Lessons Learned from Implementing Advanced Compaction Monitoring at TVA’s CCR Landfills

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ABSTRACT

Over the past five years, the Tennessee Valley Authority (TVA) has been evaluating and implementing real-time compaction quality assurance monitoring using validated intelligent compaction (VIC) for dry stacking operations at six coal combustion residual (CCR) impoundment facilities. The compaction quality program was designed to improve field process control, reduce the risk of placing poorly compacted CCR materials, and improve cost to rate payers by improving construction efficiencies. Ongoing field testing at the projects sites includes 100% spatial mapping using advanced VIC capabilities, reporting of results to a cloud-based dashboard system with real-time viewing and automated alerts, and conducting extensive independent quality control testing (drive core for density and moisture content, static plate load tests for initial and reload modulus, dynamic cone penetrometer for penetration index and California bearing ratio (CBR), borehole shear test for effective stress shear strength parameter values (cohesion and friction angle), and shallow shear wave velocity). This paper presents the key findings and challenges from implementing this state-of-the-art compaction quality program involving the placement of more than an estimated 1,500,000 yd³ of CCR materials. Over the duration of projects, quality control charts showing several test metrics identify trends that reflect compaction quality and how improved process control is achieved with real-time monitoring and testing. Further discussed in this paper are the key lessons learned from implementing this first of its kind program for the full range of material types and conditions including project specific discussions.

INTRODUCTION

After the dredge cell failure at the Kingston power generating facility in 2008, the Tennessee Valley Authority (TVA) implemented significant advancements to manage engineering assessments and improve construction processes of its coal combustion...
residual (CCR) impoundment facilities. TVA began investigating new assessment
techniques in 2012 that focused on developing new generation specifications for quality
control (QC) and quality assurance (QA) processes for construction of CCR facilities.
Several field trail projects were completed between 2012 and 2015 evaluating various in
situ testing devices and real-time compaction monitoring technologies. Some key
findings from those studies are documented in earlier World of Coal Ash (WOCA)
conference proceedings (Christopher et al. 2013, White et al. 2013).

In 2015, TVA embarked on an industry leading, state-of-the-art QC initiative to monitor
placement and compaction of CCR products produced and stored at the Bull Run Fossil
Plant (BRF) and Kingston Fossil Plant (KIF) facilities using Validated Intelligent
Compaction (VIC) technology. At each site, the initiative involved instrumenting a
vibratory compaction machine, on-site field and laboratory testing to develop site-
specific compaction calibrations, monitoring or mapping of each lift of newly-placed
CCR and geotechnical confirmation testing for compaction verification and to meet
permit requirements.

The outcomes and benefits of the VIC program from these sites are documented in a
few technical papers (White et al. 2017a, White et al. 2015a). The VIC program was
designed to improve field process control, reduce the risk of placing poorly compacted
CCR materials, and improve cost to rate payers by improving construction efficiencies.
The program’s success has led to extending the VIC program to four more sites across
the valley. Currently, VIC is being implemented at the Bull Run (BRF), Kingston (KIF),
Gallatin (GAF), Cumberland (CUF), Shawnee (SHF) and Paradise (PAF) plants. To
date, an estimated 1,500,000 yd³ of CCR materials have been placed and compacted
using the new VIC monitoring program.

In this paper, the broader lessons learned while implementing this program are
presented. Specifically, the following aspects are addressed in this paper:
understanding the CCR material properties and how they vary within and between the
sites, evaluating different in situ testing methods and properties during field VIC
 calibration efforts, and real-time monitoring of VIC production mapping for QC/QA
operations. The findings of this paper should be of interest to program managers,
project engineers, field engineers/inspectors, and contractors interested in developing
specifications and improving placement/compaction control operations at CCR
impoundment and stacking facilities.

**CCR Material Properties**

Densification of CCRs during the stacking process is an important aspect to minimize
landfill space. It is also important that the CCRs are stacked to provide enough shear
strength and to minimize volume change after construction. The QC/QA specifications
for CCRs typically include placing the material within a specified moisture range relative
to the optimum moisture content and compacting the material to a target dry density
based on laboratory standard Proctor compaction tests. These compaction QC/QA
specifications were originally developed for earthen dam construction and the fly ash
materials used in CCRs are not soil-like materials and has complex composition. To better understand the chemical composition of the CCRs micro-analysis testing was conducted including scanning electron microscopy (SEM), X-Ray diffraction (XRD), X-Ray fluorescence (XRF), and thermo-gravimetric analysis (TGA). These different testing procedures and additional details are provided in White et al. (2015b), but some key findings are provided herein.

