RETHINKING EARTHWORKS QUALITY TESTING

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ABSTRACT

Earthworks quality assurance has traditionally relied on density and moisture content testing along with California Bearing Ratio (CBR) as the primary indicators of compaction and performance. While these methods provide a useful and long-standing framework for earthworks construction control, their dominance has created a "density illusion": the belief that achieving a high target density ratio equates to long-term performance reliability. This illusion has constrained the adoption of more representative, performance-based approaches, despite advances in geotechnical science and measurement technologies. The historical perspective of density being the preferred earthworks quality test method is re-examined with comparisons with current (past 20 years) test methods.

Results of surveys show there are many common geotechnical tests that are not trusted. This is due to testing variability, correlations and interpretations of these tests. Each test is treated as a black box, but in reality the tests are laboratory or field models with associated assumptions. High precision is not the same as accuracy.

Statistical techniques such as dendrogram analysis and correlation matrices are used to show patterns and identify relationships between different test variables and compared with results in a correlation matrix. Such comparative analyses demonstrates that reliance on CBR and density testing indices can obscure other critical performance indicators. The high precision of density testing hides its inaccuracy to assess key design parameters. Correlation errors occur when relating to more accurate tests. Density testing is only step 1 of a 3 stage quality assurance process.

1 INTRODUCTION

Common practices in geotechnical engineering seem to have many silent inconsistencies that as an industry we do not question as the test or practice is widely used. This anchoring and availability bias as a cognitive dissonance was discussed in Look (2025a). The historical legacy anchoring and construction material testing (CMT) is first examined with a comparison with our trust with common geotechnical testing. This trust was determined from a poll survey of practicing geotechnical engineers and engineering geologists. The poll showed as an industry we continue to use the results of tests we do not trust. Case studies are then used to examine the reliability of such tests.

Another poll compares what attributes of testing we most desire for quality control equipment. Again, this shows the dichotomy of industry practice versus what we want to see in a practice.

Many tests were developed with a different technology or material type. In an attempt to standardise, early tests then become universal and applied to different materials and have continued to a time when technology has changed. As an industry we then adapt the tests rather that start over, so as not to criticise tests which have served industry well in the past. We are openly afraid of what is unfamiliar, uncertain or requires different skills. This presupposes knowledge is static. It is not. This should not be viewed as not adhering to principles developed to avoid past failures.

As individuals, the advice that serves you at 25 years old does not apply at 50 years old. That is stagnation. Growing up should not mean being a slave to the past. This applies to our profession, as we develop and know more, the methodology developed in our first 25 years past may not now be applicable with different processes or changing technology. That is not suggesting the founding fathers being wrong in the past. This is about growing up as a profession in the present.

This means accepting precision is not the same as accuracy on our tests. In analysis a factor of safety reported to 3 decimal places (say 1.543) implies 3 decimal places of precision (± 0.001). Experienced engineers accept that value as incorrect. Similarly, an undrained strength in a clay with a test value (say 32 kPa) is not correct to 1 kPa. Our founding fathers in geotechnics got around such inaccuracies by "classification". The strength then became a classification range (firm clay with 25 to 50 kPa range). This indexing accounts for errors with any single test value.

Words like "optimum" and "maximum" in a technical application should not be confused with an equivalent translation word of "best". This equivocation has led to many misunderstandings in the CMT industry. Are we confusing the most used tests with the most trusted?

2 SURVEY OF PRACTICING ENGINEERS

Surveys of different groups over the years were carried out (and were not specific to this paper) to establish industry practices. A few of these results are discussed.

2.1. GEOTECHNICAL TESTS TRUSTED AND NO TRUSTED

A word cloud poll survey of geotechnical professionals was carried out in November 2025 at the Queensland Geotechnical symposium for various levels of experience. A similar survey was carried out in New Zealand in October 2025 but without the age grouping. The survey responses on the question of geotechnical tests to be trusted or not trusted is summarised in **Figure 1**. Each grouping represents between 11 to 17 responses. This is a summary only as many other tests with 1 or 2 mentions only are not shown.

There is a clear conflict in the geotechnical industry practice with the following rankings:

1. The SPT is the most trusted test overall. The SPT is also the least trusted test overall.
2. The CPT is the 2nd most trusted test overall. The DCP is the 2nd least trusted test overall. Note the DCP is also trusted by some practicing engineers
3. The Vane Shear test is the 3rd most trusted test. The CBR is the 3rd least trusted test. The pocket penetrometer (PP) was also mentioned as a test not to be trusted

The CPT is trusted, but the survey did not provide any distinction between the many variants of the test e.g. seismic CPT or CPTu.

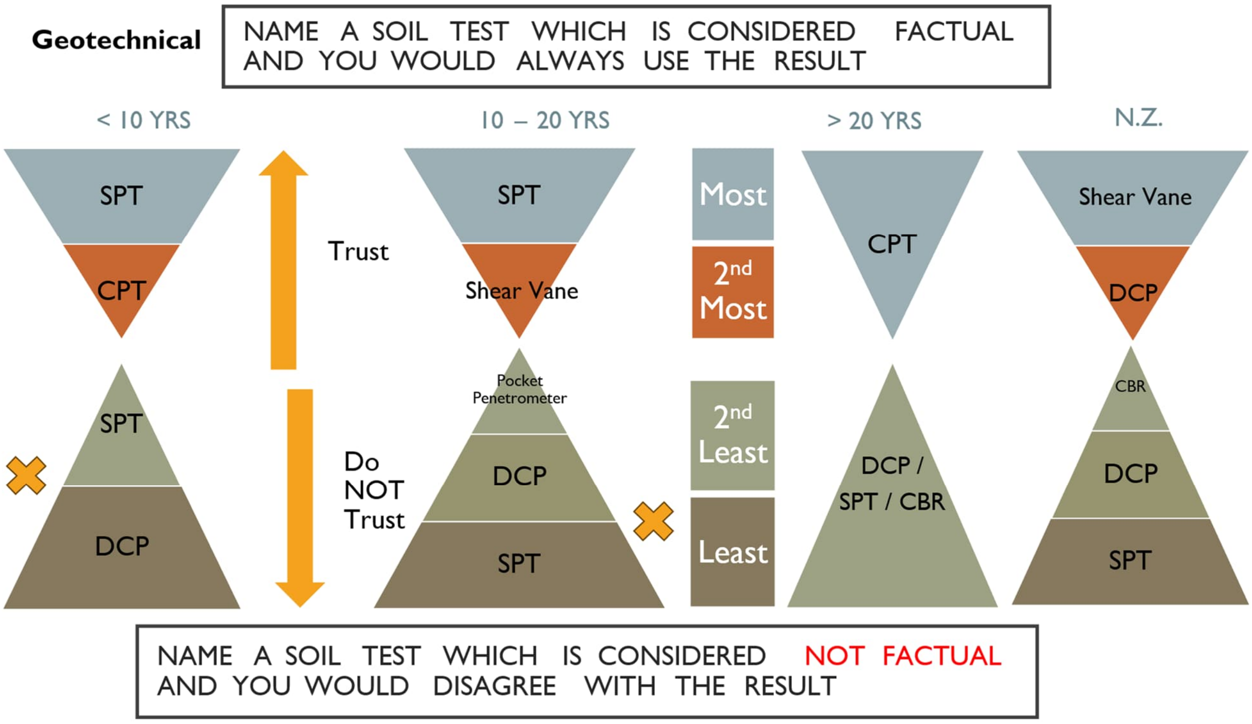


Figure 1: Survey of geotechnical professionals in 2025 on test to be trusted or not trusted. Each grouping represents between 11 to 17 responses with 54 responses in total – a yardstick only

The dichotomy of using a test and trusting its value has been exposed in this survey. One wonders if the respondents may have confused the “most used” ≈ “most trusted”. The geotechnical testing for DCP, SPT, CBR and PP are ubiquitous and raises a fundamental philosophical issue on whether we differentiate between high usage and “truth” of a test. The availability bias was discussed in Look (2025a). Our judgement is influenced by readily available information and what springs easily to mind, rather than its “truth”. As engineers we chase numerical values as a fact where there are many other factors affecting how that number should be applied. Many tests have underlying assumptions, and the procedural aspects according to standards can be trusted. Directly using the test results is another matter.

2.2. TESTS TRUSTED AND NO TRUSTED BY CIVIL ENGINEERS

When civil engineers and project managers (non-geotechnical specialists) are asked the same question, there are different sets of trusted and non-trusted words (**Figure 2**). Construction control tests such as OMC and Density Ratio tests are not to be trusted by this cohort. In all cases the experience level was approximately 10 years (90% between 5 to 25 years) but the contractor survey respondents were in the 5 - 10 year experience level.

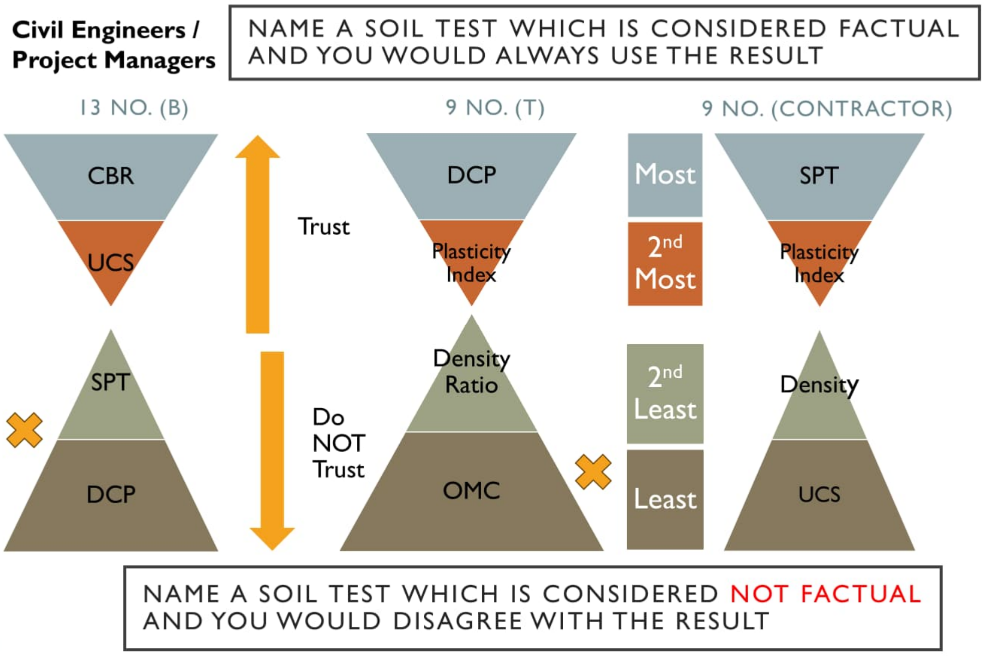


Figure 2: Survey of civil engineers and project managers in 2025 on tests to be trusted or not trusted. Each grouping represents between 9 to 13 responses with the Nos shown (31 total in survey). (B)and (T) represent the survey location

The responses to the question on "At what moisture content does the maximum CBR occur?" show most practicing professional believe this is at the optimum moisture content (OMC) (**Table 1**). Only contractors are divided on this response with 50% also believing the maximum CBR may not be at the OMC. The common fallacy of the maximum CBR being at the OMC will be discussed in subsequent sections, as a key focus of this paper. The CBR test as part of construction material testing (CMT) has many assumptions to be appropriately applied in practice.

Table 1: Responses to multiple choice question: "At what moisture content does the maximum CBR occur?"

Survey Group A, B. T and (No.)	Geotechnical (17 No.)	Civil engineers and project managers			
		A (10 No.)	B (15 No.)	T (15 No.)	Contractor (10 No.)
Maximum CBR @ OMC	59%	63%	93%	93%	50%
Dry of OMC	29%	21%	0%	0%	20%
Wet of OMC	0%	5%	0%	0%	10%
Unknown	12%	11%	7%	7%	20%

Overall, these surveys show practicing and experienced engineers have a highly variable opinion on whether a test is trustworthy.

2.3. DESISABLE ATTRIBUTES IN A TEST EQUIPMENT

A survey of 54 engineers (Look, 2018) on ranking what attributes are desirable in an earthworks quality control test equipment showed that accuracy is the most preferred attribute of any test. The preference ranking order for attributes of a test equipment from that survey was (**Figure 3**):

1. Accuracy
2. Precision
3. Time to do test
4. Time to report test

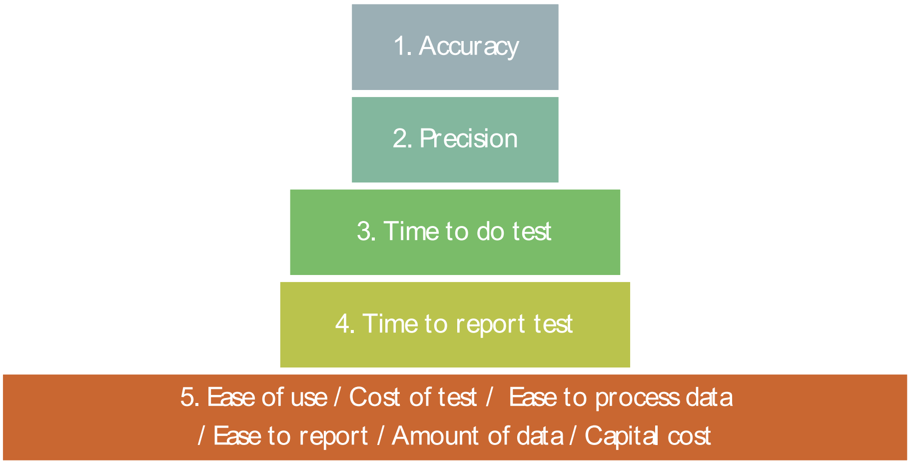


Figure 3: Survey in 2017 on what test attributes are desirable in quality control

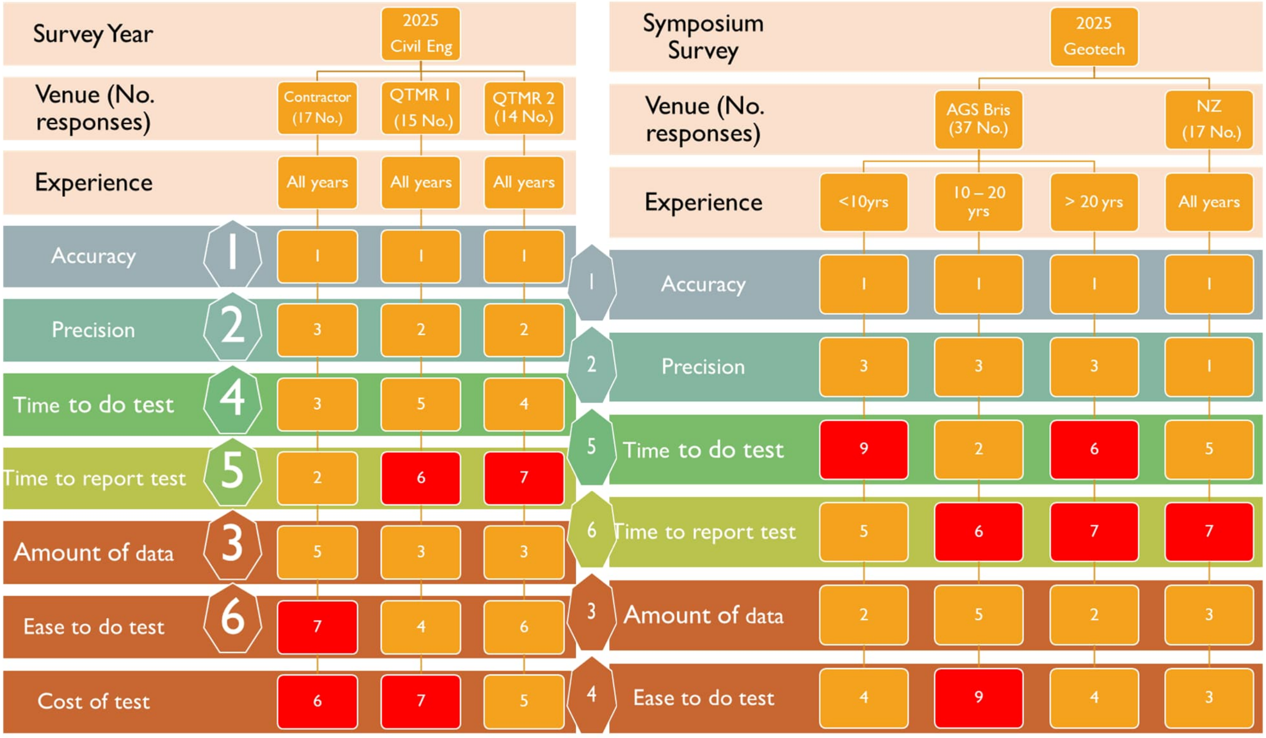
The other factors were closely ranked: Ease of use; Cost of test; Ease to process data; Ease to report; Amount of data obtained; and Capital cost of equipment. That survey was repeated in 2025 in various groups (**Figure 4**) with an attempt to differentiate for:

- Years of experience (< 10 years ; 10 – 20 years ; and > 20 years)
- Industry work (contractor / government (civil Engineers, project managers and inspectors) / geotechnical engineers and engineering geologists
- Location (New Zealand and Queensland)

The survey results shows accuracy and precision are overall ranked number 1 and 2, respectively, in all cases. However, amount of data was now (2025) ranked number 3. Times to do and report test are now (2025) not in the top 4 critical issues for geotechnical professionals with ease of test taking precedence. This order changes for the grouping of contractors, civil engineers and project managers.

