Intelligent Testing Analytics and Validated Compaction Monitoring for Gypsum Landfill

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ABSTRACT

This paper presents results of field and laboratory calibration testing performed on the gypsum impoundment and stacking facility at TVA’s Paradise Fossil Plant in Paradise, Kentucky. A test program was designed to include geospatial mapping using a vibratory smooth drum roller instrumented with validated intelligent compaction (VIC) and conducting the following point tests at selected locations: (1) 4 in. drive core for density and moisture content; (2) “quick” static plate load tests for modulus and deformation rate; (3) dynamic cone penetrometer for penetration index and California bearing ratio (CBR); and (4) borehole shear test for effective stress shear strength parameter values (cohesion and friction angle). Results show that compaction testing for gypsum requires consideration of moisture control and accounting for time-dependent compression and stiffening. The VIC map results and advanced analytics are being piloted on-site to evaluate the use of intelligent testing analytics that identify areas for the contractor to improve compaction quality and inspectors to perform independent testing to verify quality. The goal of the program is to provide real-time process control results, efficient inspection testing, and improved compaction quality. Examples of advanced testing analytics are presented in this paper.

INTRODUCTION

Tennessee Valley Authority (TVA) is currently implementing modern process control and quality assurance testing for construction of their coal combustion production (CCP) stacking facilities, using validated intelligent compaction (VIC) technology and intelligent testing analytics. The objectives of using the new technologies are to improve field process control and reduce the risk of placing poorly compacted CCP materials. Several pilot projects have been conducted at multiple TVA fossil plant facilities demonstrating successful implementation of the new technologies, and the results have been
documented in previous World of Coal Ash (WOCA) conference proceedings (White et al. 2015a, 2015b, 2017a, 2017b, 2017c). Materials evaluated at these sites included production fly ash, reclaimed sluice ash, gypsum, and hydrated lime-treated fly ash and gypsum mixtures.

The VIC technology provides real-time monitoring of compaction to aid in process control and quality assessment. A vibratory smooth drum roller is outfitted with state-of-the-art hardware for measuring, recording, and visually monitoring the results of the compaction process. Once outfitted, a field calibration is conducted using different in situ point testing methods to measure physical and mechanical parameters. After calibration, the contractor uses the VIC technology for production operations to obtain real-time feedback of the compaction operations. VIC independently verifies to the quality control/assurance (QC/QA) team that the contractor’s work: (1) achieves the minimum critical engineering parameter values over a defined percentage (e.g., 80%) of the area monitored; (2) limits the variability of critical engineering parameter values of the area monitored; and (3) restricts the size of localized contiguous areas of non-compliance (i.e., “soft spot”). The color-coded georeferenced spatial maps of the engineering parameter maps are used to target QC/QA testing locations. Non-operator users access the real-time results via a cloud-based dashboard, and automated emails.

In this paper, results from testing performed at TVA’s Paradise Fossil Plant in Paradise, KY, on gypsum material is presented. A calibration testing program was designed to include material characterization in the laboratory and field testing on a test pad. The test pad was compacted using multiple roller passes and production areas were mapped using the instrumented VIC roller to produce geospatial maps. Following compaction and mapping, field testing was conducted using a variety of field point testing methods to measure dry unit weight, moisture content, shear strength parameters, deformation characteristics, and penetration index values. Following calibration of the roller, examples of VIC results are presented. The VIC map results and advanced analytics are being piloted at the PAF facility to evaluate the use of intelligent testing analytics that identify areas for the contractor to improve compaction quality and inspectors to perform independent testing to verify quality. The goal of the program is to provide real-time process control results, efficient inspection testing, and improved compaction quality.

**CALIBRATION TESTING PLAN**

A calibration test plan was designed using laboratory and field test results that involved material characterization of a test pad and production areas.

