Evaluation of a non-nuclear density gauge as an alternate to destructive coring for airport asphalt acceptance testing

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Abstract

A non-nuclear density gauge (NNDG) was evaluated as part of an asphalt runway resurfacing project. The repeatability of the NNDG was found to be high but asphalt temperature and surface moisture had a significant effect on the reliability of NNDG inferred asphalt density. It was also found that a single NNDG inferred density, located immediately over the core location, provided greater agreement with core density than an averaged NNDG density over and around the location of the core. It was concluded that when used 1 day behind the surface paving operation, when the temperature had stabilised and the surface was dry, the NNDG was a reliable replacement for destructive coring for density measurement. Consequently, the coring frequency was reduced by 75% following NNDG calibration. However, the influence of temperature and moisture rendered the NNDG less suited to quality control during the compaction rolling process. Finally, it is recommended that additional research be undertaken to extend these conclusions to other asphalt mixtures, allowing other airports to reduce the frequency of destructive coring for density testing during asphalt resurfacing, following mixture-specific calibration of the NNDG.

Keywords Non-nuclear · Density · Gauge · Asphalt · Construction

1 Introduction

Verifying that adequate density is achieved during the construction of pavement layers is critical to pavement performance and is a fundamental assumption of pavement design. Airport asphalt surfaces are no exception and destructive coring has traditionally provided the basis of acceptance testing for the relative density achieved during construction [1]. However, destructive coring introduces weaknesses in the pavement surface, is resource intensive and in practice, can only be performed in a limited number of locations. Consequently, there is increased interest in non-destructive test methods for density acceptance during construction of asphalt surfaces, as well as other aspects of pavement investigation and construction quality assurance [2].

Non-nuclear density gauges (NNDG) are non-destructive devices for indicating relative asphalt density achieved

during construction [3]. These devices are similar to nuclear density gauges (NDG) but use electromagnetic radiation, avoiding the logistical complications associated with nuclear radiation sources. Although available since the 1990s, NNDGs have become more viable for quality control and quality assurance, including acceptance testing, with recent developments in technology increasing the reliability of results [4].

This research evaluates a commercially available NNDG for in-place density and field air void acceptance testing of a runway surface, based on data collected during a runway resurfacing case study. A PQI 380 NNDG was calibrated for asphalt density during the construction trial and was then used to determine the air void contents throughout the project, in parallel with a reduced frequency of destructive core testing. Gauge repeatability, gauge measured density variation, core measured density variation and gauge efficacy were considered and conclusions address the use of

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the NNDG as an alternate to destructive coring for airport asphalt surface construction.

2 Background

2.1 Airport asphalt construction

Airport asphalt is constructed similarly to road and highway asphalt. Except when in small patches, the hot asphalt is paved with self-propelled, heated-screed, paving machines and is compacted and finished by a combination of static and vibrating steel drum and pneumatic tyred rollers [1]. The existing surface is usually prepared by texturing with a cold planing machine and tack coated with a sprayed film of bituminous material [5].

Key outcome-focused requirements of airport asphalt construction include layer thickness, finished surface level, surface finish texture and in-place air voids [6]. Layer thickness is important for the structural capacity of the overall pavement and correct finished surface levels facilitate drainage and match into surrounding pavement and infrastructure levels. A tight and consistent surface finish is important for the minimisation of coarse aggregate particles ravelling out of the surface and the air void content is important for providing a mixture that will not deform under load, but is also impermeable.

2.2 Asphalt density

As stated above, the air void content is important for asphalt performance. Mixtures with insignificantly low air voids are unstable because the bituminous binder fills the aggregate skeleton, allowing the coarse aggregate particles to dilate, reducing the inter-particle friction that is critical to resisting deformation [7]. In contrast, mixtures with excess air voids allow air and water to enter the mixture and move through the air voids, which can be interconnected, typically at air void contents exceeding 8% [8]. The air increases the rate of bituminous binder oxidation, reducing the life of the surface, while moisture can lead to binder-aggregate separation, commonly known as stripping [9]. Furthermore, under heavy aircraft traffic, asphalt will densify to a stable air void content, with typical dense graded surfaces approaching 2% air voids after 3 years of heavy aircraft trafficking [10]. Surfaces constructed with excess air voids will densify more than surfaces with low air voids, leading to greater depressions in the wheel paths.