**Micro-Analysis**

SEM of CCRs sampled from five different plants at 5000x magnification are shown in Figure 1. These materials include fly ash (FA), gypsum (GYP), scrubber ash (SA), reclaimed scrubber ash (RSA), and reclaimed sluice ash (SA) material. SA materials are derived from a mixture of fly ash and a dry fluidized-gas desulfurization (FGD) byproduct. RSA is the SA material that has been initially placed and was then reclaimed to be placed in another landfill.

SEM images show that these materials are composed of various sizes and types of spheroids, and in some cases needle-like minerals, highly angular particles, and agglomerations of particles (see SA from GAF and FA from SHF). Particle sizes range from < 1 µm to about 50 µm. Needle-like and highly angular crystalline minerals represent formation of ettringite, which was also confirmed through XRD analysis (White et al. 2015b). For materials that showed ettringite, TGA was conducted (see White et al. 2015b) which showed that the material liberated water at different temperatures. A strong transition near 60°C was observed, which is attributed to drying of the chemically bound water to ettringite mineral. Most free water is dried before 60°C. An illustration of a four-phase system for CCRs representing air, free water, chemically bound mineral water, and solids is provided in Figure 2 (Christopher et al. 2013). XRD and XRF analysis conducted on material sampled from one of the plants (SHF) over an eight month monitoring period revealed that the chemical compositions of the material and the compaction characteristics of the materials changed with time. Further, the elemental compositions present in the material were strongly correlated with the optimum moisture content and maximum dry density of the material, as determined from the standard Proctor testing (White et al. 2015b).

This complex morphology makes routine testing like moisture content by oven drying and setting Proctor mellowing periods complex due to time and temperature dependent chemical reactions for different mineral phases. It is important that the oven drying temperatures (either 60°C or 110°C) should be material-specific and be based on chemical analysis of the material. With material morphological and chemical compositions influencing the soil compaction characteristics, it can be challenging to implement the target limits established from Proctor testing to properly characterize the material for field QC/QA purposes. Strength or stiffness or volume change based performance related target values (discussed more in later sections) can be easier to implement.
Figure 1. Scanning electron microscopy (SEM) images at 5000x magnification of the different CCR materials from five different TVA power plants.
Laboratory Compaction Characteristics

Proctor compaction tests performed on various CCRs sampled between 2015 and 2018 across the valley are shown in Figure 3. The figure illustrates the variable nature of the materials in terms of maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}). The standard Proctor γ_{dmax} varied between 69 pcf and 107 pcf, and w_{opt} varied between 16.5% and 42.1%. Three-phase diagrams representing the solids, water, and air phases for those highest and lowest γ_{dmax} values are shown Figure 4. The three-phase diagrams are helpful to review in this manner as it illustrates the amount of solids that will be placed into the landfill. Illustration of the data in this manner will also present an opportunity to evaluate the material compaction characteristics with additional compaction effort to increase the amount of solids in the landfill.

Standard Proctor γ_{dmax} and w_{opt} results from fly ash material sample multiple times over a 9-month period at KIF are shown in Figure 5. The γ_{dmax} varied between 80 and 101 pcf, and the w_{opt} varied between 18% and 33%. These results illustrate that, the material compaction characteristics can be significantly variable within a site over time and must be periodically evaluated.
Figure 3. Standard Proctor compaction curves of various CCR materials sampled from six different TVA power plants
Figure 4. Three-phase diagram of two materials representing the low and upper range dry densities of CCRs

\[ \gamma_{d_{\text{max}}} = 69.2 \text{ pcf, } w_{\text{opt}} = 42.1\% \]

\[ \gamma_{d_{\text{max}}} = 107.2 \text{ pcf, } w_{\text{opt}} = 16.5\% \]

Figure 5. Standard Proctor optimum moisture content and maximum dry unit weight values of fly ash material sampled from KIF pant over a nine month monitoring period
Moisture content and compaction effort are typically significant factors to consider for any of the materials, but some of the materials tested (e.g., SA from GAF and FA from SHF) have shown that compaction delay time (after adding water) can also have a significant impact on the achieved dry density.

