WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM

Best Practice Non-destructive Quality Assurance Testing for Asphalt – Stage 2

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SUMMARY

Main Roads currently determines in situ asphalt density and air voids compliance through conventional methods involving core sample testing. This project is aimed at developing suitable statistical acceptance criteria for Main Roads to implement use of the nuclear thin lift gauge (TLG) density testing as a part of their asphalt quality assurance procedure. A national and international literature review of nuclear TLG density testing showed that TLG has the potential to provide a suitable measure of asphalt density but it needs more appropriate calibration equations that suit local or project specific conditions. There are several factors that contribute to high variability of density data collected by nuclear density gauges including gauge calibration, mode of testing, operating procedure, asphalt layer thickness, mix design and chemical composition of aggregate. The research findings show that nuclear gauge readings generally have high variability as compared to core results as nuclear TLGs can under or overestimate density values. However, the nuclear gauges can be calibrated to establish measurement offset using density from matched core results to improve the accuracy of density readings. Generally, different calibration equations for different materials are required.

Analysis of 14 data sets collected from the Gateway WA Alliance project as a part of a TLG trial indicated greater sampling and testing variation in the standard deviation of the TLG density results compared to the core data. Some limitations of the Gateway WA Alliance trial data have been identified as follows:

- Very limited information was furnished on the nuclear TLG density measurement procedure and mode of testing used. This information is important as, when used in backscatter mode, the density readings from the nuclear devices are very sensitive to the placement and position of the gauge during testing. Generally, the airgap test mode gives more accurate results as compared to the contact mode.
- Similarly, there is no clear indication of asphalt layer thickness for the density testing. The literature suggests that nuclear TLG measurements on thin layers can be less precise as compared to thick layers. Any relationship of layer thickness to variability of the density readings could not be established due to absence of details about asphalt layer thickness.
- There is no data provided related to pavement material characteristics and asphalt mix design. The maximum specific gravity of the mix and chemical composition of the aggregates can have a significant contribution to the variability of the nuclear TLG readings which leads directly to standard deviations.

Overall, the variability of density readings determined by nuclear TLGs are generally higher than those determined from cores and this is reflected in the density data from the Gateway WA Alliance project.

The establishment of suitable statistical acceptance criteria for Main Roads in order to implement TLG density testing for asphalt quality assurance requires a sufficient data pool (preferably more than 100 points) with all details related to the testing procedure, the pavement configuration and the material characteristics.

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The research findings from this project provide a solid foundation for developing guidelines for nuclear TLG trials for further analysis. Therefore, it is recommended that Stage 3 of the project should proceed with documented procedures and guidelines for testing and data analysis to achieve this milestone.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1.1 BACKGROUND

With increased traffic loading there is increasing use of asphalt pavements in place of sprayed seal surfaced granular pavements on the Western Australian state road network. A key measure of construction quality for asphalt pavements is the level of compaction achieved as this is closely linked with assumptions regarding materials properties used in structural pavement design and the performance of this material under traffic and environmental operating conditions.

Road construction quality assurance generally involves contractors providing a quality management plan and conducting quality control procedures in line with this plan to provide assurance that specification requirements are consistently achieved. In regard to density, construction quality assessment involves assessment of construction lots of asphalt placed with representative lot based sampling of in situ density. Main Roads currently determines in situ asphalt density and air voids compliance through a conventional method based on pavement coring and laboratory density testing of the asphalt cores. The laboratory assessment of asphalt density from field cores is regarded as highly accurate. However, the major drawbacks of this approach are its destructive nature, time delays due to waiting for laboratory testing results and the costs involved.

Where asphalt pavements have been used for decades by east coast state road agencies, application of nuclear density meter methods have been adopted as a part of their asphalt quality assurance processes. The major advantage of these devices is that they are non-destructive and economical and can augment construction productivity due to rapid results and response which can be used to improve compaction processes.

While Main Roads has previously considered adoption of nuclear density meter methods for asphalt density compliance assessment (Nielsen 1992), the increased use of asphalt in recent years has re-opened consideration of this alternative technology for quality assurance testing. This is the basis of this WARRIP project.

The first stage of the project involved conducting a review of domestic and international current practices in asphalt density compliance testing with a focus on non-destructive asphalt density assessment technology.

The key findings from the first stage of the project are:

- There is limited experience with the nuclear thin-layer gauge (TLG) in Western Australia and little evidence of either poor or strong performance relative to other techniques.
- There is significant experience of nuclear TLG use in other states, so extensive field trials may not be required to enable adoption of nuclear TLG methods in Western Australia for asphalt quality assurance. However, appropriate specification requirements and practice guidance documentation would need to be developed based on best practice experiences from other jurisdictions.
- General guidance, test methods and statistical acceptance criteria are well established in Queensland through the Department of Transport and Main Roads and these could serve as a good starting point in the development of standard procedures for the nuclear TLG in Western Australia.
- Intelligent compaction control technologies are not currently mature enough to be used for asphalt compaction quality assurance, however, they may be used to supplement traditional test methods by identifying areas of potential concern in regard to compaction density and assisting in achieving uniform compaction as a quality control method.