An interesting outlier is the time to do the test for those with less than 10 years of experience. They are likely the ones doing the test, and less likely to be concerned with time and cost as their older colleagues. Conversely a contractor ordering the test has this as highly ranked. Industry would consider amount of data as important (No. 3 ranking) while contractors (who are typically project managers ordering the test) consider time to do and report the test as more important.

These factors will now be discussed in light of available construction material testing (CMT) methods. This paper discussion will focus mainly on the anomalies in **Figure 2** and not **Figure 1**, as the former is more associated with CMT while the latter is associated with site investigation overall.



Survey Year		2025 Civil Eng	
Venue (No. responses)	Contractor (17 No.)	QTMR 1 (15 No.)	QTMR 2 (14 No.)
Experience	All years	All years	All years
Accuracy 1	1	1	1
Precision 2	3	2	2
Time to do test 4	3	5	4
Time to report test 5	2	6	7
Amount of data 3	5	3	3
Ease to do test 6	7	4	6
Cost of test	6	7	5

Symposium Survey			2025 Geotech	
Venue (No. responses)		AGS Bris (37 No.)		NZ (17 No.)
Experience	<10yrs	10 – 20 yrs	> 20 yrs	All years
1 Accuracy	1	1	1	1
2 Precision	3	3	3	1
5 Time to do test	9	2	6	5
6 Time to report test	5	6	7	7
3 Amount of data	2	5	2	3
4 Ease to do test	4	9	4	3

Civil engineers and project managers **(b) Geotechnical engineers and engineering geologists**

Figure 4: Survey in 2025 on what test attributes are desirable in quality control

2.4. TRUSTED RESULTS AND PRECISION

A brief discussion on PP, SPT and DCP is provided below. These tests are not associated with CMT but were shown as conflicted in their reliability. The CPT is generally one of the more trusted field tests. However, there are source of errors associated with calibration and the load range of the cone when used in soft clays (Scholey, 2024).

Sample size often affects the test results. The pocket penetrometer (PP) is a simple test commonly used as a measure of the undrained shear strength. Its simplicity, low cost and availability often tempt many field engineers into its overuse. Due to the small test area, the PP will likely overestimate the strength in a fissured clay. The argument heard is that any test result is better than no test result. Look (2025a) discusses the availability bias as PP test results are easily obtained, but this does not mean they are useful, with often meaningless results that may lead to wrong data for analysis if such test numbers are applied (Look, 2004).

SPT N- values require an energy correction to be used in design (Look, 2025a). SPTs with high and low values are typically subject to a wide interpretation. A flawed circular argument is often used as follows:

- A clay is very soft, therefore N value ≤ 1 is correct. However, the reverse logic does not necessarily apply.
  - If N value ≤ 1 does not mean a clay is very soft.
- A driven pile is unlikely to refuse at N value < 50. Again, the reverse logic leads to an incorrect interpretation
  - If N value > 50, stating a pile has reached refusal is incorrect

At high SPTs, relative density is uncertain and the strength or modulus has a wide interpretation (**Figure 5**). This uncertainty applies when the SPTs are used in residual soils or gravels. A similar uncertainty occurs at high compaction levels when the dry density ratio (DDR) is used to infer strength or modulus. There are similar issues with correlations and material type when DCPs are used, especially at DCPs < 2 or > 10 blows / 100 mm.

The variability of test results would affect whether one would trust the results. The variability can be judged by the coefficient of variation (COV) and is discussed in Look (2024 and 2025b). Below a COV of 35% there would be a general agreement of a "uniform" result or section of a site. Above a COV of 80% the site should be considered non uniform and at COV of 60% the site is unlikely to be uniform.

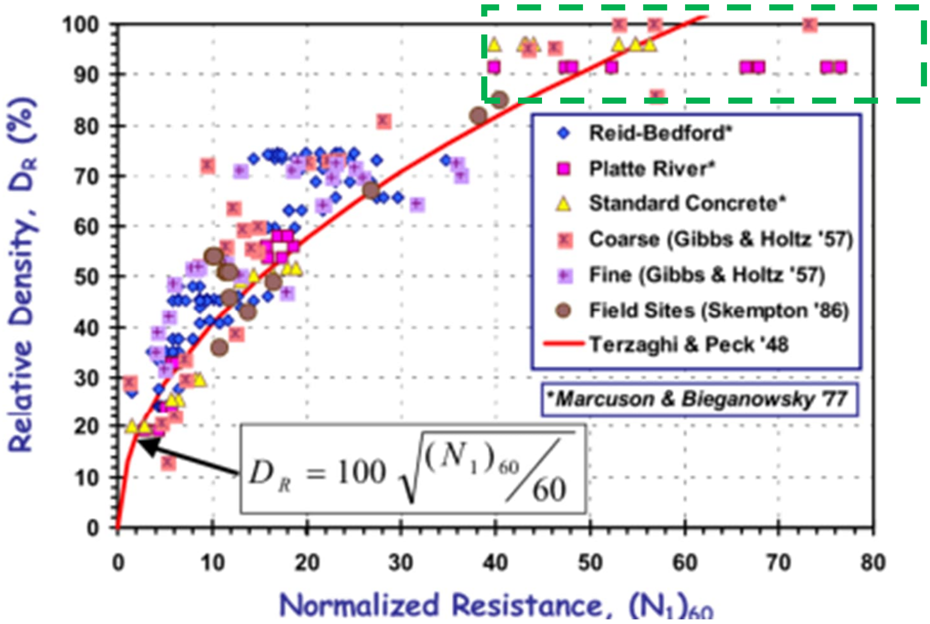


Figure 5: Relative density of clean sands from SPT (Mayne et al., 2002). Highlighted box shows the above D_r of 85% ($N_{60} > 40$), the corresponding strength or modulus would be subject to a wide interpretation

Look (2024) associates high COV with non-normal probability density functions (PDF) and there would then be 4 opinions for every 5 engineers on the "design" value and outside of a target zone (**Figure 6**). Thus a "uniform" site or selecting design values should use the COV to avoid too wide a variability. The trusted / non trusted test results and their comparative COVs are provided in **Table 2**. The typical COV was obtained from the various references in Look (2014) but based mainly on the seminal work of Phoon and Kulhawy (1999) on inherent testing variability.

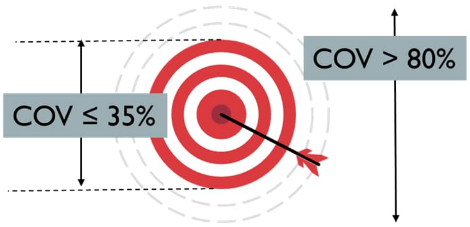


Figure 6: When can normal PDF be applied and a site is uniform vs non uniform

Table 2: Inherent soil test variability and trust

Measurement	Trust	Typical COV (%) without outliers	Comment
Shear Vane	Yes	25% (Clay)	Correction factor for Plasticity Index required
CPT		30% (Clay) ; 40% (Sand)	Improves with CPTu or seismic cone. Calibration required
Plasticity Index		24%	Discards material retained on 425 micron sieve
SPT	Yes / No	40%	Energy correction required before using as a design value
DCP		45%	Increased COV for DCP blows / 100mm < 5
MDD	No	3%	Tests requires curing and removal of over size. Above 20% oversize test is not applicable. Correction for oversize content not more than 20%.
OMC	No	20%	
CBR	Yes / No	40%	Lab compaction energy may not be the same as compaction field energy (varies with equipment used)
UCS	No	23%	The intact UCS value does not apply to apply field value for a jointed rock mass

The comparison of trust versus COV show no clear relationship. One may conclude that experience and site observations are the predominant reasons for trusting a test result. All the tests which industry does not trust have a disconnect between lab and field conditions.

The following 2 case studies from the one site illustrate the COV for a near uniform site. An area of the site with a soaked CBR average value of 8% is shown in **Figure 7** for 15 test results. This material has a COV of 39% which is comparable to the typical COV of 40% (**Table 2**). Selecting a design value is no trivial matter even for a uniform site. A designer may choose the lowest test value of CBR 5%, a lower quartile value of 6% or a median value of 7% depending on the type of project. The exponential is the best fit PDF in this case using statistical goodness of fit tests.

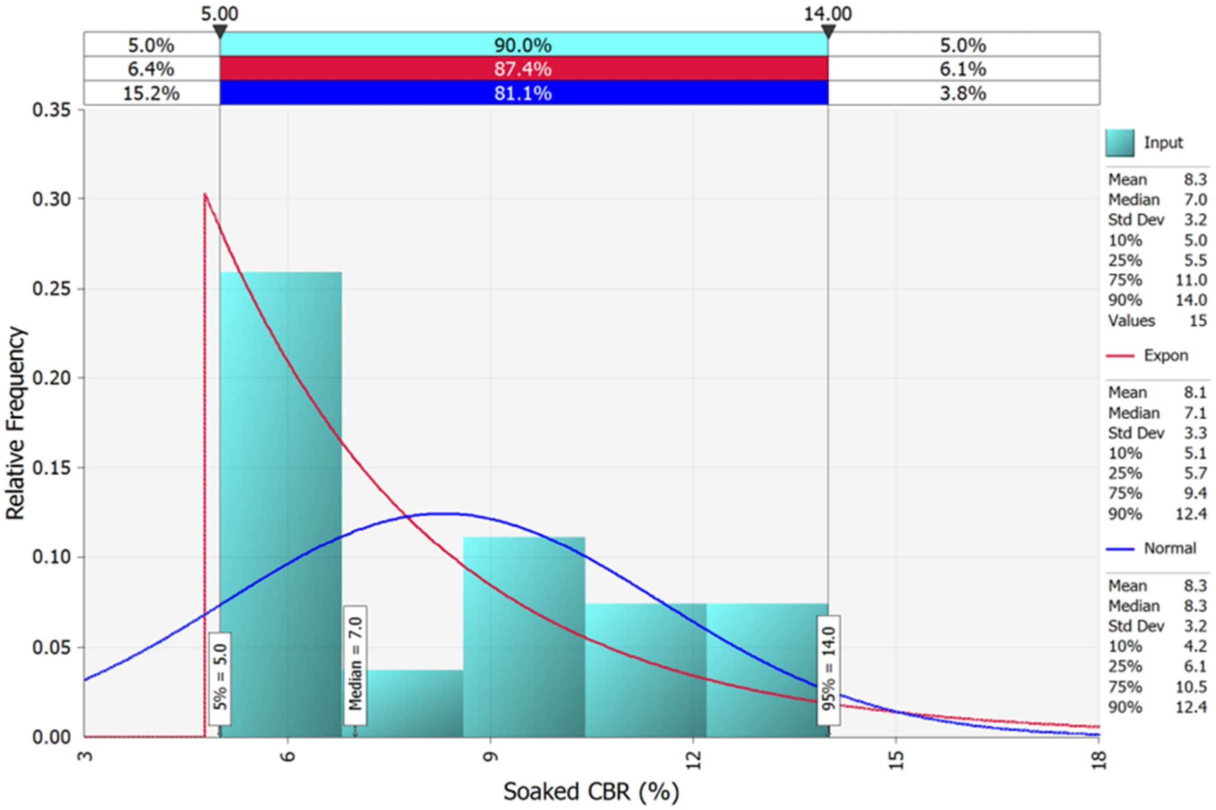


Figure 7: Clayey Sand (SC) material with 34% fines and WPI = 246

An adjacent source material at the same site was classified as Sandy Clay (CL) with a soaked CBR median value of 6% is shown in **Figure 8** for 15 test results. A minor change in fines and weighted plasticity index (WPI) results in a 2% change in the average CBR value. This would be associated with a significant increase in pavement thickness. In this case the normal PDF is the best fit curve and with a COV of 38%. A designer may choose the lowest test value of CBR 1.5%, a lower quartile value of 5% or a median value of 6% depending on the type of project.

3. A SHORT HISTORY OF QUALITY TESTING

The California Bearing Ratio (CBR) test was primarily developed to assess the load-bearing capacity of soils used in highway construction. The CBR is used with the Proctor density test at various compaction levels.

The results of the standard Proctor test should be considered in conjunction with the weight of the roller (and any vibratory enhancement) + lift thickness + number of passes to equate equivalent energy levels. A heavier compaction roller can achieve greater compaction energy and increased soil density when properly operated. Other factors, such as the type of soil, moisture content, compaction method, and roller type, also play significant roles in achieving desired compaction results.

We often default to density as if it is a proxy for performance. At the macro level, strength increases with density e.g. comparing soil with concrete or steel (**Figure 9**). But density alone tells us almost nothing about how a material will behave under load. Strength and stiffness in soil are also dependent on its confinement and stress levels. Appendix A shows how this illustration (**Figure 9**) can be misleading using corelated data.

