Comments / Questions regarding accounting for Moisture Content / Variation

1. **How is moisture ratio taken into account?**

This topic alone can be presentation in its own right and time did not permit going into this aspect during the webinar. For these test sites, Gravimetric moisture content is measured in the usual way. The volumetric moisture content is also measured in situ with a soil moisture meter

The moisture value is essential to determine the field dry density the moisture content when compacted. However, the FMC value at compaction is not the moisture content the next day when the next lift is to be placed. A 5% moisture change for some materials with an ambient day temperature above 30°C or if rain falls would not be unusual. So, in our current density-based approach we are blind to what the moisture content is at the time of placing a lift above. The moisture content at the time of sampling for the density ratio is not constant. Should we be again checking it just prior to the next lift? That question is relevant to both the existing status quo of density-based testing and to alternative testing.

The sensitivity of a specific material to the moisture content should be evaluated and incorporated into in any modulus-based earthworks specification. This relationship is expected to be material and site-specific – with some materials (typically cohesive or fines dominated) showing significant moisture dependency, whilst others show limited moisture dependency to the modulus parameter.

As an example, a current Australian infrastructure project evaluated the moisture-modulus relationship and accounted for the material-specific variation in the acceptance criteria implemented in the modulus-based specification. Based on the demonstrated moisture-modulus relationship, the minimum modulus parameter (*E*) to be validated onsite varied by 60 % as the Field Moisture Content (FMC) parameter varied between 3.5 % and 12 %. This allowed a modulus-based specification to be adopted for Earthworks QA for a material placed in various moisture states.

But that is not to say all materials would have the same moisture-modulus variation / relationship. Other materials / projects have demonstrated a single modulus parameter can be used as an acceptance criterion due to the lack of variation associated with moisture state of the compacted materials. The non-uniformity of the relationship between moisture content and modulus variation highlights the importance of initial evaluation and monitoring of the material throughout the project – regardless of the earthworks specification type adopted.

Further discussion relating to the moisture content effect on modulus-based earthworks specification will be provided in the final (Part 3) Webinar.

2. **Modulus is influenced by moisture too; so, shouldn't a comparison should MDD v Modulus include consideration of moisture content?**
3. **Was the moisture content/ratio taken into account when comparing the Density vs Modulus?**
4. **The statistical analysis doesn't acknowledge some frustrating variables (1) – e.g. Density Ratio v Modulus not considering moisture content.**

The simple answer is yes to the above questions.

Webinar time did not permit detailed discussion on this aspect. The key message for the presentation was that many alternative instruments are combining density + moisture + CBR + Underlying material into one measurement while we currently consider each independently.

The relationship between moisture content and modulus parameters is often cited as a key limitation that prevents modulus-based earthworks specifications being adopted. However, in the authors experience, the moisture-modulus relationship can easily be demonstrated and, if quantifiable, incorporated into a project- or material-specific earthworks specification.

In terms of how the moisture content relationship was incorporated into the analysis of the results collected for the recent ARRB project, all data and regression between density ratio and modulus parameters was completed via two (2) independent methods:

(i) Via single variable correlation, in which the density and modulus / penetration parameters were directly compared and did not incorporate any moisture parameter; and
(ii) Via multivariate correlation, in which the density and moisture test parameters were simultaneously considered in the comparison with the modulus / penetration test parameters. Linear and quadratic multiple variable correlations were attempted.

In terms of the density and moisture content parameters considered during the multi-variate correlations and analysis undertaken, the following were incorporated:

- *Density Parameters* – Field Dry Density, Adjusted Maximum Dry Density and Relative Dry Density (Density Ratio); and
- *Moisture Content* – Field Moisture Content, Moisture Ratio and Volumetric Moisture Content

For each “alternative” parameter considered by the ARRB study, there was both three (3) direct density-alternative parameter correlations attempted, as well as an additional 6 no. multivariate correlations attempted (incorporating a density, moisture content parameter pair). Thus, for each “alternative” parameter being compared to the results of density testing, a total of nine (9) correlations were attempted.

Although the incorporation of the moisture content parameters (i.e. the multivariate correlations) generally improved the strength of the defined relationship between density and modulus, the improvement was typically marginal. However, **at no location did the inclusion of moisture content parameters result in the correlation becoming of sufficient strength / statistically significant to demonstrate a strong relationship** (that could be adopted for use onsite).

