Cairns, Smithfield Bypass Project: Site for alternative quality testing equipment

Burt G. Look
Formerly FSG – Geotechnics and Foundations, Australia, lookburt@hotmail.com

ABSTRACT: Industry familiarity with density-based assessment for Quality Control (QC) purposes currently hampers the use of more accurate tests. An ARRB research project identified several alternative quality tests that have the potential to provide improved accuracy (as compared to density). These “new” methods (most are over 20 years old) provide a reduction in both the duration of onsite testing and turnaround of test results and provide the direct measurement of a stiffness (modulus) value. Overall, these alternative tests do not correlate well with the common density ratio (DR) test. Most alternative field equipment tests seem to be positioned between the Plate Load Test (PLT) and density in terms of accuracy and precision. The results and comparisons at the Smithfield Bypass project (approximately 11.5 km North-West of Cairns CBD) is presented. This site was tested in early 2019 and is one of several “live” test sites between 2017 and 2019. Field testing was undertaken upon an embankment being constructed over Avondale Creek and in parallel to standard tests for QC. Lessons learnt and comparisons between equipment at this site are provided. Dendrogram analysis is used to show the relative relationship between tests

KEYWORDS: Dry density ratio, dendrogram analysis, subgrade modulus, compaction, test equipment.

1 INTRODUCTION

Modern geotechnical and pavement designs are based on modulus and strength values. Many test methods have the potential to reliably provide a direct measure of the strength or in-situ modulus value; and offer considerable time savings in turnaround time of Quality Assurance (QA) test results. Several in-situ devices have been available to industry for the past 2 decades and research has shown these have significant benefits and are described in the 3-part Australian Road Research Board (ARRB) webinar by Look et al. (2018, 2020a/b).

This paper presents the background and data acquired at the Smithfield Bypass Project (SBP) in Cairns in 2019 as part of the ARRB research. This is one of many sites used in understanding the benefits and limitations of alternative test equipment. Conventional QC testing as part of the project was supplemented with other tests not typically used at that time. A key finding was that a higher density (for a well compacted material) does not indicate an increase in modulus. Hence the density QC tests do not relate back to any design parameter. Some instruments showed a decreasing or no change in value with increasing density ratio. Note QC is not the same as QA.

Measured modulus values depend on the material compaction, its quality, and its interaction with deeper underling layers (Fig. 1). Thus, density is just one contributing factor, and a weak correlation should be expected when a muti-variate issue is converted to a paired correlation. Density and moisture are independent measurements when that procedure is used.

Because of the widespread usage of density testing in quality control, this now acts as an impediment to the implementation of alternative test methods in the industry. This is due to studies trying to corelate those measured parameters with the dry density ratio (DR) used in QC. Using density as a reference test leads to requests for correlations to the DR results as if that index was the end product. Yet relative compaction was meant to be an index only of the likely strength or modulus. To measure strength or modulus and then correlate back to an index test shows how tradition encourages this force fit from a primary measured value to the 2nd order index parameter.

Look (2019, 2021) describe a methodology based on matching Probability Density Functions (PDFs) to overcome the poor correlations that often occur as described in a supplementary paper by Look (2023) at this conference. Background is presented in this paper from the Smithfield Bypass project data to illustrate the above concepts using dendrogram analysis to better understand the interrelationships between various test parameters and test equipment. Field testing on “live” projects at various sites and on varying materials were carried out in parallel with the usual density QC testing using a range of equipment (Fig. 2).

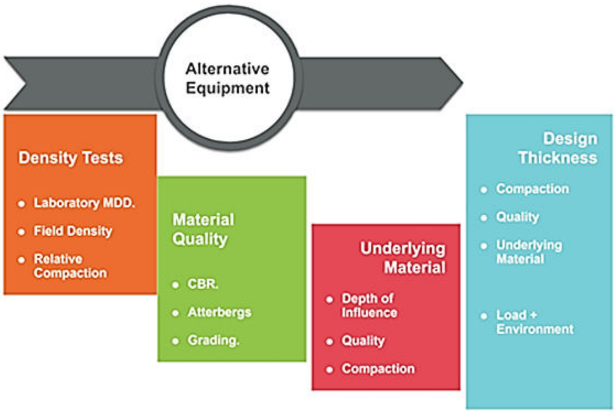

Figure 1. Comparison of density-based tests with alternative tests, which measure combined factors.

