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FACTORS AFFECTING VARIANCE AND BIAS OF NON-NUCLEAR DENSITY GAUGES FOR POROUS EUROPEAN MIXES AND DENSE-GRADED FRICTION COURSES

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Abstract. It is well known that the implementation of contractor quality control/agency quality assurance (QC/QA) can support quality improvements in hot mix asphalt (HMA) pavements, both for porous European mixes (PEMs) and dense-graded friction courses (DGFCs). On the other hand, many reasons and reports highlight the importance of proper in situ air voids content, due to major influence on service properties (rate of rutting, fatigue life, structural strength, permeability, ravelling, etc.). Another relevant standpoint is that in-lab determinations of density, though often reliable and accurate, are low-speed tests. All these facts outline the potential role of field measurement of density through non-nuclear density gauges. In the light of the above facts, the main object of the paper was confined as the study of factors affecting variance and bias of non-nuclear density gauges both for PEMs and DGFCs. Bias, variance and parameters' dependence resulted to be appreciably affected by mix typology and characteristics. In particular, when related to mix type, monovariate regressions with low-speed methods resulted able to provide a useful tool in QC/QA procedures and road asset management. Further practical applications have been outlined.

Keywords: quality assurance, quality control, non-nuclear density gauge, porous European mix (PEM), dense-graded friction course (DGFC).

1. Problem statement

Quality assurance (QA) programs have an outstanding importance to ensure that materials and procedures are satisfactory for obtaining adequate life cycle performance (Burati *et al.* 2003; Kashevskaya 2007; Petkevičius, Christauskas 2006; Petkevičius *et al.* 2006).

On the other hand, the link between pavement in-situ density (as quality measure) and service life is assessed both on a theoretical and experimental point of view (Brown *et al.* 2004; Harrigan 2002; Kennedy *et al.* 1990; Poulikakos *et al.* 2004). According to many contracts, in situ density (measured on cores) must be at least 95–97% of the laboratory density obtained, for example, through gyratory (100 gyrations for DGFCs or 50 gyrations for PEMs) or Marshall compaction (75 blows per face – DGFCs or 50 blows per face – PEMs).

Similarly, in other contracts (Spellerberg, Savage 2004), the relative density (bulk on max specific gravity) is the key-factor in judging the performance and in controlling the constructions of HMA pavements. In-lab determinations of density (dimensional, parafilm, vacuum sealing, saturated surface dry, etc), though often reliable and accurate, when applicable, present the drawback of low-speed surveys. In the light of the above facts, many research and technological efforts have been directed to nuclear and non-nuclear portable devices. In particular, non-nuclear density gauges (constant voltage, electrical impedance approach) have been evaluated under many projects (Kvasnak *et al.* 2007).

As far as non-nuclear devices are used to assess HMA courses quality, more specific problems arise. Some of them relate to the problem of measurement reliability in the case of open graded mixtures (such as the PEMs), or dense graded (such as the DGFCs), and therefore to the metrological performance in a very large range of densities (from 1.9 g/cm^3 up to 2.4 g/cm^3). Another issue is a possible deflection or modification of the electromagnetic field due to micro-layers of water beneath the surface layer or due to temperature effects. Moreover, a probable alteration of the electromagnetic field could be associated with the open structure of PEMs.

In the light of the above facts, the main object of the paper was confined to the study of factors affecting variance and bias both for PEMs and DGFCs.

Next section addresses the design of experiments, while in section 3 results are reported and discussed.

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2. Experimental plan

In the design of experiments, the project selection was based on mix design and pavement design factors and consisted of 3 projects, some of which entailed multiple paving days but the same job mix formulas.

As a consequence, this made up 3 different mix designs, of which 2 mix designs involving paving over 2 days.

In order to pursue the above-mentioned objectives, the following main variables have been considered in the project:

- densities P_J (g/cm^3): density measured by a portable non-nuclear density gauge, where $J = U$ stands for un-clustered, $J = CE$ for central, and $J = CL$, for clustered, i.e. as average of 5 cluster points, 1 at the centre, and 4 at corner points (Kvasnak *et al.* 2007);
- core specific gravities, G_{mb} (dimensionless, g/g): G_{mbdim} (dimensional method), G_{mbpar} (parafilm method), G_{mbcor} (vacuum sealing method), estimated according to the algorithms and standards specified in Table 1. In the dimensional method, the volume is based on height and diameter/width measurements. Surface irregularities (i.e. the rough surface texture of a typical specimen) introduce inaccuracy.

Parafilm method determines the volume according to the water displacement principle but uses a thin paraffin film to wrap the specimen. However, in practice, the film application may be quite difficult and test results can be inconsistent.

Vacuum sealing method (VSD) calculates specimen volume like the parafilm method but uses a vacuum chamber to shrink-wrap the specimen in a high-quality plastic bag.

