Mapping Asphalt Density with GPR Arrays

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***Abstract*—Several technical innovations in asphalt pavement density mapping have been combined in a way that may significantly extend road life. Owners and contractors will now have the data necessary to accurately and immediately control their asphalt placement process. Field trial results show that more stable antenna performance, more accurate calibration methods and high-resolution mapping combine to give contractors the real-time information they have long needed to fix density problems that inevitably occur during placement. Being able to fix the problem immediately avoids the cost and future maintenance needed to rip up and replace deficient sections.**

Keywords—Asphalt, pavement, density, GPR, mapping, intelligent compaction, PaveScan, DPS

I. Introduction

For over thirty years, Ground Penetrating Radar (GPR) has been an important method for measuring road quality. It has been needed to map the thicknesses of a road's sub-base, base, and asphalt layers. In the 1990's it was found that the method also could be used to map variations in the density of the top layer of asphalt [1]. However, only recently has GPR been accurate enough and real-time mapping been available to be truly useful to contractors during the paving process.

A. Asphalt Longevity

Placing asphalt roads is more art than science. It involves the coordinated dance of those who create the mixes (in the design lab, in the stone quarry, in the asphalt plant) and those who place the mix (from the transport vehicles, to the pavers, the rakers and the rollers). Any change in mix or delay in the "train" or failures of compaction will affect the performance and longevity of the road.

Pavement compacted too much or too little fails prematurely, resulting in reduce lifetime of 30-40% [2]. Since water/ice is the natural enemy of asphalt roads, it makes sense that pavement life depends in part on compaction. Water can penetrate the asphalt mat either from over compaction, if the larger stones become cracked or from under compaction, if the mat remains porous. There is some variability in the criteria defining the limits, but generally asphalt containing 3 -8 percent air voids have historically been acceptable [3]. However, research has shown that a 1% decrease in compaction can lead to a 10% reduction in pavement life [4]. Other research has shown that a few degrees higher compaction can even double the life to the road [5]. The importance of getting compaction right is becoming increasingly clear.

B. Some Solutions

Unfortunately, few tools exist for verifying compaction. Spot-check cores is the current state-of-the-art, which are cut into the finished product about every 100m. Everyone hates them, not just because they are sparse, inaccurate, expensive and come too late in the process, but also because it damages the new mat and often creates the first future pothole.

Non-destructive tools for measuring compaction include Nuclear and non-nuclear Gauges, which can be used to spot-check the mat as it is being placed. Like cores, these checks are sporadic and often inaccurate. Infrared cameras for measuring the asphalt temperature and accelerometers for measuring elasticity provide helpful information even if they don't actually measure mat density.

More recently, research that has been performed using a GPR system developed specifically to provide compaction information in real-time [6,7]. The results of these investigations provide a good overview of the system's capabilities and reveal the potential for using GPR to significantly improve the quality assurance practices on paving projects. A number of the most important findings are discussed in subsequent sections of this paper.

Figure 1: A 3 channel Density Profiling System (DPS)

The GPR system used for these studies, shown in Fig. 1, is different from traditional GPR systems used on roads in two important ways. Whereas typical GPR systems use large antennas that may weigh 10 kg or more, it uses small form-factor antennas less than a shoe box in size and weighing less than 1 kg. The smaller form factor simplifies mounting hardware requirements and makes it easier to mount more of the antennas close together. Second, system is not designed to output GPR scan data at all, but rather dielectric values derived from each scan. The dielectric value is calculated for each antenna and displayed as the antenna array moves along the paved surface.

The basic idea is to measure the Air/HMA surface reflection amplitude, A0, and the incident amplitude (represented by the reflection from the metal plate), Ai is used to calculate the dielectric of the surface, using Equation 1. In practice other factors like antenna height and Fresnel's equations for non-normal incidence are required for the 1% accuracy needed for industry acceptance.

$$e_r = \left(\frac{1 + \left(\frac{A_0}{A_i}\right)}{1 - \left(\frac{A_0}{A_i}\right)} \right)^2 \tag{1}$$

This surface reflection approach, using a 2GHz antenna, prevents the base layer underneath from influencing the measurement, so long as the upper lift is sufficiently thick (about 2.5 cm).

II. Methods

A. Collecting Data

For this study we have chosen four methods for collecting data, having identified the issues as timing, distance, safety, and resolution. For Quality Control (QC) asphalt density information is time sensitive.

