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Original Research Paper

Representative volume element of asphalt pavement for electromagnetic measurements

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ABSTRACT

The motivation for this study was to investigate the representative volume element (RVE) needed to correlate the nondestructive electromagnetic (EM) measurements with the conventional destructive asphalt pavement quality control measurements. A large pavement rehabilitation contract was used as the test site for the experiment. Pavement cores were drilled from the same locations where the stationary and continuous Ground Penetrating Radar (GPR) measurements were obtained. Laboratory measurements included testing the bulk density of cores using two methods, the surface-saturated dry method and determining bulk density by dimensions. Also, Vector Network Analyzer (VNA) and the through specimen transmission configuration were employed at microwave frequencies to measure the reference dielectric constant of cores using two different footprint areas and therefore volume elements. The RVE for EM measurements turns out to be frequency dependent; therefore in addition to being dependent on asphalt mixture type and method of obtaining bulk density, it is dependent on the resolution of the EM method used. Then, although the average bulk property results agreed with theoretical formulations of higher core air void content giving a lower dielectric constant, for the individual cores there was no correlation for the VNA measurements because the volume element seizes deviated. Similarly, GPR technique was unable to capture the spatial variation of pavement air voids measured from the 150-mm drill cores. More research is needed to determine the usable RVE for asphalt.

1. Introduction

Good compaction is needed for asphalt pavements to achieve good durability and long service life of the road. A traditional method for controlling the air void content is to drill cores randomly over the length of the road. The number of cores to be drilled depends on the paving area. Once the cores are in the laboratory, the air void content is determined using the appropriate standard such as EN, ASTM or AASHTO.

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Another method has emerged in recent years, which is based on non-destructive technique of using ground penetrating radar (GPR). The GPR measures the dielectric value of the asphalt pavement, which is then correlated to the air void content. Ground penetrating radars typically used are impulse radars initially developed to map the ground and therefore, the frequencies they are operating are typically less than 2.2 GHz. The GPR transmits electromagnetic (EM) waves into the ground and records the echo characteristics, such as amplitude and time delay. To obtain dielectric material property, ε_r', the measured electromagnetic quantities, amplitude (A) and phase (φ) must be converted to ε_r' via radar electronics calibration. This is usually done with metal plate. Principles of reflectivity calibration are explained in detail for example in research of Scheer (1983). Then, to obtain a conventional material property such as the density of material (ρ), another calibration is needed to correlate the physical measurements and the EM measurements. This is illustrated in Fig. 1.

The maximum density of mixture (ρ_m) is then measured and the air void content is calculated as the ratio of the asphalt pavement density (ρ_p) to the maximum density (ρ_m), see Eq. (1). A common way of doing this calibration in Finland is to drill a core and then correlate the measured air void content to the measured ε_r' of the pavement (Roimela, 1998; Saarenketo, 2009). It has been also suggested that only one or two cores are needed to do this calibration (Saarenketo and Scullion, 2000). Leng et al. (2011) recommended using two to three cores. Poikajärvi et al. (2012) concluded that more attention should be placed where the calibration core samples are drilled and they suggested taking cores when the asphalt mixture, the working method, base treatment or environmental circumstances change. They also suggested that thermal changes may exist which have influence on the signal strength and these changes should be taken into account in dielectric value calculations.

$$V_a = \left(1 - \frac{\rho_p}{\rho_m}\right) \cdot 100\% \tag{1}$$

The propagation and attenuation of the electromagnetic field depend on the electrical and magnetic properties of the medium which are electrical conductivity σ, dielectric permittivity ε and magnetic permeability μ (Annan, 2003). This study focuses on the permittivity as magnetic properties for the aggregates used which can be neglected. Permittivity ε^* is a complex variable.

$$\varepsilon^* = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon_r' + j\varepsilon_r''\right) \tag{2}$$

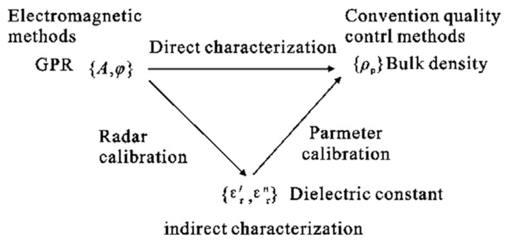


Fig. 1 – Schematic presentation of material characterization for EM measurements.

where ε_0 is the permittivity of free space, ε_r is relative permittivity of material, ε_r' is real part of relative permittivity and ε_r'' is imaginary part of relative permittivity. Real part of frequency dependent relative permittivity describes the stored energy and imaginary part accounts for energy losses.