Note that all the cores have been extracted from the location *CE* above-mentioned:

- *W* (%): moisture readings for the HMA layer, measured by the portable non-nuclear density gauge;
- W_{OA} (%): moisture readings in the open air, derived from a meteorological station in the area of survey, for the given hours;
- *T* (°C): temperature readings for the HMA layer, measured by the portable non-nuclear densimeter;
- T_{OA} (°C): temperature readings in the open air, derived from a meteorological station in the area of survey, for the given hours;
- *WI* (m/s): wind readings in the open air, derived from a meteorological station in the area of survey, for the given hours;
- *M*: mix type (two typologies have been taken into account: PEMs and DGFCs);
- *L*: lot of the particular mix type (for example, PEM I means the 1st lot of PEMs);
- *D*: day of measurements (for example, day1);
- γ_g (g/cm^3): apparent specific gravity of aggregates, determined according to B.U. CNR n. 63/78 and UNI EN 1097/3:1999;
- *NMAS* (mm): Nominal Max Aggregate Size (NMAS), i.e. sieve size one size larger than the 1st sieve to retain more than 10% of the material. Two NMASs have been considered: 10 mm, 19 mm.

The reference density measurements used were the density measurements from cores. Reasons for this rely on the importance of cores density in European contracts. Further, it is important to remark that many studies confirm that G_{mbcor} results the most reliable among the three considered methods (Cooley *et al.* 2002; Crouch *et al.* 2003).

Table 1. Main procedures for G_{mb} determination

Indicator	Algorithm	Standard
G_{mbdim} (dimensional)	$\frac{A}{V_{Geom}\gamma_w}$	AASHTO T 269
G_{mbpar} (parafilm)	$\frac{A}{D'-E'-\frac{D'-A}{F}}$	ASTM D 1188 (abs > 2%)
G_{mbcor} (vacuum sealing device)	$\frac{A}{B'-E'-\frac{B'-A}{F_t}}$	ASTM D 6752

Note: *A* – mass of the dry specimen in air; abs > 2%: absorption more than 2%; *B* – mass of saturated-surface-dry specimen in air; *B'* – mass of dry and sealed specimen; *C* – mass of HMA sample in water; *D'* – mass of the dry, coated specimen; *E'* – mass of sealed/coated specimen under water; *F* – specific gravity of the coating determined at 25°C; F_p – specific gravity of the paraffin at 25°C; F_t – apparent specific gravity of plastic bag; G_{mb} – bulk specific gravity; V_{Geom} – geometric volume of HMA sample; *VSD* – vacuum sealing device; γ_w – density of water.

3. Results

Tables 2–6 and Figs 1–16 summarize the obtained results. In Table 2 the main statistics (average, standard deviation, coefficient of variation *CV*) of the dependent (P_J) and independent (T, T_{OA}, W_{OA}, γ_g, *NMAS*, *WI*) variables are provided, together with G_{mbcor}.

Regarding the main statistics, it is possible to say that when G_{mbcor} increases (i.e. in the transition from PEMs to DGFCs), generally P_J (in particular P_{CE}) increase in terms of averages, standard deviations and coefficients of variation, while aggregate specific gravities decrease, due to the fact that, for the selected projects, the design aggregate source was basalt (igneous rock) for PEMs and limestone (sedimentary rock) for DGFCs. Similarly, when G_{mbcor} increases, *NMAS* decreases, due to the fact that the for the selected projects, *NMAS* was 19 mm for PEMs (thickness of the layer 50 mm ca.) and 10 mm for DGFCs (thickness of the layer 30 mm ca.). Averages range from 1.8 g/cm^3 (very open PEMs) up to 2.2 g/cm^3 (DGFCs).

Water content (*W*) results usually lower for PEMs than for DGFCs.

Table 2. Main statistics (averages, standard deviations and coefficient of variations)