- **Distance**: Since Quality Control (QC) operators prefer not to walk the 15-30km per day needed to create a full-coverage map of the asphalt mat, field trials are being conducted to evaluate trucks, golf carts, eScooters and robots as possible vehicles for the GPR array. Each of these has distinct advantages.
- **Safety**: Paving job sites are dangerous places. The authors have never met a QC operator without a near death story. In the US there are about 130 worker fatalities in road construction sites each year. For this reason, US DOTs are testing whether robots can be relied on to safely create GPR maps.
- **Resolution**: When asked how much resolution is needed for a density map, one expert responded, "Well, how big a pothole can you live with?" A discussion of resolution is beyond the scope of this paper; it is an involved topic, since the many stakeholders have diverse interests. But typically, a lateral resolution (the mat profile) of about 20-30cm can map the soft edges ("shoulders") compared to the center. It is understandably difficult to achieve proper density at the shoulders, especially along unconfined joints. A longitudinal resolution even as low as 1-2m is sufficient for an expert to understand what went wrong and how to fix it.
- **Timing**: This map needs to be created as close to the paver as possible, so that any problems that are identified, can still be fixed ("rolled out") before the mat has hardened and set. A density map collected afterwards can indeed be essential for Quality Assurance (QA) but is no longer helpful for QC.

B. Method for accurate calibration

Using a calibration kit, several methods exist for converting dielectric to density. Naturally, if done poorly, the map cannot be relied upon to make actionable decisions. The operators won't know whether to keep rolling or to move on. A 2% false reading of a 92% density might make a contractor lose money for no reason, or it might mean that an expected 10-year road will be in fact only a 7-year road. Although cores that get cut from the mat can be used, not only are they error prone, but also the results typically arrive too late, after the mat is set.

For this paper, the authors rely on "pucks," which look like cores, but are instead carefully manufactured using gyratory compactors in the lab prior to the job (Fig. 2). The advantage of the selected correlation method is that no extra lab work is required, since it only uses those pucks that are created for the job anyway. Pucks created in the off-season for that mix-design can also be used so long as the mix design and the aggregate source are the same.

Figure 2.: An example of a field calibration method shows a puck placed on a plastic block above a GPR antenna.

C. Methods for mapping

Methods for mapping can be created to fit the need. The simplest linear horizontal plot that shows dielectric over distance is enough to understand and detect changes or breaks in continuity. More helpful 2D maps can be overlain on top of an aerial map to give the setting (Fig. 3). Real-time maps can also be created to show progress and context.

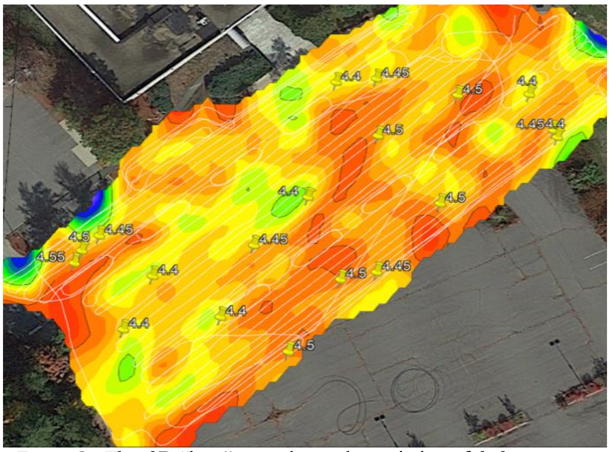

Figure 3.: This 2D "heat" map shows the variation of dielectrics over an aerial view of a parking lot paving job.

III. Results

A. Data collection Results

- **Distance**: Several attempts have been made to make large array coverage easier. As an "after-it's-too-late" QA tool, attaching the array to a highway vehicle can easily cover large distances without lane closures and without getting out of the vehicle. However, to successfully create maps inside the paving train, another method is needed. Of the many that were tried, by far the most effective has been attaching a hoverboard to the cart array. With a range of 30km it can push the cart array and a heavy person all day on a single charge (Fig.4). It is inexpensive, rugged, portable, safe and can turn on a dime. The operator can easily make several passes in the time needed for the train to move to the next 200m section.

Figure 4.: This photograph shows a hoverboard linked to the back of a Pavement Density GPR. The user can safely push the cart for about 30kms before needing to recharge. This means that dense maps can be made easily and with minimal effort by the operator.

- **Safety**: Results of a robotic solution are shown in Fig. 5. This airport runway survey intentionally avoided high traffic risk. The upper plot in the figure shows dense coverage which converts to a high-resolution density map in the lower portion of the figure. The green color indicates a density above 94%, with the blue color showing slightly lower densities. The data were collected with time enough for the roller operator to make corrections, even though the corrections were not needed. The map clearly shows exactly where difficulties occurred, typically along the longitudinal joints as expected. These occurred on both edges as well as in the center joint of the two-pass job.