It is commonly accepted that in-place field air void contents of less than 1% present a high risk of deformation, while air void contents exceeding 7% increase the risk of asphalt stripping. Importantly, different asphalt types require different air voids contents (Table 1). For dense

Table 1 Typical design air voids contents for different mixture type

Mixture type	Minimum air voids (%)	Maximum air voids (%)
Stone mastic	2	4
Dense graded	3	5
Gap graded	5	8
Open graded	12	18

graded airport asphalt, an air voids content of 4% is targeted in the mixture design process, while the in-place field air void content commonly targets 2–6% [6].

Air void content is not directly measurable. Rather, the air void content is calculated from the ratio between the maximum density of the mixture and the actual density of the sample. The sample is either a core recovered from the field or a sample of asphalt compacted in the laboratory. Because air void content is not measurable, some jurisdictions prefer to control the density of field cores. Because the air voids are more important than the absolute density, the density of cores is commonly controlled relative to a reference density. The reference density may be the maximum density or other density achieved by a standard compactive effort. For dense graded airport asphalt mixtures, 75 blows of a Marshall hammer or 75 gyrations of a Superpave gyratory compactor are commonly used to produce samples for reference density measurement. Importantly, relative asphalt density is related to the air voids content. That is, a mixture that has a target laboratory air void content of 4% and is required to be compacted to 6% air voids in the field, will have a relative density of 94% compared to the maximum density but, 98% compared to the reference density. All these approaches to specifying density or air voids are equivalent and valid, but it is important to understand which expression of relative density or air void content is being used.

Regardless of the density characteristic used, a reliable tool is required for the determination of in-place field density. Traditionally, destructive cores were taken from the surface, both at the joints and in the mat, and the density tested by an on-site laboratory. Different jurisdictions have different numbers of cores with four from mat and four from joints commonly required in the USA [11]. However, in Australia, 10 cores from the mat and four from the joints during each work period, or Lot of asphalt, is more typical [12].

There is broad agreement that avoiding destructive coring of newly constructed asphalt surfaces is preferred wherever possible. Recovering and testing cores is resource intensive and the reinstatement of core locations un-avoidably creates a weak point in the surface, allowing moisture ingress. Where reliable non-destructive test

methods are available, destructive coring can be reduced in frequency or completely discontinued.

3 Non-destructive density gauges

3.1 Nuclear density gauges

The first non-destructive density gauges were developed in the 1950s and used nuclear radiation penetration through a material as the indicator of density. The greater the density of the material, the less the radiation penetrates. For granular materials, such as fine crushed rock base course layers, a probe is inserted into a small hole and the radiation penetration is measured directly between the emitter and the receiver, with materials of greater density resulting in less radiation penetration. However, in concrete and asphalt, the emitter and receiver are both located at the surface of the layer and the backscattered or reflected radiation is measured. In this case, a denser material will result in increased radiation reflection. Either way, a material-specific calibration between radiation penetration/reflection and material density is required.

NDGs became common in civil construction, including asphalt paving, in the 1990s. However, they continue to present a logistical challenge. The radiation source requires careful handling, special vehicles are often required for transportation, tunnels and other areas with hazardous material restrictions must be avoided, nuclear material handling training is usually required for technicians and gauges are typically heavy and are not readily carried around construction sites [13]. Furthermore, many technicians report that the repeatability is inadequate, with multiple readings in the same location concerningly variable. This has also been supported by research that indicates the agreement between NNDGs and cores is better than between NDGs and cores [14–16]. NNDGs, as an alternate to NDGs, were developed in the 1990s. These devices use electromagnetic impedance as an indicator of relative density and rely on the contrasting dielectric permittivity of air (approximately 1.0) compared to water (around 80) and aggregate (4–20) [17]. Because the complications associated with nuclear radiation sources are avoided, NNDGs are preferable to NDGs as long as they are no less reliable than the NDGs.

3.2 Non-nuclear density gauges

The NNDG used in this research was a PQI 380, which uses a constant voltage, low frequency electrical impedance approach with a toroidal electrical sensing field [4]. A flat sensing plate creates the electric field when rested on the surface. The PQI 380 is intended for use on freshly

constructed asphalt surfaces ranging in thickness from 20 up to 150 mm, but it must be calibrated to the specific mixture being evaluated [4].