1.2 SCOPE AND OBJECTIVES

The aim of the project is to identify appropriate nuclear TLG density acceptance criteria for application by Main Roads. The scope of works comprises:

- a review of nuclear TLG density acceptance criteria which will provide guidance on determining suitable statistical acceptance values for Main Roads
- an assessment of a set of asphalt density data collected during the Gateway WA Alliance (GWA) nuclear TLG trial on the Tonkin Hwy in 2015 with the aim of identifying whether different acceptance criteria are required when using a nuclear TLG and if so, what this acceptance criteria should be
- identification of the next steps for the subsequent stage of this project.

1.3 STRUCTURE OF THE REPORT

This report presents the findings to date of this project. The structure and contents of the report are as follows:

- Section 2 outlines an overview of the Main Roads practice for asphalt quality assurance testing.
- Section 3 details the review of nuclear TLG statistical acceptance criteria in Australian state road agencies and overseas.
- Section 4 provides data analysis and discussion on statistical acceptance criteria for Main Roads.
- Section 5 provides conclusions and recommendations arising from the project to date.

2 MAIN ROADS PRACTICE FOR ASPHALT QUALITY ASSURANCE TESTING

2.1 CURRENT ASPHALT DENSITY CONFORMANCE ASSESSMENT

Main Roads specifies that field compacted asphalt density and in situ air voids are to be determined based on laboratory testing of a series of representative core samples taken after field laying and compaction of an asphalt layer in accordance with Main Roads Specification 201: *Quality Systems* (Main Roads 2020).

The asphalt bulk density is measured using Main Roads Test Method WA 733.1 (Main Roads 2018a) or WA 733.2 (Main Roads 2012), where the density is expressed as a percentage of the mean Marshall density determined in accordance with WA 731.1 (Main Roads 2018b) and either WA733.1 or WA 733.2.

The in situ air voids are calculated using the maximum asphalt density in accordance with WA 732.2 (Main Roads 2011) and WA 733.1.

The characteristic in situ air void content requirements for Specification 510 *Asphalt Intermediate Course* (Main Roads 2018c) courses (14 mm and 20 mm) are 3.0% – 6.0%, the upper limit of which may be relaxed to 7.0% in order to allow asphalt suppliers to implement new asphalt mix designs (Main Roads 2018b).

In order to achieve a representative sample, Main Roads Engineering Road Note 8 (Main Roads 2008) recommends at least 10 density tests per lot to be carried out for asphalt surfacing layers. In situ density conformance is based on the characteristic value of the Marshall density of each lot as summarised in Table 2.1 as per Main Roads Specification 504 *Asphalt Wearing Course* (Main Roads 2017a). An incentive scheme operates in the specification which provides full payment for full conformance and reduced payment for non-conformance within a range as shown in Table 2.1.

Table 2.1: Main Roads asphalt wearing course density conformance pay factors (Table 504.8)

Characteristic percent Marshall density, relative compaction (Rc) (%)	Quality level	Pay factor
≥ 93.0	Conformance	1.0
≥ 91.0 and < 93.0	Conditional conformance	0.15 X RC – 12.95
< 91.0	Non-conformance	N/A

Source: Main Roads (2017a).

Characteristic values of Marshall density of each lot in accordance with Main Roads Specification 502 *Stone Mastic Asphalt* (Main Roads 2017b) are summarised in Table 2.2.

Table 2.2: Main Roads stone mastic asphalt density conformance pay factors (Table 502.5)

Characteristic percent Marshall density, relative compaction (Rc) (%)	Quality level	Pay factor
≥ 95.0	Conformance	1.0
≥ 93.0 and < 95.0	Conditional conformance	0.15 X RC – 13.25
< 93.0	Non-conformance	N/A

Source: Main Roads (2017b).

2.2 MAIN ROADS USE OF NUCLEAR DENSITY METHODS

For many decades, Main Roads has permitted the use of nuclear density methods for soils and granular materials. Main Roads test method WA 324.2 (Main Roads 2019) describes the determination of field density using a nuclear density meter. This method is applicable for the dry density of soils and granular pavement materials with less than 20% retained on the 37.5 mm sieve. The calibration procedure of the device is in accordance with WA 135.1 (Main Roads 2014) which uses standard blocks. The consistency of the measurements is checked using secondary standard blocks described in WA 135.2 (Main Roads 2001). These nuclear density measurement devices should be calibrated as per WA 323.1 (Main Roads 1982) against field testing.

Although use of TLG nuclear density methods have been considered by Main Roads in the past (Nielsen 1992), Main Roads Specification 201 does not currently permit the use of the nuclear TLG for determination of in situ asphalt density. Both Main Roads and Western Australian industry have supported this approach.

The construction industry in Western Australia has expressed concerns regarding use of TLGs due to the increased risk of asphalt being rejected as a result of higher standard deviations associated with TLG nuclear testing whereas the same lot assessed by core testing could meet the specification requirements. Main Roads has similar concerns regarding the potential for greater variance of test results from TLG nuclear density methods and the distribution patterns within the data.

However, the use of TLG nuclear density methods for conformance assessment of asphalt density is well established in quality assurance approaches adopted by all state road agencies in eastern Australia.

Based on this, Main Roads is interested in a reassessment of the use of TLG nuclear methods and particularly best practice approaches to minimise variance in test results. Of particular interest are approaches adopted elsewhere to reduce inherent test variability (or to improve precision of measurement) and to reduce bias (or to improve accuracy) to acceptable levels. This would improve confidence in the use of TLG nuclear density methods for asphalt quality assurance in Western Australia.