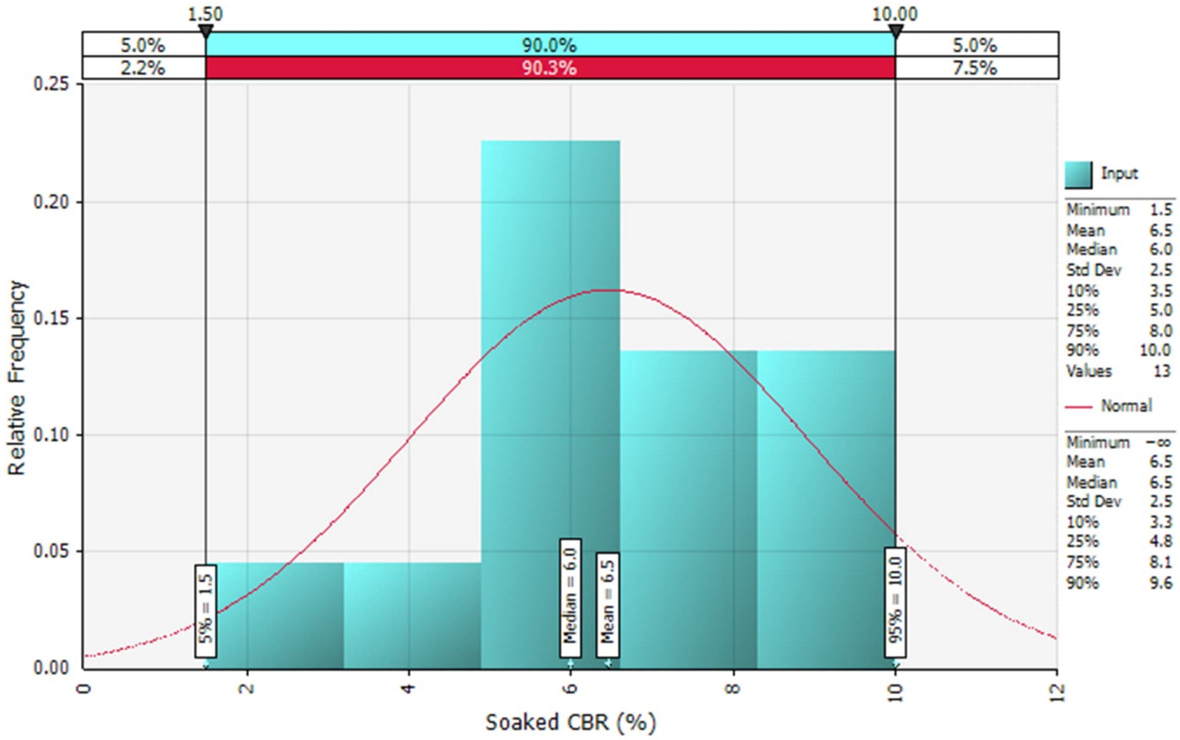


Figure 8: Sandy Clay (CL) material with 38% fines and WPI = 984

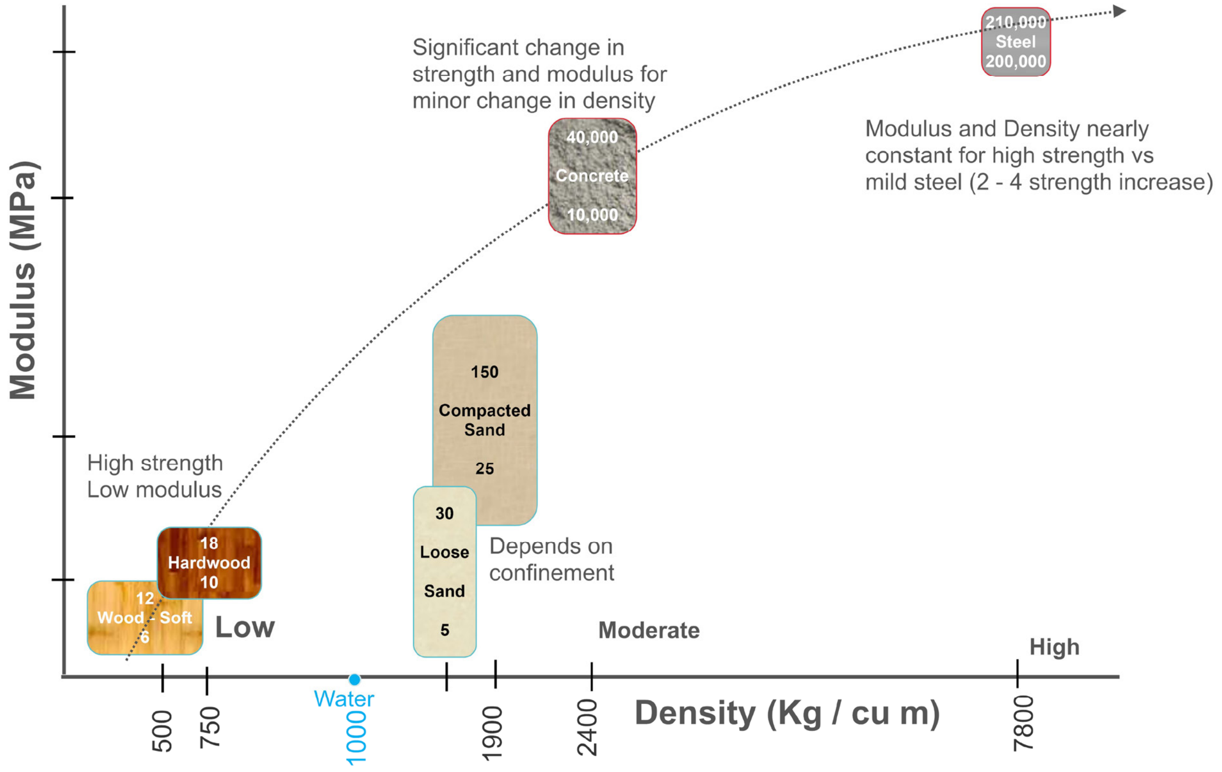


Figure 9: Increase in modulus with density

The maximum dry density (MDD) in soils is dependent on the uniformity coefficient (**Figure 10**). Well graded soils (a high uniformity coefficient) will have a higher MDD than a uniformly graded (low uniformity coefficient) soil.

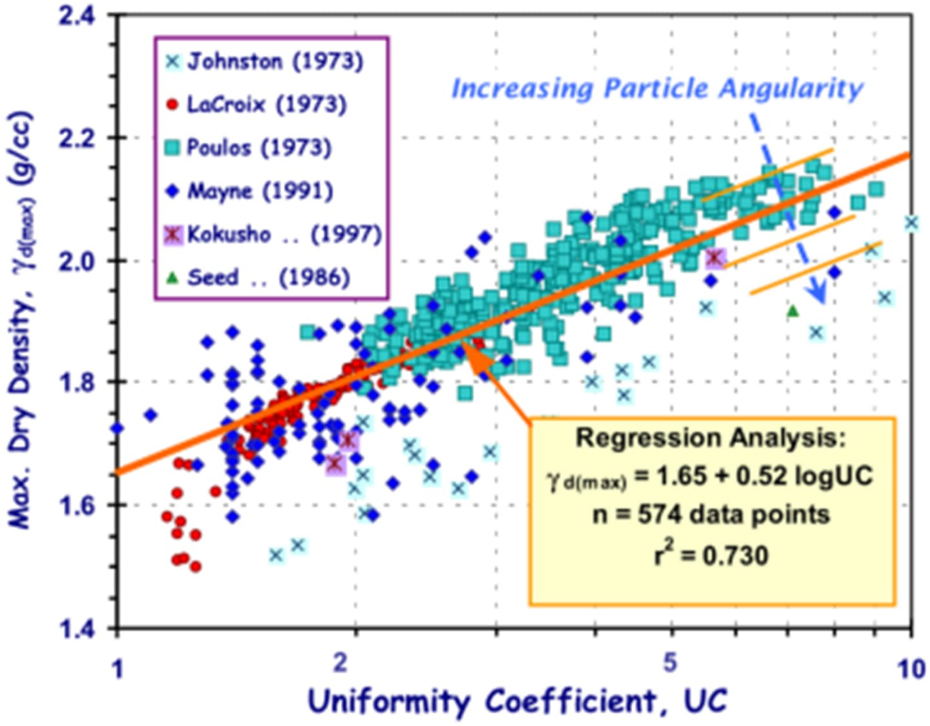


Figure 10: Maximum dry density relationship with sand UC (Mayne et al., 2002)

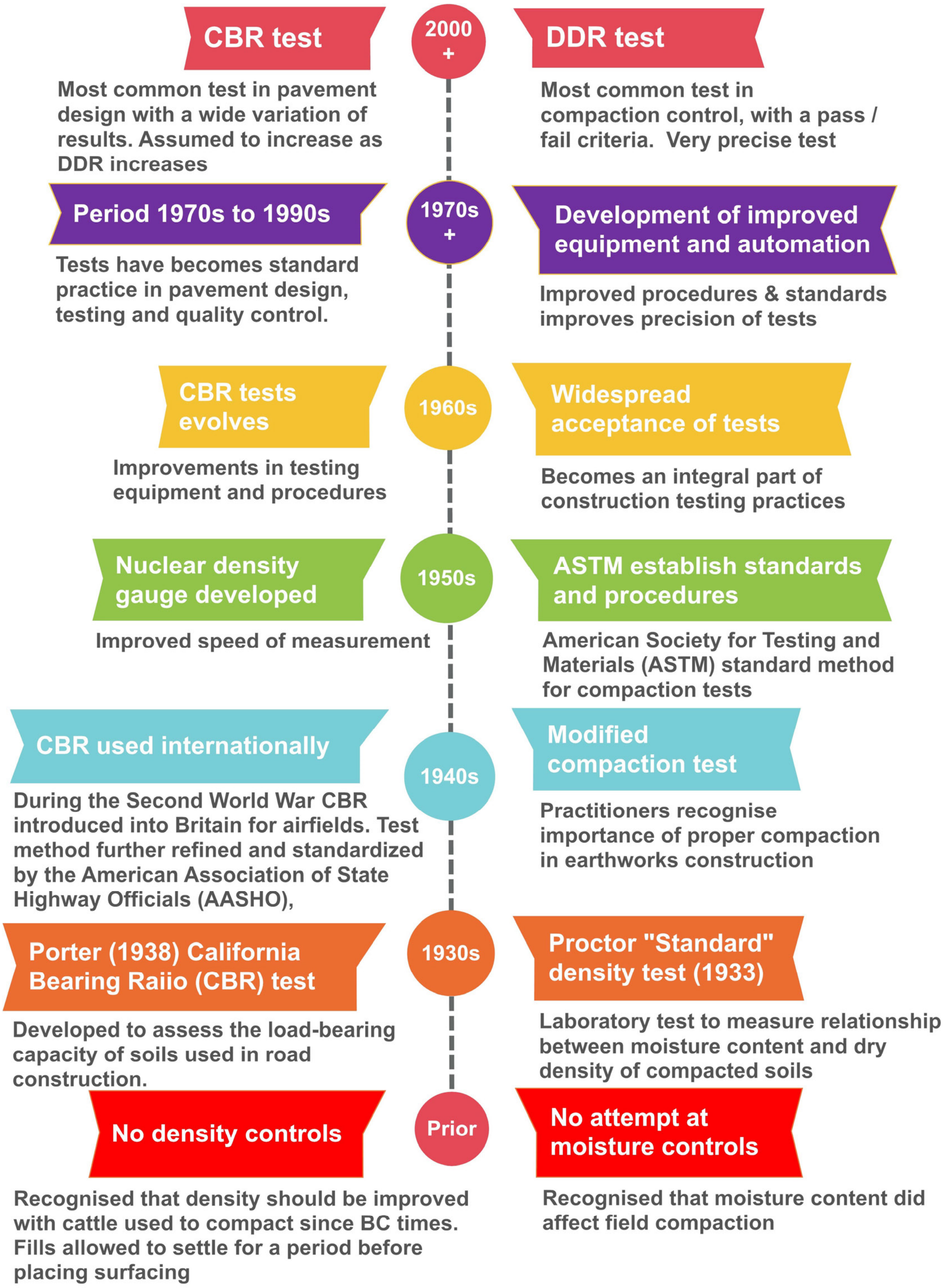
3.1. HISTORICAL TESTING AND COMPACTION HISTORY

This timeline history for the CBR and Dry Density Ratio (DDR, but also DR) tests are summarised in Figure 11. The modified compaction test evolved in the 1940s with the US Corps of Engineers for "heavy" equipment. This has been wrongly interpreted as a modified compaction test is a better test. The timeline history for the compaction equipment and vehicle loads is summarised in Figure 12. This shows that since the 1940s both equipment and vehicle loads have continued to increase and with no modified – Revision 2 , 3 or 4 compaction test. Industry has accepted a modified test despite changing loads. This logic does not improve the quality of testing.

The weight of vehicles and compaction rollers has increased over the years. Early machines prior to 1900 were 6 tons but increased to 10 to 12 tons by the time the standard Proctor compaction test was introduced in the 1930s, and increased further to 15–20 tons in the 1940s by the time the modified compaction test was introduced. During the early standardisation of tests (1950s) the development of smooth drum vibratory compaction rollers further improved compaction efficiency, with machines around 20-25 tons. This machine weight continued to increase by the 1970s. In the 1990s, advances in engineering and construction materials allowed for larger, more heavy-duty compaction rollers with typical weights of 30-35 tons. The introduction of high-frequency vibratory compaction rollers post 2000, and sophisticated control systems led to larger and heavier models weighing over 40 tons.

Vehicle weights also changed over the years. However, it is truck axle loads that governs road pavement performance. The average truck axle load was around 2.5t in the 1920s increasing to an average of 4.5t in the 1940s and 6.5t by the 1960s.

The average truck axle load further increased to approximately 8.5t by the 1980s with technological advancements in truck design. Truck axle loads vary depending on the type and purpose of the truck. However, standard axle loads of 80kN are typically used in design and the different vehicles used as an equivalent standard axle load (ESAL). Pavement fatigue and deformation are then based on standard axle repetitions (SAR).



Most common test in pavement design with a wide variation of results. Assumed to increase as DDR increases

Most common test in compaction control, with a pass / fail criteria. Very precise test

Tests have becomes standard practice in pavement design, testing and quality control.

Improved procedures & standards improves precision of tests

Improvements in testing equipment and procedures

Becomes an integral part of construction testing practices

Improved speed of measurement

American Society for Testing and Materials (ASTM) standard method for compaction tests

During the Second World War CBR introduced into Britain for airfields. Test method further refined and standardized by the American Association of State Highway Officials (AASHO),

Practitioners recognise importance of proper compaction in earthworks construction

Developed to assess the load-bearing capacity of soils used in road construction.

Laboratory test to measure relationship between moisture content and dry density of compacted soils

Recognised that density should be improved with cattle used to compact since BC times. Fills allowed to settle for a period before placing surfacing

Recognised that moisture content did affect field compaction

Figure 11: Timeline history of DDR and CBR tests

3.2. EARLY DAYS TO ASSESS BENEFITS OF TESTS

The historical decision as compared to present considerations to use DDR as the key compaction control parameter is discussed in Look (2024a) using force field analysis as a decision-making tool. The high precision of density was recognized in the early days and a governing factor in its implementation in quality control. For example, in the Highway Research Board (1967) symposium on compaction of earthworks and granular bases, Selig and Truesdale (1967) examined the independent and joint effects for:

  - M – Moisture level; S – Soil type
  - E – Compaction equipment; T – Lift thickness
  - C – Compactive effort – Least individual effect

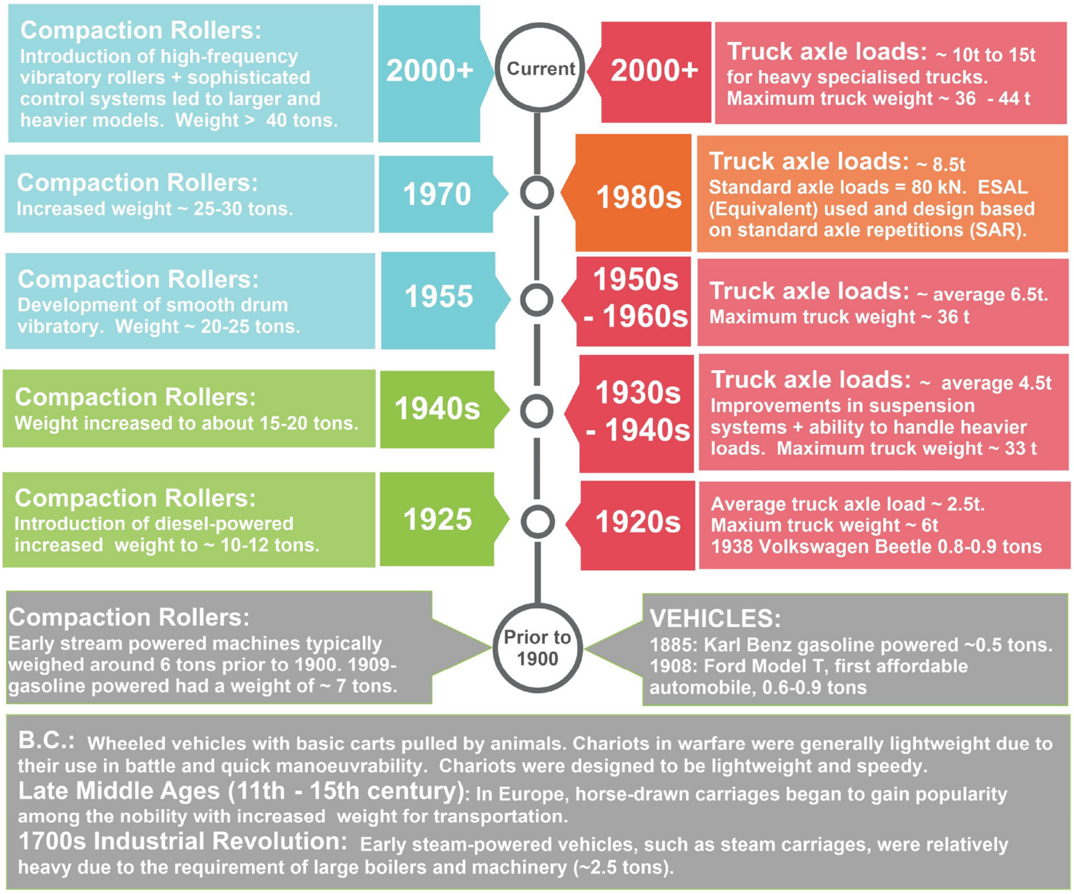


Figure 12: Timeline history of compaction equipment and vehicle loads

Table 3 summarises this variation for the properties measured by Selig and Truesdale (1967). This ranking shows density has a low variability compared to other tests. Moisture content was the most significant factor influencing the strength and stiffness of the soil, but with poor repeatability. Thus, precision took preference over the more useful but wider variability of other soil measurements of the time. DDR was thus elevated to its current prominence due its high precision and not to its superior indicator of key issues. An expanded discussion is provided in Look (2023a, 2023b).

