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ANNUAL SUMMARY REPORT

P60: Best Practice in the Quality Assurance of Pavement Layers and Subgrade – Year 4 (2019–20)

ARRB Project No.: 014925

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Prepared for: Queensland Department of Transport and Main Roads

17/11/2020

AN INITIATIVE BY:

SUMMARY

This is Year 4 of the NACOE project which explores alternative testing to quality assurance pavement and subgrade materials. Year 1 (2016–17) completed a comprehensive literature review of different test methods available. Year 2 (2017–18) undertook equipment comparison testing in Ballina NSW and Rocklea QLD. Year 3 (2018–19) continued carrying out field testing at a major TMR project in Cairns. This year's primary focus was to finalise the draft testing protocol into a technical note and conduct knowledge transfer activities to present the findings to the wider audience in Queensland and Australia.

Two webinars were presented by the NACOE project team, including presentations from two international speakers. The webinars were focussed on the implementation of the draft testing protocol and provided the road industry with updates of the latest development in the USA and the railway industry in Australia using similar technologies.

A technical note was also developed, which outlines a procedure to adopt Light Weight Deflectometer testing as a quality assurance tool for the construction of pavement layers and subgrade.

ACKNOWLEDGEMENTS

ARRB would like to acknowledge the contribution made by FSG Geotechnics and Foundations to the delivery of this project. The ARRB study team also acknowledges the contribution of Professor Soheil Nazarian (UTEP) and Mr Andrew Doe (ARTC) for delivering the industry webinar.

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1 INTRODUCTION

1.1 BACKGROUND

The Queensland Department of Transport and Main Roads (TMR) and contractors primarily use in situ dry density ratio (DDR) and California Bearing Ratio (CBR) testing during the construction of earthworks, subgrades, and unbound granular pavement layers, to control the compaction quality.

There are, however, two major disadvantages to this approach: (a) these traditional tests do not measure the in situ modulus of the layers constructed, which is a key parameter used as input into the mechanistic design of pavement structures; and (b) there can be a significant delay between the time of undertaking the DDR or CBR testing and the delivery of the final test results back to the contractor, and demonstrating compliance of the construction works to the quality requirements. Such a (routine) delay in the provision of test results can lead to costly rework being required by the contractor.

Density measurements are relatively easy to undertake during construction, and they can indeed provide a precise measurement of compaction in an easy-to-understand manner. The use of the nuclear density gauge (NDG) – the current industry standard – has the additional benefit in terms of the speed in obtaining field density results compared to (traditional) sand replacement methods. However, there remains a delay in the determination of a test site's relative compaction due to the time taken to obtain the laboratory maximum dry density (MDD) (unless an assumed value is used). CBR testing also involves a time delay due to sample curing and the soaking period required.

Previous National Asset Centre of Excellence (NACOE) research has found that although density measurements are precise, they do not correlate well with common design parameters such as modulus or material strength (i.e. density results ≠ modulus/strength parameters). The structural design of pavements, working platforms, or other bridging layers require either strength or modulus input and it is imperative that any verification testing undertaken can accurately assess, or be strongly correlated to such parameters.

Over the past several decades, alternative testing devices such as the Prima 100 LWD (Light Weight Deflectometer) have been developed to provide modulus measurements soon or immediately after testing. The Clegg Hammer and Dynamic Cone Penetrometer (DCP) are also used to evaluate pavement or earthwork strength characteristics. Some of these devices also report moduli which negate the need to rely on correlation relationships (which are often material specific) to relate measured density or CBR to in situ moduli.

1.2 PROJECT AIM AND OBJECTIVES

This project aimed to modernise the testing procedures currently used by TMR for the evaluation of earthworks and pavement layers in Queensland. The project scope was mainly focussed on assessing alternative techniques, their benefits and disadvantages, and developing guidelines and specifications that will facilitate the implementation of these alternative techniques.

The introduction of techniques with short turnaround times will allow non-conforming works to be identified and rectified sooner than is currently possible with the current testing. The focus of the study was the in situ moduli parameters, and this project specifically does not address other characteristics that density testing, or other testing, may evaluate – such as settlement potential, permeability, etc. Similarly, the determination of a direct relationship between design moduli and in situ moduli falls outside of the scope of this study, and these parameters would likely differ based on the strain magnitude variation between design (modelling) and field (in situ) evaluation techniques.

A comprehensive literature review of potentially viable alternative field evaluation equipment and international studies of their effectiveness in earthworks quality assurance (QA) evaluation and was completed within the Year 1 scope of this project. Years 2 and 3 of the project conducted multiple field trials to compare the density and in situ stiffness measurement.

In Year 4 (current year), the focus was to disseminate learning of the previous years to the industry through a series of online webinars and workshops for the TMR districts.

The key project objectives for Year 4 (2019–20) were:

- *Task 1: Finalise technical note* – A technical note was prepared in Year 4 of the project to a methodology for implementing LWD testing for earthwork construction.
- *Task 2: Prepare and deliver online webinars* – In Year 2 of the project, a successful online webinar was presented jointly by ARRB and FSG, which summarised the findings of the Year 1 scope of work. Parts 2 and 3 of the online webinars were presented this year, which summarised the findings of the fieldwork and analysis completed in Years 2 and 3. The outline of a standard methodology for implementation for earthwork construction was also presented in Part 3 of the webinar series.
- *Task 3: Prepare workshop* – Part of the knowledge transfer planned for this year was to invite an eminent international speaker (Professor Soheil Nazarian) to present a workshop. The intent of this workshop was to (i) identify the current state-of-the-art alternative QA methods for earthworks; and (ii) confirm that the scope of works and recommendations of the NACOE project aligned with industry best practice.
- *Task 4: Deliver workshop* – Undertake the formal delivery of the workshop prepared as per Task 3.
- Task 5: Annual summary report (i.e. this document).

1.3 REPORT STRUCTURE

This annual report is structured as follows:

- The introduction to this year's study findings is covered in Section 1.
- Section 2 presents the technical note which was developed based on the research to date.
- Section 3 summarises the three webinars delivered in 2019–20
- Section 4 presents the conclusions and recommendations.

2 TECHNICAL NOTE

A draft testing procedure was developed in Year 3 of this project. This year (Year 4), a technical note was developed by the project team that formalises the recommendations relating to field implementation of the LWD.

The technical note covers the following key areas:

- *Background information* – Rationale for why an alternative testing approach is required, and identification of the advantages of moving to a modulus parameter-based specification for earthworks QA testing.
- Basis of the matching probability density functions (PDFs).
- *Example technical specification* – Identification of the key items required to be included within a project- or material-specific technical specification, and a generalised step-by-step methodology for the onsite implementation of the LWD for the QA of earthworks.

A copy of the technical note is included in Appendix A of this report.

The current industry acceptance is that DDR, Plate Load Test (PLT), and CBR testing are 'reference' tests for in situ assessment of earthworks. The test methodology and resulting index/parameters are not typically questioned, and the results form the basis of common Australian earthworks QA specifications. However, the (multi-year) NACOE research to date – and as supported by comparable international studies – has repeatedly demonstrated that DDR results are poorly correlated with the results of PLTs and with many of the directly measured modulus parameter variants as provided by the alternative equipment.

The NACOE research has demonstrated that the results arising from the alternative test methods can be directly related to the results of PLTs, and should therefore be considered valid methods of assessing in situ stiffness parameters within compacted earthworks materials. However, despite the clear benefits of their use (e.g. speed of test, direct verification of design parameter), they are not routinely adopted by the industry as they cannot provide a direct, repeatable, or universal correlation back to the DDR (index) value.

In the interim, and to demonstrate a valid implementation pathway, the technical note developed as part of this project provides a baseline methodology to use LWD as an effective QA tool that can be implemented within earthworks technical specifications. This framework included in the technical note was intentionally generalised, such that the method could be effectively applied to other non-density test instruments with minor alterations.

Based on industry consultation and results of the NACOE research, it was also identified that any requirement for continuous parallel testing of DDR with LWD will be perceived as imposing additional cost burdens on the project and would likely further inhibit the potential uptake of onsite modulus-based assessments. Accordingly, it is recommended that requirements for an ongoing 'evaluation' approach – that would effectively require long-term parallel density and alternative assessment techniques (i.e. one-for-one/ side-by-side testing) – be avoided. One solution to such an issue, as outlined in the technical note, is to initially define equivalent acceptance 'thresholds" for material acceptance (based on an initial trial that incorporates project, material- and test-specific correlations) and then complete regular 're-assessment testing' (e.g. at every 10,000 m^3 of placed fill) to re-validate/re-configure the previously defined acceptance 'thresholds'.

3 KNOWLEDGE TRANSFER ACTIVITIES

The primary scope this year (Year 4) was to deliver knowledge transfer activities to allow the Australian industry to be made aware of the latest developments in the use of modulus-based testing for the QA of earthworks – both from a domestic and international viewpoint.

The most cost-effective method for these activities was identified to utilise a webinar format for the majority of activities, whilst face-to-face knowledge transfer events were planned for key stakeholders. However, due to the unexpected COVID-19 outbreak and associated travel restrictions, all knowledge transfer activities in 2020 were delivered via online platforms only.

Key events held in 2018 and 2020 included:

- Webinar (Part 1) delivered on 26 June 2018
- Webinar (Part 2) delivered on 6 February 2020
- Webinar (Part 3) delivered on 19 March 2020
- Webinar (Part 4) delivered on 14 May 2020.

The subsequent sub-sections of this report further detail the events held in 2019–20.

3.1 WEBINAR PART 2 AND 3

In Year 2 of the project, a webinar was presented jointly by ARRB and FSG covering the basics of density measurement. This event provided the audience with an overview of the research objectives as well as the basics of the field-testing equipment used. The industry expressed great interest to explore the feasibility of moving from density to modulus-based testing.

As the research progressed into fieldwork trials through Year 2 and Year 3 of this project, the project team delivered Part 2 and Part 3 of the webinar series in early 2020. The focus of these events was to present the experience obtained during a field trial and correlations observed between the results of the 'reference' and 'alternative' test techniques considered by the research. The webinar also proposed ways that the innovative technology/test methods could potentially be implemented in the field during 'live' construction projects.

3.1.1 WEBINAR PART 2

Part 2 of the webinar series was delivered as a one-hour webinar on 6 February 2020. This webinar focussed on presenting the field-testing results collected during Year 2 of the research project – specifically the results of testing undertaken at (i) Pacific Highway Upgrade near Ballina, NSW; and (ii) Ipswich Motorway Upgrade Stage 2 (Rocklea to Darra), Qld. The details of these field test results, and subsequent analysis, were reported in the Year 2 Annual Summary Report (Lee et al. 2018).

Some key messages delivered during the Part 2 webinar were:

- A recent industry survey of 54 engineers identified that the top desirable attribute in test equipment is the 'accuracy' of the test.
- While density is a very 'precise' test, it may not necessarily be 'accurate' (in terms of field validation of pavement design parameters).
- The industry is seeking a solution to the time-lag issue of traditional density testing and requires an alternative test method that can provide fast feedback to accommodate high production rates of earthworks.
- While it is often assumed that an increase in density results in an increased stiffness (modulus), this assumption has been demonstrated by the NACOE research to frequently be incorrect (for the majority of the fieldwork trials completed). Instead, some materials demonstrated a trend whereby the measured in situ modulus parameter would decrease whilst the density increases.

- For some materials, it was found that the moisture content had a greater influence on the modulus values measured than density itself.
- Based on the hierarchical clustering and dendrogram analysis, it was found that the direct comparison of alternative testing methods (i.e. in situ modulus testing) to side-by-side DDR measurements often resulted in poor and/or statistically non-significant relationships.
- This analysis also highlighted that the in situ modulus parameter reported by the alternative test methods generally correlated well to each other and with the modulus parameter arising from the 'reference' PLTs.

A copy of the webinar can be found in Appendix B.1.

3.1.2 WEBINAR PART 3

Part 3 of the webinar series was delivered on 19 March 2020. The primary focus of this webinar was to propose a standardised QA procedure using the LWD device. This webinar also presented fieldwork results collected from the Smithfield Bypass project near Cairns in 2019 – a project that both (i) completed a large-scale trial embankment utilising a project- and material-specific LWD testing specification (QA specification) as a demonstration of its appropriate field use; and (ii) undertook further research by completing side-by-side testing that utilised a suite of the alternative testing methods investigated by this NACOE project. Details of the field test results, and subsequent interpretation, were reported in the Year 3 Annual Summary Report (Lee et al. 2019).

The presenters noticed that a lot of the questions raised by the participants in Part 2 of the webinar series were related to the influence of moisture content on the test results collected, and a significant amount of time in this webinar was used to address this issue.

Some key messages delivered during the Part 3 webinar were:

- An overview of the material delivered in Part 2 of the webinar series.
- The identification and summary of international research, and the correlation between recent international studies and the current NACOE research findings:
  - the national cooperative highway research program (NCHRP) in the USA promotes the use of modulus-based testing for better-performing pavements
  - the role of intelligent compaction for quality control of earthwork materials (federal highway administration report).
- CBR (or modulus) is less correlated with DDR, yet CBR (or modulus) is related to compaction moisture content.
- Water content loss varies significantly during earthwork placement.
- The location of reference density sample is often non-representative and neglects the influence of grading, sieving of oversized material, and the influence of depth.
- A proposed LWD specification for QA purposes. This represented the initial industry introduction to the information included in the technical note produced in Year 4. The key steps of the proposed LWD specification are summarised in Table 3.1.

Table 3.1: Key steps to the proposed LWD specification

1	Define initial inputs – LWD configuration
2	Define initial inputs – Earthworks variables
3	Construct trial embankment
4	Test completed trial embankment with LWD
5	Inspect and standardise LWD dataset
6	Assess in situ modulus-moisture relationship (if present)
7	Define E_{LWD} acceptance thresholds
8	Regularly review and re-validate defined E_{LWD} acceptance thresholds

A copy of the webinar can be found in Appendix C.1.

3.2 WEBINAR (OVERSEAS EXPERIENCE AND RAILWAY EXPERIENCE IN AUSTRALIA)

In this NACOE research project, the project team has gained experience in the use of different alternative quality assurance methods and investigated if there is any direct correlation with the traditional density measurements. The knowledge from the field trial and a technical note was presented to the Australian industry through the P60 webinar series summarised in Section 3.1 of this report.

However, Australia is not the only country to consider the benefits of utilising alternative modulus-based methods, and similar research studies have been underway in the USA. An NCHRP study was conducted by Professor Soheil Nazarian from the University of Texas at El Paso, and to effectively transfer the knowledge from the NCHRP study, the NACOE project team was planning to collaborate with the Australian Geomechanics Society (AGS) to invite Professor Nazarian into Australia and present to local audiences around the country in early 2020. Due to COVID-19 international travel restrictions, the event was instead delivered in an online webinar format on 14 May 2020, and included an additional section relating to the Australian experience of using LWD for railway formation construction (as presented by Mr Andy Doe from Australian Rail Track Cooperation (ARTC))

The presentation topic of the day was listed as follows:

- Quality management of earthworks with deflection-based devices (presented by Professor Nazarian).
- ARTC inland rail shadow compliance testing with Light Weight Deflectometer (presented by Andy Doe).

Current practice for field quality control and acceptance of compacted earthworks is to determine the density and moisture content by nuclear density gauge. The consensus of the engineering community is that modulus-based testing is, in principle, a more rigorous and mechanistic approach for quality management of earthworks.

This presentation intended to discuss the theoretical background and institutional activities that had to be carried out internationally to supplement the density-based process with the modulus-based process for quality management and design verification of compacted earthworks. Professor Nazarian presented key findings from a recent NCHRP study to show the level of detail that is needed to be considered for a smooth implementation of modulus-based specifications for earthworks QA regimes. The presentation also touched on the extensive numerical analyses, laboratory testing, and field evaluations to establish a mechanistic approach for assessment and compliance testing of compacted earthworks, with a special focus on quantifying the variation in stiffness with moisture content in the field.

Professor Nazarian's presentation and the NCHRP study's recommendations are consistent with the NACOE P60 findings so far, and thus the webinar provided:

- confidence that the current NACOE research findings are valid and repeatable (and not in conflict with other studies)
- demonstration that the works undertaken by the NACOE P60 research project represent state-of-the-art research and are evaluating issues that are at the forefront of industry requirements.

A copy of the webinar can be found in Appendix D.1.

4 CONCLUSIONS AND RECOMMENDATIONS

In this year (Year 4), the project team has developed a technical note that provides a detailed roadmap for the derivation of a project- or material-specific specification that would facilitate the implementation of the use of LWD devices as a valid earthworks QA testing tool.

This was followed by two online webinars presented by the NACOE project team, which focussed on the summary and dissemination of the research findings and recommendations for Years 2 through 4. An additional webinar was organised by the NACOE project that had an internationally leading researcher from the USA and a practical example of Australian application of the LWD within a ‘live’ (railway) construction project share their findings and experience with the modulus-based testing methods.

The significant attendance at these webinars and the feedback from the webinar participants were overwhelming – and have reinforced both the industry's desire to implement this technology and some concerns that currently prevent its widespread adoption.

This year’s inclusion of an internationally renowned researcher – Professor Soheil Nazarian, University of Texas at El Paso – has also identified that the NACOE P60 findings and recommendations are consistent with the international experience. This has further provided confidence to the industry that the NACOE recommendations are valid and repeatable, and that the NACOE P60 project is addressing issues that are at the forefront of industry requirements.

REFERENCES

Lee, J, Lacey, D & Look, B 2019, ‘Best practice in the quality assurance of pavement layers and subgrade: year 2 (2017/2018)’, contract report PRP16113, ARRB, Port Melbourne, Vic.

Lee, J, Lacey, D, Look, B & Tarr, K 2020, ‘Best practice in the quality assurance of pavement layers and subgrade: year 3 (2018/2019)’, contract report PRP18027, ARRB, Port Melbourne, Vic.

APPENDIX A TECHNICAL NOTE

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BEST PRACTICE IN COMPACTION OF PAVEMENTS AND SUBGRADES

PROCEDURES AND SPECIFICATIONS

Australian Research Board (ARRB)

REPORT NO. 2091RDL07A

25 March 2020

REV	DATE	COMMENTS	AUTHOR	REVIEWED	AUTHORISED
A	25 Mar 2020	Client issue	D. Lacey B. Look	B. Look	B. Look

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1. Introduction

The NACOE project P60 "Best practice in compaction quality assurance for subgrade materials" aims to modernise testing procedure for compaction quality assurance.

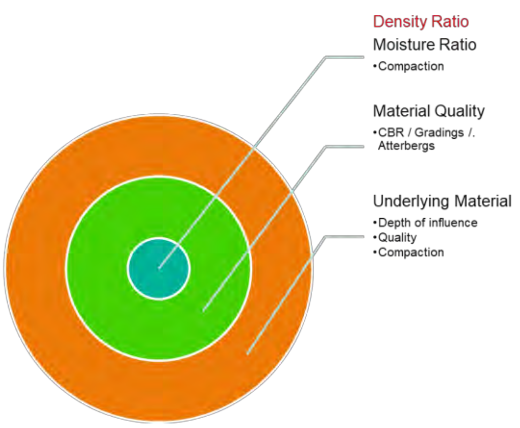
Quality is conventionally been verified using density measurements, and alternative methods have been developed over the past two decades. Many of these methods takes less time to do, results become available in a much shorter time frame, and is able to measure in situ stiffness.

The research to date has shown density may be the current target of quality control, but is poorly correlated with many of the alternative equipment tested. This is due to the alternative equipment measuring

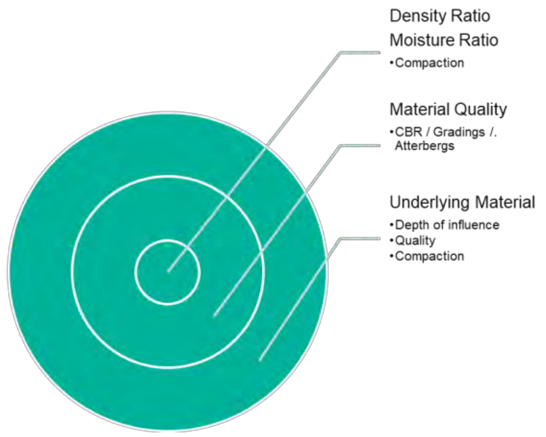
1. The density ratio, as well as
2. The moisture condition, and
3. The quality of the compacted material, and
4. The material underlying the layer being tested

This leads to combining all of the above in one measurement, while the current approach is to measure each of the above independently (Figure 1-1). Depending on the equipment there can be different proportions of these factors being measured.

Thus, correlating any 1 parameter (say compacted density) to the other equipment measurement leads to poor correlation, since a multivariate correlation is required. Such an approach would be impractical to implement in a quality control system. There is also no universal value, such as is currently used as in a 95% density ratio.



(a) Each quality measured separately



(b) Alternative Tests measure combined qualities

Figure 1-1 Current QA procedures measure compaction material quality and underlying material separately (a) while alternative tests seem to measure multiple qualities

An alternative approach is therefore required.

Intelligent Compaction (IC) was not directly part of this research, but IC requires a cross check on this new unit of measurement and which can be both accurate and measured easily and quickly. Density measurements are poorly correlated (Change et al., 2016)[1] to Intelligent Compaction measurement values (ICMV) as compared to LWD (Light Falling Weight measurements) and Plate Load Testing (PLT).

In this research, other equipment was tested (Figure 1-2), which can be broadly classified as penetration and surface-based tests. The Plate Load test (PLT) and Density Ratio (DR) or more correctly the Dry

[1] George Chang, Qinwu Xu, and Jennifer Rutledge (2011), "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials", Federal Highway Report FHWA-IF-12-002.

Density Ratio (DDR) are the reference axis as these are most accurate and precise tests, respectively. These 2 tests are also the historical anchor points in implementation of alternative testing methods. The research to date has shown a poor correlation of many equipment (including IC) with DR. Thus, if an anchor point is required for credibility of the alternative methods then the PLT becomes the reference test.

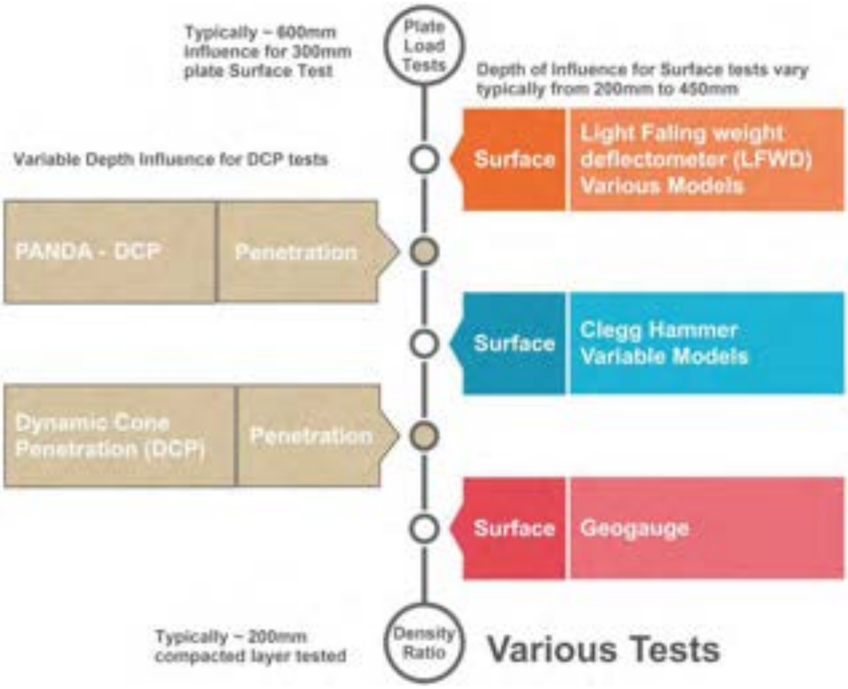


Figure 1-2 Various Alternative tests considered and the 2 historical anchor points of DR and PLT

Given established specifications and procedures for the PLT, penetration tests and Clegg hammers are available, this specification aims to fill the gap with an example Specification for Modulus based Assessment via use of Light-Weight Deflectometers (LWD).

The emphasis on quality testing in the field for this report does not reduce the requirement for design parameters which may require soaked lab values. At that stage, consideration of ASHTO procedures outlined in Standards [5] and [6] may be useful.

An initial technical advice note was provided in 2019 as a summary technical specification towards implementation of Alternative QA testing. This final report integrates that summary for completeness as a background in the next section.

1.1 Executive Summary

Industry familiarity with density-based assessment for QA purposes currently hampers the use of more accurate tests that can directly validate design parameters being achieved in the field. Although such alternative QA tests are not as precise as density testing, the density test is itself has the significant limitations of not providing near-instantaneous result and not being able to provide a reliable indication on the ground strength or modulus.

The static Plate Load test (PLT) is another industry accepted, reference test which has high accuracy, but is not as precise as the DR test. Recent Australian research have identified a number of alternative QA tests that have the potential to provide improved accuracy (as compared to density), and simultaneously offer an improvement in precision (as compared to PLT). Thus, the acceptance that DR and PLT remains the benchmarks for precision and accuracy, respectively, should be considered an outdated viewpoint. This is conceptually summarised in Figure 1-3, which attempts to correlate accuracy and other considerations for traditional (density and PLT) and 'alternative' QA tools.

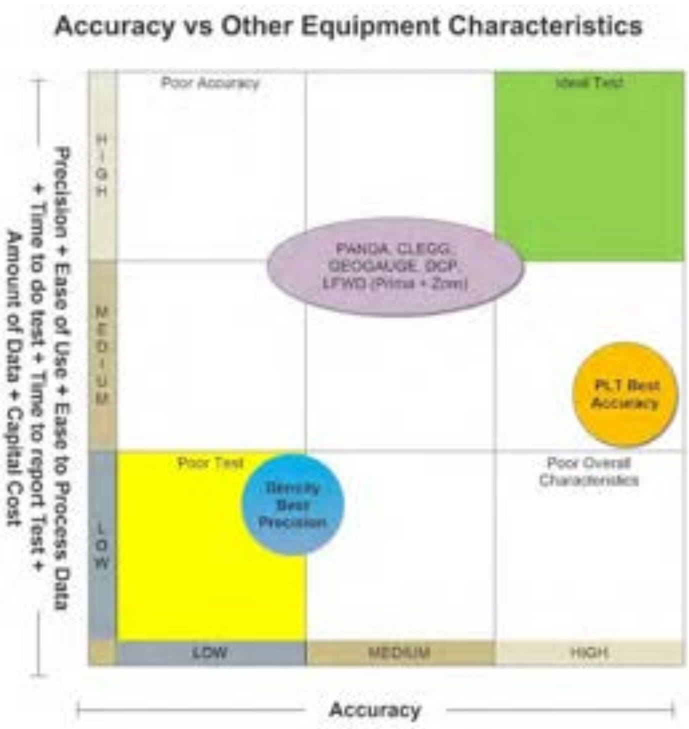


Figure 1-3 Traditional (Density & PLT) and alternative QA Tools compared with accuracy and other characteristics

Despite the clear benefits of use, the alternative tests may not routinely provide a direct reliable correlation with DDR (as density itself if not directly related to the design stiffness or strength parameters). Many of these alternatives in situ tests do not currently have Australian Standards, which also impedes their implementation.

In the interim, this technical report provides a baseline methodology to use the Light Falling Weight Deflectometer (LWD) as an effective tool that can be implemented within earthworks QA Technical Specifications. The framework of the methodology detailed herein can be similarly applied for any of the large range of non-density test instruments that are currently commercially available, with minor alterations to account for the specific parameter (and sensitivity of measurement) associated with each instrument type.

Continuous parallel testing of DDR with this alternative equipment will be perceived as additional costs to the project – and if considered on a 1-to-1 basis, parallel testing can lead to DR results demonstrating a “pass” whilst LWD (or other tools) assessment could report a “fail” (or vice versa). Such a divergence of results should be attributed to the poor accuracy of DR, rather than the more common perception of the ‘failure’ of the alternative QA tool being considered. Such a result can frequently be traced to poor sampling practices (e.g. where oversize materials are often not sampled) or evaluation issues (e.g. oversize correction not routinely applied).

An ongoing approach whereby parallel density and alternative assessment techniques is employed on a project is therefore not recommended. Instead, as detailed herein, equivalent ‘thresholds’ for material acceptance should be defined during an initial trial that evaluates project, material- and test-specific correlations – such that the existing risk profile is maintained – prior to the adoption of the alternative QA technique during production (with specified check testing frequencies to verify / update any project-specific defined correlations).

2. Background

2.1 Introduction

Traditional Quality Assurance (QA) Specifications for earthworks require the achievement of a high relative compaction. The typically applied criteria is the ratio of the field dry density achieved with the maximum dry density (MDD) achieved in the laboratory (i.e. reported as a minimum threshold of Relative Density Ratio – RDD – or Density Ratio – DR). These density-based methodologies for compaction Quality Control (QC) typically utilise either sand replacement or Nuclear Density Gauges (NDG) as their specified test methods.

Density measurements are relatively easy to undertake, provide a very precise measurement in an easy to understand parameter. Use of the NDG has the benefit of speed for obtaining field density results as compared to sand replacement. However, there remains a delay in the determination of a test site's relative compaction due to the time taken to obtain the laboratory MDD (unless an assumed value is used).

Density measurements also have a time lag due to curing and testing times, as conceptually illustrated with the typical the earthworks construction and testing processes detailed in Figure 2-1. Quality Assurance (QA) is not the same as Quality Control (QC), although QC testing and inspection is part of a QA process. Yet density is more aligned as a QC rather than a QA measurement.

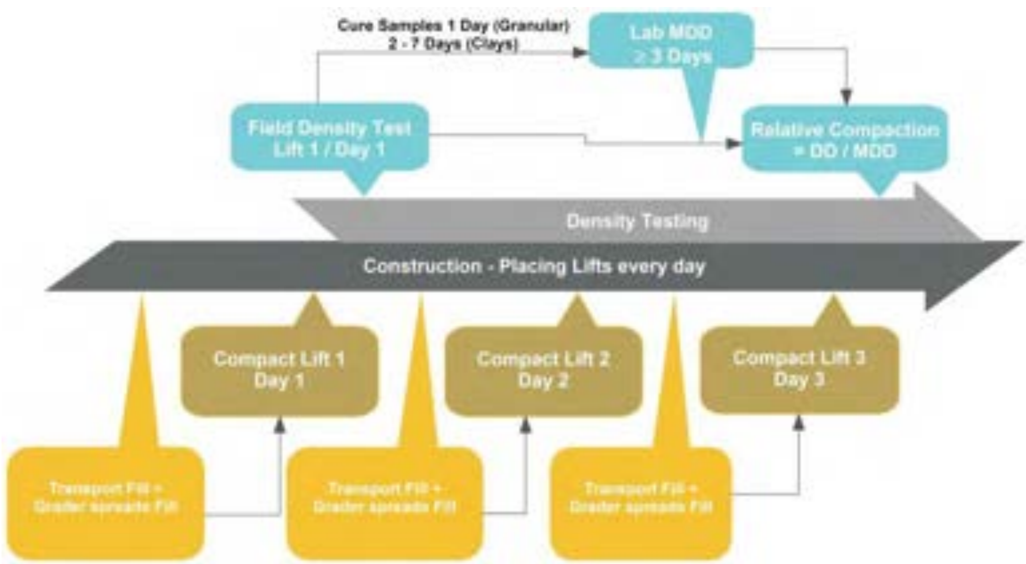


Figure 2-1   Traditional relative compaction tests (e.g. Density Tests) are lag indicators

Recent research has found density measurements are, although precise, is not very accurate due its poor correlation with the results of other modulus or strength-based tests. As the structural design of pavements, working platforms or other bridging layers requires either strength or modulus input, it is imperative that any verification testing undertaken can accurately assess, or be strongly correlated to, such parameters.

There are currently many different measuring devices which can provide a more accurate measurement of design parameters (strength or stiffness) and can provide a more direct route for parameter assessment (i.e. limit need for any inclusion of generic relationships). These options should thus be considered better QA tools, in comparison to traditional density testing, and their ability to provide near-instantaneous results can be used in situ to change the compaction process to suit project- and material-specific conditions encountered onsite.

However, such devices provide all different units of measurements and can demonstrate a poor correlation to the industry accepted density test results. The existence of the poor correlation can be due to several factors, including:

- *Varying zone of influence* – The condition of the underlying earthworks / subgrade layer can affect the result of the in-situ strength / stiffness test (compared to density testing that is isolated to a specific layer)

- *Both Material Quality and achieved Compaction State are being measured* – and thus increased variability within a test dataset can arise (compared to density testing that only evaluates compaction state)
- *Difference in nature of dataset* – Density results have a low variation and the results for a given lot are normally distributed, while other test instruments frequently demonstrate a larger variation of the measured parameter (for reasons above) and can present non-normally distributed data.

Additionally, the implementation of alternative (non-density) measurement devices for the in-situ verification of strength or stiffness parameters has been further hampered by:

- *No Standard Specification* – Limited international specifications exist, but the potential arrangements / variables associated with individual measurement device (which directly affects the resulting parameter) is not standardised in many cases. No Australian Standards currently exist.
- *Reluctance of Industry to adopt a different unit of measurement* – Industry is familiar with using an easily interpreted density ratio, whilst individual measurement devices provide various other parameters.
- *Requirement for initial demonstration to correlate to density test results* – Initial trials often require alternative QA tools to demonstrate a strong relationship to the, industry accepted, density test results. However, as stiffness and strength parameters are not directly related to achieved compaction, the alternative QA tool may provide a poor 1:1 correlation to density and thus be disregarded due to lack of confidence in test results.
- *Existence of a large variety of non-density modern equipment* – with no clear guidance of which to use, how to use, how to interpret the results and / or which tool is best suited to specific applications.

2.2 Light Falling Weight Deflectometers (LWDs)

One such promising non-density device is the Light Falling Weight Deflectometer (LWD). An LWD is a portable, self-contained device which can assess the surface modulus directly in the field.

The barrier to widespread adoption is the availability of a variety of LWDs within the market, each of which can provide a different in situ modulus parameter – due to the effect of different stress states, equipment arrangements and boundary conditions adopted by individual manufacturers. The potential non-linearity of the material modulus parameter (e.g. stress-dependency) and the effect of moisture can also affect the returned in situ modulus result.

As per the requirements of a universal standard, no preferential selection of any one manufacturer is detailed herein. However, by understanding and accounting for the characteristics of the specific LWD and the material being utilised onsite, any LWD can provide a consistent and traceable result which can be readily used for earthworks QA purposes.

Based on the results of recent Australian research, the use of suitably standardised LWDs is recommended for QA testing of earthworks. Utilising such a tool is expected to offer improved connectivity between design, construction QA and long-term performance.

The use of LWD (or similar direct parameter evaluation tools) would realise the implementation of a true QA regime, moving from the current density-based QC system – as density testing programs only assume design parameters (e.g. modulus) are been met, but do not directly evaluate any such parameter. For example, a requirement to achieve “95% of standard MDD” does not mean that 95% of peak strength or modulus has been achieved. Yet after the construction phase is completed, the asset owner will continue to assess earthworks performance based on modulus parameters rather than any incorporation of density state.

2.3 Modulus Based Specification – Adopting LWDs for Earthworks QA Testing

Considerations of the LWD procedure that would be required to develop of Technical Specification for its implementation as an effective earthworks QA tool are briefly outlined in this section and detailed in later sections. The selection of the LWD tool in particular is to progress the implementation of one such measuring device into industry.

Recent Australian research in using various other non-density measurement tools for similar QA purposes are reported elsewhere. The advancement of Intelligent Compaction (IC) also requires asset owners, consultants and soil testers to deliver alternative QA tools than can similarly verify the in-situ earthworks condition achieved, if IC technologies are to achieve their potential.

2.3.1 Key Requirements of Modulus Based Technical Specifications

Any Modulus based Technical Specification for Earthworks QA assessment would require:

- *A Target Modulus for Acceptable Compaction* – Yet in situ modulus may be dependent on moisture content, density and / or material quality. Current (density centric) compaction specifications measure each of these separately
- *A Simple Methodology for field assessment* – Any specified tests should be simple to completed and have an easily standardised methodology.
- *Testing should not require significant duplication* – due to associated cost and delays.
- *An understanding of the various factors that may affect the modulus results* – and control / account for such factors within the test procedure, interpretation and nominated threshold (target) values.
- *A standardised method for interpretation of LWD results* – as no preferential selection to any particular LWD manufacturer should be made, an allowance for the variation in commercially available LWD devices should be included. Similarly, a standardised method to evaluate the in-situ measurement / modulus parameter arising from the various devices should be detailed.

2.3.2 LWD Equipment Standardisation

Examples of variables present between types of LWD equipment – either user implemented variables or manufacturer variations – include:

- *Plate Size* – Plate diameters can vary between 100, 150, 200 and 300 mm diameter. The plate size directly influences the contact area with the ground and thus the imparted test stress. Variation in plate size would also affect the zone of influence that the composite in situ modulus parameter represents
- *Drop Height* – Maximum drop heights vary between 600, 720 and 800. Combined with the plate diameter and drop mass, this maximum drop height influences the range of test stresses that can be generated by the LWD. To an extent, the imparted test stress affects the test's 'zone of influence' – with the larger test stress generating a greater 'zone of influence' (for all other variables being equal).
- *Mass of Falling Weight* – Mass used as the generating force can vary between 2, 9, 10, 15 & 20 kg. Of these, the 10 kg weight is the most common. Some LWDs have the facility for weight variation to alter the imparted test stress.
- *Deformation Measurement* – Can either be made by an accelerometer (embedded within the plate) or a geophone (in direct contact with the ground). Due to the various location and types of the measuring sensor, the magnitude of deflection (and thus the derived in situ modulus parameter) varies between LWD types.
- *Presence / Absence of Load Cell* – LWDs fitted with a load cell allow the provision of a specific load assessment per weight drop, and can account for any variation to the theoretical load being imparted. For LWDs without a load cell, the theoretical load has to be assumed to have occurred.
- *Arrangement / Type of Buffer* – Various numbers, materials and thickness of buffers exist between LWD types (and can frequently be altered by the user). The specific arrangement alters the load pule magnitude actually transmitted to the load cell (if present) and into the ground.
- *Plate Material (rigidity)* – Plate thickness, weight and material varies between LWDs. This influences the rigidity of the LWD arrangement and can affect the shape of the load distribution into the ground (for each test)

Control of such variables should be included in any LWD Technical Specification. However, such 'control' should not necessarily exclude specific LWD types – rather the Specification should identify the required test stress(es) and minimum 'zone of influence' over which the LWD should provide assessment. Details of the normalisation of results that will be undertaken to standardise the derived modulus parameter (for comparison to the nominated target modulus value that would represent acceptable compaction) should also be completed.

