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Non destructive Assessment of Hot Mix Asphalt compaction with a Step Frequency Radar: Case study

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***Abstract*—A Step Frequency Radar (SFR) is used for assessing the compaction of Hot Mix Asphalt (HMA) layers. The system is composed of a network analyser and an Ultra Wide Band (UWB) antenna placed above the road surface. The measurements are carried out on a new-paved road in Cagny (Normandie, France). The SFR system provides the permittivity of the first overlay. The data is corrected from vehicle vibrations and calibrated at fixed locations. Then, the HMA compaction is deduced with a Lichteneker-Rother (LR) model. The results are compared with standard tests (gamma bench testing on cores and in-place nuclear gauge). We show that the SFR system allows the non-destructive assessment of HMA overlay with a high density of points, and with an accuracy close to the compaction provided by standard tests.**

I. Introduction

Hot Mix Asphalt (HMA) is a mixture of aggregates, asphalt binder and air. HMA layer compaction is a critical parameter to be assessed during the building process of new roads since it directly impacts the pavement life cycle. Compaction is defined by the ratio of the bulk specific gravity ρ (in g/cm^3) of the mix to the specific gravity of the mix ρ_r (in g/cm^3):

$$C = \frac{\rho}{\rho_r} \quad (1)$$

The specific gravity (or density) ρ_r is given by the mix design. The bulk density ρ of HMA is classically obtained by standard laboratory methods (in accordance with [1] and [2] for non absorbing mixtures) on cores extracted from HMA layers. Compaction can be calculated from equation 1. This approach is time-consuming and destructive. It is considered as the reference method for HMA compaction estimation. Nuclear gauges also provide an estimation of HMA compaction. It is used both in the laboratory (on core or slab samples in accordance with [3]) and on site (non destructively in accordance with [4] and destructively in accordance with [5] or [6] for a single borehole, and [7] in two boreholes). The main drawbacks of such methods lie in the high maintenance cost caused by the stringent requirements in the use of the nuclear source, its transportation and storage. Alternative to nuclear methods is therefore a major issue.

Some devices based on the capacitive electromagnetic (EM) method have been proposed in the 1990's as alternative methods [8]. Many studies have been presented by American organizations of transportation and these commonly confirm the possibility of using the capacitive EM method for Quality Control in new pavement construction. Since 2005, this method has become a standard test [9], applied as a qualitative tool to assess pavement density. Nevertheless, the capacitive EM methods have not yet convinced users. The following aspects can explain why: an unknown depth of investigation, a brief technical description of the method, the content and nature of the water to be considered, and the required calibration process involving other standard test methods.
Recent works have shown the capability of EM methods based on wave propagation to assess the HMA compaction [10], [11]. Here, we present the basic theoretical background where the HMA compaction is defined as a function of the measured permittivity using the SFR system. This approach validated in the laboratory is then applied on site on a new-paved HMA.

II. Basic theoretical background for compaction assessment with SFR system

A. Relation between compaction and the HMA measured permittivity

The HMA is a three-phase mix of rock aggregates (whose nature could be the quartzite, sandstone, granite, diorite, etc), asphalt binder, limestone filler and air [12]. We first present the basic model accounting for all the components of the mix and giving the compaction in function of all inherent quantities and the measured permittivity by our SFR system. Then, a methodology is presented, accounting for the various characteristics of each component, and the on-site conditions of experiment. The mix compaction C is classicaly defined by

the sum of the volume fractions of each solid component C_i:

$$C = C_a + C_b + C_f = 1 - C_{air} \quad (2)$$

where the subscripts a, b and f refer respectively to the rock aggregates, asphalt binder and filler.

