Measurement of asphalt thickness

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Date	30 June 2020	527858.00/4
Subject	**Task 4: Asphalt thickness measurements**	

An investigation has been performed into instruments and techniques for measuring the thickness of road surfacing materials, specifically Asphaltic Concrete (AC) and Open Graded Porous Asphalt (OGPA). These road surfaces have noise mitigation properties which appear to be tied to the thickness of the surface (Bull, 2020). For this reason, it would be useful to have an efficient and accurate way to measure the road surface thickness.

Thickness measurements may be used in two main scenarios, for research into road-traffic noise and for quality assurance on newly constructed roads. The measurement methodology may be different for each of these scenarios. Measurement for research purposes is likely to be interested in collecting high accuracy and resolution data and is likely to be more tolerant of slow or labour-intensive measurements whereas the preference for quality assurance (QA) measurements will be a simple, fast, and reasonably accurate method.

This memo considers a number of performance criteria for the measurement techniques and how these are affected by the two applications (research and QA). These criteria relate to the overall accuracy of the measurements, how easily the techniques can gather information along the length and width of a road, the efficiency of the measurements (in terms of time and other costs), and the impact the measurement technique will have on the road surface.

An investigation has then been performed into various measurement techniques with information given on the use and performance of each. A summary table is provided for comparison of the various methods with the performance criteria. Conclusions and recommendations are provided at the end of the memo.

1 Measurement methodology requirements

The requirements of a thickness measurement system have been proposed in this section. As any given technique will have varying performance in different areas, both ideal and minimum performance criteria have been given.

1.1 Accuracy

Accuracy is the difference between the measured value for pavement thickness and the actual true value.

The accuracy will be somewhat complicated by the small variations in the profile of the surface directly below the AC/OGPA. A surface could easily have a variation of a few millimetres over even very small horizontal distances (c.f. a chipseal first-coat can have MPD in the region of 2.0 mm).

Therefore, in practical terms, there may be little benefit in striving for a measurement accuracy better than about ± 1 mm, even under ideal conditions (i.e. constant thickness). At that level, the variation of the underlying surface will provide a greater contribution to overall uncertainty than the measurement instrumentation.

The primary motivation for the thickness measurement is to differentiate between different road surface thickness specifications, which are generally in multiples of 10 mm. An accuracy worse than ± 5 mm would be insufficient to satisfy the research objectives of other projects within the Waka Kotahi NZ Transport Agency's road surface noise research programme.

Previous road-noise research (Bull, 2020) found that there was a relationship between the surface thickness (t) and the Close Proximity (CPX) noise level of;

$$L_{CPX:P1,80} = -0.22t + 103.0$$

This relationship suggests the noise level will change by a little over 1 dB for each 5 mm change in thickness.

The ideal criteria for accuracy of the entire measurement system is ± 1 mm and the lowest acceptable accuracy is ± 5 mm.

1.2 Resolution (horizontal)

The horizontal resolution refers to how many measurements of asphalt thickness can be performed within a given road surface area.

Resolution is limited at the low end by the area over which each 'point' measurement is made (e.g. a core may be 100 mm diameter or more). This in turn affects how closely spaced the points can be. Some techniques are fundamentally point measurement techniques (e.g. coring), and need to be repeated for each point, whereas other are scanning or field techniques (e.g. LiDAR survey) that automate or semi-automate the collection of more than one point.

In general, the horizontal resolution will also be tied in with the efficiency of making the measurements, i.e. if it takes an hour to make a point measurement the likely final resolution will be lower than a technique which takes 1 minute to make a point measurement. A discussion will be provided for each option investigated looking at the efficiency of taking the measurements and how this might affect the likely actual horizontal resolution.

The ideal system will be able to provide an area-wide measurement of surface thickness, meaning that data on the thickness would be available at essentially any point on the surface.

In reality, the number of measurement systems capable of providing an area-wide measurement are limited and systems that take lower resolution or point measurements will also be investigated.

The requirement for horizontal resolution, and the willingness to spend time and money to collect the data, will vary depending on whether the data is being gathered for research or QA purposes. Less efficient systems may be acceptable for 'one-off' research measurements. Consequently, there is no one-size-fits-all definition or requirement that can be placed on resolution – each method will need to be evaluated subjectively based on a number of factors.

However, it is worth noting here that the CPX noise data is typically given as a single value for each 20 m section of road. This value takes into account contributions from the entire 20 m, rather than a single point within the length. In many cases the thickness data will be averaged over a 20 m length so it can be compared with the CPX data.

1.3 Impact on surface

The measurement methodologies can generally be split between 'destructive' and 'non-destructive'. Destructive measurements require some degree of damage to be done to the surface and/or underlying pavement, either through coring or excavation of the surface. While repairs to the surface following destructive measurements are possible, the willingness to perform large numbers of destructive tests, especially on new surfaces is likely to be low.

Non-destructive testing does not impact the pavement or the surface. The measurement methodology should ideally be non-destructive, although could be destructive provided the method had no practical consequence on the road surface and could be performed efficiently.

1.4 Range

Some of the systems have minimum and maximum working ranges within which measurements can be made. Investigation of the OGPA varieties laid in the 19/20 season on the State Highway Network showed that the specified depth ranged from 30 mm to 45 mm. It is suggested that, at a minimum, the measurement techniques are capable of measuring thicknesses in the range of 20 mm to 100 mm.