Table 3: Range / average ratio of properties for all effects (Selig and Truesdale, 1967)

Measurement	Range / Average (%)
Dry Density	19
Wet Density	23
Seismic Velocity	75
Moisture Density[1]	87
Plate Load	105
Moisture Content	112
Penetration Resistance	145
Field CBR	177

[1] Moisture Density = Wet density – Dry Density. This term is not commonly used

The relative significance of the various effects was based on growth curves for the test sections with roller coverages showed the bearing plate was influenced the most by E (compactive effort) and M (moisture level).

3.3. RECENT ASSESSMENT OF BENEFITS OF TESTS

Table 3 provided the variability of various tests in the 1960s. In recent times various test instruments were compared to density for five sites (**Table 4**) with the coefficient of variation (COV) shown in Look (2021). The COV represents the range of precision, and the density test is the standout leader (COV = 2.0%) as compared to the Plate load test with a COV of 77%. Most other test (including CBR) have a COV of 25 to 55%. However, precision is the 2nd preference as compared to accuracy (**Figure 3**).

Accuracy was assessed in terms of how well the results compared with each other for similar high, low, and median values for the 5 test sites. The PLT had the highest accuracy as described in Look (2019). The DDR has the lowest correlation with the other tests with dendrogram analysis showing these interrelationships (Look, 2021). The Plate load modulus and DDR had a correlation R^2 value less than 0.15. The same modulus values were measured once the DDR exceeded 90% i.e. 90%, 95%, or 100% DDR had the same modulus for the 3 materials tested.

Given that DDR is the most precise test (**Table 3** and **Table 4**) then how does that relate to strength and modulus? **Table 5** shows different materials have different strength and modulus values irrespective of the same 95% density ratio achieved. A DDR value does not have a direct relationship with the strength of the compacted material and strength is inferred. **Table 5** also highlights that different compaction equipment may produce different friction angles at the same DDR.

Table 4: COV for various tests considered over 5 sites

Test	Coefficient of Variation – COV (%)		
	Median	Low	High
Dry Density Ratio (DDR)	2.0	1.8	2.9
Geogauge	26.5	19.1	34.5
Prima LFWD	33.5	15.0	35.7
LAB CBR	40	17.0	58
Zorn (LFWD)	34.1	21.6	51
Clegg	36.0	26.0	54
PANDA			
(50 – 100mm)	53	34.0	74
(150 – 200mm)	50	48	92
DCP			
(50 – 100mm)	38.0	28.0	97
(150 – 200mm)	53	34.0	74
Plate Load Test (PLT)	77	14.0	142

The COV shown uses only 1 decimal place below 50% and no decimal place above 50%

Table 5: In-situ modulus and strength at 95% DDR (Look, 2021).

Fill Material Origin	PLT E_{V2} (MPa)	In situ angle of friction φ (°)	
		Smooth	Padfoot
Sandstone	70	45	45
Interbedded Siltstone/Sandstone	40	41	39
Basalt	65	39	43

Data for another site is shown in **Figure 13** comparing the Dynamic Deformation Modulus (E_{vd}) with DDR. No relationship is evident. The E_{vd} is the stiffness modulus of the soil under a dynamic load, calculated from the deflection measured during a light falling weight deflectometer (LFWD) impact. It is conceptually similar to a plate load test modulus, but is dynamic and not static and is a quick and easy test, making it ideal for compaction control.

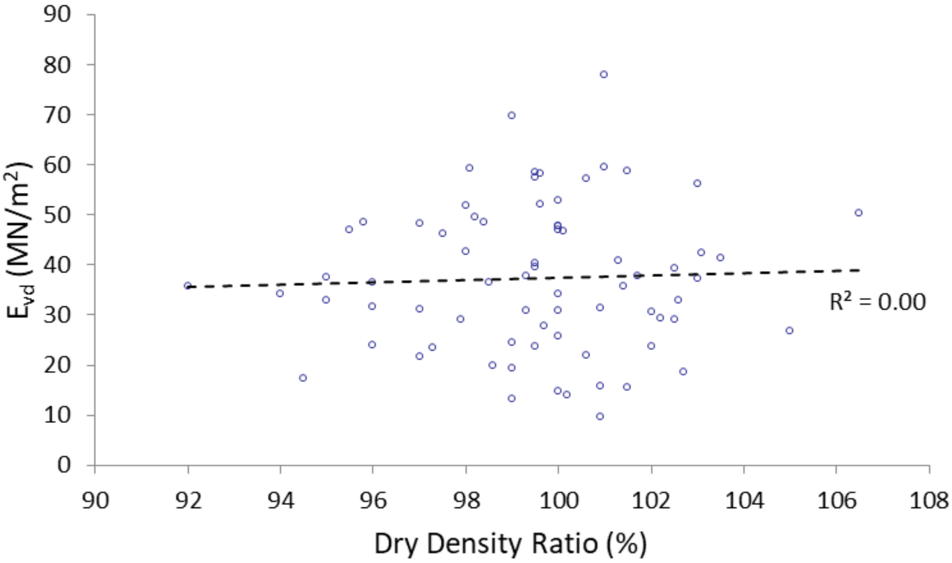


Figure 13: Dynamic Deformation Modulus (E_{vd}) versus Dry Density Ratio

The high precision of the DDR test is contrasted with its low accuracy in predicting strength or modulus values. This shows design input and construction quality have a disconnect. We incorrectly assume a high DDR produces higher strength or modulus. The aim of compaction is to reduce the air voids and typically air voids less than 10% would occur at 90% DDR. The line of optimums (LOC) for varying compaction energy is the true target, as lab compaction energy is well defined but compaction energy is unknown in the field. The LOC would be between 10% to 5% air voids.

In temporary working platforms where high construction equipment loads are used, an engineer is ill-advised to rely on density only as indictive of a strength or modulus.

Density ratio on its own should be paired with additional testing, as it is not standalone and not a performance indicator. The CBR is commonly the paired test but has many associated implications of errors in testing (**Figure 14**). Look (2019) showed density ratio reporting from 5,619 quality control results occurred 13 days (median) to 22 days (mean) after sampling. No contractor is waiting 2 – 3 weeks on results to continue placement of the next lift of a fill, as such standby times of equipment has associated project costs and delays. It is most likely testers provide verbal reporting, with quality testing certification lagging.

Density ratio testing is then becomes more a tick box approach to show quality tests have been carried out, rather than as a rigorous quality decision tool. Similarly, for 746 CBR tests were undertaken during construction. Test results were 34 days (median) to 43 days (mean) after sampling has occurred (Look, 2019). This time lag is not a quality assurance process and often results in contractual argument after the fact of placing additional fill. Surely we can do better than using these lag indicators.

Using the MDD and OMC as a reference point the CBR is carried out. The associated error (from test repeatability and reproducibility) is highlighted in **Figure 15**. The correlation error is also shown. During construction reliance on DR alone has associated uncertainties (**Figure 13** and **Table 5**) as a high densities does not necessarily mean high modulus.

3.4. EFFECT OF OVERSIZE

Aside from the poor timing of the tests, one still has the issue associated with the quality and interpretation of the results. The density testing using mould A is not valid if more than 20% of material is retained on the 19mm sieve. A check of 189 test results show 18.5% invalid reported results (**Figure 16**) with less than 80% passing the 19mm sieve according to AS 1289.5.1.1 (2017). In addition, a significant number of tests (31.5% of test results) should have a correction applied to the MDD and OMC, or should use mould B which allows up to 37.5mm size. Yet those compaction test results show no corrections applied. The gradings were done independently of the compaction tests, with test certificates showing “no oversize”. (Note these results are over 10 years ago – and possibly improvements may have occurred since that time).

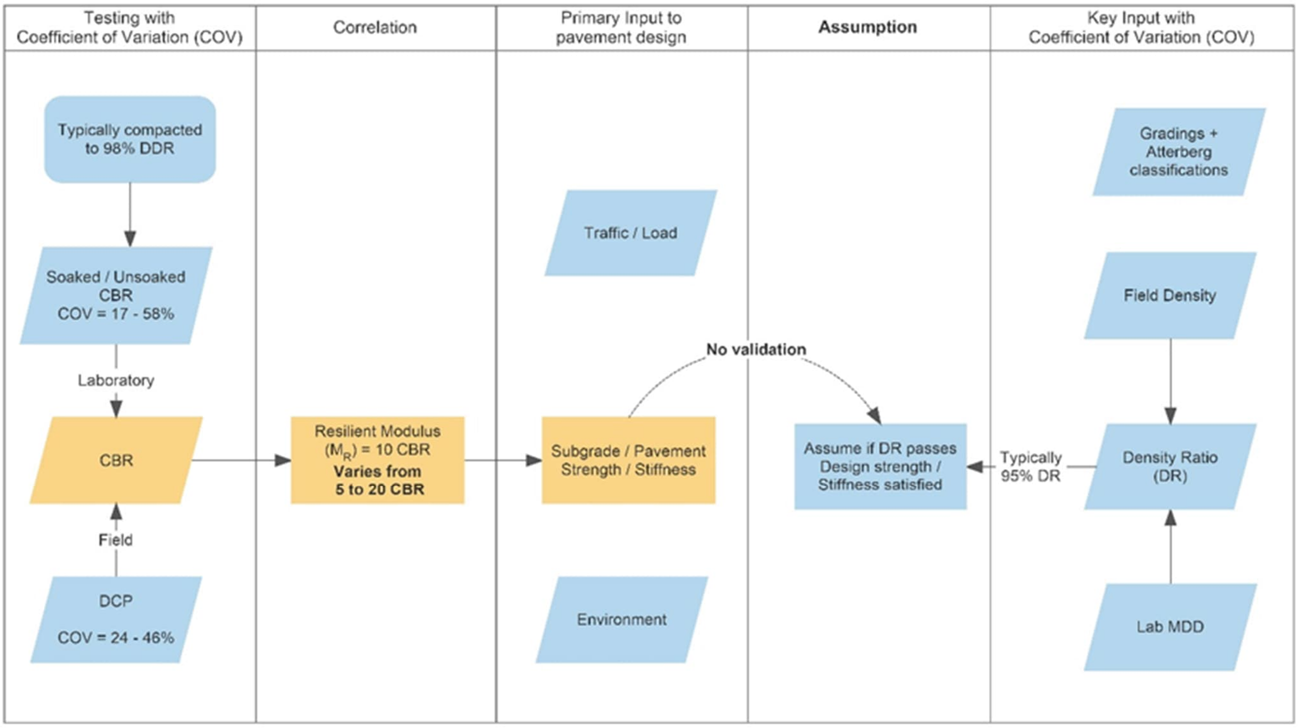
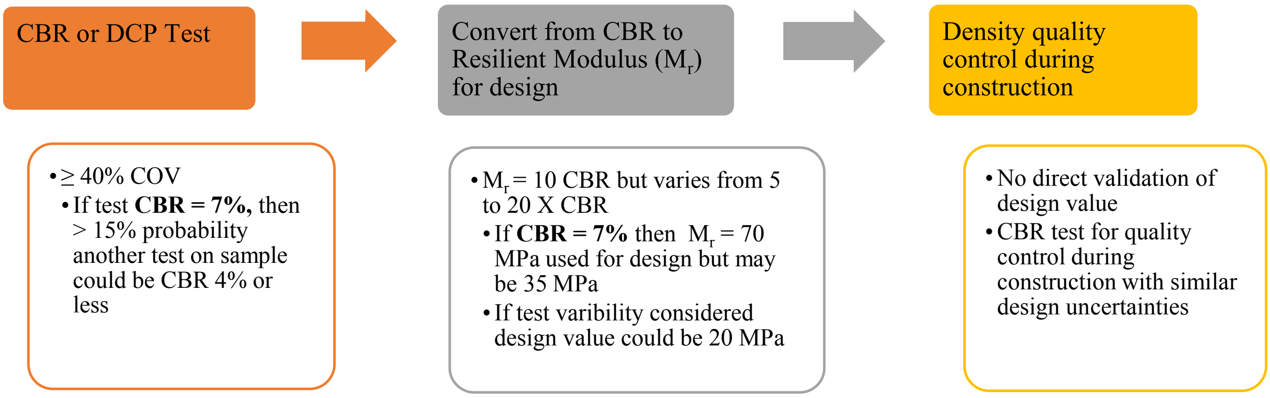


Figure 14: Key input vs implicit errors in current approach of testing 2nd or 3rd order parameters


CBR or DCP Test

- ≥ 40% COV
- If test **CBR = 7%,** then > 15% probability another test on sample could be CBR 4% or less

Convert from CBR to Resilient Modulus (M_r) for design

- M_r = 10 CBR but varies from 5 to 20 X CBR
- If **CBR = 7%** then M_r = 70 MPa used for design but may be 35 MPa
- If test varibility considered design value could be 20 MPa

Density quality control during construction

- No direct validation of design value
- CBR test for quality control during construction with similar design uncertainties

Figure 15: Industry accepted testing errors

Accounting for oversize is not new to standards. BS1377 (1975) required accounting for the percentage passing the 20 mm sieve. (Note BS uses “true” metric numbers such as 20mm while AS uses numbers such as 19mm and 37.5mm – which are “conversions” using U.S. sieve sizes).

Gravel contents greater than 20% to 30% affect compaction. When the gravel content is greater than 60% to 70% the voids are not filled and leads to reduction of the maximum dry density of the total material (Farrar, 2006). When soil contains greater than 30% larger than 19mm, a method specification should apply.

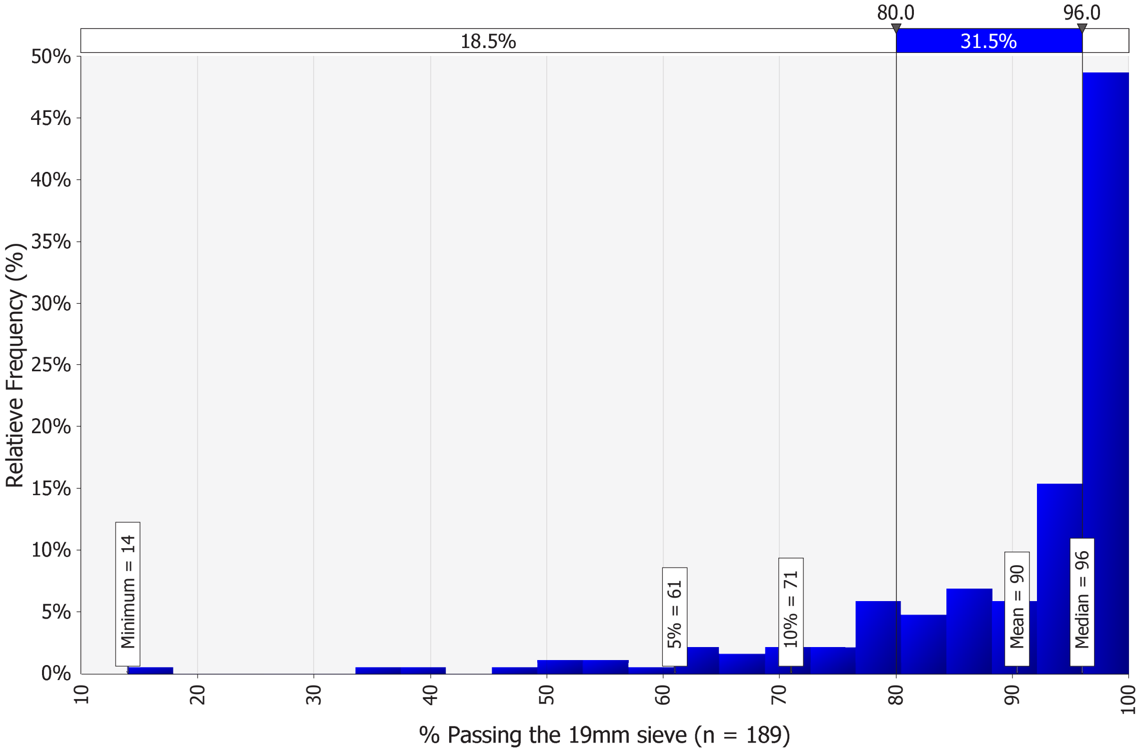


Figure 16: Density test using mould A requires over 80% of soil to be passing 19mm sieve. For this "passed" project 18.5% did not meet the test standard

4. RELEVANCE OF CBR DATA

The CBR tests were identified not to be trusted (**Figure 1**). The **CBR is an index test** that has evolved into a key design parameter for subgrade assessment. The CBR is not a fundamental soil property but enables the formulation of empirical correlations. Changing procedural aspects may lead to change in the test result. For example, curing periods or surcharge weights may alter the test results. A few aspects of the CBR testing are:

- CBRs < 8% have poor reproducibility i.e., comparing clay with rock; CBR > 100% test result can be obtained, but do not use.
- The test has a large variability; Rallings (2014) showed less than 60% of results are within ± 30% of the median value when multiple laboratories are compared with the same samples in assessing reproducibility of tests on similar samples at different laboratories.
- The test can use a soaked or unsoaked condition. A soaked CBR test is over-conservative in arid environments.
- A swell value is measured at the end of soaking and is also an important assessment parameter. For low CBR values, the swell value is arguably more important than the CBR test value.
- A 4.5 kg surcharge is used during the soaked test; this mass should be varied to be representative of the overlying material; both the CBR and swell values may be affected (AS 1289.6.1.1 (2014)
- The Equilibrium Moisture Content (EMC) is more important than testing at the OMC (Look, 2005).

