials are an essential component of the pavement system, they will not be discussed in this paper.



Figure 1. Essential components of a high performing pavement structure

FOUNDATION LAYERS IN PAVEMENT DESIGN

The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, part 2 "Design Inputs," chapter 1 "Subgrade/Foundation Inputs" states, "It is advisable to use caution when selecting a design subgrade value for a non-homogeneous subgrade" (ARA 2004). Information gaps with regard to foundation soils are also mentioned in the interim *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice* (AASHTO 2008). Statements from the interim guide include "Variation along a project creates a much more difficult task to obtain the appropriate inputs for a project" and "The number of samples that need to be included in the test program is always the difficult question to answer."

Pavement Foundation Analysis

The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, part 2 "Design Inputs," chapter 1 "Subgrade/Foundation Inputs" (ARA 2004) states, "Pavement design requires a single subgrade design value, for example California Bearing Ratio (CB), Resilient Modulus (M_R), or modulus of subgrade reaction (k-value)." The type and thickness of pavement layers developed during design are based on strength tests or various empirical correlations based on tests from the laboratory prior to construction or from tests during construction. Common practice in the United States is to design pavement layers prior to construction and to provide specifications during construction that will correlate to the pavement foundation inputs considered in design. Subsequently, QA/QC practices in the field during construction are necessary to "verify" the original design assumptions.

The stiffness of the foundation layer is often considered more critical to asphalt pavement design than PCC pavement design. A stiffer subgrade in an asphalt pavement design can significantly reduce the thickness of the asphalt pavement. In PCC pavement design, a modulus of subgrade reaction from 27 MPa/m (100 psi/in) to 136 MPa/m (500 psi/in) will only reduce the concrete pavement thickness by approximately 20 percent (ACPA 2007). Therefore, pavement engineers have purported the concept that PCC pavements effectively bridge relatively weak subgrades as long as the support conditions are "uniform."

Problems with Typical Pavement Foundation Design

Pavement design requires assumptions be made to select the foundation input values. Most projects have differing materials that require the designer to use either an average, 85% greater than, or minimum design strength for the foundation soils. Many different methods and correlations exist to estimate the stiffness of the foundation layer soils. For example, the Mississippi Department of Transportation utilizes a correlation from the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System and Group Number to estimate the California Bearing Ratio (CBR). Another common correlation, presented below, relates M_R (psi) to the CBR. The constant of 1,500 may vary from 750 to 3,000 (Huang 1993).

$$\mathbf{M}_{\mathbf{R}} = 1500^{*} \mathbf{CBR} \tag{1}$$

After selection of the single pavement foundation parameter for design, the next step is to verify the design assumption in the field during construction. Present day field testing procedures are not capable of easily verifying the design parameter due to the fact that stiffness is difficult to rapidly measure. Further, the value measured during construction may not have any significance to the final pavement design since the foundation soils will often change strength parameters after constructingthe pavement and experiencing changes in the moisture content (Griffiths and Thom 2007).

The *Mechanistic-Empirical Pavement Design Guide* (MEPDG) varies the subgrade stiffness with geographic location and freezing days. A seasonal study in Minnesota quantified the wide range of foundation soil stiffness. A frozen resilient modulus for different types of subgrade layers was found to be in the range of 1,100 MPa (16,000 psi) to 3500 MPa (50,700 psi) during the winter and in the range of 69 MPA (10,000 psi) to 191 MPa (27,700 psi) in the summer (Ovik et al. 1999). Pavement designers attempt to control the effects of frost heave and spring thaw through material specification, soil stabilization, and more recently, with the incorporation of geosynthetics that can provide a moisture barrier.

Due to variable soil, environmental, and construction conditions, determining the appropriate foundation layer parameters for pavement design is challenging. The current pavement engineering design methodologies based on one foundation layer input parameter can simply be arrived at by connecting a few lines on a chart. This oversimplification of the pavement design process has lead to the resistance of implementing new analyses and QA/QC methodologies that more fundamentally model the foundation contributions to pavement behavior (Qubain 2009).

QUALITY ASSURANCE/QUALITY CONTROL (QA/QC) TESTING

The pavement designer attempts to achieve the assumed pavement design input parameters in the field during construction through specification and QA/QC testing. Without an effective QA/QC program, construction practices can overturn the best designs (Qubain 2009). Inadequate observation and QA/QC testing by qualified engineers and technicians have been a major cause of premature pavement deterioration over the years.