1.5 Efficiency

As mentioned previously the efficiency of a measurement methodology is linked to the desired horizontal resolution for most methods. In investigating the efficiency of the measurement systems we have considered the time and labour required for the measurement and also the initial and ongoing costs of using the technique.

2 Measurement methodologies

2.1 Test pit

A common approach for investigating the layers in a road surface/pavement is to dig a test pit. This method essentially involves digging a hole in the road and directly measuring the thickness of layers within the wall of the test pit. Test pit size can vary from something created with small hand tools to something created by an excavator.

For this application the pits would not need to be very large to achieve a surface thickness measurement. This method will provide very accurate thickness data, but is only a point measurement and will be slow and inefficient when considering the time for creating and repairing the pit. This method will also have a large impact on the surface. This method has been included for completeness and has not investigated any further.

2.2 Coring

Coring is a destructive method for establishing the thickness of the asphalt surface. One of various standard test methods describing coring is BS EN 12697-36:2003. In that standard, core sizes should be between 100 mm and 150 mm in diameter and the resulting pavement thickness is the average of four measurements made at equally spaced intervals around the circumference of the core. The thickness should be measured to ± 1 mm and the resulting average pavement thickness should be reported to the nearest 1 mm.

Coring to determine the asphalt thickness of new roads appears to be common practice in the United States where the thickness and porosity are used to gauge the quality of the construction. This appears to be related to checking for the surfaces structural performance as opposed to noise performance.

One of the major disadvantages associated with coring is the time and effort required for drilling the cores, determining the thickness and fixing the resultant holes. All for a single point measurement.

Use of smaller core drills was investigated (Gopaldas et al, 2009) and found that core drills below about 40 mm in diameter overheated (even with the use of coolant) and smeared the binder making it difficult to see clear boundaries between the layers. That study also used a 52 mm corer which gave good results. The use of a small core drill might make the methodology slightly more appealing due to the smaller area of damage done to the surface and the smaller/quicker repair required. That study also investigated the use of a borehole camera inserted into the hole created in the surface. It was found to be unsuccessful unless a large enough hole was drilled for a viable core and the surface layer will generally be visible by eye.

A method known as 'key-hole' coring could also be used which essentially only differs from conventional coring in the fact that the core would be used to form a 'plug' for the repair. This methodology could slightly increase the overall efficiency of the coring through reduced repair time and being forced to measure thickness on-site.

Coring may be suitable for research work as the inefficiencies of the method can be traded for the high level of accuracy and certainty that can be achieved. For QA work over potentially long sections of road, coring is an unattractive method due to the low efficiency and damage done to the newly laid surface.

2.3 Magnetic imaging tomography

Magnetic Imaging Tomography (MIT) requires a metallic disk laid directly below the asphalt layer to act as a 'reflector' for the instrument. Variations of this methodology are available in at least three commercially available instruments. Each of the available instruments will be discussed individually along with the general measurement procedure.

2.3.1 Measurement procedure

This measurement technique is covered by the British Standard BS EN 12697-36:2003 and also by the German Standard TP D-StB 12. The basic principle of the measurement is that metallic antipoles (also referred to as 'reflectors') of aluminium or steel are laid directly beneath the asphalt surface at the level where measurement is required. Once the sealing is completed, the instruments can be used to locate the reflectors and measure the depth of the reflectors below the surface.

The instruments used for the MIT method send out magnetic pulses which induce eddy currents in the metallic antipole plates. This current in the antipole generates an 'answering' magnetic field. This 'answering' magnetic field is then measured and used to determine the vertical offset to the reflector which can be related to the pavement thickness.

BS EN 12697-36:2003 requires that the antipoles are (300 ± 10) mm x (700 ± 10) mm x 0.05 mm to 0.30 mm in dimension. This is much larger than that required by TP D-StB 12 which can use circular aluminium plates down to a diameter of 70 mm and with thickness from 0.5 mm to 1.0 mm for measurements in asphalt. The German Standard appears to be written specifically for use with the MIT-SCAN product range, of which the T3 model is discussed below. The antipoles need to be discrete to allow for eddy current generation i.e. the antipole cannot be a continuous roll of aluminium laid in the wheel path.

The basic test procedure for this methodology would be to place the antipole plates directly on top of the layer below the asphalt surface prior to laying the asphalt. The standards recommend fixing the plates in position with nails. However, experienced pavement engineers at WSP Research have recommended covering the top and bottom of the plates with bitumen to keep them in place during sealing and to limit any potential in-service surface failure due to a loss of adhesion of the asphalt around the plates. Once the plates are installed, the asphalt is laid over the top. Once it is possible to walk on the new surface, it is possible to locate the reflectors using sensors in the instrument and to then take thickness measurements.

It is interesting to note that the MIT method is not affected by the moisture content, porosity, or age of the asphalt. All three of these factors have an impact on the dielectric constant of the material and will therefore affect the use of Ground Penetrating Radar (GPR) (discussed further below).

MIT-SCAN-T3

The MIT-SCAN-T3 is a commercially available product specifically for the measurement of pavement thickness using the MIT method. The MIT-SCAN-T3 instrument is shown below in Figure 1.