In the absence of project-specific requirements, it would be proposed that the following details be included for LWD equipment standardisation in Earthworks QA Technical Specification's:

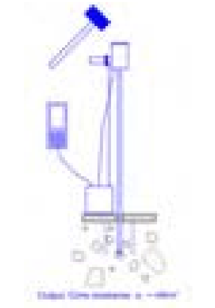
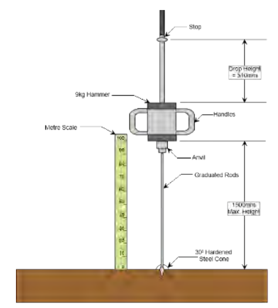
- Plate Diameter = 300 mm (providing an 'zone of influence' of approximately 390 – 450 mm)
- Modulus Parameter standardised to 100 kPa Test Stress (to remove the influences of varied drop height and drop mass configurations).

Target In situ Modulus Parameter that represents Acceptable Compaction

A typical comparative set of parameters is presented in **Table 2-1** that relates Dry Density Ratio (DDR or DR) thresholds to approximately equivalent parameters measured by alternative, non-density, QA tools – namely the cone tip resistance arising from Variable Energy DCP (Panda Probe) testing; standardised in situ modulus from the Prima 100 brand LWD; and the number of hammer blows required for a DCP rod to be penetrated 100 mm.

Note the values presented in **Table 2-1** were derived for a specific material with 60% gravel size and 20% of both sand and fines – sourced from weak metasedimentary rock and CBR < 10 %. This may be altered for other soil materials being utilised for earthworks. For example, a change to an alternative Fill material comprised of 70% gravel sized particles and exhibiting a characteristic CBR of 20% would increase the LWD threshold that represents a 96% DDR to 30 MPa or 50 MPa for Basalt or Sandstone rock materials sources respectively.

Table 2-1 Example of equivalent thresholds for four (4) in situ test techniques

Technique	**Traditional Density Testing**	**Variable Energy (PANDA) Probe**	**LWD (Prima 100) – 300 mm dia. Plate**	**Dynamic Cone Penetrometer (DCP)**
Reported Parameter	Dry Density Ratio (DDR, %)	Average Cone Tip Resistance (q_d, MPa)	In situ Modulus @ 100 kPa Test Stress ($E_{LWD\text{-}100kPa}$, MPa)	*n* = Hammer Blows / 100 mm rod penetration
Equivalent Threshold Values	≥ 96 %	≥ 8 MPa	≥ 15 MPa	≥ 4 blows
	≥ 98 %	≥ 12 MPa	≥ 25 MPa	≥ 5 blows
	≥ 100 %	≥ 17 MPa	≥ 50 MPa	≥ 6 blows
	≥ 103 %	≥ 24 MPa	≥ 120 MPa	≥ 10 blows
Test Characteristics	Very High Precision	Medium Precision	Medium Precision	Low Precision
	Very Low Accuracy	High Accuracy	Medium to High Accuracy	Low to Medium Accuracy
Schematic of Test Equipment				

For comparison purposes the California Bearing Ratio (CBR) test provide results with medium precision and medium accuracy.

Other aspects that should be noted during the development of a LWD Technical Specification include:

- The in situ modulus derived by static Plate Load Testing (e.g. E_s, E_{v1} or E_{v2}) is not necessarily similar to the in-situ modulus derived from LWD testing – this is due to factors such as the varying zone of influence, test stress, and dynamic vs. static nature of the each test technique and adopted arrangement (as detailed previously).

- The in-situ modulus parameters derived from LWD should be inspected and a maximum capping value applied to limit excessive data spread. Outlier / uncharacteristic high values can occur due to the presence of, amongst other factors, high strength rock particles present within a soil matrix. Typically, the highest 10% of LWD derived modulus values should be evaluated and limited to the capping value, if required.
- While density testing (and thus the Dry Density Ratio parameter, DDR) is not influenced by material quality, or variation thereof, many other in situ tests are affected by such quality factors. Hence, there is no singular value that can be universally applied to enable direct conversion between a DDR threshold value and an in-situ modulus / strength parameter. A DDR dataset that demonstrates low variation can have a significant corresponding range of any other in situ parameters being measured by other test techniques completed at identical locations. Direct, single parameter correlation between DDR and other in situ material parameters often results in a low correlation and the adoption of such a simplified approach hinders the industry adoption of these alternative assessment tools.

Simplified Field and Interpretation Methodology for LWD

An advantage of the use of tools that can make in situ modulus measurements and provide near-instantaneous results – such as LWDs – is that, unlike traditional density testing, the progressive change of the stiffness of the near-surface can be monitored until only minor changes are observed (Figure 2-2). This approach could be used to identify the characteristic number of compaction plant 'passes' required to achieve effective compaction.

Utilising the LWD in such an application would be undertaken as follows:

1. Undertake LWDs at six (6) testing locations after the completion of an initial, limited number of plant passes (say, three (3) passes).
2. Interpret the standardised in situ modulus parameter for each test location – $E_{LFWD-100kPa}$. Discard the highest value and apply the defined capping value (e.g. $E_{LWD-100kPa}$ = 200 MPa) to any other uncharacteristically high values. Determine the characteristic values of the dataset and establish the COV of the dataset (Standard Deviation / Mean).
3. Repeat Steps 1 and 2 after the application of additional compaction plant passes (e.g. after 6 and 8 passes).
4. Plot the progression of the characteristic LWD values under each considered arrangement
5. From the curve constructed in Step 4, assess when the COV of the dataset is less than 60% and the change in the median standardised in situ modulus parameter ($E_{LWD-100kPa}$) is less than 10% occurs between considered passes. This scenario would be considered the characteristic number of compaction plant 'passes' required to achieve full effective compaction.
6. Carry out corresponding side-by-side density testing upon effectively compacted materials, if correlation between DRR and E_{LWD} parameters is required
7. Compare median of DDR dataset to median of corresponding E_{LWD} dataset – adopt the corresponding median values as the 'equivalent' in situ target values to be achieved to represent acceptable compaction.

Note that the characteristic density and LWD test results will likely not change at the same rate, due to the comparative sensitivity of the parameter being assessed. For example, whilst the compaction state may change by ~10% as a material is progressively compacted from a medium to high compaction state (say 90% DDR to 100% DDR), the standardised LWD in situ modulus may change by a factor of more than 10 (e.g. increase from 10 MPa to > 100 MPa). This is shown conceptually in Figure 2-2, for the density and modulus changes with compaction energy (i.e. as number of 'passes' of compaction plant / applied compactive effort is increased)

The methodology of a project specific validation / trial embankment outlined above can be altered to suit the requirements of individual projects.

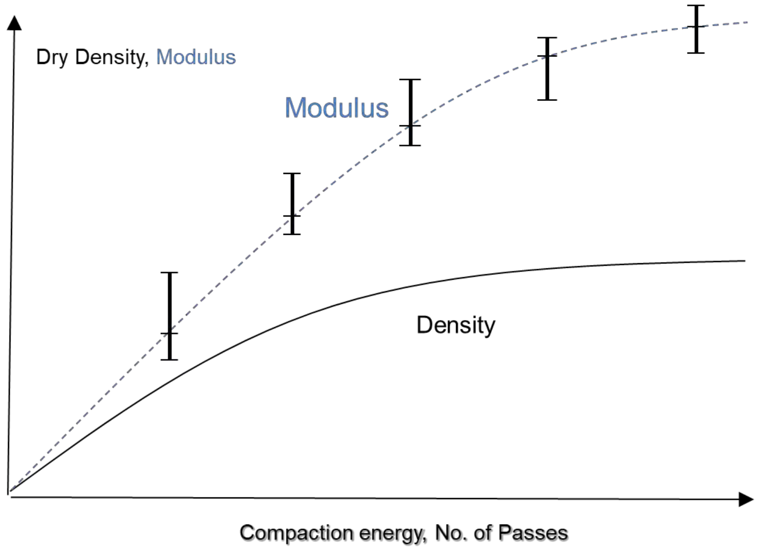


Figure 2-2 Conceptual sketch with expected relative change in density / compaction state of material and in situ modulus (stiffness) parameters during progressive compaction of earthworks

Proposed LWD Testing Frequency

In the absence of project-specific requirements, it would be proposed that the following testing frequencies be included for LWD equipment standardisation in Earthworks QA Technical Specification's

- For general earthworks and locations within fill embankments where the exposed testing surface remains a minimum of 1,000 mm below top of subgrade (i.e. not subgrade materials) = Min. six (6) LWD minimum per 1,500 m^2 of works (equivalent to 1 LWD test per 250 m^2 of prepared earthworks)
- For pavement materials and locations within fill embankments where the exposed testing surface is within 1,000 mm of top of subgrade = Min. ten (10) LWD minimum per 1,500 m^2 of works (equivalent to 1 LWD test per 150 m^2 of prepared earthworks)

LWD tests shall be specified to be performed within two (2) hours of the completion of compaction, such that the effect of surface drying on the measured in situ modulus parameter is minimised. Note this method does not account for post compaction wetting or drying and environmental effects.

For some materials (especially fine-grained materials), the in-situ modulus parameter would be expected to vary based on the moisture content of the material at the time of test (i.e. vary based on drying and wetting). Although such a change would be expected to also occur for a density-based assessment, traditional (density) QA regimes are blind to this effect and often install subsequent fill on materials that would have altered moisture contents since the completion of “passing” DDR assessments.

Thus, the moisture-dependency nature of the in situ modulus parameter of a earthworks material should not be considered a basis for not implementing a modulus-based QA specification – as it is not specific to the assessment of an in situ modulus parameter and the identification of this as a potential limitation of modulus-based QA Specifications is to hold them to a higher level of requirement than traditional (density) QA Specifications.

If required, the LWD can be used to evaluate and accommodate such moisture dependency within the derived acceptance thresholds. Alternatively, the LWD can be utilised to enhance the compaction quality assessment by continual monitoring of exposed materials following wetting / rainfall events, and should in situ modulus parameters (E_{LWD}) fall below the defined target / threshold values then additional earthworks fill layers should not be placed until suitable dry back occurs (as evidenced by an acceptable recovery of the E_{LWD} parameter assessed onsite).

3. Method of Matching Probability Density Functions (PDFs)

With a “new” equipment and an existing testing system (DDR testing) the first step is to investigate the association between the two sets of data. A poor correlation often results. One of the reasons for the poor correlation is that the density tests are normally distributed, while most of the other tests are not normally distributed.

Given that paired relationships are unsatisfactory, a different methodology is required if these instruments are to be used for QA tests. A method of matching Probability density functions (PDFs) is proposed to advance the use of the various instruments. Without such an approach the industry will keep on back checking to the dry density ratio index which provides the poor correlations. The use of modern and more accurate test equipment is then often not used due to that poor correlation. At the same time, research is consistently showing many of these instruments are superior as QA measurement tools as compared to the density ratio status quo.

3.1 Matching PDFs of DR and DCPs

The PDFs for the best fit and normal distributions are compared for the DCP in **Figure 3-1**. A normal PDF would be an incorrect assumption and using a DCP with a normality assumption results in a poor QC assessment. The Normal PDF is ranked No. 11 in goodness of fit tests. The paired matching of the DCP and DDR is shown in Figure 3-2 with an R^2 = 0.06 for the best fit trend line. This poor correlation shows an increasing DCP value resulting in a decreasing DDR, when both should be increasing.

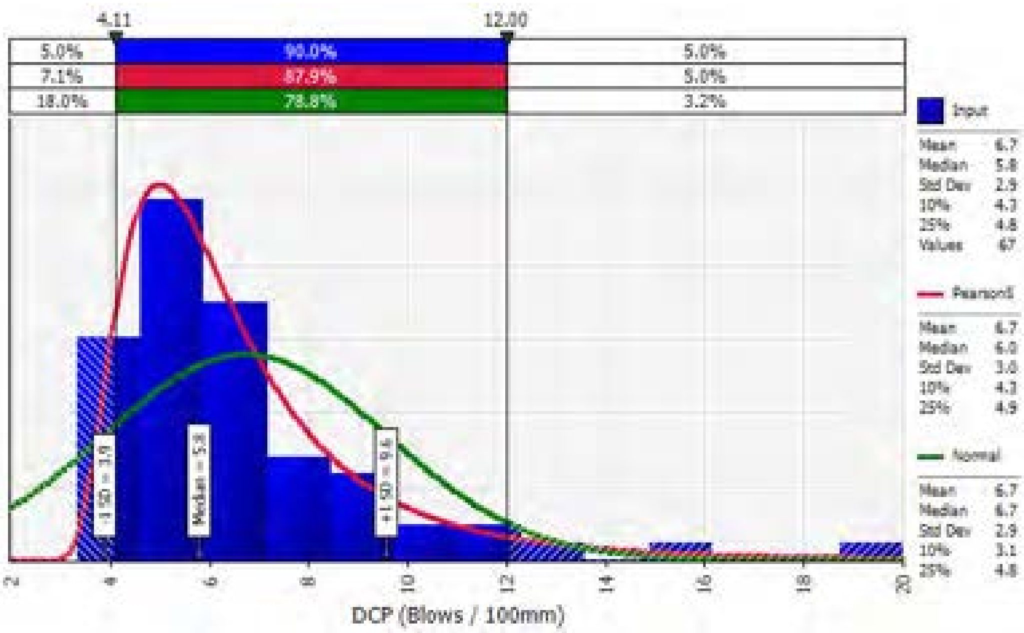


Figure 3-1 DCP tests with a with a non-normal PDF.

The approach of matching PDFs rather than paired correlations is shown in Figure 3-3. Using the appropriate PDF, the 5% value of both the DCP and Density ratio are paired. Then a similar pairing for the 10% value, 25% value, median and so on. Figure 3-4 shows the data can now be paired with a high correlation. The same data with a paired PDF matching approach now results in a strong correlation.

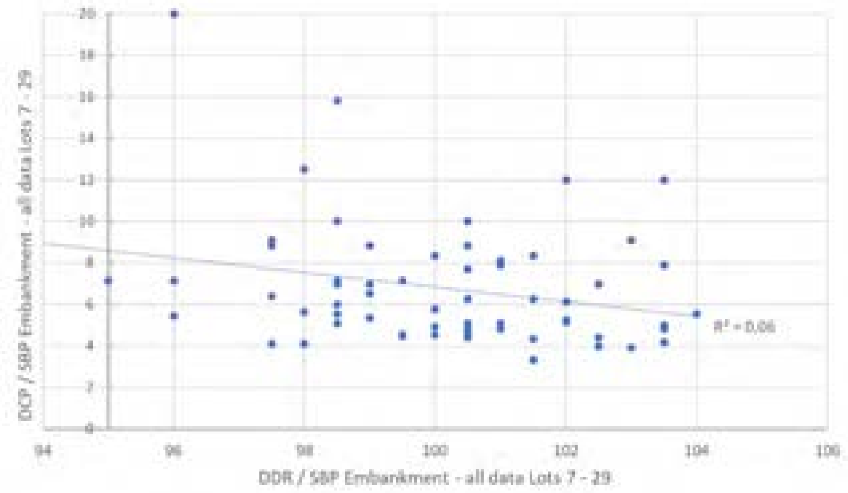


Figure 3-2 Paired matching of DDR and DCP with low correlation

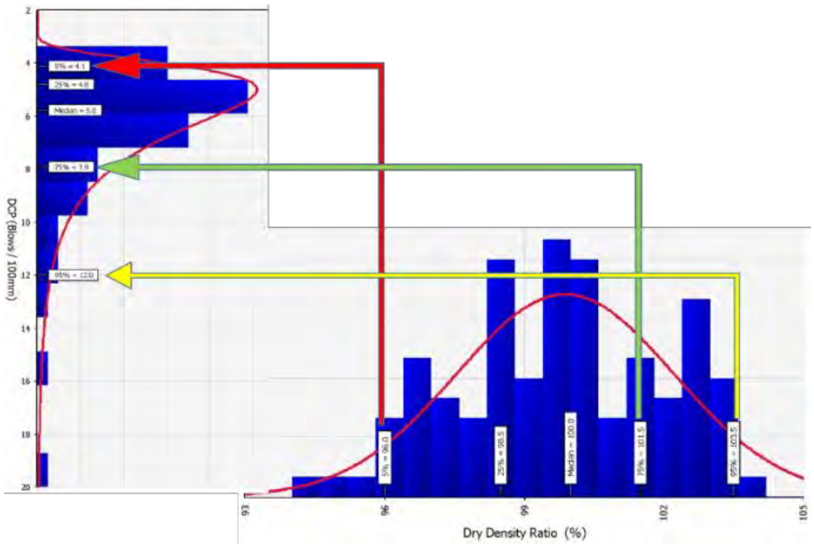


Figure 3-3 Matching the Dry Density Ratio and DCP PDFs

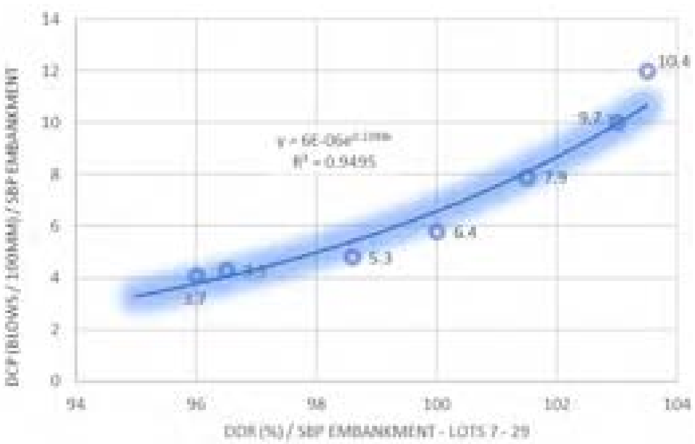


Figure 3-4 Matched PDFs for DDR and DCP are correlated.

3.2 Matching PDFs of DR and LWDs

A similar approach is also shown for LWD tests paired with DDR results. Figure 3-5 shows this paired correlation with the “low” LWD passing values and the “high” failing values when such an approach is adopted. The low R^2 value alone should discount such an approach. But the persistent of site supervisors to insist on a correlation with the density ratio continues to be the impediment of implementation of superior tests. Modulus values above 100 MPa can “fail” a 100% DDR tests and values below 30 MPa can “pass” a DDR criterion.

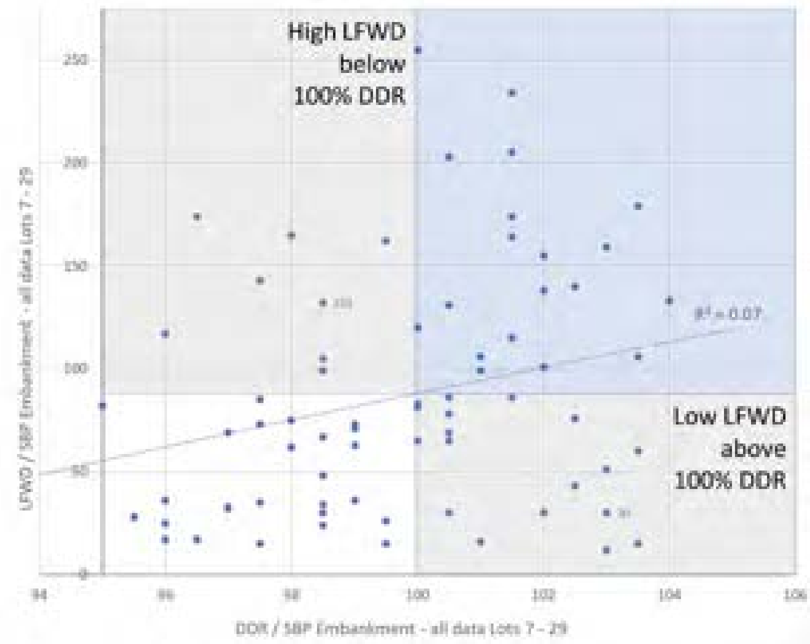


Figure 3-5 Paired matching of DDR and LFWD (Prima) tests.

Figure 3-6 shows the LWD tests with the best fit PDF as compared with a normal PDF. The normal PDF was ranked 11 in the goodness of fit test. If a normal PDF was used, the statistical errors become apparent, as large negative values can now occur at the lower 5% tail. A bounded Weibull PDF would provide the best fit PDF in this case.

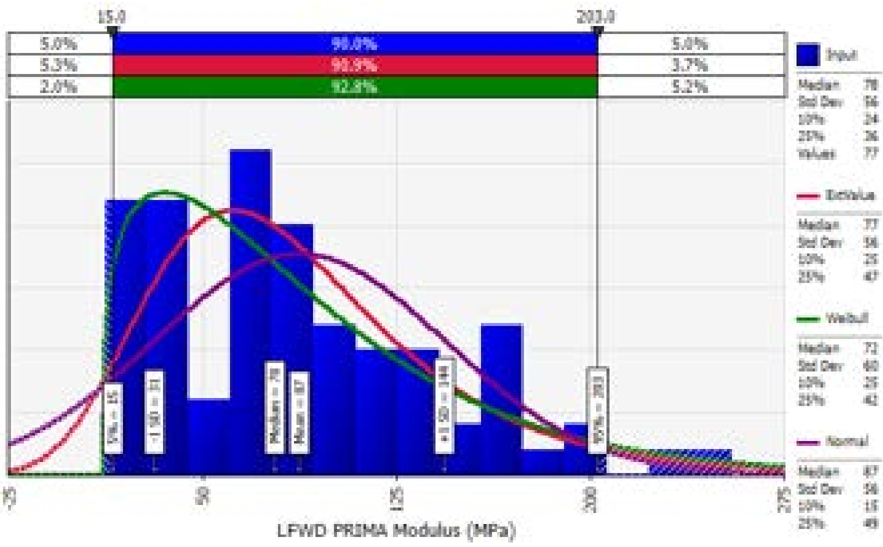


Figure 3-6 LFWD (Prima) tests with a with a non-normal PDF.

Using the procedure of matching PDFs for the LFWD, the corresponding QA values are obtained as shown in Figure 3-7. The resulting paired fit by this matching PDF method results in an $R^2 = 0.98$. This should be compared with Figure 3-5 which had a trend line with an $R^2 = 0.07$. This is the same data with a transformed analysis.

These results were summarized in **Table 2-1** with both the LFWD and the DCP results. Note that DCP has both a low accuracy and precision, but is shown here not as progressive tool but for those who rely on this commonly used measuring tool. This is a material specific relationship for this test site as different materials can have different moduli for the same 95% relative compaction.

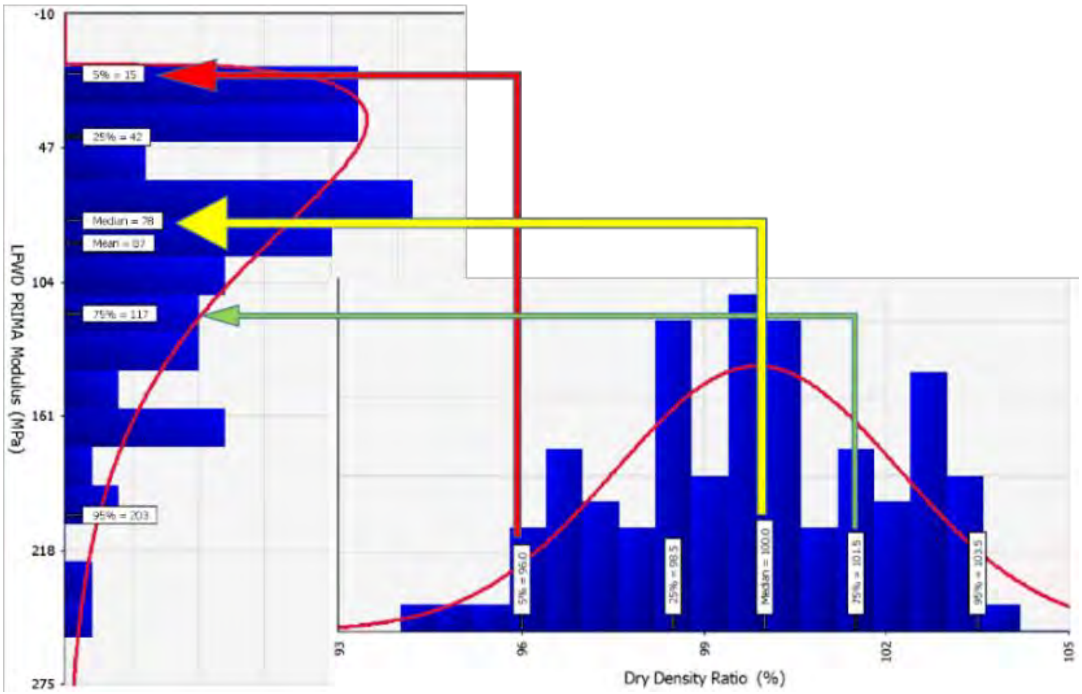


Figure 3-7 Matching the Dry Density Ratio and LFWD PDFs

3.3 Summary of Method

This method requires additional side-by-side testing over a series of defined earthworks lots (5 no.) to establish a baseline range of values for both density (DDR) and the alternative method of QA being utilised (in this example the LWD). The aim of this method is to produce a statistically valid sized dataset that allows the accurate definition of an applicable probability density function (PDF) of each of the two (2) test techniques, and then matching the corresponding characteristic statistical values to establish the project- and material-specific DRR to alternative in situ parameter relationship (in this example the $E_{LWD\text{-}100kPa}$ parameter)

This approach is as follows: -

1. Carry out side-by-side DDR and LWD testing at a minimum of 25 no. locations. Locations should be spread across representative earthworks area (say spread across five (5) earthworks lots, each including five (5) test locations)
2. Interpret the standardised in situ modulus parameter for each test location – e.g. $E_{LWD\text{-}100kPa}$. Discard the highest value and apply the defined capping value (e.g. $E_{LWD\text{-}100kPa}$ = 200 MPa) to any other uncharacteristically high values. This can be either
   a. Visually – Most outliers are self-evident
   b. Statistically – Calculate Standard Deviation (SD) and Mean. Values above 3 SDs from the mean are usually outliers. Recalculate with outliers removed.

c. Use the box-and-whisker plot to show the distribution of a dataset (Figure 3-8). The interquartile range (IQR) can be used to identify outliers.

3. Fit a Probability Distribution Function (PDF) of best fit to both the density dataset (likely a Normal distribution function) and in situ modulus dataset (likely non-normal distribution function). In the absence of a best fit analysis use a log normal PDF. Note this can also be done graphically as a cumulative frequency curve.
4. Plot the corresponding characteristic elements of each fitted PDF
5. Obtain the 'equivalent' acceptance threshold in situ modulus parameters to be utilised for LWD QA assessment that correspond to the specified DDR requirements.

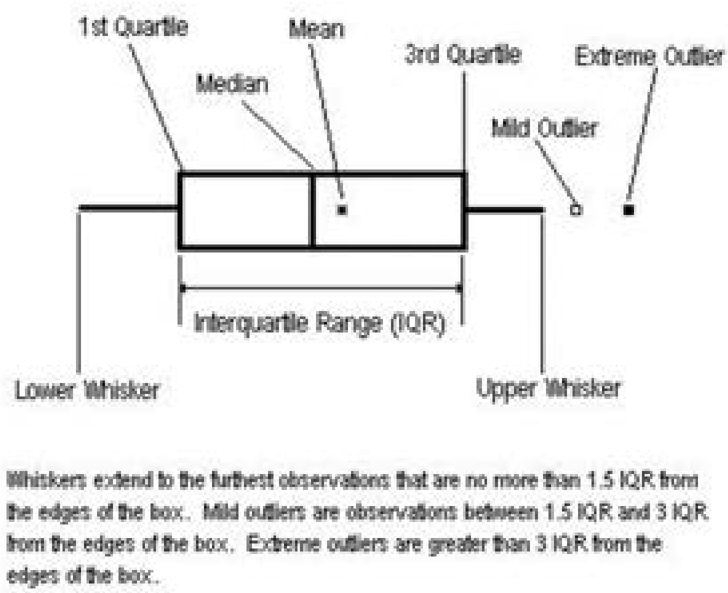


Figure 3-8 Box and Whisker plot explanation

4. General Technical Specification

Despite the clear benefits of use, the alternative tests may not routinely provide a direct reliable correlation with density. To overcome the inconsistencies related to the paired correlation approach with DDR, a method of matching probability density function PDFs was outlined. This method requires additional side-by-side testing over a series of defined earthworks lots to establish a baseline range of values for both density (DDR) and the alternative method of QA being utilised. A universal target value can be misleading as the modulus is equipment, material and project dependent.

Continuous parallel testing of DDR with any alternative equipment may be perceived as additional costs to the project. An ongoing approach whereby parallel density and alternative assessment techniques is employed on a project is therefore not recommended. Instead, as detailed herein, equivalent 'thresholds' for material acceptance should be defined during an initial trial that evaluates project, material and test specific correlations – such that the existing risk profile is maintained – prior to the adoption of the alternative QA technique during production (with specified check testing frequencies to verify / update any project-specific defined correlations).

These various approaches using an LWD is shown in Figure 4-1. While the LWD is detailed here in the approach may be also used with other alternative equipment.

The right-hand side of Figure 4-1 shows the general target value and the paired correlation approach. Neither is recommended. The method of matching PDFs improves on the paired correlation approach but still requires parallel testing.

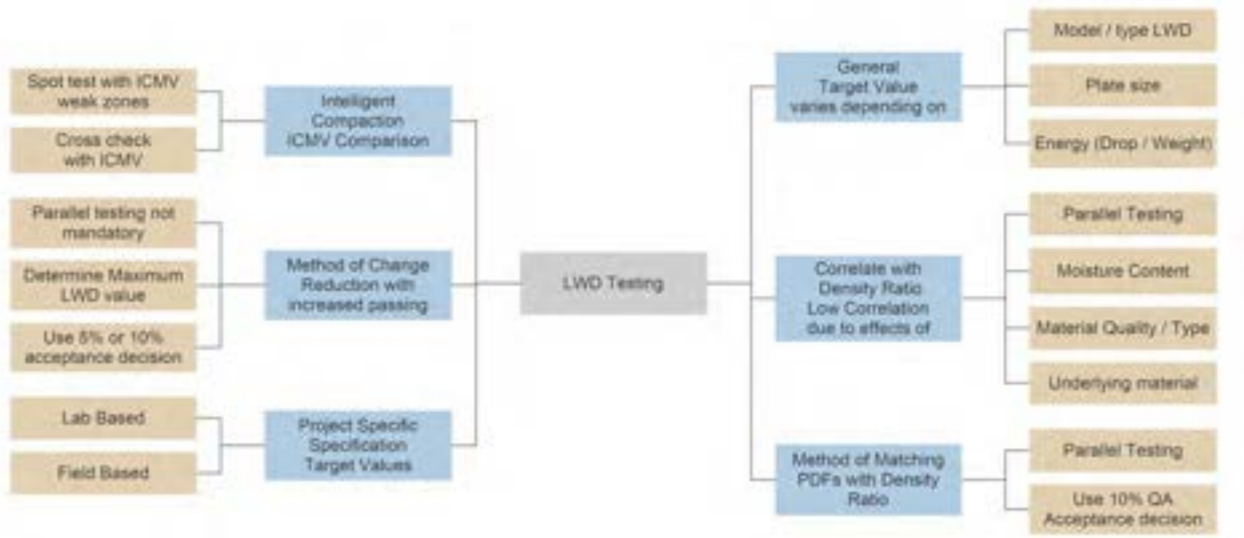


Figure 4-1 Various approaches to apply LWD testing

The left-hand side of Figure 4-1 provides a reduced testing approach which is less reliant on DR as the reference parameter. The LWD can provide an independent cross check of IC when that technology is implemented. LWD can also be used solely to determine a peak value and subsequently an acceptance value by a method of change reduction.

A field based LWD specification is further detailed in chapter 5. A more generalised method of change reduction is described in chapter 6.

4.1 Lab based target values

Project specific target values can be developed by a lab or field-based approach. The former is documented in AASHTO 2017 Standards [5] and [6].

Laboratory Determination of Target Modulus Using Light-Weight Deflectometer (LWD) maty be useful in design, especially to assess soaked conditions, but needs a significant lead up testing time. Other disadvantages include:

- X not being fully representative of the on-site material (removal of oversizes for testing)
- X not representative of the on-site compaction energy. This is the similar issue with the lab MDD approach as a reference where peak modulus is not necessarily coincident with MDD and OMC.
- X moisture content in the field needs to be factored
- X the plate size used in the lab is different from that in the field and this effect can be significant.

This lab-based approach is not discussed further.

4.2 Issues with prescribed target values

A defined target values can lead to inconsistencies in application as evident in Table 4-1 for 3 test embankments. The target value can vary with the source origin of the material.

Table 4-1 In situ E correlated to 95% Density ratio - Values

Fill Material Origin	Plate Load Test (PLT) E_{V2} (MPa)	Light Falling Weight Deflectometer (LFWD) - $E_{LFWD\text{-}100kPa}$ (MPa)
Sandstone 70% Gravel size; 10% fines	60	45
Interbedded Siltstone / Sandstone 70% Gravel size; 11% fines	35	25
Basalt 65% Gravel size; 12% fines	50	30

Table 4-2 shows typical range of results used in Germany. This is for mainly processed material while natural in situ material from cut to fill earthworks can vary much more.

Table 4-2 Laying and compaction specification for road construction in Germany

Soil layers	Density (Standard Proctor)	Bearing capacity (load bearing test, EV2)	Eveness (4 m straight edge)
Subbase	**100 - 103 % ***	**100 - 150 MN/m² ***	**20 mm**
Capping layer	**100 - 103 % ***	**100 - 120 MN/m² ***	**40 mm**
Formation	**97 - 100 % ***	**45 - 80 MN/m² ***	**60 mm**

*** depending on road classification and road design**

The moisture content at the time of testing may also affect the results significantly.

5. Example Specification - Assessment using Light-Weight Deflectometers (LWD)

5.1 Aim of LWD Specification

This generic Specification aims to provide a standard procedure under which Light Falling-Weight Deflectometers (LWD) – considered to be dynamic plate load tests – can be evaluated and utilised for on-site material evaluation and Quality Control (QC) of Earthworks. Specifically, this document aims to detail a process which can be employed to allow LWD test equipment to be incorporated into a QC framework.

5.2 Scope of Specification

This Specification describes both

(i) the field collection procedure; and

(ii) subsequent evaluation of the LWD test results, such that an appropriate in situ modulus threshold can be derived to evaluate the acceptability of the compaction achieved within a soil material.

This outcome is achieved via the construction of an initial trial embankment and the in situ LWD testing of an adequately compacted source material. This trial embankment is effectively compacted (to the desired project requirements) and subsequently assessed via the use of an LWD such that Acceptance Thresholds that be defined. The defined Acceptance Thresholds shall then be utilised for material conformance testing during full-scale Earthworks production of similar materials.

Different LWDs from various manufacturer's provide different measurements, which means that such absolute values should not be used unless correlated with PLT modulus values. Construction quality specifications must specify which model of LWD is being used. This should not be interpreted as advocating any particular brand. **Figure 5-1** provides a summary of the key elements used in defining the LWD specification. These will be discussed in greater detail in the following sections.

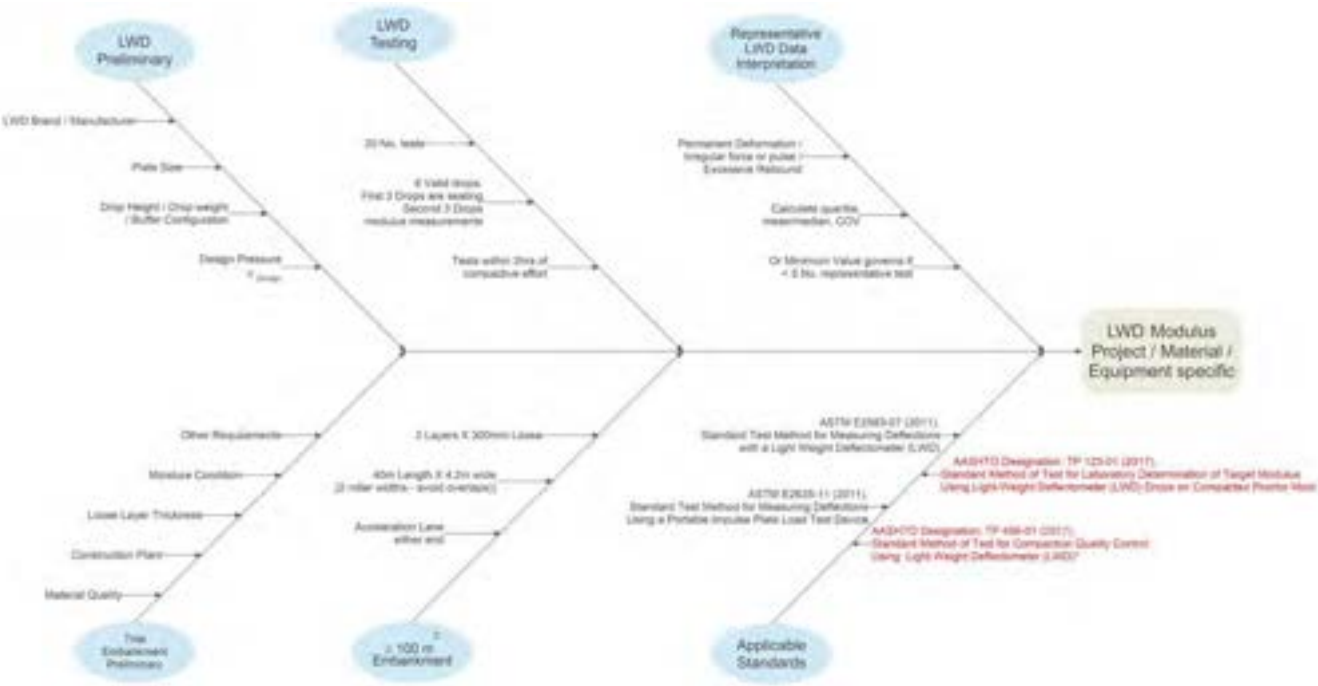


Figure 5-1   Key elements in LWD specification

5.2.1 Exclusions

This Specification does not include recommendations for a method that reliably evaluates soil moisture (water) content of materials in the in-situ condition.