The PQI 380 was released in 2016 and incorporates improvement over previous versions. The first model, PQI 100, was developed in the 1990s but in 1998 researchers found poor correlation with core densities and recommended the PQI only be used as a quality control tool and not for acceptance testing [18]. A significantly upgraded model (PQI 300 and 301) was released in 1999 and some researchers recommended its use for acceptance testing [17, 19] while others did not [15, 20]. The most comprehensive review of this model was performed by Romero [21] and found that the relationship between PQI inferred density and the density measured from cores was acceptable for quality assurance and acceptance testing only when a mixture-specific calibration is performed. In fact, when appropriately calibrated, the PQI inferred densities were not statistically significantly different to measured core densities [21]. Other NNDGs include the PaveTracker and various studies have found the two to have similar reliability [16, 21]. Both devices infer a density from impedance measurements, which is then related to a user-defined maximum density, and the relative density is displayed. By subtracting from 100%, the air void content is rapidly calculated.

3.3 Factors affecting NNDG reliability

Some researchers have reported that the aggregate source, mixture type/grading/size, binder content, mixture temperature and surface/internal moisture all effect the reliability of NNDGs. However, not all research has agreed regarding the impact of aggregate source, mixture type and binder content (Table 2). In contrast, there is no disagreement that mixture temperature and the presence of moisture on the surface significantly impact NNDG results. Furthermore, most researchers have reported some

Table 2 Summary of factors reported to affect PQI inferred density

Factor	Significant	Source
Aggregate source	Yes	[3, 22]
	No	[16]
Mixture grading/maximum size	Yes	[3, 22]
	No	[16]
Binder content	No	[13]
	Yes	[3]
Mixture temperature	Yes	[16, 22]
Surface moisture film/internal moisture content	Yes	[3, 13, 15, 16, 19, 22]
Presence of paint markings	No	[13, 16]

aspects of the mixture composition, such as aggregate source, grading and maximum size, as important, with all researchers, and the manufacturer, recommending mixture-specific calibration. Consequently, NNDGs must be calibrated to the specific mixture being tested and it is best to test the surface at a temperature and moisture content that is consistent with the conditions during the calibration. It follows that NNDGs are likely to be better suited to acceptance testing (quality assurance), which is usually performed one shift after paving, rather than as a compaction monitor (quality control), due to the highly variable moisture and temperature of the mixture during the paving, compaction and finishing processes. This contrasts the recommendations of many researchers which have recommended NNDGs for quality control, but not for quality assurance and acceptance testing.

3.4 Pavement quality indicator 380

The PQI 380 is intuitive and simple to use and weighs just 6.4 kg, so is readily carried around the construction site by a technician. Within the range of modes and options, the 'single' and 'average' modes are most applicable to density and air void assessment (Fig. 1). In single mode, the device is placed directly over the location of interest and a single reading is taken and recorded. In average mode, four adjacent locations are also tested, the results are temporarily stored, and the average result is recorded. However, the five individual results are discarded. The PQI 380 requires the maximum density of the asphalt mixture to be input by the operator and the NNDG reports the inferred field density, the density relative to the maximum density selected and the subsequently calculated air void content.

Prior to its use, a mixture-specific calibration is required. The calibration factor is known as the 'offset' and is most appropriately obtained from comparison of densities measured from cores recovered from the surface at the same location as the NNDG readings were taken. The calibration process effectively sets the average to the NNDG results to be equal to the average density of the cores. In theory, one core provides a basis for calibration. However, a minimum of three cores provides a more reliable

calibration. Because airport asphalt resurfacing works usually include production and construction trials, typically a few days before the work begins on the airfield pavements, ample opportunity exists to recover a larger number of cores for a robust calibration.

4 Materials, methods and results

The NNDG was used in parallel with density testing of destructive cores during the construction trials and subsequent construction of the new runway surface. Calibration was initially performed during the construction trial and the initial offset was determined. The offset was iteratively refined over the first two construction shifts and monitored through the construction. After the first week of construction, the frequency of coring was reduced from fourteen to just three cores per work period, with one located over a joint between paving runs and the other two located within the mat.

4.1 Materials

All asphalt tested in the project was produced to the same nominal mixture design, which was a 14 mm nominal sized dense graded Marshall-designed mixture typical of runways surfaced used in Australian for over 50 years (Table 3). The mixture contained a plastomeric modified bituminous binder and 5% reclaimed asphalt pavement, recovered from the temporary ramps constructed and removed by cold planing machines as part of the same project, produced to the same mixture design.