QA/QC during Construction

Over the years, the primary foundation QA/QC practice has consisted of moisture and density control (Yoder 1959). The moisture and density requirements are specified in the contract documents, and field personnel typically utilize either the sand cone method or the nuclear gauge method to determine the in situ moisture and density of the soil. Although some specific projects require some form of stiffness test, most highway and commercial work QA/QC programs are based on soil classification, percent relative compaction, and moisture content. In determining the percent relative compaction, the typical laboratory method consists of either the Standard Effort or Modified Effort Compaction Test (AASHTO T99 or 180). Some departments of transportation have specialized procedures for determining the maximum unit weights and optimum moisture contents. A typical specification requires a testing frequency of approximately one moisture and density test per lift for every 2,500 to 10,000 square feet of area, which is approximately equal to every 100 to 500 feet along a highway embankment. Often, the sampling frequency on a per volume basis decreases with increasing volume fill placement. Frequency of QA/QC testing is unique to every project. Compaction tests are typically taken on samples daily or when the material changes in classification.

Potential Problems with QA/QC during Construction

Fifty years ago, Yoder (1959) stated, "Ideally, the field control should be based upon a strength test." The design methodologies discussed previously all require some type of stiffness input for design. Current practice utilizes moisture and density testing during construction. A single moisture and density test evaluates approximately one square foot based, and therefore, QA/QC testing is performed on about 0.01% of the constructed material. The test spacing is so infrequent that a geospatial analysis of the data and uniformity analysis cannot be completed. Current practice attempts to overcome the shortcomings of the moisture and density control QA/QC method by utilizing the experience and judgment of the soils

technician or by specifying proof, rolling the construction area with a loaded vehicle. These methods do not always provide the level of reliability needed to construct long-lasting pavements.

Specifications typically require moisture and density testing during cutting and filling earthwork operations. A common problem in pavement construction is stable pavement layers are rutted and loosened from construction traffic and then not recompacted prior to placing the pavement layers. Specifications typically do not explicitly state to scarify and recompact the subgrade immediately before placement of the subbase or subsequent pavement layers. Improved specifications and trained construction personnel are two areas that could provide improvement in the construction process.

Traditional QA/QC moisture and density testing need to be supplemented with methods that will provide continuity between the design, construction, and laboratory testing. The QA/QC method of moisture and density control during earthwork, which has been the standard for over 50 years, must be improved to provide an acceptable level of reliability for pavements. These supplemental methods will provide the link so that performance-based specifications can be implemented (Nazarian and Correia 2009).

NONUNIFORMITY OF PAVEMENT FOUNDATION LAYERS

Although a significant national effort is going into pavement assessment and performance prediction, limited effort has focused on the as constructed, nonuniformity of pavement foundation layers. Improved pavement design methods do not fix problems with poor construction and QA/QC testing practices and do not adequately address the resulting nonuniformity that can be directly tied to pavement performance.

According to National Cooperative Highway Research Program (NCHRP) Report 583 (2007), "The bestperforming pavements...were those with bases that were neither too weak (untreated aggregate) nor too stiff (lean concrete)." The American Concrete Pavement Association (ACPA 2007) reports that "...low strength soils where construction methods provide reasonably uniform support perform better than stronger soils lacking uniformity." Stiffness, strength, and uniformity are clearly engineering parameters that affect performance, yet only limited specifications and protocols have been developed for construction, testing, and evaluation to verify achievement of these parameters.

Nonuniformity is the result of either changing materials on a jobsite or poor quality construction practices. In order to mitigate the nonuniformity of as constructed foundation layers, trained construction and QA/QC personnel are required to ensure the intended pavement design parameters are achieved during construction. The disconnect between the pavement designers and the construction process has been discussed previously. Another disconnect is found when the construction and QA/QC personnel do not understand the concept of uniformity, how the construction process impacts the performance of the pavement system, and do not have the tools to characterize uniformity.