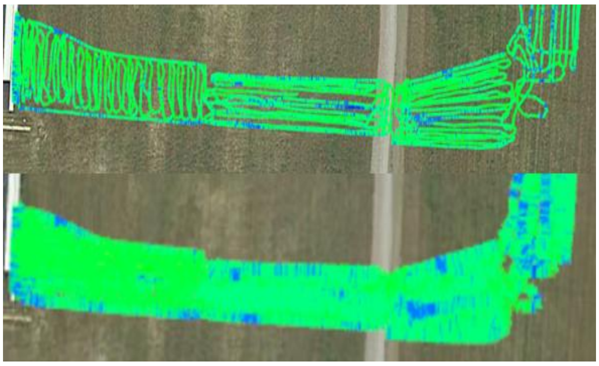

Figure 5.: This figure shows both the path of a remote controlled robot (top) as well as the resultant density map (bottom). The map is consistent regardless of the survey direction of the robot.

- **Resolution**: The results of nearly 1000 km of data show that the lower resolution maps, created at higher speeds, with much less information, may still be sufficient to reach the same conclusions about the quality of the job (Fig. 6). Once again, the center joint of the two pass job shows a consistently low density on both the high and low-resolution maps.

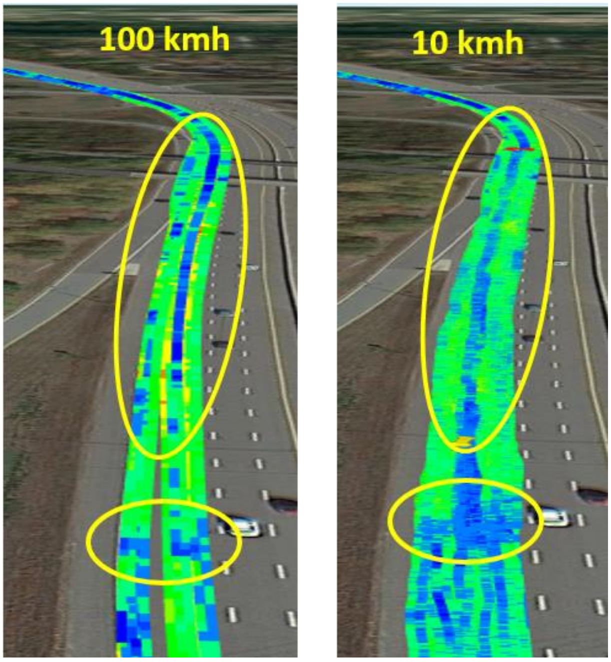

Figure 6.: These two plots show the difference in map resolution from surveys taken at high and low speeds. Note that even the poor resolution (100kmh) data generally correlates with the more detailed information in the slower (10kmh) map.

- **Timing**: It is obvious that the best time to measure asphalt compaction requires mounting a GPR under the rollers themselves (Fig. 7). Several factors including the harsh environment conspire to make this difficult. For example, GPR is especially sensitive to moisture from the roller drums, which impairs accuracy and gives misleading results. Data collection under a roller remains an active area of research to be presented at a future date.

Figure 7.: This photograph shows the placement of a GPR sensor under a roller

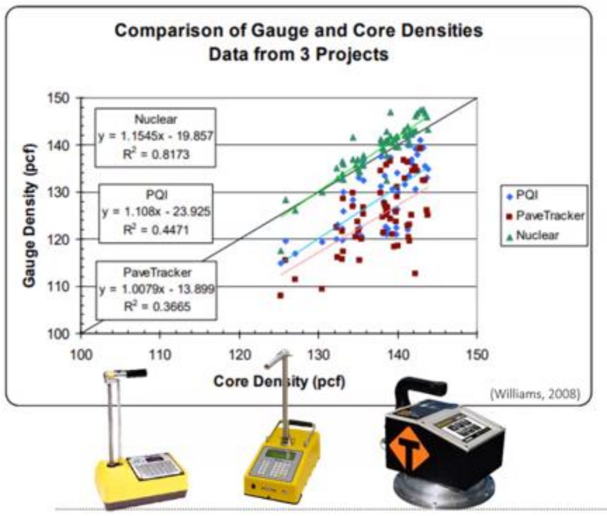

Figure 9: This plot compares the calibration accuracies of other methods of determining asphalt density. Nuclear gauges gave the highest average R^2 values of about 0.8.