Figure 1. MIT-SCAN-T3 instrument.

This product includes GPS functionality so that the measured thickness data can be easily mapped. The measurement range of the instrument is 15-500 mm deep and is based partly on the antipoles used. The instrument needs to be calibrated on-site by measuring the depth to a reflector with, and without, a spacer of known thickness below the instrument.

There is an agent for the product in Australia[1] and current prices for the various components are given in Table 1 below.

Table 1. Prices for components of the MIT-SCAN-T3 instrumentation.

Item	Price	Comment
MIT-SCAN-T3 instrument	$28,500 AUD	Single measurement instrument and software.
AL RO 07	$3.50 AUD	70 mm diameter aluminium reflector. Suitable to depths of 120 mm.
AL RO 12	$5.50 AUD	120 mm diameter aluminium reflector. Suitable to depths of 180 mm.
AL RO 30	$10.50 AUD	300 mm diameter aluminium reflector. Suitable to depths of 350 mm.

[1] www.insitutest.com.au Robin Power. Robin.Power@insitutest.com.au +61 404 114 751

There is potential to have reflectors made locally although care needs to be taken as the instrument is calibrated to the material properties of the plates being used.

The MIT-SCAN-T3 instrument has a stated accuracy of ±0.5% of the measurement plus 1 mm. This would be ±1.25 mm for a 50 mm thick surface. Resolution is limited by the (minimum) 70 mm size of the reflectors.

This method is already a reasonably widely used method with fully commercialised instrumentation and customer support. While still being based on spot measurements, the reasonably quick measurement time makes the achievable horizontal resolution reasonably high. The instrument measurement time of 1 minute per location. This is more than sufficient for research purposes and should also be sufficient for QA purposes, particularly if the data is useful for other QA applications such as confirming thickness for structural requirements and checking volumes laid.

As part of this study a quick investigation was done to try and identify if any of these units were currently being used in New Zealand. No instruments were located within New Zealand although the Australian supplier suggested there may be companies in Australia (with links to New Zealand) with MIT instruments who could be interested in New Zealand trials. It is highly likely that parts of the industry would be interested in trialling this system as a QA tool and the cost could potentially be shared over multiple trials.

2.3.2 StratoTest 4100

The StratoTest 4100[2] is another MIT type instrument which relies on the placement of aluminium antipoles (reflectors) within the asphalt.

The functionality of the StratoTest seems to be similar to the MIT-SCAN-T3 instrument although there does not appear to be any GPS included in this system. This system requires the antipoles described by BS EN 12697-36:2003, 700 mm x 300 mm and 1,000 mm x 300 mm, which is significantly larger than those required for the MIT-SCAN-T3, and therefore more limiting on resolution. An image of the StratoTest 4100 is shown below in Figure 2.

Figure 2. StratoTest 4100 instrument.

[2] https://www.elektrophysik.com/en/products/road-layer-thickness-measurement/stratotest-4100/

The StratoTest 4100 has a measurement range of 0 to 400 mm. For the measurement range we are interested in, the instrument has a precision of 1 mm and an accuracy of ±2 % of the measurement plus 1 mm (±2 mm for a 50 mm measurement).

A price of around $12,500 NZD is given for the instrument although no contact has been made with the supplier. No pricing has been found on the antipoles required (standard household aluminium foil is insufficient) for this instrument. Thickness results are available immediately on taking the measurement.

2.3.3 Fischer Dualscope FMP100

Fischer Technology used to sell an MIT type measurement device specifically for the measurement of road surface thickness (Isoscope M30 Road), however, this product was discontinued because of low sales. Similar functionality can be achieved through the use of another of their products although it is not specifically designed for this application: the Fischer Dualscope FMP100[3] has a price of a little under $9,000 NZD for the instrument and appropriate antenna. This instrument is not set up for easy use in a roading application.

2.4 Ground penetrating radar

Ground Penetrating Radar (GPR) is a method that is regularly used for gathering information on the internal components of structures or underground. GPR works by emitting radio wave pulses into the underlying material and measuring the two-way travel time for the returning echo. Reflections are created whenever the pulse encounters an interface with a material with contrasting electromagnetic properties (dielectric constant and conductivity) to the medium through which it is propagating, i.e. a change in structure. Depending on the relative dielectric strength of the two materials, the polarity of the radio wave can also be reversed in the returning reflection, providing some information regarding the possible nature of the material at the interface.

GPR data can be analysed in two ways, analytically by investigating time history of the signals, or visually by investigating radargram images created by the instruments.

A large amount of work has been done on analytically analysing GPR data in previous research for Waka Kotahi NZ Transport Agency (Bull, 2020) and will not be discussed in detail here. That research used a vehicle mounted 2 GHz air coupled GPR unit and found that the use of GPR was an unreliable method for determining the surface thickness.

