Sensor	Mounting	Function	Example sensor devices
frames only) Note 1			quadrature output plus index, 1,024 pulses/revolution

Note 1: With the NZS frame, the potential through wear of having loose fitting connections of the lever arm to the load frame, the hammer to the lever arm and the tamper with the hammer is very high.

All the outputs from the sensors would be fed into a data acquisition unit, sampling at greater than 2,000 samples/sec. This would ensure that all data samples are synchronised.

Comparison of the graphed outputs would allow the assessment of the compaction in terms of duration, sample behaviour and vibrating hammer componentry.

6 Summary

Ellis provided a summary of the extensive Opus study (Ball 2008) into vibrating hammer compaction in New Zealand (Ellis 2009). The conclusions drawn were as follows:

- New Zealand variability values appear to be two to four times larger than those stated in the British standard. This is quite significant and may justify a rework and/or revision of the current test standard.
- The hammer calibration method may need revision. It was suggested an attempt could be made to incorporate a maximum limit of vibrating power input rating.
- Hammers with high input power ratings tend to provide higher dry density values, although this only accounts for roughly 10% of the variability.
- Five laboratory results out of the 33 laboratories, ie 15% of results, were excluded from data analysis due to the extent of variability observed in these five results. It is evident that the way in which the vibrating hammer compaction test method is conducted can significantly influence the reliability of the results obtained.

The following factors were considered to contribute to the overall variation of results experienced with the New Zealand vibrating hammer compaction test.

- hammer type (frequency, amplitude, power)
- hammer age (degradation of performance over time)
- presence or absence of perforations in the base plate/mould type and spacer (water movement)
- gap between tamper plate edge and mould wall (water loss)
- tamper mass (total surcharge, energy transfer)
- method of securing hammer (frame or hand-held, energy transfer)
- testing technique (technician skill, dedication)
- hammer calibration (consistency)
- sample grading/preparation and placement in mould (segregation, accuracy)
- final compacted sample height and measurement method (calliper, ruler, on sample, on tamper)
- smooth curve fitting to data points (data accuracy).

From the investigations undertaken for this review it is possible to add the following to the list:

- frame age and condition (degradation of performance, energy transfer)
- frame type (BS lever or ASTM frame)
- mould type (NZS or BS type)
- tamper type (NZS foot or BS piston)
- time of compaction (shorter time, longer time)
- treatment of water and slurry loss (removal or replacement)
- laboratory and field density measurements (mass, NDM)

- material properties (selection of compaction method)
- test not being performed in accordance with the New Zealand standard.

All of the evidence described in this report suggests there is enormous scope for variability in the New Zealand vibrating hammer compaction test and that scope for introduction of an alternative method, such as the vibrating table method or the gyratory compaction method, does exist. The characteristics of each method are summarised in table 6.1 below:

Table 6.1 Characteristics of the three main compaction methods

Characteristics	Vibrating hammer	Vibrating table	Gyratory compactor
Cost	**Relatively low cost**	**Moderate cost**	**High cost**
Ease of purchase	Different suppliers necessary for hammer, frame, moulds	One supplier needed for all components	One supplier for all components
Ease of use	Can be fiddly. Some experience useful	Some issues with movement of heavy surcharges and moulds	Very easy to use. Needs compressed air feed
Messy	Can allow wet slurry to be expelled from mould. Has no effect on the equipment	Should remain relatively clean. Could affect equipment if enters mechanism	Should remain relatively clean. Leaking slurry can be difficult to clean and can damage equipment
Operator training	Can be tricky. Not straightforward to obtain consistent results	Appears very straightforward	Very straightforward
Consistent energy input	Not necessarily. Appears very variable	Appears to be consistent	Yes
Controllable energy input/compaction load	Equipment energy output, amplitude and frequency set by manufacturer, surcharge weight user adjustable	Equipment energy, frequency, sample surcharge user adjustable	Compaction load, gyration angle and frequency fully adjustable
Controllable compaction time	Yes	Yes	Yes
Compaction energy measurable	Possible	Possible	Yes. Indeed it is known precisely
Long term reliability	Typically good but does wear out over time	Poor reputation for long term reliability which may or may not be better with new equipment	Typically good reputation
Correlation to field compaction	Widely used, but not necessarily good	Not known in New Zealand	Not known in New Zealand but good correlations in USA
History of use in New Zealand	Significant history of use	Limited/little history of use in New Zealand	Limited/moderate history of use in New Zealand
High degree of compaction	Not necessarily	Appears to achieve high degrees of compaction	Achieves high degrees of compaction
Damage to sample	Yes. Particle degradation widely observed	Typically less damage	Typically lower than other methods

Characteristics	Vibrating hammer	Vibrating table	Gyratory compactor
Different mould sizes	Yes. 152 and 300 mm	Yes. Any size that will fit onto table top is possible	No. Only 150 mm with current equipment. No plans to develop larger mould
Sample ‘scalping’ required	Yes, with 152 mm mould No, with 300 mm mould	No	Yes
Different designs	Yes. Many different hammers and frames available	Yes. Many different table designs available	Fewer suppliers. One supplier appears to be leader
Temperature/environmental control	Possible to use inside environmentally controlled cabinet	Would probably need environmentally controlled room	Would probably need environmentally controlled room
Local suppliers/service agents	Yes	Not known	Yes

Note: Green = good or advantageous characteristic; Orange = neutral or moderately disadvantageous characteristic; red = disadvantageous characteristic.