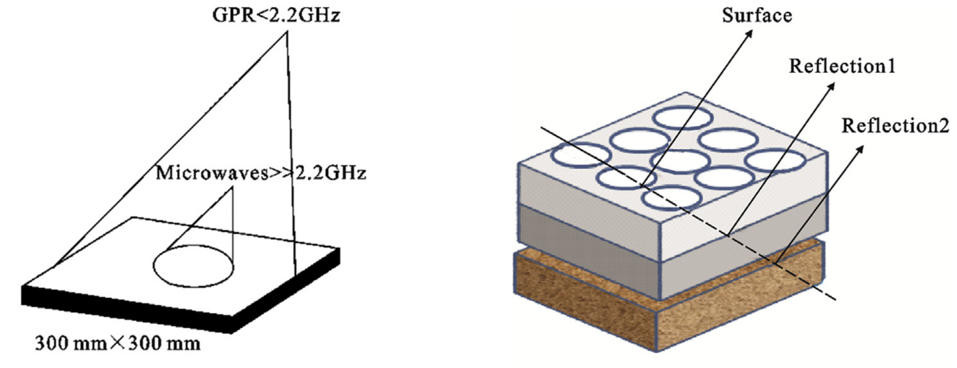
The motivation for this study was to investigate the viability of using only one core for GPR calibration. Field experiments were conducted in the summer of 2013 in real conditions on highway Vt3 in Finland, near the City of Tampere. The test road had 2-lanes for one direction and road was paved with the Stone Mastic Asphalt mixture SMA 16. Road was overlaid with 40 mm thick new pavement layer. A total of 27 cores were obtained from the road and tested in the laboratory for the air void contents. To obtain a reference or a base line measurement, independent of the GPR, the in-situ GPR measurements were compared with the Vector Network Analyzer (VNA) measurements conducted in the laboratory of electrical engineering. The vector network analysis is a method of accurately characterizing signal deformations by measuring their effect on the amplitude and phase of swept-frequency test signals. The VNA measurements can then be considered giving the "true" permittivity values and therefore they give the baseline to evaluate the GPR measuring technique. The VNA used in this research was the model "Wiltron 360 Network Analyzer" and transmission through the sample was used. In this paper the phrase asphalt is used referring to the hot-mix asphalt or asphalt concrete mixture/pavement following the European convention.

2. Bulk properties versus RVE

2.1. *GRP measuring principle*

The nominal center frequency of the typical GPRs is usually less than 2.2 GHz and as the beam width is proportional to the antenna opening the GPR with 2.2 GHz covers ca. 300 mm × 300 mm area of pavement. The depth resolution depends also on the frequency and for 2.2 GHz the theoretical wavelength of the signal is 136 mm in the air. The total thickness of bound asphalt concrete layers can range from 50 to more than 200 mm depending on road classification and traffic volumes. At low volume roads where the asphalt concrete thickness is less than 120 mm, depth resolution may then reach down to unbound aggregate base layers. For thin asphalt layers, the dielectric constant of asphalt is obtained from the signal reflecting from the surface as is shown in Fig. 2. Depending on the attenuation of the signal, there is then the possibility that multiple depth reflections are recorded (Loulizi et al., 2003; Loizos and Plati, 2007; Lahouar and Al-Qadi, 2008). Therefore, the measured ε_r' is a volume "bulk property" for the asphalt as Fig. 2 illustrates.

When a core is drilled from the asphalt pavement, it represents a discrete point measurement. Then, depending on the homogeneity of the pavement, the antenna foot print of 300 mm × 300 mm may cover variable material properties. Therefore, a representative volume element (RVE) must be determined to quantify this variation for the assessment of paved road quality.



(a) Beam width is proportinal with antenna opening (b) Bulk dielectric properties

Fig. 2 – Spatial coverage of GPR measurements and asphalt cores.

Thus, a coring plan was developed to study the spatial variation of the air voids of asphalt in the GPR measurement area. Although quality measurements are obtained from the right wheel path, it was decided to investigate both the wheel path and the center of the road. In this way we would have a reference location, which should not have densification due to traffic. In the continuous measuring mode, the GPR used in the experiment is scanning ten times per meter and then averaging these measurements to produce one stored data record per meter. As the scanned footprint area is 300 mm × 300 mm, one data record represents area of 0.3 m × 1 m.