3 REVIEW OF NUCLEAR TLG DENSITY ACCEPTANCE CRITERIA

A review of nuclear TLG density acceptance criteria and test methods used by the state road agencies in Australia and overseas has been undertaken. The aim of this review was to identify best practices which would allow Main Roads to develop guidance around specifications and test methods for use of nuclear TLG methods in statistical acceptance of asphalt density in Western Australia. Identification of current best practice would help in minimising risks of scatter in test results impacting density conformance assessment.

Nielsen (1992) reported a Main Roads investigation into the suitability of TLG nuclear methods to determine the density of asphalt with sufficient accuracy and reliability for use in deciding conformance with project specifications. Nielson (1992) found that for dense graded asphalt, the gauge underestimated density with high variability of measurements in comparison with core results, while for open graded asphalt, the gauge overestimated results with lower variability. At that time, it was concluded that the gauge had potential to provide suitable measurement of asphalt density, but more appropriate calibration equations were needed. The following sections investigate various approaches by other state road agencies to this issue with the TLG.

3.1 QUEENSLAND DEPARTMENT OF TRANSPORT AND MAIN ROADS

The Queensland Nuclear Gauge Testing Manual (TMR 2019) describes the use of nuclear surface moisture density gauges and nuclear TLGs for density assessment of thin asphalt layers. This comprehensive manual includes test methods, operating instructions, calibration requirements, and statistical acceptance criteria. The TLG nuclear method statistical acceptance criteria for asphalt density testing involves the following key elements:

General TMR requirements:

- The TLG nuclear method is allowed for density measurement of compacted asphalt having a nominal maximum size of 40 mm and nominal layer thickness between 25 and 100 mm. However, the use of the backscatter (BS) mode is restricted to nominal layer thicknesses where 80% to 90% of the measurement depth is within 50 mm of the layer surface.
- The test method is dependent on the manufacturer of the TLG. Routine density measurements are taken with the gauge in one measurement position for specific TLG makes (e.g. BS is accepted for Troxler, Humboldt and Instrotek gauges) or two measurement positions for other TLG makes (e.g. BS and AC in CPN gauges).
- Measurement depth for the moisture content decreases with increasing moisture content of the material (e.g. for a moisture content range of 0.1 to 0.3 t/m^3, the measurement depth is about 250 to 200 mm respectively).
- Compacted density is reported to the nearest 0.001 t/m^3.

Assessment of TLG precision:

- TLG calibration using standard blocks must be carried out in accordance with AS 2891.14.3 at least once every two years to address deterioration in the TLG radiation source.
- Density calibration using standard blocks involves acceptance limits for the difference between initial density and current density for a particular source rod position. The difference should not exceed 0.050 t/m^3 for backscatter measurements and 0.020 t/m^3 for direct transmission measurement.
- Results are obtained for two orientations of the TLG at each test site to determine asphalt density. The difference in the density results between two orientations should not exceed 0.075 t/m^3.

Assessment of accuracy – bias correction:

- There is evidence that TLGs tend to provide lower results as compared to traditional core testing. For many materials, this difference is small and can be ignored. However, for some materials the difference or bias is substantial, and an adjustment of the standard block calibration process may be necessary. This involves a secondary block calibration in accordance with relevant Australian Standard (e.g. AS 1289.5.8.1). The secondary block shall have minimum dimensions of length 500 mm, width 290 mm and depth not less than 200 mm and at least 50 mm deeper than the greatest depth at which the check will be conducted.
- The formulas proposed for calculation of the bias (and limits for acceptance of a proposed bias) are important to highlight. The TMR approach requires ten test sites to be randomly selected from a representative compacted lot of asphalt. At each of these sites a density measurement is taken with the TLG placed in the roller direction and then a second measurement is taken with the TLG rotated to 180° of the roller direction. An asphalt core sample (150 mm diameter) is then taken centrally over each TLG test location for determination of the compacted asphalt density which is measured in the laboratory by means of the presaturation method Q306B (TMR 2018a) (essentially as for AS/NZS 2891.9.2) or the silicon sealing method Q306C (TMR 2018b).
- The measured density with the TLG device and the core compacted density are compared for all locations, with a standard error for the lot calculated according to Equation 1.

$$SE_\rho = 2\sqrt{\frac{\sum(D_c - \rho_G - \overline{D_c} + \overline{\rho_G})}{n-2}} \qquad 1$$

where

SE_ρ	=	density standard error (t/m^3)
D_c	=	core compacted density at each test site (t/m^3)
ρ_G	=	standard blocks wet density at each test site (t/m^3)
$\overline{D_c}$	=	average core compacted density for the test sites (t/m^3)
$\overline{\rho_G}$	=	average standard blocks wet density for the test sites (t/m^3)
n	=	number of test sites

- The density standard error must not exceed 0.025 t/m^3. Should the error exceed this value, the density error is to be calculated for each corresponding pair of values. The pair with the largest error is then to be eliminated, and the standard error for the lot calculated again. Should the standard error still exceed 0.025 t/m^3, another density data pair may be eliminated, with this process repeated until the standard error is less than 0.025 t/m^3 or until more than 20% of test pairs are eliminated.

  If the error remains higher than 0.025 t/m^3, then this lot is not suitable for the calculation of a single asphalt density bias. This may be due to inconsistent material or poor construction practices or could indicate an error with the device and may warrant closer investigation.