However, an appropriate method for the evaluation of in situ soil moisture content measurement shall be identified and implemented during all fieldwork, such that the field moisture content of the near-surface profile at the same time as LWD assessment can be rapidly determined.

The in-situ measurement and evaluation of the moisture condition at the time of LWD testing is important such that

(i) the presence of a defined moisture content-modulus relationship can be defined and incorporated into the Acceptance Thresholds; and /or

(ii) to ensure the material being assessed during production Earthworks remains consistent with that utilised in the trial embankment.

5.3 Preliminaries

5.3.1 Definition of required LWD Test Configuration

Due to variation in various available LWD equipment – in terms of plate size, available drop weights, methods used to measure resulting ground deflections, presence of load cell, buffer arrangements etc. – it is imperative that the LWD utilised for initial material evaluation and derivation of the Acceptance Thresholds be the same type and configuration as that used during for all subsequent in situ LWD testing during production phase earthworks.

As such, the following variables require definition prior to commencement of trial / production LWD testing:

- **Design pressure (σ_{design})** – Pressure at which the compacted materials will be evaluated, and pressure at which the in-situ modulus will be standardised;
- **LWD Brand / Manufacturer** – Such that the measurement sensors to be utilised and applicable ASTM (or similar) test methodology can be identified
- **Plate Size**, **Drop Weight Magnitude**, **Buffer Configuration** & **Drop Height** – Adopted so the test arrangement routinely can impart the defined Design pressure (σ_{design}). Where multiple LWD test arrangements may be available for use – based on the capabilities and calibrated ranges of the LWD test equipment – it is recommended that the arrangement that incorporates the largest possible plate diameter be utilised.

If, for any reason, the defined LWD type or test configuration is required to be altered during the completion of Earthworks production, then additional trial embankment testing shall be completed in order that revised E_{LWD} Acceptance Thresholds can be derived.

Equipment has been calibrated in accordance with manufacturer's requirements.

5.3.2 Definition of required initial Trial Embankment variables

As the aim of the trial embankment testing is to reflect the production earthworks arrangement, the configuration of the materials and construction plant to be used for the trial embankment require definition prior to project commencement.

The required details of the production earthworks methodology to be reflected in site- and material-specific LWD trials shall include:

- **Material Quality** – Such that the characteristics of the source material can be identified (and applicable bounding parameters identified);
- **Construction Plant** – The same plant shall be used for compaction of trial embankment materials as per use in production earthworks;
- **Loose layer thickness** – The nominated loose layer thickness for production earthworks shall be adopted for the LWD trials;

- **Moisture Condition** – The same moisture conditioning techniques proposed to be utilised in earthworks production shall be adopted for the LWD trials (and applicable bounding parameters identified)
- **Other Requirements** – Any minimum and / or characteristic value of design parameters (e.g. modulus, bearing capacity) or compaction level (e.g. density ratio) that are required to be verified by the QC regime being applied to the compacted Earthworks shall be identified.

5.4 Construction of Trial Embankment for Field Verification of LWD Thresholds

A trial embankment shall be constructed utilising the source materials and compaction characteristics as proposed to be utilised for the earthworks production methodology. A minimum of two (2) layers of earthworks – adopting the identified loose layer thickness – shall be constructed, such that the second layer is compacted directly upon the first.

During the construction of the trial area, the source materials shall be handled as close as possible to the method proposed to be used for sourcing of materials during the earthworks production phase.

A ramp / approach area shall be constructed to allow the construction plant to accelerate to proposed production speed prior to entering the trial area. This ramp / approach area shall not be considered to form part of the trial embankment.

Figure 5-2 shows a typical minimum trial embankment layout. This shall consist of

- Minimum Area = 40 m length X 4.2m wide (~ 2 roller widths)
- No. of tests = 2 X 5 = 10 Min / Layer / roller width. This allows at least 5 tests at 5 m apart
- 2 Layers of ~ 300mm loose layers. This allows the influence of an underlying layer to be determined. The first layer will be affected by the underlying material.

The above equates to 20 Min. No. tests over the 2 roller widths and 2 layers placed. This minimum volume of material being tested is ~ 100 m^3.

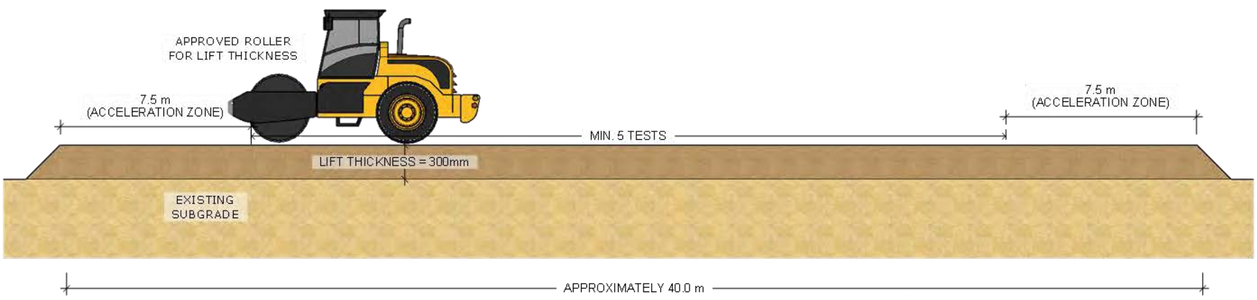


Figure 5-2 Trial embankment (Minimum Area = 40 m length X 4.2m wide)

For clarity, a separate trial embankment shall be prepared for each moisture condition and/or source material to be assessed by LWD testing.

5.4.1 In-situ Testing of Trial Embankment – LWD Testing

A minimum number of 20 LWD tests shall be completed within the trial embankment prepared area, with test locations selected in a random and unbiased manner, and away from the acceleration zone.

LWD testing of the prepared (compacted) trial embankment surface shall be undertaken via the adoption of the relevant ASTM (or equivalent) test methodology standard applicable to the LWD being evaluated.

The application of the LWD test shall achieve the defined σ_{design} magnitude with each weight drop.

A minimum number of six (6) 'valid' drops and the recording of the [peak deflection magnitude] shall be made at each test location. Of the 'valid' drops, the initial three (3) 'valid' drops shall always be considered "seating" blows and shall not be incorporated for the calculation of the average peak observed stress or deflection unless specifically identified to be representative of the remaining 'valid' drops. Any additional “seating” drops shall be identified, and are defined as consecutive drops in which the observed [peak deflection magnitude] is in excess of 10%.

The remaining test records (minimum three (3) no. drops) shall be termed “representative” of the test site being considered and adopted for further data interpretation.

All LWD tests shall be performed within two (2) hours of the completion of compactive efforts, such that the effect of surface drying on the measured data is minimised.

At all LWD test locations the field assessment of in-situ moisture content shall also be undertaken (or representative samples taken for associated laboratory determination of field moisture content).

5.4.2 In-situ Testing of Trial Embankment – Other Associated Testing

If any other test techniques are to be incorporated into the evaluation of the LWD equipment being assessed, they shall be undertaken at the same locations of all LWD testing completed upon the compacted trial embankment (i.e. at a ratio of 1:1).

All associated testing shall be undertaken at a distance no greater than 500 mm offset from the outer edge of the LWD testing completed.

At any specific location, all associated testing shall be undertaken within +/-30 mins of the completion of the LWD test.

5.5 LWD Interpretation – Standardised Method for Determination of In-situ Modulus

5.5.1 Inspection of “Representative” Data

An initial inspection of the “Representative” Data collected at each test location shall be completed. As a minimum, the following assessments shall be completed:

- Evaluation of **permanent deformation** being observed due to imparted stress – which may be indicative of a bearing capacity issue
- Identification of data where **‘irregular’ force / deformation shaped pule / deformation curves** exist;
- Identification of data where **excessive ‘rebound’ within deformation curves** exist;
- Identification of data where the peak stress deviates by **+/- 5% from the defined σ_{design} magnitude**.

If any of the above items are identified to exist within the “Representative” Data then the individual test records shall be discarded as being ‘unrepresentative’ of the design condition’s being verified.

All remaining ‘representative’ peak deflection magnitudes (δ_{peak}) applicable to each test location shall be averaged, and the 25th Percentile, 75th Percentile, Standard Deviation, and Coefficient of Variation (CoV) of the dataset shall be calculated. Outliers shall be identified within these test records and be excluded from further calculations.

The average ‘peak deflection’ shall be calculated for all remaining ‘representative’ peak deflection magnitudes applicable to each test location. This shall be termed the test site’s peak deflection – δ_{peak} – and shall be reported in microns (μm).

If the inspection process described herein yields a dataset that is reduced to less than five (5) ‘representative’ test records for any individual site, then the test result shall be either

a) termed “undeterminable” and the test site shall be removed from the constructed LWD dataset, or

b) a non-statistical approach applies to the material / project specification and the minimum value then governs

Note that b) is considered more likely to be onerous on the contractor.

5.5.2 Calculation of In-situ Modulus Parameter – Per Test Site ($E_{LWD\text{-}SITE}$)

The in-situ modulus attributable to each LWD Test location ($E_{LWD\text{-}SITE}$) shall be calculated in accordance with the recommendations of the manufacturer of the LWD equipment being utilised for testing and applicable ASTM (or equivalent) test standard.

Specifically, it would be expected the following equations would be applicable to transform the [σ_{peak}, δ_{peak}] parameters into $E_{LWD\text{-}SITE}$ values:

- For LWDs fitted with a Load Cell (conforming to ASTM E2583):

$$E_{LWD\text{-}SITE}\ (\text{MPa}) = [A \times \sigma_{peak} \times R \times (1 - \nu^2)] / \delta_{peak} \qquad \textit{(Equation 1)}$$

Where:

- $E_{LWD\text{-}SITE}$ = In situ (composite) modulus, under σ_{peak} pressure conditions
- A = Stress Distribution Factor, selected from:
  - o Mixed Soil (uniform contact) = 2
  - o Granular Material (parabolic contact) = 8/3
  - o Cohesive Material (inverse parabolic contact) = π/2
- R = Radius of LWD plate (in metres, m)
- σ_{peak} = Average peak stress applied during test, as determined in accordance with the methodology detailed in Clause 1 (in Megapascals, MPa)
- δ_{peak} = Average peak deflection magnitude recorded during test, as determined in accordance with the methodology detailed in Clause 1
- ν = Poisson's Ratio (which may be obtained from **Table 5-1**)

- For LWDs not fitted with a Load Cell (conforming to ASTM E2835):

$$E_{LWD\text{-}SITE}\ (\text{MPa}) = [A \times \sigma_{peak} \times R \times (1 - \nu^2)] / \delta_{peak} \qquad \textit{(Equation 2)}$$

Where:

- $E_{LWD\text{-}SITE}$ = In situ (composite) modulus, under (assumed) σ_{peak} pressure conditions = Dynamic Modulus *(E_{vd})*
- A = Stress Distribution Factor = 2
- R = Radius of LWD plate (in metres, m)
- σ_{peak} = σ_{design} = Assumed peak stress applied during test as defined in Clause 5.3 (in Megapascals, MPa)
- δ_{peak} = Average peak deflection magnitude recorded during test, as determined in accordance with the methodology detailed in Clause 1 (in metres, m)
- ν = Poisson's Ratio = 0.5

Where required, and in the absence of other site- or material-specific information, the Poisson's Ratio adopted in **Table 5-1** shall be adopted.

Table 5-1 Poisson's Ratio – Typical Values (after NCHRP, 2004)

Material Type	Poisson's Ratio (ν)	
	Range of Values	Typical Value
Granular (mixed) Materials	0.30 – 0.40	0.35
Gravelly SAND	0.30 – 0.40	0.35
Coarse Grained SAND	0.15	0.15
Fine Grained SAND	0.25	0.25
Dense SAND	0.20 – 0.40	0.30
Silty SAND	0.20 – 0.40	0.30
Sandy CLAY	0.20 – 0.30	0.25
CLAY – Saturated	0.40 – 0.50	0.45
CLAY – Unsaturated	0.10 – 0.30	0.20
SILT	0.30 – 0.35	0.325
Cement Treated Granular Materials	0.10 – 0.20	0.15

Material Type	Poisson's Ratio (ν)	
	Range of Values	Typical Value
Cement Treated Fine Grained Materials	0.15 – 0.35	0.25
Lime-Stabilised Materials	0.10 – 0.25	0.20
Fly Ash Stabilised Materials	0.10 – 0.15	0.15

5.5.3 Evaluation of variation of $E_{LWD\text{-}SITE}$ across prepared and tested surface

The average (μ), standard deviation (σ) and Coefficient of Variation (CoV) of the calculated $E_{LWD\text{-}SITE}$ parameters shall be completed for the trial embankment dataset (i.e. uniform material condition).

Typical CoV values determined for various material classification categories are detailed in **Table 5-2**. If the CoV of the LWD datasets are calculated to be above the applicable range identified in **Table 5-2**, this may be indicative of a non-consistent compaction state being achieved onsite. Observance of excessive CoV values (beyond the upper limits identified in **Table 5-2**) shall trigger a review of the data and material source in order to ascertain the reason for such variation.

Table 5-2 Typical Coefficient of Variation (CoV) of $E_{LWD\text{-}SITE}$ Parameters, by material type

Material Type	Typical Coefficient of Variation (CoV) of $E_{LWD\text{-}SITE}$
GRAVEL dominated materials	10 – 20 %
SAND dominated materials	15 – 35 %
FINES dominated materials	30 – 60 %

5.6 Determination of In-situ Modulus Acceptance Threshold Values

5.6.1 Moisture-Dependent behaviour of In-situ Modulus parameter ($E_{LWD\text{-}SITE}$)

The dataset of $E_{LWD\text{-}SITE}$ parameters shall be individually paired with the correlating Moisture Content (MC) or Moisture Ratio (MR) test result, as collected during field testing. A paired dataset of [$E_{LWD\text{-}SITE}$, MC (%)] or [$E_{LWD\text{-}SITE}$, MR (%)] data points shall be constructed for further evaluation.

The range of the moisture parameter (MC or MR, %) observed onsite becomes a limiting range to which any modulus-moisture dependent relationship is defined. Additional trial assessments utilising the LWD are required to demonstrate the validity of any relationships beyond the observed moisture condition extents.

The constructed [$E_{LWD\text{-}SITE}$, Moisture Condition] paired dataset shall be plotted on a scatterplot, with the $E_{LWD\text{-}SITE}$ parameter plotted as the dependent variable. If multiple LWD trial sites have been completed (as per Clause 5.4) in order evaluate the in situ modulus parameter, and potential variation thereof, applicable to a single source material prepared under different moisture conditioning, then all relevant [$E_{LWD\text{-}SITE}$, Moisture Condition] paired data shall be plotted on a single scatterplot.

Both linear and non-linear relationships shall be determined for the plotted [$E_{LWD\text{-}SITE}$, Moisture Condition] data. If the relationship of best fit achieves a Coefficient of Determination (R^2) of, or in excess of, 0.3 and a 95% confidence level (i.e. $\alpha < 0.05$), then the material shall be considered "Moisture Dependent" for the purposes of LWD assessment. Otherwise, the material shall be considered "Non- Moisture-Dependent".

If the [$E_{LWD\text{-}SITE}$, Moisture Condition] analysis result in a material being defined as "Moisture-Dependent", then two (2) functions that describe the observed relationship are required to be defined:

- *Function A* – The function that relates the $E_{LWD\text{-}SITE}$ and moisture parameter (MC or MR, %); and
- *Function B* – The lower bound 90^{th} Percentile Confidence Interval applicable to the defined relationship.

In addition, for datasets where a valid $E_{LWD\text{-}SITE}$ and in-situ moisture parameter is defined, the average of the absolute residual values associated with the application of Function A to the available [$E_{LWD\text{-}SITE}$, Moisture Condition] dataset shall be determined. This value shall be termed the "Moisture Content Residual Value" (MCRV).

5.6.2 Derivation of Acceptance Threshold Values - E_{LWD} parameter

For materials defined as "Non-Moisture Dependent"

For non-moisture dependent soil materials undergoing earthworks compaction assessment, the following criteria shall be implemented to assessment of LWD field test results ($E_{LWD\text{-}Field}$) arising during Earthworks production:

If < 5 tests a non-statistical approach applies

- *Criterion #1* – No single test within any earthworks lot shall fall below the minimum value observed within the LWD trial embankment. This value shall be terms $E_{LWD\text{-}MIN,}$ and Equation 3 shall be applied:

$$E_{LWD\text{-}Field} \geq \text{Min. } [E_{LWD\text{-}SITE}] \qquad \textit{(Equation 3)}$$

If ≥ 5 tests statistical approach applies.

- *Criterion #2* – The arithmetic mean value for the processed dataset of $E_{LWD\text{-}Field}$ parameters observed within any single earthworks lot shall be, or exceed, a value 20% below the arithmetic mean of the applicable LWD trial embankment, as per Equation 4, or the median value $E_{LWD\text{-}Field}$ whichever is greater:

$$\bar{x}\ [E_{LWD\text{-}Field}] \geq 0.8 \text{ x } \bar{x}\ [E_{LWD\text{-}SITE}]\text{: Mean} \qquad \textit{(Equation 4)}$$

$$\bar{X}\ [E_{LWD\text{-}Field}] \geq \bar{X}\ [E_{LWD\text{-}SITE}]\text{: Median}$$

- *Criterion #3* – The Lower-bound Characteristic Value (LCV) applicable to any processed dataset of E_{LWD} parameter dataset shall be determined as per Equation 5:

$$\text{LCV } [E_{LWD}] = \bar{x}\ [E_{LWD}] - k\ s \qquad \textit{(Equation 5)}$$

  Where s is the standard deviation and k is the multiplier based on the number of tests as provided for the producer's risk (α) = 20% and proportion defective (p) = 10%. This is **not** the k value in the Queensland Main Road Technical Specifications MRTS01 which applies to density tests. The k values are provided in the Appendix A of this report.

  For a single earthworks lot to be considered acceptable, then the calculated LCV of $E_{LWD\text{-}Field}$ dataset shall remain equal to, or above, the LCV calculated for the applicable LWD trial dataset ($E_{LWD\text{-}SITE}$), in accordance with Equation 6:

$$\text{LCV } [E_{LWD\text{-}Field}] \geq \text{LCV } [E_{LWD\text{-}SITE}] \qquad \textit{(Equation 6)}$$

For a particular Earthworks Lot to be considered to demonstrate an acceptable compaction level, then the

LWD test results associated with the earthworks lot must satisfy either Criterion #1 for low number if tests or Criterion #2 and/or Criterion #3.

For materials defined as "Moisture-Dependent"

For materials defined as "Moisture-Dependent" the in-situ modulus parameter (E_{LWD}) requires test results to be considered individually. The applicable Acceptance Criterion for any single earthworks Lot shall be that no single test result may fall below the requirements of Criterion #4 or Criterion #5.

- *Criterion #4* – For any individual E_{LWD} test result, once paired with the corresponding (1:1 ratio) in-situ moisture condition – the test specific Acceptance Threshold shall be determined and satisfy the requirements of Equation 7:

$$[E_{LWD\text{-}Field}, \text{Moisture Condition}] \geq f\,(\text{Moisture Condition}, E_{LWD\text{-}SITE}) - \text{MCRV (MPa)} \qquad \textit{(Equation 7)}$$

  Where the function included in Equation 7 is Function A (as defined in Clause 5.6.1)

- *Criterion #5* – The individual paired data [$E_{LWD\text{-}Field}$, Moisture Condition] shall also be assessed such that Equation 8 is satisfied:

$$[E_{LWD\text{-}Field}, \text{Moisture Condition}] \geq f_{\text{90th Percentile}}\,(\text{Moisture Condition}, E_{LWD\text{-}SITE}) \text{ (MPa)} \qquad \textit{(Equation 8)}$$

Where the function included in Equation 8 is Function B (as defined in Clause 5.6.1)

Other (common) Requirements

For all production lot LWD testing, the in-situ condition being assessed must remain within the upper and lower moisture content bounds utilised for the trial embankment.

The same method of assessment of moisture content shall be undertaken for both trial and production phase testing.

5.6.3 Summary of Acceptance Threshold Values / Criterion

The method for calculation of the applicable Acceptance Threshold of E_{LWD} parameters for material acceptance vary based on the definition of the material as a "Non-Moisture Dependent" or "Moisture-Dependent" – for datasets assessed as per the definitions provided in Clause 5.6.1. **Table 5-3** summarises the equations for determining the applicable Acceptance Thresholds, based on the determined material type.

Table 5-3 Summary of Acceptance Thresholds to be determined from Trial Embankment assessment and Implemented for modulus (LWD) based Production Earthworks QC testing

Material Definition	Modulus Parameter is "Non-Moisture Dependent"	Modulus Parameter is "Moisture Dependent"
Required Data for Assessment	In-situ Modulus ($E_{LWD\text{-}Field}$)	In-situ Modulus (E_{LWD}) + In-situ Moisture Condition (Moisture) at time of LWD Testing
Minimum Requirement *(Individual test sites Evaluated)*	$E_{LWD\text{-}Field} \geq$ Min. [$E_{LWD\text{-}SITE}$] Where n < 5 tests	$E_{LWD\text{-}Field} \geq E_{LWD\text{-}SITE}$ – MCRV (For E_{LWD} @ equivalent Moisture Condition) $E_{LWD\text{-}Field} \geq$ 90th Percentile Confidence Interval of fitted ($E_{LWD\text{-}SITE}$, Moisture) Function (For E_{LWD} @ equivalent Moisture Condition)
Typical Value *(Full Earthworks Lot Considered)*	$\bar{x}$ [$E_{LWD\text{-}Field}$] ≥ 0.8 x $\bar{x}$ [$E_{LWD\text{-}SITE}$]: Mean $\tilde{X}$ [$E_{LWD\text{-}Field}$] ≥ $\tilde{X}$ [$E_{LWD\text{-}SITE}$]: Median	N/A
Lower Characteristic Value *(Full Earthworks Lot Considered)*	LCV [$E_{LWD\text{-}Field}$] ≥ LCV [$E_{LWD\text{-}SITE}$] – k s	N/A
In-situ Moisture Condition at time of LWD Testing *(Individual Test Sites Evaluated)*	Within Extents observed during Field Trials	Within Extents observed during Field Trials

Regardless of the classification of the source material, all applicable criteria must be satisfied for Earthworks Lot Acceptance.

5.7 Production Earthworks Testing – Frequency of LWD testing

During the implementation of LWD testing during production phase earthworks, the following minimum test frequencies shall apply:

- For general earthworks and locations within fill embankments where the exposed testing surface remains a minimum of 1,000 mm below top of subgrade (i.e. not subgrade materials) – A minimum of six (6) LWD tests shall be completed per 1,500 m^2 of works (equivalent to 1 LWD test per 250 m^2 of prepared earthworks)

- For pavement materials, and locations within the exposed testing surface of compacted general earthworks materials are within 1,000 mm of top of subgrade – A minimum of ten (10) LWD tests shall be completed per 1,500 m^2 of works (equivalent to 1 LWD test per 150 m^2 of prepared earthworks)

All nominated test frequencies consider a single layer / "lift" of material being placed as a single Earthworks lot (i.e. testing shall occur on each compacted layer at nominated frequencies).

6. Method of Change Reduction

Given any test value η, the method of change reduction is based on establishing a specification by first establishing either

1. A peak test value η_{max} at a high number of passes (say 12 No. passes) or
2. As changes are minor at (say 8 No. passes) then that reduced number may be used to also establish η_{max} such that any change (Δ) is
    a. less than 5% for subgrade or pavement assessments
    b. 10% for general fill material below the depth of subgrade

The value η may be a PLT, LWD, Clegg or Geogauge test value. Each of these can be measured in a test section as defined in section 5.4. However, the COV does vary for each of these tests and would need to be factored in any statistical analysis of results.

A minimum value should be established (at say 4 passes). Subsequent passes would typically produce reduced change as additional compaction occurs. At high compaction a reduction (material breakdown) may also occur. This over compaction (reduced) value should be ignored and the peak value only used. Hence a diminishing return with compactive effort is used to establish the peak value without the necessity to continuously over compact. The actual number of passes required to achieve η_{max} is dependent on both the type and size of compaction equipment, and the material being compacted as well as its thickness and moisture content

Figure 6-1 and Figure 6-2 provides the summary procedure for establishing these target values.

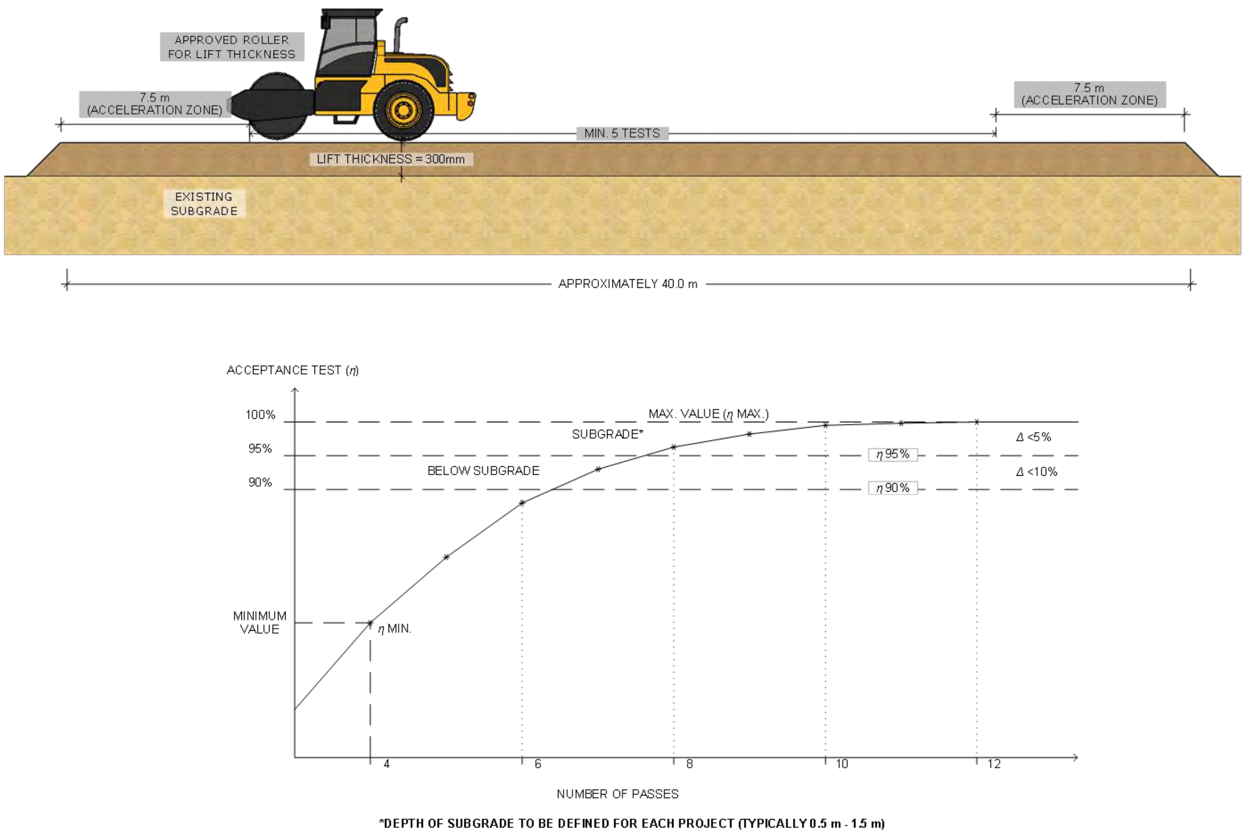


Figure 6-1 Defining a maximum target value

Figure 6-1 shows a typical minimum trial embankment layout. This shall consist of

- Minimum Area = 40 m length X 4.2m wide (~ 2 roller widths)
- No. of tests = 2 X 5 = 10 Min / Layer / roller width. This allows at least 5 tests at 5 m apart

- 2 Layers of ~ 300mm loose layers. This allows the influence of an underlying layer to be determined. The first layer will be affected by the underlying material

The above equates to 20 Min. No. tests over the 2 roller widths and 2 layers placed. This minimum volume of material being tested is ~ 100 m^3. Ideally 20 No. tests should be carried out at each layer.

A $\eta_{90\%}$ and $\eta_{95\%}$ quality specification can then be used along with an acceptable COV. As a COV is both material and test dependent, the values shown in **Table 5-2** are considered preliminary only for the LWD and need to be established during the trials.

This field procedure uses such alternative equipment (such as LWD) as standalone without the need to corelate to DR.

As material changes then these trials would need to be reassessed, but this should occur at no less than every 10,000 m^3 of placed fill for major roadways. These trials then become part of the placed fill.

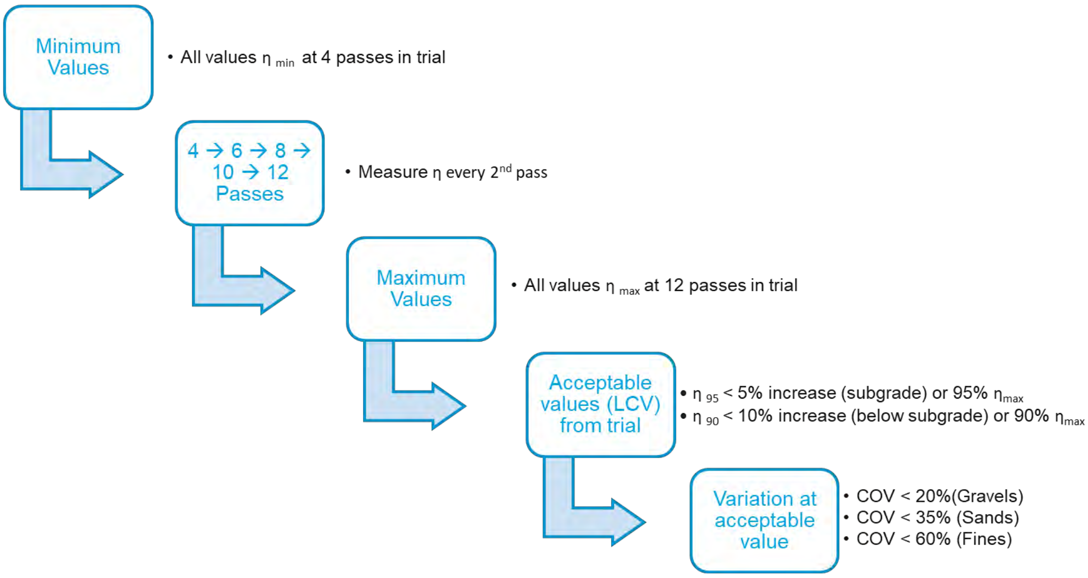


Figure 6-2 Procedure for determination of an acceptable value

7. References

[1] Fleming, P. R., and Edwards, J.P. 2019. LWD Best Practice Guide, https://hdl.handle.net/2134/27577 (accessed 10 March 2019)

[2] National Cooperative Highway Research Program (NCHRP), 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Part 2 – Design Inputs, Transportation Research Board, National Research Council, Reference 1-37A

[3] ASTM E2835-11 (2011). Standard Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device, ASTM International, West Conshohocken, PA.

[4] ASTM E2583-07 (2011). Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD), ASTM International, West Conshohocken, PA.

[5] AASHTO Designation: TP 123-01 (2017). Laboratory Determination of Target Modulus Using Light-Weight Deflectometer (LWD) Drops on Compacted Proctor Mould. Standard Method of Test

[6] AASHTO Designation: TP 456-01 (2017). Compaction Quality Control Using Light Weight Deflectometer (LWD) Standard Method of Test

[7] Engineering Road Note 8 (2008) “Statistically based quality control for density in road construction” Department of Western Australia

[8] AUFF, A (1986): "The Selection of Statistical Compliance Schemes for Construction Quality Control". Special Report 30, Australian Road Research Board.

8. Conclusion

In Earthworks testing using density ratios is applied widely in quality control. Density ratio tests take significant time for results to be reported. Yet because of its widespread usage, this now acts as an impediment to the development of alternative methods of testing. Although such alternative QA tests are not as precise as density testing, the density test is itself has the significant limitations of not providing near-instantaneous result and not being able to provide a reliable indication on the ground strength or modulus.

Modern geotechnical and pavement designs are based on modulus and strength values. It is therefore reasonable to investigate the use of alternative test methods for QA purposes, which measures these parameters directly. Several in-situ devices have been available to industry for the past 2 decades and research has shown these have significant benefits.

However, studies then try to corelate those measured parameters with the density ratio. Correlating to density is flawed as the alternative equipment measurement combines:

1. The density ratio, as well as
2. The moisture condition, and
3. The quality of the compacted material, and
4. The material underlying the layer being tested

This leads to combining all of the above in one measurement, while the current approach is to measure each of the above independently. Depending on the equipment there can be different proportions of these factors being measured.

Continuous parallel testing of DDR with this alternative equipment will be perceived as additional costs to the project – and if considered on a 1-to-1 basis, parallel testing can lead to DR results demonstrating a "pass" whilst LWD (or other tools) assessment could report a "fail" (or vice versa). An ongoing approach whereby parallel density and alternative assessment techniques is employed on a project is therefore not recommended.

Various methods to advance the technology of alternative quality control testing are provided herein.

Finally, we draw your attention to the attached Important Information about your FSG report.

Please contact the undersigned if any further information or clarification is required.

Regards,

David Lacey
Associate

Burt Look
Principal

Appendix A
Acceptance Constants

Characteristic Value

The lower characteristic value (LCV) is based on

$$LCV = X_{av} – k\ s$$

Where

X_{av} = mean of the individual test results

k = an acceptance constant dependent on the number of tests

s = standard deviation of ten dividual test results

Table 12(b) is taken from QTMR specifications MRTS01 for determining the acceptance constants. It applies to density lots, but should **not be used for alternative quality tests**. This k value is a one tailed significance test, which is based on a probability of acceptance (P) of 90% and a proportion defective (p) of 10% (a 90/10 scheme). This means that both the consumer's and producer's risk is 10%.

Further discussion on statistical based quality controls can be found in [7] and [8].

Table 12(b) – Acceptance constants

Number of Tests or Measurements	Acceptance Constant (k)	Number of Tests or Measurements	Acceptance Constant (k)
2	0.403	19	0.937
3	0.535	20	0.946
4	0.617	21	0.952
5	0.675	22	0.959
6	0.719	23	0.965
7	0.755	24	0.972
8	0.783	25	0.978
9	0.808	30	1.002
10	0.828	35	1.020
11	0.847	40	1.036
12	0.863	45	1.049
13	0.877	50	1.059
14	0.890	60	1.077
15	0.901	70	1.091
16	0.910	80	1.103
17	0.919	90	1.112
18	0.928	100	1.120

Density Ratio is a very high precision test with a low COV (typically < 3%) while alternative tests typically range have a range of 20% to 50%. This higher COV also applies to CBR tests which would not typically use such k values.

Using the values in Table 12(b) would result in material testing as "failing" due only to its larger variation of results. Chapter 3 specified the requirement and approaches to remove outliers which would affect the results.

Table 4 is taken from [7] where the multiplier k value is based on the number of tests (n), the producer's risk (α) and the proportion defective (p).

TABLE 4
VALUES OF THE MULTIPLIER (k)

p	α=5%			α=10%			α=20%			α=50%		
	10%	15%	20%	10%	15%	20%	10%	15%	20%	10%	15%	20%
n												
3	0.33	0.09	0.13	0.53	0.31	0.11	0.80	0.57	0.38	1.50	1.20	0.97
4	0.44	0.22	0.02	0.62	0.40	0.21	0.85	0.62	0.43	1.42	1.14	0.92
5	0.52	0.30	0.11	0.67	0.46	0.27	0.88	0.66	0.47	1.38	1.11	0.90
6	0.57	0.36	0.17	0.72	0.50	0.32	0.91	0.68	0.50	1.36	1.10	0.89
7	0.62	0.40	0.22	0.75	0.54	0.35	0.93	0.71	0.52	1.35	1.09	0.88
8	0.65	0.44	0.26	0.78	0.56	0.38	0.95	0.72	0.54	1.34	1.08	0.88
9	0.69	0.47	0.29	0.81	0.59	0.41	0.97	0.74	0.56	1.33	1.07	0.87
10	0.71	0.50	0.32	0.83	0.61	0.43	0.98	0.75	0.57	1.32	1.07	0.87
15	0.80	0.58	0.41	0.90	0.68	0.50	1.03	0.80	0.61	1.31	1.06	0.86
20	0.86	0.64	0.46	0.95	0.72	0.54	1.06	0.83	0.64	1.30	1.05	0.85

Analysis of the variability of LWD result show a p = 10% and α = 20% would more closely match the LWD results for the producer's risk.

Appendix B
Important Information about your FSG Report

Deep foundation and geotechnical engineering problems are a principal cause of construction delays, cost overruns, claims and disputes. The following information is provided to help you to understand this report and its limitations and manage your risks.