GPR measurements are affected by the dielectric constant of the material being measured and one of the main issues with using GPR on asphalt surfaces is using the correct value for the dielectric constant. There is a method for determining the dielectric constant non-destructively which involves passing the GPR unit over a metal plate, and then over the surface to be measured. By comparing the reflected signal from the metal plate and the asphalt surface, a dielectric constant can be calculated. A study into the determination of dielectric constants in asphalts (Porubiakova, 2015) found that using the dielectric constant determination method mentioned above led to an error on thickness measurements of 1.42 % in AC, 12.4 % in OGPA and 17.6 % in Stone Mastic Asphalt (SMA). For 40 mm thick surfaces, that level of error is well under 1 mm for AC surfaces and around 5 mm for OGPA. A 2 GHz air-coupled GPR unit was used for that study. Another study (Von Quintas et al, 2009) found that GPR units could be used to repeatably measure the thickness and porosity of asphalt surfaces although unfortunately no details were provided on the specifics of the GPR unit used.

Radargram images are generally available directly from the GPR units without significant post processing. There are software packages to help with interpreting these images although in general they need to be analysed by someone with specific training. Local GPR suppliers were

[3] https://www.fischer-technology.com/en/united-states/products/coating-thickness-measurement/portable-measurement-instruments/fmp-100-150/ Contact: Stephen Allen, KK&S Instruments. stephen@kks.com.au. +61 2 88503755.

contacted and their general recommendation was an instrument made by IDS GeoRadar[4], the HiPave. This sensor can use a range of antenna frequencies, has an air coupled antenna, and can be mounted on a vehicle and operated at very high speed (well over 100 km/hr). The system has specialised software for recognising layers within pavements. Figure 3 shows sample data (provided by GPR suppliers) from the HiPave unit using a 2 GHz antenna on an asphalt surface. The red and blue lines are interfaces between layers. A rough price of $72,000 + GST has been given by one supplier[5].

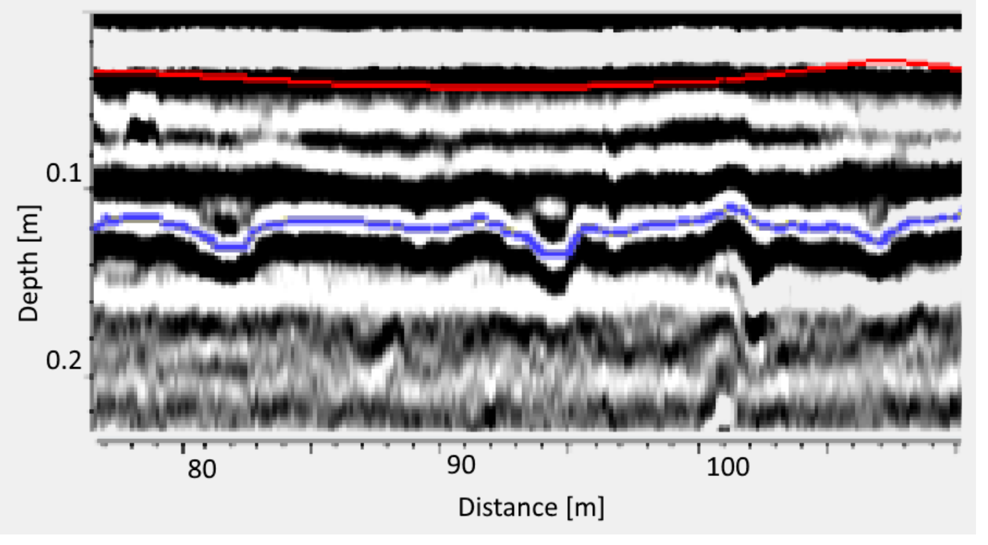

Figure 3. Image supplied by IDS GeoRadar of output from 2 GHz air coupled GPR unit on an asphalt surface.

There are a number of different types of GPR units which have different performance and can give significantly different results. Some of the variations within GPR units are:

- Air coupled vs ground coupled
- Antenna frequency
- Mounting and mobility

The following sections discuss the above GPR variants in some more detail.

2.4.1 Air coupled vs ground coupled

Coupling refers to how the radio waves leave the GPR antenna and enter the material being investigated. Air coupled units are mounted with a gap between the antenna and the material being investigated. For our application, this means that the radio waves need to travel through the air before they enter the road surface. Having an air coupled antenna generally allows for faster measurements and more manoeuvrability as the unit does not need to be in contact with the material. Air coupled antenna have the disadvantage that the signal will be reflected from the surface of the road as well as any changes in structure below the surface. This reflected signal can cause issues with the data processing, particularly when details of interest are near the surface as the reflected signals from the surface and any nearby details can become intermingled. This area near the surface with intermingled signals is sometimes called the 'hazy' zone.

Ground coupled systems are significantly less efficient for taking measurements as they need to be set up on the road, a measurement taken, and then moved to the next location.

[4] https://idsgeoradar.com/products/ground-penetrating-radar/ris-hi-pave

[5] Global Survey, New Zealand. Also available through Accurate Instruments (NZ) Ltd.

2.4.2 Antenna frequency

The frequency with which the GPR antenna operates effects both the total depth that the radio waves can penetrate but also the resolution of returning data. Higher frequency units will also have more ability to look at features just below the surface. Typically, GPR units use a fixed frequency that ranges between models from a few hundred MHz through to around 8 GHz (although units with frequencies higher than around 3.5 GHz are rare).