With a compliant standard error, the asphalt density bias can be calculated (to the nearest 0.001 t/m^3) by Equation 2:

$$B_\rho = \overline{D_c} - \overline{\rho_G} \qquad (2)$$

where

B_ρ = asphalt density bias (t/m^3)

$\overline{D_c}$ = average core compacted density for the test sites (t/m^3)

$\overline{\rho_G}$ = average standard blocks wet density for the test sites (t/m^3)

- After the acceptance of an asphalt density bias for a material, an additional three pairs of nuclear gauge densities and core compacted densities are to be taken following the compaction of each 10 000 tonnes of material. The three new pairs are added to the previously accepted data, and the three pairs with the lowest chronological number removed. An amended asphalt density bias is then calculated, with this process repeated for the next 10,000 tonnes of material.

3.2 NEW SOUTH WALES ROADS AND MARITIME SERVICES

Roads and Maritime Services (RMS) Technical Guide L-G-002 (RMS 2015 outlines the testing and calibration methods for nuclear density gauges to assess moisture content and density of compacted pavement materials. This document suggests that the device can be used on most asphalt types but not on open graded asphalt. The main highlights of the RMS technical guide for nuclear density moisture measurement are as follows:

- A TLG nuclear device can be used to determine the compacted density of asphalt for layers of between 25 to 100 mm thickness.
- The calibration range for TLGs is generally between 1.72 t/m^3 to 2.76 t/m^3. A different test method (e.g. non-nuclear gauge) must be used for readings where the compacted density is outside this calibrated TLG density range.
- A TLG must not be used if the proportion of oversize (+37.5 mm) material is greater than 20%.
- One 4-minute reading of layer density, with two separate density counts recorded, is required at each site.
- Monthly in-house gauge checks on a standard density block or on a secondary block (e.g. sandstone or granite) should be conducted.
- Two separate density standard counts (one for each measurement system) must be taken simultaneously at the start of each lot.
- Density offsets must be determined and applied for each asphalt mix as described in AS/NZ 2891.14.2:2013 to adjust the nuclear TLG readings for backscatter effects due to aggregate chemistry.
- Sampling of asphalt by coring is required in order to establish or check density offsets.

RMS Quality Specification R116 (RMS 2019) describes the procedure to calculate in situ air voids and bulk density either from cores in accordance with AS/NZS 2891.9.2:2014 or nuclear density measurements taken in accordance with AS/NZS2891.14.2. The nuclear density method is not to be used when steel reinforcement exists within 300 mm of the surface of the layer. The upper (V_U) and lower (V_L) characteristic values of in situ air voids of the lot are calculated using Equations 3 and 4:

$$V_U = \bar{a} + ks \quad (3)$$

$$V_L = \bar{a} - ks \quad (4)$$

where

V_U	=	the upper characteristic value of in situ air voids of the lot
V_L	=	the lower characteristic value of in situ air voids of the lot
s	=	the standard deviation of sub-lot air voids expressed as percentage
k	=	value stated in RMS Q6 Annexure Q/L Clause L3.2 (RMS 2012)
$\bar{a}$	=	the arithmetic mean of in situ air voids expressed as percentage for all sub-lots and $a = \left(\frac{MD-BD}{MD}\right) \times BD$
MD	=	mean maximum density of the lot determined in accordance with AS/NZS 2891.7.1 or AS/NZS 2891.7.3
BD	=	bulk density of the sub-lot determined in accordance with AS/NZS 2891.9.2 (for cores) and AS/NZS 2891.14.2 and AS/NZS 2891.14.3 (nuclear density gauge)

Note: Values of V_U and V_L are rounded and reported to the nearest 0.1%.

3.3 VICROADS

VicRoads' Technical Note 106 (VicRoads 2011) provides guidance on different aspects of surveillance including gauge operation, lot testing, site selection and conduct of the field test and sampling for laboratory work.

- Six test sites must be selected for a lot. For smaller lots (< 500 m^2), three test sites may be selected using mean plus 2% criteria.
- If the original test site is unsuitable, the gauge can be relocated within 0.5 m of the selected test site location.
- For each measurement of layer density, two independent 4-minute density readings must be taken with the long axis of the gauge in the direction of compaction rolling.
- The gauge offset should be determined for each asphalt mix according to AS/NZS 2891.14.2.
- The TLG is used for thicknesses between 25 mm to 50 mm.

3.4 OTHER STATE ROAD AGENCIES

The Department of State Growth in Tasmania adopted VicRoads standard specifications in 2016 and in line with this they allow TLG nuclear density testing in their Standard Specification, Section 407 Clause 22.

- The clause refers to VicRoads Code of Practice 500.05 and 500.16 (VicRoads 2017a & b). The density is measured by cores and nuclear gauges and then an offset value is assigned to the nuclear gauge readings based on the correlation between density of the cores and the nuclear gauge reading.
- Six tests per lot should be conducted and a characteristic value of density ratio is defined by the mean and standard deviation of individual density ratio test values for the lot.
- Acceptance criteria are shown in Table 3.1.