The laboratory testing included micro-analysis on the gypsum material using: (a) scanning electronic microscopy (SEM) to assess particle sizes/shapes; (b) energy-dispersive spectroscopy (EDS) for micro-characterization the material, and (c) thermo-gravimetric analysis (TGA) to assess changes in physical and chemical properties of the material. In addition, laboratory compaction parameters were measured using standard Proctor compaction test results.
Field testing included VIC mapping in production areas and a test pad constructed with 8 to 12 inches of loose material placed over compacted gypsum over an area of about 30 ft x 150 ft. The test pad was compacted in 3 lanes – Lane 1 with 8 roller passes, Lane 2 with 11 roller passes, and Lane 3 with 2 roller passes, and tests were conducted at 4 to 5 test locations along each lane. A lane adjacent to the test pad was also mapped and tested. A picture of the VIC roller and the test pad setup are shown in Figure 1. One of the production areas that was tested as part of the calibration work included areas of uncompacted and compacted lifts (compaction performed by the contractor) with variable moisture content (referred to as Area 4). The area was mapped on the day of the uncompacted lift placement, and the next day to assess changes in material conditions.

![Figure 1. Instrumented VIC roller and gypsum test pad divided into three roller lanes.](image)

The following point tests were performed at selected locations: (1) 4 in. drive core (DC) for density and moisture content; (2) 30 in. diameter loading plate “quick” static plate load tests (PLT-Q) for initial and reload modulus of subgrade reaction ($k_1$ and $k_2$); (3)
dynamic cone penetrometer (DCP) for penetration index and California bearing ratio (CBR), and (4) borehole shear test for cohesion \( (c') \) and friction angle \( (\phi') \) properties. The test procedures are briefly described in the following section of the paper. Pictures of in situ testing devices are shown in Figure 2. In situ point tests were conducted at a total of 26 locations and global positioning system (GPS) measurements of the test locations were obtained using the on-site real-time kinematic (RTK) GPS hand rovers.

![Figure 2. In situ point testing methods used during calibration: (a) automated plate load testing trailer, (b) 30 in. diameter loading plate setup for PLT-Q tests, (c) borehole shear test (BST) setup, (d) shear head, and (e) dynamic cone penetrometer](image)

**TESTING METHODS**

**LABORATORY TESTING**

Laboratory testing was performed to assess morphological and chemical composition properties and compaction characteristics of the gypsum material. The procedures followed are summarized below.

**Scanning Electron Microscopy**

SEM micrographs were obtained at different magnifications (50x, 150x, 500x, 1500x, and 5000x) using FEI Quanta-250 SEM equipped with a field-emission gun providing a resolution of 1.0 nm. Tests were conducted at the Material Analysis Research Laboratory (MARL) at Iowa State University.

**Energy-Dispersive Spectroscopy (EDS)**
EDS technique uses X-rays to obtain elemental analysis of the material, and provides both qualitative and quantitative results with a measure of the different elements present in the material. An Aztec system equipped with Oxford's X-Max 80 was used for EDS testing. Tests were conducted at the Material Analysis Research Laboratory (MARL) at Iowa State University.

**Thermo-Gravimetric Analysis (TGA)**

TGA includes recording mass loss during a defined time/temperature profile. The results indicate moisture loss and phase changes which occur at set temperatures indicative of the compound. Tests were conducted at the Material Analysis Research Laboratory (MARL) at Iowa State University.

**Proctor Compaction Testing**

Standard Proctor compaction testing was conducted in accordance with ASTM D698-10. Samples were prepared at 5 desired target moisture contents and compacted within 4 hours of fill placement. Optimum moisture content and maximum dry density values were determined.

**FIELD TESTING**

Field testing was performed on calibration test pads using several point test methods to measure moisture-density properties, and shear strength and stiffness properties. TVA’s Caterpillar CS56B vibratory smooth drum roller (Figure 1) instrumented with Ingios’ VIC system was calibrated to the above-mentioned material properties. An index parameter referred to as XMV was also obtained from the VIC roller as an initial assessment of the variability, which is calculated using drum accelerations. A brief description of the different point testing methods is provided below. Pictures of field testing procedures are shown in (Figure 2). An overview of the point testing procedures is provided below.

**Drive Core Density and Moisture Content**

Drive core (DC) testing was performed to determine in situ density and moisture content in accordance with ASTM D2937-10. After excavating the sample from the ground, the drive core was carefully sealed in a zip-loc bag and was immediately transported to the on-site mobile laboratory for testing. Total unit weight of the material was determined and moisture content of the representative sample was obtained using oven-drying test procedure (at 60°C, based on TGA results).