As an example, Table 1 compares the derived strength of correlations for a specific tested material – as reported by the Correlation Coefficient (R^2) – and statistical significance (p) for density to modulus relationships that: (i) did not; and (ii) did include moisture content as a variable. Table 1 relates to the modulus observed from Light Falling Weight Deflectometer (LWD) testing being compared to density tests, but the trends have been consistent with all modulus-based “alternative” test techniques.

Table 1 Strength of multiple linear correlation assessments between Prima 100 LWD modulus, moisture content and Density parameters

Density Parameter	Moisture Content Parameter Incorporated	Max Coefficient of Correlation (R^2)	Statistical Significance (p)	Change in R^2 due to incorporation of Moisture Content
Field Dry Density (FDD) (n = 79)	NIL	R^2 = 0.05	p = 0.16	N/A
	Field Moisture Content (FMC)	R^2 = 0.14	p < 0.01	+0.09
	Moisture Ratio (MR)	R^2 = 0.15	p < 0.01	+0.10
	Volumetric Moisture Content (VMC)	R^2 = 0.08	p = 0.10	+0.03
	NIL	R^2 = 0.14	p < 0.01	N/A

Maximum Dry Density (MDD)	Field Moisture Content (FMC)	$R^2 = 0.27$	$p < 0.01$	+0.09
	Moisture Ratio (MR)	$R^2 = 0.34$	$p < 0.01$	+0.10
(*n* = 79)	Volumetric Moisture Content (VMC)	$R^2 = 0.18$	$p < 0.01$	+0.03
Relative Dry Density (RDD)	NIL	$R^2 = 0.15$	$p < 0.01$	N/A
	Field Moisture Content (FMC)	$R^2 = 0.21$	$p < 0.01$	+0.06
	Moisture Ratio (MR)	$R^2 = 0.22$	$p < 0.01$	+0.07
(*n* =61)	Volumetric Moisture Content (VMC)	$R^2 = 0.20$	$p < 0.01$	+0.05

A similar result is illustrated in Figure 1, this time for the secant modulus parameter derived from static Plate Load Tests (PLT) vs. density test results. As the per the LWD modulus vs. density case study presented above, the incorporation of the moisture content parameter does increase the strength of the parameter, but it does not provide a relationship of suitable strength for it to be defined as acceptable for use.

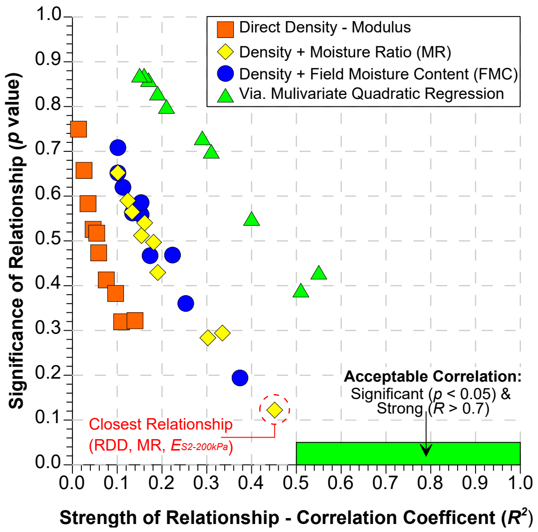

Figure 1 Plot demonstrating reported significance (*p* value) and strength (R^2) of attempted correlations between density, moisture content and PLT derived modulus using Secant Modulus (E_S) as dependent parameter.

All attempted correlations and analyses are fully detailed in the relevant ARRB project reports. **However, the consistent nature of the results demonstrates that – for the materials / sites evaluated by the ARRB project – there is no consistent evidence of a density to modulus parameter relationship, either via direct correlation (density – modulus) or via the incorporation of a moisture parameter (density, moisture – modulus).**

Presenting such technical details in a short webinar is not a good idea.

Further discussion relating to the moisture content effect on modulus-based earthworks specification will be provided in the final (Part 3) Webinar.

5. What was the moisture variations within all the testing?

The moisture content of the completed test sites (i.e. *insitu* moisture content of the compacted earthworks assessed at the time of testing) varied between the individual materials being considered. The range of field moisture content and moisture ratios reported for each of the assessed materials are summarised in Table 2. Full details of the characterisation of the materials that were subjected to assessment are included in the relevant ARRB project reports.