The dielectric behaviour of a mix containing the previous homogeneous materials and the air can be described by the Lichtenecker-Rother [13] (LR) equation:

$$\epsilon_{HMA}^{\alpha} = C_a\epsilon_a^{\alpha} + C_b\epsilon_b^{\alpha} + C_f\epsilon_f^{\alpha} + C_{air}\epsilon_{air}^{\alpha} \quad (3)$$

where α is an empirical parameter ($\alpha \in [-1, 1]$). When a new HMA layer is implemented, the road builders specifying provides a mix design detailling the following quantities:

1) the density of aggregates ρ_a (g/cm^3) and the quarry the rock is extracted from;
2) the filler density ρ_f (g/cm^3) and its quarry origin;
3) the asphalt binder density ρ_b (g/cm^3);
4) and the mass fraction of constituents as defined by $T_i = \frac{m_i}{m_a+m_b+m_f}$.

From both equations 2 and 3, the HMA compaction can be expressed according to the following:

$$C = \frac{(\epsilon_{HMA}^{\alpha} - 1)Z}{\epsilon_a^{\alpha} + \frac{\rho_a T_b}{\rho_b T_a}\epsilon_b^{\alpha} + \frac{\rho_a T_f}{\rho_f T_a}\epsilon_f^{\alpha} - Z} \quad (4)$$

Where $Z = 1 + \frac{\rho_a T_b}{\rho_b T_a} + \frac{\rho_a T_f}{\rho_f T_a}$ is a constant and T_a, T_f and T_b are the mass fractions of the aggregates, filler and asphalt binder, respectively. A similar expression is provided in [11], whose authors studied compaction models based on various permittivity models and on measurements carried out with a Ground Penetrating Radar (GPR). As shown in equation 4, ϵ_{HMA} is the also permittivity measured by the SFR system, and the only unknown is the permittivity of aggregates (respective permittivities of limestone and asphalt binder are known), the alpha parameter that has not been set yet. We discuss hereafter the importance of each quantity.

B. Discussion on model and parameters

1) The filler and the asphalt binder and aggregate influence : An evaluation of the filler, asphalt binder and aggregate contents influence can be achieved. Let consider the T_f, T_b and T_a values given in the Table I. We make the assumption that the associated standard deviations are 2% for these quantities. Then the difference between compaction we would assess taking account such standard deviations would be respectively about 0.3% and 0.01% and 2%. We see that the aggregates content has to be accurately known.

2) The importance of aggregates: We expected the knowledge of permittivity would be sufficient to assess the HMA compaction: the volume fraction of aggregate in HMA ranges from 88% to 94%. So, knowing the permittivity of the rocks composing the HMA sample is therefore highly relevant in describing the dielectric behaviour of the mixture. For that purpose, the dielectric characterization of rocks used in roads construction has been undertaken first, in the last years, in Normandy region, and second, will be considered in the whole country in further studies. First results on dielectric characterization of rocks are presented in [14]. The main idea of this approach is to provide an onsite tool for the compaction evaluation that required just the usual data provided by the road builders and a new data, the measured permittivity of the rock aggregates. Nevertheless, more and more new roads are partly built with recycled aggregates (10 to 20% of the total aggregates) whose quarry origin is often unknown. Therefore, the agregates permittivity must be corrected considering first, the known origin and permittivity of the aggregates and second, the unknown origin and permittivity of the recycled aggregates. In this study, the proposed solution consists of calibrating the SFR assessed compaction using standard-controlled cores extracted from at few points of the pavement by adjusting the apparent permittivity value ϵ_a of the aggregates.

We see the alpha parameter can vary from -1 to +1. If $\alpha = 0.5$, Eq. 3 is the so-called Complex Refractive Index (CRI) model [15].This model has been studied in [14] for estimating the compaction of various HMA slabs whose the nature of aggregates was known and the aggregates permittivity were perfectly characterized in cylindrical cavities. The alpha parameter was adjusted in order to best-fit the compaction estimated by SFR method in comparison with the compaction provided by the standard nuclear tests. In this paper, we choose to adjust in Eq. 4 only one parameter (the permittivity of the aggregates) by keeping constant the alpha parameter to 0.5.