Figure 2. Various equipment used at project site in single location.

2 COMPACTION TESTING

2.1 *Compaction History*

Density testing has been applied widely in QC. The emphasis on density has led to the belief that it is the key parameter, yet it is an index only, i.e. we assume an increased density means an increased strength or modulus. Technology has now advanced to measure those parameters directly, yet many road and approving authorities still use density testing as the main quality evaluation parameter because of our longstanding experience. The key index of DR is based on 2 simple measurements – the field dry density and maximum dry density.

$$Density\ Ratio\ (DR) = \frac{Field\ \text{Dry}\ Density\ (FDD)}{Max\ Dry\ Density\ (MDD)}$$

An implicit assumption used by site engineers, is that an increase in DR is due to an increase in FDD. Yet in material derived from residual soils and weathered rock an increase in DR could be due to crushing of the granular materials with a decrease in MDD (Look 2021). This may result in a decrease in strength and modulus measurements. Many engineers assume that density is the end game. Some other assumptions include:

- There is a direct and reliable relation with density and CBR, strength or modulus. As the DR increases the CBR, strength or modulus increases.
- The reported density measurement is accurate. Density is a precise test, but precision is different from accuracy.
- The higher energy imparted to the soil via higher number of passes, increases the density ratio and hence also the CBR, strength or modulus.

These many assumptions may be incorrect for some materials and discussed in Look (2019, 2021). The high precision (reproducibility and repeatability) of density should not be confused with accuracy. A DR of 95% can have a wide range of strength and modulus values, with some materials compacted at 90% exceeding the modulus of another compacted to 95% DR. A specified density ratio is really a targeted means to reducing the air voids. This requirement is often confused with 2 supporting recommendations in Standards. Figure 3 illustrates the concept of requiring the DR to achieve the reduction in air voids with the 2 supporting recommendations of the moisture ratio and the lift thickness.

The target moisture ratio is climate dependent (Look, 1994) while the target lift thickness is equipment dependent. These recommendations should not be given the same emphasis as the density requirement. For example, if a density ratio requirement is achieved without a specified moisture ratio (say at OMC± 2%) or thickness (say 250mm compacted thickness instead of a 200mm target) would this be considered a failed quality test? In many homogeneous and clay materials, the testing variation can be OMC± 5% at MDD, and that is prior to considering material variability. Thus, moisture content range "failure" can occur from testing variation only.

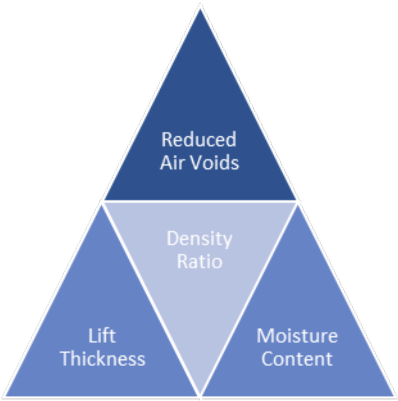

Figure 3. Aim, requirements, and recommendations for compaction.

2.3 *Laboratory data*

Many field equipment (various Light Falling Weigh Deflectometers - LFWD, PLT) measure modulus, but with different zones of influence and strains. This acts as an impediment to a "universal" value as is done with density ratio of say 95% compaction. DR is not used in design but the CBR test, which is then corelated to a modulus. The state of practice accepts the highly variable CBR tests + a widely varying correlation to modulus. Ironically industry has an issue with a direct measurement of modulus due to variability in measurement from various equipment.

Although CBR is the key design input for pavement design, the density measurements are the key "quality" parameter for construction assessment. Yet dry density and MDD are poorly correlated to the CBR (the key design input) as shown in the companion paper at this conference (Look, 2023). A high plasticity clay would have its high strength wet of optimum (below MDD), while a granular material (Fig. 4) would have its peak strength dry of optimum (below MDD). Peak CBR does not usually occur at MDD / OMC.