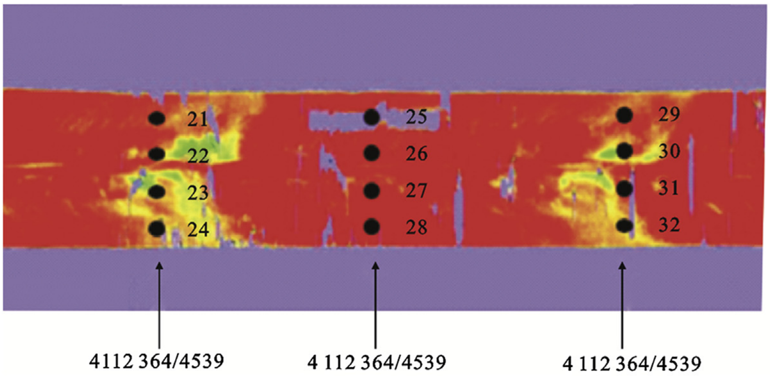
2.2. *Asphalt pavement homogeneity*

The magnitude of the pavement non-homogeneity depends on the level of physical segregation of mixture. Studies show that asphalt pavement suffering from truck load-end segregation may have variation in the binder content up to ±1.5% depending on the mixture type (Pellinen, 1985; Stroup-Gardiner and Brown, 2000; Nevalainen, 2014). The air voids variation may be confounded by the thermal segregation, but variation from 0 to 5–6% within less than 10 m distance is quite typical. Fig. 3 shows truck load-end segregation of SMA 16 mixture detected by thermal camera from a recent study by Nevalainen (2014). Cores taken from the coarse portions (21–24 and 29–32) and from the fine portion (25–28) of the segregated truck loads reveal the variation of binder content and air voids with the subsequent calculated volumetric quantities VMA and VFA (discussed more later in this paper).

Asphalt is a composite material with aggregates, bitumen and air. The effective, bulk dielectric properties of composite materials are determined by dielectric properties of its components. Different mixing formulas in respect of asphalt are studied (Al-Qadi et al., 2001; Leng, 2011; Leng et al., 2011). One of the simplest ones Eq. (3) is the complex refractive index model (CRIM), where $\varepsilon'_{\mathrm{reff}}$ is the effective dielectric value obtained by combining material components with volume portions, V_a is volume of air, V_s is volume of rock aggregate and V_b is volume of bitumen in the pavement.

$$\sqrt{\varepsilon'_{\mathrm{reff}}} = V_a\sqrt{\varepsilon'_{\mathrm{ra}}} + V_s\sqrt{\varepsilon'_{\mathrm{rs}}} + V_b\sqrt{\varepsilon'_{\mathrm{rb}}} \tag{3}$$

Asphalt EM modeling is quite complex and the influence of aggregates dominates the dielectric value of this composite. Yet, the dielectric properties of aggregates are not well reported and many researchers have just back-calculated the value from the asphalt dielectric bulk properties (Leng et al., 2011). This may lead to large errors in assessing pavement density. Thus, although we talk about dielectric constant, the EM properties for rock types are not constant. The ε'_r for rocks depends on their mineral composition, porosity, fluid content and frequency and due to this diversity values from literature have large variation. Only few studies are available where



Core No.	pb%	Va%	VMA%	VFA%
21	5.5	3.3	15.15	78.46
22	5.4	3.6	15.03	76.13
23	5.5	0.6	12.87	95.48
24	4.7	2.7	13.65	80.04
25	5.5	1.0	13.47	92.74
26	5.3	0.0	12.44	100.00
27	6.4	2.7	14.61	81.36
28	5.2	2.0	13.30	85.21
29	6.0	5.7	15.60	63.23
30	5.1	6.8	14.78	53.83
31	5.4	3.1	14.34	78.28
32	5.1	2.4	12.87	81.54
Max	6.4	6.8	15.60	100.00
Min	4.7	0.0	12.44	53.83
Range	1.7	6.8	3.16	46.17

Fig. 3 – Truck load-end segregation of SMA 16 mixture detected by thermal camera (Nevalainen, 2014).

dielectric constant of aggregates has actually been measured. French researchers reported measured values ranging from 4.5 to 7.7 (Fauchard et al., 2013). Olkkonen et al. (2014) measured values of 6.17–6.24 for the metavolcanic rock, and 4.5 and 4.76 for the pegmatite. These rocks were obtained from a quarry which supplied aggregates for the asphalt mixture in this study. The bitumen ε_r' is reported to vary between 2.6 and 2.8 although no actual measurements have been done and air has ε_r' value of 1.

2.3. *Bulk volume proportions of asphalt*

To obtain the air void content of asphalt, one has to first measure pavement density, as discussed above. There are several methods of obtaining pavement density for asphalt depending on the asphalt mixture type. Based on gradation and packing of aggregates, asphalt mixtures can be categorized into four different types (Fig. 4).

The most used mixtures are the dense graded mixtures (DAC), which are proportioned to have tight aggregate packing. The Stone Mastic Asphalt (SMA) is a heavy duty mixture with strong aggregate skeleton filled with bitumen rich mastics. Porous Asphalt (PA) has similar aggregate skeleton, but without mastics as this mixture is intended to be water permeable. Porous Asphalt is a popular surface mixture in Europe for motorways as it drains itself and in this way prevents splash and spray and hydroplaning. In the Mastic Asphalt (MA), all the voids are filled with mastic and there are no air voids in the mixture. MA is self-leveling and roller compaction is not needed.