Table 2 Summary of Field Moisture Content and Moisture Ratio ranges associated with each test site

Year of Study	Site ID	Field Moisture Content (FMC)		Moisture Ratio (MR)	
		Range	Median	Range	Median
2017 (Year 2 of ARRB Project)	Site 1 (10 sub-sites)	4.5 – 6.6 %	5.5 %	51.1 – 68.8 %	58.5 %
	Site 2 (10 sub-sites)	8.4 – 11.3 %	9.8 %	76.1 – 97.4 %	82.9 %
	Site 3 (5 sub-sites)	7.2 – 8.8 %	8.7 %	77.7 – 82.9 %	80.0 %
	Site 4 (8 sub-sites)	5.4 – 7.0 %	6.2 %	67.5 – 77.8 %	75.1 %
	Site 5 (10 sub-sites)	12.3 – 23.4 %	15.0 %	84.5 – 104.0 %	89.5 %
	Site 6 (4 sub-sites)	4.7 – 5.9 %	5.3 %	74.3 – 98.3 %	83.3 %
	Site 7 (4 sub-sites)	6.5 – 6.7 %	6.7 %	72.2 – 74.4 %	73.9 %
2018 (Year 3 of ARRB Project)	Site 1 All Sub-Sites (*n* = 132 tests)	4.2 – 10.1%	7.1 %	52.5 – 126.3 %	84.9 %

Comments / Questions regarding turnaround time for completion of Density / CBR tests

6. Density Ratio can be performed within 1 day as per AS 1289 5.7.1.

This is correct and applied to the Hilf Method. As an Australian Standard this is accepted practice.

The method suffers from the same oversize issues as the traditional "slower" density testing. The Hilf method is quick as it bypasses "proper" curing as per other standards. Data was shown on initial webinar slides (slides 12 and 13) on the differences in results that occur with and without curing. As the moisture varies from OMC (wet or dry side) the Hilf method becomes less reliable.

7. Most Victorian testing for earthworks is using rapid HILF method which does not normally require curing if within the test method range.

See above response. This approach is used across Australia and is an accepted test procedure. There is little recent research data in literature to quantify the reliability of this accepted practice. Any data would be appreciated on the reliability of the Hilf Method, specifically the effect of not curing which is known to change results but has not been quantified.

8. He [the presenter] is referring to assigned value and not the HILF compaction.

Correct. Thank you for these comments as Hilf is an accepted approach. The Australian Standard 5.4.2 with Assignment of MDD and OMC values is also a "quick" approach, but requires curing – and that was what was mentioned.

Comments

CBR results in commercial labs are typically reported within 2 weeks.

This is true and thank you for the comment. The results shown were provided to us from commercial labs and the difference in time between time of sampling and issue of certificate was unexpected. This timeframe – all from commercial laboratories – can vary based on the material type, required surcharge and soaking length, laboratory workload etc.

Based on the authors experience, the length of time taken to return a soaked CBR test – as typically required by earthworks specifications – is often longer than that available to make onsite decisions. Thus, it is frequently observed that materials have been covered with other works (and are now potentially inaccessible) prior to the CBR test results being available.

Furthermore, in the context of assessing modulus parameters from CBR – e.g. to validate the design modulus parameter via CBR testing – the CBR to modulus relationship is also known to be extremely variable. As per the Austroads' (2009) discussion paper on the topic, use of typical CBR to modulus relationships parameter would be expected to yield a modulus parameter that may be "100% to 300% higher or lower than expected". Accordingly, in the context of this project, the use of insitu, direct modulus assessment techniques that allow near-instantaneous results to be achieved, was being evaluated.

Comments / Questions regarding other test methods & parameters presented

9. **Are there any case history recorded significant numbers of PLT vs LFWD?**

The authors have, over the previous 5 years, developed a database of approximately 250 sites where side-by-side static Plate Load Tests (PLTs) and Light Falling Weight Deflectometer (LWD) tests have been conducted. These tests are currently being written up into a separate technical publication.

In terms of existing published research, Table 4-16 of the Year 1 Report for the current ARRB project has a list of relevant technical publications where modulus parameters derived from PLT and LWDs are fully detailed, along with the LWD and PLT configurations adopted for the study and the derived correlation. This report can be freely downloaded from http://nacoe.com.au/publications/ (document ID: PRP16036)

10. **PLT has shown vice-versa results and how can we take it PLT as reliability test?**

Firstly, the PLT results may be the one most likely to be skewed as compared to the other results. The plot shown in Slide 26 for the Plate Load Test (PLT) was an initial assessment of the variation of the PLT test results based on determining interquartile variation of results at each site. This initial assessment was different to that employed for the other test results and was due to the smaller sized dataset (3 to 4 only at each site due to the time associated with the PLT). With all other equipment tested 5 to 10 tests were generally able to be carried out in the same time at each test site but with up to 20 PANDA tests. This non equality of tests may affect the actual results. However, the overall ranking conclusion would be similar.

