Rapid Assessment of Cement/Fiber Stabilized Soil Using Roller-Integrated Compaction Monitoring

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ABSTRACT

Test sections consisting of varying amounts of high-early strength (Type III) Portland cement, polypropylene monofilament fibers, and soil stabilizer machine ground speeds were constructed at the Bradshaw Field Training Area in the Northern Territory, Australia as part of a Joint Rapid Airfield Construction (JRAC) project. Aprons, taxiways, and a helipad were stabilized using these materials in combination with screened native soil. The purpose of the test sections was to (1) evaluate the resulting properties for different stabilization dosage rates, (2) develop construction methods, criteria (including limits) and quality control guidelines, and (3) provide a hands-on training opportunity for the joint United States and Australia military construction teams. Testing and monitoring consisted of roller-integrated compaction monitoring and in-situ testing which included dynamic cone penetration tests, Clegg impact tests, and light weight deflectometer tests. Following the test sections, construction of the helipad helped refine the construction methods and quality control testing for the selected stabilization dosage rates and machine speed. Lessons learned on the helipad were applied to the subsequent aircraft parking aprons and taxiways. This paper provides recommendations for rapid construction methods and quality control testing for cement-fiber stabilized soils and demonstrates the application of roller-integrated compaction technology to document compaction effort and uniformity.
INTRODUCTION

In June 2007, a joint exercise between United States and Australian defense forces constructed an unsurfaced airfield in the (BFTA) Bradshaw Field Training Area in the Northern Territory of Australia. The exercise was completed in 22 total days of construction, demonstrating a spectrum of technologies designed to speed contingency engineering operations. This project was the culmination of the JRAC (Joint Rapid Airfield Construction) Program and showcased several technologies such as digital designs integrated with GPS (Global Position Systems) machine control, roller-integrated compaction monitoring, and rapid soil stabilization. The soil stabilization technique utilized a combination of polypropylene fibers and high-early (Type III) strength cement to quickly increase soil load-bearing properties. As part of the airfield construction, a helipad (40 x 50 m), two taxiways (70 x 20 m), and two parking aprons (61 x 68 m) were stabilized.

The focus of this paper is on the initial construction of six on-site stabilized test sections to evaluate a few key construction variables. These included fiber dosage rates, stabilizer machine ground speed, roller-integrated compaction monitoring, and strength gain versus time plots for in-situ dynamic cone penetration (DCP), light weight deflectometer (LWD), and Clegg Impact Value (CIV) tests. Based on the results of the test sections, construction guidelines and target acceptance values were established. These construction guidelines and acceptance criteria were implemented on construction of the helipad, which was also intended as training and refinement of practice for the more critical taxiway and apron structures. This paper represents the first detailed discussion using rapid construction techniques and roller-integrated compaction monitoring for cement/fiber stabilized soil.

CONSTRUCTION EQUIPMENT AND METHODS

The construction sequence consisted of pre-compacting the stabilization layer at optimum moisture content and trimming to final grade elevation. After being trimmed to the design elevation, the surface was sprayed with water and ripped with a motor grader and sprayed again prior to cement bag layout. Cement placement (Fig. 1) was accomplished by placing unopened cement bags along the center line of the lane at predetermined intervals to provide the proper addition rate. The cement was spread by hand using a rake to provide a relatively uniform distribution. Fibers were distributed after the cement, also by hand (Fig. 2). Mixing with a Terex RS 325 soil stabilizer commenced immediately after distributing the cement and fibers. Two different mixing rates (30 and 45 ft/minute or 9.1 and 13.7 m/minute) were investigated following the test matrix in Table 1. The purpose of varying the mixing rate was to evaluate the influence of mixing on the performance of the compacted layers, which as discussed later, was of consequence for these materials.

After mixing, compaction was achieved using a CAT CS-563E vibratory smooth drum roller. Each of the three test section lanes were rolled with eight passes — a single pass consisted of forward rolling at ~4 km/hour with low amplitude vibration (0.85 mm) and reverse rolling with no vibration. The AccuGrade Office system captured the machine speed, coverage, and compaction meter value (CMV) for all roller passes in real-time and were displayed on a computer screen in the cab of the roller and at a central location on the project. The CMVs were analyzed to establish machine compaction curves for each test section and resulting target value for use during production compaction. CMV technology uses accelerometers installed on the
drum of a vibratory roller to measure roller drum accelerations in response to soil behavior during compaction operations. CMV can be calculated as:

\[
CMV = C \cdot \frac{A_1}{A_0}
\]  

(1)

where \( C = \) constant (300), \( A_1 = \) acceleration of the first harmonic component of the vibration, and \( A_0 = \) acceleration of the fundamental component of the vibration (1, 2).