Scope and Applicability of this Report

This report has been prepared for a specific purpose and scope and its applicability is limited. FSG cannot accept any responsibility for the use of this report outside of the stated scope and purpose. If a service has not been explicitly included in the scope, it must be assumed that it has not been provided. Assessment of soil or groundwater contamination does not form part of this geotechnical report and any reference to any potential site contamination is for information only. If you are uncertain about the applicability of the results for any particular purpose, you should consult FSG to avoid any misunderstanding or miss-application.

This report has been prepared for the nominated Client and project only and should not be relied upon by other parties, or for other purposes, without consulting FSG. Any party relying on this report beyond its specific purpose and scope does so entirely at their own risk and responsibility. FSG does not take responsibility for the use of this document by any other person or party than the Client.

Project Details and Information Provided

This report has been based on project details as provided to us at the time of the commission. We have assumed that the information supplied to FSG by the client or other external sources on behalf of the client, is correct unless explicitly stated so. FSG does not accept any responsibility for incomplete or inaccurate data provided by others.

If any project details change during the course of the project or observed conditions are considered to differ from those expected or assumed, FSG should be notified in order to investigate if and how changes in project details affect the conclusions and recommendations in our report. If FSG is not consulted when changes are made to the initial project details, we cannot accept any responsibility for problems arising from these changes.

Geotechnical Information and Interpretation

Site investigations only sample discrete parts of the ground, and that extrapolation and interpolation of collected information can be used with varying degrees of risk and uncertainty depending on the extent and quality of the site investigation, the variability of the subsurface conditions and the consequences to the proposed works.

The analyses and recommendations in this report rely on the results of site investigation information, and other reported geotechnical information that is relevant to the works. This may include the results of pile load testing, other geotechnical testing, and inspections and observations from studies that have been performed as part of the works or in the vicinity of the works previously.

We have endeavoured to incorporate the available information into an appropriate geotechnical model based on our interpretation of the likely subsurface conditions. This process, and the geotechnical analysis and interpretation based on that model, is an inexact science, as a model is but a simplification of reality to derive a geotechnical solution. While we endeavour to incorporate realistic model parameters, our models, interpretations and the outcomes or our work generally may differ from reality for a range of reasons including:

- Spatial Variability: Geotechnical and geological variability across the site which may not have been captured in the site investigation works that have been used in our works. Geotechnical site investigations are very limited in the extent of physical investigation compared to the size of the entire site. No site investigation, no matter how comprehensive, can reveal all subsurface details and anomalies and conditions that differ from those observed in the site investigation will occur;
- Temporal Variability: Subsurface conditions can change with time due to man-made events such as cutting or filling or any construction works on or adjacent to the site which can also affect the site drainage and hence underlying properties; or by natural events such as floods or groundwater fluctuations.
- Variability in Mechanical Properties: Normal geotechnical variability in the inferred properties of materials represented in the boreholes, the performance of foundations or other elements that are tested or observed, and the performance of structures that are in contact with the ground in general. The data collected is only directly relevant to the exact location where the investigation was undertaken. The subsurface conditions between test locations have been inferred based on judgement and experience with the facts available at that time and related to the relative position of the proposed works;

- Testing Limitations: Uncertainty associated with geotechnical testing, design correlations associated with those tests or material descriptions, and case histories from which geotechnical parameters may have been inferred or in design and/or analysis methods that have been adopted;
- Construction Effects: Variability in the performance of construction equipment, such as hammers, cushions, guides and associated equipment for piling, construction effects that may influence the way structures interact with the ground, as well as inaccuracies in data measurement and testing methods that may have been used to record construction processes.

The results provided should be considered as indicative of the best estimate of likely outcomes (or range thereof), and should not be considered to be definitive or absolute, or represent the full range of possible outcomes at this site. Caution and prudence should be exercised when making decisions with significant implications for your project. The limitations of this report as outlined herein should be incorporated in decision making, and appropriate contingencies should be put in place to accommodate unexpected variability in relation to the works

Geotechnical Modelling

Model parameters that are used may vary in nature depending on the purpose of the analysis. Where it is necessary to make a realistic evaluation of the soil model, we would normally describe this as a 'best estimate' (BE). Depending on the particular application, it may be important to understand the sensitivity of the solution to soil model changes. We may then also define an 'upper-bound' (UB) soil model and a 'lower-bound' soil model, being estimates of the likely, strongest and weakest soil conditions which are anticipated based on the available geotechnical information and inferred geotechnical parameters. In certain circumstances, such as cases where the ground conditions appear to extremely uncertain or variable, we may also define 'extreme upper bound' (XUB) and 'extreme lower bound' (XLB) parameters which are intended to represent the likely extremes of the site conditions. In all cases, these models are inferred using engineering judgement from the available information and actual conditions and associated outcomes may differ from those assumed or given in our report, due to the inherent unpredictability of the ground, as outlined in the preceding section.

It should be noted that depending on the particular application either upper-bound or lower-bound analyses could be deemed conservative.

Disclaimer

The results, opinions, conclusions and any recommendations in this report are based on assumptions made by FSG in order to carry out the work. FSG specifically disclaims responsibility: arising from, or in connection with, any change to the site conditions or the nature of the proposed works including change in position of the structure or proposed works relative to the available data; to update this report if the site conditions or project details change or if the report is used after a protracted delay; and for liability arising from any of the assumptions that have been made or information provided being incorrect, incomplete or inaccurate.

Subject to the terms of an Agreement for Professional Services between FSG and the client, and to the maximum extent permitted by law, all implied warranties and conditions in relation to the services provided by FSG and this report are excluded.

Closure

Unless otherwise documented by way of a signed agreement for the services provided, all services in preparing this report have been provided under FSG's standard Terms and Conditions which are referenced in our fee proposal. The report is specific to the brief provided with its associated time and cost constraints.

Should you require any further information or clarification in relation to this report, please contact FSG.

APPENDIX B WEBINAR ON 6 FEBRUARY 2020

B.1 PRESENTATION SLIDES

1

Today’s Moderator

Rosemary Pattison
Knowledge Hub
Australian Road Research Board

P: +61 3 9881 1590
E: training@arrb.com.au

2

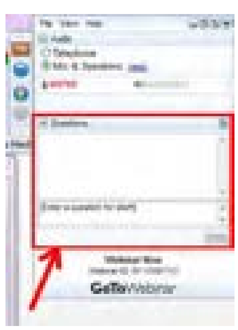
Housekeeping

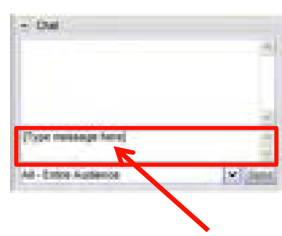
Webinar is = 50 mins
Question time = 10 mins

3

GoTo Webinar functions

Raise your hand





Please type your questions here

Check for messages

4

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Part 1 – An Overview **(Conceptual)**

- ✓ Density Basics
- ✓ Rationale for this equipment research
- ✓ Equipment overview + a few initial findings

Part 2 – Test Results **(Technical)**

- Details of testing from various sites
- Correlations with "Standard" practice
- Time vs Reliability vs Useful Data

Part 3 – Moving Forward **(Procedural)**

- Procedures and Specifications
- Advantages and limitations
- Implementation

2018 Presentation

2020 Presentations

7

P60: Best practice in compaction quality assurance for subgrade materials

ARRB Project Leader: **Dr. Jeffrey Lee**

TMR Project Manager: **Siva Sivakumar**

http://nacoe.com.au/

NACOE NATIONAL ASSET CENTRE OF EXCELLENCE

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NACOE P60

Aim and Background of the Project

- Aim
  - To modernise testing procedure for compaction quality assurance
- Background
  - Quality is conventionally been verified using density measurements
  - Alternative methods have been developed over the past two decades
  - Many of these methods takes less time to do, results become available in a much shorter time frame, and is able to measure in situ stiffness.

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Compaction Basics In 5 slides

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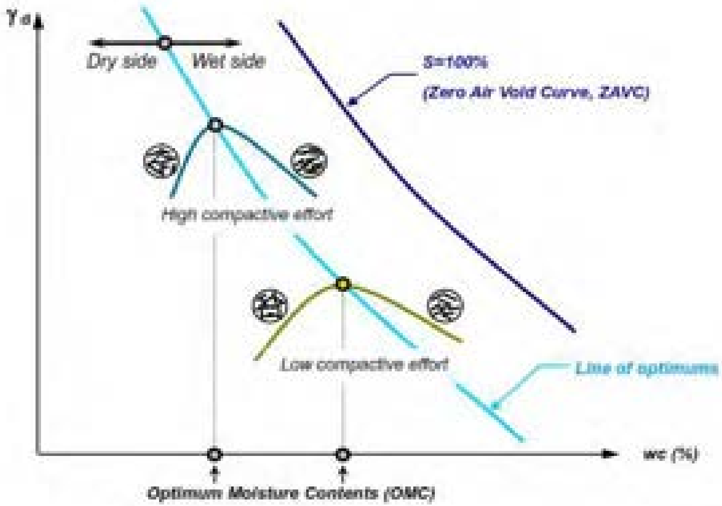
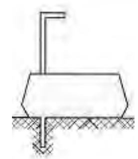
Target low air voids →Line of optimums





Examples of compaction curves (modified after Lambe 1962).

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Sampling Curing is required

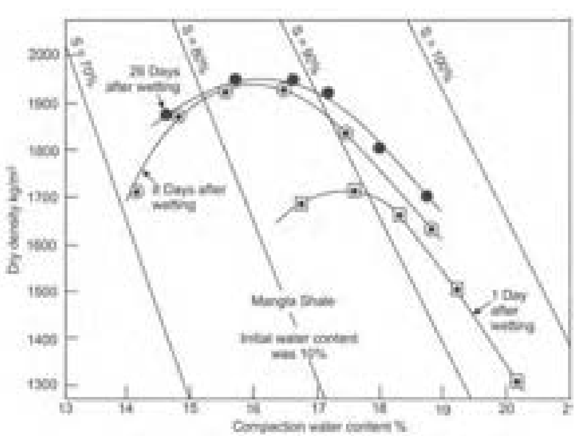

TABLE 4

MINIMUM CURING TIME

Plasticity	Condition of prepared sample	
	Within 2% of OMC	Greater than 2% from OMC
Sands and granular material*	2 h	2 h
Low (LL ≤35%)	24 h	48 h
Medium (35% < LL ≤50%)	48 h	96 h (4 days)
High (LL > 50%)	96 h (4 days)	168 h (7 days)

* These can include naturally occurring sands and gravels, crushed rocks and manufactured materials with fines content typically less than 12%.

LEGEND:
LL = liquid limit
OMC = optimum moisture content

Australian Standard

Methods of testing soils for engineering purposes
Method 5.1.1: Soil compaction and density tests—Determination of the dry density/moisture content relation of a soil using standard compactive effort

Blight, 2013

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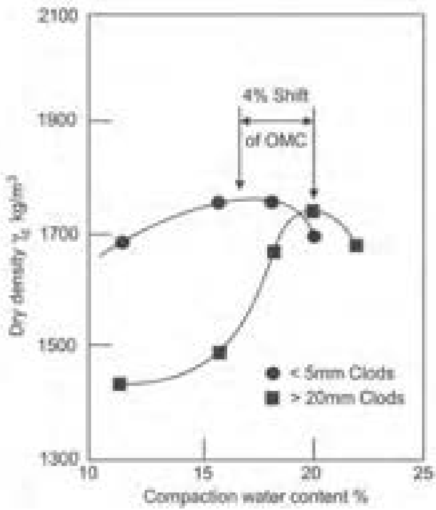
Sampling preparation – Clod sizes



5 SAMPLE PREPARATION PROCEDURE

5.1 Preliminary preparation of soil

Reduce the size of soil clods as received by chopping, grating or crumbling until aggregations of soil pass a 10 mm screen, taking care not to crush individual particles. Recombine all particles retained on the 10 mm screen with the soil fraction and mix thoroughly.

NOTE: If the material is too wet to permit preliminary preparation, it should be air-dried or placed in an oven operating at a temperature not exceeding 50°C, until it is just dry enough to permit crumbling of the soil aggregation to enable sieving through the 10 mm screen.

Australian Standard

Methods of testing soils for engineering purposes

Method 1.1: Sampling and preparation of soils—Preparation of disturbed soil samples for testing

Blight, 2013

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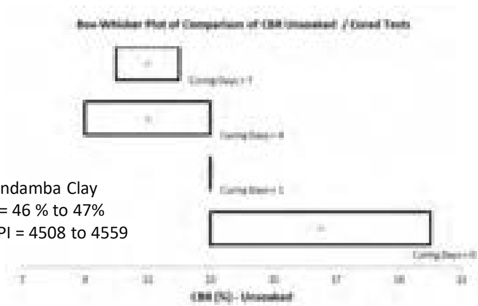
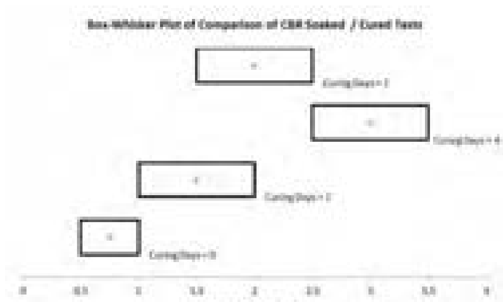
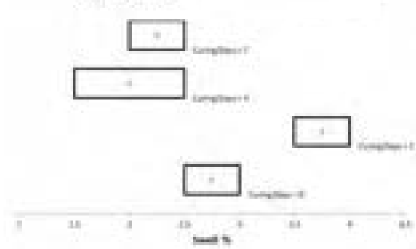
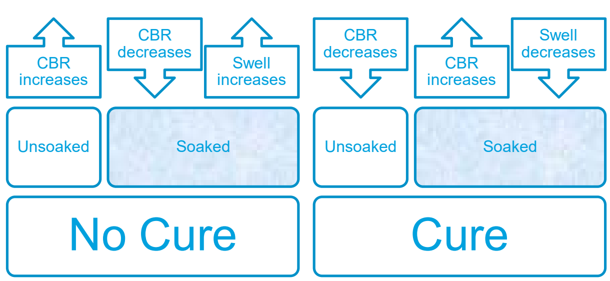
Unsoaked + CBR – Effect of curing



Bundamba Clay
PI = 46 % to 47%
WPI = 4508 to 4559







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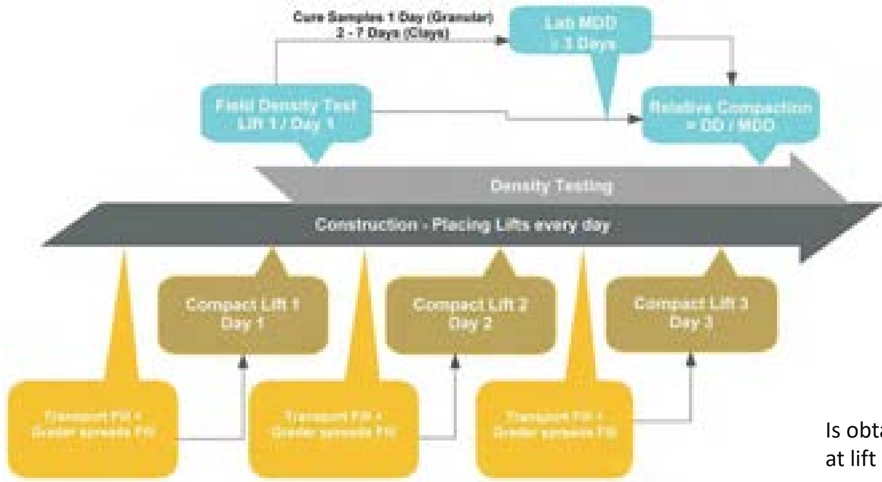
Density Ratio compaction tests are lag indicators



Is obtaining density results at lift 2 or 3 QA or QC ?

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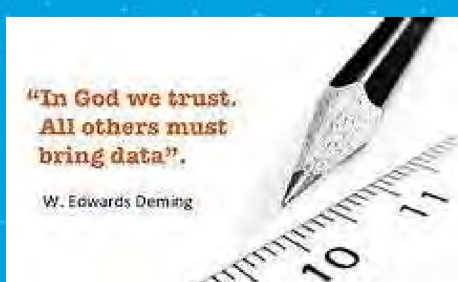

What does Quality look like ?

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Quality Control (QC) vs Quality Assurance (QA)

QA is *process* oriented (**verification**) vs QC is *product* oriented (**validation**).

QA aims to prevent defects. QC aims to identify and fix defects

- Quality **Assurance** makes sure you are doing the right things, the right way
- Quality **Control** makes sure the results of what you've done are what you expected.

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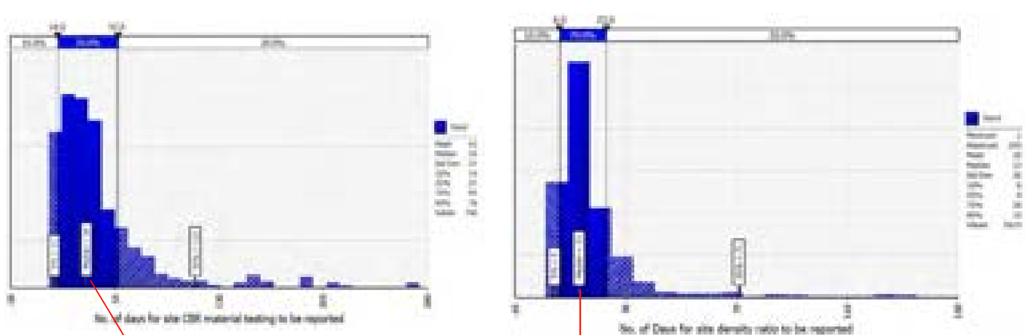
Construction records – Quality tests reporting



Material Quality
- CBR
- Atterberg
- Gradings

\+

Compaction
- Field Density
- Lab MD
- Density Ratio

\+

Underlying Material
- Depth
- Quality
- Compaction

→

Quality
- No of samples
- Variability
- LCV

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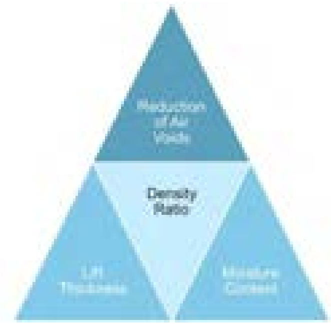
Density Ratio tests – Objectives + Process



Many contractors, often place additional lifts before the test results are known / reported.

This has a risk, but is based on the assumption that they have achieved compaction and the tests are simply validating (QC) what they already known based on

- ✓ No. of passes
- ✓ Lift Thickness
- ✓ Moisture Content

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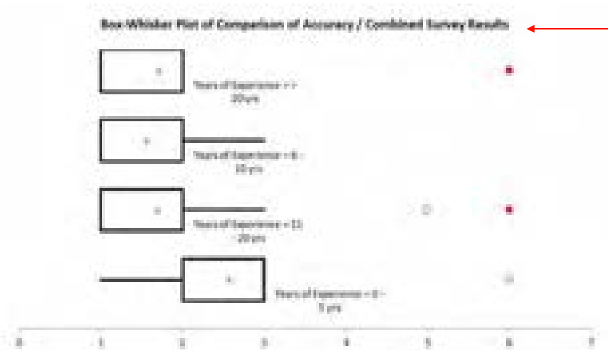
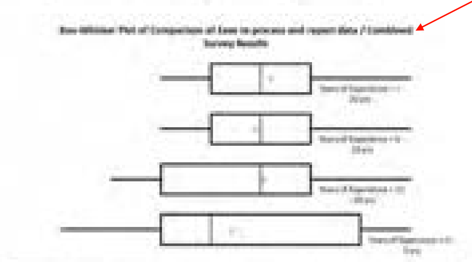
What do Engineers want





1. Accuracy
2. Precision
3. Time to conduct test
4. Ease of use
5. Time to process results
6. Ease to process and report
7. Amount of data obtained
8. Capital cost of equipment

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Preference Ranking based on years of experience

Rank	0 - 5 yrs	6 - 10 yrs	11 - 20 yrs	> 20 yrs
No in Sample	7	9	23	15
1. Accuracy	No. 2 / 3	No. 1 / 2	No. 1 / 2	Narrow Band No. 1 / 2
2. Precision	No. 3	Wide Band No. 3	Wide Band No. 3 / 4 / 5	Narrow Band No. 2
3. Time to conduct test	Wide Band No. 4 / 5	Wide Band No. 5	Wide Band No. 3 / 4	Wide Band No. 4 / 5 / 6
4. Ease of use	Wide Band No. 4	Wide Band No. 5	Wide Band No.5	Wide Band No. 4
5. Time to process results	Wide Band No. 4 / 5	Wide Band No. 4 / 5	Wide Band No. 3 / 4	Wide Band No. 5
6. Ease to process and report	Wide Band No. 4	No. 5	No. 5	No.5
7. Amount of data obtained	Narrow band No. 7	Wide Band No. 6	Wide Band No. 5	Wide Band No. 5
8. Capital cost of equipment	No. 7	Wide Band No. 6 /7	Wide Band No. 5 / 7	Narrow band No. 7

A survey of 54 engineers ranked what attributes are desirable in a test equipment

Attributes were ranked

1. Accuracy

Accuracy refers to closeness of the measurements to a "true" value, while precision refers to the closeness of the measurements to each other (repeatability).

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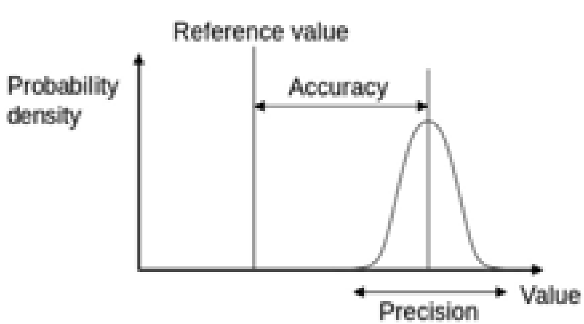
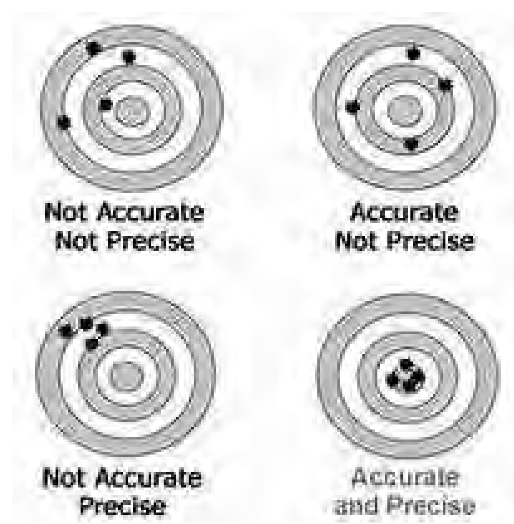
Accuracy vs Precision





https://en.wikipedia.org/wiki/Accuracy_and_precision

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Comparison of Test Equipment

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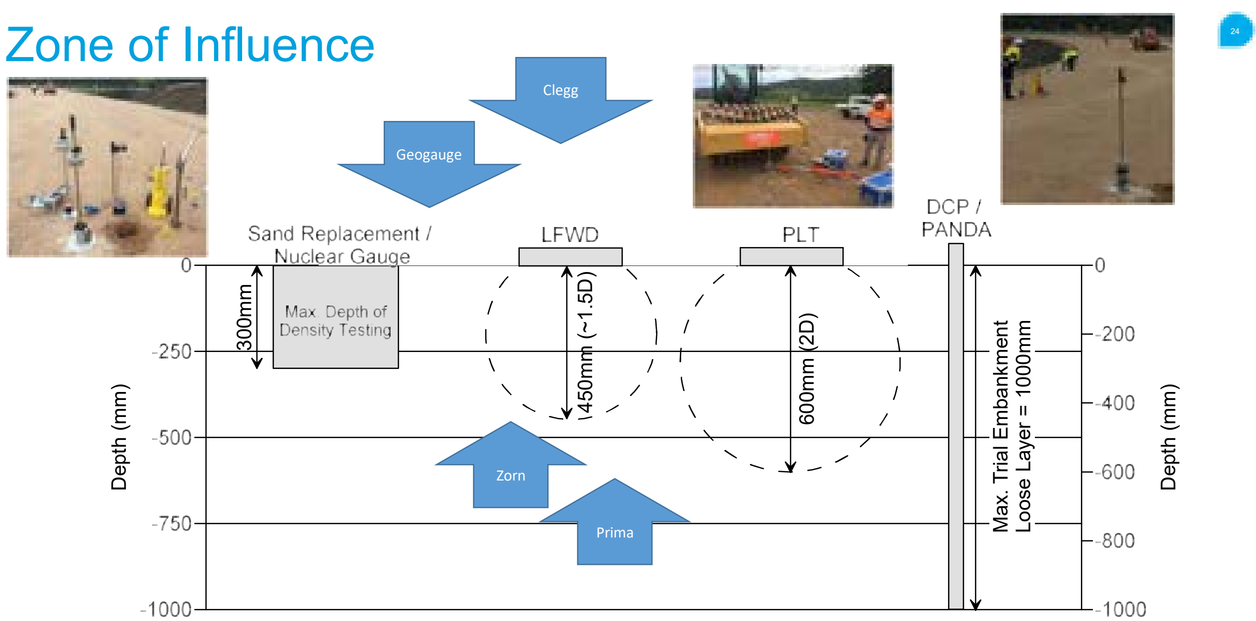
Zone of Influence



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Testing

Clegg Hammer

LFWD - Blue Tooth Connectivity

Plate Load Test

25

Intelligent Compaction - Testing with roller

CMV – Compaction Meter Value

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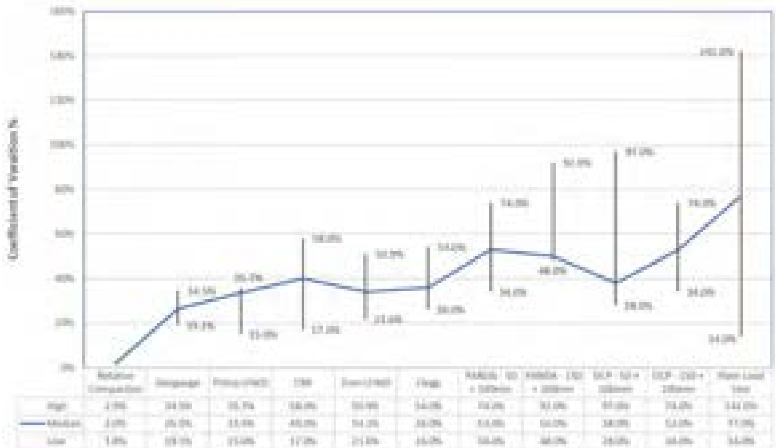
Equipment Precision



High precision
- Relative Compaction
- (Density)

Medium
- Geogauge
- PRIMA LFWD
- CBR
- Zorn LFWD / Clegg

Medium – High (Penetration Tests)
- PANDA 50 - 100mm_
- PANDA 150 – 200mm
- DCP – 50 – 100mm
- DCP – 150 – 200mm

Low Precision
- Plate Load Test

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Equipment matches to other tests (5 sites)

Accuracy	PLT	Density	Geogauge	LFWD - ZORN	LFWD - PRIMA	Clegg	PANDA - 100mm	PANDA - 200mm	DCP 100mm	DCP 200mm	CBR	Moisture Ratio
PLT		1	0	0	3	3	4	2	0	5	3	1
Density	1		0	1	1	1	1	2	0	4	1	1
Geogauge	0	0		3	5	0	0	0	2	0	0	1
LFWD - ZORN	0	1	3		3	0	0	1	2	0	0	1
LFWD - PRIMA	3	1	5	3		0	0	0	2	1	0	1
Clegg	3	1	0	0	0		3	3	2	0	3	0
PANDA -50/100mm	4	1	0	0	0	3		3	0	2	5	1
PANDA -150/200mm	2	2	0	1	0	3	3		1	1	3	1
DCP 50/100mm	0	0	2	2	2	2	0	1		0	0	0
DCP 150/200mm	5	4	0	0	1	0	2	1	0		1	1
CBR	3	1	0	0	0	3	5	3	0	1		1
Moisture Ratio	1	1	1	1	1	0	1	1	0	1	1	
No. of Matches	22	13	11	11	16	15	19	17	9	15	17	9
Rank ito cross matching	1	8	9	9	5	6	2	3	11	6	3	11

- High
- Median
- Low

Sites compared for 5 sites tested

No. of matches used as an indicator of accuracy

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Summary of some field test equipment attributes

Accuracy	Amount of Data / Capital Cost	Precision	Time
1. PLT	1. Plate Load $$$$$	1. Sand Replacement	1. LFWD – Zorn - T
2. PANDA	2. LFWD – Prima $$$$	2. Nuclear Density	2. Geogauge – 1.3 T
3. LFWD - Prima	3. Clegg Hammer $$$	3. Geogauge	3. Panda – 1.4 T
4. Clegg Hammer	4. Panda $$$$$	4. LFWD – Prima	4. DCP - 1.8T
5. DCP: 100 – 200mm	5. LFWD – Zorn $$$$	5. LFWD – Zorn	5. Clegg Hammer – 2.3T
6. Density Ratio	6. Geogauge $$$	6. Clegg Hammer	6. LFWD – Prima* - 2.6T
7. LFWD – Zorn	7. DCP $	7. PANDA	7. Nuclear Density ↑ - 6T
8. Geogauge	8. Sand Replacement $$	8. DCP / 100 – 200mm	8. Plate Load* Test – 6T
9. DCP: 0 -100mm	9. Nuclear Density $$	9. DCP / 0 – 100mm	9. Sand Replacement ↑- 10T
		10. PLT	

* Complete Stress Strain response provided – not provided by other equipment
↑ Larger Reporting time. Moisture or air voids may be determined

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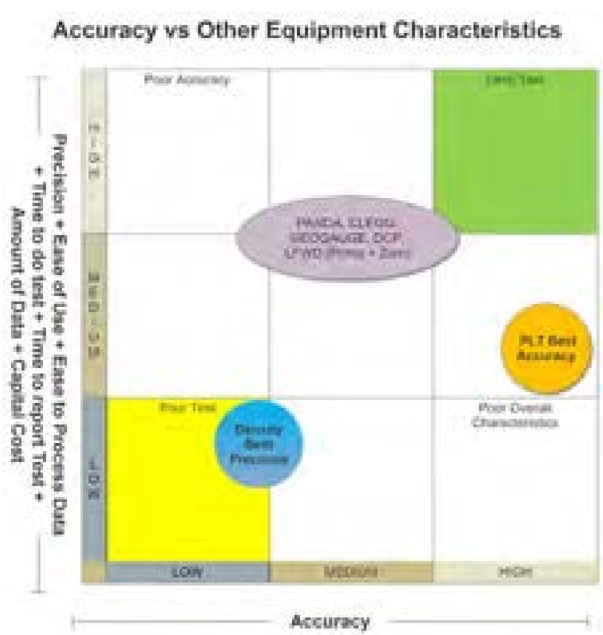
What industry wants and equipment position



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Alternative Equipment / Testing

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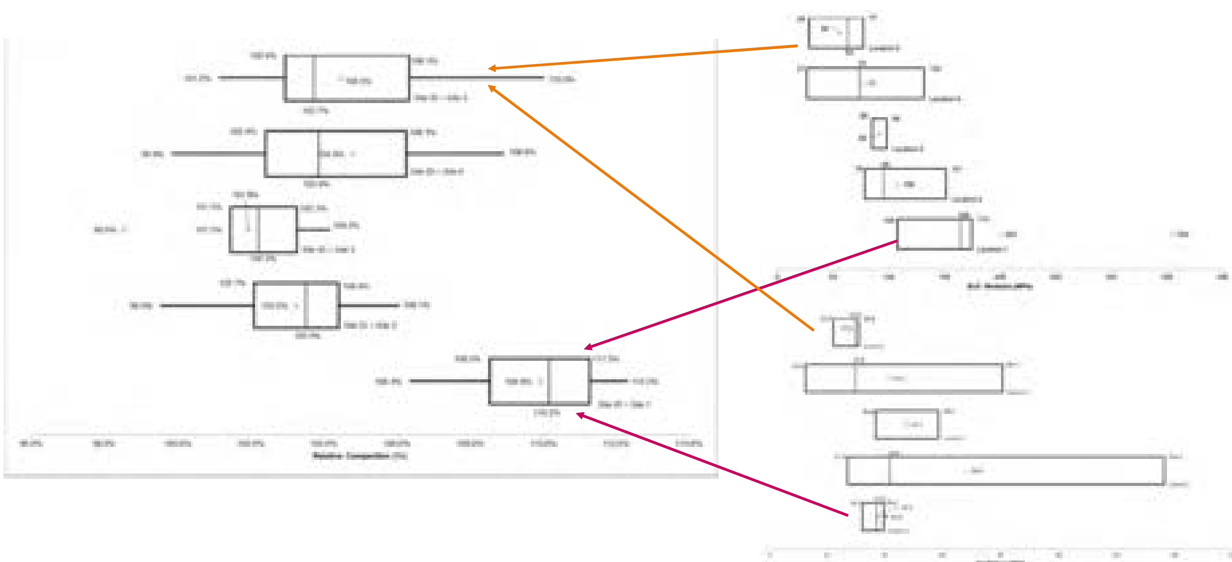
Tests results – 5 sites



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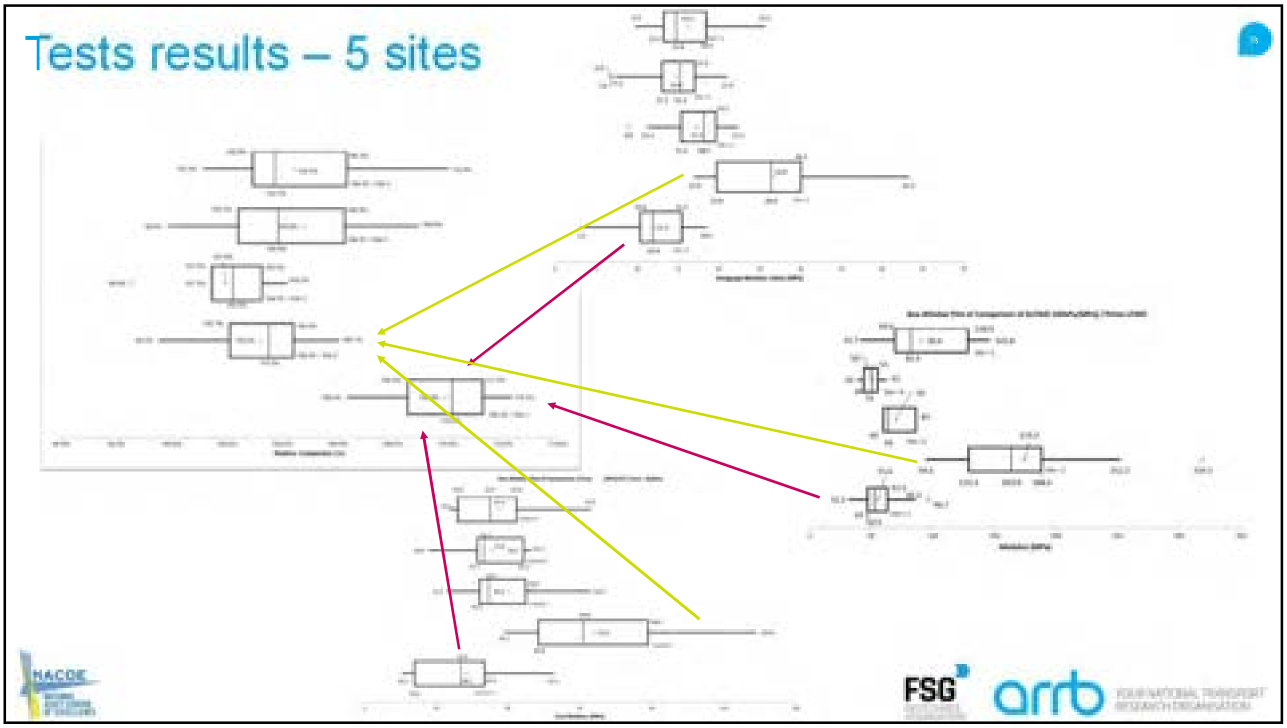
Tests results – 5 sites
NACOE
FSG
arrb

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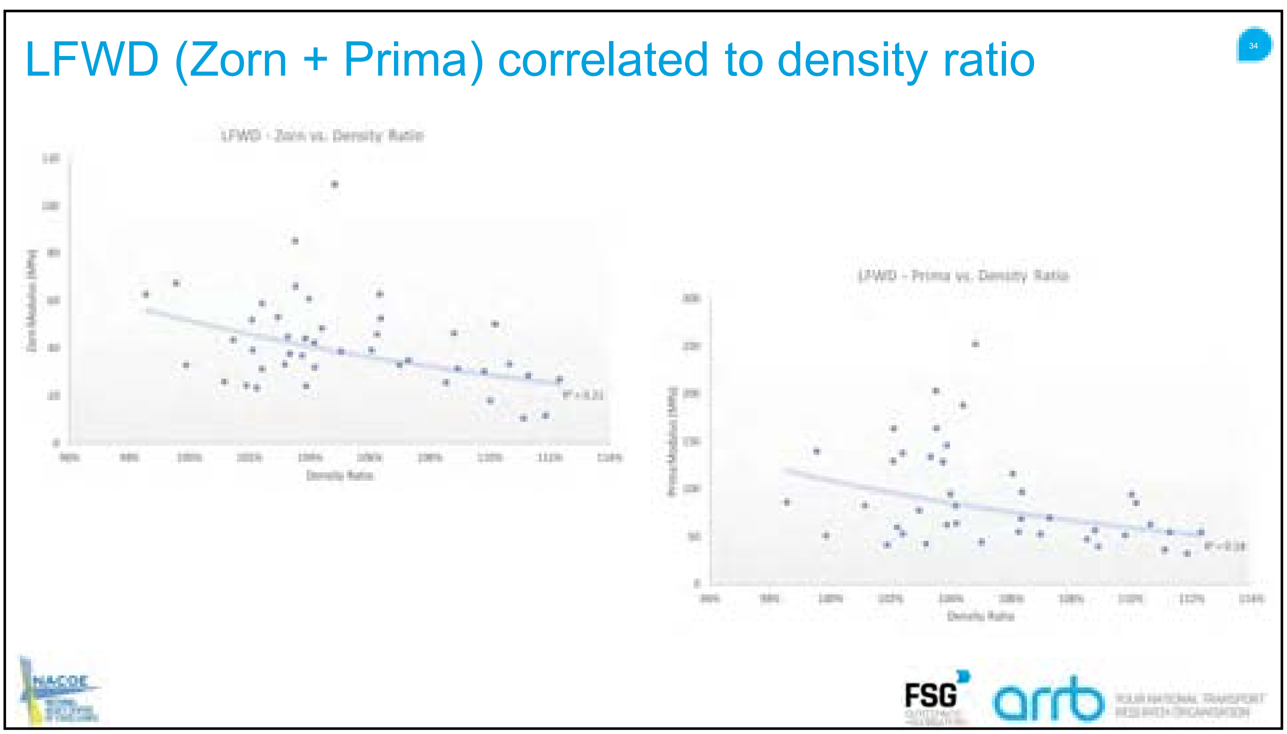
LFWD (Zorn + Prima) correlated to density ratio
LFWD - Zorn vs. Density Ratio
Density Ratio
LFWD - Prima vs. Density Ratio
Density Ratio
NACOE
FSG
arrb

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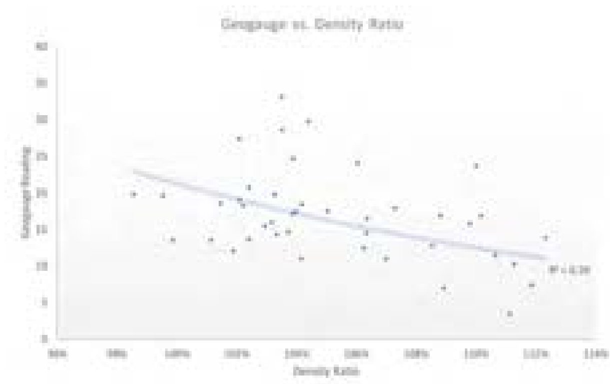
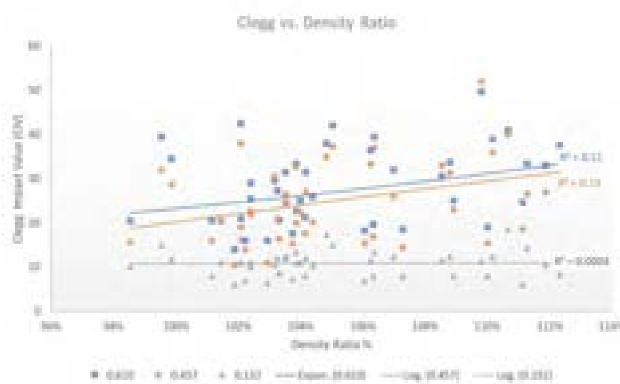
Geogauge and Clegg correlated to density ratio





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Paired Correlations

Some base assumptions made

- As density ratio increases the CBR, modulus, or strength increases
- A suitable trend line would be apparent - may not necessarily be linear
- Relative Compaction (Density ratio) as the well-established measurement would be correct (accurate)

Density Ratio compared with modulus measured with 2 different LFWD (ZORN + PRIMA) + CLEGG + GEOGAUGE

- Low correlation ($R^2 \sim 0.2$) shows such relationships should not be used
- More importantly as density ratio increased, all alternate tests decreased. Suggests that as compacted density increases to high values the modulus decreases. This is counter intuitive.
- Results for this data show common assumption that ↑ DR→ ↑ modulus may be incorrect.