Some of the underlying assumptions associated with this test will be discussed to show the effect of not following procedures. Discussion points includes:

- One point versus multi point CBR
- Soaked versus unsoaked and soaking time
- Effect of surcharge
- Curing preparation

- CBR dependence on the many other input parameters such as compaction density ratio (DR), swell or moisture ratio after soaking. This will be examined using:
    - Dendrogram analysis
    - Pearson correlations
    - Sperman rank correlation
- Field versus laboratory CBR
- Field values compared with other types of tests

Most engineers believe that the peak CBR occurs at the OMC (**Table 1**). This has the led to many one point CBR tests where the CBR at MDD / OMC is used. This interpretation error will be first discussed as it is so commonly used.

4.1. ONE POINT VERSUS MULTI POINT CBR

Engineers assume a direct relation between density and strength or modulus (i.e., the greater the density, the higher the modulus of the compacted material - **Figure 9**). However, the peak CBR does not necessarily occur at the MDD. Seed and Chan (1959) had shown the peak strength is lower at the MDD and is higher at the lower moisture content even though the density is lower (**Figure 17**). The key take away from this figure is that we have **known this since 1959**.

The peak CBR not being coincident with the OMC / MDD was shown in Look (2023b) for a granular material with its peak strength dry of optimum (below MDD) and for a CH clay with its peak CBR wet of OMC. Thus, using a one point CBR value, while commonly used in industry is not an indicator of peak CBR value. Using a CBR at OMC is likely to be conservative, and therefore errs on the "correct" side. The above discussion is for a soaked test. An unsoaked test would have its maximum CBR dry of OMC.

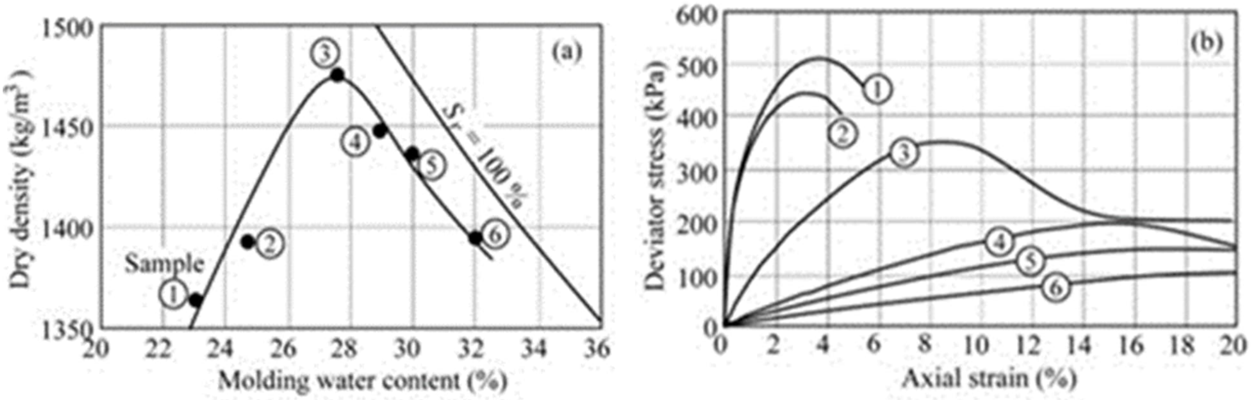


Figure 17: Influence of moulding water content on the dry density (a) and stress-strain relationships (b) for compacted samples (Seed and Chan, 1959; here from Leroueil and Hight, 2013).

4.2. SOAKED VERSUS UNSOAKED RESULT

There are many instances when a soaked result should not apply, although that is often a de-facto approach in industry. An unsoaked conditions should apply to material with:

- < 15% fines
- Excellent drainage
- Low rainfall environments (< 500 mm annual rainfall)

The soaked condition is representative of a 4-day flood which can produce a reduced strength but is not necessarily the design value. In Australia, a 4-day flood is not representative of extreme flood events and 7 or 10-day soaked tests are more appropriate for soaked conditions for low permeability materials.

The significant effect of soaking is shown for a site at Ipswich, Queensland, with a Weighted Plasticity Index (WPI) of above 5000 – an extremely reactive clay site. The unsoaked CBR is significantly higher than the soaked test with little difference in CBR between the 4 day and 7 day soaked tests (**Figure 18**). However, for a high WPI material the movement and not the strength governs the design. The CBR swell is significantly different for the 10 day versus the 7 day soaked test value (**Figure 19**).

This site has a history of flooding and the unsoaked CBR is inappropriate. The moisture content (MC) at the top 25mm depth of soaked sample is more highly correlated to CBR (**Figure 20**) than the MC of the remainder of the sample (**Figure 21**) with correlations R^2 of 0.43 and 0.17, respectively, for the 4 day soaked value. The correlation improves for the 10 day soaked value and suggests the sample had not yet reached its full "soaked" value at 4 days.

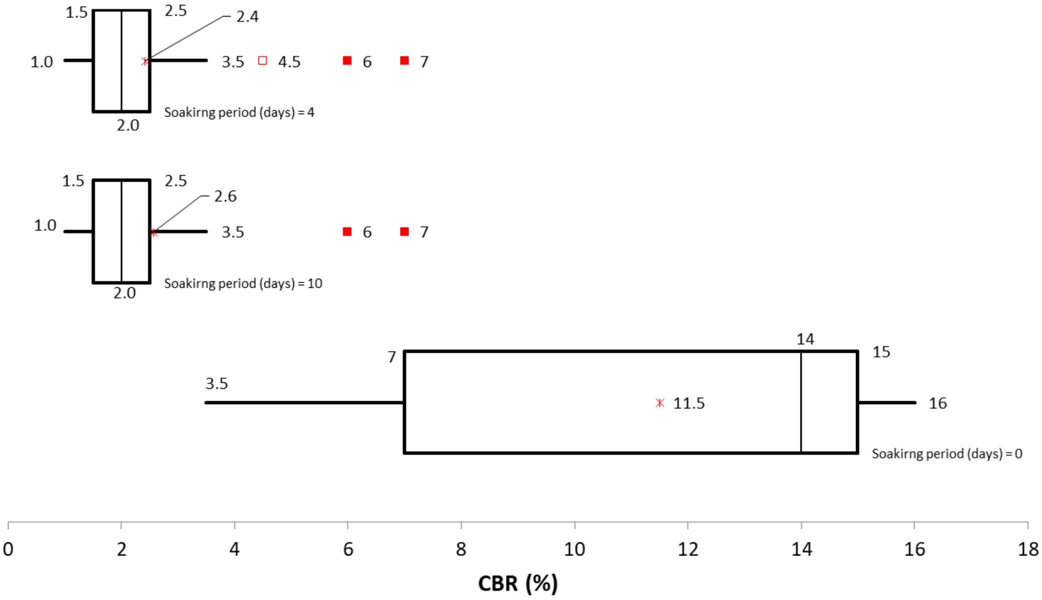


Figure 18: Effect of soaking on CBR for a high WPI material

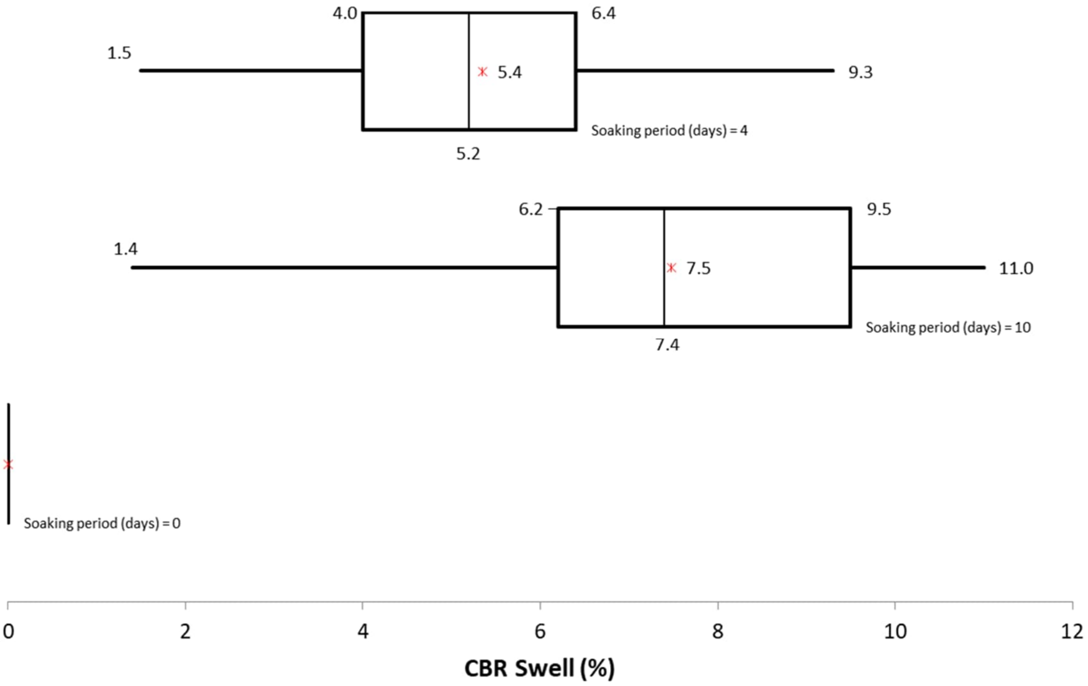


Figure 19: Effect of soaking on the CBR swell for a high WPI material

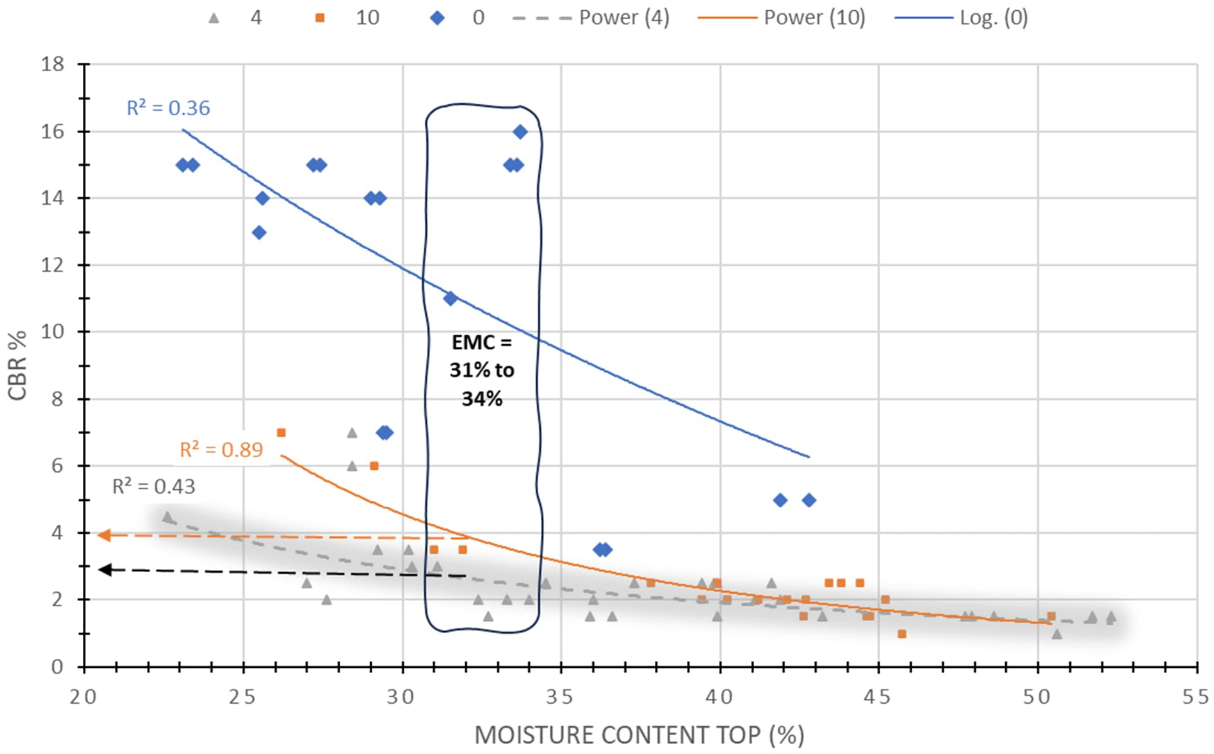


Figure 20: Selecting the design CBR value based on EMC of 31% to 34%. Top 25mm MC of sample applies

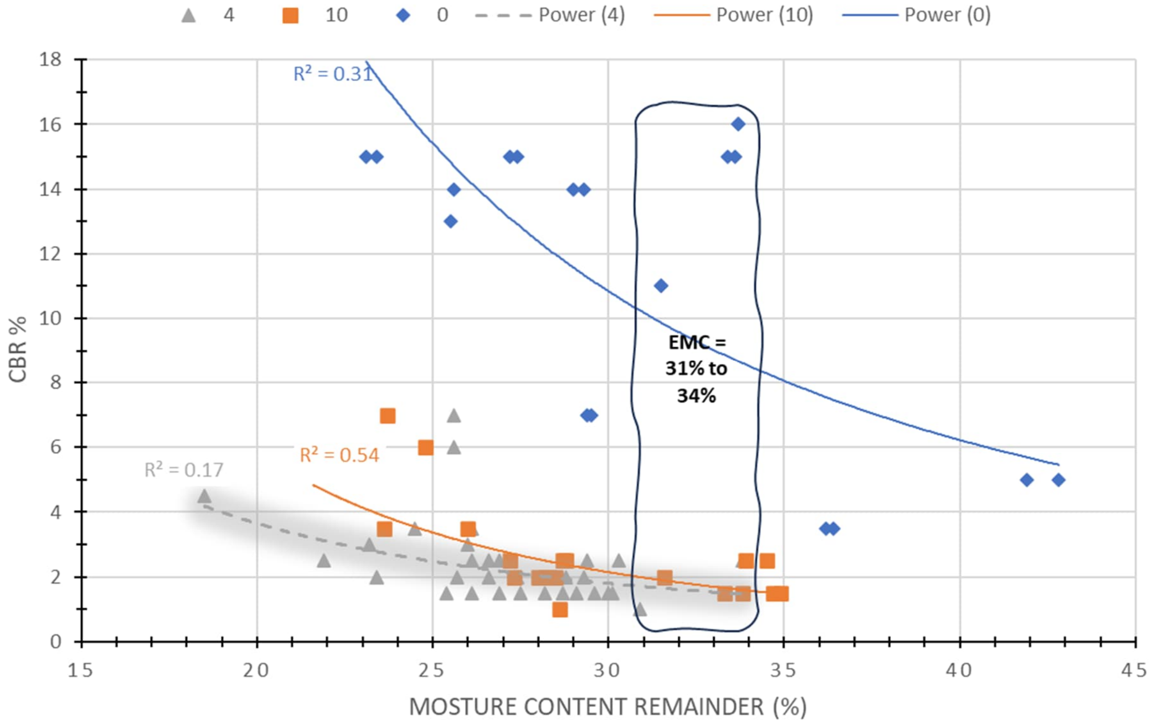


Figure 21: Selecting the design CBR value based on an EMC of 31% to 34% at this site. MC of sample shown

Selecting an appropriate CBR test is no trivial matter, yet the majority of reports sighted simply used a 4 day soaked CBR (value of 1.5% at the lower quartile value) at the OMC (23%). The steps illustrated in **Table 6** show the rationale and associated errors for an over simplified approach using a 4 day soaked CBR test only. Comparisons show issues with selecting:

- Soaked / unsoaked or 4 day / 10 day soaked
- EMC vs OMC
- MC of rest of sample vs top of sample

Table 7 shows the equivalent steps and rational for selecting a design swell value.