**Dynamic Cone Penetrometer**

DCP tests were conducted in accordance with ASTM D6951-03. The tests involve dropping a 17.6 lb hammer from a height of 22.6 in. and measuring the resulting
penetration depth. The penetration depth and the number of blows were automatically recorded in the device. Based on the penetration depth and the number of blows, the penetration index (PI) values in units of mm/blow or in/blow are calculated. Using the PI values, California bearing ratio (CBR) were calculated per ASTM D6951-03.

Bore Hole Shear Test

Bore hole shear tests (BSTs) were performed per manufacturer guidelines to determined drained cohesion and friction angle values of the material in situ (Handy Geotechnical Instruments, Inc., 2013). The test involved preparing a 2.8 in. cavity by pushing a Shelby tube down to a depth of about 6 inches below surface and conducting the test by placing the shear head in the cavity. The test involved applying a 7.3 psi normal stress and allowing for about 3-minute consolidation time and applying shearing stresses until it reaches a peak value. The peak shear stress and the normal stress are recorded. Then the test procedure was repeated for 14.5 psi and 21.8 psi normal stresses. Using the results, shear stress versus normal stress plots were generated with a best fit linear regression line to determine cohesion ($c'$) and friction angle ($\phi'$) values.

Plate Load Testing

Static plate load tests (PLTs) was performed using a 30 in. diameter loading plate using two loading cycles. The test setup and deflection measurements were in accordance with AASHTO T222. The loading procedure was modified herein to perform the test in a rapid fashion, and hence are referred to as the “quick” plate load tests (PLT-Q). The PLT-Q tests involved one seating load of about 1,000 lbs followed by a 20,000 lb load and repeating the same for 2nd loading cycle – with 1 minute wait time at each load/unload step. Extended static PLTs were also conducted by maintaining the 20,000 lb load for about 40 minutes to evaluate the creep behavior of the gypsum material.

Modulus of subgrade reaction ($k$) values were calculated as the ratio of applied stress over measured deformation (in units of kPa/mm) for both 1st and 2nd loading cycles using the stresses and deformations at the end of the seating load and 20,000 lb load steps. The deformation values using the $k$ value calculation were corrected for plate bending (per AASHTO T222), but no corrections were made for future saturation. The 1st and 2nd loading cycle $k$ values are referred to as $k_{Q(1)}$ and $k_{Q(2)}$, respectively.

The AASHTO T222 test standard requires the load be maintained for 3 minutes for each step after the deformation is relatively constant (< 0.001 in/min). The load was only maintained herein for about 1 min., and for cases where the required deformation rate of 0.001 in./min. was not achieved, the time versus deformation data was fit with a power relationship to forecast the time needed to achieve the deformation rate plus the additional 3 minutes, and calculate the corresponding total deformation at the forecasted time to calculate the $k_1$ and $k_2$ values.
LABORATORY CHARACTERIZATION

Results of micro-analysis testing indicated that calcium sulfate dihydrate (CaSO₄·2H₂O) is the primary constituent in the PAF Gypsum, along with impurities. The water content of the material is characterized by two components: free water and bound water. Free water is the water not chemically bound within the gypsum crystal. Bound water is chemically coordinated within the gypsum. Based on the molecular weight of calcium sulphate dihydrate (172.6) and the two water molecules (34.014), the chemically bound water in pure gypsum is (34.014/172.6) – 19.7% (based on total weight basis). Free water is used to target the field moisture content.

TGA analysis (Figure 3) shows that the wetted gypsum weight (%) initially decreases with increasing temperature with a relatively constant weight between 40° and 100°C. Weight (%) drops again as temperature increases above 100°C and then slightly decreases up to 200°C. The initial weight loss is attributed to free water and the second weight loss increment is attributed to loss of the bound water. Based on these results, 60°C ± 5°C was determined as the drying temperature for moisture-content determination for the gypsum material at this site.

