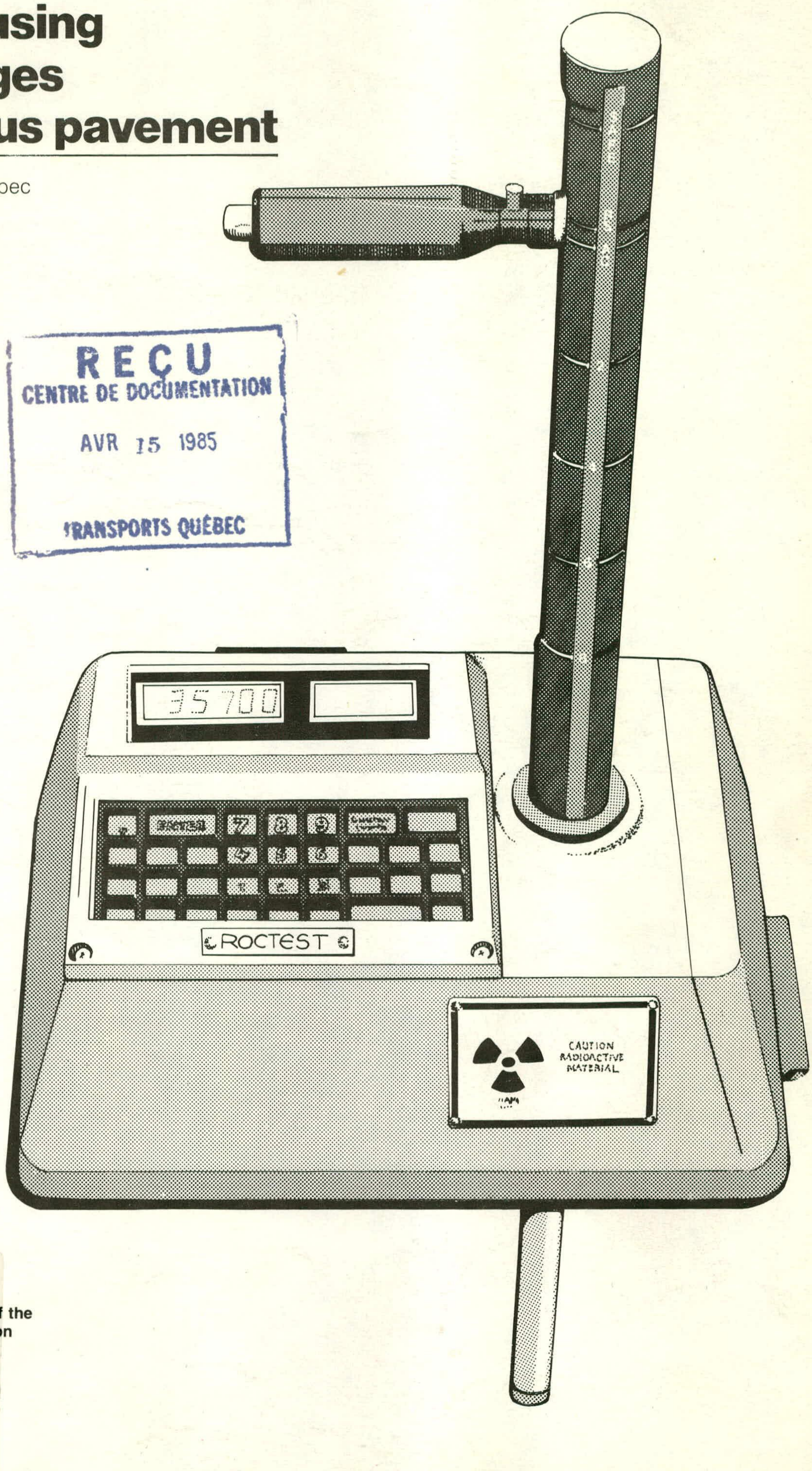
Methods of using nuclear gauges on bituminous pavement

Gouvernement du Québec
Ministère
des Transports



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ADDRESS
given at the 25th Annual Convention of the Canadian Technical Asphalt Association

Victoria, November 1980

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Sommaire

Après avoir évalué l'importance de l'utilisation des nucléodensimètres au Québec, au Canada et aux États-Unis, les auteurs traitent de principe de fonctionnement et des erreurs relatives à divers modèles d'appareil. Ils évaluent, par le fait même, les erreurs systématiques inhérentes à la technologie de ces appareils.