Example results for SA material sampled from GAF are presented in Figure 6. The results and the procedures are described in detail in White et al. 2017b. In brief, the testing involved preparing 2 in. x 2 in. compacted samples at 3 moisture contents, 4 compaction delay times, 3 samples each, and 3 compaction energies (low, medium, and high), with a total of 108 specimens. A bulk material sample was obtained immediately after it was delivered the landfill stack area (time, t = 0), and the sample was compacted after 1 to 2 hr, 3 to 4 hr, 5 to 6 hr, and 7 to 8 hr compaction delay times.

To statistically assess the impact of compaction delay time, compaction energy, and moisture content on dry density, multi-variate analysis was conducted. Results are presented in Figure 6, which show that all three factors are statistically significant in terms of influence on the achieved dry density. Shapley value statistical analysis was conducted to determine the relative contribution of each independent variable on the predicted dependent variables (dry density). Results show that for dry density the moisture content, compaction effort, and compaction delay contribute 41%, 37%, and 23%, respectively. This means that all three parameters are important to control to maximize the field density. It is highly desirable to achieve maximum density to maximize the amount of material being placed in the finite landfill space.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percent Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content</td>
<td>41%</td>
</tr>
<tr>
<td>Compaction Effort</td>
<td>37%</td>
</tr>
<tr>
<td>Compaction Delay</td>
<td>23%</td>
</tr>
</tbody>
</table>

Figure 6. Results of multi variate analysis characterizing influence of moisture content, compaction, and compaction delay on predicted dry density (White et al. 2017b).
Validated Intelligent Compaction (VIC)

The validated intelligent compaction (VIC) technology was developed by Ingios Geotechnics, Inc., and provides real-time monitoring of compaction to aid in compaction process and quality assessment. Compaction monitoring sensors are outfitted on any vibratory smooth drum roller (in less than 1 day) with state-of-the-art hardware for measuring, recording, and visually monitoring the results of the compaction process (Figure 7). The data is presented real-time as color-coded geospatial maps on the on-board display monitor (Figure 7). The VIC compactor is outfitted with global positioning system (GPS) equipment to measure drum location which is coordinated with data to create color-coded compaction maps. Once outfitted, a field calibration process involving a suite of in situ testing methods to measure material physical and mechanical properties is implemented.

![Figure 7. Vibratory compactor outfitted with VIC technology and roller operator view with on-board monitor for real-time viewing of compaction data.](image)

Recent field calibrations on CCR materials using this approach showed coefficient of determination \( R^2 > 0.85 \) are achievable with plate load testing (PLT) measurements and shear wave velocity measurements, while \( R^2 > 0.6 \) are achievable with dynamic cone penetrometer (DCP) test measurements. For all TVA sites, a target unitless parameter called as the X-measurement value (XMV) is determined based on the calibration testing with the soil physical and mechanical properties and the compaction curve data.

In the sections below, brief descriptions and some on-site examples of field calibration and production mapping operations are presented.

Field Calibration

Field calibration tests performed during trial and pilot projects since 2012 have shown that it is critical to evaluate process control measures, specific to the material type, during the field calibration process. Typically, based on the initial laboratory testing on the material, the process control measures (e.g., moisture variation, lift thickness,
compaction delay) are determined and are incorporated for evaluation in the calibration field testing plan.

Based on lessons learned from the initial field trails and pilot projects, a generic field VIC calibration test plan has been developed for TVA and has been implemented successfully at multiple TVA sites. Two types of field calibration have been implemented for VIC. One is a test pad compaction calibration that involves conducting a series of tests on a test pad of loose lift material placed over a stable platform (see Figure 8). The second is a mapping calibration that involves conducting a series of test over a production mapping area (Figure 9).

The compaction calibration is performed in a test pad area where fresh material is placed with a targeted lift thickness. The test pad areas are typically 30 ft wide (3 roller widths) and 100 to 150 ft in length. Compaction is performed using multiple passes by continuously monitoring the average XMV values. The maximum number of passes is decided based on the compaction curve. Lanes within the test pad are constructed based on predetermined criteria such as variable moisture conditions (e.g., -4%, 0%, and +2% of optimum moisture conditions), variable lift thicknesses (e.g., 8-in, 12-in, etc.), variable compaction delay times for materials that exhibit time-dependent strength gain (1 hr, 2 hr, 4 hr, etc.), and/or variable material mix ratios.