TABLE I
MIX DESIGN OF THE STUDIED HMA IMPLEMENTED ON THE NEW ROAD OF CAGNY

Specific gravity: ρ_r (in g/cm^3)=2.464			
	aggregates	filler	asphalt binder
Mass fraction (%)	93.9	0.5	5.6
Permittivity	Unknown	5.5	2.52
Density (g/cm^3)	2.67	2.65	1.04

C. Permittivity measurement with radar system

SFR is used as a non-destructive tool for assessing the HMA compaction of new roads. Our monostatic SFR system is composed of a vector network analyzer connected to an Exponential Tapered Slot Antenna, which is an ultra-wideband antenna of the "Vivaldi" family [17]. The analyzer (Agilent E82163 model) generates a step-by-step sinusoidal EM signal (1601 points) over the selected [0.4-6 GHz] frequency range. The S11-parameter measured in the frequency domain is converted into time-domain reflected amplitude (through an Inverse Fast Fourier Transform). Data processing as time domain windowing yields similar results to conventional time domain GPR systems. The whole SFR system, which is vehicle-mounted, has already been described in [18] for thin HMA layers thickness estimation. According to our calcultation and our experience in the field, an IF bandwidth of 10 kHz with a max speed of 10 km/h allow a scan survey every 0.5 m.

We aim to show how the performances of the SFR system lead to a more accurate assessmenent of the HMA compaction. We compare our system composed of E82163 vector network analyser mounted in a vehicule with a ETSA antenna, with a common Ground Penetrating Radar used for road assessment and equiped of a 2 GHz horn antenna.

D. Permittivity calculation on HMA surface

In the monostatic configuration used here, the HMA permittivity is deduced from the measured reflection coefficient on the HMA surface according to the following classical relation [19]:

$$R_{01} = \frac{A_{HMA}(h_{ref})}{A_{metal}(h_{ref})} \tag{5}$$

where R_{01} is the reflection coefficient of EM wave at the air (medium 0) and HMA (medium 1) interface, $A_{HMA}(h_{ref})$ and $A_{metal}(h_{ref})$ are the reflection amplitude moduli in the time domain respectively from the HMA surface and a flat metal plate (total reflection) recorded at the same antenna height h_{ref}.
However during the road survey, the antenna height h_i is varying (due to vehicle vibrations) and it is necessary to correct the measured amplitude $A_{HMA}(h_i)$. To do so measurements were performed at the laboratory on a metal plate to determine the dependence of the reflected amplitude as a function of the antenna height (due to geometrical spreading) h_i. The following dependence :

$$A_{HMA}(h_{ref}) = A_{HMA}(h_i)\frac{h_i + h_0}{h_{ref} + h_0} \tag{6}$$

was fitted from experimental data by considering the antenna as a virtual point source located at h_0 from the antenna terminations. The value $h_0 = 2.02710^{-1}$ m was found (see [20] for further explanation).

It is possible to give a reformulation of the eq.5 taking into account the influence of the antenna height variations during the HMA surface survey as:

$$R_{01} = \frac{A_{HMA}(h_i)}{A_{metal}(h_{ref})}\frac{h_i + h_0}{h_{ref} + h_0} \tag{7}$$

During the survey, the reference height measured at calibration points is equal to 47.1 cm. Then, the real relative permittivity $\epsilon'_{SFR,surface}$ measured on the HMA surface is:

$$\epsilon'_{SFR,surface} = (\frac{1 + R_{01}}{1 - R_{01}})^2 \tag{8}$$

This measured permittivity is then used in the eq.4 for assessing the HMA compaction.