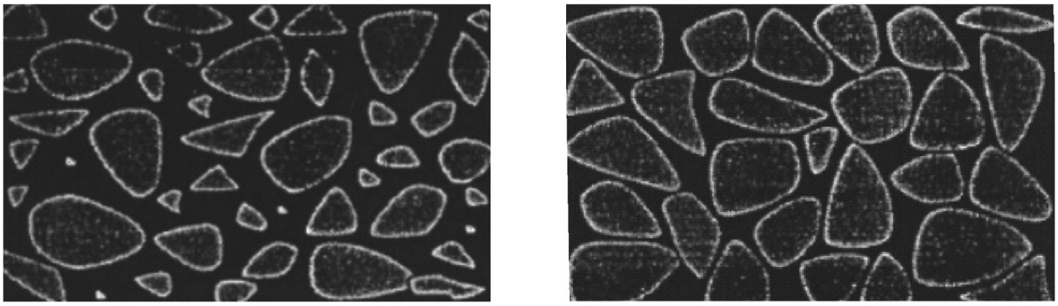
All these mixtures have different volumetric requirements. Fig. 5 shows some typical values based on Finnish Asphalt Specifications (FAS, 2011). The weight–volume relationships and subsequent volume-related quantities in the asphalt mixture are the voids in mineral aggregate (VMA), the voids Filled with Bitumen (VFB) and the air void content (V_a). These quantities are calculated from the volume of bitumen and the volume of aggregate blend. The VMA varies between 15% and 30% and the volume of air may range from 0 to 22%–25% as illustrated in Fig. 5. The formula to obtain VMA is shown in Eq. (4)

$$\mathrm{VMA} = \left(1 - \frac{P_s \rho_p}{\rho_s}\right) \cdot 100\% \tag{4}$$

where ρ_p is the pavement density, ρ_s is the aggregate solid density and P_s is the percentage of aggregate in the mixture.

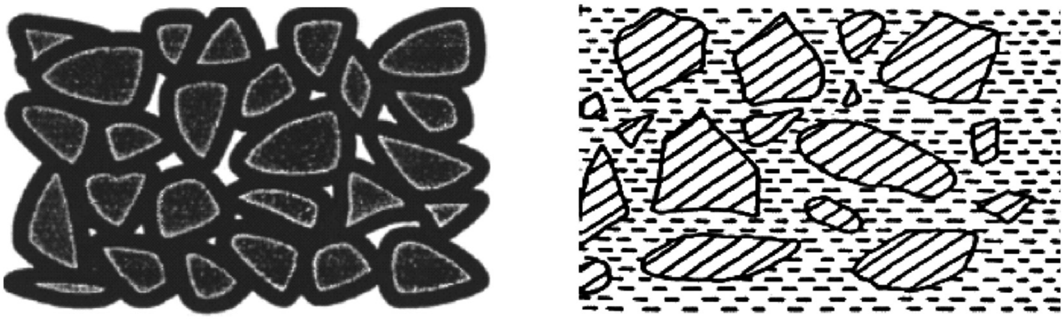
A requirement for asphalt density is placed for the air void content. It has to be less than 5% to 6 % to have durable impervious pavement which can withstand freeze and thaw conditions. With the development of nondestructive testing (NDT) methods, there has been a gradual shift from the conventional destructive quality control/quality assurance (QC/QA) methods to these new techniques. However, is the EM technology matured enough to be used as the QC/QA tool in assessing the compaction of asphalt pavements? Loizos and Plati (2011) have investigated the assessment of asphalt air voids and stiffness based on asphalt dielectric values. However, their models do not count for the rock aggregate type variation.

All measurements have precision and bias, and ultimately the question stays whether we can separate these from the true material variation caused by production. Quality assessment gets complicated when we start mixing testing methods with different precisions. Pellinen and Kutczek (2007) have studied this issue and determined the allowable testing variation for the VMA to be ±0.5%. Eq. (4) shows that the allowable



(a) Dense Asphalt, DAC

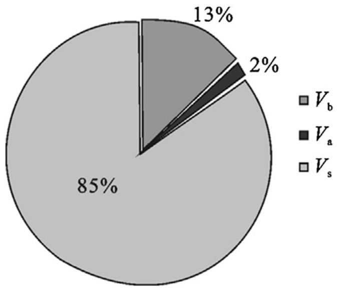
(b) Stone Masti Asphalt, SMA



(c) Porous Asphalt, PA

(d) Mastic Asphalt, MA

Fig. 4 – Asphalt mixture types and their aggregate packing arrangements.



	MA(DRY)	DAC(DRY)	SMA(SSD)	SMA(DIM)	RA(DIM)
V_b	25%	13%	15%	15%	8%
V_a	0%	2%	3%	6%	22%
V_s	75%	85%	82%	79%	70%
VMA	25%	15%	18%	21%	30%

Fig. 5 – Typical volumetric properties for asphalt mixtures with variable packing (Measurement methods dry, SSD or dimensions are given in parenthesis after the mixture type).

testing variation for the VMA is a combination of testing variations of three conventional laboratory tests for P_s, ρ_p and ρ_s. Fig. 3 shows that for segregated pavement the range of VMA was ca. 3%. A production variation covering the physical segregation is therefore within ±1% change of the VMA in the asphalt bulk property. Asphalt density is thus needed to determine the weight–volume relationships and to calculate the volumetric quantities. To obtain acceptable and accurate enough reading for the air inside the specimen, several methods of obtaining the density or bulk specific gravity of compacted sample have been developed.