En 1979 et 1980, le ministère des Transports du Québec a utilisé des nucléodensimètres à titre expérimental pour déterminer la compacité des revêtements bitumineux. Un compte rendu de ces expériences est donné et conclut que leur emploi deviendra plus fiable si les variations causées par l'erreur de surface, l'erreur de composition des matériaux auscultés et la profondeur de pénétration des rayons gamma peuvent être contrôlées. Les auteurs font ressortir les imprécisions et les variations occasionnées par l'utilisation du sable comme agent correcteur de la rugosité de surface. Ils recommandent plutôt l'eau comme moyen de correction.

Une méthode pour utiliser les nucléodensimètres d'une façon fiable et juste sur les revêtements bitumineux est développée. Les erreurs de surface et de composition sont déterminées de façon précise et sont intégrées dans les calculs. Une calibration par voie humide doit être effectuée pour pouvoir utiliser l'eau comme agent correcteur. Cette nouvelle méthode permet d'atteindre un haut niveau de justesse dans la détermination de la masse volumique des revêtements bitumineux.

Summary

After an evaluation of the use of nuclear devices in Québec, Canada and United States, the authors deal with the theory of measurement and the errors of different types of gauges. They evaluate the systematic errors related to the technology of nuclear gauges.

In 1979 and 1980, the ministère des Transports du Québec used nuclear gauges on an experimental basis to determine the compaction of bituminous pavement. A report of these experiments is given and concludes that their use would be more reliable if the variations caused by the surface error, the composition error and the depth of gamma ray penetration could be controlled. The authors emphasized the inaccuracy of sand as a correcting agent of surface roughness. They recommend using water instead of sand.

A procedure for using nuclear gauges with accuracy is developped. The surface and composition errors are found with precision and are integrated into the calculation. A wet calibration curve must be determined to take into account the use of water as a correcting agent. This new method makes possible a high level of accuracy in the determination of bituminous pavement density.

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1.0 Introduction

Over the past 20 years, the use of nuclear gauges has increased considerably on construction sites. These devices, primitive and cumbersome to begin with, are becoming increasingly efficient and sophisticated. Techniques for use and calibration methods have also progressed. These instruments were first used on soils but have gradually been adapted for use in the field of bituminous concrete. However, comparatively few people have a thorough knowledge of the operating principles or the factors that can influence the values of the measurements obtained. Therefore, a team from the ministère des Transports du Québec conducted a study on these factors and their consequences, and many experiments have been undertaken to test the reliability of the instruments and the accuracy of the measurements they give.

2.0 Use of nuclear gauges in Québec

The MTQ bought its first nuclear gauges at the beginning of the 1960s, during the construction of the Trans-Canada highway, when a great deal of crushed stone was used for the foundations. Between 1972 and 1978, a few experiments were carried out on bituminous pavement, but no real results were obtained.

It should be noted that private firms are responsible for the quality control of 50% of all soil contracts and 65% of bituminous concrete laid by the MTQ. However, these companies are only authorized to use nuclear gauges for soil quality control. Contractors tend more and more to acquire these instruments in order to optimize their operations and carry out their own quality controls, a trend that meets with the MTQ's full approval.

In 1978, following the purchase by tender of eight of these devices of a new make, tests were carried out on various materials with the same model, before the instruments were accepted. Positive results were obtained and this was the beginning of a much vaster experimental program. The possession of an instrument we had never had before, one that had a special mode for AC (Asphalt Concrete) probes, encouraged us to extend our research in the field of bituminous concrete. The ultimate goal was to replace coring by a process that was not destructive and gave reliable results.

Table I shows the distribution of nuclear gauges in Québec in 1980. Of a total of 155 instruments, 60% belong to private laboratories.

It must not be forgotten that private firms are responsible for the quality control of 50% of soils and 65% of bituminous concrete laids by the MTQ. These companies are, however, authorized to use nuclear gauges only for soil surveys. There is now a tendency for contractors to obtain these instruments to optimize their operations and carry out their own surveys, a trend that has the MTQ's full approval.