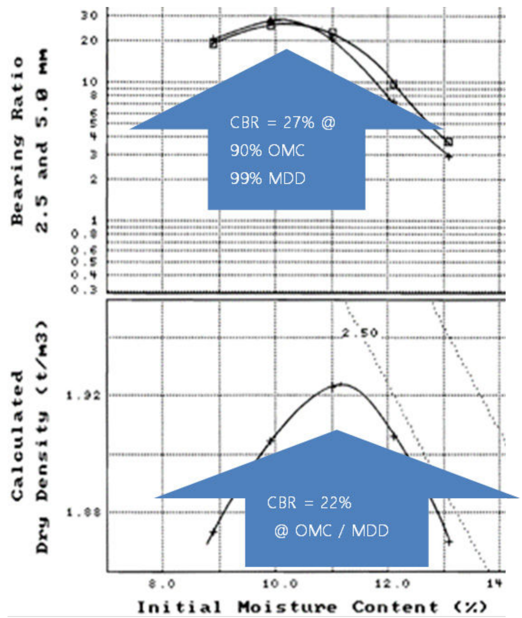

Figure 4. Maximum CBR for a Clayey Sand.

High strength occurs at dry of OMC compaction. Soil suction has a significant effect on shear strength. At OMC (Degree of Saturation ~ 85%) there is no continuous air as the material is near saturation. As saturation increases, the material's strength decreases significantly, but with large strains to failure as shown by Seed and Chan (1959) and discussed in Leroueil and Hight (2013). Figure 6 shows the change in deviatoric stress along the compaction curve from dry of optimum to wet of optimum. These test samples are at or above 90% MDD.

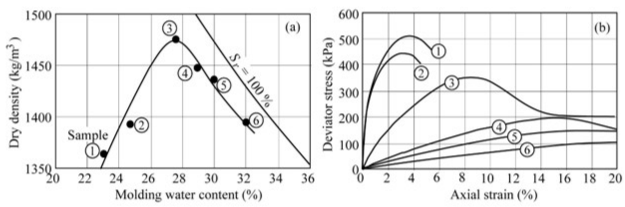

Figure 5. (a) Influence of moulding water content on the dry density and (b) stress-strain relationships for compacted samples (Seed and Chan, 1959; here from Leroueil and Hight, 2013).

Data from earlier ARRB test sites showed that DR may not be highly correlated to modulus. This was unexpected and required further testing with expanded data. Hence the Smithfield project site was used to compare various tests with compaction parameters. This showed show some tests were associated more with the moisture / CBR while other tests are more associated with the DR. Thus, the non-efficacy of correlating another test result to DR. Note that this was only recognized in hindsight, by re-examining current and previously available data.

In field compaction, there is a tendency to compact dry of optimum to increase the strength, yet in an expansive clay material this induces a higher swell (Look, 2023). This effect is best assessed in laboratory soaked CBR test which is not part of this paper discussion.

3 TRADITIONAL / CONVENTIONAL TESTS COMPARED WITH OTHER EQUIPMENT

All field assessment involved the direct (side-by-side) comparison testing of the "innovative" (alternative) test equipment with "conventional" techniques implemented for routine QA assessment of compacted earthworks, namely:

- **Relative Compaction** – AKA Density Ratio (DR)
- **Field Moisture Content** – Measured on a post-compaction sample and reported as Gravitational Field Moisture Content (FMC) and as a Moisture Ratio (MR)

The following alternative field assessment test equipment were used at the SBP field work to supplement standard tests as part of the ARRB research (Fig. 6) but only over the Lots over a 2 week period:

Surface Based Plate Testing:

- **Static Plate Load Testing (PLT)** – considered the 'reference' test for insitu modulus.
- Light Falling weight Deflectometer (LFWD) **– Prima 100 LFWD** (Manufactured by Sweco)
- Light Falling weight Deflectometer (LFWD) **– Terratest 5000 BT USB LFWD (**Manufactured by Terratest)
- 9.1 kg, Variable Height **Clegg Hammer** – Manufactured by Dr. Baden Clegg

Near-Surface Penetration Testing:

- **PANDA Probe** (Variable Energy Dynamic Penetrometer)
- **Dynamic Cone Penetrometer** (DCP)
- TEROS 12 – **Field Measurement of Volumetric Water Content** (VWC), Temperature and Electrical Conductivity (EC) in soil