2.4. *Density measurement methods*

There are a number of methods available to obtain asphalt density and each one uses a slightly different way to determine specimen volume, which may result in different density values. In water displacement methods, which are based on Archimedes principle, specimen volume is calculated by weighing the specimen in and out of a water bath. The difference in weights is then converted to the volume of the specimen. The three methods that are used in SFS-EN 12967-8 for obtaining the density of the compacted asphalt sample are a dry method (no water in sample); a saturated surface dry method (SSD) where water fills the asphalt air voids; a method based on sample dimensions (DIM); and a method where sample is sealed, for instance wrapped with parafilm. The dry method is used for the dense mixtures such as MA and DAC while the SSD is used for the SMA mixtures. Dimensions are not used for other than the porous asphalt i.e. open graded asphalt as the large voids cannot be measured with other methods. In addition, obtaining density with core dimensions is not considered accurate enough method for the DAC and SMA. A correlation between different measurement methods can be developed but it will be mixture dependent. Typically, differences are increasing with the increasing air voids and specimen surface roughness.

Asphalt density is thus needed to determine the weight–volume relationships and to calculate the volumetric quantities. To obtain acceptable and accurate enough reading for the air inside the specimen, several methods of obtaining the density or bulk specific gravity of compacted sample have been developed.

3. Experiment set up for RVE determination

To set up the experiment for the RVE of asphalt, a quantity designated as the "measured volume element" (MVE) was defined. The MVE for the field measurements was dictated by the GPR measuring system and coring was done using a 150 mm core drill pit. Fig. 6 illustrates the six MVEs

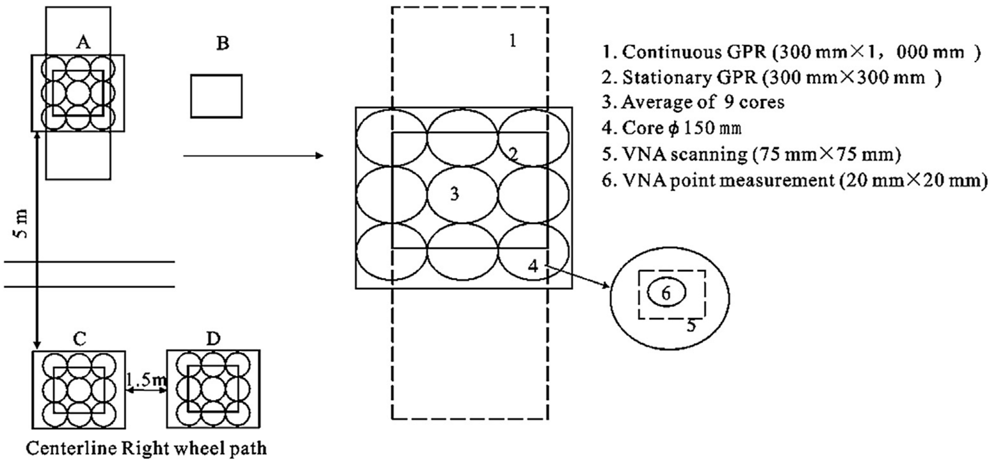


Fig. 6 – Schematic presentation of MVE for GPR and coring (not in scale).

Table 1 – Description of MVEs in this study.

MVE	Description	Area (m^2)	Height (m)	MVE (m^3)	MVE ratios	
1	Continuous GPR 0.3 m × 1 m	3.00E-01	0.04474	1.34E-02	–	–
2	Stationary GPR 0.3 m × 0.3 m	9.00E-02	0.04474	4.03E-03	MVE2/MVE1	0.30
3	Area of 9 cores 0.5 m × 0.5 m	2.50E-01	0.04474	1.12E-02	MVE3/MVE1	0.83
4	One core ϕ 150 mm	1.77E-02	0.04474	7.91E-04	MVE4/MVE1	0.06
5	VNA scanning 75 mm × 75 mm	2.50E-03	0.04474	1.12E-04	MVE5/MVE4	0.32
6	VNA point 20 mm × 20 mm	3.14E-04	0.04474	1.41E-05	MVE6/MVE4	0.02