The microstructure of the gypsum was observed using SEM imaging at 50 to 5,000x magnification (Figure 4) including EDS (Figure 5) to map elemental composition (O, Mg, Si, S, Ca, and Ir). The SEM images show the crystal shapes, particle size ranges (1 μm to over 50 μm), agglomerations of particles, and points contacts between particles.

Figure 3. Thermogravimetric analysis (TGA) results on PAF gypsum material.
Figure 4. Scanning electron microscopy (SEM) images of PAF gypsum material at: (a) 50x, (b) 150x, (c) 500x, and (d) 1,500x magnifications.

Figure 5. Energy dispersive spectroscopy (EDS) results of PAF gypsum material.
Results from standard Proctor testing are shown in Figure 6. The optimum moisture content ($w_{opt}$) of the material was 17.7% and the maximum dry unit weight ($\gamma_{dmax}$) was 93.3 pcf. The Proctor testing was completed within about 4 hours of material placement on site. Figure 6 includes the in situ drive core test results in reference to the laboratory test results. Moisture-density field results are discussed in the following section of the paper.

Figure 6. Laboratory standard Proctor test results along with in situ dry density test results from field calibration testing
CALIBRATION FIELD TEST RESULTS

TEST PAD CALIBRATION TESTING

The test pad constructed with 8 to 12 inches of loose lift gypsum material was compacted in three roller lanes (lanes 1 to 3), along with a lane (lane 4) adjacent to the test pad that was already well compacted. Lane 1 was compacted with 8 roller passes, Lane 2 with 11 roller passes, and Lane 3 with 2 roller passes, and tests were conducted at 4 to 5 test locations along each lane. Lane 4 was compacted using 4 roller passes. XMV geospatial map on the test pad along with in situ test locations from last roller pass are shown in Figure 7.

XMV compaction curves for each roller lane are shown as box plots in Figure 8. In the box plot, the solid black line within the box represents the median, the bottom and the top ends of the box represent the 25th and 75th percentiles, respectively, and the whiskers on the bottom and the top represent the 10th and 90th percentiles, respectively. XMV compaction curves from multiple passes on the test pad indicated that the XMVs increase with compaction passes up to about 3 or 4 roller passes and remain relatively constant thereafter.

Figure 7. XMV color-coded spatial map in calibration lanes 1 to 4 along with in situ test point locations.
Average XMV in lane 1 after 8 passes was about 43.8, in lane 2 after 11 passes was 44.0, and in lane 3 after 2 passes was 32.4. Similar changes were noted with DCP, BST, and PLT-Q tests.

DCP tests showed the DCP-CBR (average in the top 12 inches) values in lane 2 (11 passes) achieved an average of 13, lane 1 (8 passes) achieved an average of 14, and lane 3 (2 passes) achieved an average of 11.

BST results from two test locations from lane 2 (8 passes) indicated $\phi' = 35.6$ to $38.1$ degrees with $c' = -1.5$ to $1.5$ psi. From lane 3 (2 passes), two test locations indicated $\phi' = 17.0$ to $28.5$ degrees with $c' = 1.5$ to $2.1$ psi. From lane 4 (adjacent to test pad), two test locations indicated $\phi' = 33.7$ to $35.0$ degrees with $c' = 0.7$ to $0.9$ psi. Comparison of shear stress versus normal stress plots from one test location in each of the lanes is provided in Figure 9.
Shear Stress, psi
Normal Stress, psi

PT15: Lane 4 - Production area outside the test pad
\(c' = 1.5\) psi, \(\phi' = 35.6^\circ\)
PT5: Lane 2 - 11 compaction passes
\(c' = 0.7\) psi, \(\phi' = 35.0^\circ\)
PT13: Lane 3 - 2 compaction passes
\(c' = 1.5\) psi, \(\phi' = 28.5^\circ\)
Target: \(c' = 0, \phi' = 28^\circ\)

Figure 9. Normal stress versus shear stress plots from BSTs at three test locations.

PLT-Qs performed on the test pad showed that \(k_{Q1}\) values in lane 2 (11 roller passes) varied between 166 and 219 pci with an average of 186 pci, while values in lane 3 (2 roller passes) varied between 144 and 167 with an average of 153 pci. Similarly, the \(k_{Q2}\) values were also higher in lane 2 (average = 761 pci) compared to lane 3 (average = 627 pci).