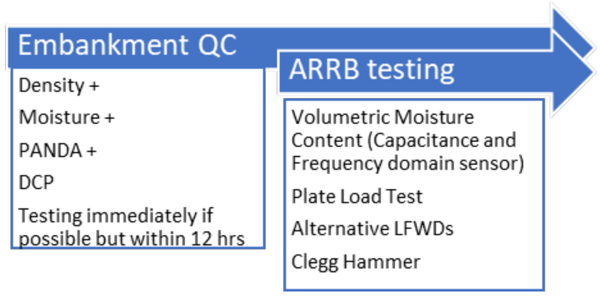

Figure 6. Test equipment used at SBP, Cairns.

4 FIELDWORK TEST SITE

The field-testing was conducted between in early 2019 on the "live" greenfield Smithfield Bypass Project (SBP). This bypass links McGregor Road to Cairns Western Arterial Road and the Captain Cook Highway and is located approximately 11.5 km North-West of Cairns CBD. All field testing was undertaken upon an embankment being constructed over Avondale Creek as part of an 'early works' component of the project (Fig. 7).

Figure 7. Field trial site near Avondale Creek (Nearmap 13/06/2019).

Table 1. Embankment fill material pre and post compaction

Fill material	*Particle size distribution (4 No. tests) Range / Average*	
	Pre compaction	Post compaction
Cobbles	10 – 22/ 19%	0 – 11/ 4%
Gravels	31 – 51/ 40%	29 – 55/ 43%
Sand	15 – 31/ 22%	25 – 41/ 32%
Fines	16 – 23/ 20%	14 – 27/ 21%

The imported embankment fill material broke down following compaction from some cobble sizes to increased gravel / sand sizing. Table 1 shows the sizing pre and post compaction. The weighted plasticity index (WPI) pre compaction was in the range 174 – 766 with 290 an average value from 27 No. tests. The range and average PI were 5.0 – 11.0% and 8.4%, respectively

4 EQUIPMENT TEST RESULTS

A few interesting findings are presented initially and followed by dendrogram analysis for equipment comparisons. Lots 7 to 38 were used to compare between DR and other test equipment.

4.1 *Disagreement between quality tests*

Two lots (Site 21 and 24) are presented to show disagreements between LFWD and density tests, and the lessons learnt. These 2 sites are well compacted "passing" sites and typical or better than other lots for the density ratio tests (Table 2). However, both sites had a rain period associated. The low Coefficient of Variation (COV) is evident.

Table 2. Density ratio tests of compacted embankment fill

Site ID	*Density Ratio tests*			
	No. of tests	Min / Max. %	Mean %	COV %
21	4	97.7 / 102.3	99.8	1.9
24	6	98.6 / 102.7	100.6	1.5
All Lots 7 to 38	132	95.0 / 104.1	99.7	2.1

The density testing was carried out shortly after the final layer compaction occurred at Lot 21. A period of rain occurred shortly after testing. A testing recheck of values after rain fell at lot 21 shows a decrease of median LFWD values (Table 3). Density tests would not have picked that change as no retest was carried out. Yet the tests 2 days after compaction shows significant changes due to rainfall. Density testing would be business as usual i.e., proceeding without explicitly acknowledging or acting for changing conditions. A retest was carried out immediately adjacent to the 4 prior tests then at another 10 test locations

Table 3. Comparison of testing before and after a rain period at Lot 21

Testing Period	*LFWD modulus (MPa) @ 100kPa*		
	No. of tests	Quartile /Median	Ratio change Median/quartile
Dry– shortly after fill compaction	4	72.8/113	Reference Value
Rain fell– adjacent to previous tests	4	67.4/98.3	1.15 / 1.08
Rain fell – additional tests	10	81.1/101	1.12 / 0.90

Results show rain falling after the initial testing changed the median modulus to 88% of the Dry Value. Note the LFWD modulus values were still a pass result despite a reduction. The results also show that without the paired tests (immediately adjacent to the initial tests), the 10 additional tests (at different locations) yield values varying by 10%. The key lessons being:

- A passing density should not mean that subsequent layers can be placed, especially following rainfall. Proof rolling would be required
- Modulus values are constantly changing but is not being recognized by the current DR approach
- Hard spots (values above 200 MPa) affect the statistical interpretation – likely due to underlying large stones
- The median value would better highlight this change

At Lot 24 the LFWD values suggested "failing" results although the assumed density (expected) showed "passing" results. There was a disagreement between traditional density testing and LFWD testing. The contractor saw this as the alternative LFWD tests being more stringent or incorrect. Recheck of values allowed to dry back shows an increase of values (Table 4). Density tests would not have picked that change as no retest was done or required.