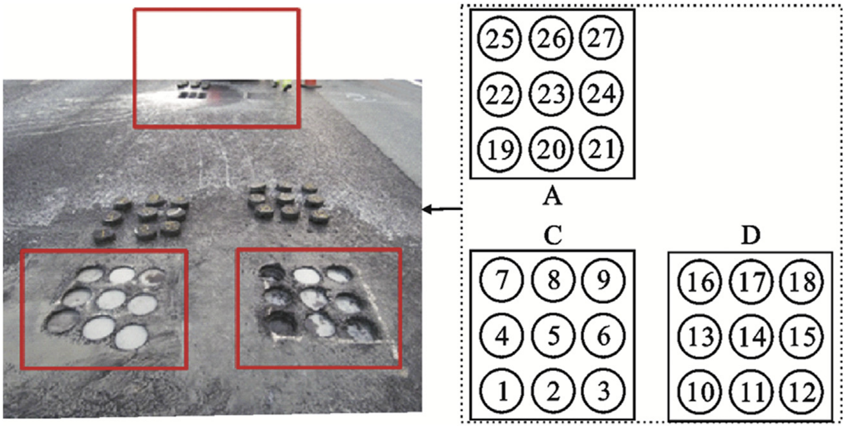


Fig. 7 – Core locations and numbering of cores (perspective gives slightly distorted scale).

determined for this study and details are given in Table 1. The largest MVE of 1.34E-02 m^3 was for the current GPR measurement method and the smallest MVE of 1.41E-05 m^3 was for the VNA point measurements. The VNA point measurement MVE is 98% smaller than the core MVE. The layer thickness needed in the calculations was estimated from obtained cores.

The GPR used in the experiment was impulse radar with 2.2 GHz horn areal antennas. Measurements were done from the right wheel path and from the centerline of the road. The stationary measurements were conducted by stopping the vehicle and taking scans from the same spot continuously for 100 times. Continuous measurements were done by measuring a stretch of the road and the data records were matched with the help of GPS coordinates. During paving work and measurements the weather was warm and dry.

A total of 27 cores of 150 mm diameter were taken from road. Fig. 7 shows visually how the GPR measurements were conducted relative to the core locations. The coring area was ca. 0.5 m × 0.5 m and the stationary measurements were matched on that same spot. The distance between cores in each test spot was kept within few centimeters to minimize the material variation due to physical and thermal segregation. A distance between locations A–B and C–D was ca. 5 m. Location B was not cored. Core No. 19 broke during coring.

4. Results

Table 2 summarizes the results for stationary and continuous measurements. For the stationary measurement, areas B and D have the same ε_r' while areas A and B are significantly different in statistics.

Tables 3–5 summarize laboratory measurements for cores. Pavement density i.e. bulk specific gravity G_{mb} was measured using methods B (SSD) and C (DIM) according to SFS-EN 12967-8. The maximum density i.e. maximum specific gravity of the mixture is G_{mm} and V_a is the voids in total mix or the air voids of specimen.

Table 2 – GPR stationary and continuous measurements on test locations.

Location		Stationary 300 mm × 300 mm including 100 × avg. of 10 scans		Continuous 0.3 m × 1 m average of 10 scans	
		Avg. ε_r'	Stdev. ε_r'	Avg. ε_r'	Stdev. ε_r'
A	Centerline	5.38	0.04	5.0	0.1
B	Wheel path	5.43	0.06	5.3	0.1
C	Centerline	5.66	0.05	5.1	0.1
D	Wheel path	5.43	0.06	5.4	0.1

Table 3 – Bulk specific gravities of cores for location A in the centerline of the road.

Core no.	G_{mb} (DIM)	G_{mb} (SSD)	G_{mm}	V_a% (DIM)	V_a% (SSD)
19	–	–	–	–	–
20	2.370	2.494	2.538	6.6	1.7
21	2.349	2.489	2.536	7.4	1.9
22	2.261	2.484	2.538	10.9	2.1
23	2.275	2.491	2.544	10.5	2.1
24	2.378	2.505	2.545	6.6	1.6
25	2.327	2.458	2.538	8.3	3.2
26	2.370	2.471	2.539	6.7	2.7
27	2.378	2.499	2.538	6.3	1.5
Avg.	2.338	2.486	2.539	7.9	2.1
Stdev.	0.047	0.015	0.003	1.85	0.57

Table 4 – Bulk specific gravities of cores for location C in the centerline of the road.

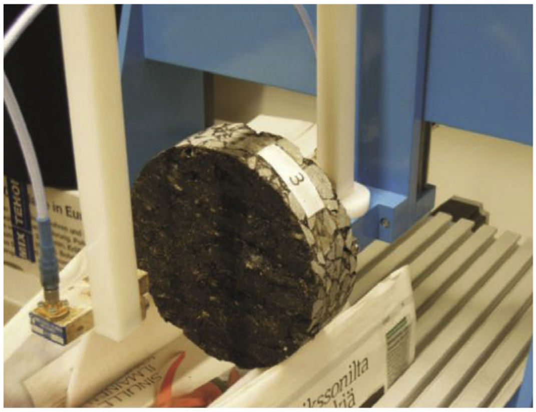
Core no.	G_{mb} (DIM)	G_{mb} (SSD)	G_{mm}	V_a% (DIM)	V_a% (SSD)
1	2.387	2.482	2.542	6.1	2.3
2	2.398	2.499	2.539	5.5	1.6
3	2.356	2.500	2.541	7.3	1.6
4	2.296	2.486	2.533	9.3	1.8
5	2.338	2.490	2.534	7.7	1.7
6	2.379	2.482	2.532	6.0	2.0
7	2.348	2.487	2.535	7.4	1.9
8	2.426	2.495	2.543	4.6	1.9
9	2.227	2.484	2.538	12.3	2.1
Avg.	2.351	2.489	2.537	7.4	1.9
Stdev.	0.060	0.007	0.004	2.30	0.23