The fact that higher frequency radio waves give higher resolution and shallower depth may make them particularly suitable for our application. Table 2 below the differing performance[6] with antenna frequency.

Table 2. Comparison of GPR performance with antenna frequency.

Antenna Frequency	Typical max depth [m]	"Hazy" zone [mm]	Sample applications
1.5 GHz	0.5	25	Structural concrete, roadways, bridge decks.
1 GHz	1	100	Concrete, shallow soils, archaeology.
400 MHz	4	153	Shallow geology, utility, environmental, archaeology.
200 MHz	8	305	Geology, environmental.

The "hazy" zone referred to in Table 1 is that region near the surface where reflections from the air/material interface can interfere with the signal. Higher frequency units can gather higher resolution data on this reflection and can more easily distinguish the surface reflections and those caused by shallow details, leading to a shallower "hazy" zone.

A study investigating the use of high frequency GPR units for use on a large range of projects (Utsi, 2014) found that layers in asphalt surfaces were clearly defined in Radargram images when using high frequency antenna. Of particular interest was the investigation of a bridge deck where surface layers are clearly visible at depths of much less than 50 mm with a 4 GHz GPR unit.

A brief investigation into whether any high frequency GPR units (2.6 GHz+) units were available for trials in New Zealand found no instruments. WSP Research have a 2.6 GHz hand held GPR unit which is normally used for locating steel reinforcing bars in concrete. Due to the high usage of that device and the timing of the COVID-19 lockdown an informal trial has not been possible to date, but could be arranged in future.

2.4.3 Mounting and mobility

GPR units can be fixed to vehicles, allowing them to be driven along the road, in some cases at highway speeds. This obviously leads to a dramatic increase in the efficiency of the measurements. Vehicle mounted GPR units are also air coupled, meaning that the radio waves need to travel through the air between the GPR unit and the road surface. It seems to be reasonably common practice internationally to take GPR measurement from moving vehicles to assess a range of pavement properties.

GPR units are also available set up as push-along units. These units are smaller and more manoeuvrable, which comes at the expensive of being able to cover lengths of road more quickly.

[6] GSSI SIR20 User Manual. https://www.geophysical.com/wp-content/uploads/2017/11/GSSI-SIR-20-Manual.pdf

These push-along units appear to be more commonly used for the detection of services or archaeological work rather than for assessing pavement properties.

Smaller hand held GPR units are also available which are quick and easy to use for very short sections or point measurements. Figures 4,5, and 6 show examples of different configurations of GPR units.

Figure 4. Vehicle mounted GPR system.

Figure 5. Push-along GPR system.

Figure 6. Hand-held GPR system.

2.4.4 *Other potential GPR techniques.*

The use of a metallic material between the base material and the surface material could significantly improve the performance of the GPR units. For point measurements this could make the GPR unit performance similar to the MIT units.

It may be that a semi continuous metallic film (or automatically laid line of metal disks) could be laid beneath the wheelpaths prior to sealing that would dramatically increase the performance of the more commonly available, lower frequency, GPR units.

Another GPR measurement method encountered in the research is the common midpoint method. This method uses two coupled GPR units, one to be used as the transmitter and one as the receiver. The position of the two units is carefully controlled to maintain an equal spacing from the centre mark while the units are moved away from the centre in 1 mm increments. This method was investigated (Edwards et al, 2011) and found an average error of over 20 mm even with the system calibrated using data from a nearby core. This approach also requires a significant amount of time for measurement and post processing of data for each point measurement. This method was not investigated in further detail.

2.5 Survey methods

There are a range of methodologies and technologies that have been included in the survey methods group. These range from extremely simple measurements made with a ruler through to full 3D scans of a wide area. Each of the survey methods have been discussed below.

All of the survey methods require measurements to be taken prior to the surface being laid and a second set of measurements after the surface has been laid.

2.5.1 *Basic vertical measurement from datum line*

The extremely basic and poorly written standard DIN EN 13863-1 explains a survey method where a string line is run above the road prior to laying the surface. Vertical measurements can be taken between the string line and the surface prior to sealing and then again after the surface has been laid. This method would need modification to be practical and a system would need to be devised so that the lines could be removed during surfacing and reinstated in the same locations afterwards.

This system seems very simple with little technical knowledge or skill being required for the measurements. String lines could potentially be set up directly over wheelpaths and reasonably dense data could be gathered, along a single line. This method is likely to be fairly slow due to being largely manual.

There is some potential to automate this procedure. Some things to be considered with automation might be:

- Using an optical displacement measuring device with logging function to take the measurements.
- System for ensuring the string is in the same location and has the same tension.
- Instrumentation could be developed to automatically traverse the optical range finder along the string line. A system could be developed to measure the horizontal offset along the line as well as the vertical distance to the base/surface.

2.5.2 *3D laser scan*

Laser scanning survey equipment can take high resolution height measurements in an area surrounding the instrument with a radius of around 25 m. The scanner instrument works by emitting a laser pulse which is reflected from the ground back to the instrument. The two-way flight time is measured along with the horizontal and vertical angle of the laser direction. The two-way flight time is used to calculate the distance along the laser path to the ground. By combining this with the vertical and horizontal angles, the height of each scanned point can be defined. The scanner can cycle through thousands of vertical and horizontal angles to build a high resolution survey of the surrounding area. Each of the measurements is essentially a true point measurement and with angular accuracy of 8” (seconds of arc) the horizontal resolution at 25 m from the instrument (assuming a 1.5 m instrument height) can be as good as about 15 mm.