Spot checks utilizing Nuclear Density Gauge (NDG) testing was not able to effectively identify the soft spots such as weak (wet) zones that cannot be compacted to the similar level. Neither was it able to identify the changes that occurred from drying back. These weak zones would have been identified by deflection testing or proof rolling and action would typically be required.

Table 4. Comparison of testing before and after a rain period at Lot 24

Testing Period	*LFWD modulus (MPa) @ 100kPa*		
	No. of tests	Quartile /Median	Ratio change Median/quartile
Shortly after fill compaction	4	15.6/23.0	Reference Value
Next day dry back	4	16.3/37.4	0.95 / 0.61
Further dry back	10	70.2/117	0.22 / 0.20

Such weak zones are OK (if density passes) only if allowed to dry back. It is not acceptable if used with a more expensive layer such as a base / subbase material overlying being placed or as a working platform subgrade for heavy plant. Overlying material on weak zones either punch through during compaction or do not compact properly. The question now arises on whether the initial test results or the dried back test result applies.

The modulus is dependent on both moisture and density. As it is the overall stiffness which matters then a passing density with a weak material from excessive moisture is clearly unacceptable. A passing modulus 24 hours after (i.e., dried back) seems acceptable provided the density test passes. Figures 8 and 9 show the wet spots that visually should be a "fail" as rut marks and wet spots are evident, yet has a passing density test i.e. density is a lag indicator.

Figure 8. A density "pass" with a fail LFWD disagreement area

The modulus is dependent on the moisture content. A passing DR could have a low-test modulus if rainfall occurred shortly after the test. Additional layers should not be placed even with passing DR tests. Conversely, the test modulus can increase if considerable time (say ½ day) occurred after compaction was completed and with sun and wind drying. A DR test does not show significant changes with ambient in-situ moisture changes occurring after compaction as it is the dry density being ratioed, and with moisture content a separate consideration.

Thus, to be comparable, the LFWS tests should be caried out within 2 hours of the DR tests, but preferably at the same time.

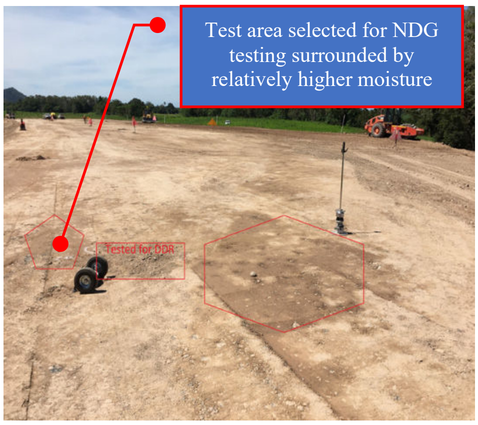

Figure 9. A density pass does not "notice" adjacent wet spots

4.2 *Reducing testing variability*

A key issue in implementation of any alternative testing was shown to be the large COV of such tests, despite its superiority in most other areas (accuracy, time to do the tests, etc.). A stepwise reduction to develop an understanding of this outlier effect is shown herein for the Prima LFWD tests. The procedure may be used for other test instruments and this analysis does not suggest any preference to that test only. Figure 10 shows the PDF for all "reliable" 71 LFWD tests results.