The VNA measurements were conducted using the transmission method of measuring through the sample (Fig. 8). Measurements were done using two volume elements with frequency sweep of 7–17 GHz. First a point measurement with effective antenna footprint of ca. 20 mm × 20 mm was used. Then, few samples were 2D scanned with scanning area of 75 mm × 75 mm. As this was a new measuring set up in progress, only two samples No. 11 and No. 14 were measured. From the measured amplitude (A) and phase (φ), the dielectric constant was then obtained by linear regression (Fig. 9).

Table 5 – Bulk specific gravities of cores for location D in the right wheel path.

Core no.	G_{mb} (DIM)	G_{mb} (SSD)	G_{mm}	V_a% (DIM)	V_a% (SSD)
10	2.265	2.471	2.541	10.9	2.8
11	2.246	2.467	2.541	11.6	2.9
12	2.212	2.462	2.542	13.0	3.2
13	2.317	2.488	2.530	8.4	1.7
14	2.332	2.451	2.537	8.1	3.4
15	2.343	2.477	2.546	8.0	2.7
16	2.378	2.485	2.545	6.6	2.3
17	2.384	2.473	2.538	6.1	2.6
18	2.322	2.471	2.543	8.7	2.8
Avg.	2.311	2.472	2.540	9.0	2.7
Stdev.	0.059	0.011	0.005	2.32	0.49

(a) VNA



(b) Core sample measurement

Fig. 8 – VNA and core sample measurement set up.

The microwave frequencies used have a wavelength less than 40 mm, so we are able to see more closely the granularity of asphalt compared with the bulk properties of asphalt measured by the GPR. However, as the VNA point measurement is only ca. 2% from the core volume, it may be too small relative to the measured bulk density of the core. Fig. 10 shows a picture of core No. 11 and the scanning area 75 mm × 75 mm superimposed over the core's surface area. Now the MVE is ca. 32% of the core volume and the scanned results should have a better match for the bulk density of the cores. Based on test results, shown in Table 6, indeed this is the case as both

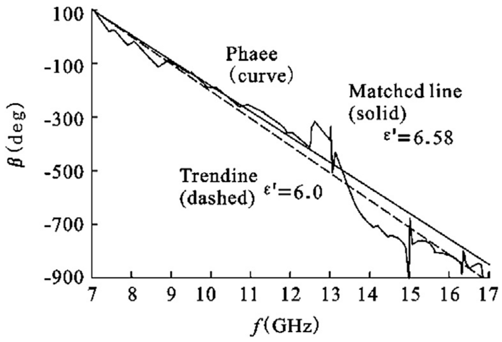
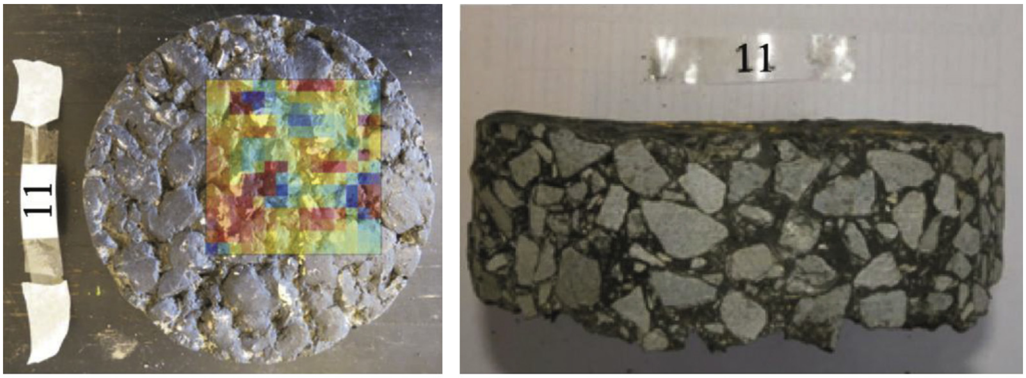


Fig. 9 – VNA data analysis to obtain dielectric constant.



(a) Scanned area (b) Side view of the core

Fig. 10 – Core sample of No. 11.

Table 6 – VNA results for all cores.