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QUESTIONS?

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Measurement
Shift
CLOSE ENOUGH
http://favoritememes.com/news/close_enough/2014-07-27-342
Alternative
Equipment / Testing

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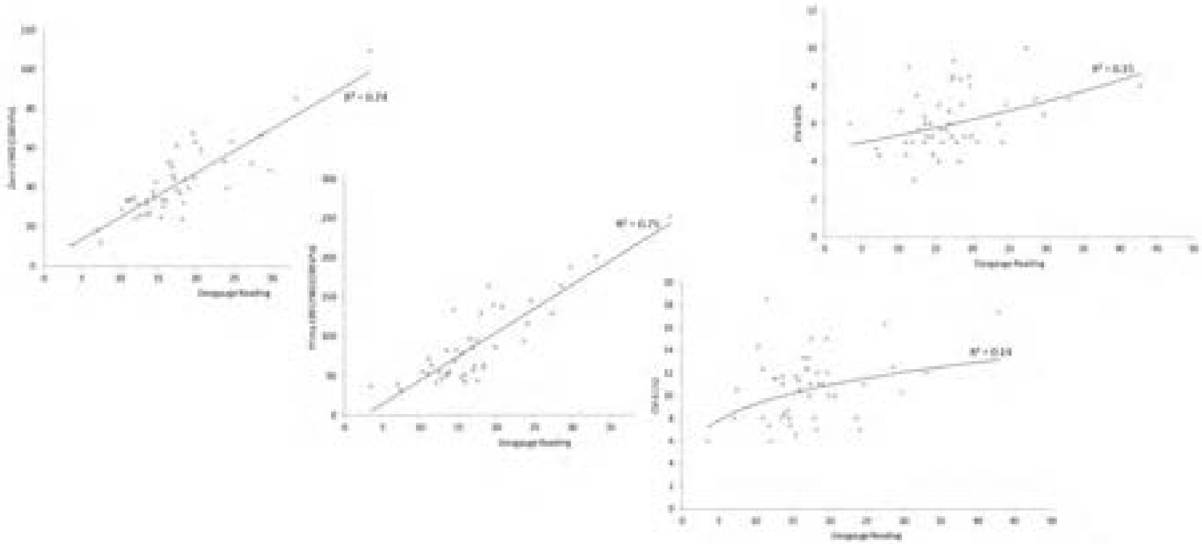
But Alternate Tests correlate to each other



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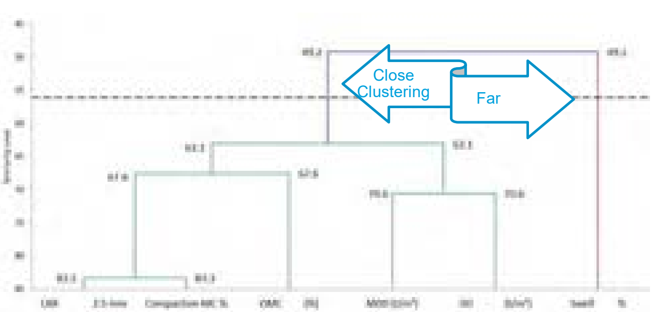
Dendogram Analysis

- In statistics, hierarchical clustering builds cluster trees (Dendograms) to represent clustered data.
- The groups of data are nested and organized as a tree with each group in liking to other successor groups. StatTools (version 7) is an add-in to Microsoft Excel and was used for the cluster analysis.
- The Cluster Analysis command searches for patterns in a data set in order to classify observations or variables into groups of similar items. The analysis supports a variety of agglomerative hierarchical methods and distance measures. The *clade* is a branch in the tree. Clades that are close to the same height are similar to each other and clades with different heights are dissimilar. Greater distance in height the more dissimilarity



- Dendogram for Cooroy (CH) clay Soaked CBR.
- Clustering provides visual evidence that CBR is more closely clustered to compaction moisture and the OMC rather than the density.

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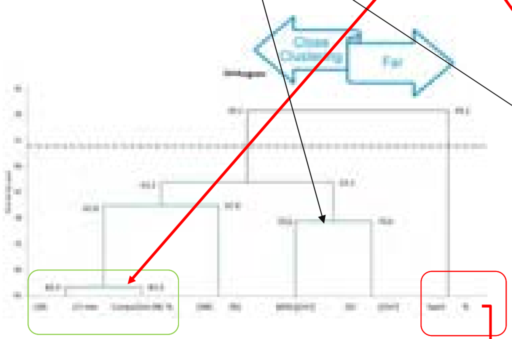
Dendogram vs correlation matrix (6 variables)

- CBR most strongly correlated with compaction MC (0.691)
- Least with the MDD (-0.04)
- CBR negatively correlated with swell (-0.834).



Correlation Matrix	Comp MC %	DD (t/m³)	OMC (%)	MDD (t/m³)	CBR @ 2.5mm	Swell %
Comp. MC %	1.00					
DD (t/m³)	-0.30	1.00				
OMC (%)	0.23	-0.38	1.00			
MDD (t/m³)	-0.04	0.46	-0.34	1.00		
CBR @2.5 mm	0.69	0.04	0.40	0.32	1.00	
Swell %	-0.85	0.06	-0.14	-0.38	-0.83	1.00

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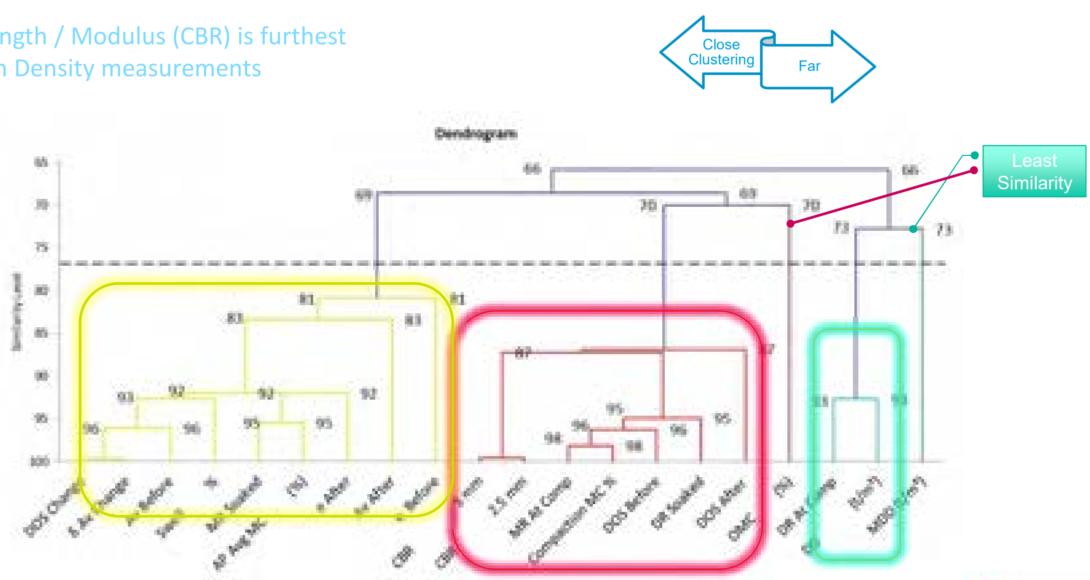
Dendogram of 20 variables in a soaked CBR test

Strength / Modulus (CBR) is furthest from Density measurements



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Correlation Matrix Soaked CBR

Correlation	Compaction MC %	DD (t/m³)	OMC (%)	MDD (t/m³)	OVMC (%)	CBR 2.5 mm	CBR 5 mm	Swell %	Avg MC after soak	DD (t/m³) after soak	MC Top Layer (%) AP	Avg MC (%) AP	δ GMC (%)
Compaction MC %	1.00												
DD (t/m³)	-0.84	1.00											
OMC (%)	0.84	-0.89	1.00										
MDD (t/m³)	-0.88	0.97	-0.92	1.00									
OVMC (%)	0.82	-0.84	0.98	-0.86	1.00								
CBR 2.5 mm	-0.47	0.61	-0.49	0.59	-0.47	1.00							
CBR 5 mm	-0.56	0.66	-0.49	0.66	-0.46	0.90	1.00						
Swell %	0.41	-0.62	0.57	-0.64	0.55	-0.79	-0.75	1.00					
Avg MC after soak	0.43	-0.84	0.72	-0.82	0.62	-0.61	-0.65	0.66	1.00				
DD (t/m³) after soak	0.39	0.20	-0.04	0.22	0.13	0.53	0.52	-0.58	-0.68	1.00			
MC Top Layer (%) AP	0.33	-0.71	0.61	-0.74	0.49	-0.71	-0.76	0.79	0.94	-0.76	1.00		
Avg MC (%) AP	0.55	-0.89	0.78	-0.87	0.71	-0.64	-0.69	0.71	1.00	-0.67	0.94	1.00	
δ GMC (%)	-0.24	-0.23	0.16	-0.28	0.11	-0.84	-0.86	0.89	0.58	-0.60	0.70	0.56	1.00
δ DD (t/m³)	-0.77	0.45	-0.45	0.32	-0.50	-0.60	-0.60	0.74	0.22	-0.73	0.48	0.21	0.78
VMC at Comp.	0.96	-0.72	0.75	-0.76	0.73	-0.39	-0.49	0.29	0.31	0.45	0.21	0.41	-0.35
VMC after soak	0.18	-0.71	0.46	-0.63	0.24	-0.29	-0.26	0.18	0.85	-0.25	0.64	0.86	0.17
δ VMC	-0.85	0.13	-0.21	0.07	-0.30	-0.91	-0.89	0.85	0.49	-0.51	0.64	0.47	0.97
MR at comp	0.42	-0.05	-0.07	-0.06	-0.10	0.03	-0.08	-0.34	-0.27	0.48	-0.33	-0.21	-0.64
MR soaked	-0.02	-0.19	-0.11	-0.11	-0.18	-0.76	-0.73	0.68	0.50	-0.53	0.57	0.47	0.66
DR at Comp	0.01	0.27	-0.04	0.05	-0.06	0.18	0.11	-0.05	-0.29	0.14	-0.13	-0.33	0.05
Dr soaked	0.64	-0.17	0.36	-0.28	0.39	0.56	0.55	-0.59	-0.36	0.85	-0.53	-0.35	-0.66
VMC at comp	0.40	-0.01	-0.07	-0.05	-0.10	0.01	-0.10	-0.30	-0.29	0.46	-0.34	-0.23	-0.63
VMR soaked	-0.29	0.01	-0.47	0.13	-0.65	-0.51	-0.47	0.44	0.49	-0.24	0.52	0.50	0.44
Gs assumed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gs Interpreted	-0.03	0.13	0.07	0.12	0.16	0.03	0.11	0.03	0.55	0.14	0.47	0.64	0.14
e before	0.74	-1.00	0.89	-0.92	0.83	-0.38	-0.45	0.45	0.84	-0.20	0.71	0.87	0.23
e after	-0.39	-0.20	0.04	-0.22	-0.13	-0.53	-0.52	0.58	0.68	-1.00	0.76	0.67	0.60
Av before	-0.69	0.16	-0.22	0.15	-0.24	-0.55	-0.52	0.50	0.16	-0.52	0.27	0.11	0.76
Av after	-0.59	0.37	-0.36	0.37	-0.30	-0.31	-0.33	0.43	-0.12	-0.58	0.10	-0.13	0.44
δ Av	-0.62	-0.15	0.01	-0.10	-0.07	-0.81	-0.78	0.62	0.57	-0.35	0.58	0.56	0.78
n before	0.74	-1.00	0.89	-0.92	0.83	-0.38	-0.45	0.45	0.84	-0.20	0.71	0.87	0.23
n after	-0.39	-0.20	0.04	-0.22	-0.13	-0.53	-0.52	0.58	0.68	-1.00	0.76	0.67	0.60
δ n	-0.77	0.45	-0.45	0.33	-0.50	-0.60	-0.60	0.74	0.22	-0.72	0.48	0.21	0.78
DOS before	0.79	-0.27	0.33	-0.27	0.35	0.45	0.41	-0.39	-0.04	0.51	-0.16	0.00	-0.68
DOS after	0.58	-0.40	0.37	-0.40	0.30	0.28	0.30	-0.39	0.16	0.55	-0.06	0.18	-0.42
δ DOS	-0.68	-0.08	-0.04	-0.04	-0.12	-0.84	-0.81	0.66	0.54	-0.36	0.58	0.53	0.82

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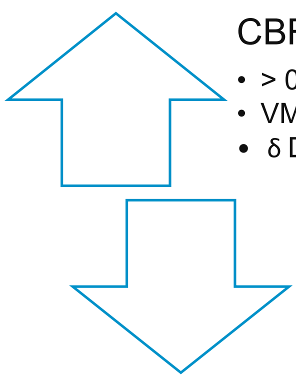
Correlation Matrix Soaked CBR



CBR ~ Modulus

- > 0.80
- VMC / GMC
- δ DOS / δ Air Voids

DR 0.18 / 0.11

MR 0.03 / -0.08

From 36 variables in a CBR test
Construction focuses on DR and MR
which are poorly correlated to CBR (Modulus)

		CBR 2.5 mm	CBR 5 mm
1	CBR 5 mm	0.898	1.000
2	CBR 2.5 mm	1.000	0.898
3	δ VMC	-0.912	-0.889
4	δ GMC (%)	-0.843	-0.858
5	δ DOS	-0.838	-0.810
6	δ Av	-0.814	-0.783
7	MC Top Layer (%) AP	-0.706	-0.759
8	Swell %	-0.787	-0.754
9	MR soaked	-0.762	-0.728
10	Avg MC (%) AP	-0.637	-0.688
11	MDD (t/m³)	0.589	0.662
12	DD (t/m³)	0.606	0.661
13	Avg MC after soak	-0.608	-0.652
14	δ n	-0.602	-0.604
15	δ DD (t/m³)	-0.602	-0.604
16	Compaction MC %	-0.471	-0.564
17	Dr soaked	0.558	0.552
18	DD (t/m³) after soak	0.529	0.520
19	n after	-0.529	-0.520
20	e after	-0.529	-0.520
21	Av before	-0.548	-0.517
22	VMC at Comp.	-0.391	-0.488
23	OMC (%)	-0.488	-0.488
24	VMR soaked	-0.511	-0.471
25	OVMC (%)	-0.465	-0.460
26	n before	-0.382	-0.449
27	e before	-0.382	-0.449
28	DOS before	0.446	0.408
29	Av after	-0.309	-0.326
30	DOS after	0.280	0.298
31	VMC after soak	-0.286	-0.256
32	DR at Comp	0.185	0.111
33	Gs Interpreted	0.026	0.109
34	VMC at comp	0.009	-0.099
35	MR at comp	0.026	-0.081
36	Gs assumed	0.000	0.000

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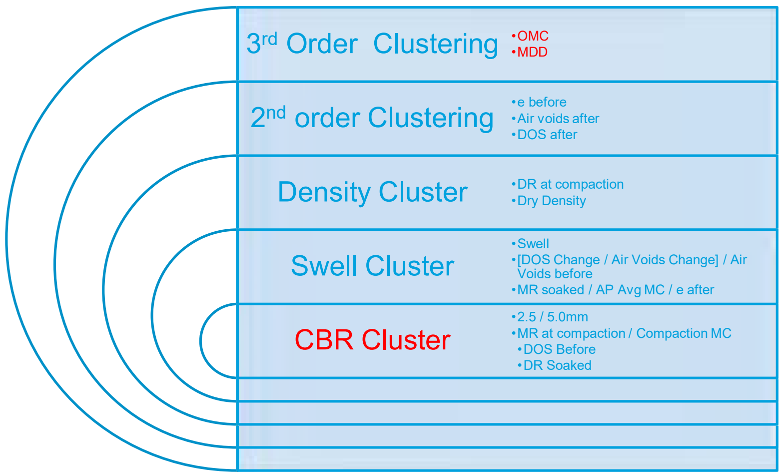
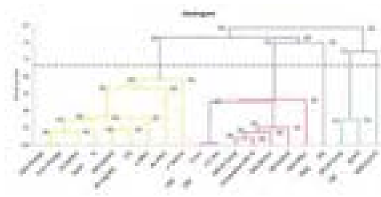
Dendogram Clusters (20 variables)





Measuring Density may not be indicative of strength / modulus

Not clustered

CBR related mainly to MC and MR at compaction

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Comparison of Density vs alternative testing

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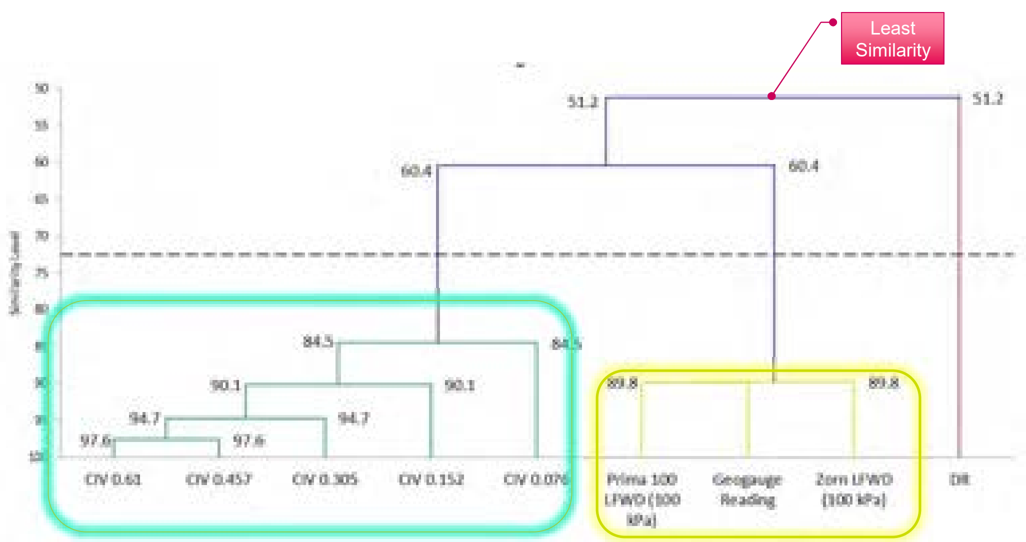
Alternate Testing Dendograms



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Density Ratio is least correlated to the other 4

Correlation	DR	Geogauge Reading	Zorn LFWD (100 kPa)	Prima LFWD (100 kPa)	CIV 0.076	CIV 0.152	CIV 0.305	CIV 0.457	CIV 0.61
DR	1.00								
Geogauge Reading	-0.32	1.00							
Zorn LFWD (100 kPa)	-0.23	0.79	1.00						
Prima 100 LFWD (100 kPa)	-0.30	0.77	0.81	1.00					
CIV 0.076	0.03	0.39	0.51	0.30	1.00				
CIV 0.152	0.10	0.24	0.40	0.17	0.79	1.00			
CIV 0.305	0.28	-0.02	0.13	-0.11	0.65	0.89	1.00		
CIV 0.457	0.35	-0.01	0.10	-0.13	0.62	0.83	0.94	1.00	
CIV 0.61	0.31	-0.06	0.10	-0.11	0.62	0.83	0.93	0.95	1.00

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Is
Density Ratio
the end game ?

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Method vs Performance specifications

Prescriptive specifications are recipes:

- ✓ Do all these things
- ✓ We will accept the results as well compacted
- ✓ Used successfully on many projects and many countries
- ✓ Not entirely certain exactly what you have – non quantitative assessment

Performance specifications are not complete recipes – although some ingredients are specified

- ✓ Does not tell the contractor how to do the work
- ✓ Tells the contractor what we want.
- ✓ Contractor's decision to provide appropriate equipment to meet performance objectives
- ✓ Density ratio is the measure of performance – quantitative assessment

Table 15.3-A – Layer thickness for compaction

Material / Location	Loose Layer Thickness (mm)	
	Minimum	Maximum
Earth fill material in road embankment or subgrade treatments	150	300
Fill material in water retaining embankments	150	200
Backfill – except sand	100	100
Backfill – sand	150	300

QTM R
MRTS04 Example

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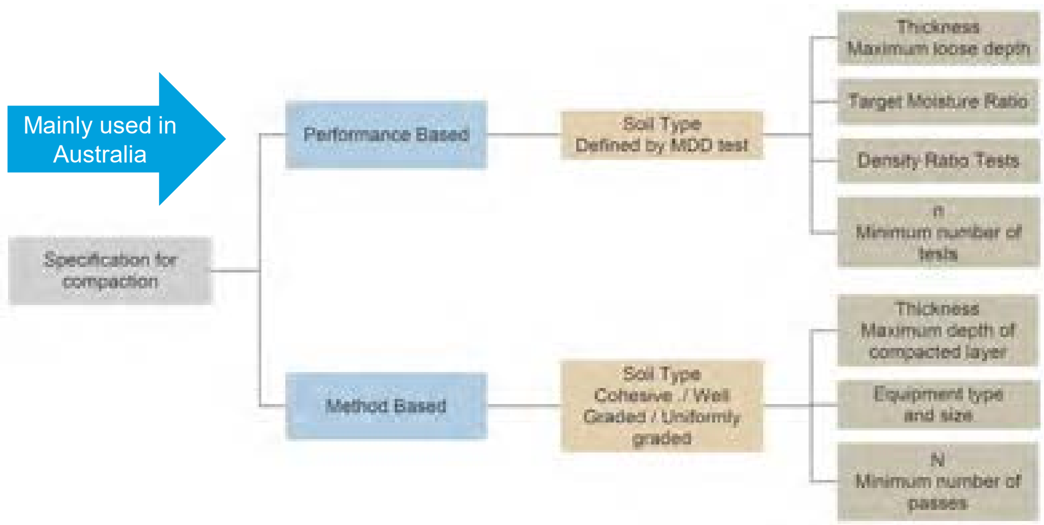
Performance based mainly used in Australia



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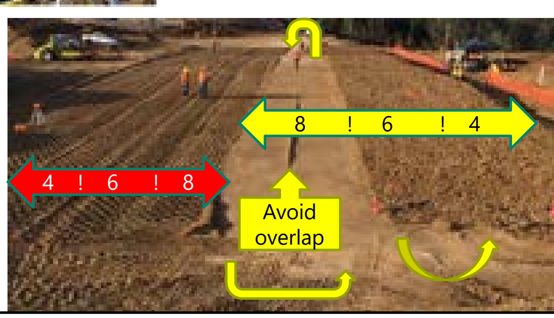
Performance based uncertainty

Performance based specification used as it has more certainty – Does it?

Pad Foot + Smooth Drum vibrating rollers



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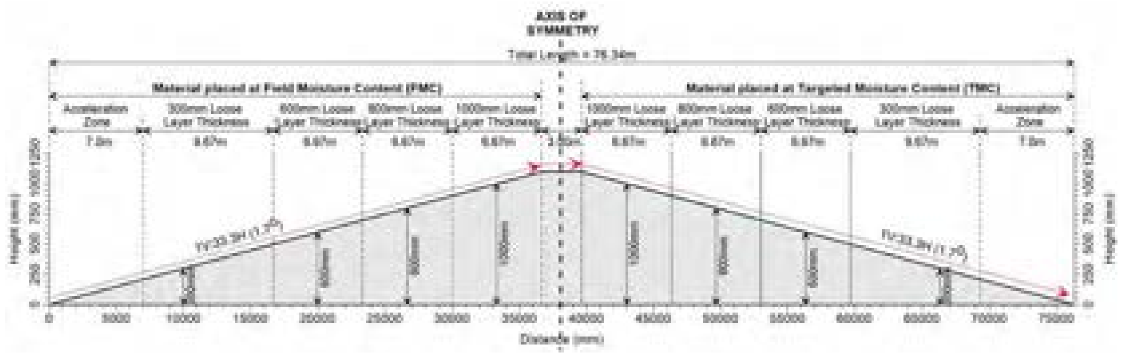
Trial Embankment Layout Elevation



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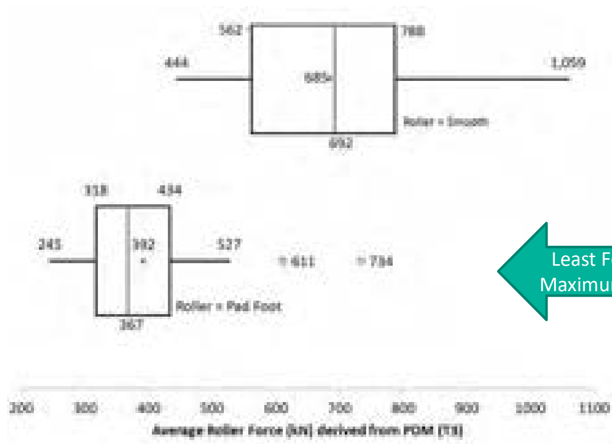
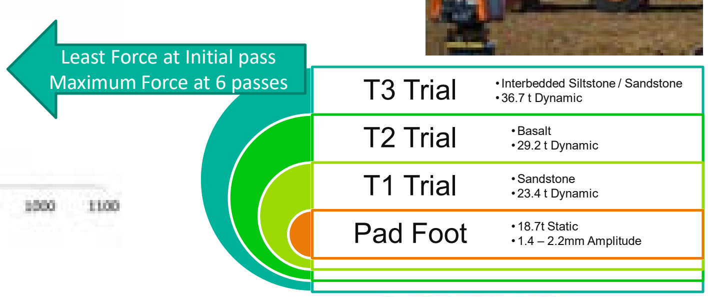
Dynamic Monitoring - Force

Dynamic Force
Smooth = 1.8 X Pad Foot for interbedded
Smooth = 0.9 x Pad Foot for sandstone





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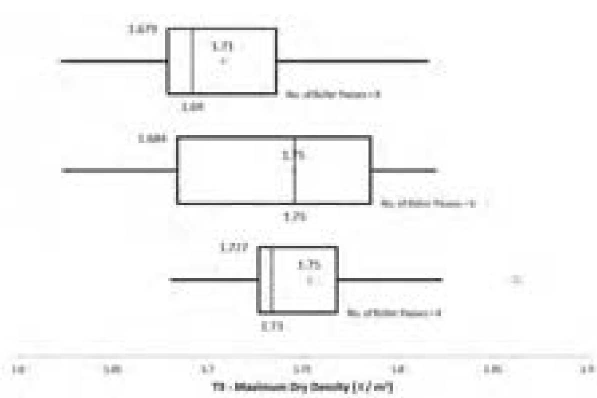
Maximum Dry Density – T3 interbedded Siltstone / Sandstone



At 8 passes MDD Decreases (T3 – Sandstone)

This suggest loss of strength at higher compaction passes but more "passing" results (a 3% benefit in this example)

We think we are increasing the Field Density

We may be decreasing MDD with higher number of passes

$$Density\ Ratio = \frac{Field\ Density}{Max\ Dry\ Density}$$

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In situ E correlated to 95% Density ratio

Fill Material Origin	Plate Load Test (PLT) E_{V2} (MPa)	Light Falling Weight Deflectometer (LFWD) $E_{LFWD-100kPa}$ (MPa)
Sandstone: **70% Gravel size; 10% fines**	60	45
Interbedded Siltstone / Sandstone **70% Gravel size; 11% fines**	35	25
Basalt **65% Gravel size; 12% fines**	50	30

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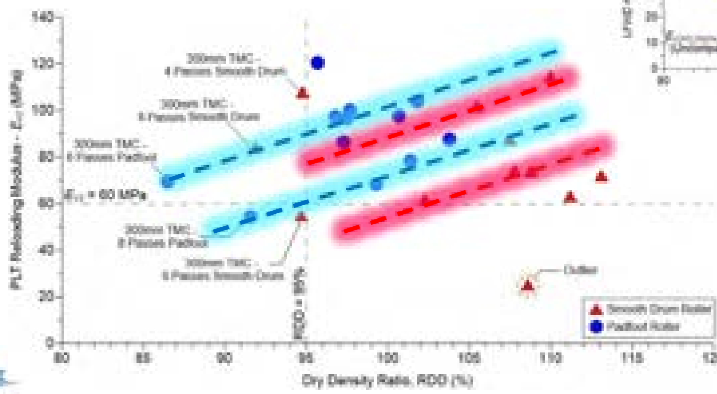
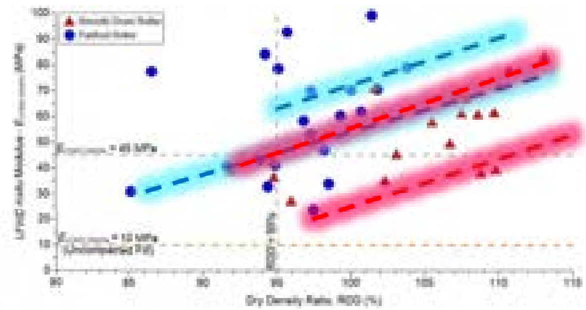
Modulus correlated to DR for sandstone material





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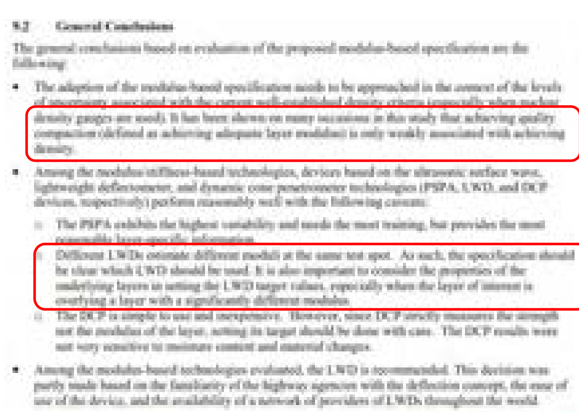
These findings are not unique


Geo-Congress 2014 Technical Papers, GSP 234 © ASCE 2014 2340

A Comparison of Density-Based and Modulus-Based In Situ Tests for Earthwork Quality Control

Firas S. Tehrani, S.M.ASCE, Christopher L. Meehan, M.ASCE, and Farshid Vahedifard, M.ASCE


9.2 General Conclusions

The general conclusions based on evaluation of the proposed modulus-based specification are the following:

- The adoption of the modulus-based specification needs to be approached in the context of the levels of uncertainty associated with the current well-established density criteria (especially when nuclear density gauges are used). It has been shown on many occasions in this study that achieving quality compaction (defined as achieving adequate layer modulus) is only weakly associated with achieving density.
- Among the modulus/stiffness-based technologies, devices based on the ultrasonic surface wave, lightweight deflectometer, and dynamic cone penetrometer technologies (PSPA, LWD, and DCP devices, respectively) perform reasonably well with the following caveats:
  - The PSPA exhibits the highest variability and needs the most training, but provides the most repeatable layer-specific information.
  - Different LWDs estimate different moduli at the same test spot. As such, the specification should be clear which LWD should be used. It is also important to consider the properties of the underlying layers in setting the LWD target values, especially when the layer of interest is overlying a layer with a significantly different modulus.
  - The DCP is simple to use and inexpensive. However, since DCP strictly measures the strength not the modulus of the layer, setting its target should be done with care. The DCP results were not very sensitive to moisture content and material changes.
- Among the modulus-based technologies evaluated, the LWD is recommended. This decision was partly made based on the familiarity of the highway agencies with the deflection concept, the ease of use of the device, and the availability of a network of providers of LWDs throughout the world.


Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate

DRAFT FINAL REPORT

Prepared for
National Cooperative Highway Research Program
NCHRP Project 10-84

Transportation Research Board
of
The National Academies

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DR used to assess Strength or modulus

- ✓ DR is currently the basis to assess quality during construction
- ✓ Prior to this research we assumed higher density was also a higher strength or modulus
- ✓ We were wrong
- ✓ Correlating alternative testing to DR often results in a poor correlation
- ✓ Alternate testings generally correlate to each other
- ✓ These tests are combining DR + several other factors
- ✓ Modulus is more dependent on moisture rather than DR
- ✓ DR is a very precise test – but may not be accurate

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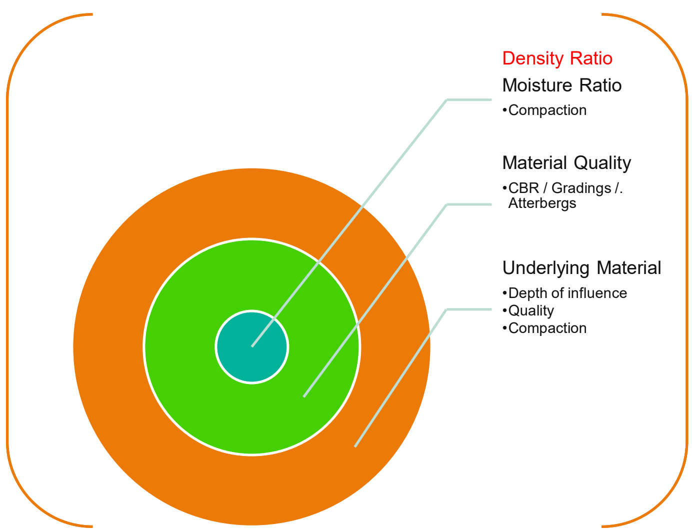
Multiple Targets measured: DR + Quality + Underlying interaction

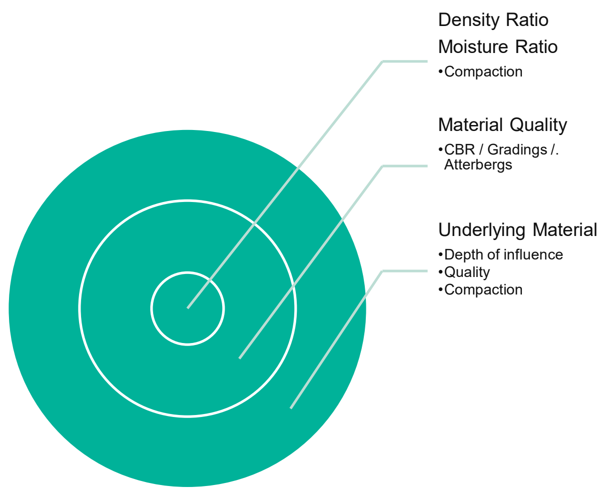


Alternate Tests are measuring more than 1 variable

Partly accounts for the low R^2

60

Alternate Tests measure – One Target



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Stay tuned for part 3

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Thank you for your participation today.