Table 3.1: Limits for Characteristic Density Ratio (six tests) adapted from Table 407.221 (Tasmania Department of State Growth 2016)

For layers less than 50 mm thickness		For layers 50 mm thickness Or greater	
Characteristic value of the density ratio (Rc)	Assessment	Characteristic value of the density ratio (Rc)	Assessment
94.0% or more 91.0% to 93.9%	Accept lot Lot may be accepted at a reduced rate calculated by P = 10 Rc – 840	96.0% or more 91.0% to 95.9%	Accept lot Lot may be accepted at a reduced rate calculated by P = 6 Rc – 476

The Department of Planning, Transport and Infrastructure in South Australia uses nuclear gauge density testing for stabilisation of roads and soil testing. There is currently no specification related to asphalt testing in South Australia.

3.5 INTERNATIONAL REVIEW OF NUCLEAR TLG DENSITY ACCEPTANCE CRITERIA

This section details the international review of nuclear density gauge acceptance criteria in order to provide guidance on determining an appropriate statistical acceptance value for Main Roads.

Stroup-Gardiner and Newcomb (1988) carried out statistical evaluation of nuclear density gauges under field conditions using more than 900 density readings using 31 different gauges by three gauge manufacturers in USA (Texas, Virginia and Nevada) in order to investigate the precision achieved when using the Standard ASTM D2950M (2014). Statistical tests used to evaluate the test results include:

- t-statistic is used to determine whether there was a statistical difference between the readings based on reading durations (i.e. 15-sec, 1-min, 4-min). The paired t-statistic is calculated by t=d/s, where d is average of the differences and s is standard deviation of the differences. The calculated t-statistic value is compared with the t-table. If the calculated t-statistic is greater than the table value, there is a statistical difference between the two sets of data. However, if the calculated t-statistic is less than the table value, there is no reason to suspect a difference between the data sets. Nuclear gauge reading durations of 15-sec, 1-min, or 4-min do not produce significantly different density readings.
- Two-way analysis of variance ANOVA (computer-aided calculations in MINITAB) are used to evaluate two factors (variables)/ two F-values. One F-value determines whether the variables in Factor 1 are statistically different. The second F-value determines whether the variables in Factor 2 are statistically different. Calculated F-vales are compared with table F-values (table is based on population size, degree of freedom, level of confidence and level of significance). If the calculated F-value is greater than the table value, there is a statistical difference between the means. However, if the calculated F-value is less than the table value, there is no reason to suspect a difference between the means.
- Ratio of variances – Databases with different variables (e.g. material conditions) are compared by calculating the F-value which is a ratio of variances (i.e. standard deviation squared) and is calculated by Equation 5.

$$F - Value = S_1^2/S_2^2 \quad (5)$$

where

S_1^2 = the largest of two variances

S_2^2 = the variance of the other population

The conclusions are drawn in a way similar to that used for two-way ANOVA.

A series of correlations between core laboratory results and field TLG nuclear testing was carried out using regression analysis by Stroup-Gardiner and Newcomb (1988). Regression equation constants include average per site variances, F-values (variances for the test method only) in addition to population sizes. The coefficient of determination (r^2) was calculated for each correlation model to indicate the fit of the model to the data. It was concluded that the variance in density measurements, calculated in any manner, is a function of specific site conditions. Each gauge although capable of providing accurate correlations with cores, may have its own individual regression equation. There appeared to be no relationship between r^2 and the average of the difference between each core density and its corresponding nuclear gauge reading.

Tidwell et al. (1993) evaluated the nuclear density gauges for acceptance testing of asphalt concrete overlays and reported that the nuclear density gauges are generally very sensitive to improper seating that could result in erratic gauge readings. Significant scatter in the individual data points existed in both gauges used (i.e. Troxler 4640 and 3411-B). The standard deviations of nuclear gauge densities were significantly higher than the standard deviations of the field core densities.

Oregon Department of Transportation (2010) conducted research on density measurement verification through different methods and found that the nuclear TLG results were variable in spite of being corrected for the effect of underlying layers using previous density data. Esch (1972) reported that the airgap testing with one airgap count generally produced standard deviations approximately 20% higher than the normal backscatter mode. Density variations of several pounds per cubic foot could be expected to occur between different depths within an asphalt pavement due to minor changes in gradation, asphalt content and compaction. Similarly, the upper 12 mm of material had roughly 50% influence on the indicated nuclear density, but only a 25% influence on the density of a 50 mm core. Therefore, variations in density between core and nuclear tests at the same point should be expected. Schmitt et al. (1997) reported that the variability of densities determined by nuclear gauge measurements were higher than those determined from cores in 9 out of 14 hot mix asphalt overlay projects (i.e. in 64% of the cases). They also found that density results obtained by nuclear gauges become more variable if asphalt thickness decreases. The cost of a nuclear density test is about ten times less than a core sample test; however, concern remains about the reliability of nuclear test results.

Huot et al. (1966) observed that the variation in the nuclear gauge results was twice as great as those noticed with the core testing results. Surface texture tended to create great variations in the nuclear gauge readings (i.e. wide range of variations can be expected in open graded mixes). The aggregate class (e.g. gravel and limestone) influenced the nuclear gauge readings such that it caused measured density to vary by ±2%. Other factors included temperature differentials, use of latex as a modifier, milled pavement surfaces, mode of testing (e.g. airgap) and skills of the nuclear gauge operator. Analysis of the data revealed that the calibration curve provided by the manufacturer was highly inaccurate. A different calibration curve was required for different pavements to minimise variations in nuclear gauge results.