C (Centerline)		D (Right wheel path)			A (Centerline)	
Core no.	Point ε_r'	Core no.	Point ε_r'	Scanned ε_r'	Core no.	Point ε_r'
1	5.85	10	5.78	–	19	–
2	5.90	11	5.78	5.41	20	5.51
3	6.11	12	6.08	–	21	5.49
4	6.86	13	5.47	–	22	6.13
5	7.64	14	5.74	5.67	23	5.95
6	5.65	15	5.48	–	24	5.84
7	5.88	16	5.92	–	25	5.83
8	5.26	17	5.33	–	26	5.80
9	5.72	18	6.04	–	27	5.19
Avg.	6.10	Avg.	5.74	–	Avg.	5.72
Stdev.	0.72	Stdev.	0.26	–	Stdev.	0.30

Table 7 – Summary of results for all MVEs.

Locations	1. GPR cont. ε_r'	2. GPR stat. ε_r'	5. VNA scan ε_r'	6. VNA point ε_r'	3. Cores V_a% (DIM)	3. Cores V_a% (SSD)
A	5.0	5.38	–	5.72	7.9	2.1
B	5.3	5.43	–	–	–	–
C	5.1	5.66	–	6.10	7.4	1.9
D	5.4	5.43	5.54	5.74	9.0	2.7
All avg.	5.3	5.48	5.54	5.85	8.1	2.2

scanned VNA measurements give lower permittivity values than the point measurement which we considered a better match to the conventional measurement of core density.

Table 7 and Fig. 11 are comparing MVEs for the EM and traditional measurements using the bulk properties by averaging core measurements at each location A, C and D. The overall bias in the measurements depends on the method of obtaining core density. The core dimensions method give the average air voids of 8.1% and the SSD method gives 2.2%. Interestingly, when the MVE increases the ε_r' value decreases. This suggests that the EM methods “see” more aggregates when the volume element decreases. This seems a logical result as the highest permittivity values were obtained for the VNA point measurements with the smallest MVE at microwave frequencies.

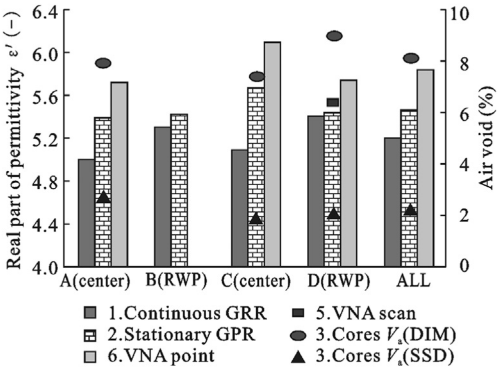


Fig. 11 – Comparison of material properties with variable MVEs.

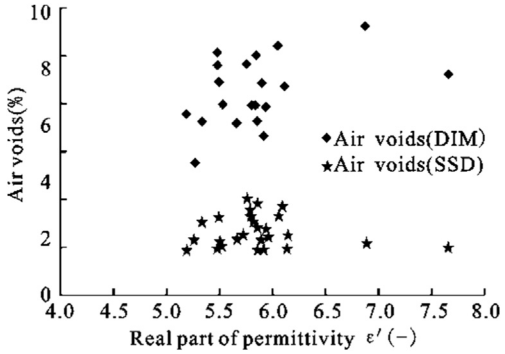


Fig. 12 – Correlation of air voids with MVE-4 and VNA point measurements with MVE-6.

Table 7 shows that overall the VNA point measurements did not capture the bulk properties of cores. This is confirmed by Fig. 12, which shows that there was no correlation between the air voids obtained from 150 mm diameter cores and the VNA point measurements.

5. Conclusions

There are a number of methods available to obtain asphalt density and each one uses a slightly different way to determine the specimen volume. This will result in a variable precision of determining the air voids of the mixture. However, all mixtures are measured with the similar precision by the nondestructive EM-methods. There are two EM measuring methods that were used for asphalt: a free space transmission method, in which the material under test has been placed between two antennas, and the reflection measurement method or the radar principle, in which the reflected waves from the surface are used. The precision of these two methods for measuring asphalt is not known at the moment. The average bulk property results agreed with theoretical formulations and the air void content obtained from cores was increasing when the dielectric constant was decreasing. Interestingly, when the measured volume element (MVE) increased the ε_r' value decreased. This was the case for both EM techniques employed. This suggests that the EM methods "see" more aggregates when the volume element decreases. Therefore, it can be concluded that the RVE for the EM measurements is highly frequency dependent. However, for the individual cores, there was no correlation for the VNA measurements because the volume element seizes deviated. Similarly, GPR technique was unable to capture the spatial variation of air voids measured from the 150 mm drill cores. As the RVE for EM measurements is frequency dependent, in addition to being dependent on asphalt mixture type and density measurement method, it is dependent on the resolution of the EM method used. Therefore, in the GPR measurement method the bulk property air void content cannot be reliably correlated to only one drill core for calibration purposes because one core is too small relative to the volume element where the traditional GPR is measuring. More research is needed to determine the usable RVE for asphalt. Authors are currently further developing a method of scanning the specimen when using microwave frequencies.

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