After compaction, CIV (3), and LWD (4) were performed at 0, 2, 6, 18, 24, 48 and 96 hours after final compaction. DCP (5) tests were only performed at 0 and 24 hours after compaction. The purpose of these tests was to evaluate the variability of a given section and the strength gain versus time relationships.

**FIGURE 1.** (a) Cement bag placement according to pre-selected addition rates, and (b) distribution of cement by hand spreading using rake on test sections.

**FIGURE 2.** (a) Monofilament polypropylene fibers, and (b) distribution of fibers after hand spreading on test sections.
MATERIALS

The helipad design was for nominal 250 mm of select stockpile fill using Modified Proctor compaction. Laboratory testing was performed on quarry material collected in June 2006 but similar to that used for stockpile aggregate. The compaction curves for the unstabilized and stabilized soil are presented in Figure 1. The target moisture content prior to stabilization was 7.8% with +2 to –1 % tolerance.

![Modified Proctor Curve for Bradshaw -1/2" Borrow Soil](modified_proctor_curve.png)

**FIGURE 3.** Moisture-density relationships of BFTA quarry soil passing a 12.5 mm sieve.

The stockpile soil was a non-plastic lateritic gravelly silty-sand that classifies as SM according to the Unified Soil Classification System. The construction site consisted of sparse rocky sandstone outcrops interspersed with areas of weathered sand, pebbles, cobbles, and boulders. This surface soil is of low plasticity and forms the base for the select stockpile fill. DCP testing indicated a range of CBR (California Bearing Ratio) values from 30-75 with an average of 45 (two per test section item, 12 total).

**Stabilizer Background**

Santoni and Webster (6) demonstrated the efficacy of polypropylene fibers in various lengths for stabilization of sandy soil. These researchers found that increasing fiber contents from 0.6 to 1 percent by dry weight of soil significantly increased the engineering properties necessary for expedient road and airfield construction. Unconfined compressive strength tests demonstrated that, as the strain level increased the fibers developed tension and the composite soil/fiber mixture yielded higher strengths. Fiber lengths beyond 2-inch (51 mm) were not found to significantly improve soil properties and proved more difficult to work with in both laboratory
and field experiments. Fiber denier (e.g. linear mass density of fibers) was not found to be a significant variable (7). Fibrillated fibers yielded better results over tape, monofilament, and mesh fibers. Field experiments also indicated that it was necessary to ‘fix’ the surface using emulsion to prevent fiber pullout under traffic.

Studies of blends of fiber, cement, and soil have shown significant benefits of fiber addition to soil-cement mixtures. Sobhan and Mehedy (8, 9) demonstrated the importance of using toughness as a measure of performance. These studies showed that increases in tensile strength with added high density polyethylene (HDPE) strips were not realized but large increases in toughness resulting from increased strain capacity was observed. With increasing toughness, much of the expected performance benefits due to fiber inclusion are in the post-peak load portion of the stress-strain behavior. Thus, as the fibers develop tension, an improved stress-strain response is the result. However, improvements in fatigue behavior were not noted.

**TEST MATRIX**

Table 1 summarizes the test section variables of cement content, fiber content, and the Terex RS-325 soil stabilizer ground speed. This allows the evaluation of mixing efficiency with low or high fiber content and low or high soil stabilizer ground speed. The cement dosage rates combined with different fiber dosages provided for the establishment of minimum values for CMV, CIV, and LWD immediately after compaction and during curing. Each of the test sections was comprised of one Terex RS-325 cutter head (‘lane’ width of 1.83 m) approximately 25 m in length by 150 mm mixing depth. Prior to placement of the cement and fibers, the stabilization layer was placed, compacted and trimmed to design grade elevation using motor graders outfitted with onboard GPS guidance systems. By compacting and trimming to design elevation prior to stabilization, it was determined that little or no trimming would be required after final compaction. Minimizing post-compaction trimming is necessary due to the difficulty of grading fiber-stabilized soils. Note that a control section with no stabilizers was not necessary as the runway was constructed without stabilizers so the pertinent construction variables were already known at the time of the test section construction.