As with other survey methods, surveys are required both before and after the surface has been laid, with the difference between the surveys giving the surface thickness.

2.5.2.1 Accuracy

3D scanner units have a base accuracy of ± 1.2 mm on distance measurements[7]. However, when the inaccuracies caused by mounting etc are accounted for, the accuracy for a single scan is estimated to be around ± 5 mm. When accounting for two survey setups and alignment of the data through reference points, a senior surveyor at WSP estimates that the accuracy is likely to be in the order of ± 10-15 mm on thickness measurements.

The accuracy of this technique is directly affected by the reference points used to align the survey data from before and after surface laying surveys. There are two main ways of aligning reference points;

- Taking GPS reference measurements in both surveys and aligning the data through these points.
- Using fixed features, that have not moved between surveys, to align the data between surveys.

Using fixed features to align survey data is the preferred method as it cancels out several possible sources of systematic error, in effect turning the method from an ‘absolute’ one to a ‘relative’ one (assuming the fixed features are truly fixed). Kerb and channel will always be in place prior to asphalt surface laying and this would be a good fixed feature for survey alignment.

From re-analysis of 3D scan data from a previous study (Bull, 2020) it was found that using fixed features for aligning survey data leads to higher accuracy than using GPS reference points. Figure 7, shows surface thickness profiles, one corrected with GPS reference points and one corrected using fixed features (the central median in this case). For interest, figure 7 also shows the target thicknesses used for surface construction.

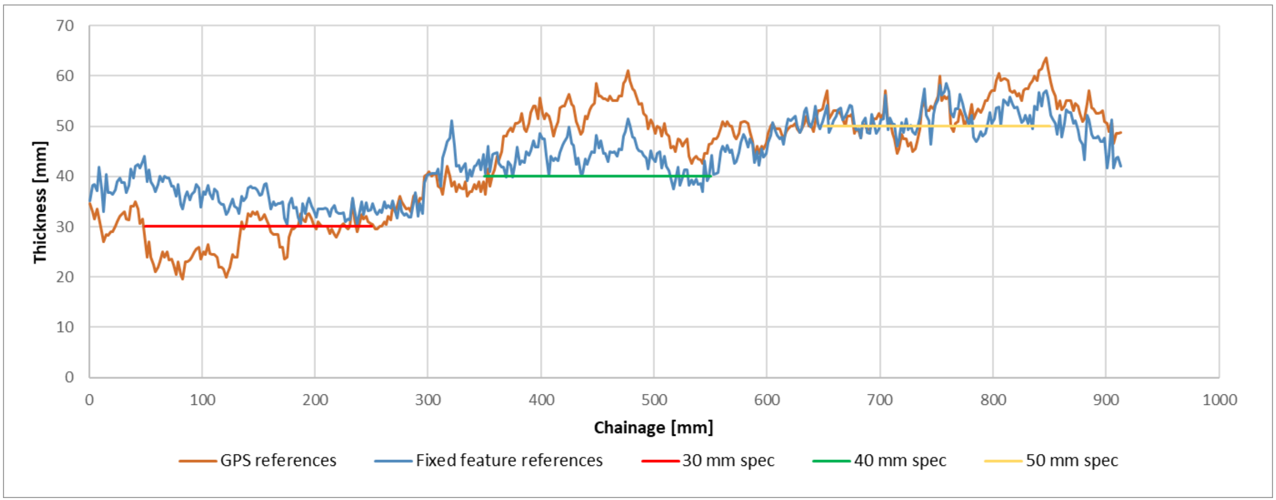

Figure 7. Thickness profiles from 3D scan survey data showing the difference between using GPS references and fixed feature references.

From Figure 7, it can be seen that the profile using GPS references showed a minimum thickness of around 20 mm. An actual porous asphalt thickness of 20 mm is very unlikely due to issues with

[7] Leica P40 data sheet.

construction which would generally bring the lack of surface thickness to the attention of the contractors. From Figure 7, assuming that the actual surface thickness was close to the target specification, the 3D scanner using fixed feature references is consistent with an accuracy of around ± 10 mm.

While the accuracy of the 3D scanner does not appear to meet the requirements defined in section 1.1, the fact that this method can collect very high resolution data over a large area with no impact on the surface is still appealing. It is recommended that some additional work be done on fully investigating the accuracy of this technique. That investigation should include a full discussion with the survey provider and specification of the survey method to be used to ensure the highest levels of accuracy can be achieved.

2.5.3 Total station

A total station is a more conventional style of surveying where a pulsed laser is sent out from the station and reflected from a prism back to the station. From the two-way travel time the distance to the prism can be calculated while the total station measures the vertical and horizontal angle to the prism. Using this method, a number of locations can be surveyed before and after the surface has been laid and compared to calculate the surface thickness. This is very much like the 3D scan discussed above except that this process manually collects point measurements, and a prism is used to reflect the laser.