E. Comparison of SFR and GPR performances

In order to compare the SFR and GPR performances, the output signal of both systems was studied in the laboratory. Both devices were switched on half an hour before measurement in controlled conditions: a constant temperature and a fixed antenna height. We placed the antennas above a large metal plate (1m*1m) at 40 cm height and we recorded the normalized reflected modulus A_{metal} in the time domain during one hour (Fig. 1a). As shown in Table II, we obtain $A_{metal,SFR} = 0.996 \pm 0.002$ and $A_{metal,GPR} = 0.969 \pm 0.01$. For both systems, a time drift is observed inherent to the electronic stability. It means that the calibration reference value of 1 is valid at a given time and varies during the experiment. In other words, any measurement in the field at a given location would require a calibration. Actually, such process is impossible on site: engineers that control thickness on roads use to perform one or two calibration points before the whole measurement, trusting in their device performances. And fortunatly this methodology works for thickness measurement because the time drift is low enough to allow an accurate thickness estimation: if we consider the above mentionned mean value of amplitude for both systems, the error on thickness measurement would be respectivelly 0.4% and 3%. For example, the thickness we would calculate for both SFR and GPR systems on an HMA of 5 cm would be 4.98 cm and 4.85 cm, respectivelly. Such difference is not significant for thickness measurement. This is not the case for assessing the density/compaction. Let us consider the mix design given in Table I, with a given aggregate permittivity $\epsilon_a = 5.5$. Then the HMA permittivity, density and compaction we would deduce at a given location taking account for the calibration value shown in the Fig.1a) are respectively displayed in the Fig.1b, c and d. We see that the time drift has a minor influence on permittivity assessment, but leads to major error in density and compaction assessment. This basic study clearly demonstrates how the SFR performances system overcome the classical GPR system in terms of signal stability, and hence, for compaction assessement.

TABLE II
MEAN, STANDAR DEVIATION, MAXIMUM AND MINIMUM VALUS OF THE REFLECTION MODULUS OF A METAL PLATE MEASURED DURING 1-HOUR MONITORING PERIOD WITH THE SFR AND GPR SYSTEMS RESPECTIVELY AND THE RESPECTIVELY DEDUCED PERMITTIVITY, COMPACTION AND DENSITY GIVEN THE HMA DESIGN IN TABLE I

	Val.	A_{metal}	$\epsilon'_{surface}$	C	$\rho(g/cm^3)$
SFR	Mean	0.996	4.544	0.913	2.249
	Std	0.002	0.013	0.002	0.006
	Min	0.994	4.516	0.908	2.236
	Max	1	4.563	0.917	2.258
GPR	Mean	0.969	4.759	0.953	2.349
	Std	0.010	0.081	0.015	0.037
	Min	0.955	4.550	0.910	2.246
	Max	1	4.926	0.984	2.424

III. CASE STUDY: COMPACTION ESTIMATION ON NEW ROAD WITH SFR SYSTEM COMPARED WITH STANDARD TESTS.

A. Site location and HMA materials description

The studied road is located in Cagny (Normandy, France) and is connected to the highway A13. It is a new paved-road. The mix design of the first layer whose compaction is assessed in this work, is presented in the table **??**. A B-scan obtained