4.2 Methods

The NNDG was used to assess asphalt densities at the same locations as destructive cores were also recovered from the surface for density testing. In addition, the NNDG assessment was performed repeatedly in a single location and multiple locations within a consistent area of one asphalt paving lane, to determine the repeatability of the NNDG results, as well as the impact of asphalt layer temperature and moisture condition on the reliability of the NNDG. During the trials and the initial works, the NNDG was recalibrated twice, after which the coring frequency was reduced.

In total, 88 NNDG gauge readings without collocated cores and 111 NNDG readings with cores were analysed. Linear correlations and Student's *t* tests for the differences of means between paired density values were used to objectively assess the efficacy of the NNDG and the associated reduction in coring frequency.

Fig. 1 **a** Single and **b** averaged density operating modes

Table 3 Asphalt mixture properties

Property	Value	Specification limits	Units
Filler content	0.8	Report only	% by mass of aggregate
Bitumen content	5.6	Minimum 5.4	% by mass of mixture
Marshall stability	13.6	Minimum 12.0	kN
Marshall flow	2.8	Maximum 3.0	mm
Marshall bulk density	2404	Report only	kg/m ³
Marshall air voids	4.1	3.5–4.5	%
Voids filled with bitumen	74.8	70–80	%
Percentage passing			mm
13.2	100	96–100	%
9.5	82	76–88	%
6.7	69	66–74	%
4.75	59	56–64	%
2.36	44	40–48	%
1.18	33	29–37	%
0.600	25	21–28	%
0.300	15	13–19	%
0.150	8.9	7–13	%
0.075	5.4	4–6	%

Table 4 NNDG repeatability of density (kg/m³)

Test	Location 1	Location 2	Location 3
Repeat 1	2425.1	2423.8	2424.7
Repeat 2	2434.2	2425.0	2424.2
Repeat 3	2434.9	2418.8	2434.8
Repeat 4	2434.2	2428.2	2436.2
Repeat 5	2433.7	2423.8	2430.4
Average	2432.4	2423.9	2430.1
SD	4.1	3.4	5.6
CoV (%)	0.17	0.14	0.23

Table 5 NDGG averaged density (kg/m³) variability

Test	Location 1	Location 2	Location 3
Sub-location 1	2454.7	2400.3	2441.2
Sub-location 2	2448.6	2411.9	2409.0
Sub-location 3	2452.4	2431.6	2444.8
Sub-location 4	2433.9	2403.3	2411.0
Sub-location 5	2438.0	2414.8	2436.5
Average reading	2445.5	2412.4	2428.5
SD	9.1	12.3	17.2
CoV (%)	0.37	0.51	0.71

4.3 Results

First, the repeatability of the NNDG was assessed by five repetitive densities assessments at three locations away from joints (Table 4). The average, standard deviation (SD) and the coefficient of variation (CoV) are also provided. Second, three locations, approximating the corners of an equilateral triangle with 1 m² long sides, were assessed using the averaged PQI protocol (Fig. 1) to determine the asphalt density, after calibration correction (Table 5).

Next, the value of the averaged and the single NNDG reading options were considered by performing both at 14 locations where cores were recovered for actual density testing (Table 6). Ten locations were away from joints and four locations were over joints, as typically specified for airport asphalt construction. These CoV values are comparable to NNDG CoV values reported by others (Table 7). Many factors would affect the variability of the results,

Table 6 Summary of NNDG single, averaged and measured core density (kg/m³)

Statistic	Core	Single NNDG	Averaged NNDG
Minimum	2383.5	2415.2	2389.3
Maximum	2514.3	2517.8	2490.8
Average reading	2444.0	2447.8	2421.5
SD	34.3	32.5	32.1
CoV (%)	1.40	1.33	1.33
Count	14	14	14

including the variability of the asphalt production and associated aggregate supply, which would also affect the density measured from destructive cores.

Finally, the same location was tested five times each, at the end of rolling (while the surface was still hot) at the end of the night of construction (when the

Table 7 Summary of NNDG result variability based on data collected by others [15]

Data set designation in [15]	CoV (%)	Number of results
28-197A	0.7	18
28-197B	0.6	28
171-344D	3.1	18
172-390A	1.3	40
173-405C	0.9	14
172-389E	0.5	59

asphalt was warm) and at the end of the following night (when the asphalt had cooled to ambient temperature) (Table 8). Furthermore, the same location was tested five times each when dry, with a film of roller tyre water visible on the surface and filling the surface texture, and once the upper surface of the aggregate had dried but moisture remained visible in the surface interstices, all at nominally the same surface temperature (Table 9). It is noted that the degree of moisture on the surface was assessed subjectively and was not controlled. Because the aim was to determine whether the presence of moisture affected the NNDG reading, developing a relationship between the thickness of the moisture film and the NNDG reading was not attempted. Consequently, the subjective nature of the moisture condition was of no concern. Further research may considered a prediction model between water film thickness and NNDG air voids or density.