	PEM I	PEM II					PEM	DGFC				All mixes
	day 1	day 1	day 2	day 3	day 4			day 1	day 2	day 3		
						Average						
P_{CL}, g/cm^3	1.92	1.89	1.89	1.90	1.88	1.89	1.90	2.19	2.02	2.02	2.05	1.95
P_U, g/cm^3	1.92	1.89	1.89	1.90	1.89	1.89	1.90	2.19	2.02	2.02	2.05	1.94
P_{CE}, g/cm^3	1.92	1.89	1.89	1.90	1.89	1.89	1.90	2.20	2.03	2.02	2.05	1.95
W, %	12.85	19.95	4.96	6.93	5.90	6.00	7.83	19.09	16.18	15.53	16.45	10.68
T, °C	19.20	34.26	42.39	39.88	32.10	37.66	32.73	27.05	23.84	21.86	23.78	29.77
T_{OA}, °C	14.66	21.00	20.47	20.35	19.50	20.40	18.86	17.71	17.65	16.31	17.28	18.34
W_{OA}, %	65.54	78.00	81.57	75.37	85.95	79.20	75.56	74.18	67.57	81.55	72.58	74.57
γ_g, g/cm^3	2.86	2.86	2.88	2.87	2.87	2.87	2.87	2.77	2.71	2.76	2.73	2.83
$NMAS$, mm	19.00	19.00	19.00	19.00	19.00	19.00	19.00	10.00	10.00	10.00	10.00	16.03
G_{mbdim}	1.78	1.83	1.85	1.86	1.85	1.85	1.83	2.09	2.05	1.95	2.04	1.85
G_{mbpar}	1.87	1.92	1.92	1.90	1.94	1.92	1.90	2.12	2.09	2.03	2.08	1.95
G_{mbcor}	1.95	1.96	2.00	2.01	2.01	1.99	1.98	2.17	2.13	2.08	2.12	2.00
WI, m/s	6.03	6.91	4.74	4.65	5.41	5.38	5.55	5.99	3.97	5.10	4.61	5.24
						Standard deviation						
P_{CL}, g/cm^3	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.18	0.11	0.15	0.15	0.11
P_U, g/cm^3	0.04	0.03	0.02	0.02	0.03	0.03	0.03	0.19	0.11	0.15	0.15	0.11
P_{CE}, g/cm^3	0.04	0.03	0.02	0.02	0.03	0.02	0.03	0.19	0.11	0.15	0.15	0.12
W, %	1.60	15.13	1.08	1.11	0.89	1.32	3.34	5.02	4.04	4.94	4.58	5.55
T, °C	3.28	6.50	7.33	6.12	4.46	7.31	10.43	3.12	2.91	4.02	3.66	9.75
T_{OA}, °C	0.76	0.00	0.42	0.48	0.14	0.60	2.62	0.47	1.40	1.00	1.33	2.40
W_{OA}, %	8.40	0.00	3.28	3.93	1.19	4.77	8.48	1.88	8.51	3.64	9.06	8.78
γ_g, g/cm^3	0.02	0.04	0.04	0.01	0.02	0.03	0.03	0.00	0.02	0.04	0.04	0.07
$NMAS$, mm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.24
G_{mbdim}	0.06	0.05	0.04	0.05	0.07	0.05	0.06	0.10	0.03	0.13	0.08	0.08
G_{mbpar}	0.05	0.05	0.04	0.05	0.06	0.04	0.05	0.08	0.04	0.09	0.07	0.10
G_{mbcor}	0.04	0.03	0.03	0.05	0.05	0.04	0.05	0.07	0.03	0.10	0.06	0.07
WI, m/s	2.00	0.24	0.33	0.79	0.29	1.07	1.41	0.47	0.83	0.54	1.05	1.37
						Coefficient of variation						
P_{CL}, g/cm^3	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.08	0.05	0.08	0.07	0.06
P_U, g/cm^3	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.09	0.06	0.08	0.07	0.06
P_{CE}, g/cm^3	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.09	0.06	0.08	0.07	0.06
W, %	0.12	0.76	0.22	0.16	0.15	0.22	0.43	0.26	0.25	0.32	0.28	0.52
T, °C	0.17	0.19	0.17	0.15	0.14	0.19	0.32	0.12	0.12	0.18	0.15	0.33
T_{OA}, °C	0.05	0.00	0.02	0.02	0.01	0.03	0.14	0.03	0.08	0.06	0.08	0.13
W_{OA}, %	0.13	0.00	0.04	0.05	0.01	0.06	0.11	0.03	0.13	0.04	0.12	0.12
γ_g, g/cm^3	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02
$NMAS$, mm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26
G_{mbdim}	0.04	0.03	0.02	0.03	0.04	0.03	0.03	0.05	0.02	0.07	0.04	0.05
G_{mbpar}	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.04	0.02	0.04	0.03	0.05
G_{mbcor}	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.01	0.05	0.03	0.03
WI, m/s	0.33	0.03	0.07	0.17	0.05	0.20	0.25	0.08	0.21	0.11	0.23	0.26
						G_{mbcor}/P						
averages	1.02	1.04	1.06	1.06	1.06	1.05	1.04	0.99	1.05	1.03	1.03	1.03
St. dev	1.11	1.13	1.13	2.23	1.89	1.78	1.52	0.38	0.24	0.64	0.43	0.60
CV	1.09	1.09	1.07	2.11	1.77	1.69	1.46	0.38	0.23	0.62	0.41	0.58

Note: P_J values (P_{CE}, P_U, P_{CL}) result similar as far as averages are considered.

Though the appreciable variance, this fact could be related to the different characteristics of water dispersion between PEMs (high) and DGFCs (low).

Of course, meteorological parameters (T_{OA}, W_{OA}, W) confirm independence from mix type.

Moreover, both for PEMs and DGFCs, G_{mbcor} is usually higher than P_{CE} (3~4%, Fig. 1 and Table 2). The coefficient of variation of P_{CE} is lower than that of G_{mbcor} for PEMs, while it has an appreciable increase for DGFCs.

Table 3 and Figs 2, 3 show the R-square values obtained in the case of monovariate correlations, while in Figs 4–9 main scatter plots are reported (the dotted line in Fig. 4 refers to the line of equality).