The Civil Engineering Testing Association of New Zealand (CETANZ) Technical Guideline (2014) provides detailed guidelines on the use of nuclear density meters. The main points of the guideline are:

- The gauge should be turned on at least ten minutes before the test in order to give it ample time to warm up.
- Daily standard counts should be taken at the start of each day. Drifts of no more than 1% for density count and 2% for moisture count would be expected.
- A reading of 1-minute is recommended for backscatter mode, however, a 4-minute reading improves the precision by a factor of two.

State of Wisconsin Department of Transportation (WisDOT) *Construction and Materials Manual* (WisDOT 2020) suggests a nuclear density gauge comparison for hot mix asphalt by comparing two or more gauges with 5 four-minute density tests. The methodology is helpful in developing acceptance criteria for nuclear

TLG testing. The main quality assurance issues are location of testing (within a lot), surface condition (e.g. levelled or uneven surface) and duration of testing. Salient features as suggested in the manual are:

- If the selected test site does not meet the criteria (e.g. uneven surface below the gauge), it can be moved to 5 feet ahead or back and 2 feet right or left of the initially selected site.
- Two tests are taken at each location with the gauge rotated to 180° between the two tests. If the difference between two readings is more than 1.0 pcf (16 kg/m^3), a third reading is conducted in the same orientation as the first reading. All three readings are averaged, the individual test reading of the three which falls farthest from the average value is discarded, and the average of the remaining two values is used to represent the location for the gauge.

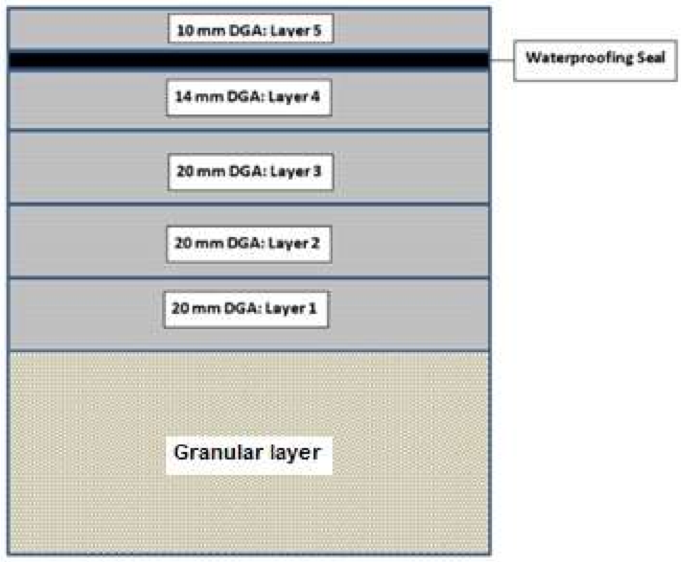
4 STATISTICAL ACCEPTANCE CRITERIA FOR MAIN ROADS

This section details the review of nuclear TLG density acceptance criteria with reference to ERN8 based on a sample of density data collected from the Gateway WA Alliance (GWA) project in 2015. The sample data was provided by Main Roads for consideration in this project to support the development of an appropriate statistical acceptance value for Main Roads.

4.1 TRIAL DATA

The trial of nuclear TLG testing was conducted at the GWA project (a major project to upgrade Tonkin Highway near Perth Airport). The pavement used for the trial was full depth asphalt (FDA) pavement consisting of a granular subbase overlain by three layers of 20 mm nominal aggregate size dense graded asphalt (DGA) which was overlain by a layer of 14 mm nominal aggregate size DGA covered by waterproofing seal under 10 mm nominal aggregate size DGA wearing course. The pavement configuration is illustrated in Figure 4.1 which shows the three structural layers of 20 mm nominal aggregate size immediately below the 14 mm DGA layer.

Figure 4.1 Typical Main Roads full depth asphalt (FDA) pavement configuration



The main features of the project data are summarised below:

- The section was located on the GWA project at Tonkin Highway SLK 8.92 to 10.14 and a nuclear TLG device was used by Main Roads staff to determine asphalt density on this section.
- There were 14 lots in the data: 10 lots of 20 mm nominal aggregate size DGA and 4 lots of 14 mm nominal aggregate size DGA.
- Core samples were collected for density testing a day after the asphalt was laid by the contractor as indicated in Table 4.1.
- The nuclear TLG used to measure the density data was calibrated in accordance with AS/NZS 2891.14.3:2013.
- The nuclear TLG reading offset calibration was carried out using asphalt cores.
- Nuclear TLG density testing was conducted on a lot basis, at different locations to the core locations.

- Each set of calibrated density measurements from the nuclear TLG device were paired with the maximum density reported by the contractor on the same lot and the same day with same mix design and compaction effort to enable reporting of relative compaction.
- Asphalt layer thickness was not recorded.

Table 4.1 summarises the location and asphalt mix information for each of these samples.