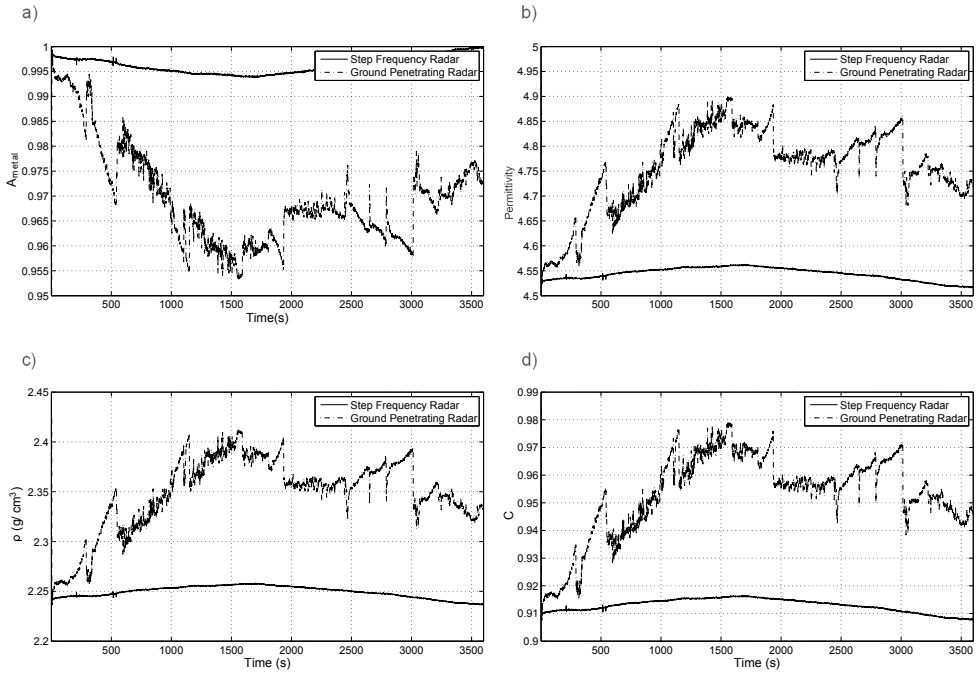


Fig. 1. a) Monitoring of the normalized amplitude reflected on a flat metal plate during one hour (1 meas/s) with the SFR and the GPR systems.b) Assessed permittivity on a given HMA, considering the calibration values from a). c) and d) are respectively the density and the compaction we would obtained at a given point on a given HMA at various time during one hour. We see the GPR drift leads to major over-estimation of density/compaction.

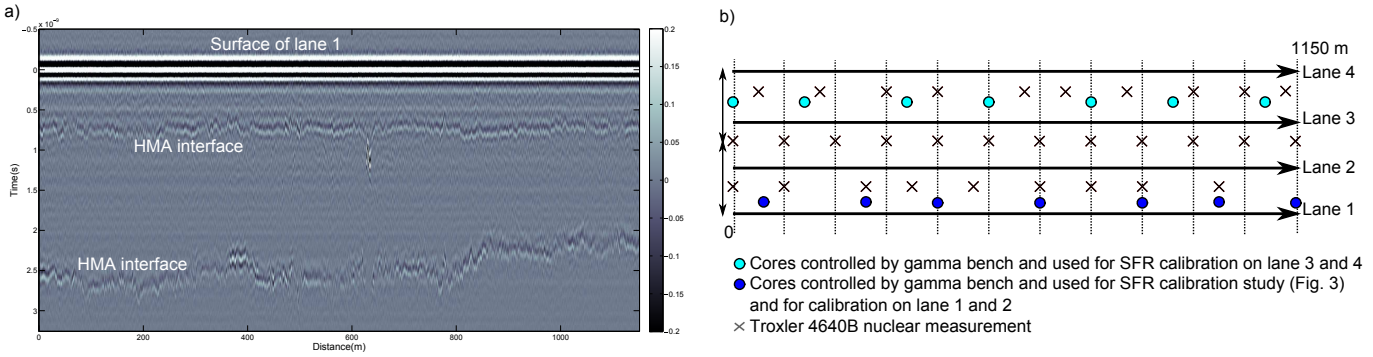


Fig. 2. a) B-scan performed on the tested road of Cagny. The estimated compaction in the present work concerns the first layer between 0 and 1 ns. The B-scan shows two road layers. The respective designed thicknesses are approximately 6 cm and 15 cm. b) Sketch of SFR profiles, core and nuclear testing locations.

during the road survey with our vehicle-mounted SFR system is shown in the Fig.2,a. The SFR profiles were realized on four lanes of 1150 m length. Additional measurements were performed with a commercial pavement density nuclear gauge (Troxler Model 4640, [4]) which measures the bask-scattered gamma radiation from the pavement surface. At the end of the experiment, HMA cores were extracted from the pavement surface at a distance less than 2 m from where the SFR and Troxler measurements were made. These cores were then used at the laboratory to determine the HMA compaction from gamma bench measurement [3]. The sketch of the SFR survey and standard tests locations is shown in the Fig.2,b.

As discussed below in section B, the joint knowledge of the HMA compaction with the gamma bench and of the HMA real relative permittivity with the SFR system will help us in the calibration of the HMA relative permittivity model, provided the other quantities in eq.4 are known. These quantities are the permittivity of the filler and bitumen which enter systematically into the HMA design in the considered region. The permittivity of these materials is consequently known and already referenced in a permittivity database [21]. The permittivity of the rock aggregates has to be evaluated since the quarry origin of 20% of rock aggregates is unknown (recycled aggregates). To know it, a calibration process is

required.