This method is a reasonably quick and easy way of taking measurements at a number of locations, although it does require two site visits to perform the measurements. A typical total station can achieve an accuracy of around ± 1 – 1.5 mm [8] on a single measurement. This level of accuracy will drop when the actual thickness value is calculated from the comparison of data from two surveys with separate setups. However, the accuracy should remain within ± 5 mm.

One potential difficulty with this method will be determining the exact location that measurements were taken prior to the surface being laid, once the surface is down.

2.6 Tracesheet

A method was trialled (Bull, 2020) where the contractor's records were used to estimate the surface thickness. That method uses assumptions on the asphalt density, the asphalt delivery times and mass, the width of the seal, and the paver speed to estimate the thickness. The original trial found that the methodology did not give reliable results and has not been considered further here.

2.7 Shear wave measurement

A method of determining the stiffness and depth of layers by measuring shear waves in the surface was investigated. This method uses an impact on the surface to generate shear waves which are then measured by two precisely spaced sensors attached to the surface. From these measurements and assumptions on the behaviour of the surface materials, the modulus and the thickness of the surface layers can be calculated.

A limited information on commercially available instrumentation for this method could be found and it seemed this technique is largely used in academic research alone. The papers investigated on this technique gave a comparison of the measured thickness against the actual thickness[9].

The investigation into the technique (Sheu et al, 1986) found that the thickness measurements were generally within about 10% of the 'actual' values while the performance of the technique in another study (Zakaria et al, 2014) was significantly worse. A third study (Edwards et al, 2011) investigated two surface wave methods on AC surfaces and found errors of at least 30 mm. That

[8] Leica FlexLine Total Station data sheet.

[9] Sheu, et al used boreholes to give the 'actual' thickness measurement for comparison while Zakaria et al simply used the original spec for the pavement as the 'actual' value.

study also commented that these systems are less suitable for surfaces thinner than 75 mm, are affected by the relatively low modulus of asphalt, and are temperature dependant. These measurements are laborious to set up, slow, and rely on assumptions.

Surface wave methods have not been investigated further.

2.8 Ultrasonic tomographic imaging

Ultrasonic tomographic imaging can be used for revealing voids, cracks and reinforcing bars within concrete structures. These systems work by using a high frequency (20 – 100 kHz) ultrasonic signal which can penetrate through structures and is reflected back from any boundaries created by inconsistences within the structure.

There are at least two commercially available ultrasonic imaging units available that can be used from a single surface of a structure i.e. the receiver doesn't need to be on the opposite side of the structure to the transmitter[10,11]. These systems are primarily for investigating concrete structures although the use of the MIRA system in measuring AC thickness was investigated (Edwards et al, 2011). That investigation found that the use of this technique gave variable results which seemed to be particularly sensitive to temperature. It found that there are a number of draw backs for this method, including that the system can only detect the upper most change in the surface. If this happened to be a void within the AC layer then the boundary between the AC and the layer below would be obscured. That study was based on Asphalts in the US with very deep layers. Ultrasonic systems generally can't make measurements in the top 50 mm of a surface.

2.9 Falling weight deflectometer

Falling Weight Deflectometers (FWDs) are regularly used to investigate the physical properties of pavement layers. The basic principle is that a weight is dropped on the surface and a number of radially spaced geophone sensors are used to measure the shape of the 'deflection bowl' generated. Normally the thickness would be assumed and used to calculate the layer stiffness although by assuming the stiffness the thickness could be calculated.

Contractors have existing equipment that can streamline the measurement process, essentially an instrument on a trailer than can be moved quickly and frequently to take a large number of measurements.

A number of assumptions are required to calculate the thickness through this method and this coupled with the variation in FWD measurements will inevitably lead to errors in the calculation. It is very unlikely to meet the accuracy requirements in section 1.1.

[10] Proceq Pundit product range.

[11] MIRA product range.

3 Summary table

A summary table of the measurement techniques discussed in section 2 is given below. Measurement techniques that we believe should be investigated further are highlighted in blue.

Measurement methodology	Accuracy	Resolution (horizontal)	Impact on surface	Range	Efficiency	Equipment required	Comments
Testpit	± 1 mm	Point measurement (down to Ø 100 mm) – limited by efficiency.	Full repair required.	unlimited	Very slow, including repair.	No new technology required.	Coring has similar performance but less impact on the road surface.
Coring	± 1 mm	Ø 100 mm Point measurement – limited by efficiency.	Full repair required.	0 - 600 mm approx	Very slow, including repair.	No new technology required.	More suitable for research work due to high accuracy but very low efficiency. Potential for keyhole coring to reduce repair time.
Magnetic imaging tomography	± 2 mm (StratoTest 4100) ±1.25 mm (MIT-SCAN-T3)	Point measurement – limited by efficiency. 700 mm x 300 mm (StratoTest 4100)	Very little, target retained below surface layer.	0-400 mm (StratoTest 4100) 15-500 mm (MIT-SCAN-T3).	Target installation required prior to surfacing. Unknown measurement time (StratoTest 4100)	Instrument purchase required. $12,500 NZS (StratoTest 4100) $28,500 AUD (MIT-SCAN-T3)	Multiple brands available. Specifically designed and marketed for road surface thickness measurement. Reflector cost for MIT-SCAN-T3 is $3.50 AUD per location. Sufficient efficiency to be used as a QA tool.