For further information on the topic, please contact:

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Dr Burt Look	blook@fsg-geotechnics.com.au

Website:
https://www.nacoe.com.au

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APPENDIX C WEBINAR ON 19 MARCH 2020

C.1 PRESENTATION SLIDES

Webinar: Part 3 – Procedures
Advanced Method for Compaction Quality Control

1

Rosemary Pattison

Webinar Moderator

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2

Housekeeping

Webinar 60 mins

Questions 5 mins

3

GoTo Webinar functions

4

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NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

P60: Best practice in compaction quality assurance for subgrade materials

ARRB Project Leader: Dr. Jeffrey Lee

TMR Project Manager: Siva Sivakumar

http://nacoe.com.au/

AN INITIATIVE BY arrb Queensland Government

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NACOE P60

Aim and Background of the Project

- Aim
  - To modernise testing procedure for compaction quality assurance
- Background
  - Quality is conventionally been verified using density measurements
  - Alternative methods have been developed over the past two decades
  - Many of these methods takes less time to do, results become available in a much shorter time frame, and is able to measure in situ stiffness.

NACOE FSG arrb

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Density Ratio
Moisture Ratio
- Compaction

Material Quality
- CBR / Gradings /. Atterbergs

Underlying Material
- Depth of influence
- Quality
- Compaction

Summary of Previous 2 Webinars + Basics

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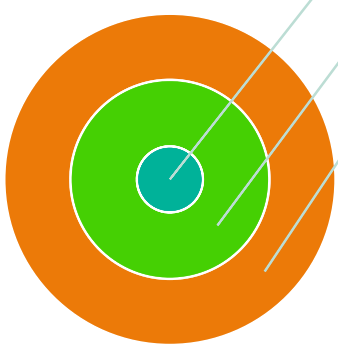
Multiple Targets measured: DR + Quality + Underlying interaction

Alternate Tests are measuring more than 1 variable

Partly accounts for the low R^2

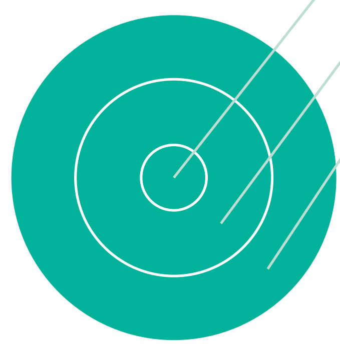


Density Ratio
Moisture Ratio
- Compaction

Material Quality
- CBR / Gradings /. Atterbergs

Underlying Material
- Depth of influence
- Quality
- Compaction

Alternate Tests measure – One Target



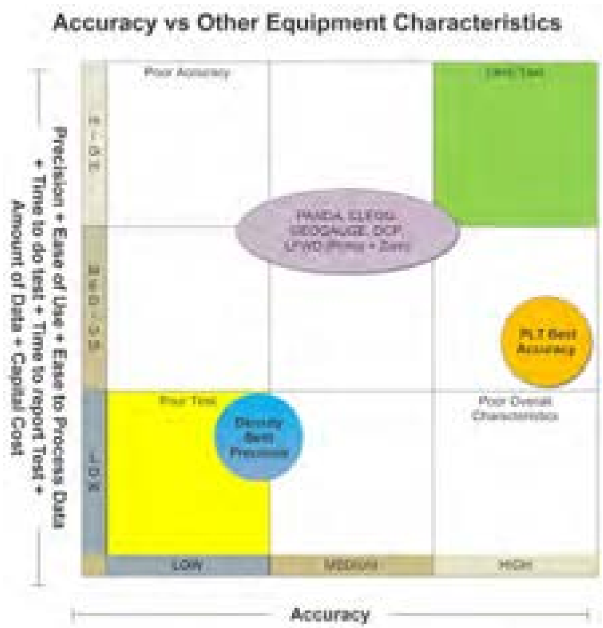
Density Ratio
Moisture Ratio
- Compaction

Material Quality
- CBR / Gradings /. Atterbergs

Underlying Material
- Depth of influence
- Quality
- Compaction

10

What industry wants and equipment position



11

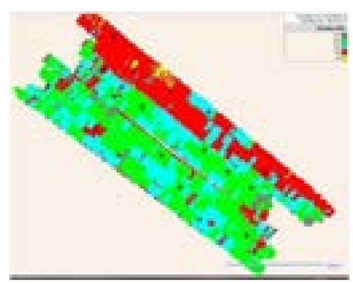
Intelligent Compaction implementation (FHWA 2011)

Univariate Correlations

Correlation of ICMV to NG dry unit density

Figure 96 presents the correlation results between ICMVs and the NG dry unit density r_d. The main conclusions are summarized as follows:

- ICMV increases with increasing r_d as expected, and overall a poorer correlation is achieved than that of E_{LWD}, E_{FWD}, and E_{V1} and E_{V2};
- Dependent on the specific test strip and materials, either the direct linear, or the logarithmic scaled linear function may achieve better correlation;
- For some cases, significant scatter in the relationships is shown (e.g. MS TBs1, 2, 4 CCV, and KS TB1 and TB2 MDP80). These values are likely influenced by different material type encountered and narrow range of MDP80 values on each material type.
- Different materials show different correlation results and variation trends (e.g. KS TB3 foundation shale and clay materials). These separate trends could be a result of differences in the underlying support, material, and moisture conditions.



Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials

Final Report

Publication No. FHWA-IF-12-002

July 2011

U.S. Department of Transportation
Federal Highway Administration

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The future of Modulus Based Measurements


READY RESULTS

NCHRP

May 2017

Measuring Modulus for Better-Performing Pavements

NEXT STEPS

Put It into Practice

WHAT WE LEARNED

WHY IT MATTERS

REAL-WORLD NEED

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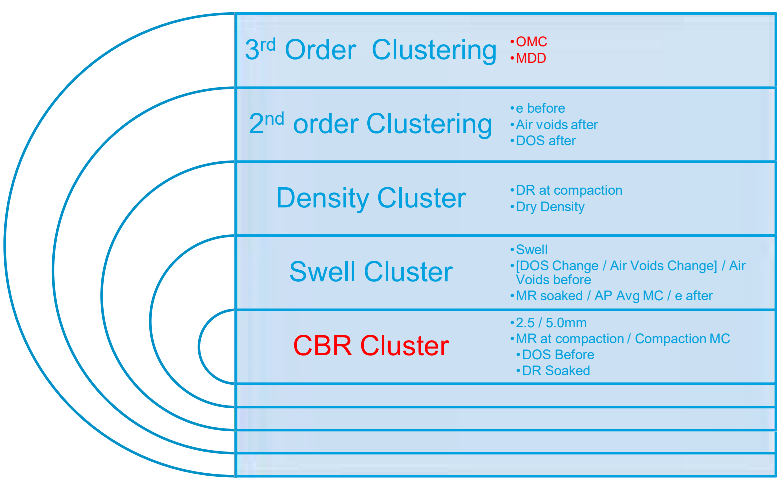
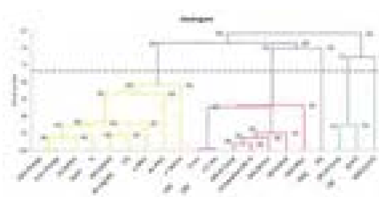
Dendrogram Clusters (20 variables)





Measuring Density may not be indicative of strength / modulus

Not clustered

CBR related mainly to MC and MR at compaction

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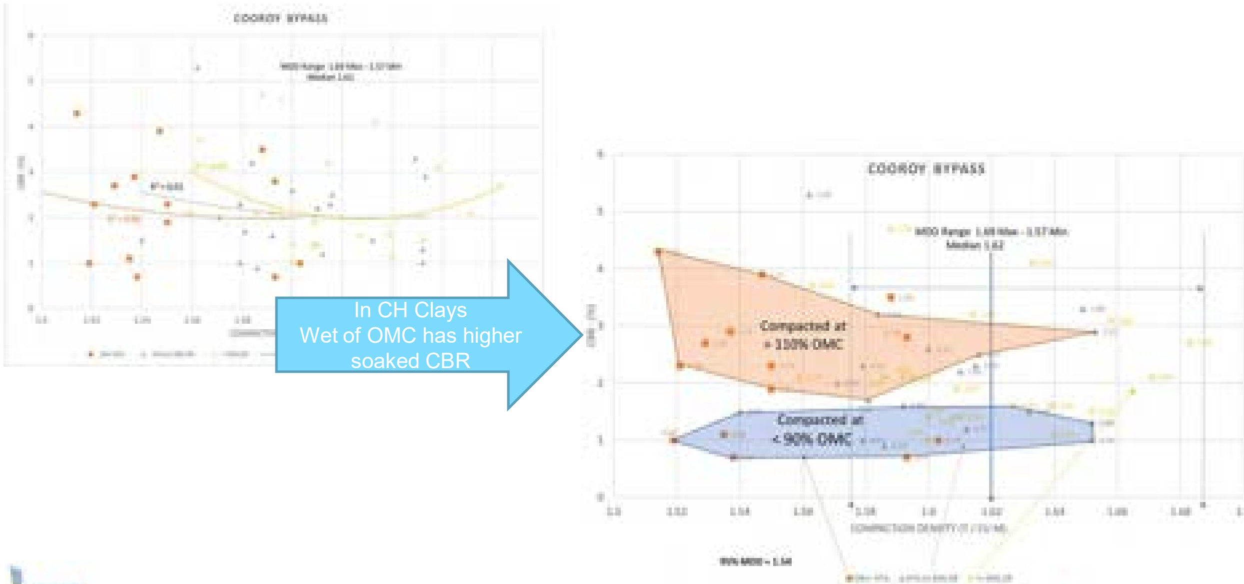
CBR (~Modulus) is less related to compaction density



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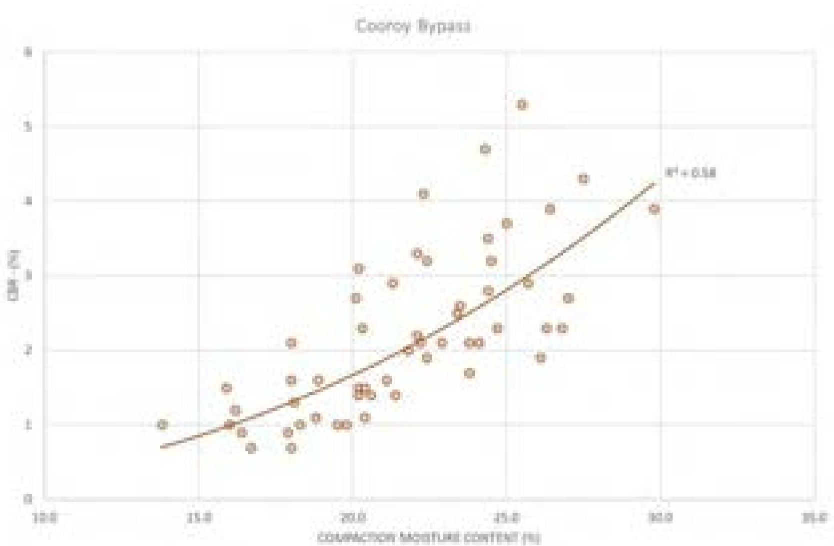
CBR (Modulus) is related to compaction MC



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Unsaturated soil models based on VMC

Note Dry Density is only a minor part of these strength models

Fredlund DG, Xing A, Fredlund MD, Barbour SL. The relationship of the unsaturated soil shear to the soil-water characteristic curve. Can Geotech J 1996;33(3):440–8.

$$\tau = c' + (\sigma - u_w)\tan\emptyset' + (u_a - u_w)\,[\,\vartheta^{\kappa}\ \tan\emptyset'\,]$$

Volumetric Moisture Content (θ)
= Volume of water / Total Volume

$\theta = w\,\gamma_d / \gamma_w$

γ_w = unit weight of water
γ_d = dry unit weight of soil

$$\tau = c' + (\sigma - u_w)\tan\emptyset' + (u_a - u_w)\,[\,\tan\emptyset'\ (\frac{\theta - \theta_r}{\theta_s - \theta_r})]$$

Vanapalli SK, Fredlund DG, Pufahl DE, Clifton AW. Model for the prediction of shear strength with respect to soil suction. Can Geotech J 1996;33(3):379–92.

τ = unstaurated sher strength
c' = effective cohesion
σ = total confining stress
u_w = pore water pressure
$\emptyset'$ = effective friction angle

ϑ = normalized volumetric moisture content
= θ / θ_s where θ = volumetric moisture content
and θ_s = volumetric water content at saturation

κ = fitting parameter dependent on the Plasticity Index
$\kappa = -0.0016\, I_p^2 + 0.0975\, I_p + 1$
Other relationships for κ (eg Tang et al. (2019), "Model Applicability for prediction of residual soil apparent cohesion)

where θ = volumetric moisture content
and θ_s = volumetric water content at saturation
θ_r = residual volumetric water content

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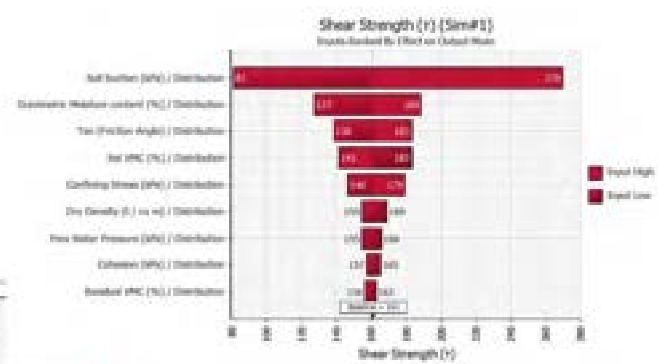
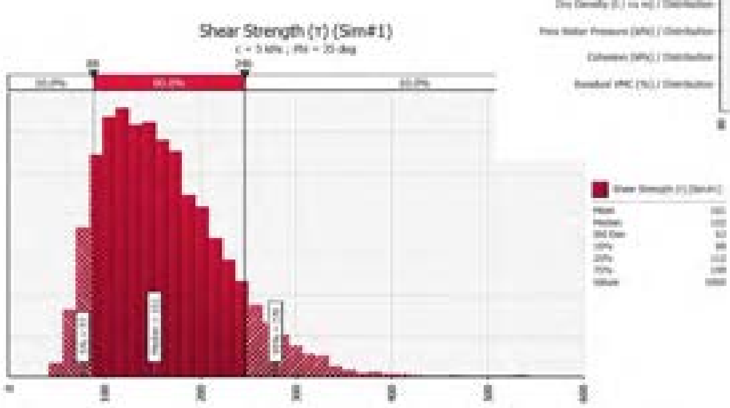
Monte Carlo Simulation of all variables

$$\tau = c' + (\sigma - u_w)\tan\emptyset' + (u_a - u_w)\,[\,\tan\emptyset'\ (\frac{\theta - \theta_r}{\theta_s - \theta_r})]$$

Not practical to measure these parameters



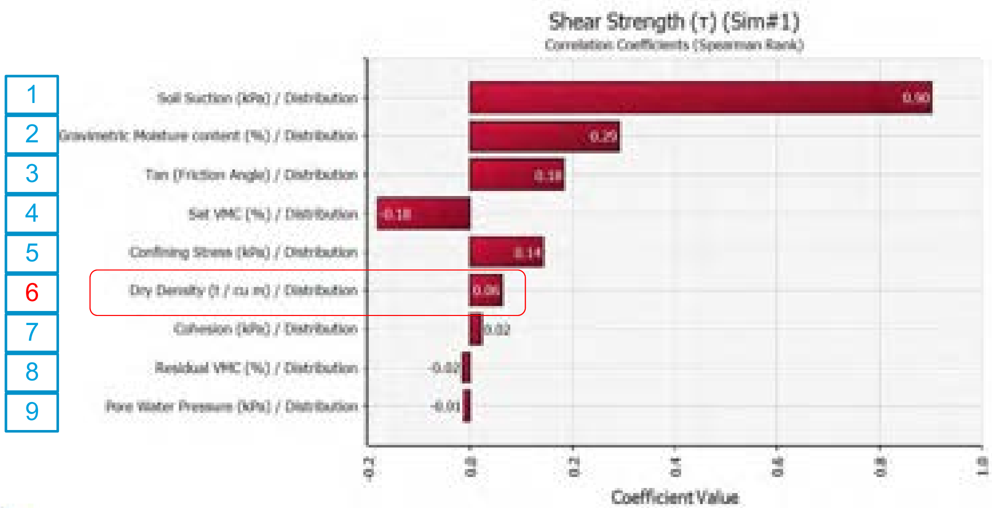
$c' = 5\ kPa$
$\emptyset' = 35\,°$



18

Spearman Rank of all variables

$\tau = c' + (\sigma - u_w)\tan\emptyset' + (u_a - u_w)\,[\tan\emptyset' \,(\frac{\theta - \theta_r}{\theta_s - \theta_r})]$



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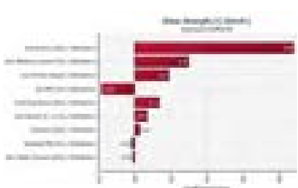
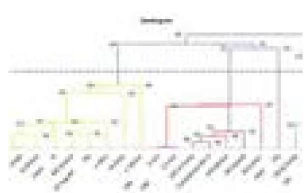
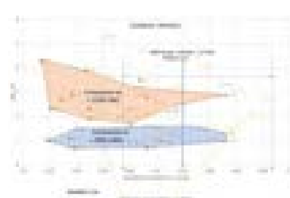
Summary

We emphasise density in QC but it is not the primary parameter







- **Unsaturated soil models**
- 9 Variables
- MC effect is No. 3
- DD effect is No. 6

- **Dendrogram Clustering analysis**
- 20 Test variables
- CBR affected by MC more than DR

- **Lab Correlations**
- CBR affected by MC more than DR

- **Field Testing**
- Modulus has low correlation with DR
- Instruments well correlated to each other

Total unit weight = Total density (ρ_b) = W / V

Dry unit weight = Dry density = W_s / V = ρ_b / (1 + w)

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2019 Test site Lessons Learnt

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Compaction Levels

Med

Very Dense

Dense

Med Dense

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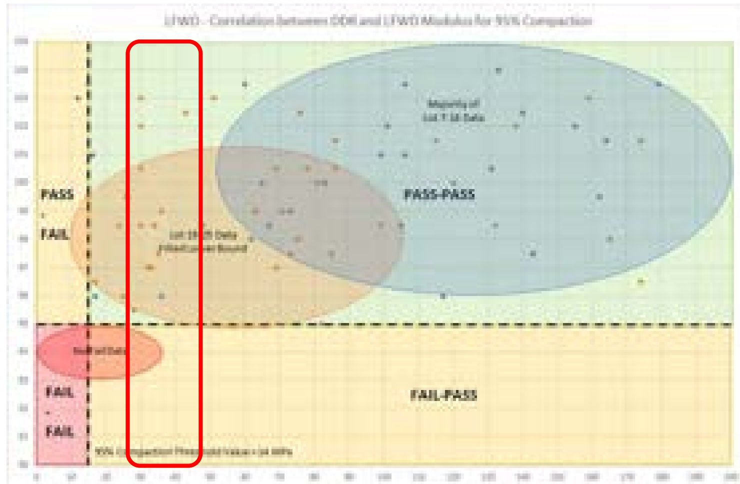
LFWD Thresholds - initial then with more data

Note : This test site is "live" with any testing is parallel. Contractor more likely to "over compact".

- Data at 90% to 95% which was on drawings were not obtained.
- No Data at 90% to 95%
- 97% at subgrade level was max., yet this compaction for most of results with ¾ of results over 97% and ½ over 100%



Previous experience Range

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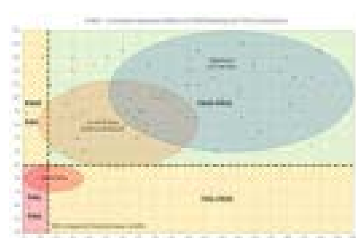
Test QA – Thresholds Related to RDD

Available data used to develop correlations during 'Live' Construction Project



Based on 72 Tests using Prima 100 LWD

Threshold		Fail / Fail	Pass / Pass	Density = Fail LFWD = Pass	Density = Pass LFWD = Fail
RDD	LFWD				
96%	15 MPa	0	69	2	1
98%	30 MPa	5	50	11	6
100%	60 MPa	16	30	18	8
103%	160 MPa	54	1	9	8

Correct Assessment (RDD + LFWD Agree)	RDD + LFWD Disagree (1 Test Passes / 1 Test Fails)
96%	4%
77%	22%
64%	36%
76%	24%

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A density pass → but fail LFWD → disagreement

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Variation in Material Moisture content

Spot check with NDG testing may not be able to effectively identify the "soft" spots such as wet zones

Test area selected for NDG testing surrounded by relatively higher moisture content

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Lot 24 - LFWD Tests

- Lot 24 LFWD "failing" ≠ assumed density "passing" results
- Recheck of values: allow to dry back → increase of modulus values. Is this allowed? Density had already passed
- < 12 hr dry back : Median 125% of Dry Value: 163% of quartile
- 24 hr dry back : 3.5 – 5.1 increase in modulus

Testing Period	No. of Tests	LFWD Modulus (MPa) @					
		50kPa	100kPa	50kPa	100kPa	50kPa	100kPa
		Median		Quartile		Ratio Change Median / Quartile	
Shortly after fill compaction	4	46.5	23.0	28.4	15.6	Reference Value	
Next Day – Dry backed	4	58.0	37.4	18.2	16.3	1.25 / 0.6	1.6 / 1.0
Further Dry Back	10	167.0	116.5	99.4	70.2	3.6 / 3.5	5.1 / 4.5

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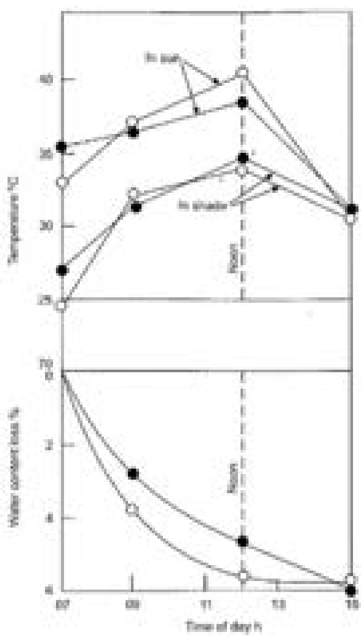
Water content evaporation loss



Blight and Leong, 2012

Water content losses through the entire thickness from
- 2 X 200mm thick, loose,
- Uncompacted soil layers
- Arid conditions

5% loss in 5 hrs whether in shade or sun
Varies on wind and ambient temperature

Water content is not a constant

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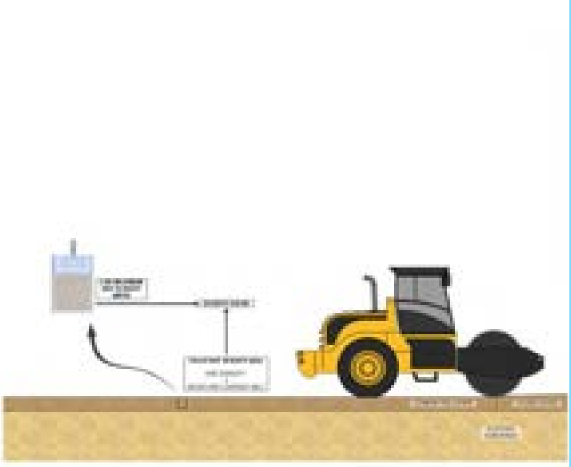
Sun, wind or rain after density test



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Lot 21 - LFWD Tests

- Density testing was carried out shortly after final layer compaction occurred. A period of rain then occurred shortly after testing
- Tests 2 days after compaction shows significant changes due to rainfall wetness
- Density testing was business as usual i.e. proceeding without explicitly acknowledging or taking action for changing conditions

Testing Period	No. of Tests	LFWD Modulus (MPa) @					
		50kPa	100kPa	50kPa	100kPa	50kPa	100kPa
		Median		Quartile		Ratio Change Median / Quartile	
Dry – shortly after fill compaction	4	116.9	113.0	64.1	72.8	Reference Value	
Rain fell – adjacent to previous tests	4	91.1	98.3	59.6	67.4	1.28 /1.07	1.15 / 1.08
Rain fell – additional tests	10	84.5	100.5	70.9	81.1	1.38 / 0.90	1.12 / 0.90

88% Compacted value

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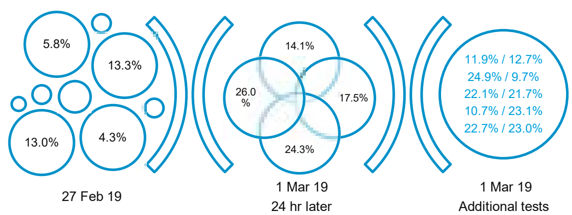
Lot 21 – Field Volumetric Moisture Content

ProCheck TEROS-12

- A passing density should not mean that subsequent layers can be placed, especially following rainfall.
- VMC X 2 following rainfall
- 88% X Initial Modulus values
- PANDA – little change - deepens by 0.03m



Median = 9.9% → 20.9% / 21.9%

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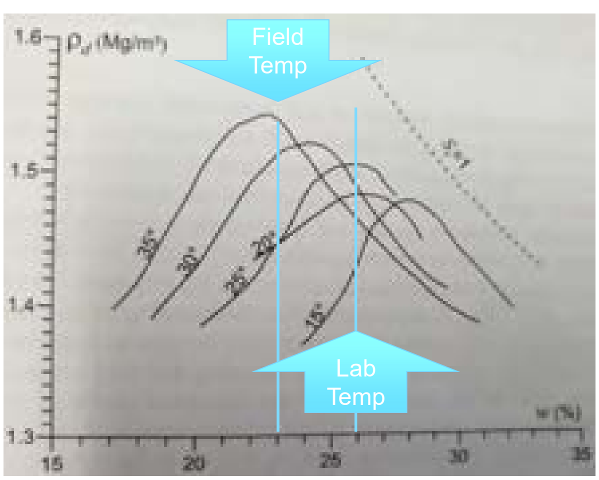
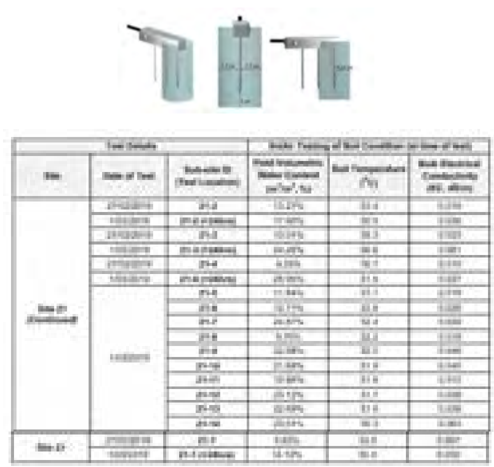
Effect of Temperature on Proctor compaction curves

Soil Temperature varied by up to 6.2 °C - ambient would be more





Fry (1977) - Figure is here from Caicedo (2019), "Geotechnics of Roads: Fundamentals

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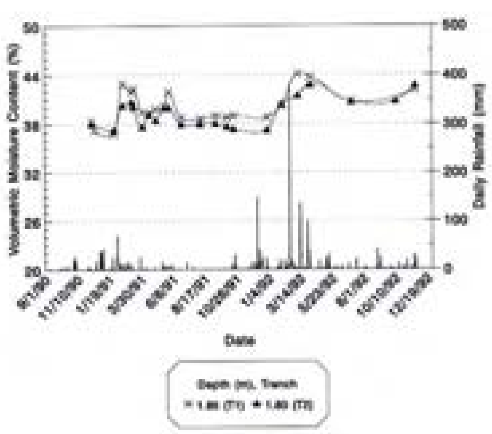
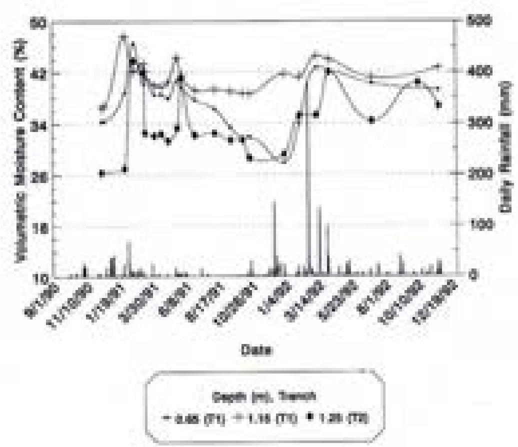
Moisture measurements in active + (assumed) stable zone

Below existing (30yr) road at Cooroy (1700mm annual rainfall)





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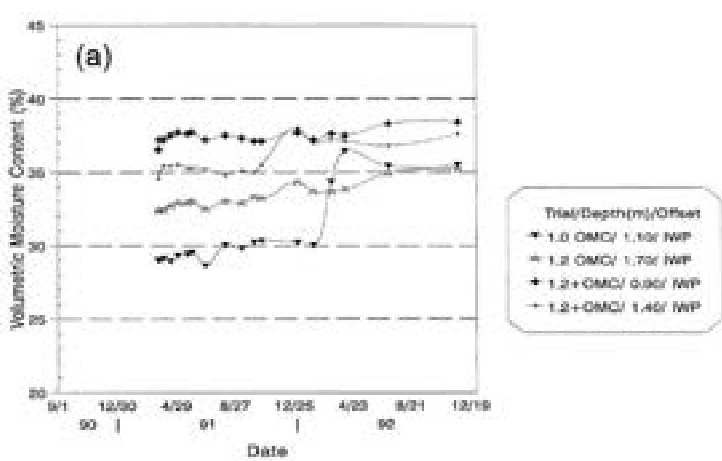
Monitoring of trial embankments

Constructed at various moisture contents (Cooroy – CH clays)



Moisture Content at construction is not the long term moisture content

Equilibrium Moisture Content (EMC) determines long term strength NOT the OMC at construction which is the short term construction condition

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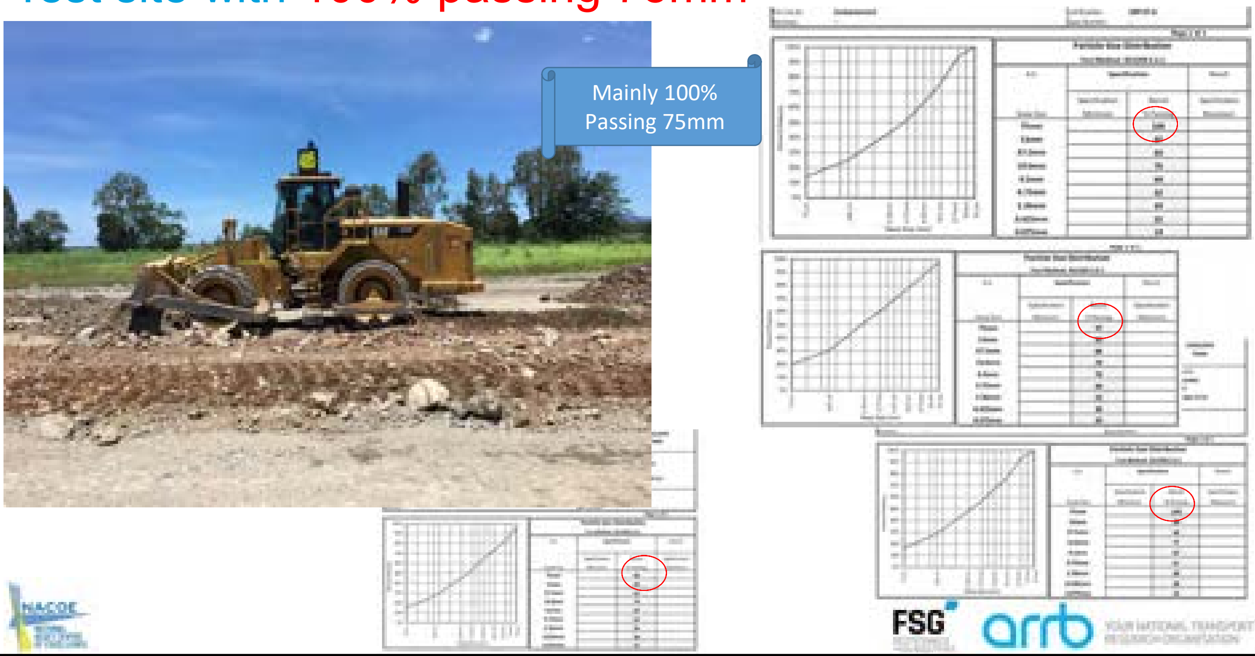
Test site with 100% passing 75mm



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Sampling – Test site in practice

Excavations not vertically sided

Shallow excavation samples crushed material at top

Discarding boulders (> 200mm) from samples

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Sampling – Ideal hole

- ✓ Sampling requires that all material from a vertical-sided hole (excavated to the depth that the NDG source rod was placed) must be recovered for laboratory testing.
- ✓ The hole permitted to be enlarged in plan, but no deeper than the depth of test, to obtain sufficient material for moisture content and laboratory compaction testing.
- ✓ It is extremely important to take the sample from the full depth of the test, this captures any moisture gradient in the layer being tested. Failure to take the sample properly can lead to very erroneous results.

RMS: Technical Guide | L-G-002 | February 2015
Field density testing by using a nuclear density gauge

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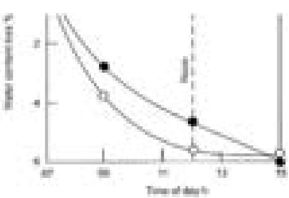
Summary

Moisture Content + Construction



Assessment (NDG + LFWD Agree)	(1 Test Passes / 1 Te Fails)
96%	4%
77%	22%
64%	36%
76%	24%

- **Water content loss**
- Varies significantly during placement

- **Equilibrium Moisture Condition**
- EMC – Long term
- OMC – short term

- **Field density Sampling**
- Often non representative
- Gradings + oversize + depth

- **Field Testing**
- 1/3 to ¼ disagreement between high density and modulus controls
- OK at lower density values

Density is not a fundamental indicator of strength or modulus +
Moisture content (a better indicator of modulus) is highly variable and changes

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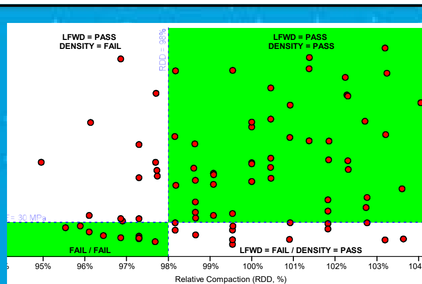

Contractor Risk		Good	Poor
Acceptance Decision	Accept	Correct	Type II Error [illegible] Risk Not Rejecting a Lot when it is Not OK
	Reject	Type I Error Contractor's Risk Rejecting a Lot when it is OK	Correct

QA OPTIONS

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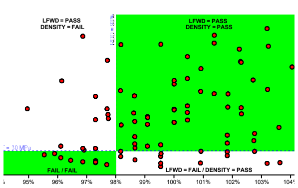
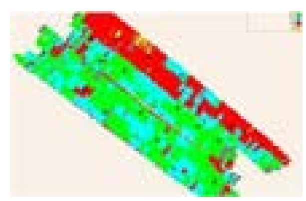
Specifications options

Specify Values?



Contractor Risk		Good	Poor
Acceptance Decision	Accept	Correct	Type II Error [illegible] Risk Not Rejecting a Lot when it is Not OK
	Reject	Type I Error Contractor's Risk Rejecting a Lot when it is OK	Correct



- Correlation Approach linked to Standard Density approach
- Project and material specific. Parallel Testing
- Likely to be most variable. Many "good" values fail and "bad" values pass
- Skews QA approach

- Method Of matching PDFs linked to Standard Density approach
- Project and material specific. Parallel Testing
- Uses 10% QA – acceptance decision

- Method of change reduction
- Not linked to Standard Density approach
- Parallel testing not mandatory
- Uses QA acceptance decision

- Intelligent Compaction verification
- NCHRP 676 Options
- Various approaches linked with parallel non density testing

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Typical Specifications – Values

Issues with correlations to DDR

DDR	$LFWD_{100\ kPa}$	Correct Assessment (RDD + LFWD Agree)	RDD + LFWD Disagree (1 Test Passes / 1 Test Fails)
96%	15 MPa	**96%**	4%
98%	30 MPa	**77%**	22%
100%	60 MPa	**64%**	36%
103%	160 MPa	**76%**	24%

When correlated with DDR

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In situ E correlated to 95% Density ratio - Values

Varies with each material

Fill Material Origin	Plate Load Test (PLT) E_{V2} (MPa)	Light Falling Weight Deflectometer (LFWD) $E_{LFWD\text{-}100kPa}$ (MPa)
Sandstone: 70% Gravel size; 10% fines	60	45
Interbedded Siltstone / Sandstone 70% Gravel size; 11% fines	35	25
Basalt 65% Gravel size; 12% fines	50	30

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Various acceptance LFWD for Base Course materials & Layers

TENTATIVE EQUIVALENCES BETWEEN PERCENT COMPACTION AND COMPOSITE MODULUS AT OPTIMUM WATER CONTENT FOR BASE AND SUBBASE COURSE AGGREGATE

Relative Compaction Based on AASHTO T180 (%)	Equivalent LWD Composite Modulus (MPa) at Optimum Water Content
90	92
95	115
98	130
100	139

Steinart et al. (2005)

FACTOR TO CORRECT COMPOSITE MODULUS MEASURED AT FIELD WATER CONTENT TO EQUIVALENT VALUE AT OPTIMUM WATER CONTENT

Water Content Relative to Optimum		Correction Factor to Be Added to Composite Modulus (MPa) Measured at Field Moisture Content
Dry of OMC*	-4%	-31
	-3%	-23
	-2%	-15
	-1%	-8
At OMC*		0
Wet of OMC*	+1%	8
	+2%	15
	+3%	23
	+4%	31

Laying and compaction specification for road construction in Germany

Soil layers	Density (Standard Proctor)	Bearing capacity (load bearing test, EV2)	Eveness (4 m straight edge)
Subbase	100 - 103 % *	100 - 150 MN/m² *	20 mm
Capping layer	100 - 103 % *	100 - 120 MN/m² *	40 mm
Formation	97 - 100 % *	45 - 80 MN/m² *	60 mm

* depending on road classification and road design

From BOMAG

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LFWD PROCEDURE QA

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Standards – LWD Laboratory Determination

Standard Method of Test for

Laboratory Determination of Target Modulus Using Light-Weight Deflectometer (LWD) Drops on Compacted Proctor Mold

AASHTO Designation: TP 123-01 (2017)

1. SCOPE

1.1. This test method describes the procedure to determine the target modulus (or deflection) required for compaction quality control of geomaterials using Light Weight Deflectometer (LWD) drops on a compacted Proctor mold in the laboratory.