B. Calibration process

In order to explain the calibration process, the following example deals with some local SFR measurements performed every 50 m along a 1150 m profile in stactic mode and by considering seven cores realized at close locations. These calibration points are shown as dark blue circles in Fig.2,b. At these locations, a first estimation of the HMA compaction was first done from eq.4, knowing the HMA permittivity from the onsite SFR measurements (according to es. 8and using data from Table I. At this stage we uesd a value of $\epsilon_a = 5.78$ from the rock aggregate permittivity as given by our rock permittivity database. In the following, this estimated compaction will be denoted as $C_{SFR-noCal1}$. Then the permittivity of the aggregate was considered as a free parameter and calibrated in order to best fit the modelled compaction obtained from SFR permittivity (using eq.4) and in-lab gamma-bench measured compaction from gamma-bench measurements [3] of on-site extracted cores close to these locations.The best-fitted value was $\epsilon_a = 5.47 \pm 0.01$. In the following, the new estimated compaction will be denoted as $C_{SFR-Cal}$.

The assessed compaction for different scenario are shown in Fig. 3. $C_{SFR-noCal2}$ is the same as $C_{SFR-noCal1}$ but considers the height variations corrections during the survey, as described in the section II-D. $C_{SFR-Cal}$ is the compaction corrected with calibration. $C_{\gamma Nuclear}$ is the compaction given by the Troxler nuclear gauge illustrated in Fig. 2,b. $C_{\gamma Bench-Core}$ is the compaction controlled in the laboratory with the gamma bench standard method at the seven calibration points previously described. The error bars refer to the standard deviation calculated from the gamma-bench compaction on the cores. The results show that a wrong initial value of the permittivity aggregates leads to a major error in the SFR-estimated compactions, that height variations corrections cannot compensate. The calibration process formerly described shows that the expected compactions can be assessed on the whole profile provided that the permittivity of the unknown aggregate entering the mixture can be calibrated on the basis of gamma-bench estimated HMA compactions through cores extracted at point locations

C. Estimation of compaction on the four lanes case study

In this section, the SFR estimated HMA compaction is achieved from SFR measurements in an active mode, i.e. SFR measurements are performed every 0.5m, along each 1050 m lane and by following the same procedure as described in the previous section. Hence during the survey, the compaction of lanes 1 (Fig.4,a), and 2 (Fig.4,b) and lanes 3 (Fig.4,c) and 4 (Fig.4,d) are respectivelly deduced from the calibration values of cores shown in dark and light blue circles in the Fig.2,b. For each calibration undertacken along the four lanes, we obtain the following aggregates permittivity results reported in Table III with an averaged value $\epsilon_a = 5.50 \pm 0.01$. A difference between the static and dynamic mode retrieved aggregates permittivity value on lane 1 can be observed which could be mainly dure to the intergration over greater surface in dynamic mode as the analyser sweeps the frequency band than in static mode. Nevertheless, the mean aggregate permittivity relative to the four measured lanes ($\epsilon_a = 5.37 \pm 0.01$) are very close to the aggregate permittivity dedueced from the local calibration ($\epsilon_a = 5.47 \pm 0.01$). The SFR estimated HMA compaction

TABLE III
PERMITTIVITY OF AGGREGATES ESTIMATED FROM CORES AND SFR MEASUREMENTS CALIBRATION

	ϵ_a
lane 1	5.24 ± 0.01
lane 2	5.60 ± 0.01
lane 3	5.31 ± 0.01
lane 4	5.33 ± 0.01
Mean	5.37 ± 0.01