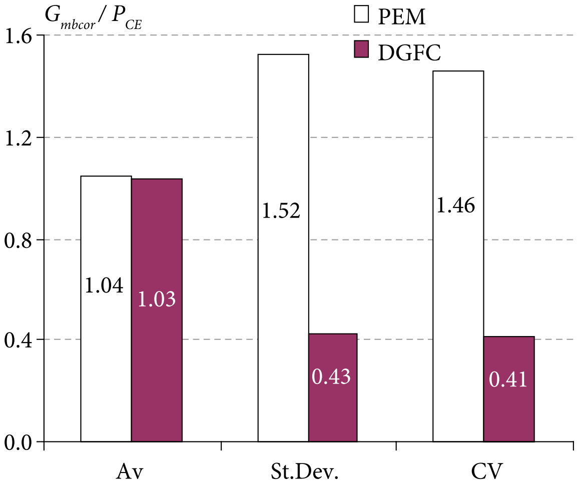

Fig. 1. Main statistics of P_{CE} and G_{mb} compared

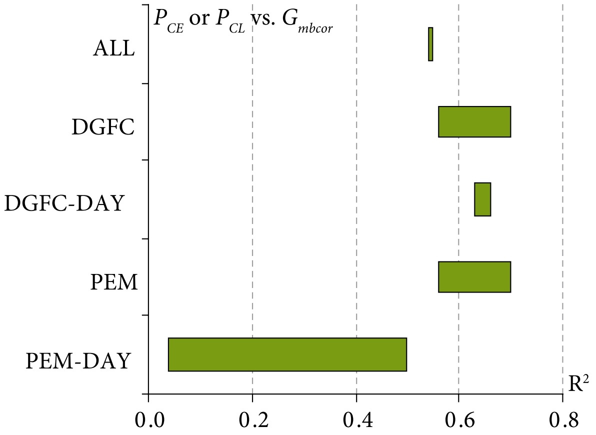

Fig. 2. R-square values of the correlations P_J vs. G_{mbcor}

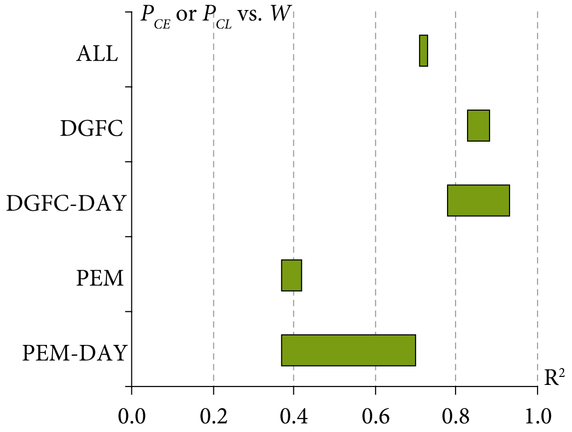

Fig. 3. R-square values for the regressions P_J vs. W

Table 3. R-square values (all the mixes)

	All mixes											
	P_{CL}	P_{CE}	G_{mbdim}	G_{mbpar}	G_{mbcor}	W	T	WI	W_{OA}	T_{OA}	γ_g	$NMAS$
P_{CL}	1.00	0.96	0.52	0.75	0.54	0.71	0.06	0.01	0.05	0.05	0.29	0.40
P_{CE}	0.96	1.00	0.52	0.75	0.54	0.73	0.06	0.01	0.04	0.05	0.28	0.38
G_{mbdim}	0.52	0.52	1.00	0.91	0.87	0.14	0.04	0.05	0.00	0.06	0.27	0.46
G_{mbpar}	0.75	0.75	0.91	1.00	0.93	0.42	0.00	0.19	0.00	0.02	0.57	0.66
G_{mbcor}	0.54	0.54	0.87	0.93	1.00	0.24	0.00	0.09	0.01	0.01	0.31	0.46
W	0.71	0.73	0.14	0.42	0.24	1.00	0.32	0.02	0.18	0.36	0.45	0.53
T	0.06	0.06	0.04	0.00	0.00	0.32	1.00	0.00	0.14	0.62	0.19	0.19
WI	0.01	0.01	0.05	0.19	0.09	0.02	0.00	1.00	0.01	0.01	0.06	0.11
W_{OA}	0.05	0.04	0.00	0.00	0.01	0.18	0.14	0.01	1.00	0.11	0.08	0.03
T_{OA}	0.05	0.05	0.06	0.02	0.01	0.36	0.62	0.01	0.11	1.00	0.06	0.10
γ_g	0.29	0.28	0.27	0.57	0.31	0.45	0.19	0.06	0.08	0.06	1.00	0.81
$NMAS$	0.40	0.38	0.46	0.66	0.46	0.53	0.19	0.11	0.03	0.10	0.81	1.00

Regarding the correlations of P_J (i.e. P_{CE} or P_{CL}) and each of the remaining variables (G_{mb}, W, T, WOA, WI, TOA, γ_g, $NMAS$), it is possible to say that (Figs 2–9):