		Ø70 mm (MIT-SCAN-T3)			Approx. 1 min per measurement (MIT-SCAN-T3)		
Ground penetrating radar (2 GHz)	±5 mm	Continuous – linear.	None.	<25 - <500 mm	Potentially very high efficiency if vehicle mounted.	Reasonably widely available already.	Some success in other research. Found to give unreliable measurements in previous New Zealand research (Bull, 2020).
Ground penetrating radar – IDS HiPave (≥ 2 GHz)	± 5 mm assumed	Continuous – linear.	None.	<25 - <500 mm	Potentially very high efficiency if vehicle mounted.	Instrument purchase required. Approx $72,000 NZD for vehicle mounted unit (2.6 GHz).	Accuracy assumed (Porubiakova, 2015). No reliance on pre-installed reflectors. Suitable for research and QA related measurements.
Ground penetrating radar – hand-held device	± 5 mm assumed	Short continuous lengths – linear.	None.	<25 - <500 mm	Reasonable efficiency. Limited to continuous measurements of a few metres at a time.	Instrument purchase required. Approx $30,000 NZD.	Accuracy assumed (Porubiakova, 2015). System available for trail through WSP Research.
Survey – Manual vertical measurement	± 1 mm	Short continuous lengths – linear.	None.	Unlimited.	Low. Manual measurement required before and after.	None.	Accuracy is probably worse than ± 1 mm in reality. Slow manual measurement with difficultly in identifying exact location for second set of measurements.
3D laser survey scan.	± 10 mm	Area wide.	None.	Unlimited	Two site visits and post processing required.	Widely available already.	The accuracy is estimated at ± 10 mm but has not been established through a controlled study. Recommend a further trial as the method is otherwise appealing.

Total station survey	±5 mm	Multiple points. Actual point measurement.	None.	Unlimited	Two site visits and post processing required.	Widely available already.	Requires two visits to site but is a reasonably quick and simple method for gathering reasonable accurate measurements at a number of points. Locating the exact location of the first measurements may be challenging.
Tracesheet	Unknown, too low.	Averaged over width.	None.	Unlimited.	High. Post processed from existing data.	None.	Found to be difficult and to not give good results.
Shear wave measurement	Unknown, too low.	Point measurement – limited by efficiency. (approx. Ø50 mm)	None.	unknown	Low. Precise setup required. Slow post processing required.	Equipment purchase required. Unknown source or price.	Unsuitable.
Ultrasonic tomographic imaging	Unknown	Continuous – linear.	None.	50 – 2,000 mm	3 seconds for data acquisition. Some additional for processing.	Approx $ 45,000 for Proceq Pundit.	Unsuitable – can't measure below 50 mm.
Falling weight deflectometer	unknown	Point measurement – limited by efficiency. (approx. Ø1,000 mm)	None.	unknown	Moderate.	Widely available already.	Uses many assumptions in calculations. Accuracy and repeatability poor.

4 Recommendations and conclusions

This document presents research into techniques for measuring the thickness of road surface layers, particularly those made from AC and OGPA. Section 1 defines performance criteria that the measurement techniques should meet. For this, two uses of the measurement techniques were considered; use as a tool for research purposes where a high level of accuracy is required but the resolution and efficiency could be reduced, and the use as a QA tool where resolution and efficiency are important, but accuracy could potentially be slightly worse.

Several measurement techniques have been investigated and a summary table of the techniques complied (chapter 3). The techniques that have been identified as promising and worthy of more research are:

- GPR. Either the IDS HiPave device or a smaller, hand-held, higher frequency (2.6+ GHz) unit could be used for determining surface thickness. Both systems will likely achieve a similar level of accuracy.
    - The HiPave system is larger and more expensive than the hand-held system but has software to help determine layer thickness. The HiPave system can be vehicle mounted so would be particularly suited to use as a QA tool.
    - The smaller had held GPR scanner unit is less efficient and would only generally be used over short distances. Software may be available to help with layer detection. This unit is more suited for use as a research tool.
- MIT. This technique requires that aluminium reflectors are placed within the surface during sealing. Fully commercial instrumentation is available and once the reflectors are installed, measurements can be performed in 1-minute per location. This system requires some setup prior to sealing but the efficiency is still high enough to be used as both a research and QA tool.
- 3D scanner survey. While the estimated accuracy of the 3D scanner does not meet the requirements stated, the high resolution data and non-destructive nature of the measurements mean it excels in terms of resolution, which still makes the system appealing. It is recommended that more work is done in close conjunction with a surveying contractor to further trial this method.
- Total station. Surveying through the use of a total station is much slower and has lower resolution than using a 3D scanner but may still be an appealing option particularly for research measurements.
- Coring. While coring is inefficient and destructive, it is simple and provides very accurate data. It is likely to still be used in some research applications to determine pavement thickness.

Contact was made with several contractors and other organisations within the New Zealand industry to enquire if they had either MIT or high frequency GPR devices which could be used as part of a trial in the future. Neither of these two types of devices were found within New Zealand.

While performing this research, we became aware of a broad interest from within the industry in measuring surface thickness for reasons other than road-noise. It may be possible to share the cost of instrumentation or further trials between other parts of the industry.

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