Extended static PLTs were performed to evaluate time-dependent creep behavior at three test locations: lane 2 (PT5), lane 3 (PT13), and lane 4 (PT14). Results are presented for the 1st load increment for the three test locations in Figure 10, where the load was maintained for about 40 minutes. Results demonstrated that to reach a deformation rate of 0.001 in./min. at PT5 the time was about 61 min., at PT13 the time was about 93 min., and at PT14 the time was about 15 min. The \(k_1\) values at the three locations were 109 (PT5), 66 (PT13), and 155 pci (14). The results suggest that the time to achieve a relatively constant rate of deformation (≤ 0.001 in./min) can be reduced and thereby the stiffness can be increased, by increasing the compaction effort.

For all PLT-Qs performed at this site, an attempt was made to determine the \(k_1\) and \(k_2\) values by calculating deformations at times equal to 3 minutes after reaching a deformation rate of 0.001 in. per minute based on the power model fit to the load versus deformation measurements obtained during the 1 minute test. But the \(k_1\) and \(k_2\) values could not be determined because of the extended creep response (time-dependent movement) of the gypsum materials (as has been observed at other TVA gypsum stacks). Based on comparing the results from this site and other sites with similar tests, it was determined that forecasted results from the power model are reasonable if the deformation rate is ≤ 0.005 in./min at the end of the load step.
Figure 10. Time versus plate deformation results for the three ‘creep’ tests performed by applying a 20,000 lb nominal load on a 30 in. diameter loading plate.

The in situ moisture contents in the test pad area varied between -3.0% to +0.7% of w_{opt} and relative compaction (RC) varied between 96% and 101% of the standard Proctor $\gamma_{d_{max}}$. The in situ moisture content and dry unit weight results are shown in relationship with the laboratory Proctor test results in Figure 6. Although Lane 3 compacted used 2 roller passes showed slightly lower dry densities on average, there were no statistically significant differences in the achieved RC between the three lanes.

In summary, the static PLT k values, DCP-CBR, BST $\phi'$ values, and XMVs showed trends of higher strength/stiffness in lanes 1 (11 passes) and 2 (8 passes) compared to lane 3 (2 passes), while RC showed no statistically significant differences between the three lanes.

MAP AREA CALIBRATION TESTING

Geospatial XMV maps were obtained from four different production areas for calibration testing. The in situ moisture contents in the production mapping areas varied between -9.1% to +2.6% of w_{opt} and RC varied between 93% and 106% of $\gamma_{d_{max}}$. One out of the nine test locations in the production mapping area achieved RC < 95%, while the moisture contents at three out of the nine locations were outside the -4% to +2% of w_{opt} moisture limits. Greater variability was observed in the production areas compared to the test pad area.

One of the production area maps (Area 4 map) covered a previously compacted gypsum area and an adjacent area where gypsum was placed the same day and was not compacted (Figure 11).
Figure 11. XMV color-coded spatial maps in a production area with zones of compacted lift and uncompacted lift: (a) Day 1 map along with DCP-CBR profiles at one test location in each zone, and (b) Day 2 remap in uncompacted lift zone.
The XMV in the compacted area averaged 46 and in the uncompacted area averaged 21. DCP tests performed in the uncompacted area (PT25) and compacted area (PT21) confirmed the differences observed in the XMV maps (Figure 11). The uncompacted area was re-mapped the next day, and average XMV increased to 33. Histogram plots of XMV comparing results from day 1 and day 2 are provided in Figure 12. The results suggest that the additional compaction pass improved the ground stiffness conditions.

![Histogram plots of XMV and univariate statistics comparing compacted and uncompacted areas on day 1 map and day 2 remap](image)

**Figure 12. Histogram plots of XMV and univariate statistics comparing compacted and uncompacted areas on day 1 map and day 2 remap**

**CALIBRATION ANALYSIS**

Data obtained from the test pad and the production mapping areas were analyzed to calibrate with XMVs. Results from calibration analysis for different measurement values from PLT-Qs and DCP-CBR are presented in Figure 13. A summary of the regression relationships showing the coefficient of determination ($R^2$) value, number of test measurements ($N$), root mean squared error (RMSE), and the range of measurements for each regression are shown in Table 1.