- the following main dependences can be considered very significant: P_{CL} (or P_{CE}) vs. G_{mb} (Table 3 and Fig. 4), P_{CL} (or P_{CE}) vs. W (Table 3 and Fig. 5), as for W_{OA}, T, WI and T_{OA} small correlations have been usually obtained (Table 3 and Figs 6–9);
- for PEMs, single day, R-square values (P_J vs. G_{mbcor}) range from 0.04 up to 0.50 and R-square values for P_J vs. W regressions range from 0.37 up to 0.66 (Figs 2 and 3);
- for DGFCs, single day, R-square values range from 0.64 up to 0.66 (P_J vs. G_{mbcor}), while, for P_J vs. W, R-square values range from 0.78 up to 0.91 (Figs. 2 and 3);
- if different days are considered, the explained variance can decrease by 2~6% for DGFCs, by 3~6% for PEMs-lot 1, of 0~32% by PEMs-lot 2; day-specifity (i.e. the dependence of data on the day of survey) results to be relevant for PEMs as far as P_J vs. W relationships are considered (Fig. 3). Such experimental evidences support the importance of daily calibrations, especially for PEMs. On the contrary, as far as more days, more lots are considered for PEMs, there is an improvement of density gauge performance (Fig. 2). Note that in general density gauge performance for DGFCs don't result day-specific (Figs 2, 3);
- as for R-square values among "independent" variables (W, W_{OA}, WI, T_{OA}, γ_g) it is possible to point out that they are usually uncorrelated. 3 exceptions can be listed: T vs. T_{OA} (due to the intrinsic meaning of T and T_{OA}); $NMAS$ vs. W (the lower $NMAS$, the higher W, probably due to an increased aptitude to detect surface phenomena and/or to high moisture contents for DGFCs); $NMAS$ vs. γ_g. In particular, Fig. 8, in which P_{CE} is compared to aggregate specific gravity, shows that for the selected sections of the project PEMs mixes had frequently high quality aggregates;
- dependence on W results to be day-specific both for PEMs and DGFCs, but this phenomenon is more evident for PEMs (Fig. 3); this fact could be the reason for the consequent day-specificity of relationships P_J – G_{mb} (Fig. 2).

The level of significance of correlations (all the mixes, p-values) is summarized in Table 4. The value reported in it 4 represents the probability of making the "wrong decision", i.e. a decision to reject the null hypothesis (the 2 variables are not correlated), when the null hypothesis is actually true (Type I error, or "false positive determination"). The smaller the p-value, the more significant the result is said to be. It is confirmed that: the "P_{CE} vs. G_{mb}" correlations are significant (at a 1% level of significance); T, WI, W_{OA} and T_{OA} are, in general, low significant for P_{CE}; the P_{CE} vs. W correlation is significant at a 1% level of significance.

Figs 10–15 refer to the coefficients obtained for the linear regressions involving P_{CE}. It is possible to observe that the coefficient a represents the 1st derivative and is intrinsically related to the R-square value, the coefficient b represents the value of P_{CE} if the water content (or G_{mb}) approaches the 0, i.e. if it becomes negligible. As far as P_{CE} and P_{CL} correlations with cores specific gravities are concerned, coefficients a_i and b_i results are quite similar (for this reason only P_{CE} coefficients are reported in the plots). Note that the higher the reference density (G_{mbcor}), the higher the variance and the coefficient of variation of P_{CE} (as above-observed in Table 2), the lower the constant (b) of the relationship P_{CE} vs. W (Figs 10 and 12), the higher the 1st derivative a of the relationship P_{CE} vs. W (Figs 10 and 13), the stronger the dependence on water content (W, Fig. 14) and, of course, the stronger the correlation with the effective density (Fig. 15).

Table 4. Correlation significance (all the mixes)

	P_{CL}	P_{CE}	G_{mbdim}	G_{mbpar}	G_{mbcor}	W	T	WI	W_{OA}	T_{OA}	γ_g	$NMAS$
P_{CL}		0.000	0.000	0.000	0.000	0.000	0.000	0.034	0.000	0.000	0.000	0.000
P_{CE}	0.000		0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000
G_{mbdim}	0.000	0.000		0.000	0.000	0.000	0.019	0.010	0.647	0.023	0.000	0.000
G_{mbpar}	0.000	0.000	0.000		0.000	0.000	0.986	0.000	0.681	0.275	0.000	0.000
G_{mbcor}	0.000	0.000	0.000	0.000		0.000	0.442	0.001	0.308	0.443	0.000	0.000
W	0.000	0.000	0.000	0.000	0.000		0.000	0.010	0.000	0.000	0.000	0.000
T	0.000	0.000	0.019	0.986	0.442	0.000		0.591	0.000	0.000	0.000	0.000
WI	0.034	0.029	0.010	0.000	0.001	0.010	0.591		0.041	0.676	0.000	0.000
W_{OA}	0.000	0.000	0.647	0.681	0.308	0.000	0.000	0.041		0.000	0.000	0.004
T_{OA}	0.000	0.000	0.023	0.275	0.443	0.000	0.000	0.676	0.000		0.000	0.000
γ_g	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000
$NMAS$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	