EMERGING TOOLS FOR QA/QC TESTING

Beyond proper training of construction and QA/QC personnel, new QA/QC testing tools that can measure the stiffness of the pavement foundation layers more frequently and rapidly must be incorporated. New QA/QC tools must be capable of providing an acceptable level of reliability while also providing an increase in the number of test points in relation to the present system of moisture and density control. Implementation of new construction, testing, and characterization technologies, including intelligent compaction and rapid non-destructive testing methods, have the potential to improve selection of foundation materials, characterization of performance-related engineering properties, and development of construction specifications with meaningful QA/QC testing. Fundamental to the QA/QC testing is that the measured foundation layer properties must be linked with the selected pavement design inputs.

Intelligent Compaction

Intelligent compaction technology uses accelerometers installed on the drum of a vibratory roller to measure roller drum accelerations in response to soil behavior during compaction operations. The use of machine drive power (MDP) as a measure of soil compaction is a concept originating from study of vehicle-terrain interaction. MDP, which relates to the soil properties controlling drum sinkage, uses the concepts of rolling resistance and sinkage to determine the stresses acting on the drum and the energy necessary to overcome the resistance to motion (White et al. 2007). Figure 2 presents an example of subgrade nonuniformity based on intelligent compaction maps with Compaction Meter Value (CMV) measurements.



Figure 2. Nonuniformity observed in pavement foundation based on intelligent compaction measurements (from White et al. 2007)

Dynamic Cone Penetrometer

The dynamic cone penetrometer (DCP), shown in Figure 3, is a testing device that provides the stability characteristics of pavement layers. The test involves dropping an 8 kg hammer 575 mm and measuring the penetration rate of a 20 mm diameter cone. Penetration index, which typically has units of mm per blow, is inversely related to penetration resistance (i.e., soil strength). The DCP test has been correlated to CBR as presented in ASTM D 6951-03.



Figure 3. Strength determination using dynamic cone penetrometer (from White et al. 2007)

Clegg Impact Hammer

Clegg impact hammers, which were developed by Clegg during the late 1970's and later standardized as ASTM D 5874-02 for evaluating compacted fill and pavement materials, are shown in Figure 4. The Clegg impact value is derived from the peak deceleration of a 4.5 kg or 20 kg hammer free falling 450 mm in a guide sleeve for four consecutive drops. Clegg impact values (CIV 4.5 kg or CIV 20 kg) have been correlated to CBR (Clegg 1986, White et al. 2007).



Figure 4. Strength determination using Clegg impact testers: 4.5-kg (left)and 20-kg (right) (from White et al. 2007)

Falling Weight and Light Weight Deflectometers

Falling weight deflectometers (FWD) and lightweight deflectometers (LWDs) can also be used to determine pavement layer stiffness. In performing the tests, a known weight is dropped to produce a dynamic load on a plate. The load and deflection are recorded during the test. From load and deflection data, a soil layer modulus can be calculated. One type of FWD is shown in Figure 5. Two different models of LWDs are presented in Figure 6 (White et al. 2007).



Figure 5. KUAB model FWD



Figure 6. 300 mm LWDs: Zorn ZFG (left) and Keros (right) (from White et al. 2007)

CONCLUSIONS

Proper structural design, quality materials, and quality construction are the three essential components of a long-lasting pavement. With increased traffic loads and owner's desires to increase the life span of pavement structures, the current process of foundation layer construction and QA/QC must be improved. The current design-construction process has a mutual disconnect, with the pavement designer often being absent from the construction process and the construction and QA/QC personnel not fully comprehending the impact of field decisions on the long-term performance of the pavement. Owners should recognize that increased capital investment in the foundation layers is required to construct high-performing pavements.

Selecting design inputs for the foundation layers at first appears to be as simple as determining a representative stiffness from a correlation. However, the actual foundation layer stiffness parameters will change with moisture conditions and environment and will also be influenced by the quality of construction and drainage. Further, QA/QC procedures utilizing moisture and density control at widely spaced intervals do not provide direct measurement of the design parameters and the widely spaced intervals generally do not provide an acceptable level of reliability The process of excavation, compaction, and backfill in tandem with QA/QC from real-time measurements from the compaction equipment or rapid in situ testing will provide the degree of reliability required to construct long-lasting pavements (Lytton and Masad 2009). In situ testing devices, such as intelligent compaction, DCP, Clegg Impact Hammer, FWD, and LWD, are presently being studied in order to develop supplemental testing methods in addition to the method of moisture and density control. Griffiths and Thom (2007) state, "Confidence in design is an abstract concept, which is controlled by construction practice as much as it is by calculation and specification."

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