Additionally, the PLT would have a different COV at E_{V1} or E_{v2}

The key point relating to the variability of the *insitu* tests is that the CoV associated with the density test results is significantly lower than all other tests techniques. This is considered to demonstrate the comparative precision of the density test results, but not the accuracy of its ability to assess the ground conditions in terms of the accompanying variables that influence the embankments performance. The density parameter is not reflective of variation of the design parameter typically observed across the prepared surfaces (i.e. all modulus test techniques demonstrate ~30% CoV across the prepared surface) – and as it is the design parameter (i.e. modulus) that should be being verified by the QC testing, the comparative precision (due to the 1 variable being assessed) offered by the density test is not specifically advantageous.

Your question is valid as the PLT has such large variability in a statistical sense. In practice, we would not apply statistics to PLTs because of the low number of tests able to be carried out. Instead we would adopt the lowest PLT value (from the 3 or 4 tests say) as confirming acceptance of a minimum strength or modulus. The statistically high variation should not diminish its usefulness as a reliable test – it is the statistical approach on a low number of tests that is unreliable.

The other tests had a larger samples size and considered to be statistically reliable.

Thank you for this question which highlights statistical reliability.

11. The statistical analysis doesn't acknowledge some frustrating variables (2) – e.g. density ratio v CBR not considering material type

These were 5 different sites – all were what were made available to us for "live" projects to compare equipment. Our focus was not on actual values but on comparison between equipment hence not providing specifics on material types. Details on material type were not presented for brevity. Variation of sites as follows for sites 1 and 5 shown below

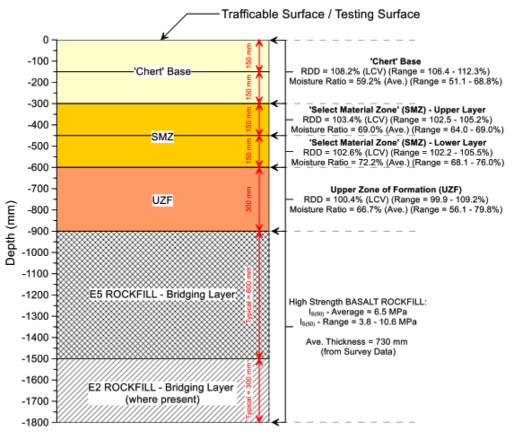

Figure 2-1 Sketch showing near-surface profile and characteristic density test results for testing Site

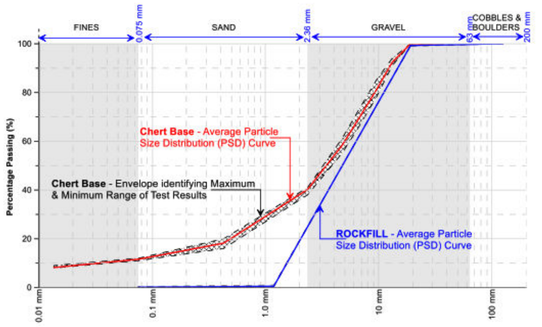

Figure 2-2 Particle Size Distribution Curve – Materials utilised at Site 1 for which grading information available

Table 2-7 Site 1 – Atterberg Limits and Soaked CBR test results for 'Chert' Base Layer (pre-compaction)

No. of Samples (*n*)	Liquid Limit (%)		Plastic Limit (%)		Plasticity Index (%)		Soaked CBR (%)*	
	Range	Average	Range	Average	Range	Average	Range	Average
5	19 – 20%	19.4%	13 – 16%	14.4%	4 – 6%	5%	80 – 120%	98%

* CBR Samples compacted to 100% Max. Dry Density and OMC

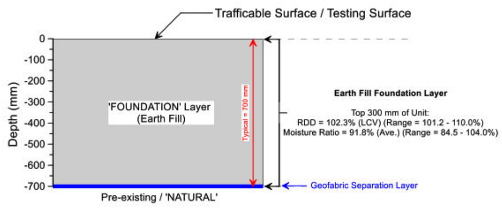

Figure 2-9 Sketch showing near-surface profile and characteristic density test results for testing Site 5

Table 2-27 Site 5 – Atterberg Limits & Soaked CBR Test Results (post-compaction condition)