1.2. The same LWD type in terms of brand name, buffer stiffness, and deflection measurement location (on top of the plate or on top of the soil layer) used for the laboratory target modulus testing must be used during the field testing. This is to eliminate differences between measurements from different devices.

1.3. This procedure shall be performed in the laboratory on representative soil samples before the field compaction operations.

1.4. Gradation, moisture content inconsistency, and surface texture on the mold can affect the material moduli results.

1.5. The target surface modulus values can be compared to the field measured modulus in accordance with the TP 456-01 specification for compaction quality control/quality assurance purposes.

7. APPENDIX

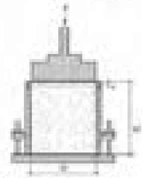

Figure 1—Schematic of LWD Testing on Proctor mold

Table 1—Suggested LWD Drop Heights on Proctor Mold for 10-kg Drop Weight

LWD type	Drop Heights (in.)					
Zorn	1	2	3	4	5	12.7
Dynatest	2	3	4	5	6	-
Olson	1	2	3	4	5	8.5

Table 2—Typical Values of Poisson's Ratio (from MEPDG)

Material	Range of values	Typical value
Untreated Granular Materials	0.30 - 0.40	0.35
Cement-Treated Granular Materials	0.10 - 0.20	0.15
Cement-Treated Fine-Grained Soils	0.15 - 0.35	0.25
Lime-Stabilized Materials	0.10 - 0.25	0.2
Loose Sand or Silty Sand	0.20 - 0.40	0.3
Dense Sand	0.30 - 0.45	0.35
Saturated Soft Clays	0.40 - 0.50	0.45
Silt	0.3 - 0.35	0.32
Clay (Unsaturated)	0.1 - 0.3	0.2
Sandy Clay	0.2 - 0.3	0.25
Coarse-grained Sand	0.15	0.15
Fine-grained Sand	0.25	0.25

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Standards – LWD compaction Quality

Standard Method of Test for

Compaction Quality Control Using Light Weight Deflectometer (LWD)

AASHTO Designation: TP 456-01 (2017)

1. SCOPE

1.1. This test method describes the procedure to assess the compaction quality of a road base or subgrade by comparing the field surface moduli to the laboratory determined target moduli using a Light Weight Deflectometer (LWD).

1.2. The same LWD type in terms of brand name, buffer stiffness, and deflection measurement location (on top of the plate or on top of the soil layer) used for the laboratory target modulus testing must be used during the field testing. This is to eliminate differences between measurements from different devices.

1.3. This procedure shall be performed within two hours after compaction to eliminate the effect of surface drying on the modulus values. This method does not count for post compaction wetting/drying and environmental effects.

1.4. An appropriate in situ method of soil moisture content measurement shall be used to rapidly determine the moisture content at the time of compaction and testing.

1.5. The target modulus should be corrected for a base or subbase layer of finite thickness compacted over subgrade.

6. SAMPLING FREQUENCY

6.1. In order to ensure that LWD testing is performed over the entire lot and not concentrated in one area, stratified random sampling using random locations within sublots is recommended according to ASTM D 3665.

6.2. The minimum frequency of LWD test shall be as outlined herein. Additional testing shall be performed if deemed necessary by the Engineer.

- For subgrade, base, and subbase compaction: Divide each lane mile into 4 subsections per lift and perform a minimum of 10 LWD tests per subsection at random locations.
- For road embankment material that is 1 ft or more below the top of subgrade: Divide each lane mile into 4 subsections per lift and perform a minimum of 5 LWD tests per sublot at random locations.

7. ACCEPTANCE

7.1. The average moisture content of the samples collected immediately after compaction shall fall within the acceptable moisture content range as determined by the TP 456-01 specification and agency policy.

7.2. The field-to-target ratios calculated per Section 5.4 shall be evaluated for acceptance using the percentage of material within specification limits method (PWL) following R 9-05 specification. The preliminary recommendations for lower specification limit shall be 1 with a PWL of 80%.

7.3. A spatial COV of about 20% shall be maintained to ensure uniform compaction within the lot.

7.4. The lot shall be rejected once a "large" percentage is outside the specification limit according to R 9 Section 8.12.7. Local agencies may want to perform additional implementation studies to refine the lower specification limit and/or the acceptable PWL. Typically, the lot may be rejected if PWL is less than 50%.

7.5. Appropriate remedial procedures shall be adopted for the materials that do not meet the acceptance criteria. These materials shall be re-tested for acceptance after corrections.

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Proposed LWD Specification

1. Define Initial Inputs – LWD Configuration

- What **design pressure** is to be verified by onsite testing? → σ_{Design}
- What **LWD Brand** is proposed to be utilised for onsite testing? → **LWD Type**
- Is the **LWD Configuration** capable of achieving the σ_{Design} pressure? (and +/- 20% of σ_{Design}) → **Defined LWD Variables** – Plate Diameter, Drop Weight, Buffer Arrangement & Drop Height
- What equipment will be utilised to **assess the Insitu Moisture Condition** at time of LWD Testing? → **Defined Insitu Moisture Content Assessment Technique**

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Proposed LWD Specification

2. Define Initial Inputs – Earthworks Variables

- What **Material** is to be used as the source for Earthworks? → **Material Type and Quality**
- What **Loose Layer Thickness** is to be utilised during Earthworks? → **Lift Thickness**
- What **Compaction Equipment & Methodology** is to be utilised to achieve effective compaction → **Compaction Technique – Equipment & Method**
- What **Moisture Conditioning** will occur prior / during completion of compaction? → **Insitu Moisture Condition (at time of LWD Testing)**

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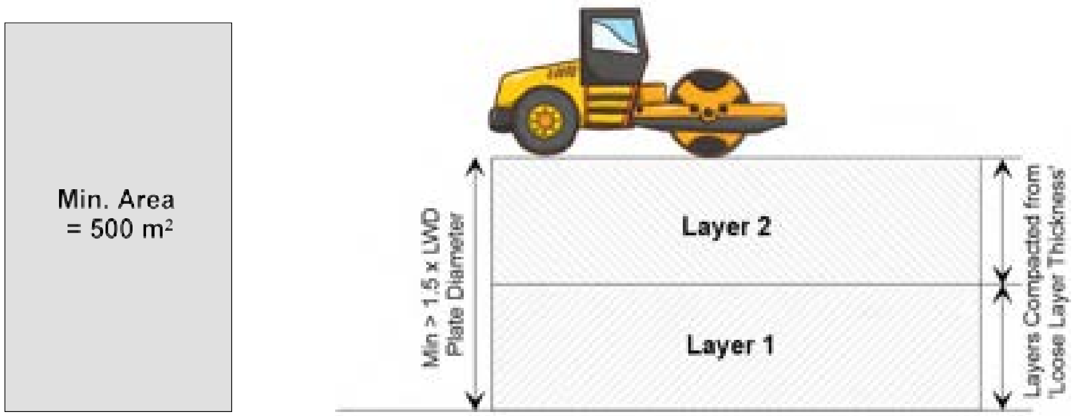
Proposed LWD Specification

3. Construct Trial Embankment



PLAN **ELEVATION**

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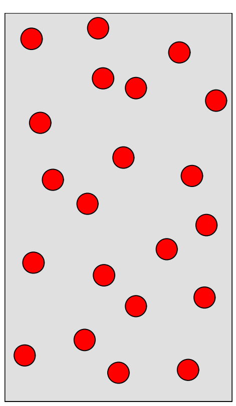
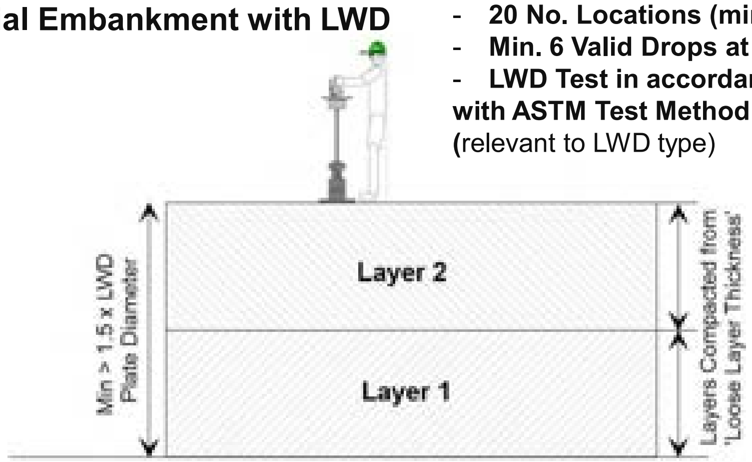
Proposed LWD Specification

4. Test Completed Trial Embankment with LWD

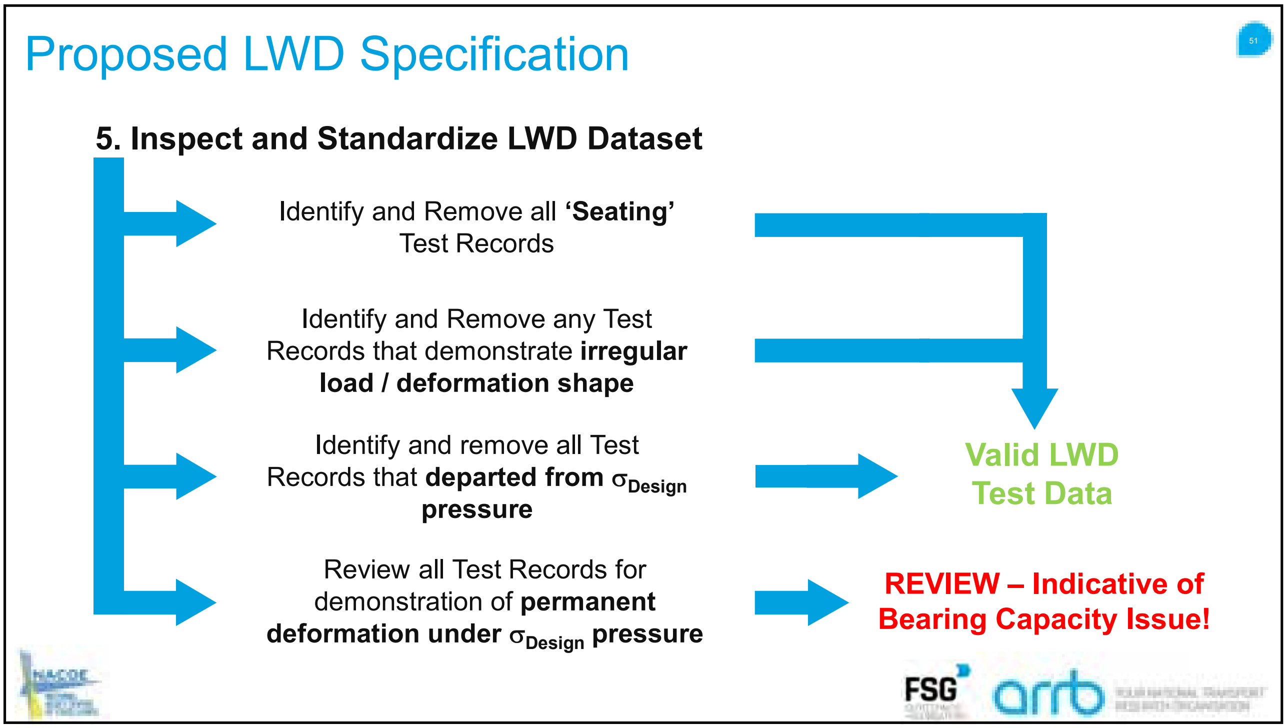
- **20 No. Locations (min.)**
- **Min. 6 Valid Drops at σ_{Design}**
- **LWD Test in accordance with ASTM Test Method** (relevant to LWD type)





PLAN **ELEVATION**

50


Proposed LWD Specification
5. Inspect and Standardize LWD Dataset
Identify and Remove all 'Seating' Test Records
Identify and Remove any Test Records that demonstrate irregular load / deformation shape
Identify and remove all Test Records that departed from σ_{Design} pressure
Review all Test Records for demonstration of permanent deformation under σ_{Design} pressure
Valid LWD Test Data
REVIEW – Indicative of Bearing Capacity Issue!
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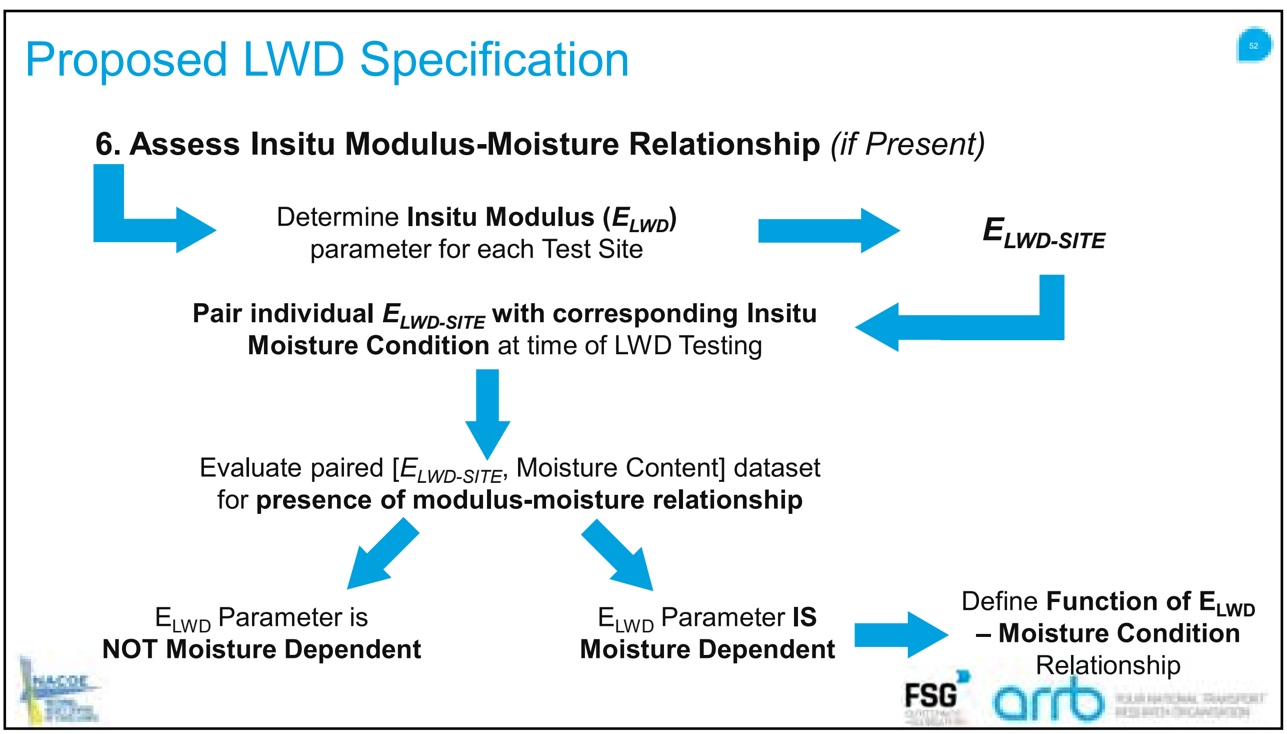
Proposed LWD Specification
6. Assess Insitu Modulus-Moisture Relationship (if Present)
Determine Insitu Modulus (E_{LWD}) parameter for each Test Site
$E_{LWD-SITE}$
Pair individual $E_{LWD-SITE}$ with corresponding Insitu Moisture Condition at time of LWD Testing
Evaluate paired [$E_{LWD-SITE}$, Moisture Content] dataset for presence of modulus-moisture relationship
E_{LWD} Parameter is NOT Moisture Dependent
E_{LWD} Parameter IS Moisture Dependent
Define Function of E_{LWD} – Moisture Condition Relationship
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Moisture dependent

Material Type	Typical Coefficient of Variation (CoV) of $E_{LWD\text{-}SITE}$
GRAVEL dominated materials	10 – 20 %
SAND dominated materials	15 – 35 %
FINES dominated materials	30 – 60 %

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Proposed LWD Specification

7. Define E_{LWD} Acceptance Thresholds (for Production Earthworks QA Testing)

A. For Materials where E_{LWD} IS NOT Moisture Dependent

Criteria #1 – All E_{LWD} results for a single earthworks Lot must exceed the minimum $E_{LWD\text{-}SITE}$ value
(i.e. Assessment that minimum insitu modulus parameter has been achieved at all locations)

Criteria #2 – Mean E_{LWD} within a single earthworks Lot must exceed 80% of the mean of the $E_{LWD\text{-}SITE}$ dataset
(i.e. Assessment that typical insitu modulus parameter has been achieved across a Lot)

Criteria #3 – Lower Characteristic E_{LWD} within a single earthworks Lot must not fall below the Lower Characteristic of the $E_{LWD\text{-}SITE}$ dataset
(i.e. Assessment that variability of insitu modulus parameter does not exceed expectations)

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Proposed LWD Specification

7. Define E_{LWD} Acceptance Thresholds (for Production Earthworks QA Testing)

B. For Materials where E_{LWD} IS Moisture Dependent

Criteria #4 – Measured E_{LWD} must exceed [$E_{LWD\text{-}SITE}$ – Average of Function Residuals] when E_{LWD} & $E_{LWD\text{-}SITE}$ are determined at corresponding Insitu Moisture Contents
(i.e. Assessment that observed insitu modulus parameter achieves typical value)

Criteria #5 – Measured E_{LWD} must remain above the Lower Bound 95th Confidence Interval Value for defined $E_{LWD\text{-}SITE}$ – Insitu Moisture Content relationship
(i.e. Assessment that observed insitu modulus parameter exceeds minimum requirement)

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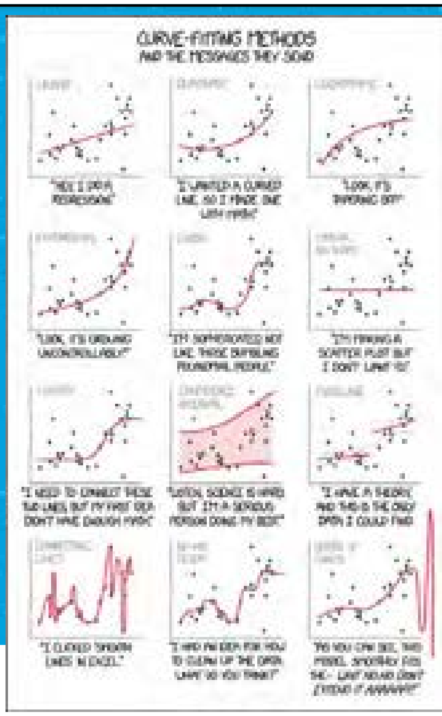

Correlation which avoids curve fitting
Method of Matching PDFs
QA

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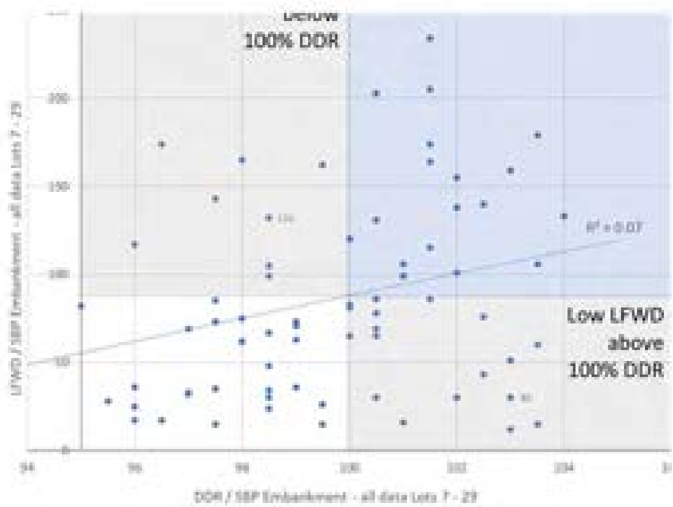
Paired matching of DR and LFWD (Prima) tests



High Modulus values (> 100 MPa) can "fail" a 100% DR tests

And

values below 30 MPa can "pass" a DR criterion

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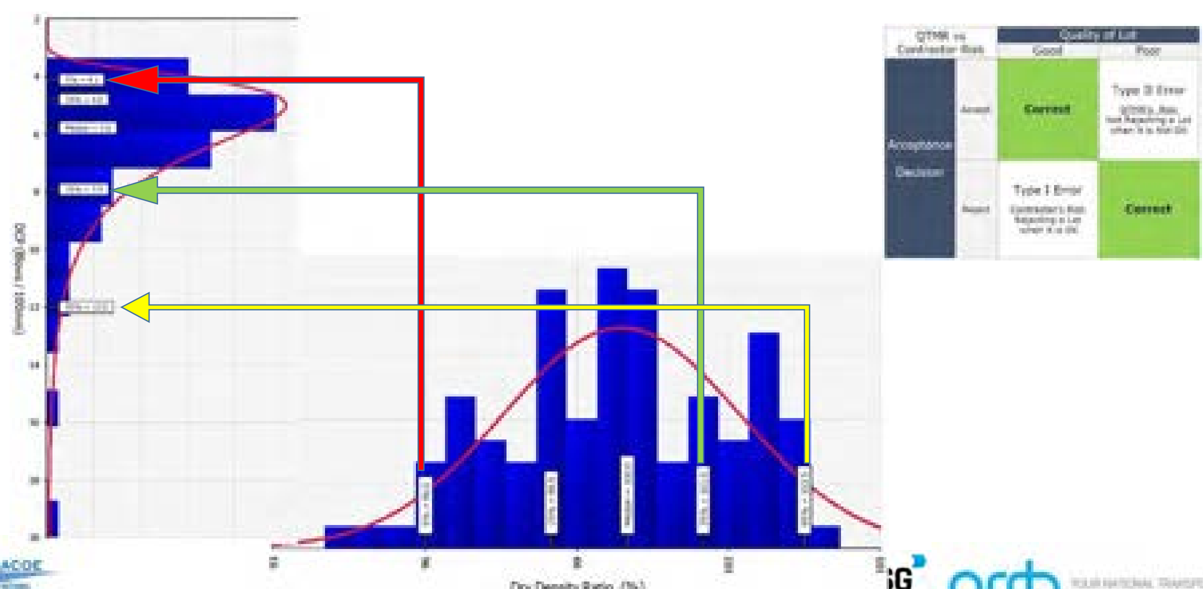
Method of Matching PDFs



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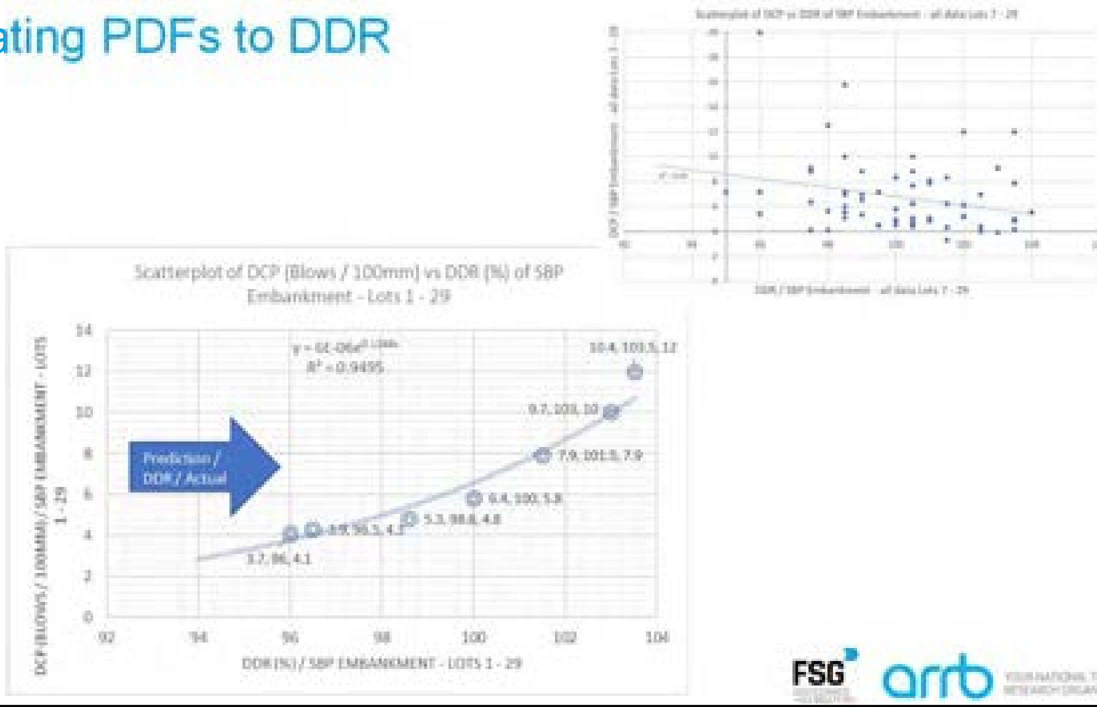
Relating PDFs to DDR



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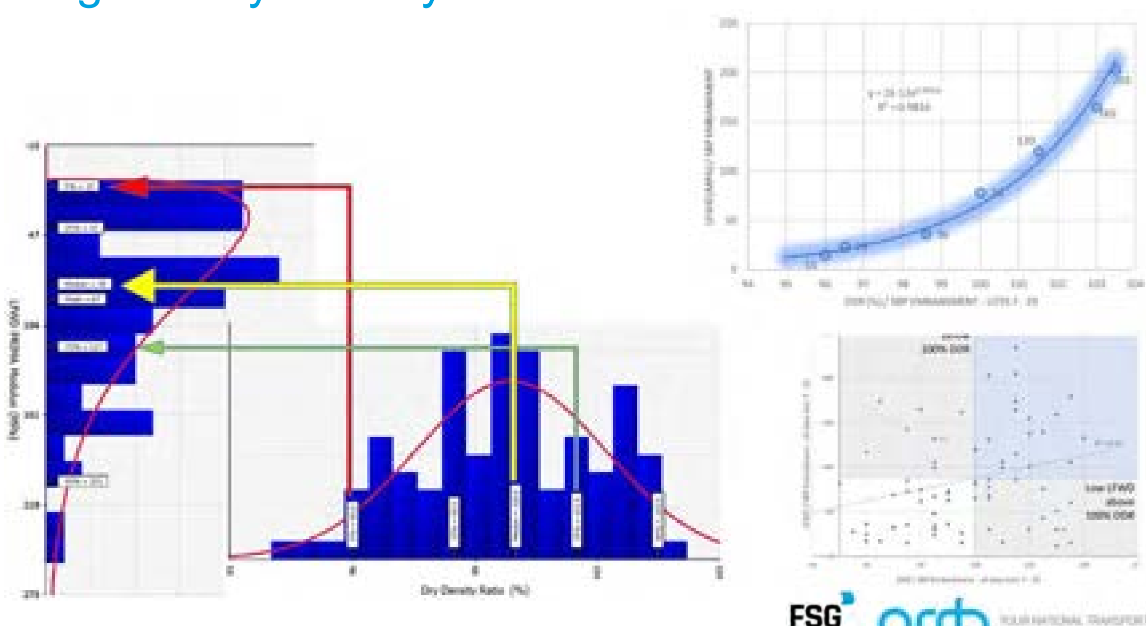
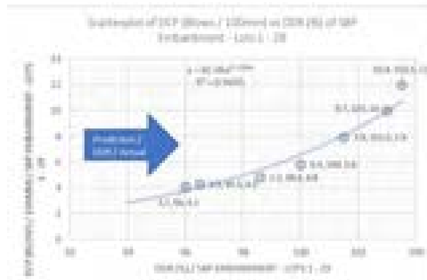
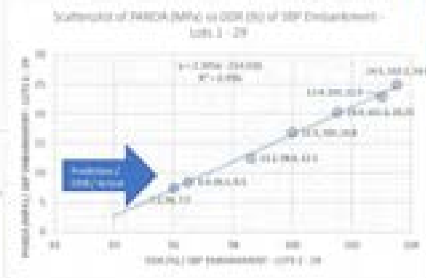
Matching the Dry Density Ratio and LFWD PDFs

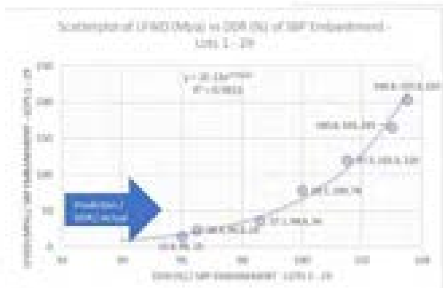


60

Relating PDFs to DDR







DDR	$LFWD_{100\ kPa}$	Correct Assessment (RDD + LFWD Agree)	RDD + LFWD Disagree (1 Test Passes / 1 Test Fails)
96%	15 MPa	**96%**	4%
98%	30 MPa	**77%**	22%
100%	60 MPa	**64%**	36%
103%	160 MPa	**76%**	24%

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% Maximum Target Value H Method of Change Reduction QA

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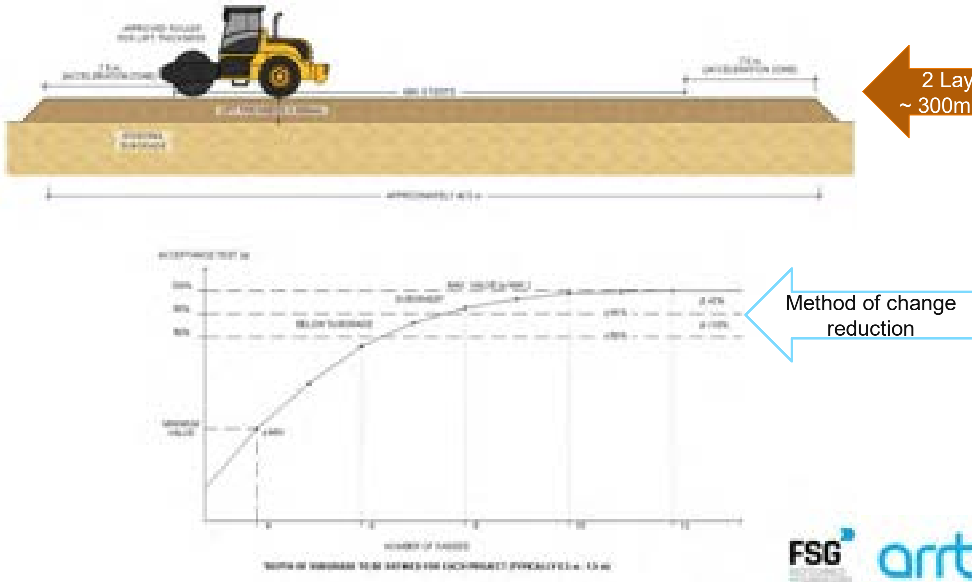
% Maximum Target values

Minimum Area = 40 m length X 4.2m wide: No. tests = 2 X 5 =10 Min / Layer : 2 Layers



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QA - Acceptance Criteria

10 Min Tests (Ideally 20 No.)

Minimum Values
- All values η_{min} at 4 passes in trial

4 → 6 → 8 → 10 → 12 Passes
- Measure η every 2nd pass

Maximum Values
- All values η_{max} at 12 passes in trial

Acceptable values (LCV) from trial
- η_{95} < 5% increase (subgrade) or 95% η_{max}
- η_{90} < 10% increase (below subgrade) or 90% η_{max}

Variation at acceptable value
- COV < 20%(Gravels)
- COV < 35% (Sands) -?
- COV < 60% (Fines) -?

Varies with test equipment

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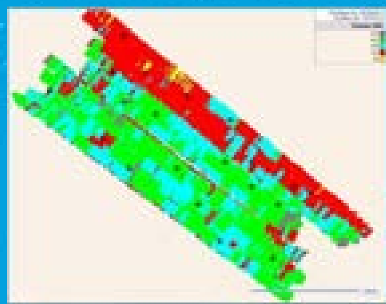

Intelligent compaction QA

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IC + Modulus testing

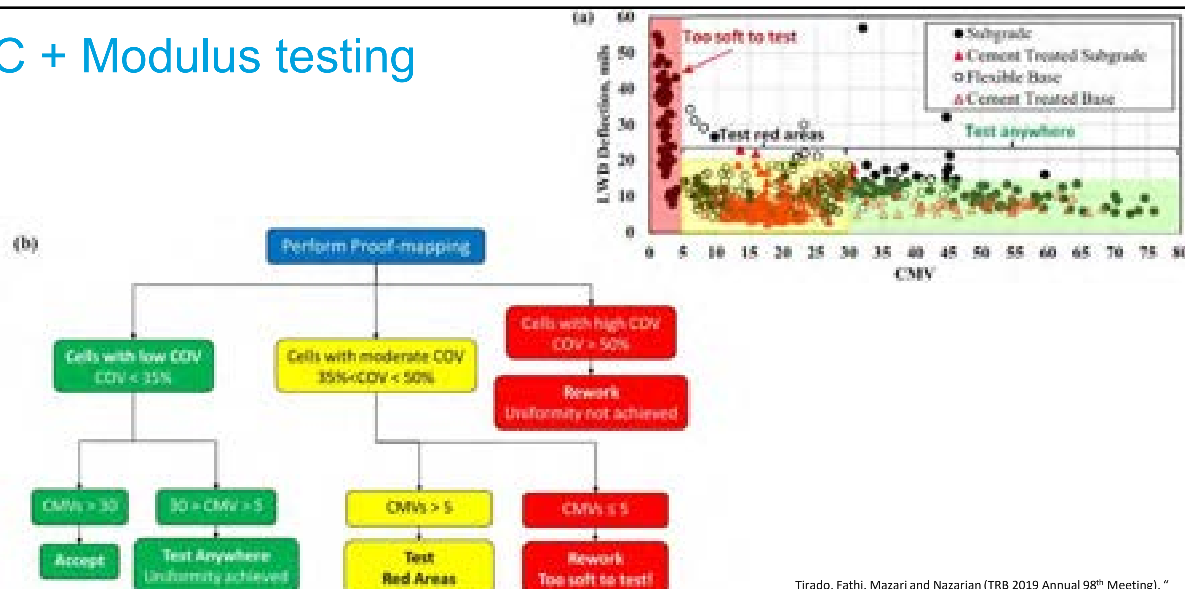

FIGURE 2 (a) Relationship between CMV and deflections measured from LWD mass drops for all sites and (b) proposed protocol for project acceptance.

Tirado, Fathi. Mazari and Nazarian (TRB 2019 Annual 98th Meeting), " Design Verification of Earthwork Construction by integrating intelligent compaction technology and modulus based testing

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Is
Density Ratio
the end game ?

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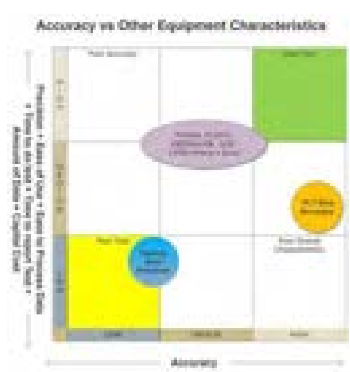
Summary and conclusions

3 most common tests are PLTs, Density and DCPs → do not correlate well with each other.

- ✓ Density Ratio testing is the most precise test. However, it is a poor indicator of strength or modulus, once the pass compaction has been achieved
- ✓ PLT is very accurate, but low precision
- ✓ DCPs has a low precision but has other characteristics (ease of use and depth profiling) which make this test attractive

No clear leader for the combined 8 criteria used

- ✓ Direct or meaningful correlations should be project + material specific
- ✓ Many Alternative tests are more related to Moisture content rather than density
- ✓ Moisture content changes likely to occur and affect modulus values
- ✓ Correlating back to density is unlikely to advance the use of alternative testing
- ✓ A relative value for QA assessment can be used, similar to the currently used relative density approach. Various procedures outlined.
- ✓ Currently the most used tests of DCPs, CBR and density all use Australian Standards. Overseas Standards (ASTM) for many of the other alternative tests



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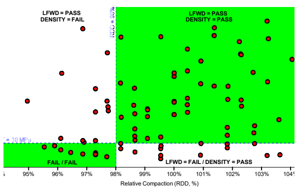
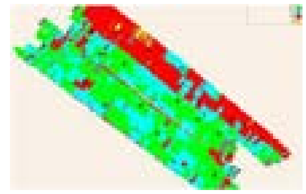
Specifications options

Target Value cannot be universal





- Correlation Approach linked to Standard Density approach
- Project and material specific. Parallel Testing
- Likely to be most variable. Many “good” values fail and “bad” values pass
- Skews QA approach

- Method Of matching PDFs linked to Standard Density approach
- Project and material specific. Parallel Testing
- Uses 10% QA – acceptance decision

- Method of change reduction
- Not linked to Standard Density approach
- Parallel testing not mandatory
- Uses QA acceptance decision

- Intelligent Compaction verification
- NCHRP 676 Options
- LFWD parallel testing

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Thank you for your participation today.