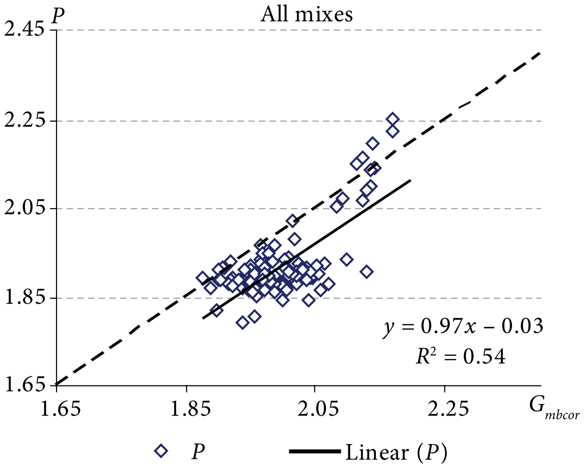

Fig. 4. P_{CE} vs. G_{mbcor}

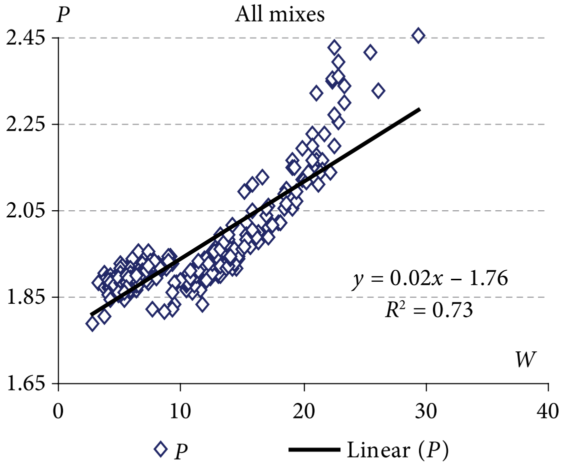

Fig. 5. P_{CE} vs. W

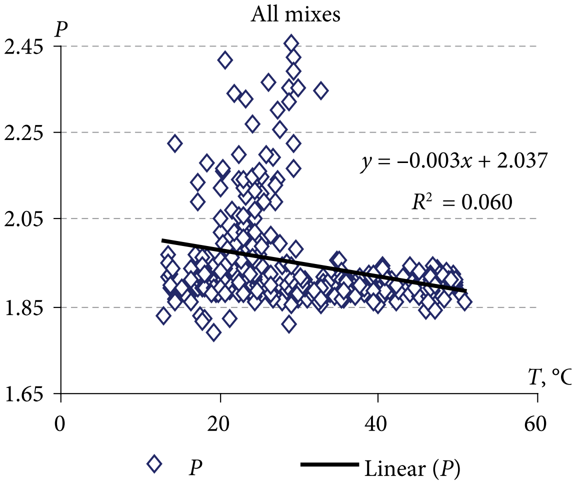

Fig. 6. P_{CE} vs. T

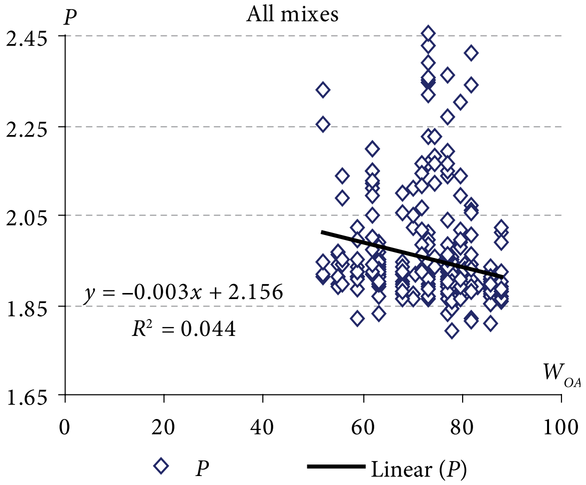

Fig. 7. P_{CE} vs. W_{OA}

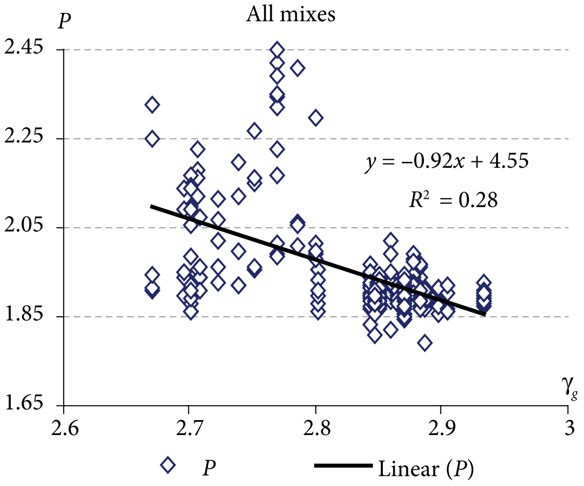

Fig. 8. P_{CE} vs. aggregate apparent specific gravity

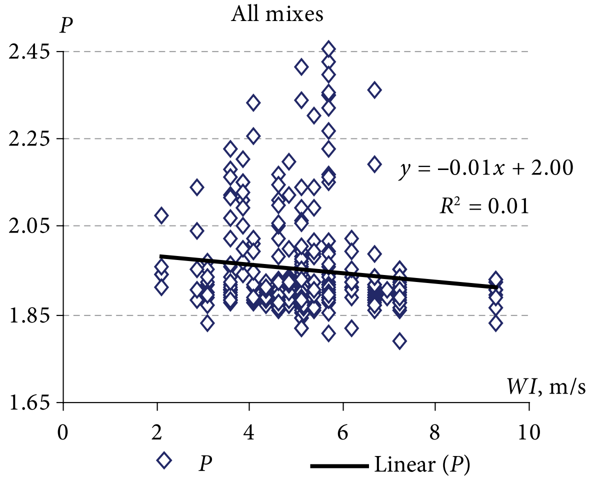

Fig. 9. P_{CE} vs. WI

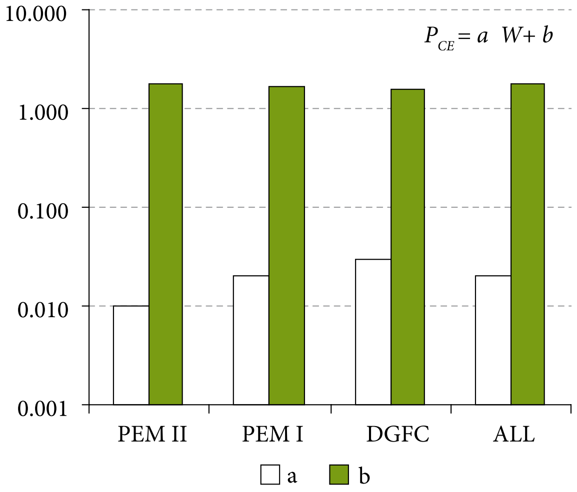

Fig. 10. P_{CE} vs. W: coefficients

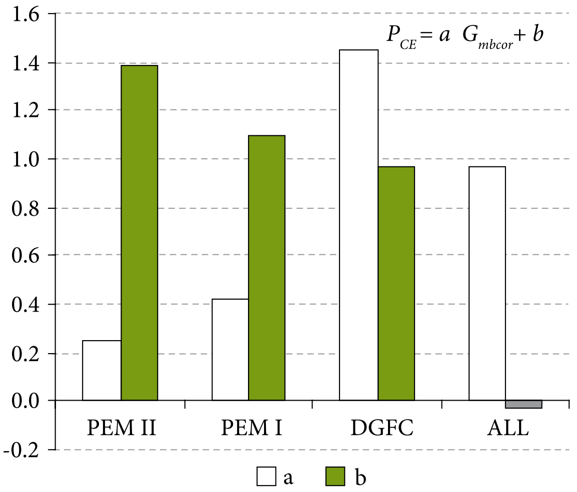

Fig. 11. P_{CE} vs. G_{mbcor}: coefficients

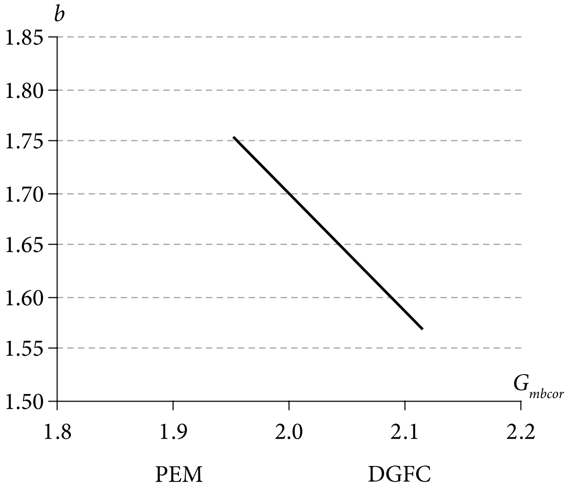

Fig. 12. Constant b of the correlation $P_{CE} = aW + b$

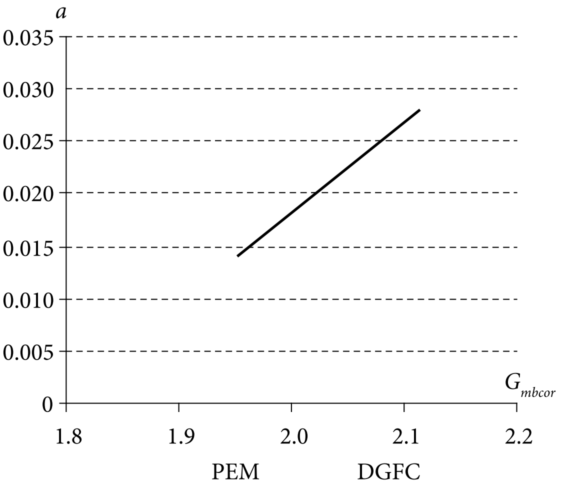

Fig. 13. 1st derivative a of the correlation $P_{CE} = aW + b$

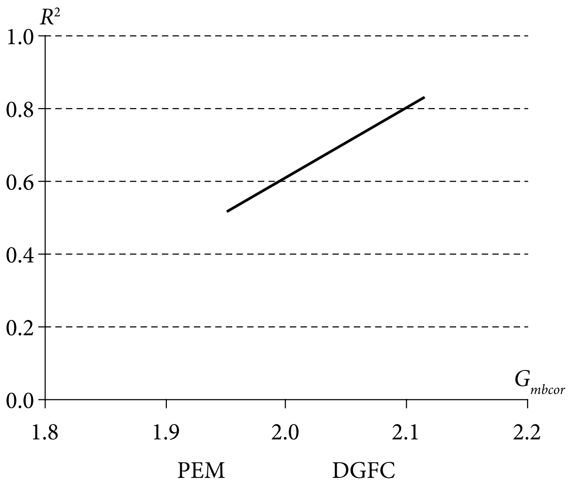

Fig. 14. R-square values of the correlation $P_{CE} = aW + b$

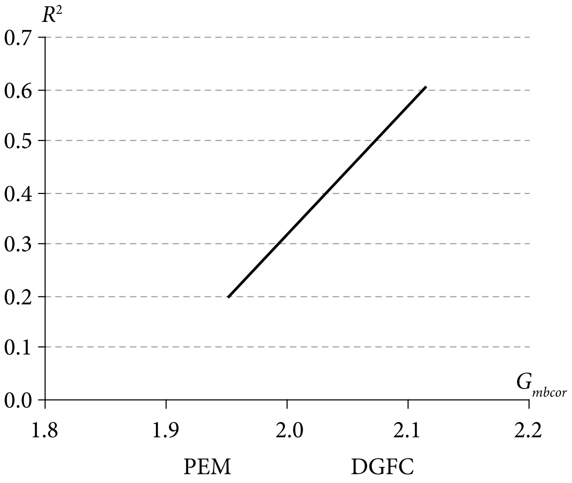

Fig. 15. R-square value of the correlation $P_{CE} = a_1\ G_{mbcor} + b_1$

The significance of such behaviour could rely in better performance (both for W and P measurement) as far as denser mixes (influence of mix typology) and "surface/interface" properties are concerned, probably due to the distribution of the electromagnetic field in the layer. Figs 14, 15 provide a synthesis of this issue.

Tables 5, 6 show monovariate and multivariate R-square values for each of the considered monovariate and multivariate models. Only linear equations have been considered. α, β, λ, μ and ε have been determined according to the least square method for each of the considered specific gravity (G_{mbdim}, G_{mbcor}, G_{mbpar}).