Table I – Nuclear gauges in Québec in 1980

Agency	Troxler 2401	Troxler 3401	Troxler 3411	Troxler 3411B	CPN MC2	Sea-man	Total
MTQ	9	—	—	8	15	—	32
Private laboratories	41	16	26	6	4	—	93
Contractors	1	1	2	2	2	10	18
Others	3	4	3	1	1	—	12
TOTAL	54	21	31	17	22	10	155

3.0 Use of nuclear gauges in the United States and Canada

In March 1979, the MTQ sent to all the American states and the Canadian provinces a questionnaire on quality assurance with a view to setting up two fact-finding missions. The questionnaire includes some questions about bituminous concrete and nuclear gauges.

Forty-six of the 51 American states and 7 provinces, including Québec, replied. Table II gives questions and answers concerning the use of nuclear gauges and acceptance plans for bituminous concrete.

The answers obtained showed that the use of nuclear gauges is approximately the same in both countries. They are widely used for verifying soil density and to a lesser extent for bituminous pavement. In the latter case it seems that their use is largely experimental since most agencies also take cores. In Canada, all the provinces which responded stated that they used coring to determine pavement densities. It is clear that confidence in these devices is limited and doubts exist as to their reliability and the accuracy of the results they give.

Table II – Percentage of positive responses

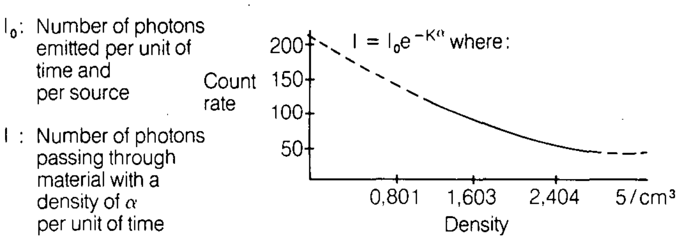
Subject	U.S.A.	Canada	U.S.A. & Canada
Acceptance plans and quality assurance for bituminous concrete are based on penalties	48	14	43
Soil density is measured by means of nuclear gauges	87	86	87
Density of bituminous pavement is measured by means of:			
(a) nuclear devices	72	71	72
(b) coring	72	100	75

4.0 Operating principle

In the design of an instrument using radioisotopes to measure density and moisture content, various components are assembled to constitute the geometry of the device. The choice and position of the radioactive sources, the detectors, the electronic unit and the mechanical parts vary depending on the make and model of the nuclear gauge.

Theoretical and practical studies were necessary in assembling all these components in order to apply the general principle of gamma ray absorption:

Figure I



Two methods for measuring density may be considered when using a nuclear gauge. The first is based on the phenomenon of backscattering and the second on that of direct transmission.

Figure II (a)

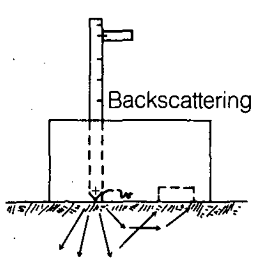
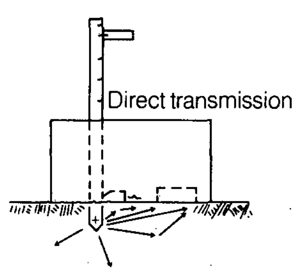


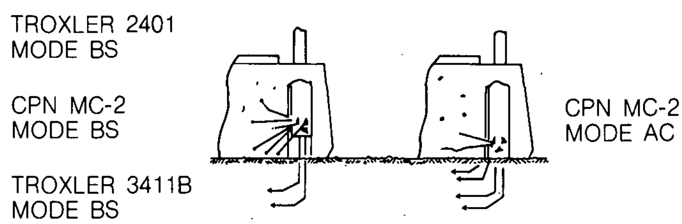
Figure II (b)



Using the general principle of gamma ray absorption requires that the high-energy photons (662 keV) from the source be picked up principally by the detectors. Thus, the measuring method presented in Figure II(a) is less accurate than the direct transmission method. Backscattering is more practical for use with bituminous concrete, while for soils direct transmission is preferable because of its greater accuracy. The source may be situated at 50.8 mm, 101.6 mm, 152.4 mm or 203.2 mm, depending on the thickness of the test material.

The ministère des Transports owns three different nuclear gauge models. Figure III shows the position of the source in these models when the count is taken from test material near the surface. The CPN MC-2 model has two modes for taking the count rate while the Troxler models have only one. It should be noted that the distance between the source and the base varies from model to model.

Figure III



In the area of soils, dry density is most often used for measuring, while in the case of bituminous concrete wet density must be used.