Separately, the NNDG was used in parallel with coring during the construction trial and 17 subsequent nights of asphalt surface construction. Including the initial setting, three calibration adjustments were made and 111 density measurements were compared to NNDG results (Fig. 2).

Table 8 NDGG single density (kg/m³) at different temperatures

Test	End of rolling (47 °C)	Following morning (38 °C)	Following night (31 °C)
Repeat 1	2443.1	2443.8	2424.7
Repeat 2	2453.5	2446.8	2444.5
Repeat 3	2439.8	2435.7	2425.3
Repeat 4	2451.1	2438.1	2432.1
Repeat 5	2455.4	2450.6	2437.8
Average	2448.6	2443.0	2432.9
SD	6.8	6.1	8.4
CoV (%)	0.28	0.25	0.35

Table 9 NDGG single density (kg/m³) at different moisture conditions

Test	Dry	Moist	Surface wet
Repeat 1	2465.4	2478.8	2502.0
Repeat 2	2427.2	2445.0	2464.6
Repeat 3	2468.4	2456.8	2497.6
Repeat 4	2458.0	2469.0	2514.1
Repeat 5	2451.6	2463.9	2462.7
Average	2454.1	2462.7	2488.2
SD	16.4	12.7	23.2
CoV (%)	0.67	0.52	0.93

5 Discussion

5.1 Device variability

When the NNDG was used to assess the density of the asphalt five times in the same location, the repeatability was high, with all three CoVs less than 0.25%. Furthermore, the difference between the mean of the density at each test location was significantly greater than the variability of the results of the five repetitions at each particular location (Fig. 3). This suggests that the concerns regarding repeatability expressed by other researchers for the earlier models of PQI have been addressed and are not significant for the current model.

5.2 Test location pattern

The NNDG manual [4] describes the single and average modes of NNDG operation, as illustrated in Fig. 1. Intuitively, it is expected that the averaged results would be more reliable than the single results. However, the CoVs in Table 5 (from averaged reading densities) are approximately double that of the CoVs in Table 4 (repeated single reading densities) as shown in Fig. 4. Furthermore, the fourteen measured core densities indicated marginally better agreement with the single reading densities than the averaged densities (Fig. 5). This indicates that the variation of the density of the asphalt within the area assessed by the average density protocol significantly exceeds the repeatability of the NNDG inferred density at a single location. It follows that the additional time required to obtain the averaged density reading is not justified and is actually detrimental to replacing intrusive core testing with calibrated NNDG readings.

5.3 Effect of temperature

Research has indicated the importance of temperature on the reliability of the NDG results (Table 2). Even over

Fig. 2 Core and NNDG density results **Fig. 3** NNDG repeatability at three locations

a modest range of temperatures (31–47 °C) the NNDG inferred mixture increased with temperature at approximately $1 \text{ kg/m}^3 / ^\circ\text{C}$ (Fig. 6). This observation was confirmed during the construction trial, when the NNDG was used on the same day as the trial was constructed. Consequently, the asphalt remained at different elevated temperatures during NNDG use and the calculated air voids, which are inversely related to the density for a specific mixture, reduced as the asphalt temperature increased (Fig. 7). Consequently, the need to calibrate the NNDG at a temperature that is consistent with the temperature during testing was confirmed.

5.4 Effect of moisture

Research has indicated the effect of surface moisture on the reliability of the NNDG results (Table 2). This was confirmed with increasing surface moisture returning a higher NNDG inferred density at the same location (Fig. 8). The variability of the five repetitions of density assessment also increased as the moisture increased.