7 Recommendations for establishing standardised compaction energy

This project was initiated to examine the variability that exists with the vibrating hammer laboratory compaction testing as it currently exists in New Zealand, and then to consider how to standardise the compaction energy that is input into test samples, either by improvement of the existing method, or by introducing an alternative method. This general area has been extensively studied and reviewed and a review of that literature was undertaken.

Analysis of the literature and discussions with technicians in the sector permitted recommendations to be made for developing approaches that might improve upon the current situation.

In his summary of the large Opus investigation into laboratory vibrating hammer testing, Ellis (2009) made recommendations aimed at reducing the variability of the laboratory results as listed below:

Step 1: Establish an appropriate **minimum** dry density that is needed for an example aggregate to ensure adequate strength and performance in the pavement is achieved.

Step 2: Carry out repeatability trials using a single laboratory set up and a specifically chosen example aggregate. Compare against benchmark BS and ASTM variance values, should they exist. Explore the effect of different hammer models, mould type and other factors. Choose options with the least variation contribution and from there agree on a standardised hammer type, mould and technique, while ensuring data generated from chosen equipment and technique will produce appropriate MDD from step 1 above.

Step 3: Review and rewrite as appropriate the test methodology based on the findings above, providing an improved degree of prescriptive guidance.

Step 4: Verify the reproducibility by carrying out a new national proficiency test using the new methodology.

The gyratory compaction technique was not considered in either Ball (2008) or Ellis (2009), but the literature reviewed here suggests it is a technique that may well be worth further consideration. No NZS method currently exists for its application to the problem of aggregate compaction.

Two approaches may be taken to achieve the outcome of reducing compaction test result variability through the concept of standardising the compaction energy. The first is to substitute the vibrating hammer test for a new test adapted to the New Zealand context, such as the vibrating table test or the gyratory compactor test. The second approach is, as suggested by Ellis, to reassess the vibrating hammer test and tighten up on its contributing factors and details.

Some indication of costs for new and/or upgraded equipment suggests the gyratory compactor would be the most expensive, but the vibrating table and all the equipment required for the vibrating hammer test (hammer, frame, mould) would be in the region of US$20,000 each.

It is not clear at the current time if changing to either the vibrating table test or the gyratory compactor test would provide any practicable improvement to the current situation; this can only be determined with a rigorous testing programme and prescriptive standard.

Recommendations are as follows:

- Examine the ASTM and BS standard methods for the vibrating hammer and adopt them more closely where applicable.

- Instrument the vibrating hammer equipment to provide an understanding of the existing method and to enable its assessment, including what possible aspects and refinements to consider.
- To allow the effect of variables to be estimated and allow limits for these variables to be derived, develop a Matlab model based on the data obtained from the instrumented hammer.
- Compare the vibrating hammer, vibrating table and gyratory test methods side by side to obtain results from each method and determine if any of these methods offer improved compaction results and/or variability.
  - Use two specific but differently sourced basecourse aggregate samples from diverse geological sources. They should be M/4 specified basecourses because the grading, history and typical test results will be previously understood.
  - Use samples applied in new constructions so contemporary laboratory and field compaction results could be compared with those obtained by the new investigation.
  - Use brand new equipment for each test. Clearly the vibrating table would be new as there are few, if any in New Zealand. Similarly the entire vibrating hammer system must be new, including the hammer, the frame and the moulds so the test comparisons all start from the same point. The type of frame would also need to be well considered. Perhaps the gyratory compactor might not need to be new, but any instrument chosen would need to be well serviced prior to use. Some judgement would be required regarding which equipment models should be used.
  - Undertake an experimental design in order to investigate the test parameters that would be determined as being important to the test outcome, such as: compaction time; aggregate grading; surcharge weight; sample temperature and other possible variables. This may be a ruggedness test (eg ASTM E1169), but may be a more simply designed experiment.
  - Recruit one operator to perform the tests. This operator would ideally be experienced in sample preparation and the management of the testing. Additionally, this operator would undergo remedial training in order to reinforce the current test standard method.
  - Following assessment and determination of acceptable methodologies, recruit several further operators to perform the tests under exactly the same conditions and analyse their results for variability.
  - Roll out the methods across New Zealand so they can be performed in different environments and the variability assessed.
  - Investigate the 300 mm mould.

If, the above programme results in a decision to adopt a compaction method other than the vibrating hammer method then a new New Zealand standard would need to be derived. If the outcome is to continue with the vibrating hammer test, it is likely the current standard would need to be revised and tightened up. One example of such a revision is the calibration method, where there should be a range for compacted density rather than simply a minimum value.

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