When the nuclear gauge gives a wet density count, gamma radiation penetrates all the chemical elements constituting the material: limestone, silica, hydrogen, hydrocarbon, etc. Thus, the water absorbed by the granular materials and the H^+ elements of asphalt and of certain mineralogical elements of the test material are incorporated in the count. If dry density were used complex corrective values would be required to take account of these factors.

Using the information contained in the manufacturers' instructions, we have been conducting further experiments on bituminous concrete since the spring of 1979.

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5.0 Experiments at Trois-Rivières, Québec and Sherbrooke

These experiments were conducted by the personnel of the Centres régionaux. The object was to see whether or not nuclear gauges could be used for the statistical evaluation of pavement sections according to the methods recommended by the companies. The information given in Table III summarizes the different kinds of experiments carried out.

Table III – Summary of experiments

Place Type of mix	Number of tests	Duration of tests	Troxler 2401 BS	Troxler 3411B BS	CPN MC2 BS	CPN MC2 AC	Correction agent	Number of cores	Place core taken
Trois-Rivières MB-2 MB-3 MB-4	1800	1 min.	1	2	1	1	Fine sand surrounding	132	Different from test
Québec MB-2 MB-3 MB-4	160	1 min.	1	—	—	1	Silica 40	80	Same as test
Sherbrooke MB-2 MB-3 MB-4	480	4 min.	—	1	1	1	Silica 40	80	Same as test

The results showed that on a rough surface the use of a correcting agent generally increased the counts taken directly on the pavement. It may be assumed that in this case part of the gamma radiation was scattered across the air voids between the base of the instrument and the test material even though the correcting agent, which was dry, not compacted and of a different density, lessened the effects of the surface roughness. With a smooth surface the procedure results in no correction and may even decrease the value of the count taken directly on the pavement.

It was observed that there were differences between the devices and even between the BS and AC modes with the same instrument. The value of the correction made by using a correcting agent is different for each device.

It is difficult to compare the results from these various devices with those from coring because the correlations are not sufficiently significant. The mean and the standard deviation of the differences of each count in relation to the core results are too high. The correcting agent does not improve the correlations.

Since the Sherbrooke study was more methodical, the results are considered more significant and are shown in Table IV.

The four studies give, for the 20 test locations, the mean, the standard deviation, the coefficient of correlation between the test and the core, the mean of the differences between the test and the core and the standard deviation of this value.

Given the difficulties of interpretation and as a result of technical meetings with representatives of manufacturers and those responsible for calibration for France at the Centre de matériels radioisotopes in Angers, we decided to make a more extensive study of the various factors which could influence the test values. A series of studies was begun to assess the relative importance of each of these factors: surface error, error in the chemical composition of the components and depth of radiation penetration.

Table IV – Sherbrooke

MB – 2

Instrument	3411B	CPN	CPN	Core	Pavement	3411B	CPN	CPN
Mode	BS	BS	AC	—	—	BS	BS	AC
Corrective	Nil	Nil	Nil	—	—	Silica 40		
$\bar{X}$, g/cm³	2.354	2.316	2.268	2.449	60.7 mm	2.356	2.338	2.296
σ	0.69	0.074	0.096	0.042	14.0 mm	0.062	0.066	0.080
Cor. coef.	0.91	0.83	0.58			0.87	0.86	0.47
Diff.	0.086	0.132	0.182			0.093	0.111	0.152
σ	0.034	0.045	0.080			0.033	0.037	0.071

MB – 3

Instrument	3411B	CPN	CPN	Core	Pavement	3411B	CPN	CPN
Mode	BS	BS	AC	—	—	BS	BS	AC
Corrective	Nil	Nil	Nil	—	—	Silica 40		
$\bar{X}$, g/cm³	2.378	2.341	2.361	2.423	49.3 mm	2.373	2.332	2.324
σ	0.043	0.045	0.038		6.1 mm	0.032	0.043	0.048
Cor. coef.	0.66	0.66	0.66			0.84	0.76	0.74
Diff.	0.045	0.080	0.059			0.059	0.091	0.099
σ	0.043	0.043	0.043			0.019	0.037	0.038