Fig. 4 NNDG single reading repeatability and averaged reading variability

Fig. 5 NNDG single and repeated readings versus measured core density

5.5 Initial calibration

Prior to the initial asphalt production, the NNDG retained the calibration, referred to by the manufacturer as the offset, from the previous project. Consequently, the field air voids inferred by the NNDG was significantly different to that measured from the cores (Fig. 9) and the construction trial was used to calibrate the NNDG to the core densities. The calibration process simply adjusts the NNDG offset so the average NNDG density is equal to the average

core density, and this can be replicated manually after the testing is complete (Fig. 10). Although the corrected average NNDG inferred air void content is equal to the average core-measured air void contents, there remains some deviation between individual results. This likely reflects the variation in temperature (20–90 °C) as well as surface moisture condition during the initial trial calibration due to the NNDG testing being completed immediately following the rolling operation.

Fig. 6 Effect of temperature on NNDG density **Fig. 7** Effect of temperature on NNDG air voids from first work period

5.6 Final calibration

During the subsequent works, a final (minor) calibration was applied after a full work period. This better reflected the actual temperature and moisture condition during testing, which was performed one work period behind the asphalt construction, resulting in a dry pavement surface, ranging in temperature from 23 to 38 °C and averaging 31 °C over the subsequent 17 work periods. Following

manual correction to replicate the final calibration (or off-set setting) the agreement between the core and NNDG air void contents was adequate (Fig. 11).

5.7 Overall efficacy

Following the final calibration, the agreement between the NNDG and core air voids (Fig. 12) was reasonable, with the difference averaging 0.0% and having a

Fig. 8 Effect of moisture on NNDG density **Fig. 9** Pre-calibration NNDG and core densities

standard deviation of 0.6%. However, there were anomalies with a maximum difference between the core and NNDG air voids of 1.6% (Fig. 13). Furthermore, the correlation coefficient between NNDG and core air voids exceeded 0.74 (Fig. 14). This is relatively high when the low range of air voids (2–7%) is considered. It is also consistent with other research, where the correlation coefficient generally ranged from 0.4 to 0.8 for both NNDGs and NDGs [15].

5.8 Limitations

The limitation of the NNDG to consistently indicate asphalt density at different temperatures was demonstrated in Fig. 6 and via the calculated air voids in Fig. 7. The reduction in NNDG reliability on moist and wet surfaces was demonstrated in Fig. 8. As the work progressed through the intersection of two runways, the NNDG assessment and the reduced-frequency coring was performed in an

Fig. 10 Initial calibration NNDG and core densities **Fig. 11** Initial and final calibration of NNDG and core air voids for a single work period

area that had moisture applied to the surface to prevent asphalt adhering during the construction operations. This contrasted with all other areas of work, where the coring and NNDG testing was performed on a dry surface. Consequently, the NNDG inferred air voids were consistently 0.5% lower than the core air voids for the three cores affected (Fig. 15). Following review of this data, a re-calibration was proposed, but was rejected on the basis

of the moist surface. The following test locations (tested dry) returned high agreement with the core air voids. This further reinforces the limitation of the NNDG when the surface moisture condition is likely to be anything other than completely dry.

In practice, using NNDGs during construction to determine when the rolling has adequately compacted the layer is when the pavement surface moisture and

Fig. 12 NNDG and core air voids following final calibration **Fig. 13** Frequency of difference between NNDG and core air voids

the asphalt temperature will vary the greatest. These are the conditions that render the NNDG unreliable. However, this is the only application for which the NNDG has been recommended by some other researchers. In contrast, the NNDG has greatest reliability when the asphalt temperature is consistent with the temperature during

device calibration and when the surface is completely dry. That is, NNDGs are better suited to quality assurance or acceptance testing, conducted one shift behind the construction process, than for quality control during the compaction process.

Fig. 14 Correlation between NNDG and core air voids following calibration **Fig. 15** Correlation between NNDG and core air voids following calibration

6 Summary and conclusions

Based on data collected during an airport asphalt resurfacing project, the efficacy of a calibrated PQI 380 NNDG as a replacement for destructive coring and density measurement was demonstrated. The repeatability of the NNDG was high and the 'average' result mode was less reliable than the 'single' result mode. Importantly, the influence of asphalt temperature and surface moisture condition on NNDG inferred density was confirmed.

It is concluded that once calibrated to the specific mixture being produced, the NNDG provides a reliable indication of relative asphalt density, when testing is performed one shift behind the asphalt construction, allowing the surface to cool to a consistent temperature and completely dry. In contrast, the influence of moisture condition and temperature on NNDG inferred density prevents reliable use as a quality control tool during rolling operations. Further research is required to extend the range of mixtures assessed and the temperatures

and moisture conditions considered, and to strengthen the general applicability of these conclusions.

Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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