Mapping calibration is performed in a production area where the material was previously placed and compacted. The area is mapped first in a proof mapping rolling pattern, and based on the XMV map, the field-testing locations are selected. Typically, 10 to 25 test locations in the mapping area are selected for drive core, dynamic cone penetrometer (DCP), shear wave velocity, and plate load testing. 3 to 5 of these test locations should be selected for borehole shear testing. Typically, 3 to 6 locations in each compaction lane for drive core, dynamic cone penetrometer, and plate load testing. 1 test location in each lane is selected for borehole shear testing.

The different in situ testing procedures typically used for calibration are shown in Figure 10. The test procedures are described in detail elsewhere (White et al. 2019, White et al. 2017a), but in brief: (1) 4 in. drive core (DC) testing are conducted for density and moisture content measurement; (2) 30 in. diameter loading plate “static plate load tests are conducted to determine initial and reload modulus of subgrade reaction; (3) dynamic cone penetrometer (DCP) tests are conducted to determine penetration index and California bearing ratio (CBR) values; (4) borehole shear test (BST) to determine angle of internal friction ($\phi$) and cohesion ($c$); and (5) impact hammer tests are conducted to determine shear wave velocity (Vs) measurements. Pictures of these different field tests are shown in Figure 10.
Generic Test Pad Compaction Curve Calibration Test Plan for CCP Materials

- Test pad must be 30 ft wide x 100-150 ft long
- CCP material is placed in relatively uniform lift thickness across the test pad.
- Lanes may be used for testing after multiple roller passes (e.g., Lane 1 – 2 passes, Lane 2 – 4 passes, and Lane 3 – 8 passes).
- For materials that exhibit time-dependent strength gain, the different lanes may be used to assess influence of compaction delay time.
- Moisture conditioning across the test pad should vary from wet to dry of optimum, per project permit requirement limits (e.g., -4% to +2% of optimum)
- Additional test pads may be required for additional materials on site or assess influence of loose lift thickness to establish process control measures.

### DAILY ACTIVITY/TEST PLAN

<table>
<thead>
<tr>
<th>TEST</th>
<th>Calibration Tests at Pass No. 0 2 4 8 Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC</td>
<td>x x x 12 in. thick fill placed over compacted previously placed fill</td>
</tr>
<tr>
<td>q-PLT</td>
<td>x x 30 in. static plate load test – 2 load/unload cycles.</td>
</tr>
<tr>
<td>BST/ST</td>
<td>x Push 3 in. dia. X 18 in. long tubes. Perform BSTs at ~8 in. below grade.</td>
</tr>
<tr>
<td>DCP</td>
<td>x x x Full depth (~2.5 ft)</td>
</tr>
<tr>
<td>DC/SC</td>
<td>x x Scrape of top 1 in. and perform test.</td>
</tr>
<tr>
<td>GPS</td>
<td>x x x Define perimeter and interior (topo). Each test point.</td>
</tr>
</tbody>
</table>

**Notes**
- Develop XMV calibration model using all test point data and set calibration values based on statistical analysis.
- Standard Proctor, pH, and micro-analysis (XRF, XRD, TGA) on each material.

**Figure 8.** Example VIC compaction calibration test plan on a test pad.

Generic Mapping Calibration Test Plan for CCP Materials

**DAILY ACTIVITY/TEST PLAN**

<table>
<thead>
<tr>
<th>Test Measurement</th>
<th>Cal. Tests [MAP]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC</td>
<td>x Map existing layer. Forward direction only</td>
<td></td>
</tr>
<tr>
<td>PLT</td>
<td>x 30 in. static plate load test – 2 load/unload cycles.</td>
<td></td>
</tr>
<tr>
<td>BST/ST</td>
<td>x Push 3 in. dia. X 18 in. long tubes. Perform BSTs at ~12 in. below grade.</td>
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<tr>
<td>GPS</td>
<td>x Define perimeter and interior (topo). Each test point.</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**
- Select 10 to 25 test locations within the IC map areas to perform calibration testing to capture a wide range of material conditions.
- BST tests at 3 to 6 locations.
- Develop XMV calibration model and re-assess any additional calibration test points to complete model.

**Laboratory Test Measurement**
- Standard Proctor: 6 points
- Gas Pycnometer & pH testing
- Micro-analysis (XRF, TGA, particle size)

**Figure 9.** Example VIC mapping calibration test plan.
Figure 10. In situ point testing methods typically used during calibration: (a) automated PLT trailer, (b) 30 in. diameter loading plate setup for static PLTs, (c) dynamic cone penetrometer (DCP), (d) shear wave velocity, (e) borehole shear test (BST) setup with shear head in the insert, and (f) drive cylinder testing.