No. of Samples (n)	Liquid Limit (%)		Plastic Limit (%)		Plasticity Index (%)		10 Day Soaked CBR (%)	
	Range	Average	Range	Average	Range	Average	CBR Value	CBR Swell
1	–	39%	–	23%	–	16%	5%	1.8%

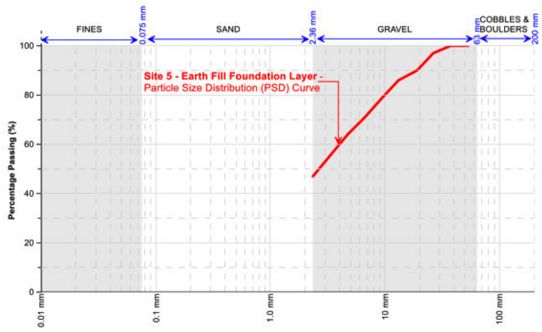

Figure 2-10 Particle Size Distribution Curve – Grading information available for Earth Fill Foundation Layer installed at Site 5

12. Embankments need to have a required modulus for strength as well as minimise settlement. Isn't density a measure of minimising settlement and therefore still important?

Density is important. So also, is moisture content. Minimising settlement is a key objective and is important. Their importance was not the focus of this presentation.

The discussion's focus is on what does a particular density ratio mean. Yes, an embankment needs a required modulus or strength, but how do we determine that from a density ratio? An example was shown of a 95% density ratio having a varying modulus for 3 different materials (35 MPa to 60 MPa).

As the strength, modulus or minimising settlement is always important, this webinar focuses on how do we measure those important aspects - as density ratio does not give us a clear answer.

13. A dry material with low density will have a high modulus, but is this all we care about?

Any one slide is not indicative of "all we care about". Information in any presentation is in parts and concepts amalgamated at the end.

Density ratio – being the assessment of the achieved (field) vs. maximum dry density – can be used as a measure of the remaining air voids and can be used as an assessment of if additional effort would result in further compaction the material (noting that effort vs. reward dramatically reduces as the density ratio increases between 95 and 100%).

However, such information is not the sole domain of density testing. For example, the assessment for the further potential of material compaction can be made via comparison of the initial vs. reloading modulus from Plate Load Tests (i.e. E_{v2}/E_{v1}) or the load vs. deformation graph constructed by the Light Falling Weight deflectometer (i.e. the amount of settlement observed under a known, and variable load). Thus, the proposed "alternative" test techniques have an equally valid ability to identify locations that would be susceptible to future settlement under loading as the density test currently does.

Questions / Comments regarding Specific Presentation Slides

14. **Slide 17 – These are awful results and not representative of road construction projects in NSW. What is the source of this data? PS. You are showing density (ratio) results and not quality test results!**

Agreed these were surprising and are "awful" results as we expected faster turnover of results. This is simply tabulating data given to us and its date of sampling and dates of test reporting.

Slide 17 details the reported time (number of days) between site material testing being completed and the test certificate being issued, for both CBR and Density Tests. This is based on a sample of 746 (CBR) and 5619 (Density) certificates, available to the authors.

We are not attesting that the turnaround time is always the same / always excessive – as the results show there is a wide variation in the turnaround times presented. Additionally, it is likely there was verbal reporting prior to the certificate. However, the point of the slide was to demonstrate that the results are not always provided quickly and the delays can be considerable.

As per the comment, the slide does include density test results, so the title should read "Material Quality and Compaction Tests".

15. **Slide 19 – One crucial item is the location of the test results, that is layer and GPS / Chainage and Offset! Why is this mixing?**

Slide 19 (and surrounding Slides) don't have any information relating to the spatial location of the tests being conducted, so the authors are unsure of the intent of this comment.

Assessment were on a lot basis

However, as per the comment, the correct (random) location of tests is critical to any earthworks Quality Assurance (QA) program. The assessment of a true range of material conditions within a prepared lot is required regardless of whether the specification is based upon traditional (density) based or via "alternative" assessment methods – such that the undertaken testing has the best chance to both (i) identify the weakest area; and (ii) provide the characteristic condition of the prepared materials.

16. **Slide 23 – If you are placing and compacting in 300 mm lifts, the LFWD and PLT will not give you reliable results as it influenced by the underlying layers. Therefore, why would you use this equipment?**

Correct. The range of test depths in the trail were selected to show both influence and no influence. 300mm is also a reference depth used in many Standards, this sets the base case. The selected depths were required by both the contractor and Road authority.