**TABLE 1. Summary of test section variables**

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Type III Cement Content (%)*</th>
<th>Polypropylene monofilament fiber content (%)*</th>
<th>Mixing speed with Terex RS 325 (ft/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>0.4</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>4</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>4</td>
<td>45</td>
</tr>
</tbody>
</table>

Notes: *based on dry weight of soil at modified proctor density; * selected for implementation for helicopter pad construction
RESULTS AND DISCUSSION

Compaction CMV – Test Sections

For each test section the roller-integrated CMV measurements were evaluated as a function of roller passes. The results described herein are presented only for test section 1 as this was the mix design implemented for the remainder of the helicopter pad construction. Figure 4 shows the CMVs versus distance for test section 1 for selected passes (passes 1, 2, 3, 4, and 8). For passes 1 and 2 the CMVs overlap to some extent and represent a relative loose condition. Passes 3, 4 and 8 show relatively even increments of increasing CMV. The results further show that in areas of low or high CMV, the results are mirrored to some extent in subsequent passes (for example between 10 and 15 m).

Generally, the increase in CMV as a function of roller passes follows a logarithmic relationship where the incremental increase in CMV per pass decreases with increasing passes \((10, 11, 12)\). The average values for all passes for test section 1 are shown in Figure 4(a). A logarithmic trendline is fit to the data following the form of:

\[
\text{CMV} = a \ln \text{(pass#)} + b
\]  

(2)

Close inspection of the CMVs for multiple passes shows that the values are relatively repeatable between passes in that the high and low trends are similar. This provides confidence that the CMVs are reliable and repeatable. It is surmised that the underlying subgrade layer is being reflected through the stabilization layer to some extent and contributes to the high and low trends in CMV measurements.

Figure 5 shows the machine compaction curve for all six test sections. For several data sets, however, one or more points were eliminated from the regression analysis. Eliminating data points was justified because the roller operator “off-tracked” during roller operations. Off-tracking refers to the roller operator driving the machine outside the previous travel path onto uncompacted material which reduces the CMVs. Figure 6 shows off-tracking up to 1m for passes 6-8 for test section 4 and demonstrates the benefit of having GPS location measurements.

![FIGURE 4. CMV versus position for passes 1, 2, 3, 4, and 8 for Test Section 1.](image)
In-Situ Test Measurements

Results of LWD and CIV results are presented in Figure 7. The LWD measurements indicate that sections with the slower 30 ft/minute mixing rate result in increased strength at short cure times. This is assumed to be result of improved cement and fiber distribution. DCP results at 100mm depth are shown in Table 2 and also indicate significant strengthening after 24 hours of curing.

<table>
<thead>
<tr>
<th>Test Section</th>
<th>CBR at 100mm at 2 hours</th>
<th>CBR at 100mm at 24 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>Refusal</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>Refusal</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Helicopter Pad Construction

Building on the experience of the test sections, a target CMV value of 30 was established for the helicopter pad construction. The mix design of test section 1 (Table 1) was selected for the construction. Construction methods were to replicate the test section (cement/fiber distribution, mixing at 30 ft/minute with 8 roller passes). A few changes were observed during construction that deviated from test strip construction, however. Differences included: (1) additional passes of the water truck, (2) rolling with no vibration and variable number of passes, (3) use of motor graded on north quarter of pad to spread material, and (4) use of motor grader to rip the surface prior to placing the cement and fibers. Additional moisture conditioning was necessary to provide optimum water contents.

Figure 8 shows the roller pass coverage and CMV results for the helicopter pad and test section areas. Inspection of the results shows that roller passes were completed with a variable number of coverages (1 pass (forward and reverse) = 2 coverages). The minimum number of passes was set at eight on the test section construction (i.e. 16 coverages). Poor compaction operation (no vibration) and a lack of adequate monitoring resulted in low CMV values and an inadequate number of passes. This led to low CMV for a large portion of the pad. An excessive number of roller tracks remained in the surface after curing, indicating that further compaction should have been performed.