For further information on the topic, please contact:

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Dr Burt Look blook@fsg-geotechnics.com.au

Website:
https://www.nacoe.com.au

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APPENDIX D ONLINE WEBINAR ON 14 MAY 2020

D.1 PRESENTATION SLIDES

NACOE WEBINAR

Webinar Title: Quality Management of Earthworks with Deflection-based Devices

Presenters: Prof. Soheil Nazarian and Andrew Doe

NACOE Project: *P60 – Best practice in compaction quality assurance for subgrade materials*

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1

This webinar is brought to you by:

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2

Rosemary Pattison & Jeffrey Lee

Webinar Moderators

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NACOE

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3

Housekeeping

Webinar is 60 mins
inc. question time of 10-15 mins

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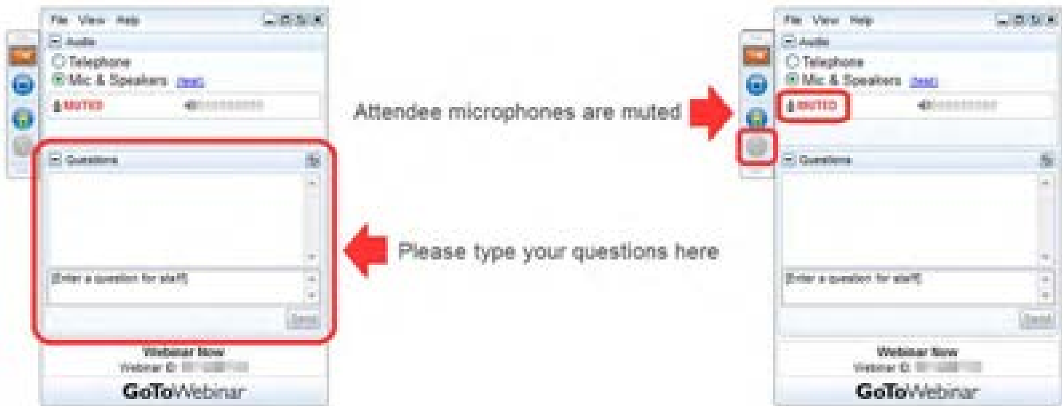
4

GoTo Webinar functions



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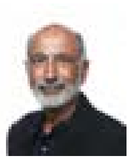
Webinar Presenters



Professor Soheil Nazarian
Director of the Center for Transportation Infrastructure Systems
University of Texas at El Paso

Andrew Doe
Geotechnical Project Manager (Program Enabling)
Inland Rail

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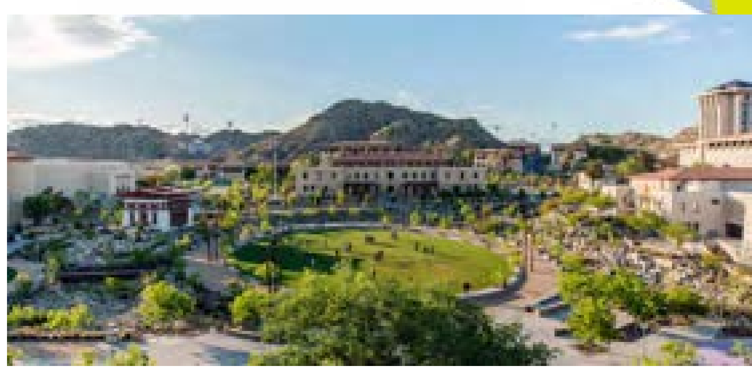
Quality Management of Earthworks with Deflection-based Devices



Soheil Nazarian, PhD, PE, DGE
Director, Center for Transportation Infrastructure Systems

Macintosh Murchison Endowed Chaired Professor
Department of Civil Engineering
The University of Texas at El Paso
500 W. University Avenue, El Paso, TX 79968
Office: 915-747-6911
http://ctis.utep.edu/

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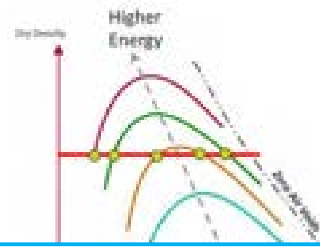
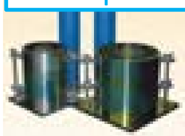
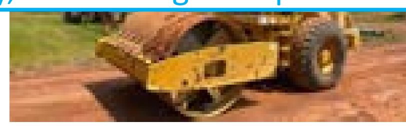
Traditional Density-Based Compaction

- They did the best they could with what was available to them ~70 years ago to solve a major problem
- Engineering community pragmatically agreed that these tests improve quality, even though not perfect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Famous Quotes of Ralph Proctor

- Strength is not achieved by density alone.
- Optimum moisture is for compaction.

Proctor(1945), Trans 110, ASCE

- "No use is made of actual peak dry weight."
- "Measure of soil compaction used is penetration resistance."

Proctor Penetrometer

Courtesy of John Siekmeier

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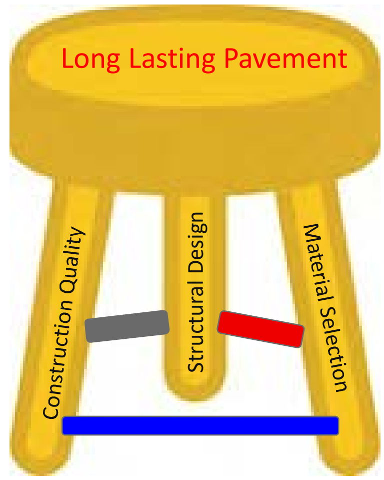
Why Modulus-Based Field Testing

- We do not check whether the modulus designer assumed is achieved
- We do not check whether the material selected provides the modulus assumed by designer
- We assume Lab Moisture-Density Curve represents Field Compaction process

Not a good position to be



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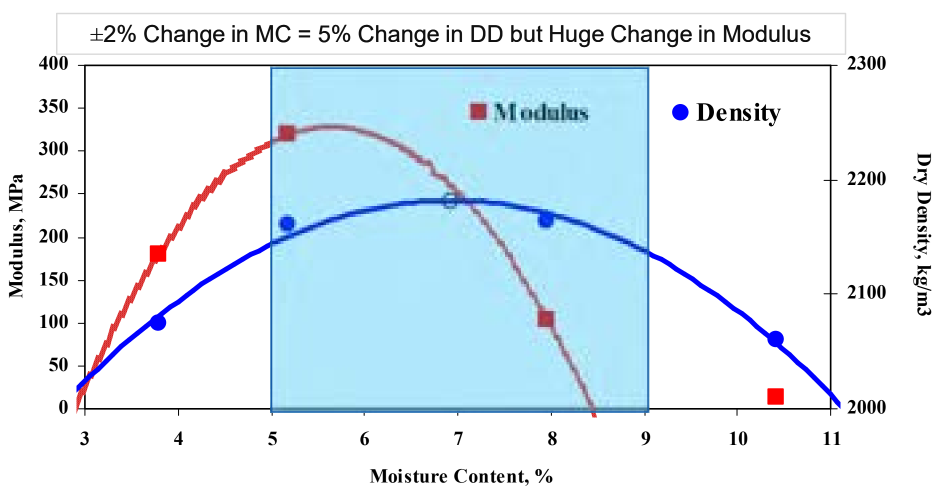
Why transition from density



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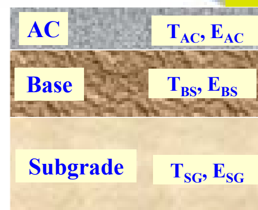
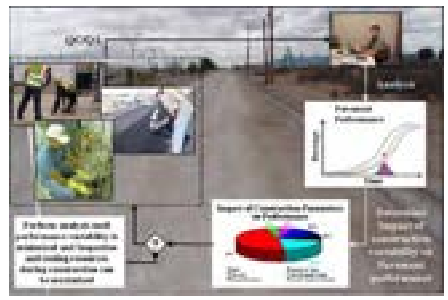
Quality Management vs. Performance Management



Eventual Goal: to ensure that pavement lasts for a pre-defined life uniformly

One way to reach it:

- Settle on a design methodology (e.g. Pavement ME)
- Define Parameters that are directly important to performance (e.g., modulus)
- Focus on these parameters



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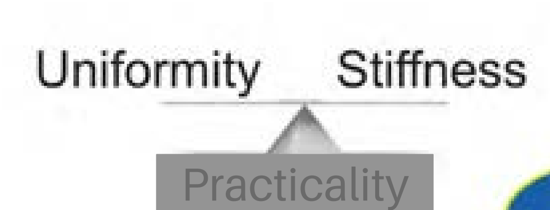
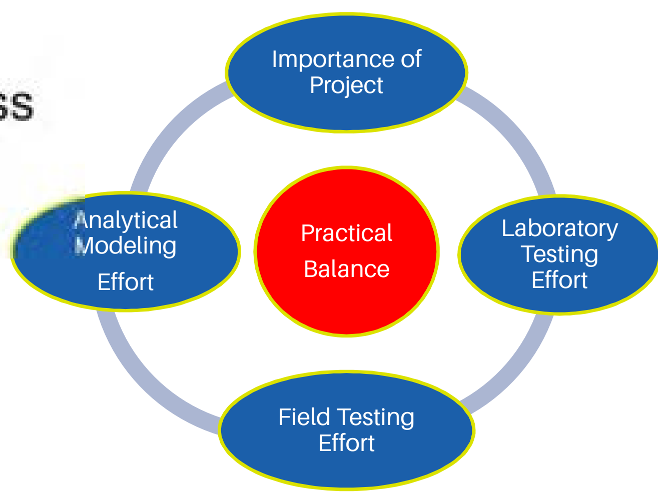
Appropriate Performance Management





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Major Steps for Balance Performance Management

1. Selecting Suitable Material
2. Selecting Appropriate Design Parameters
3. Selecting Target Field Values
4. Field Process Control
5. Acceptance Process

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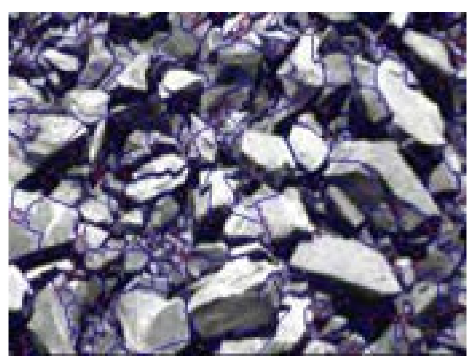
Selecting Suitable Material

A stiff/strong material does not correspond to a durable material.

- Parameters, such as hardness of aggregates, percent fines and plasticity should be controlled for durability.

Do not abandon specifications on this subject



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Selecting Appropriate Design Parameters

Conducting laboratory resilient modulus tests before structural design → Utilizing results from a catalog of most common soils that have been tested → Estimating modulus based on calibrated models that are functions of index parameters → Using presumptive design values based on experience

Best Option → Worst Option

Set Target Values using design algorithm → Set target Values using design algorithm → Estimate target values using test strip → Use traditional density based approach

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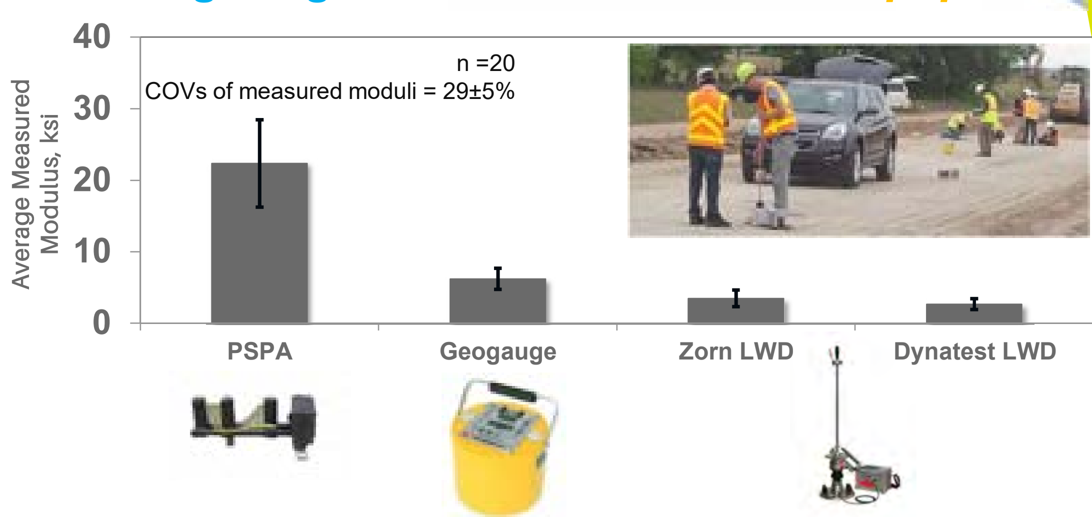
Selecting Target Field Moduli: Which Equipment?



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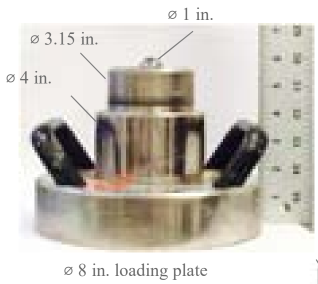
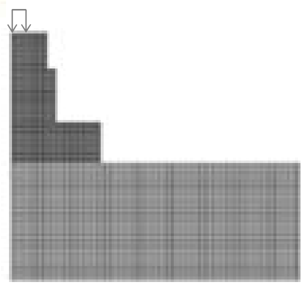
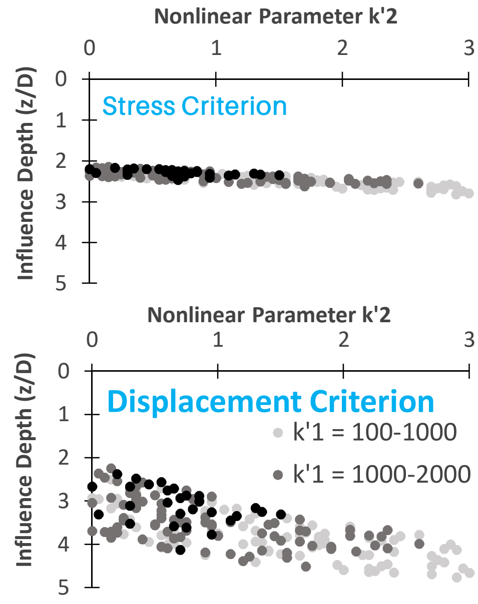
Depth of Influence for LWD







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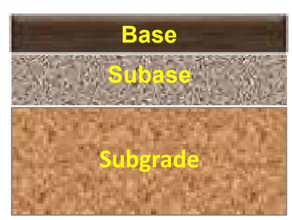
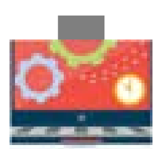
Selecting Target Field Moduli

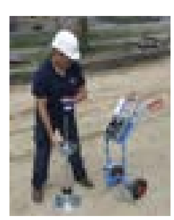
- **Input**
  - Thickness of each layer
  - Poisson's ratio of each layer
  - Modulus of each layer





Can easily be part of design

- **Output**
  - Target Deflection



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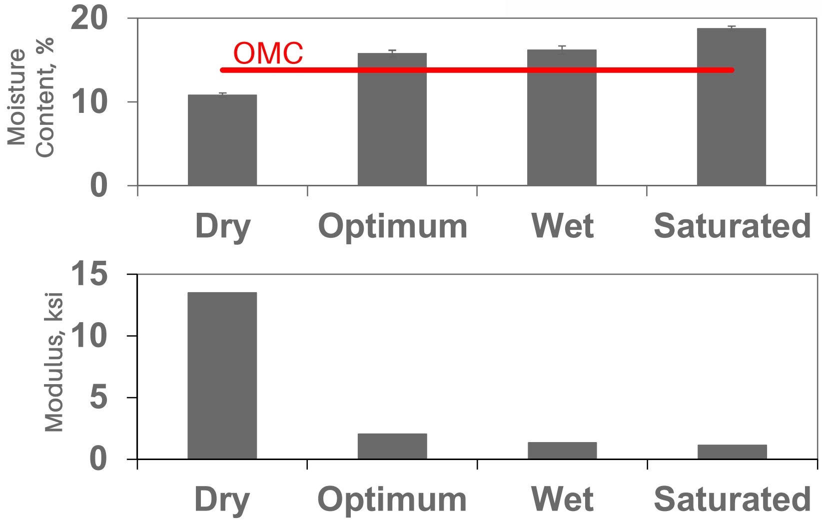
Impact of Moisture Content at Compaction



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Field Process Control

Changes in materials and moisture content have significant impact on modulus	Process control will ensure a more uniform and higher quality final product.	Quantifying variability is important to achieve uniformity
Need a strategy to manage variability	Need to ensure a rigid process control not less	Intelligent compaction can be used for this purpose

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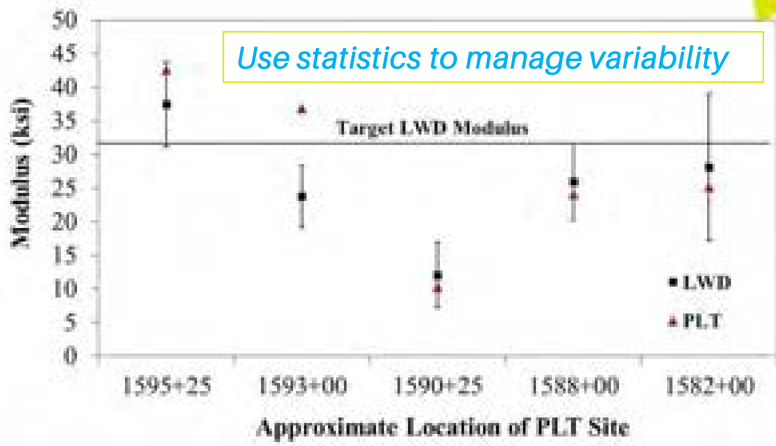
Field Process Control: Manage Variability



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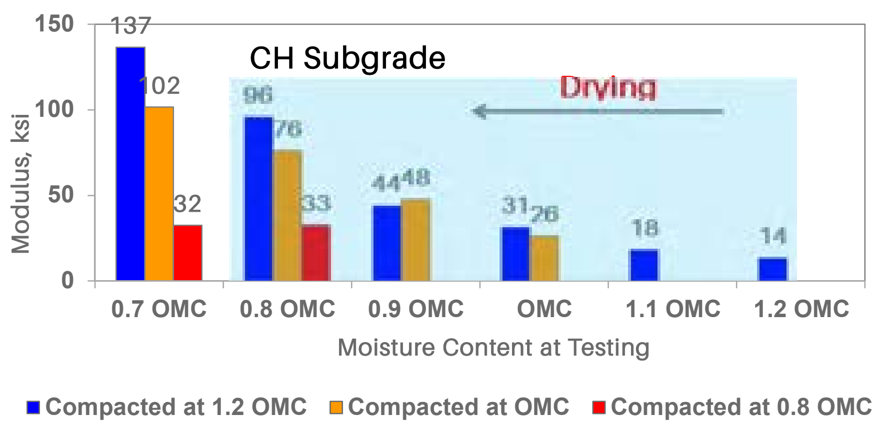
Field Process Control: Moisture Content



Constant Density Specimens prepared at MDD

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Field Process Control: Unsaturated Soil Principles)

Degree of Saturation, %

120, 115, 110, 105, 100, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 10, 5, 0

Moisture Content, %

Dry Density, pcf	5%	7%	9%	11%	13%	15%	17%	19%	21%	23%	25%
90	15%	22%	28%	34%	40%	46%	53%	59%	65%	71%	77%
95	17%	24%	31%	38%	45%	52%	59%	66%	72%	79%	86%
99	19%	27%	35%	43%	50%	58%	66%	74%	81%	89%	97%
104	22%	31%	39%	48%	57%	66%	74%	83%	92%	101%	109%
109	25%	35%	45%	55%	65%	75%	85%	95%	105%	115%	125%
115	29%	40%	52%	64%	75%	87%	98%	110%	121%	133%	145%
121	34%	48%	61%	75%	88%	102%	116%	129%	143%	156%	170%
127	41%	57%	74%	90%	106%	123%	139%	155%	172%	188%	204%
133	51%	71%	91%	111%	131%	152%	172%	192%	212%	233%	253%
140	65%	91%	118%	144%	170%	196%	222%	248%	274%	300%	327%
147	90%	127%	163%	199%	235%	271%	308%	344%	380%	416%	452%
154	143%	200%	257%	314%	371%	428%	486%	543%	600%	657%	714%

$$S_r = \omega G_s \rho_d / (G_s \rho_w - \rho_d)$$

G_s = specific gravity
ρ_d = dry mass density
ρ_w = mass density of water

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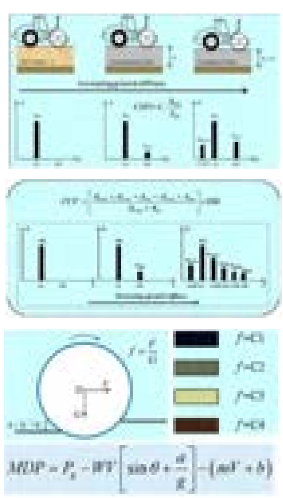
Intelligent Compaction for Uniformity

CMV

CCV

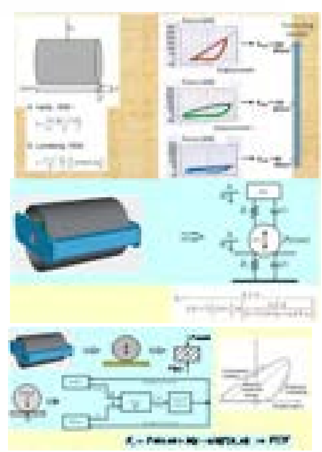
MDP



Evib

Kb

VCV



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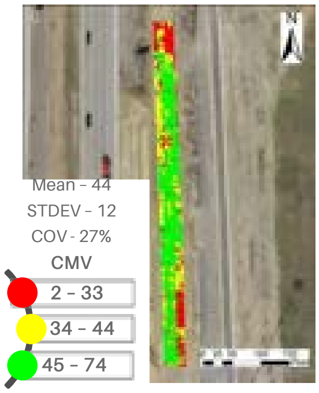
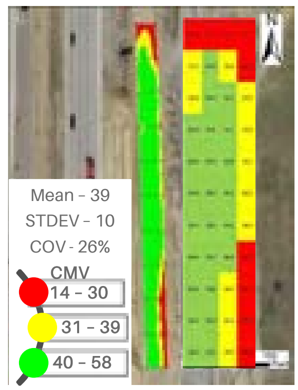
Field Process Control: Uniformity

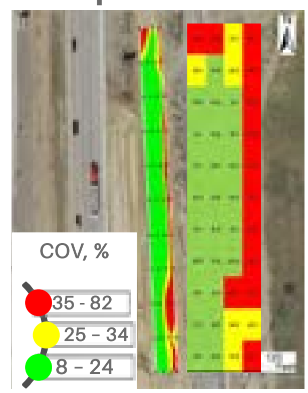
Traditional



Sublot Concept



CMV



COV of CMV

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Step 5: Acceptance Process

Based on moisture-adjusted deflection

$$d_{adj} = d_{meas} / (K_{lab\text{-}field} \ K_{moist})$$

Include in target value for convenience

$K_{lab\text{-}field}$ adjusts for differences in lab and field moduli at same moisture content and density

K_{moist} adjusts for differences in compaction and testing moisture contents.

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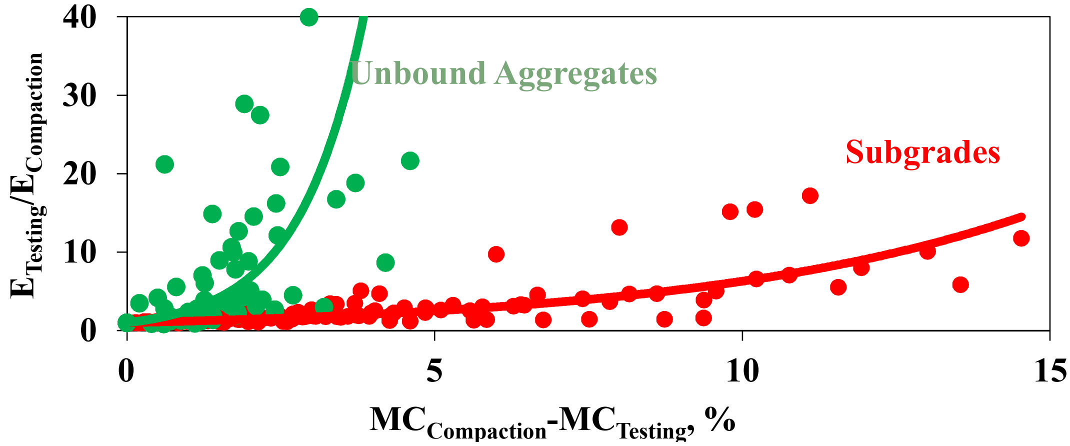
Impact of Delay in Testing

$K_{moist} = e^{\eta(\omega C - \omega T)}$

η = 0.18 for subgrades
η = 1.19 for unbound aggregates



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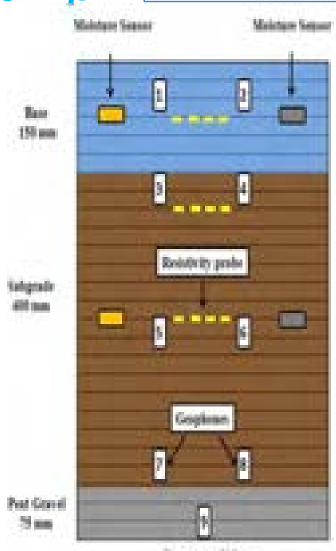
Field to lab Relationship

over 30 specimens



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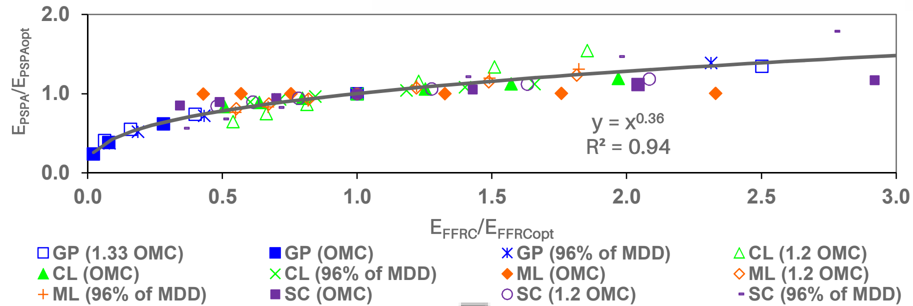
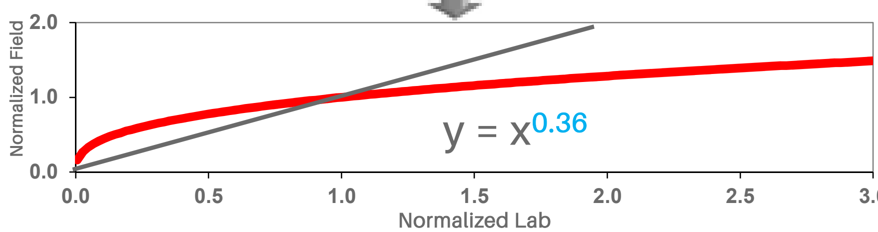
Lab vs. Field Moduli





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Service Life

LWD
12" Lime Treated Subgrade

Chainage (ft)	LWD Modulus (ksi)			
	D	C	B	A
250	6	5	4	5
225	6	6	7	6
200	7	5	6	6
175	7	6	4	6
150	16	9	11	7
125	14	10	6	6
100	9	6	7	6
75	8	6	5	6
50	9	5	6	8
25	5	4	5	8
0	6	4	5	8

+

LWD
12" Base + 8" LTS

LWD Modulus (ksi)			
D	C	B	A
43	38	51	32
38	35	41	43
27	30	46	26
33	35	39	30
34	31	36	36
36	35	45	34
37	29	39	30

Red < 75% of Average Value

Backcalculation
12" Base

LWD Modulus (ksi)			
D	C	B	A
66	82	122	74
57	66	162	151
43	74	151	58
71	107	160	75
68	90	104	87
153	148	240	79
106	98	148	60

Simulation Tandem Axle Rutting

7.5" HMA 500 ksi
12" Base 50 ksi
12" LTS 10 ksi Subgrade

Comparison

Service Life Reduction

Life reduction %			
D	C	B	A
234%	84%	180%	44%
168%	87%	57%	75%
52%	34%	94%	26%
55%	44%	49%	33%
65%	29%	48%	62%
38%	31%	64%	57%
52%	20%	50%	44%

Red < 75%

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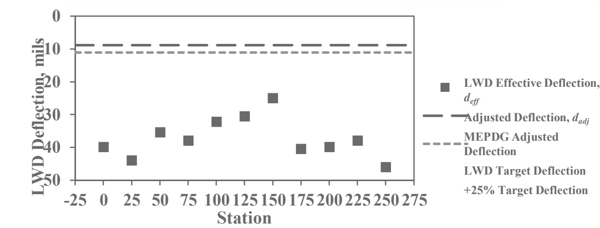
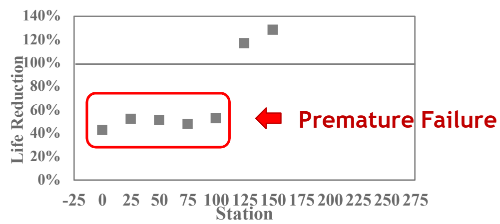
Service Life Reduction

Chainage (ft)	Life reduction %			
	D	C	B	A
250				
225				
200				
175				
150	234%	84%	180%	44%
125	168%	87%	57%	75%
100	52%	34%	94%	26%
75	55%	44%	49%	33%
50	65%	29%	48%	62%
25	38%	31%	64%	57%
0	52%	20%	50%	44%

Site 2





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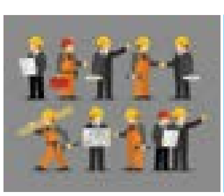
Concluding Remarks

- They did the best they could with what was available to them ~70 years ago to solve a major problem
- Engineering community pragmatically agreed that those tests improve quality, even though not perfect



Let's us pragmatically work toward implementing modulus-based technology to improve further construction quality **even though not perfect**

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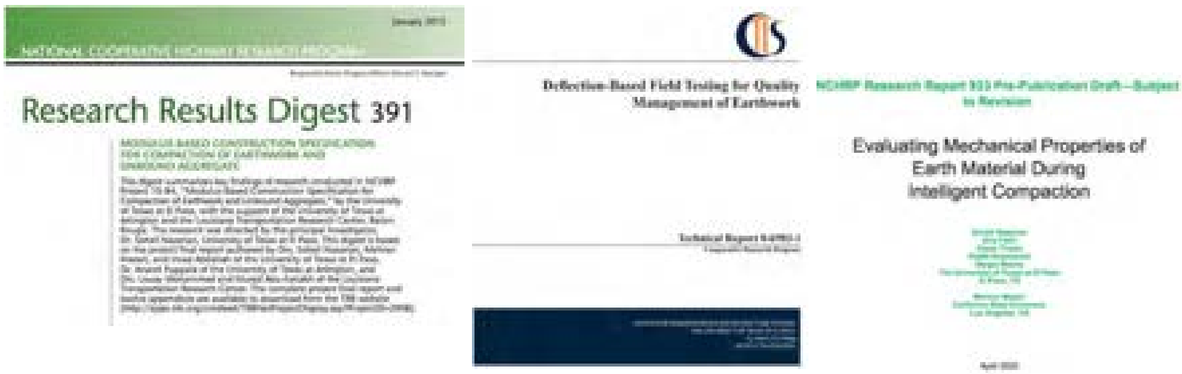
More info!!



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Thank you!!

- **A number of colleagues and students**
  - Cesar Tirado
  - Sergio Rocha
  - Mehran Mazari
  - Aria Fathi
  - Jose Garibay

Texas Department of Transportation

NCHRP

mn DEPARTMENT OF TRANSPORTATION

NRRA

Federal Highway Administration

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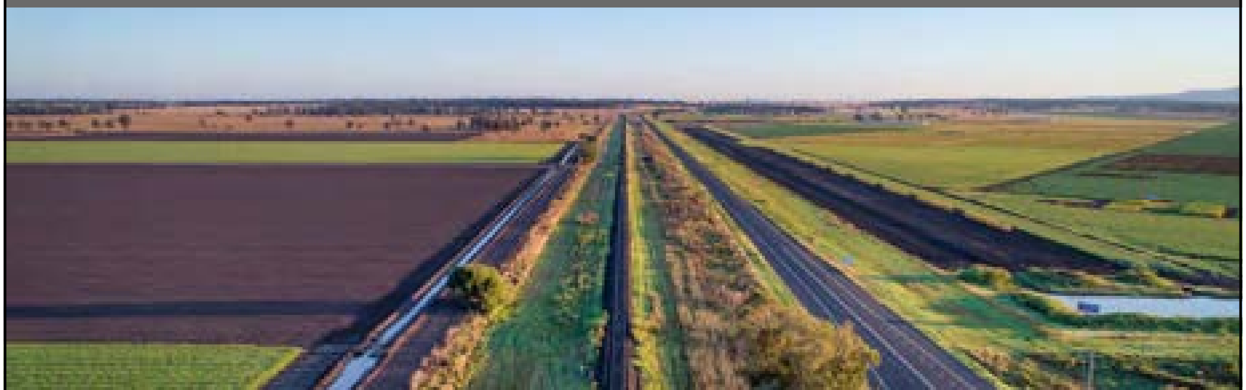
INLAND RAIL



- ARTC INLAND RAIL SHADOW COMPLIANCE TESTING
- LIGHTWEIGHT DEFLECTOMETER (LWD)

Andy Doe, B App. Sci. (Geol), M Eng. Sci. (Geotech), RPEQ, CGEOL.

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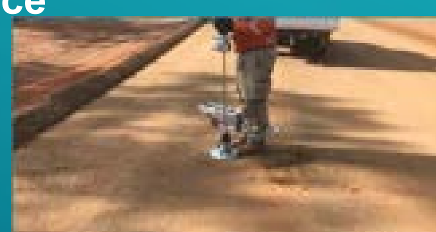
Introduction

INLAND RAIL

What, why and how of ARTC IR LWD 'shadow' testing

1. What testing did we do
2. Why look at alternative compliance
3. How we carried out the testing
4. Results



Lightweight deflectometer test next to standard compliance test

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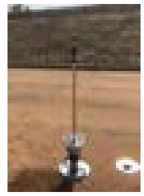
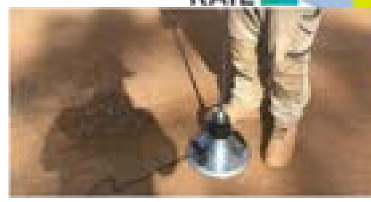
What?

INLAND RAIL

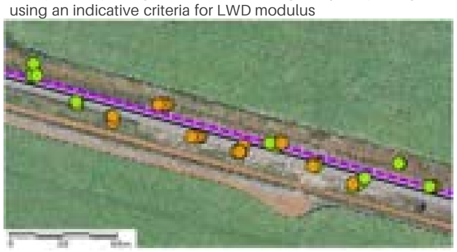
Test numbers carried out as part of shadow testing

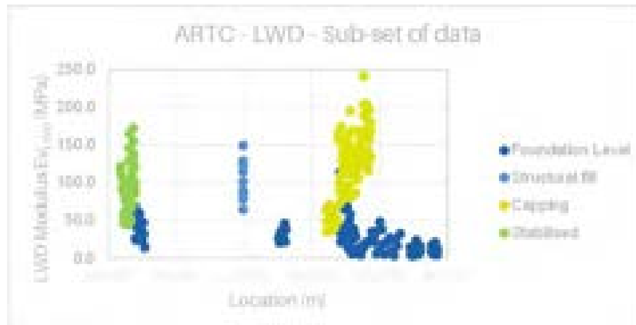
Material type	Approx No. of LWD tests	LWD test frequency
Capping	104	5 tests at 20m centres (40 test per 1000m²)
Structural Fill	124	3 tests at 20m centres (24 test per 1000m²)
General fill	113	5 tests at 20m centres (55 test per 1500m²)
Foundation level	238	1 to 5 tests at 8m centres
Total	579	





Geospatial reporting of results – 'traffic light' style reporting using an indicative criteria for LWD modulus





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Why?

INLAND RAIL

Why look for alternatives to standard compliance?

- Reduces time lag associated with standard compliance tests
- Instrumentation allows geospatial reporting
- Standard compliance uses index tests – with correlation margin for error
- ARTC amended earthworks spec in 2018 to allow for alternative testing

Why LWD?

- Tested parameters match design (no index tests!)
- Easily portable and safe to use
- Reports directly to geospatial platform
- Able to align with ongoing studies

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How?

INLAND RAIL

- An inland rail earthworks construction project was targeted for the LWD testing.
- LWD testing shadowed the standard compliance testing on four materials – foundation level, general fill stabilised with lime, structural fill and capping.
- The standard compliance testing included:
  - for fill - Atterberg limits, PSD, CBR and compaction testing
  - for foundation level – DCP, SVT where DCP results were low
- LWD tests were situated within compliance testing lots. Where possible LWD tests were carried out adjacent to standard compliance tests.

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Results

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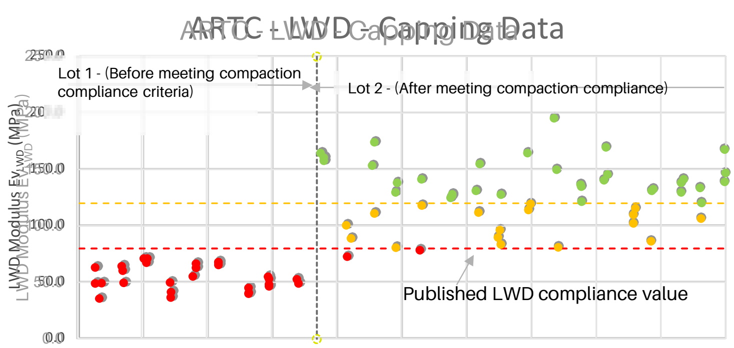

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ANY QUESTIONS?
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Closing Remarks
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