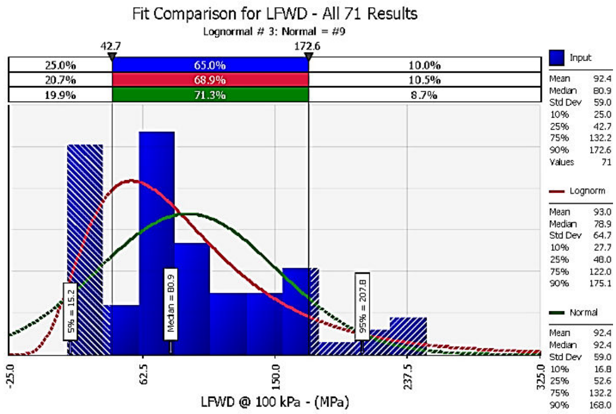

Figure 10. PDF for LFWD @ 100 KPa for all 71 tests

Figures 11 to 12 show outliers occurring with those tests. This was attributed to likely hard spots from the underlying oversize material. Figure 11 compares the same lots divided into DDR. This shows:

- LFWD modulus increases as the density ratio increases (which should be expected)
- Variability increases at high density ratios. Outliers occur at high DDR

Figure 12 compares the same lots divided into moisture ratios (MR). This shows:

- LFWD modulus increases as the moisture ratio decreases (which should be expected)
- This modulus ratio compared to "dry" tests is 60% to 40%, for MR= 80% to 100% and MR > 100%, respectively
- Variability increases at low moisture ratios

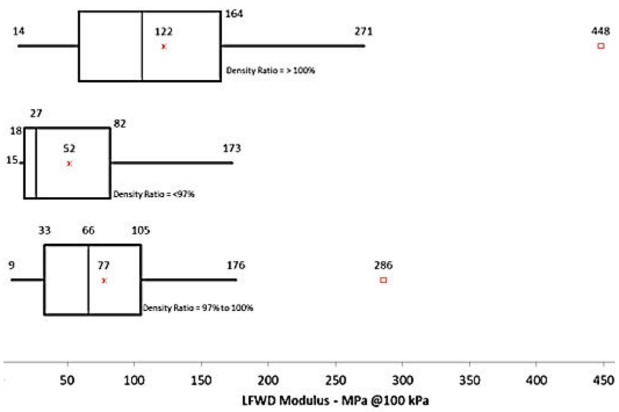

Figure 11. LFWD Modulus comparisons: DDR < 97%, DDR between 97% - 100% and DDR > 100%

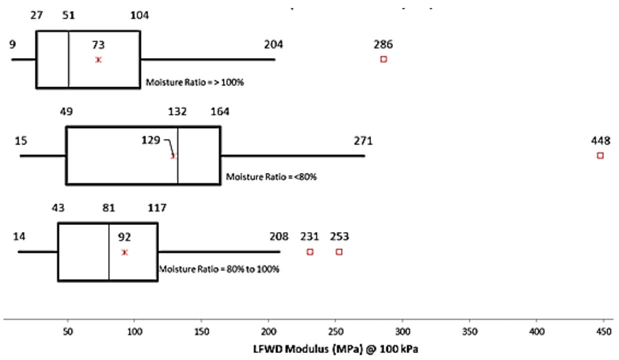

Figure 12. LFWD modulus comparisons: Moisture Ratios < 80%, 80% - 100% and > 100%

Table 5 shows the summary statistics of this progressive removal of the upper value – which could be a "high" outlier. Significant changes occur for the first 4 high values removal (5.6% of population). By 9 No. removed (12.7%), PDF distortion occur, and the normal PDF dominates ito kurtosis values which approaches 3. Values above 200 MPa (upper 5% of tail) are considered outliers (also beyond equipment test range reliability) and setting this as an upper bound would reduce the COV to below 60%. Removal of additional values beyond that distorts the results. Above 13% removal the normal PDF dominates and is considered excessive with data distortion. The revised PDF with outliers removed is shown in Figure 13.

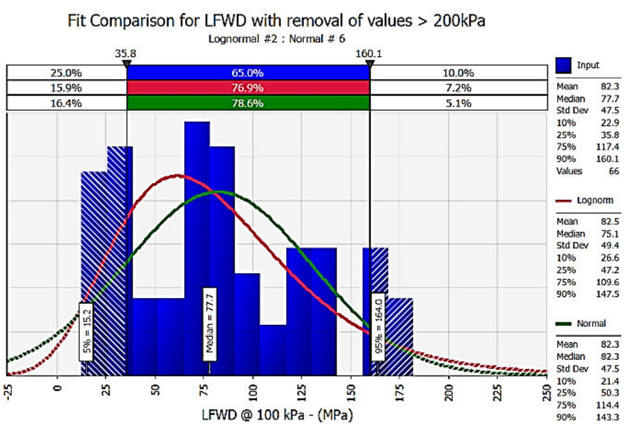

Figure 13. PDF for LFWD @ 100 KPa for values above 200 MPa removed (upper 5% of results)

This supports the outlier analysis carried out in Figures 11 and 12, which also identified values above 200 MPa from that approach. Note that the mean would drop from 92.4 MPa to 82.3 MPa with removal of these 4 outliers. Removal of these high values has the most change at the lower characteristic values.