As further verification of poor compaction, in-situ measurements of LWD and CIV are summarized in Table 2. Results indicate that the average values are lower for the helicopter pad for the selected cure times (18 hours for LWD and 24 hours for CIV) and more variable based on comparison of the range of values compared to the test section.
FIGURE 5. (a) CMV compaction curves for test sections 1 through 6.
FIGURE 6. GPS position of drummer drum during multiple passes showing off-tracking for passes 6-8 for Test Section 1.

FIGURE 7. (a) CIV and (b) LWD versus time results for all test sections.
FIGURE 8. Helicopter pad construction.

TABLE 2. Comparison of in-situ measurements for Test Section 1 and helicopter pad.

<table>
<thead>
<tr>
<th>In-Situ Measurements</th>
<th>Test Section 1</th>
<th>Helicopter Pad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>LWD</td>
<td>160</td>
<td>90 to 216</td>
</tr>
<tr>
<td>CIV</td>
<td>56</td>
<td>33 to 61</td>
</tr>
</tbody>
</table>
FIGURE 9. CAT AccuGrade Office results for helicopter pad and test sections (a) number of coverages (as defined in this paper 1 pass = 2 coverages), and (b) achievement of target CMV (blue = CMV >30 and red = CMV < 30).
RECOMMENDATIONS

Based on the results of the test sections and the observations made during helipad construction, several recommendations were adopted for apron and taxiway construction.

1. The operation tempo was adjusted such that a continuous operation of material, placement, mixing, and compaction was achieved. The slowest process (in most cases compaction) dictated the speed of the operation.

2. No more than three lanes of materials were placed ahead of the mixing operation. This prevented material wastage in the event of a shutdown.

3. The target average moisture content was dropped from 7.8 to 7.3%, in-line with field observations based on runway (no stabilizer) and helipad (with stabilizer) construction. The moisture content was an average of four measurements per lot (500 m²). No measurements outside the range of 5.3 and 10.3% were allowed without action (more water or drying).

4. Cement bags were staggered across the stabilizer lane width to improve cement distribution.

5. The maximum ground speed of the Terex RS-325 soil stabilizer was set at 9.1 meters/minute (30 feet/minute).

6. Compaction commenced within 30 minutes after mixing.

7. Target CMV was 30 with eight roller passes per stabilization lane. Eight passes consisted of a vibratory roll in the forward direction and a static roll in reverse. Additional static rolling was allowed as needed to remove roller marks. Compaction was closely monitored to insure that target values were being met.

8. Target values for CIV were set at 25 (within 30 minutes of final compaction) for an average of four measurements within each lot) and a minimum value of 20 for action (more compaction).

9. Grading was avoided unless absolutely necessary. If grading was needed, it was accomplished within two hours of final compaction.

10. Surface smoothness and elevation prior to mixing dictated the smoothness and elevation after mixing and compaction. It was noted that it was ideal to have an area at the same grade that extends approximately 5 meters beyond the stabilization perimeter. This prevented surface undulations due to tipping of the cutter head as the machine encounters elevation changes outside the stabilization perimeters. This also allows for lowering and raising of the cutter head in unstabilized soil that can be later graded to restore surface smoothness.

SUMMARY AND CONCLUSIONS

A test area was constructed to evaluate key construction variables and methods for determination of criteria, material placement, compaction, and quality control. The test area provided data for establishing quality control criteria for CMV, roller passes, in-situ tests, fiber content, and stabilizer machine speed. These criteria and other construction variables were implemented for helipad construction. Unfortunately, poor compaction monitoring led to low compaction levels (low CMV) on the helipad. This resulted in a critical evaluation of helipad construction procedures and several ‘lessons learned’ that became the basis for construction criteria, close
compaction monitoring, and procedures for apron and taxiway construction. Apron and taxiway Bravo were constructed non-stop beginning at 12:30 am on June 26 2007 and ended at 11:00 pm on June 26 2007 using a single Terex RS-350 soil stabilizer. Apron Alpha was constructed beginning at 11:00 pm June 26 and ended at 1:00 pm June 27 2007 and used a Terex RS-325 and 350RS. A C-17 aircraft was allowed to operate on the surface of Apron Bravo within 16 hrs of final construction (3:00 pm June 27 2007). On June 29, two C-17 aircraft operated on Aprons Alpha and Bravo. The roller-integrated compaction monitoring capabilities played an important role in providing real-time process control and resulted in a more uniformly compacted surface.

ACKNOWLEDGMENTS

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REFERENCES