$C_{SFR-Cal}$ shown in Fig.4 is then deduced from SFR measuremenst performed every 0.5 m. A moving average of 10 m is applied in order to best-visualize the results and smooth noisy effects due to rough surface conditions and depth-varying density due to compaction HMA implementation. The in-lab and onsite compactions are respectivelly related to the gamma bench results and nuclear gauge measurements and are represented as top-oriented triangles with error bars and bottom oriented triangles. The global results are detailled in Table IV. The standard deviation of the assessed compaction is about 2% and 3% and is based on the relative error of the measured permittivity (3%) with our SFR system ([10], p.116) calibrated on paraffin slabs samples. The assessed compaction follows the local compaction estimated with standard tests in the laboratory and is lower than the compaction estimated with the onsite standard nuclear tests. The Fig.4 clearly shows that the estimated compaction with SFR system provides results as accurate as the standard methods. The main outcome is the higher density of measurements and the non-destructive compaction assessment provided by the SFR system.

TABLE IV
COMPACTION RESPECTIVELY ASSESSED WITH SFR, GAMMA TROXLER GAUGE ON SITE AND NUCLEAR BENCH IN THE LAB.

	Val.	Lane 1	Lane 2	Lane 3	Lane4
SFR	Mean	0.904	0.884	0.911	0.910
	Std	0.028	0.023	0.025	0.031
	Min	0.846	0.840	0.862	0.839
	Max	0.972	0.941	0.966	0.965
Cores	Mean	0.900		0.896	
	Std	0.014		0.019	
	Min	0.878		0.87	
	Max	0.923		0.927	
Nuclear	Mean	0.924		0.928	0.923
	Std	0.014		0.012	0.006
	Min	0.906		0.903	0.911
	Max	0.951		0.956	0.933

IV. CONCLUSION

The main objective of this work was to show the ability of a field SFR system to assess the HMA compaction in order

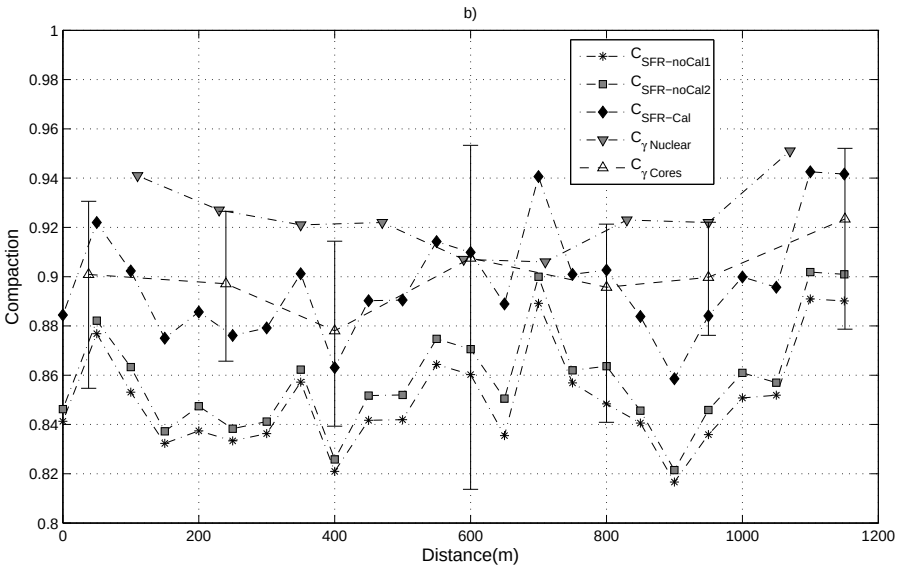


Fig. 3. Compaction calculated at calibration points. $C_{SFR-noCal1}$ and $C_{SFR-noCal2}$ are respectively the compactions without and with antenna correction and $\epsilon_a = 5.78$. $C_{SFR-Cal}$ is the compaction with an adjusted aggregate permittivity tacking account the unknown origin of recycled aggregates $\epsilon_a = 5.47$. $C_{\gamma Nuclear}$ and $C_{\gamma Bench-Core}$ are respectivley the controlled compaction with the on-site nuclear and in-the-lab cores mehtods.

to replace the destructive testings and nuclear testings usually performed. We showed the permittivity model parameters used needed to be first calibrated from local measurements of both HMA permittivity with the SFR system and compaction from standard test on onsite extracted cores. Additional corrections of the vehicle-mounted antenna height variations during the survey were also needed. Such a calibration process lies in the unknown content of recycled aggregates that often compound the new-paved HMA. Under this latter consideration, this work has shown how SFR electromagnetic system could replace in an efficient way the standard tests for HMA compaction. Further studies will have to be performed in order to consolidate the developed method.