Table 6: Steps associated with obtaining a design CBR value for this high WPI site

Soaking Test	**CBR (%) at EMC = 31% to 34%**		**CBR at OMC = 23%**		**Comment**
	MC of top 25mm of sample (Figure 20)	**MC of remainder of sample (Figure 21)**	**MC of top 25mm of sample (Figure 20)**	**MC of remainder of sample (Figure 21)**	
Unsoaked	11%	9.0%	16%	17%	Inappropriate as site has a history of flooding
4 day	3.0%	1.5%	4.0%	3.0%	Inappropriate as inundation exceeded 4 days
10 day	**4.0%**	1.5%	8.0%	4.0%	Appropriate CBR – but MC of top of sample governs. The CBR at OMC is not appropriate

Table 7: Steps associated with obtaining a design swell value for this high WPI site

Soaking Test	**Swell (%) at EMC = 31% to 34%**		**Swell at OMC = 23%**		**Comment** **(Figures not shown)**
	MC of top 25mm of sample	**MC of remainder of sample**	**MC of top 25mm of sample**	**MC of remainder of sample**	
Unsoaked	0%	0%	0%	0%	Inappropriate as site has a history of flooding
4 day	3.5%	6.5%	0.5%	3.0%	Inappropriate as inundation exceeded 4 days
10 day	**5.0%**	9.0%	0.0%	4.0%	Appropriate CBR – but MC of top of sample governs. The CBR at OMC is not appropriate

Interestingly the extended 10 day soaked test provided a higher CBR value than the 4 day soaked test. However, as indicated previously, the CBR swell (movement) governs the design and not the subgrade strength. The improved correlated swell at 10-days soaking were also evident with higher swell values at 10-days (**Table 7**).

The tables compare the many factors to be considered in selecting a design subgrade value from a CBR test. For the 12 factors considered, there were 3 combination of factors for which the CBR = 4%. One may “luckily” still have the appropriate CBR at the OMC in a 4 days soaked – despite that model not being appropriate. However, as the swell governs at such high WPI then the designer would have underestimated the ground movement.

4.3. EFECT OF SURCHARGE

The Australian Standards for determination of CBR for soil allows for a change in surcharge weight depending on the layer thickness above. Anecdotal discussions with laboratories suggest that over 99% of testing is caried out on surcharge of 4.5 kg only. This surcharge would be appropriate for a layer thickness less than 200mm above the subgrade.

A low compressibility silt (A-4 soil) and a granular material with fines (A-2-4) was examined by Khalid et al. (2022). The results show an increase in CBR value with a higher surcharge (**Figure 22**).

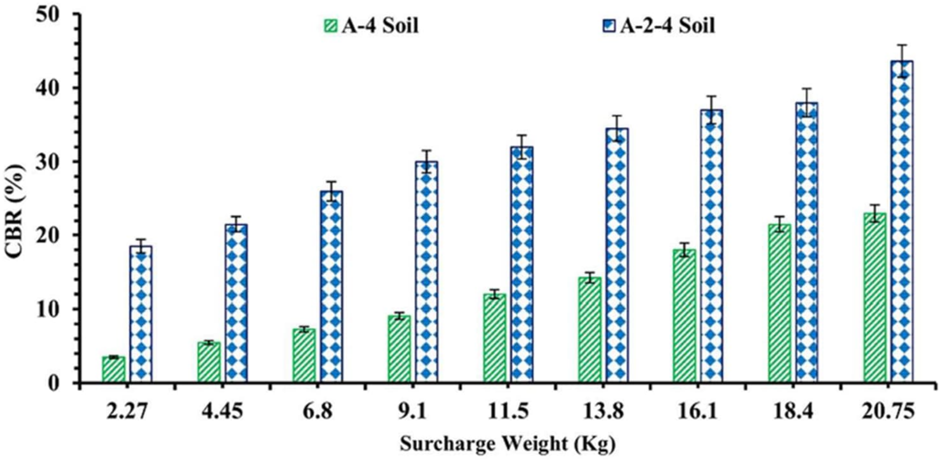


Figure 22: CBR compared to different surcharge weight (Khalid et al., 2022)

Using the data of **Table 7**, the effect of surcharge on the swell values is show in **Figure 23**. At the EMC, the swell change is minor, from 4.0% to 3.5% for the surcharge changing from 4.5 kg to 18kg, respectively. This is for a 4 day soak, and based on the trends of **Table 7**, the swell may be larger for a 10 day soak.

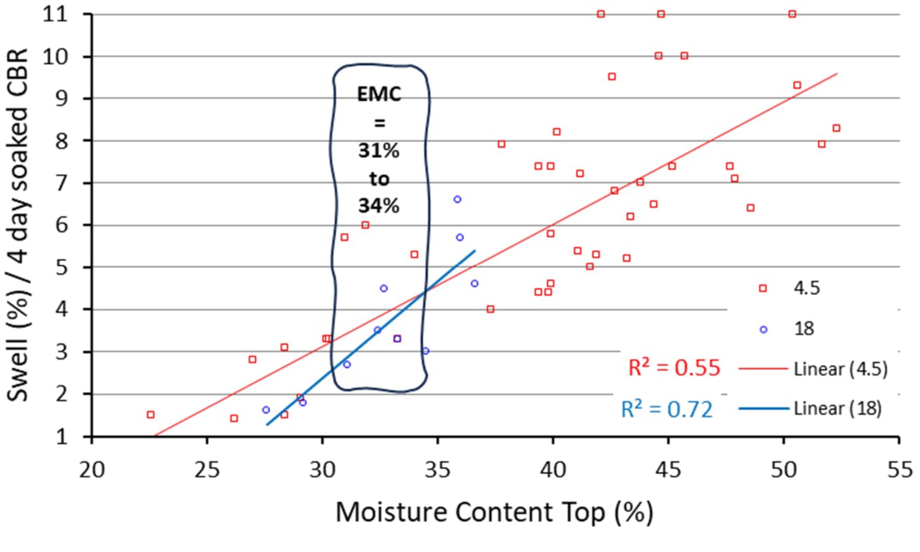


Figure 23: Effect of surcharge weight (4.5kg and 18 kg) on CBR swell at 4 day soaked

4.4. CURING PREPARATION

An example of the effect of curing time is shown for a Bundamba clay with a plasticity index of 47% and grading with 97% passing the 425-micron sieve and 69% to 82% fines (Look, 2021). Samples from the site were prepared and cured for 0, 1, 4 and 7 days, compacted, and the CBR (soaked and unsoaked tests) determined at the various times. The following observations were made from compaction and CBR tests on these samples:

- Curing for 0 to 1 days produced higher MDD values than 4 to 7 days. This leads to more compaction effort in the field being required, or the *in-situ* material is more likely to fail the density ratio test (**Figure 24**).

- Lower curing days produced higher CBR swell values which incorrectly required more remove and replace of material than is necessary for limiting reactive soil movements of pavement subgrades. This leads to increased construction costs. There is a significant difference in swell values depending on whether the initial sample was wet or dry i.e., the field moisture content at the time of sampling influences the soaked CBR swell test results when there is inadequate curing.
- A curing time of 0 days produced a lower CBR (soaked) value. This results in over-design of the pavement (**Figure 25**).

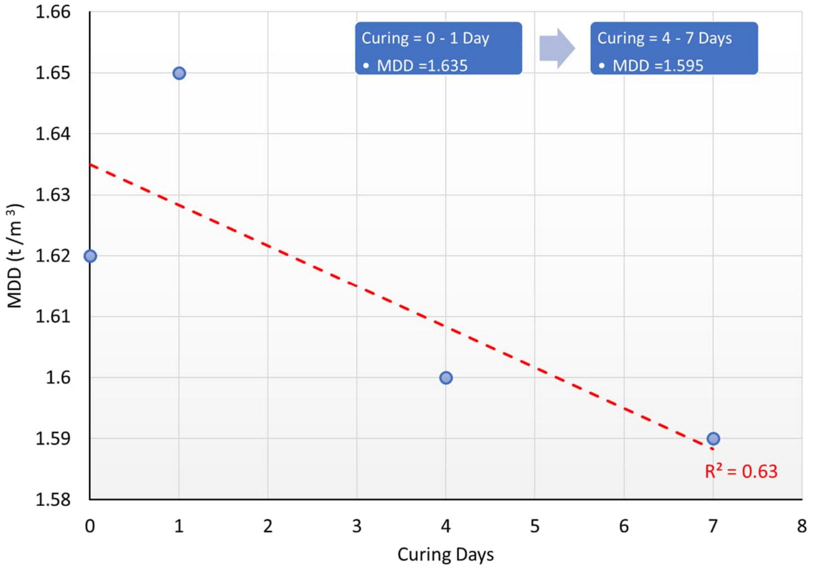
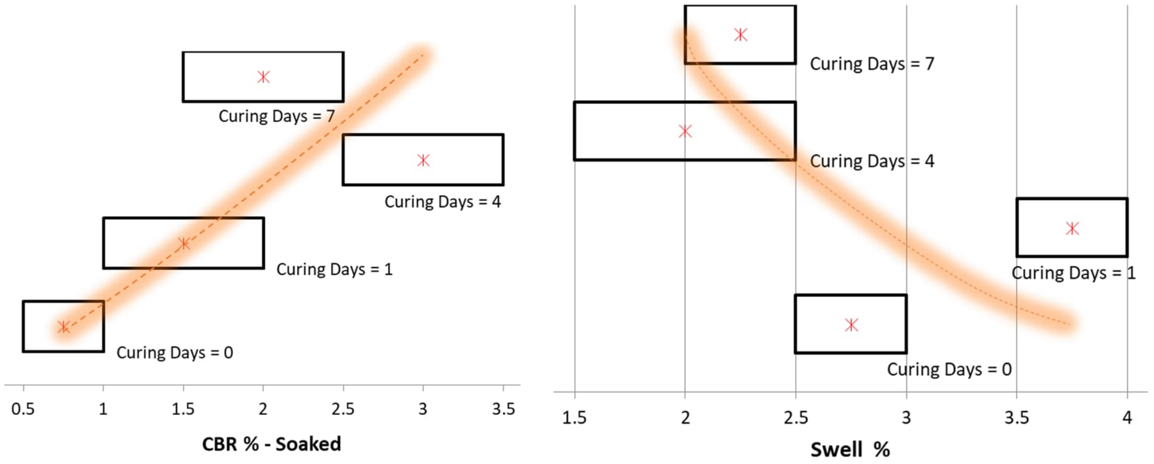


Figure 24: Curing – effect on MDD



(a) Soaked CBR (Lower cure → Lower CBR) (b) CBR Swell (Lower cure → Higher swell)

Figure 25: Curing – effect of soaked CBR

High plasticity clay samples require 4 to 7 days curing time according to Australian Standards. Over the years I have observed many NATA laboratory test reports not satisfying this procedural test requirement. Curing requirements for the granular or low plasticity material requiring 1 to 2 days curing, would typically be satisfied. These unnoticed procedural aspects have both design and construction implications.

4.5. DATA SCIENCE AND PREDICTIVE STATISTICAL MODELS

Making predictions from geotechnical data requires grouping to generate valuable insights. The Pearson linear correlation (as used in EXCEL) is the most common approach and assumes a bivariate relationship. The primary goal of analyzing bivariate data is to understand the relationship between the two variables. Scatterplots are commonly used to visualize bivariate data, and the correlation coefficient is often used to quantify the strength and direction of the linear relationship between the variables The Pearson correlation assumes a normal distributed relationship and is sensitive to outliers. The Spearman Rank order correlation is used when the bi-variate data distribution is non-normal or when the data is ordinal level. The data is replaced by their ranking, and a parametric correlation is found between the ranks for a rank correlation coefficient. Geotechnical data is often non-normal and has outliers and the Pearson coefficient used in EXCEL is often not appropriate. Both the Pearson and Sperman coefficient analyses are used on construction quality data to illustrate the pitfalls in only using the EXCEL approach

Multivariate analysis with complex and multiple data relationships requires looking beyond paired correlations. The multiple relationship factors can be shown by Principal Component Analysis (PCA) or dendrogram analysis (Look, 2021, 2025c). Hierarchical clustering is used on test data to predict groupings within the data set by generating a link between each single observation and its nearest neighbour. Those distances between parameter values are then used to predict sub groups within a data set. A dendrogram is a visualisation tool that show the similarities and branching between groups in a tree like structure. By clustering similar data points together, dendrogram analysis can help geotechnical engineers gain insights into the underlying relationships present in the data.

4.6. DENDROGRAM AND CORRELATION ANALYIS OF CBR TESTS

Dendrogram and PCA analysis application in geotechnical engineering are shown using CBR test data in Look (2021, 2025c). The CBR is used in design and (incorrectly) assumed to be most closely related to the compaction density which is used in earthworks quality control testing. The dendrogram analysis of a CH clay material (55 data sets) for the relationship factors is shown and visualised with dendrogram analysis (**Figure 26**) using nonparametric statistical tests. This analysis shows the after-swell moisture ratio governs the CBR test value, and the density ratio at compaction is least related to the CBR value. The moisture related parameters (degree of saturation (DOS), moisture ratio (MR) at compaction) are most related to the CBR while, the density related parameters (Density ratio (DR) at compaction, Dry density(DD) and maximum dry density (MDD)) are least related.

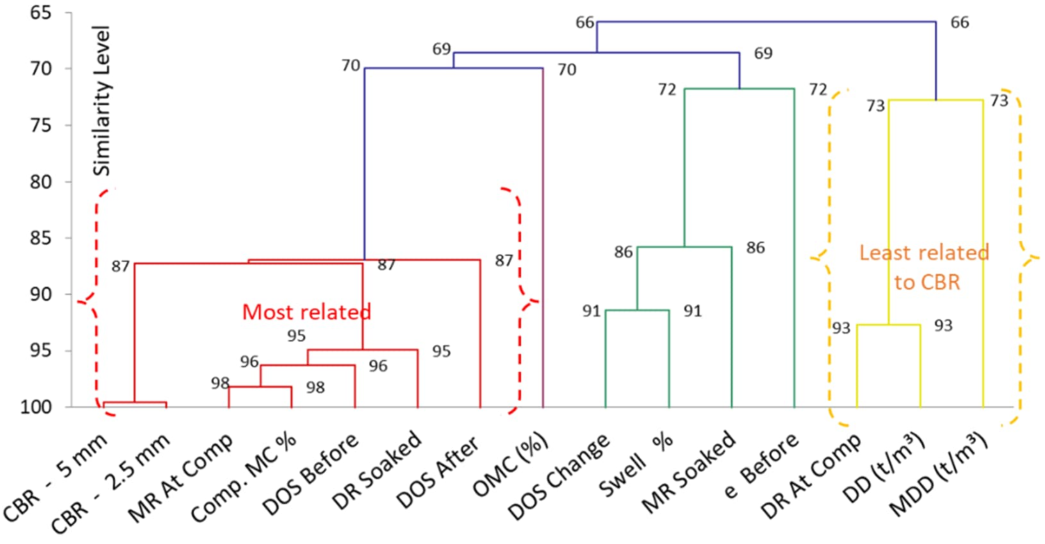


Figure 26: Dendrogram of 15 parameters in a soaked CBR test (Look 2025c)

This visualization provides simplified insights that may have been achieved by carrying out multiple plots such as **Figure 27** for the relationship of CBR with the density and moisture ratio (MC/OMC) when compacted and after soaked, respectively. The data noise and non-normal distribution is evident which fails to show the many associated parameters affecting the CBR value. This data shows the poor relationship of the soaked CBR index (strength indicator) and the compacted density ratio (DR). Yet the DR is the key quality control parameter used to assess strength during construction material testing. By adopting such hierarchical clustering analysis, data noise is removed and key risk factors for geotechnical modelling can be identified.