Table 4.1: Sample information – GWA Project (Tonkin Highway)

Sample no.	Location/lot no.	Mix type	Binder	Aggregate size (mm)	Grading used	Chainage (m)	Date laid	Date sampled
1	GWA01037RPAVASP0096	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	9784-10139	20/04/2015	21/04/2015
2	GWA01037RPAVASP00100	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	9774-10083	23/04/2015	24/04/2015
3	GWA01037RPAVASP00102	DG 20 mm Main Roads Interim JM49 75B	C600	20	Main Roads 510 – DG20/INTM/JM49	9323-9595	22/04/2015	23/04/2015
4	GWA01037RPAVASP00105	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	9770-9846	28/04/2015	29/04/2015
5	GWA01037RPAVASP00110	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	8924-9259	29/04/2015	30/04/2015
6	GWA01037RPAVASP00112	DG 14 mm Main Roads Interim JM52 75B	A15E	14	Main Roads 510 – DG14/INTM/JM52	9827-10164	6/05/2015	7/05/2015
7	GWA01037RPAVASP00115	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	9783-9871	30/04/2015	1/05/2015
8	GWA01037RPAVASP00121	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	8933-9289	6/05/2015	7/05/2015
9	GWA01037RPAVASP00127	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	8931-9263	7/05/2015	8/05/2015
10	GWA01037RPAVASP00130	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	8930-9246	8/05/2015	9/05/2015
11	GWA01037RPAVASP00131	DG 14 mm Main Roads Interim JM52 75B	A15E	14	Main Roads 510 – DG14/INTM/JM52	9815-10049	8/05/2015	9/05/2015
12	GWA01037RPAVASP00134	DG 20 mm Main Roads Interim JM42 75B	C600	20	Main Roads 510 – DG20/INTM/JM42	8945-9223	11/05/2015	12/05/2015
13	GWA01037RPAVASP00136	DG 14 mm Main Roads Interim JM52 75B	A15E	14	Main Roads 510 – DG14/INTM/JM52	8944-9258	12/05/2015	13/05/2015
14	GWA01037RPAVASP00138	DG 14 mm Main Roads Interim JM52 75B	A15E	14	Main Roads 510 – DG14/INTM/JM52	8928-9185	13/05/2015	14/05/2015

4.2 DATA ANALYSIS

Nuclear TLG and core density tests were averaged for a number of samples at each test location. The standard deviation of the density for each test is presented in Table 4.2.

Table 4.2: Sample data analysis – GWA Project (Tonkin Highway)

Sample no.	Average core density (t/m^3)	Core depth (mm)	Standard deviation (t/m^3)	Average nuclear density (t/m^3)	Standard deviation (t/m^3)	Difference (Percentage of the mean core density)
1	2.451	72	0.026	2.357	0.042	3.84%
2	2.444	60	0.022	2.423	0.040	0.86%
3	2.407	62	0.027	2.375	0.032	1.33%
4	2.388	69	0.033	2.376	0.031	0.50%
5	2.397	64	0.027	2.359	0.027	1.59%
6	2.372	51	0.031	2.327	0.015	1.90%
7	2.394	98	0.016	2.416	0.033	0.92%
8	2.381	64	0.029	2.367	0.028	0.59%
9	2.376	66	0.027	2.353	0.053	0.97%
10	2.402	70	0.023	2.336	0.043	2.75%
11	2.348	60	0.023	2.315	0.028	1.41%
12	2.376	74	0.016	2.313	0.029	2.65%
13	2.352	49	0.027	2.293	0.033	2.51%
14	2.379	57	0.022	2.367	0.028	0.50%

4.3 DISCUSSION OF RESULTS

The data analysis indicates that some of the TLG testing sites matched the core sites where Main Roads conducted offset calibration of the nuclear density gauge and core samples. Once the offset had been established the TLG testing was done on a lot basis separate to the cores taken by the asphalt supplier. It is not clear whether some auditing of the contractor’s method occurred to improve confidence in contractor’s testing. It could be a potential source of error or inconsistency in core density data and its variability. Although some of the nuclear TLG reading locations were different from core locations, an indicative comparison between TLG density data and core data can be made:

- 6 out of 10 lots of 20 mm DGA have standard deviation for the TLG data significantly higher than the core standard deviation, however, the remaining 4 lots exhibit standard deviation values for both measures reasonably close to each other.
- Only 14 data sets were available for analysis which is well below a proper statistical data pool. Preferably the data pool would have at least 100 paired samples for conclusive results. It would be better to assess different gauge manufacturers, different gauge operators, different asphalt mix types and a range of layer thicknesses. Based on this, the data set should cover some more variables such as gauge type/brand, asphalt mix detail, layer thickness, texture depth, temperature at the time of measurement.

Nuclear TLG density results exhibit higher variability demonstrated by a higher spread of nuclear TLG density results as compared to core density results for a given lot of asphalt layer construction. As described in the literature review (Section 3), there are several factors that have profound impact on nuclear TLG measurement results such as:

- calibration of the nuclear gauge
- measurement methodology
- selection of the test location

- orientation of measurement (e.g. 180°)
- test site surface condition (e.g. levelled surface)
- type of asphalt and aggregate used in the asphalt mix
- mode of testing (e.g. airgap or contact).

All the above-mentioned factors must be recorded to explain the relationship of density data and its variability in order to clarify its spread and to establish the statistical acceptance criteria for Main Roads.

Although the backscatter method is simple to perform and entirely non-destructive, there are limitations of backscatter measurement devices (Tidwell et al. 1993) such as:

- Depth of measurement with this method cannot be closely controlled and one calibration curve cannot be used for all materials.
- Material near the surface has the greatest influence on the test results as about 80% to 90% of the density assessment is influenced by the top 50 mm of the layer.