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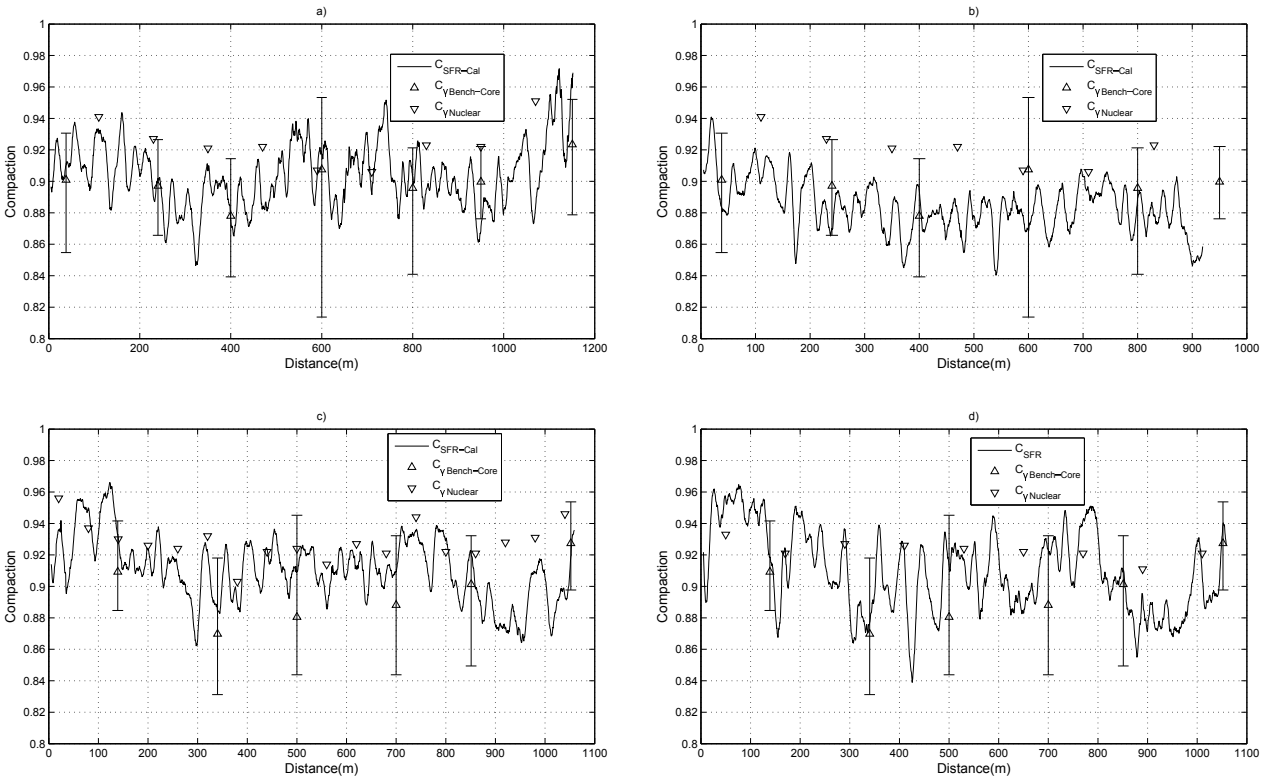


Fig. 4. Compaction $C_{SFR-Cal}$ estimated with the SFR system compared with the compaction $C_{\gamma Nuclear}$ obtained via nuclear test on cores [3] and the compaction $C_{\gamma Bench-Core}$ measured with the Troxler test. Figures a), b), c) and d) refer respectively to the measurement performed on lanes 1, 2, 3 and 4 shown in the Fig. 2,b.

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