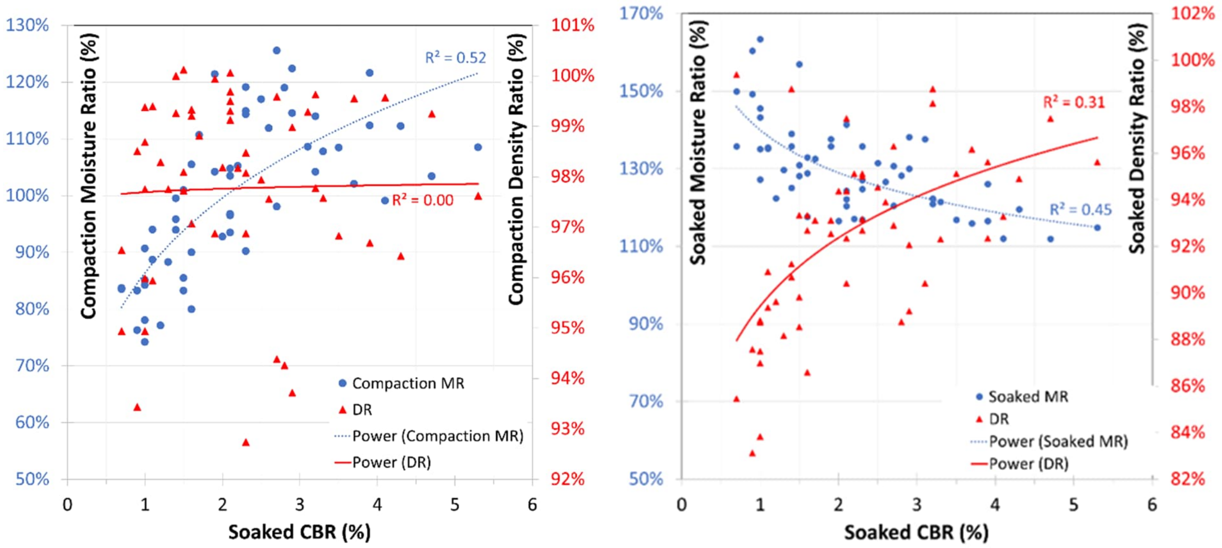


Figure 27: (a) Soaked CBR vs compaction MR and DR (b) Soaked CBR vs after soak MR and DR

Many of the parameters are derived while some are measured results. An expanded data base (172 data sets), which includes the above Cooroy clay as a subset, and rationalised dendrogram analysis (removing Dry Density and MDD as it is part of DR) is shown in **Figure 28**. This expanded data analysis shows that the CBR is most related to the DOS before soaking and the moisture ratio at compaction, but is least related to the DR at compaction.

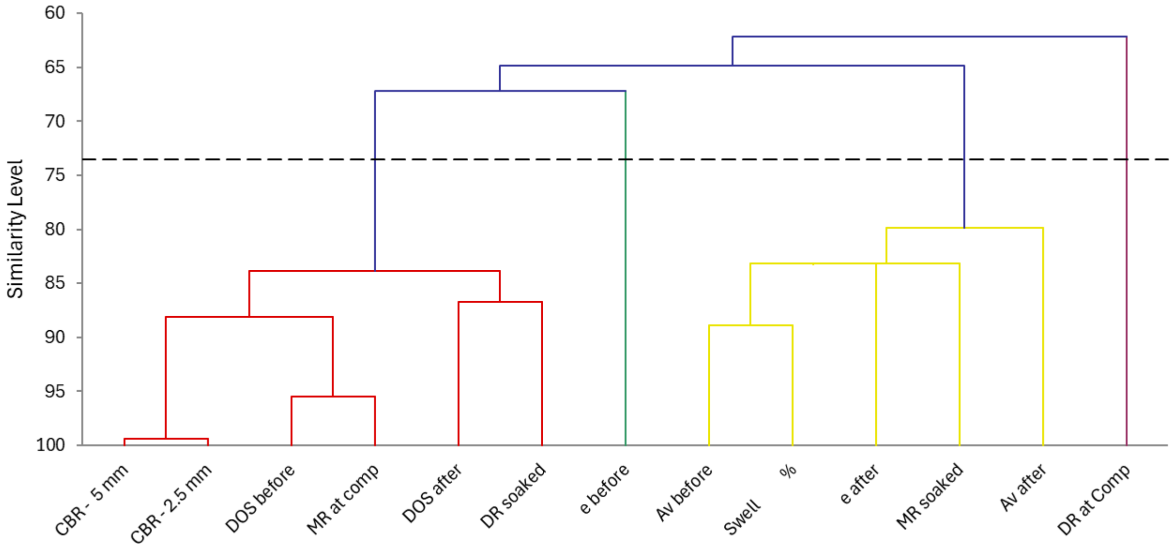


Figure 28: Dendrogram of 13 parameters in a soaked CBR test (n= 172)

This unsupervised[1] dendrogram analysis was compared with the more traditional Pearson and Spearman correlation matrices in **Table 8** and

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[1] Supervised algorithms such as classification and regression have the labels to train the model. Unsupervised models such as clustering, PCA or dendrogram analysis has unlabelled data without target variables. The model's goal is to discover hidden patterns, structures, or relationships within the dataset without explicit guidance.

Table 9, respectively. These tables show the parameters of MDD and DD for completeness, although they are not shown in the dendrogram for simplicity. Disappointedly, the three methods do not all provide similar results but it is noted that PCA and Dendrogram are multivariate analysis, while paired correlations accepts data noise. The analysis shows following observations:

- Dendrogram analysis (**Figure 28**)
    - The CBR is most related to the interaction of the DOS before soaking, and the MR at compaction. The MR at compaction is derived from the compaction moisture content and OMC (not included)
    - The CBR is least related to the density ratio at compaction noting that this parameter is derived from the maximum dry density and dry density (not shown)
- Correlation matrix using Pearson (**Table 8**)
    - The CBR is most related to the average moisture content after soaking, the void ratio before soaking and the dry density at compaction
    - The CBR is least related to the density ratio at compaction, which matches the dendrogram analysis. The air voids before compaction also had little effect on the CBR

Correlation matrix using Spearman Rank (

- **Table 9**)
    - The CBR is most related to the swell and moisture ratio when soaked
    - The CBR is least related to the moisture ratio and density ratio at compaction. Yet these are the 2 main parameters in quality control.

The one constant in all 3 analyses is the density ratio at compaction had the least effect on the CBR value after soaking.

Industry practice (implicitly) associates a higher strength with a higher density, as strength or modulus is not traditionally measured in quality control. This is a reasonable assumption as seen in **Figure 29** for CBR vs DD. When the density ratio is used (combining DD with MD) there is no relationship (**Figure 30**). This is evident in both the Pearson and Spearman ranking of **Table 10** and the dendrogram of **Figure 28**.

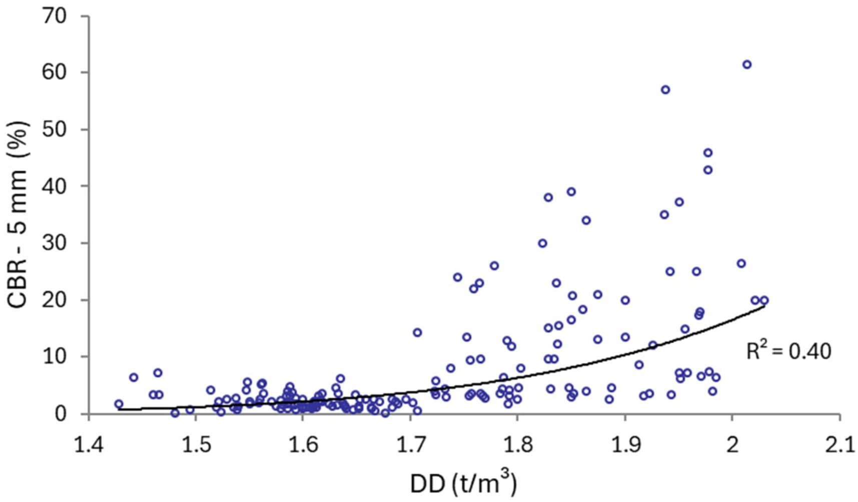

Figure 29: CBR is dependent on the dry density (n= 172)

Because a high strength is associated with a high density, industry has incorrectly applied an inverse logic of a low density implies a low strength. The latter has a partial truth and applies only to material which are inherently strong. The higher CBR material requires compaction to 95% to 101% for DR to achieve its inherent strength properties (**Figure 31**). This should not be extrapolated to mean a higher DR has a higher strength. A low strength material (CBR < 10%) will not achieve a higher strength at high levels of compaction (say 98% DR). Yet a 98% DR of such low strength material is assumed (incorrectly) to be stronger than a 95% DR.

The following density ratios are required to be achieved for different CBR material(**Figure 31**):

- High CBR > 10% : DR = 94.5% to 100.5%. Aside from one data point this could be 96% to 100.5%
- Low CBR < 10% : MR = 92.5% to 100.5%

Table 8: Correlation matrix between parameters using Pearson correlation

Linear Correlation	Comp MC %	DD (t/m^3)	OMC (%)	MDD (t/m^3)	CBR - 2.5 mm	CBR - 5 mm	Swell (%)	Avg MC after soak	DD (t/m^3) after soak	MR at comp	MR soaked	DR at Comp	DR soaked	e before	e after	Av before	Av after	DOS before	DOS after
Comp MC %	1.00																		
DD (t/m^3)	-0.84	1.00																	
OMC (%)	0.85	-0.89	1.00																
MDD (t/m^3)	-0.86	0.98	-0.91	1.00															
CBR - 2.5 mm	-0.49	0.53	-0.46	0.51	1.00														
CBR - 5 mm	-0.54	0.60	-0.50	0.58	0.97	1.00													
Swell (%)	0.27	-0.56	0.54	-0.57	-0.46	-0.49	1.00												
Avg MC after soak	0.66	-0.95	0.84	-0.95	-0.69	-0.74	0.67	1.00											
DD after soak	0.41	0.27	-0.05	0.21	0.46	0.45	-0.65	-0.74	1.00										
MR at comp	0.37	-0.07	-0.15	-0.09	-0.17	-0.21	-0.34	-0.11	0.52	1.00									
MR soaked	-0.05	-0.26	-0.12	-0.26	-0.39	-0.40	0.59	0.42	-0.59	0.20	1.00								
DR at Comp	0.06	0.26	0.06	-0.07	-0.01	-0.08	0.10	-0.25	0.19	0.03	-0.09	1.00							
DR soaked	0.63	-0.10	0.36	-0.30	0.52	0.51	-0.63	-0.45	0.87	0.55	-0.68	0.17	1.00						
e before	0.81	-1.00	0.91	-0.96	-0.66	-0.71	0.49	0.94	-0.28	0.02	0.23	-0.43	0.09	1.00					
e after	-0.42	-0.29	0.06	-0.21	-0.47	-0.46	0.66	0.75	-1.00	-0.53	0.60	-0.20	-0.87	0.29	1.00				
Av before	-0.56	-0.04	-0.07	-0.00	0.03	-0.01	0.62	0.20	-0.64	-0.75	0.41	-0.14	-0.67	0.04	0.65	1.00			
Av after	-0.47	0.33	-0.27	0.34	-0.17	-0.18	0.36	-0.08	-0.61	-0.39	0.17	0.13	-0.77	-0.33	0.60	0.35	1.00		
DOS before	0.71	-0.18	0.26	-0.21	-0.24	-0.19	-0.47	0.02	0.62	0.75	-0.32	0.07	0.68	0.17	-0.64	-0.97	-0.37	1.00	
DOS after	0.44	-0.36	0.28	-0.35	0.13	0.14	-0.22	0.12	0.58	0.35	-0.13	-0.16	0.74	0.35	-0.56	-0.30	-1.00	0.32	1.00

Table 9: Spearman rank order correlation matrix between parameters

Rank-Order Correlation	Comp MC %	DD (t/m^3)	OMC (%)	MDD (t/m^3)	CBR - 2.5 mm	CBR - 5 mm	Swell %	Avg MC after soak	DD (t/m^3) after soak	MR at comp	MR soaked	DR at Comp	DR soaked	e before	e after	Av before	Av after	DOS before	DOS after
Comp MC %	1.00																		
DD (t/m^3)	-0.84	1.00																	
OMC (%)	0.84	-0.89	1.00																
MDD (t/m^3)	-0.88	0.97	-0.92	1.00															
CBR - 2.5 mm	-0.47	0.61	-0.49	0.59	1.00														
CBR - 5 mm	-0.56	0.66	-0.49	0.66	0.90	1.00													
Swell (%)	0.41	-0.62	0.57	-0.64	-0.79	-0.75	1.00												
Avg MC after soak	0.43	-0.84	0.72	-0.82	-0.61	-0.65	0.66	1.00											
DD (t/m^3) after soak	0.39	0.20	-0.04	0.22	0.53	0.52	-0.58	-0.68	1.00										
MR at comp	0.42	-0.05	-0.07	-0.06	0.03	-0.08	-0.34	-0.27	0.48	1.00									
MR soaked	-0.02	-0.19	-0.11	-0.11	-0.76	-0.73	0.68	0.50	-0.53	0.06	1.00								
DR at Comp	0.01	0.27	-0.04	0.05	0.18	0.11	-0.05	-0.29	0.14	0.10	-0.14	1.00							
DR soaked	0.64	-0.17	0.36	-0.28	0.56	0.55	-0.59	-0.36	0.85	0.53	-0.61	0.13	1.00						
e before	0.74	-1.00	0.89	-0.92	-0.38	-0.45	0.45	0.84	-0.20	-0.03	0.19	-0.44	0.17	1.00					
e after	-0.39	-0.20	0.04	-0.22	-0.53	-0.52	0.58	0.68	-1.00	-0.48	0.53	-0.14	-0.85	0.20	1.00				
Av before	-0.69	0.16	-0.22	0.15	-0.55	-0.52	0.50	0.16	-0.52	-0.76	0.34	0.05	-0.61	-0.16	0.52	1.00			
Av after	-0.59	0.37	-0.36	0.37	-0.31	-0.33	0.43	-0.12	-0.58	-0.48	0.20	0.03	-0.79	-0.37	0.58	0.52	1.00		
DOS before	0.79	-0.27	0.33	-0.27	0.45	0.41	-0.39	-0.04	0.51	0.76	-0.26	-0.07	0.63	0.27	-0.51	-0.98	-0.52	1.00	
DOS after	0.58	-0.40	0.37	-0.40	0.28	0.30	-0.39	0.16	0.55	0.46	-0.17	-0.05	0.77	0.40	-0.55	-0.50	-1.00	0.51	1.00

Table 10: Comparing correlation matrix ranking between parameters

Parameter	Linear Correlation (Pearson)			Spearman Rank Order		
	Rank	CBR-2.5mm	CBR-5mm	Rank	CBR-2.5mm	CBR-5mm
CBR – 2.5mm	1	1.00	0.97	1	1.00	0.90
CBR – 5.0mm	2	0.97	1.00	2	0.90	1.00
Swell (%)	11	-0.46	-0.49	3	-0.79	-0.75
MR soaked	13	-0.39	-0.40	4	-0.76	-0.73
DD (t/m^3)	5	0.63	0.60	5	0.61	0.66
MDD (t/m^3)	7	0.51	0.58	6	0.61	0.66
OMC (%)	10	-0.46	-0.50	7	0.61	0.66
Avg MC after soak	3	-0.69	-0.74	8	-0.61	-0.65
DR soaked	6	0.52	0.51	9	0.56	0.55
A_v before	18	0.03	-0.01	10	-0.55	-0.52
e after	9	-0.47	-0.46	11	-0.53	-0.52
DD after soak	12	0.46	0.45	12	0.53	0.52
Comp MC %	8	-0.49	-0.54	13	-0.47	-0.56
DOS before	14	-0.24	-0.19	14	0.45	0.41
e before	4	-0.66	-0.71	15	-0.38	-0.45
A_v after	16	-0.17	-0.18	16	-0.31	-0.33
DOS after	17	0.13	0.14	17	0.28	0.30
DR at Comp	19	-0.01	-0.08	18	0.18	0.11
MR at comp	15	-0.17	-0.21	19	0.03	-0.08

In conclusion, there is a poor relationship with CBR and density ratio. A higher strength / modulus is associated with a higher DR, but one should not apply the reverse logic and associate a high DR with a high strength or modulus. Yet most practicing engineers (**Table 1**) incorrectly believe that the maximum CBR occurs at the MDD (100% DR).