The following relationships can be drawn from the analysis of the available data related to the GWA project:

- The backscatter devices are very sensitive to their placement and their position during testing has a substantial impact on gauge density reading. The integrity of the collected data is largely dependent on the gauge placement in the field during testing; however, very limited information has been furnished related to the nuclear TLG density measurement procedure at the GWA Project. Standard deviations in the nuclear TLG density data indicate the presence of sampling and testing variation.
- Different modes of testing have different levels of accuracy. It is not known which mode of testing was adopted for the nuclear TLG density measurements at the GWA project trial section. Generally, the airgap test mode gives more accurate results as compared to the contact mode (WisDOT 2020). Similarly, there is no data provided related to core sampling and testing procedures.
- The available data do not provide details about asphalt layer thickness. The core depths vary from 49 to 98 mm for different core samples as shown in Table 4.2 indicating different asphalt layer thickness at different core locations. The data provided shows that the density results obtained by the nuclear TLG become more variable if asphalt thickness decreases. AECOM Infrastructure & Environment UK (2016) reported that nuclear TLG measurements on thin asphalt layers appear to be less precise as compared to thick layers. For instance, the gauge measurements of one-minute reading duration in the thin overlay mode would produce a standard deviation of ±16 kg/m^3 for a 25 mm thick layer, whilst the measurements under the same condition would produce a standard deviation of ± 8 kg/m^3 for a 63 or 100 mm thick layer.
- The variability of densities determined by the nuclear TLG are generally higher than those determined from cores (Schmitt et al. 1997) which is reflected in the data from the GWA Project as well. However, the above-mentioned factors related to the data collection and pavement configuration are required to explain this variability in order to establish suitable statistical acceptance criteria for use of the TLG. Without these factors being addressed, there is a risk of rejection of asphalt work due to high variability of density determined using a TLG. It is difficult to separate true variation in asphalt density from TLG measurement variability and a constructed lot may have passed if measured through conventional coring and density measurement methods.
- RMS and VicRoads require 4-minute count whereas TMR requires a 1-minute count for nuclear TLG testing. According to CETANZ (2014), increasing count duration for backscatter mode from 1-minute to 4-minutes improves precision by a factor of two. However, on the flip side, taking two 4-minute counts for every test location, and repeating if they are not sufficiently close, does tend to add up in terms of the time per test.
- Pavement thickness, maximum, specific gravity of the mix and chemical composition of the material as well as cross-sectional variability of the placed material has a significant contribution towards variability of the nuclear TLG measurements which leads directly to increased standard deviation. The data provided includes no information related to pavement material characteristics and asphalt mix design.

- There is published information which indicates a relationship between nuclear TLG density and core density such that nuclear TLG measures density lower than cores at lower asphalt densities, and higher than cores at high asphalt densities which is a significant factor in increasing variability of the nuclear TLG density measurements.

The establishment of a suitable statistical acceptance criteria for Main Roads in order to implement TLG density testing for asphalt quality assurance requires a sufficient data pool (preferably at least 100 points) with all measurement related details including testing methodology, calibration, gauge use procedure and pavement configuration/thickness and material characteristics (e.g. asphalt mix design, PSD, chemical composition of aggregate etc.). This would enable the spread and standard deviations of the TLG density measurement values to be explained and procedures for the offset from the core results to be accurately established for the projects.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the national and international literature review of the nuclear TLG application in asphalt density measurement for quality assurance purposes and analysis of the density data provided by Main Roads, the following conclusions can be drawn:

- The studies show that readings of the nuclear TLG and density of the cores had a strong correlation to one another, but the relationship is not consistent. Since the nuclear density gauges can significantly over or underestimate the core densities, the use of nuclear density measurements in lieu of core samples, with existing acceptance limits is not appropriate.
- Nuclear TLGs have the potential to provide a suitable measurement of asphalt density, but more appropriate calibration equations are needed.
- Due to the excessive variability and high standard deviations between the gauge readings and field core/laboratory densities, the nuclear TLG cannot be used as a sole method for acceptance testing of asphalt pavements unless the offset from the core results and reason behind variability is explained and suitable acceptance criteria are established.
- More attention is required to manage the effect of gauge calibration on the density readings.
- The chemical composition of the asphalt mix should be determined to know whether the gauge readings will be higher or lower than the field core readings.
- Extreme care should be taken by the operator in setting up gauges to eliminate the possibility of set-up error.
- The limited data from the GWA project trial (14 data points) without other details about data collection and documented procedure of the use of the nuclear gauge cannot be used to establish statistical acceptance criteria for asphalt density.
- Main Roads requires more data (i.e. at least 100 data points) with documented facts about testing such as test method, gauge seating, calibration details, bias calculation, pavement thickness, asphalt mix design and materials chemical composition for detailed data analysis in order to establish a statistical density acceptance criteria.
- Stage 1 of this project also indicated the need for nuclear TLG trials and a demonstration project for Main Roads to be scoped at some stage.
- Research findings from a comprehensive review of the nuclear TLG related scientific literature covering state road agency practices from within Australia and overseas as well as analysis of the Main Roads data provide a solid foundation for further analysis. Key findings of the first two stages of this project can be used to develop guidelines for nuclear TLG trials on a Main Roads nominated project to collect more density data and develop suitable statistical acceptance criteria. Therefore, it is recommended that Stage 3 of the project proceed in order to achieve the milestone of nuclear TLG implementation for asphalt quality assurance testing on Main Roads projects to capture long term cost benefits.

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