MB – 4

Instrument	3411B	CPN	CPN	Core	Pavement	3411B	CPN	CPN
Mode	BS	BS	AC	—	—	BS	BS	AC
Corrective	Nil	Nil	Nil	—	—	Silica 40		
$\bar{X}$, g/cm³	2.349	2.327	2.304	2.386	39.9 mm	2.341	2.311	2.296
σ	0.035	0.046	0.089	0.042	5.6 mm	0.032	0.048	0.077
Cor. coef.	0.64	0.75	0.43			0.88	0.73	0.32
Diff.	0.038	0.059	0.082			0.046	0.075	0.091
σ	0.038	0.032	0.080			0.021	0.034	0.075

MB – 4

Instrument	3411B	CPN	CPN	Core	Pavement	3411B	CPN	CPN
Mode	BS	BS	AC	—	—	BS	BS	AC
Corrective	Nil	Nil	Nil	—	—	Silica 40		
$\bar{X}$, g/cm³	2.295	2.263	2.271	2.269	25.4 mm	2.267	2.236	2.224
σ	0.038	0.035	0.040	0.038	4.3 mm	0.034	0.042	0.042
Cor. coef.	0.57	0.063	0.78			0.52	0.67	0.8
Diff.	0.024	0.075	0.001			0.002	0.035	0.046
σ	0.035	0.032	0.027			0.035	0.032	0.026

6.0 Study of factors

6.1 Verification program

Before beginning studies on the various factors, a complete program to check the mechanical and electronic operation of the devices to be used was carried out.

Each instrument was examined by means of a statistical analysis of a series of consecutive readings on its reference standard.

After checking out five calibration blocks, we carried out a standard calibration of the instruments by using the Troxler procedure and data processing method; this gave us the most useful information concerning the influence of the mineral composition of the test materials as well as the surface error. Each of these factors merits particular attention when field tests are assessed.

6.2 Surface error

This systematic error represents the inaccuracy of the count caused by the air voids between the instrument and the surface of the test material.

It is determined during calibration, on the basis of two counts, one on the surface of the limestone calibration block, and the other with the instrument raised 1.27 mm.

This difference between the two readings for the three models and for the different positions of the source is shown in Table V.

Table V – Average surface error (g / cm³)

Source Position	Troxler 2401	Troxler 3411B	CPN MC-2
AC	—	—	−0.111
BS	−0.144	−0.085	−0.063
50.8 mm	−0.051	−0.032	−0.024
101.6 mm	−0.019	−0.022	−0.005
152.4 mm	−0.013	−0.022	−0.002
203.2 mm	−0.003	−0.013	−0.003

According to these values, which are taken from our calibration charts, the surface roughness error varies according to the model and the position of the source. The deeper the test is made the less influence this error has on the result. Near the surface however it becomes important, and it was exactly this situation that was studied with a view to the use of these devices on asphalt concrete.

In order to take this systematic error into consideration, the Troxler company applied a correction to the counts taken by its instruments. This correction is 0.25 times the surface error determined during calibration, as shown in Table V. For model 3411B, these values are processed directly by the data processor forming part of the device, before recording the count.

Using different calibration blocks, we assessed in the laboratory the effects of air voids under the base of the various models by varying these spaces. The results obtained confirm the various degrees of sensitivity of the different models. We also varied the thickness of the fine sand (silica 40) used under the device in order to test the effects. The density of the test material decreases in proportion to the thickness of the correcting agent.

In our search for a test procedure, in order to attenuate the maximum error caused by the roughness of the pavement surface, we carried out field experiments on different correcting agents.

6.3 Field trials with correcting agents

Given the inaccuracies resulting from the use of sand as a correcting agent, various materials were tried with a view to finding a more effective one.

Series of tests were made on four pavement sections, each of a different bituminous mix. Table VI summarizes the differences in percentages between the density of cores taken and that obtained by the instruments. The two types of dust used in general reduced the difference between the values. When water was used, in 80% of the cases this difference was reduced even further.