Table 5. Progressive removal of upper value

% Removed	Value Removed	Mean	COV %	Lognorm Kurtosis	Lognorm./ Norm rank
Full Population		92.4	64	8.6	3 / 9
2.8	231	88.1	61	5.8	7 / 12
5.6	204	84.2	59	4.8	6 / 12
7.0	182	82.3	58	4.4	6 / 11
9.9	173	79.3	57	4.1	5 / 8
12.7	164	76.5	56	3.8	6 / 5
16.9	156	72.1	54	3.4	6 / 3
18.3	143	70.7	54	Lognormal is N/A Kurtosis = 3 indicates Normal PDF	< 14 / 1
21.1	140	68.2	53		< 15 / 3
25.4	123	64.3	51		< 15 / 3
31.0	117	59.8	50		< 13 / 3

Applying a 10% LCV for modulus measurements can create anomalies unless the best fit PDF is used. If a statistical approach is not used, then a median based value should be adopted to account for the skewness of the test data. For this site, a 25% LCV and median approach would have an LFWD modulus @ 100 kPa of 45 MPa and 75 MPa, respectively.

4.3 *Dendrogram Analysis*

A dendrogram cluster analysis is used to visually show the relationships between some of these field tests. Other dendrogram analysis and further explanation on this multivariate analysis technique and on other data is provided in the companion paper (Look, 2023). Highly correlated measurements are clustered close to each other in the tree diagram. As we move up the dendrogram tree branch, the interrelationships are shown with reduced similarity indicating a lower correlation.

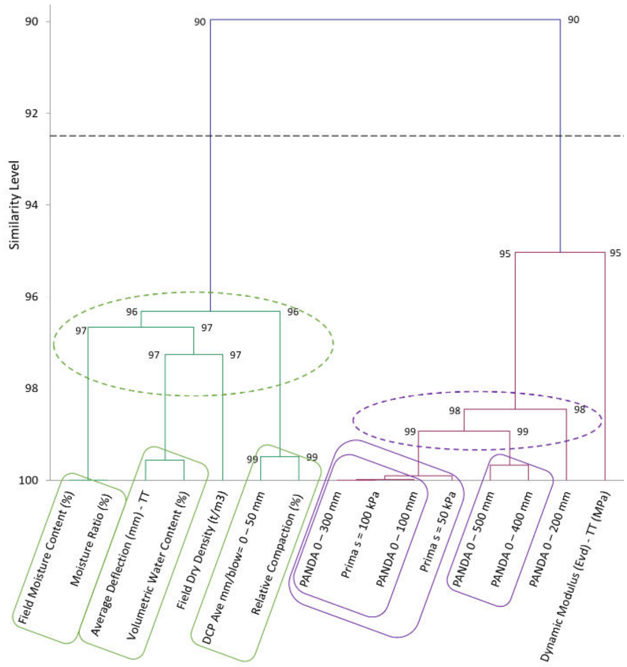

Figure 14. Dendrogram relationships for compaction tests with PRIMA and TT LFWD, PANDA, and DCP at penetration shown.