Table 5. 1st to 3th multivariate models

Model	Equation
Model (I)	$G_{mb} = P_{CE} + \alpha \times W + \beta \times T$
Model (II)	$G_{mb} = P_{CE} + \alpha \times W + \beta \times T + \varepsilon \times W_{OA}$
Model (III)	$G_{mb} = \mu \times P_{CE} + \alpha \times W + \beta \times T + \lambda$

As far as multivariate correlations between P_{CE} and G_{mb} are concerned (Table 6), it is possible to point out that the augmentation of R-square values due to the consideration of 1 or 2 additional independent variables (W or W and T) ranges from 5% up to 13% in terms of explained variance.

Table 6. Regressions G_{mb} vs. P_{CE}: R^2 values

Model	G_{mb}		
	G_{mbdim}	G_{mbcor}	G_{mbpar}
monovariate	0.52	0.54	0.75
PQI_{corr} (I)	0.65	0.64	0.80
PQI_{corr} (II)	0.64	0.64	0.80
PQI_{corr} (III)	0.66	0.65	0.80

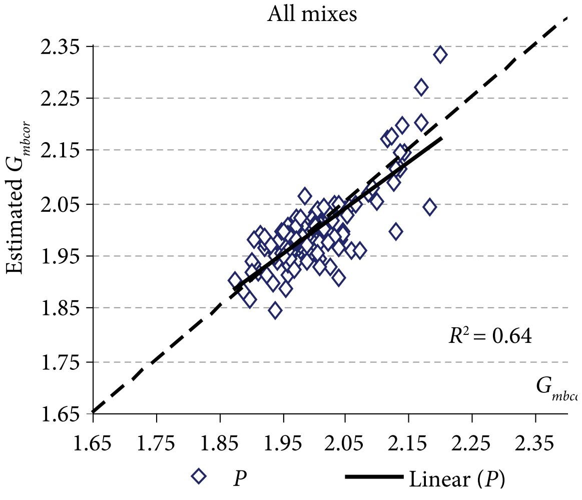

Fig. 16. Scatter plot of G_{mbcor} estimated (multivariate correlation – model I – y-axis) vs. G_{mbcor}

Fig. 16 shows the statistical performance of model (I). It is very interesting to observe that it is (model I Table 5):

$$\frac{\partial G_{mbcor}}{\partial P_{CE}} \approx 1.$$

4. Conclusions

It is well-known that high-speed, high precision, security and safety are key factors in QA/QC procedures and strategies.

In a context in which dense-graded and open-graded HMA courses do coexist, non-nuclear portable density gauges could be the answer to many contractor-agency controversies.

Putting at work new procedures in the aim to obtain better performance and lower costs still remains a challenge.

In the light of the obtained results the following conclusions can be drawn.

1. P_J values are greatly affected by water content. This fact can be crucial due to seasonal variations and calls for a better analysis and measurement of pavement moisture.
2. The interface between the gauge and the tested HMA layer is of primary importance: the denser and the dryer it is, the lower the bias, the better the correlation with reference core densities.
3. Mix type affects regressions coefficients and biases: the denser the mix, the better the performance even if the higher the dependence on water content.
4. Mix type, or better, mix density seems to affect greatly the variance of P_J as related to the variance of reference density (G_{mbcor}, for example): the denser the mix, the higher the variance. This fact could depend on the high sensitivity to the state of the surface layer.
5. Pavement temperature did not result in consistently affect density gauge performance.

As a practical application that is relevant to QC/QA procedures it is interesting to observe that at the end of each day the ratio P_{CE}/G_{mbcor} ranged from 1.02 up to 1.06 for PEMs and from 0.99 up to 1.05 for DGFCs.

Future research will aim to address a better understanding of the above-mentioned phenomena and their consequences on contractor and agency risks, through the consideration for other mix types and through the optimization of the experimental plan.

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