<table>
<thead>
<tr>
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<th>Uncompacted Area</th>
<th>Compacted Area</th>
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<td><strong>COUNT</strong></td>
<td>1,805</td>
<td>1,185</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td>20.9</td>
<td>46.4</td>
</tr>
<tr>
<td><strong>COV</strong></td>
<td>36%</td>
<td>29%</td>
</tr>
<tr>
<td><strong>% &gt; TV</strong></td>
<td>12%</td>
<td>89%</td>
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<tr>
<th></th>
<th>Uncompacted Area</th>
<th>Uncompacted Area</th>
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<tr>
<td><strong>COUNT</strong></td>
<td>1,805</td>
<td>2,419</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td>20.9</td>
<td>33.0</td>
</tr>
<tr>
<td><strong>COV</strong></td>
<td>36%</td>
<td>30%</td>
</tr>
<tr>
<td><strong>% &gt; TV</strong></td>
<td>12%</td>
<td>62%</td>
</tr>
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</table>

Calibration analysis results showed that the XMVs are more strongly correlated to strength (i.e., CBR) or stiffness (i.e., $k$ values) properties than with material dry unit measurements.
Figure 13. XMV calibration results with kQ2 determined from PLT-Qs, k2 determined from creep tests, and DCP-CBR measurements.
Table 1. Summary of regression relationship to predict the different material properties.

<table>
<thead>
<tr>
<th>Predicted Property</th>
<th>N</th>
<th>R² Adj.</th>
<th>RMSE</th>
<th>Range of Measurement</th>
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<tr>
<td>XMV-κ₂ (psi/in.)</td>
<td>17</td>
<td>0.67</td>
<td>79</td>
<td>600 to 1100</td>
</tr>
<tr>
<td>XMV-κ₂ (psi) [from extended tests]</td>
<td>3</td>
<td>0.98</td>
<td>43</td>
<td>1180 to 1800</td>
</tr>
<tr>
<td>XMV-CBR (0-12in. depth)</td>
<td>26</td>
<td>0.67</td>
<td>2.0</td>
<td>7.0 to 21</td>
</tr>
<tr>
<td>XMV-CBR (3-12in. depth)</td>
<td>26</td>
<td>0.76</td>
<td>2.3</td>
<td>8.1 to 26</td>
</tr>
<tr>
<td>XMV-Δw = w-wₜₐₜ (%)</td>
<td>22</td>
<td>0.45</td>
<td>2.0</td>
<td>-9.1 to +2.5</td>
</tr>
<tr>
<td>XMV-RC (%)</td>
<td>22</td>
<td>0.20</td>
<td>2.0</td>
<td>93 to 106</td>
</tr>
</tbody>
</table>

PRODUCTION MAPPING AND QC/QA TESTING

Based on the field-testing results on the test pad and the production mapping areas, the following QC/QA target values and procedures are recommended and have been implemented for this site:

- Apply a minimum of 2 roller passes on loose lift of material – the roller pass count can be reduced if the target XMV is achieved.
- Target XMV = 30. A minimum 80% of the area should have XMV ≥ 30.
- DCP-CBR = 10 (using 8 kg hammer) for the full thickness of the compaction layer. Average CBR of the compaction layer be determined by calculating DPI as the total number of blows to the bottom of the layer divided by the thickness and using CBR = 292/(DPI)^1.12 relationship.
- DPI = 20.3 mm/blow, 1.25 blows/inch (using 17.6 lb hammer) for the full thickness of the compaction layer.
- Maintain moisture contents between -4 to +2% of w₀ as determined by standard Proctor method. Field testing results showed that RC > 95% can be achieved with relatively minimal compaction effort, although the needed strength/stiffness is not achieved. A modified Proctor test is recommended to evaluate if a higher density requirement and lower moisture content is needed for the material.
- Moisture contents should be measured at a drying temperature of 60± 5°C.