Example test pad calibration from BRF site on fly ash material are presented in Figure 11. Testing was performed on three lanes prepared at different moisture contents relative to the $w_{opt}$, and was compacted using multiple roller passes. Example mapping calibration from the same site on fly ash production area is presented Figure 12. DCP-CBR profiles and drive core test results overlaid on Proctor compaction data at three selected "soft", "medium stiff", and "stiff" areas (as identified with low, medium, and high XMVs) are shown in Figure 12. Results show a visual confirmation of areas with low dry unit weight and low CBR showed low XMV and vice versa.

Following field testing, calibration analysis are performed using VIC algorithms to predict XMV and various soil physical and mechanical properties (i.e., moisture content, XMV, moisture content, dry density, DCP index values, plate load testing modulus, etc) as desired. Example XMV calibration analysis from a site with plots of predicted versus measured parameters and regression statistics are shown in Figure 13. Results from this site showed that $R^2 > 0.9$ are achievable with PLT, Vs, and DCP measurements, while $R^2 > 0.7$ are achievable with dry density measurements. $R^2$ was low for moisture content prediction.

Based on the regression analysis and compaction curve data from multiple passes, a target XMV is determined for each site. Target XMVs developed for different CCR materials from different TVA plants are summarized in a bar chart in Figure 14.
Figure 11. Example VIC test pad calibration at BRF plant on loose lift material placed with controlled moisture contents.
Figure 12. Example VIC mapping calibration at BRF plant in a production area.
Figure 13. Example VIC-XMV Calibration record for different in situ test measurements

Target XMV of 25 to 60 for GAF-SA to account for time-dependent strength gain

Target XMV of 20 to 30 for GAF-RSA to account for time-dependent strength gain

Figure 14. Target XMVs for different sites and materials.
Quality Metrics for Production Monitoring

During contractor production operations, the VIC technology uses advanced algorithms to provide real-time feedback of the compaction operations. Three following quality metrics are also monitored during production operations:

- **Percent Passing Target Values**: % passing the target values is based on the number of geospatial grid points from the VIC output that meet or exceed the minimum target parameter value (e.g., XMV) for the selected material. A target minimum of 80% is currently being implemented at the TVA sites.

- **Compaction Quality Index (CQI)**: CQI is a relative compaction index based on the percentage of the geospatial area that meets the minimum target values for the set engineering parameter value that accounts for the uniformity of compaction using a weighting factor. The default minimum target CQI is 95% using a uniformity weight factor of 50%.

\[
CQI = 100 - (\text{Min.TV \% Passing} - \text{Measured \% Passing}) \\
- [(\text{Measured COV} - \text{Max.TV \% COV}) \times \text{Uniformity Weighting Factor}]
\]

- **Calibration Index (CI)**: The CI parameter provides a measure of whether the calibrated measurements (i.e., XMV) are within or out of calibration. CI parameter should be determined for each production map, using the calibration test results as follows:

\[
CI = \min\left(\frac{UL - \mu}{3\sigma}, \frac{\mu - LL}{3\sigma}\right)
\]

- UL = upper limit of the calibration
- LL = lower limit of the calibration
- \(\mu\) = calculated average of the predicted values
- \(\sigma\) = calculated standard deviation of the predicted values

If \(CI < 0.0\) = All data is outside calibration limits. Equipment needs recalibration.
If \(0.5 < CI > 0.0\) = Some data is outside calibration limits.
If \(0.5 > CI < 1.0\) = Most data is within calibration limits.
If \(CI > 1.0\) = All data is within calibration limits.

Production Mapping Using VIC

Production VIC mapping is performed by the contractor. During initial field trials and pilot projects (prior to 2018), production data was downloaded, plotted and a compaction report was generated and sent to project managers for review. Although the data was providing valuable information for the contractor in real-time, the compaction
report development added engineering time to the project cost and more importantly delayed viewing data by the project managers by at least 1 day after mapping. This prompted the need for real-time monitoring of the VIC data for TVA managers and the contractor and the automated reporting of the VIC compaction reports. Ingios Geotechnics, Inc developed an online dashboard tool to specifically address this challenge (Figure 15).