The insitu modulus parameter derived by the LWD and PLT are composite values that are generally taken as representative of 2.0 x the Plate Diameter (static PLT) and 1.3 – 1.5 x Plate Diameter (LWD). As both test techniques can be completed using variable sized plates, the tailoring of the test technique to the compacted lift thickness can be easily achieved. For example, the LWD plates typically come in 100-, 200- and 300-mm diameters, whilst the common plate sizes available for a PLT are 100-, 150-, 200- and 300-mm diameters. This means the LWD can effectively assess lifts with thicknesses of between 130 and 450 mm (compacted) depth, whilst the PLT could assess 200 to 600 mm compacted thicknesses.

Accordingly, both the PLT and LWD test techniques can be easily tailored to match the 300 mm (uncompacted layer thickness) as well offering the potential for evaluation of thicker lifts. This highlights the versatility of the plate load tests used in the study.

As it is the limitations of the current (density) test techniques that currently limit the allowable lift thickness – modern construction plant can effectively compact the full thickness of lifts placed well in excess of 300 mm – the use of the LWD and PLT offer significant efficiencies to the project due to their greater 'zone of influence' (test depths).

In terms of the use of the LWD and PLT in the ARRB study being discussed, the nature of the material was fully evaluated by the accompanying penetration tests (i.e. PANDA and DCP test results extended to full depth of 'zone of influence' of plate tests). Similarly, the Prima 100 LWD was undertaken with a combination 100-, 200- and 300-mm diameter plates at each test site, and thus the depth that the LWD test evaluated (and any non-linearity in the resulting load vs. deformation plots that arose due to the state of the underlying layers) was assessed.

Additional tests were carried out at depths while the embankments were deconstructed.

The purpose of those slides on that trial was mainly to show test data which is not typically measured eg the change of dynamic force with each pass, and different for each layer and each material.

17. **Slide 25 – You have only tested and analysed one formation material. How can you draw any early conclusions?**

Slide 25 relates to rollers fitted with Intelligent Compaction (IC) based devices, and was included in the presentation as an example of other modulus-based measurement technologies that are becoming increasingly available. However, this was not specifically evaluated in the NACOE project that the presenters were discussing – and the one slide was included only to raise awareness of other methods of measurements. The compaction meter value (CMV) used in IC is a different unit of measurement from density or density ratio, or Clegg impact value or Plate Load EV_2 or Deflectometer modulus, etc. That IC slide was not an "early conclusion"- only to show another measurement unit. As mentioned in the webinar, IC is a separate ARRB project.

The comment presumably also relates to the effectiveness of IC technologies and the potential for hand-held based modulus-based field tests (e.g. Clegg Hammer, PLTs or LWDs) to correlate the IC derived modulus value (i.e. modulus parameter from field testing relates to the IC provided modulus value / index). Although not part of the "core" project being discussed in the presentation, the authors have personally been involved in Australian based field-trials where such relationships have been demonstrated. There are extensive publications upon this topic (largely based on international field testing) that can also be reviewed.

18. **Slide 29 – Work in the USA has shown the portable hand held FWD devices are suspectable to moisture content of the material being tested and have you taken this into consideration to the reliability of the test results from these devices?**

Yes – as in any test moisture content is a variable that should be considered. The ARRB project also incorporated a full assessment of any relationship between the insitu modulus parameters reported by the Light Falling weight Deflectometers (LWDs) and the moisture content of the material being tested.

Please see comments made in reply to Questions 1 to 4 for further details. The authors fully acknowledge that the moisture content – modulus relationship of materials must be evaluated and, if required, incorporated into the project-specific earthworks specification.

19. **Slide 50 - You would have to be a brave road agency engineer to allow a contractor to use 1000 mm lifts for embankments with a 18 T padfoot roller!**

Agreed. This is a Trial, and the 1,000mm was selected as it was expected to "fail". The road authority needed to compare the results associated with "failure" as well as passing results eg 300mm.

The inclusion of the 1,000 mm (uncompacted) lift thickness and evaluation of the achieved level / depth of compaction within the trial embankment was to ensure the limitations of the rollers included in the trial could be demonstrated. The expectation was that the depth of effective compaction would not be "full layer thickness" for the 1,000 mm area and was included in the trial embankment in order to demonstrate this – the results did indeed show the upper limit of the rollers was to compact a lift placed at between 600 and 800 mm (uncompacted thickness).

No-one suggested that a 1,000 mm lift thickness would be viable in this scenario or should be included in any earthworks specification.