Figure 14 shows that the relationships with 2 distinct clusters. Cluster 1 shows strong relationships of:

- Field moisture content and moisture ratio (as expected)
- Deflection of LFWD (TT) model with VWC
- DCP (0 – 50mm) with relative compaction

Cluster 2 shows strong relationships between

- PANDA (0 – 300mm) with PRIMA LFWD (100 kPa) and PANDA (0 – 100mm). These are also similar to the PRIMA LFWD at 100 kPa
- The PANDA (0 - 400mm) and (0 – 500mm) penetration are similar, although interrelated with the other depths
- The modulus of the TT LFWD model is within this cluster but less correlated to the PANDA and PRIMA LFWD

Overall, this cluster analysis suggests modulus values from PRIMA and TT models, as well as PANDA penetration depths are poorly correlated to relative compaction. Figure 15 shows additional interrelationships with the PLT at different pressures and the Clegg Impact Values (CIV) at different drop heights. This is from different Lots, although on the same site and material. The 4 clusters visually show:

- FMC and moisture ratio are clustered (as expected). Similarly, the E_{v1} (first cycle modulus) and E_{v2} (second cycle modulus) at varying stresses are clustered but is the furthest cluster from the compaction measurements. This suggests that DR is poorly correlated to PLT modulus
- CIV values at 0.076 and 0.152m drop height is more related to the moisture, while CV at 0.457m is closer to the relative compaction. There is the anomaly of 0.305m drop height being slightly further away
- The LFWD is more related to the PLT E_{v1} than to the relative compaction. Given that the E_{v2} would be the closest measurement to a design value, this analysis shows that relative compaction is a poor indicator of modulus values

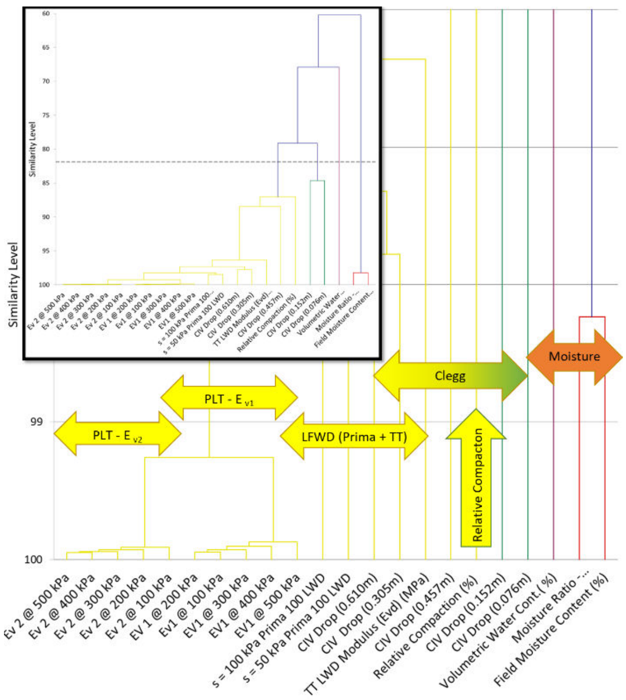

Figure 15. Plate load test at varying stress with dendrogram relationships.

5 SUMMARY

This SBP was used as a test site. The embankment was a uniform imported material. Density QC testing was used in parallel with DCPs, PANDA and PRIMA LFWD tests. A large database was able to be obtained. For a shorter 2-week period PLTs, Clegg and an alternative LFWD (Terratest) were also used. Some key findings were (not all were covered in this paper due to space):

- Paired test values have poor correlations between density and the other units of measurements. Thus, a method to avoid such an approach was required
- Contractors view parallel testing as additional costs and time. Combined with the inconsistencies of the density correlations, then such methods may not be advanced unless industry accepts these different units of measurements
- Ironically, density (as the standard) is not considered an accurate test and is a lag indicator, as it is not able to assess changes occurring, as was seen when rain fell between density testing and the next lift. Other tests can show such changes and one should not then rely on that lag density measurement to assess whether another lift can be placed.
- The many tests measure combination of moisture and density. At the top 100mm or low energy drop heights moisture governs, while correlation at larger drop heights or depths have less of the moisture effect. However, in all cases the correlation is poor. DCPs and CIV at low drop heights are more related to moisture than DR
- Density is just one of several components affecting the subgrade modulus. Multivariate analysis is required as paired correlations are usually poor. Using data at this site, dendrogram analysis was applied and shows the relative relationship compared for various test. Modulus type tests are poorly correlated to compaction tests.

An additional paper at this conference (Look, 2023) provides other aspects of using current technology versus the ubiquitous density tests for quality control.

6. ACKNOWLEDGEMENTS

David Lacey and Roozbeh Mirjalili were active in the acquiring of some of the test data presented.

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