Once the compaction operator initiates “mapping” operations, all QC/QA managers receive an email/text notification with a link to the online dashboard for real-time viewing of the data. Once the compaction operator is done “mapping” an area, the operator pushes a button that triggers the raw data file to be submitted automatically to the cloud. Ingios software tools read the data and automatically generate the VIC compaction report. With the Ingios online dashboard tool, the data upload process to compaction report development requires less than 5 minutes. The compaction report includes various data analytics/statistical summaries and various plots of color-coded information. An example VIC compaction report generated by the dashboard tool along with a summary of the quality metrics included in the report are shown in Figure 16.

The dashboard tool also allows monitoring the VIC quality metrics from each compaction report as control charts. An example control chart from an 18 month monitoring period at the BRF plant is shown in Figure 17, which shows average XMV and the percentage passed results with reference to the target values. The dashboard tool also allows viewing on-site webcam, uploading QC/QA point testing data, and uploading imagery.

An example CI control chart, which tracks the validity of the calibration of the machine, from the KIF plant over an 8 month monitoring is shown in Figure 18. These control charts are critical for project QC/QA managers to monitor and assess the quality of the CCR stacking operations.

![Dashboard to view ongoing active operations, live-view site cameras, and review VIC compaction records and QC/QA point test measurements.](Image)
### Quality Analysis

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>CQI</td>
<td>107.3</td>
</tr>
<tr>
<td>% Passing Target</td>
<td>90.7</td>
</tr>
<tr>
<td>CoV of MVs</td>
<td>0.27</td>
</tr>
<tr>
<td>i-Score Blob</td>
<td>N/A</td>
</tr>
<tr>
<td>w%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Figure 16.** Example VIC compaction report showing XMV map and quality analysis metrics for an area that met the XMV target value (TV) requirement,
**Figure 17.** Example VIC-XMV control charts over an 18 month pilot monitoring period at BRF plant

**Figure 18.** Example VIC Calibration Index over a eight month pilot monitoring period at KIF plant showing validity of the VIC measurements
Summary of Lessons Learned

Following are the key lessons learned and challenges addressed:

- CCR materials sampled across the valley exhibited variable chemical compositions and morphological properties. At some sites, the CCR materials exhibited variable properties over time based on the coal blend being used.

- Proctor compaction tests conducted on CCRs sampled from multiple sites across the valley showed that the maximum dry density varied between 69 pcf and 107 pcf, and optimum moisture content varied between 16.5% and 42.1%. Further, significant variations were also observed over time at a given site. These variations are linked to the changes in the chemical and morphological properties of the CCR materials.

- With material morphological and chemical compositions influencing the soil compaction characteristics, it can be challenging to implement the target limits established from Proctor testing to properly characterize the material for field QC/QA purposes. Strength or stiffness or volume change based performance related target values (such as VIC-XMV or shear strength/stiffness based values) can be easier to implement.

- Moisture content and compaction effort are typically significant factors to consider for any of the materials, but some of the materials tested (e.g., scrubber ash) have shown that compaction delay time (after adding water) can also have a significant impact on the achieved dry density. For those materials, a careful laboratory study to assess impacts of compaction delay is needed to establish field process control measures (e.g., lift thickness and time). Roller mapping operations can be used to ensure those process control measures are being followed.

- A VIC monitoring program was designed for TVA to improve field process control, reduce the risk of placing poorly compacted CCR materials, and improve cost to rate payers by improving construction efficiencies. The program was successfully implemented on pilot projects at multiple TVA plant sites across the valley for different CCR materials.

- A successful VIC monitoring program is possible with careful laboratory characterization of the materials on site, field VIC calibration with construction of test pads and detailed in situ testing characterizing the CCR material physical and mechanical properties, and near real-time monitoring of the VIC process during production operations.
• Near real-time monitoring of VIC production operations, live-view of construction area through an on-site webcam, and review of compaction QC/QA testing records and control charts is now possible with the dashboard tool.

• Field calibrations on CCR materials using the VIC approach showed that $R^2 > 0.85$ are achievable with PLT measurements and shear wave velocity measurements, while $R^2 > 0.6$ are achievable with DCP test measurements. $R^2$ values with dry density and moisture content are typically low, but in a few cases achieved $> 0.5$. For all TVA sites, a target unitless parameter called as XMV is determined based on the calibration testing with the soil physical and mechanical properties and the compaction curve data.

• Average XMV control charts along with other quality metrics such as the percent passing the target XMV, CQI and CI are monitored and reported.

• The use of VIC and the online dashboard tool for QC/QA assessment of CCRs is a significant step forward to help reduce risk for the owner and improve construction efficiencies for the contractor.

REFERENCES