Production compaction operations by the contractor involved using the VIC-XMV color-coded map as a QC measure during compaction process to monitor changes in the color and perform a mapping final pass over an area of unmapped fill. Once mapping is finished, the operator pushes a button on the on-board screen that triggers the raw data file to be submitted automatically to a remote server to read the data and automatically generate the VIC compaction report. The report includes various data analytics/statistical summaries and plots of color-coded information. Some example plots from one production compaction operation is shown in Figure 14, showing color-coded geospatial maps of XMV and ΔXMV (XMV minus target XMV).
Figure 14. Example production area XMV map (top) and ΔXMV map (bottom) from 10/12/2018 along with QA point test locations (shown as black dots), DCP-CBR profiles at two select locations, and moisture/dry-density results at the test locations.
The production area shown in Figure 14, showed an isolated “soft” area in red (near the southeast corner of the map area), that did not meet the target XMV (30) set from calibration testing. In situ QA testing with DC tests were performed at 9 test locations randomly spread-out across the mapping area. The tests showed that all tests met the RC requirement of 95%, and all but one test met the moisture requirement of being within -4% to +2% of $w_{opt}$. The one failed test location showed moisture content > +2% of $w_{opt}$ and was in the “soft” area detected with low XMVs in the geospatial VIC maps. DCP-CBR tests showed in the area also showed that the average CBR in the top 12 inches was < 10 (target determined from calibration testing).

Currently, intelligent testing analytics such as using the Ingios’ I-score map are being explored to locate the QA test locations, rather than randomly selecting the locations. Simply put, the I-score map is a map of statistically significant contiguous areas (> 20 ft$^2$) with XMVs < XMV target values. An example I-score map of the same production map area is presented in Figure 15 (with a red “blob”), along with an automatically generated in situ QA test location based on the size of the highlighted area. With using this intelligent testing analytics, the test location information (GPS) will be automatically generated by the software and will be sent to the QA testing engineer. The goal here is to reduce the amount of QA testing locations to targeted areas.

![Figure 15. Example production area I-Score map highlighting](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>TV</th>
<th>% Passing</th>
<th>CGI</th>
<th>CI</th>
<th>Area (ft$^2$)</th>
<th>Area (Acres)</th>
<th>Avg. St. Dev.</th>
<th>COV</th>
<th>Min.</th>
<th>Max.</th>
<th>Avg. ΔXMV</th>
<th>Min.</th>
<th>Max.</th>
<th>Avg. ΔXMV</th>
<th>Max. ΔXMV</th>
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<tbody>
<tr>
<td>XMV</td>
<td>30</td>
<td>78.6</td>
<td>91.34</td>
<td>0.8</td>
<td>208339</td>
<td>4.78</td>
<td>11.65</td>
<td>30.6</td>
<td>4.9</td>
<td>101.1</td>
<td>8.1</td>
<td>-25.1</td>
<td>+71.1</td>
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</table>

Automatically generated in situ QA test location based I-Score map.
SUMMARY AND CONCLUDING REMARKS

In this paper, results from a VIC calibration testing performed on gypsum material at the TVA’s Paradise Fossil Plant in Paradise, Kentucky are presented. Details of the calibration testing program, results from laboratory characterization of the gypsum material, results from field testing performed to evaluate compaction properties, strength and stiffness properties, and time-dependent deformation properties are presented.

Laboratory micro-characterization of the material provided a better understanding of the presence of chemically bound water within gypsum that lead to setting drying temperatures during QC/QA testing for moisture content. Field test pad results aided in development of process control measures about the minimum number of passes required to achieve the desired level of compaction, and QA target values for DCP-CBR values and XMVs. PLTs performed at this site showed that gypsum material at this site exhibits time-dependent creep behavior. Comparison between lanes compacted with different compaction passes showed that with additional compaction effort, the material stiffness can be increased, the time-dependent deformations can be reduced, and the materials’ shear strength properties can be increased. Dry densities in the compaction layer did not show any improvements with increased compaction effort, however.

VIC mapping is being successfully implemented at this study for monitoring production compaction operations. Advanced intelligent analytics are being piloted on-site to identify areas for the contractor to improve compaction quality and inspectors to perform independent testing to verify quality.

REFERENCES