B. Results of Calibration

Calibration results calculated from only one puck show highly reliable correlations with other pucks of the same mix, but over a wide range of densities (Fig.8). This confirms the robustness of the method, especially as compared to other methods like nulcear gauges (Fig.9) [8].

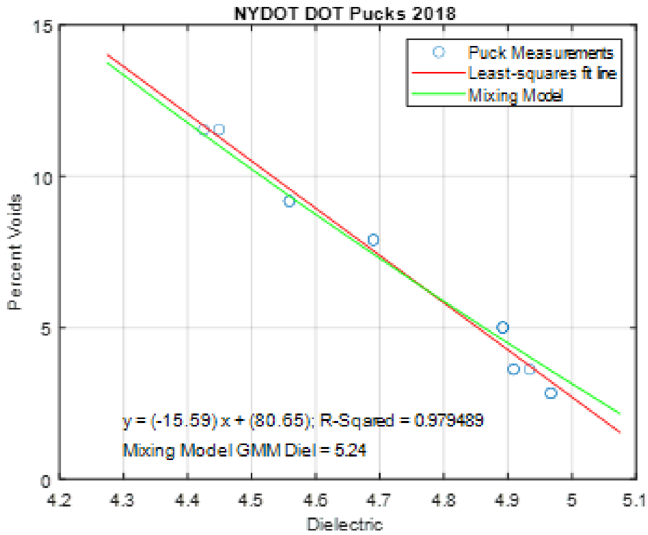

Figure 8: This plot compares the results of one calibration to a least square fit line. All available calibrations from dozens of pucks from plants all across the USA consistently show similar results, with R^2 values well above 0.9.

C. Results of Mapping

In Fig. 10, the entire story of one night's paving job is clearly laid out in the data. The two train stoppages created regions of low density. Dark blues spots indicate where the paver stopped. Regions like the triangular shape show areas where the Breakdown Roller had to remain idle while the train was stopped. This data was taken too late to be helpful, but if this had been taken in near-real-time, the low spots could have been fixed by re-rolling over the needed areas until uniform density was achieved.

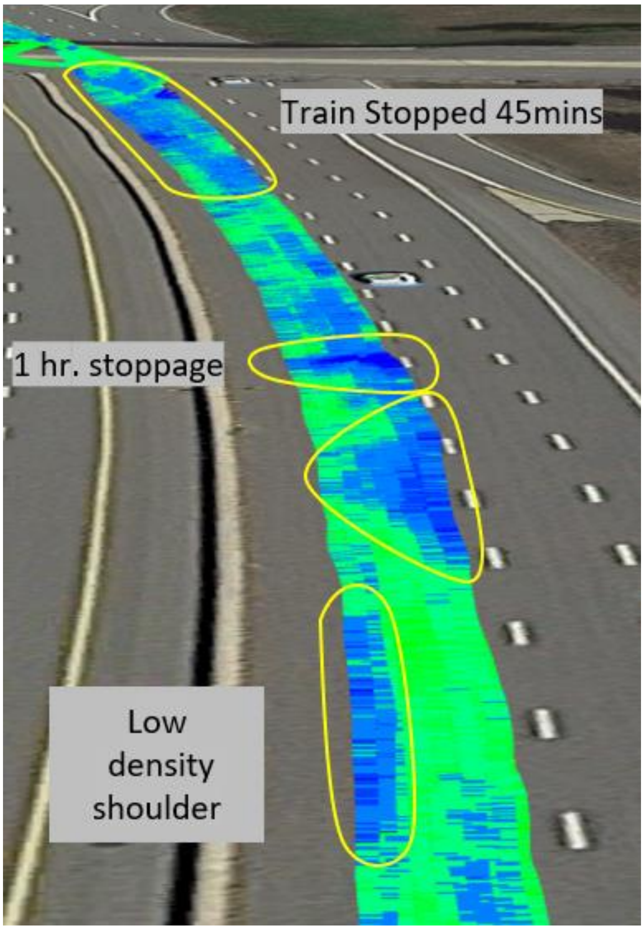

Figure 10.: This KML plot shows the rich and consistent information that is provided by a high-resolution GPR density map.

IV. Conclusions

Fig.10 also shows the power of accurate compaction mapping since it creates a tool for the contractor that has never been available before. If problems can be detected early enough, they can be fixed, or at least reported back to the plant to modify the mix for the next day. Instead of ripping up 750 ton sections when a low-density core is pulled, the data might instead show that only a small section needs to be repaired. Or perhaps coring will no longer be needed. A uniformly good mat with properly compacted joints will reduce years of road maintenance costs, patches and pothole repairs. This should translate into longer road life-cycles, happier taxpayers and more relaxed commuters.

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