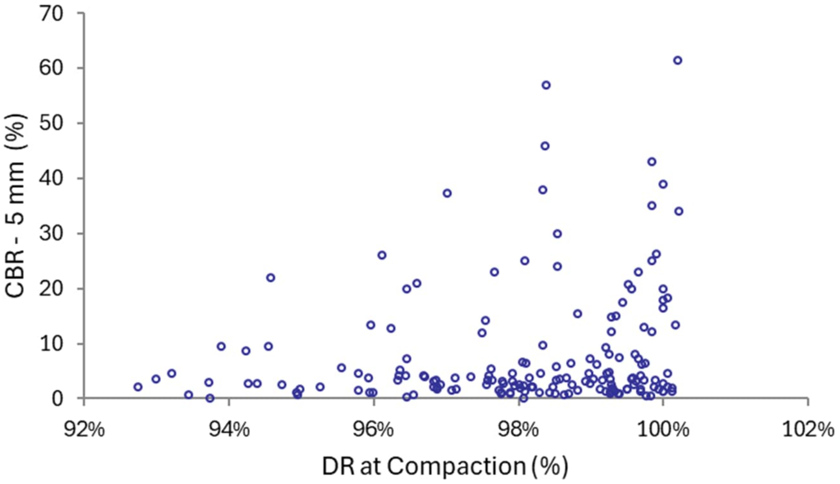

Figure 30: CBR is not dependent on the density ratio (n= 172)

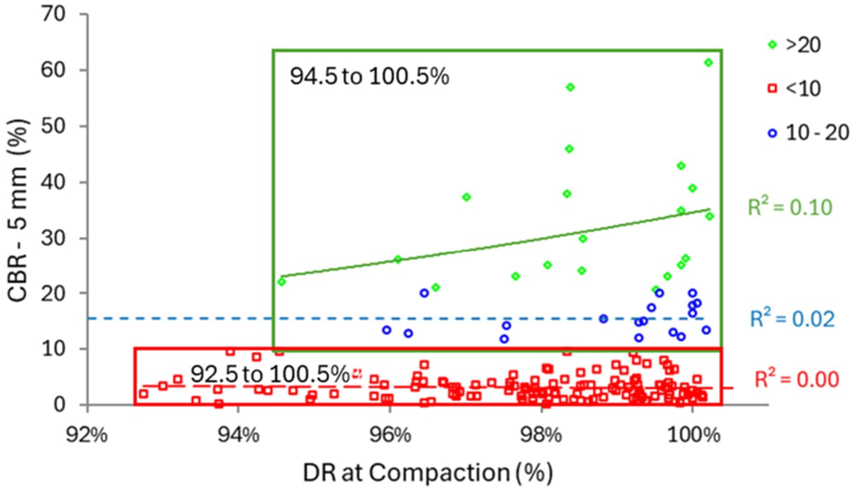

Figure 31: High CBR requires a high DR. This should not be extrapolated as higher DR produces a higher CBR

The following moisture ratios are required to be achieved (**Figure 32**) to ensure the corresponding CBR is achieved:

- CBR > 20% : MR = 75% to 105%
- CBR = 10 to 20% : MR = 70% to 115%
- CBR < 10% : MR = 65% to 130%

The compaction moisture range should be related to the CBR and EMC and not to the OMC. The latter represents a correspondent value related to achieve the MDD but has risen above its importance, as if it were also a target value.

These DR and MR graphs show that a high strength material (CBR > 20 %) requires a narrow range. This validates our state of practice. However, the same logic is then forced on to lower strength material as if high compaction of a CBR < 10% material can achieve high strength. It does not. In such materials a wide range of DR and MR can achieve the same strength.

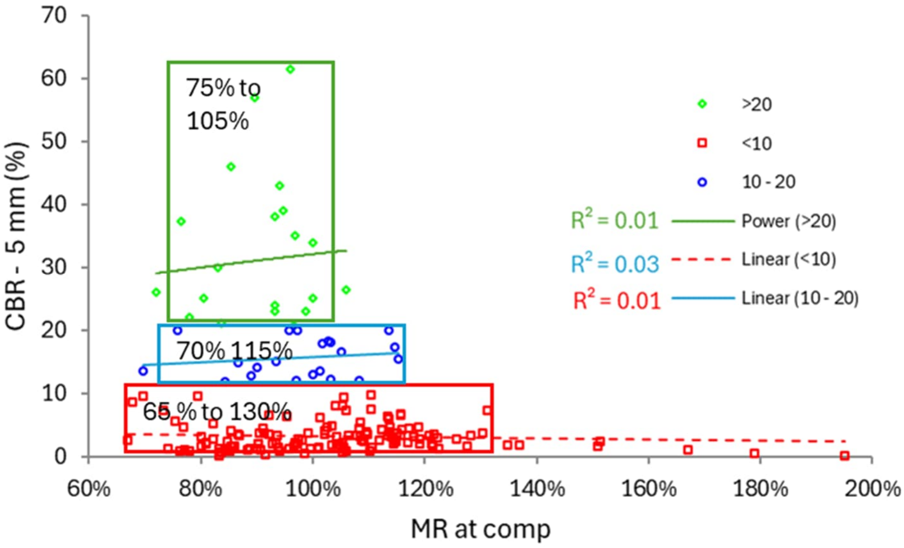

Figure 32: Higher CBR material requires a tighter moisture ratio (MR) at compaction (n= 172)

5. CONCLUSIONS AND RECOMMENDATIONS

There are many inconstancies in testing, with industry practice not consistent with what is considered a trusted or not trusted test. This is partly due to large testing variation in most tests. The density ratio and CBR are ubiquitous in CMT and were used to illustrate the many variables assumed in such testing laboratory models. In particular, consideration of curing time and oversize particles are required by testing standards and when these considerations are not rigorously applied, this may lead to significant variation in test values as demonstrated with case studies.

Laboratory and field tests are models. Understanding the limitations and application of such models are required. Design optimisation requires an appropriate test model and specifying:

- Equilibrium moisture content
- Soaked / Unsoaked CBR testing
- 4 day / 10 day soaking in applying the soaked CBR test
- Surcharge value
- Avoiding 1 point CBR testing in variable and / or high swell materials

It should not be left to the laboratory to specify the above as default values. The lab model relating MDD and OMC are useful construction indices, but a lab model does not consider the related EMC or CBR which are more relevant to long term conditions.

Case study data was compared using advanced statistical techniques to show:

- Use of a trend line automatically generated or normal PDFs has associated bias with outliers included
  - Not using the default Pearson Coefficient (as used in EXCEL) for high outliers or non-normal PDFs.
  - Comparing correlation matrix rankings between Pearson and Spearman correlations was shown with CMT data
- In multivariate analysis, using other techniques such as dendrogram analysis. This was compared with results in the standard bi-variate graphs and tabulated correlation matrices. This can be intimidating with data overload and time consuming to carry out.

The high precision of density testing hides its inaccuracy to assess key design parameters at high compaction levels. Once a minimum DR of say 92% is achieved to reduce the air voids, any increased compaction as judged by a DR value has little relation with strength or modulus. Both DR and MR have construction ranges related to the type of material. Since high strength materials can achieve a high DR, the reverse logic has incorrectly being widely applied, i.e. a higher DR achieves a higher strength. Assuming a DR of 98% is stronger than a DR of 95% is not necessarily correct and other testing is then required. Correlation errors occur when relating DR to more accurate tests.

For a high strength material (say CBR > 20%), compacting to a high DR (say 98%) will have a benefit.

Testing variation combined with broad correlations suggests our placid acceptance of errors simply because as an industry we have grown to accept such historical inaccuracies. A few key takeaways with testing are:

- Density is not performance. At high values density is poorly correlated to strength or modulus (stiffness).
- Strength is not linearly related to stiffness
- Modulus is not a constant

In the case of working platforms, designs have minimum modulus or strength requirements, and density testing alone is insufficient. Case studies on such applications are provided by Look and Honeyfield (2016), Barounis and Smith (2017), Barounis and Philpot (2025).

This paper focused on local Australia and New Zealand CMT practices and data, but the conclusions are not unique. Riad at al. (2023) show that density based quality control specifications do not provide engineering properties that can be used to ensure optimal performance of tested unbound pavement materials. Modulus based specifications have been successfully used by many USA state authorities and European countries. However greater spatial test data variability and the significant effect of moisture content are some of the challenges. This is no different from the early work of Selig and Truesdale (1967) shown in **Table 3** when precision took precedence over accuracy in elevating DR testing to its current prominence. Referring to that early and more comprehensive research by Selig and Truesdale (1967) they found the order of importance as:

1. Moisture was **by far** the most significant factor influencing the measurements. The MR soaked accounts for 73% to 76% of variance of CBR according to the Spearman Rank Order (**Table 10**) and was the highest influence
2. Soil type
3. Compaction equipment. Effectiveness depends on soil type. Effect changed with soil thickness
4. Lift thickness. Moisture and thickness had little interaction. Significant effect on density
5. Compactive effort. The DR at compaction accounted for 11% to 18% of contribution to the soaked CBR value (**Table 10**)
6. Dry density measurement was the least variable while field CBR, Moisture content and plate load were the most variable

This paper did not have cover all of the important factors above. Permeability is also an important factor but no data was available for such discussion.

The primary objective of compaction is to reduce the air voids and current practice achieves this indirectly by the Proctor MDD and OMC approach. CMT then often use the MDD and OMC as an aim, but this is incorrect. It is a simple and precise test to infer air voids (to reduce settlement) has been reduced to an acceptable level. With currently available technology and this research of influence of test variables, the recommendation is for a 3 step quality process

1. **Step 1**: Use the conventional DR approach to reduce air voids and control settlement. Once compaction to over 90% is achieved the air voids is likely 5% to 10% air voids. But density is not a performance indicator. As shown high density is poorly related to strength or modulus
2. **Step 2**: Assess strength or modulus. Many testing tools are available but such discussion was not the focus of this paper. These include plate load test (PLT), Clegg impact hammer, Geogauge, geophysical based devices and Light falling weight deflectometers (LFWD). A challenge is that the "modulus" values can vary between these different equipment due to varying strain levels and depths of influence. Different commercially available LFWD equipment may measure different values at the same site. A key consideration is not to correlate to DR due to unreliable correlations (Look, 2019).
3. **Step 3**: Assess uniformity of site compaction with a representative quantity of testing now economically possible with some of the testing equipment mentioned above. Proof rolling has traditionally been used in parallel with DR, but this "proof roll test" also has its limitations. Intelligent compaction would better serve industry in this regard.

CRediT authorship contribution statement

Burt Look: Writing - original draft.

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APPENDIX – RELATIONSHIPS OF DENSITY, STRENGTH AND MODULUS

We often default to density as if it is a proxy for performance. At the macro level, strength increases with density was shown in **Figure 9**. That data is now repeated with the correlation (R^2) of 0.65 and 0.61 for the high and low modulus values, respectively (**Figure 33**). This may seem a reasonable correlation. Removing the data points for man-made materials (high strength and low strength steel and concrete with its density and modulus values) result in the correlation (R^2) of 0.23 and 0.05 for the high and low modulus values, respectively (**Figure 34**). This is now a weak correlation. This shows modulus is <u>not</u> related to density.

Using 131 undrained strength results in residual soils (**Figure 35**) also show no correlation between strength and dry density correlation (R^2 = 0.04).

These results suggest the common assumption of strength or modulus is related to density is incorrect. Yet density testing is the basis of quality control in CMT and we then assume appropriate strength or modulus for that material.

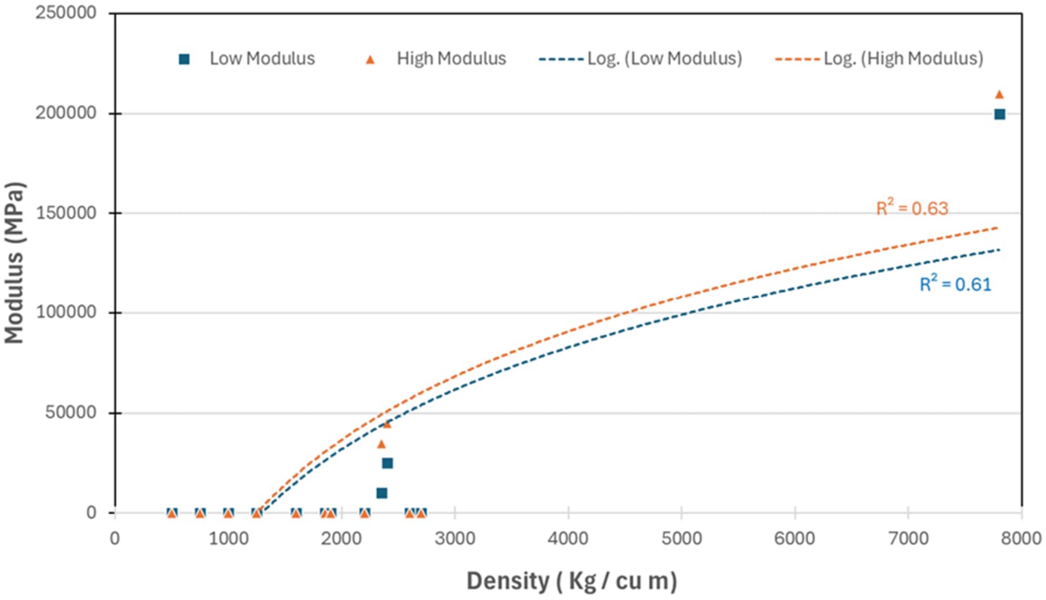

Figure 33: Change in modulus with density for varying material

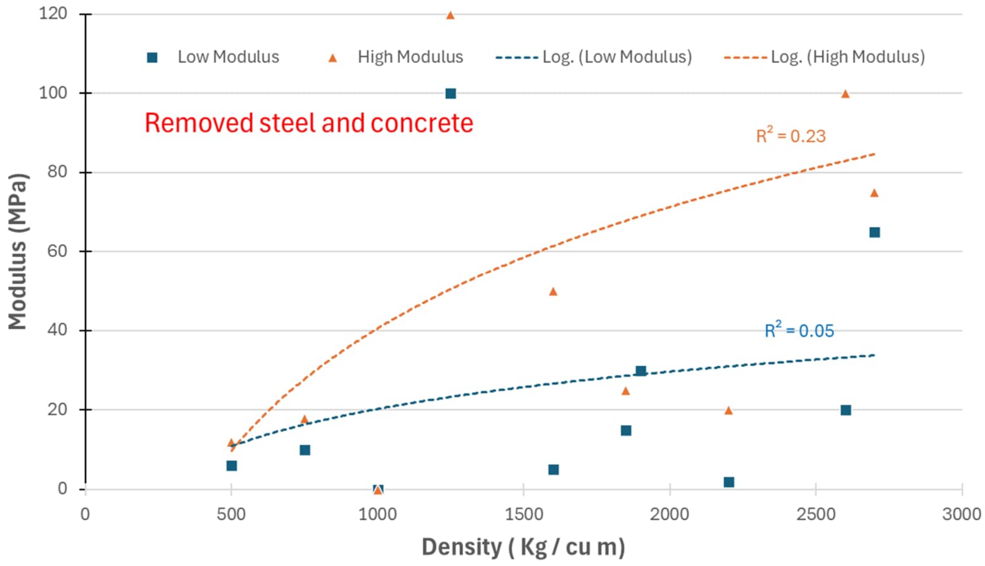

Figure 34: Change in modulus with density for material with steel and concrete values removed

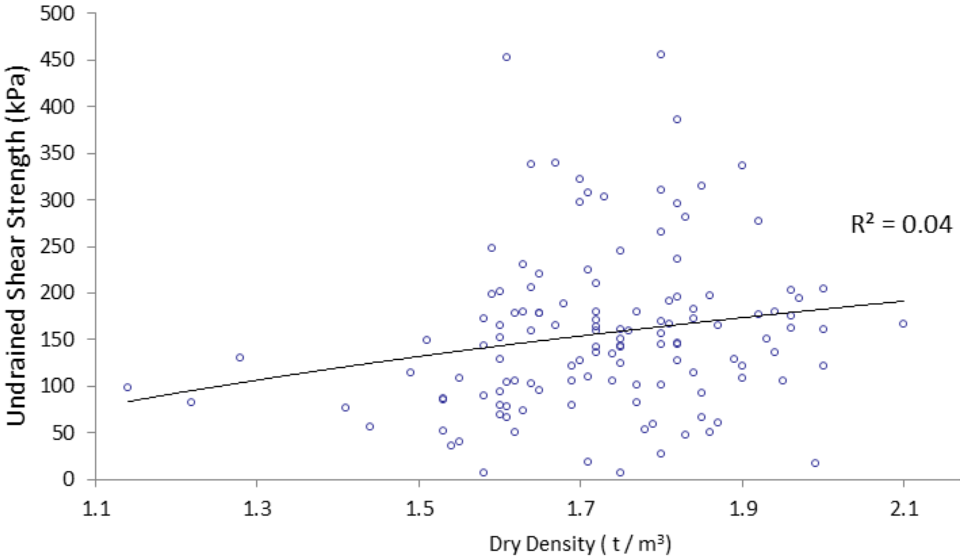

Figure 35: Change in undrained strength with dry density for residuals soils