Table VI – Difference between core and nuclear gauge in %

Type of mix	Troxler 3411B	Troxler 2401	CPN BS	CPN AC	Correcting agent
MB-2	2.92	3.63	2.85	4.41	None
	2.40	2.27	2.07	2.66	Silica dust
	1.82	2.14	2.53	2.85	Limestone dust
	1.43	0.32	0.78	1.43	Water
MB-3	1.45	−0.79	2.17	3.09	None
	0.97	0.39	1.51	2.43	Silica dust
	1.58	0.39	1.97	2.50	Limestone dust
	1.12	−0.59	1.05	2.10	Water
MB-4	0.63	−0.02	1.54	3.30	None
	0.84	−0.49	0.77	2.11	Silica dust
	0.84	−0.77	1.26	1.90	Limestone dust
	0.35	−1.75	0.14	0.84	Water
MB-5	1.27	0.40	1.40	2.74	None
	0.80	0.20	0.20	2.27	Silica dust
	0.80	−0.33	1.40	2.00	Limestone dust
	0.60	−1.67	0.06	0.80	Water

Study data for each mix: – three places
– three models, four modes
– one test without corrective and one test with corrective with each model at each spot
– duration of test – 4 min.
– two cores per place

The use of water on an impervious pavement has many advantages. Its density is well known (1g/cm^3), it is abundant and it is easy to use. Some field tests showed that the amount of water used made little difference if the air voids under the instrument were filled. We repeated a series of tests in the laboratory under controlled conditions and obtained the same results. The use of water as an agent to correct surface error proved acceptable.

In making tests with solid agents it proved difficult to apply a standard procedure. It is not easy to level the correcting agent in a uniform way for this operation depends on the operator, the tool used, the moisture content and the thickness of the agent, as well as the moisture content and the texture of the surface. These factors caused variations in the count.

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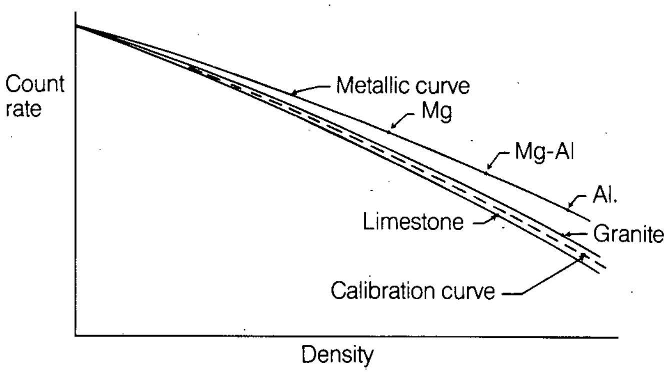
6.4 Composition error

The composition error is determined during calibration. Five standard calibration blocks are used to find the calibration curve for the density. Count rates were computed with each device on each calibration block, with the source placed at each measurement position.

During the processing of data, the metallic calibration curve is defined by the Mg, Mg-Al and Al metallic blocks. The limestone and granite blocks make it possible to obtain the calibration chart. In Figure IV the resulting calibration curve is indicated by a broken line.

Figure IV



This curve corresponds to 50% granite and 50% limestone according to the procedure adopted for processing data. These two calibration blocks were chosen because most construction materials have attenuation coefficients situated within the absorption coefficients or the stopping power of these blocks.

It should be pointed out that the composition error is calculated on the basis of the calibration chart. Table VII shows the composition error values according to the model and the position of the source.

Table VII – Mean composition error (g / cm³)

Position of source	Troxler 2401	Troxler 3411B	CPN MC 2
AC	—	—	0.035
BS	0.029	0.051	0.059
50.8 mm	0.013	0.032	0.019
101.6 mm	0.008	0.024	0.014
152.4 mm	0.005	0.018	0.014
203.2 mm	0.005	0.021	0.014

This systematic error is less than the surface roughness error. It is present when the material tested has components whose proportions differ from 50% Ca and 50% Si.

6.5 Depth of gamma ray penetration

Materials with different densities were used to determine the depth of gamma ray penetration for the various models. In order to measure this penetration precisely, panes of glass 4.76 mm thick were added to the Mg block until the count gave a constant value.

The graphs shown in Figure V indicate the sensitivity of the count for each type of instrument in accordance with the thickness of the material tested.

Figure V

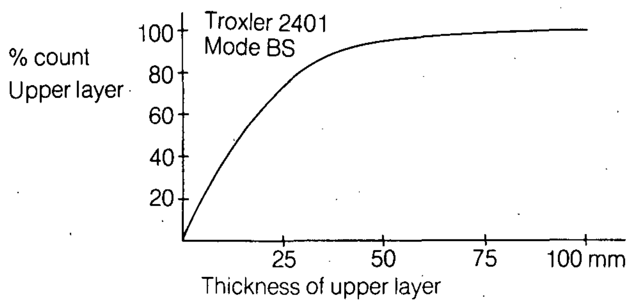


Figure VI

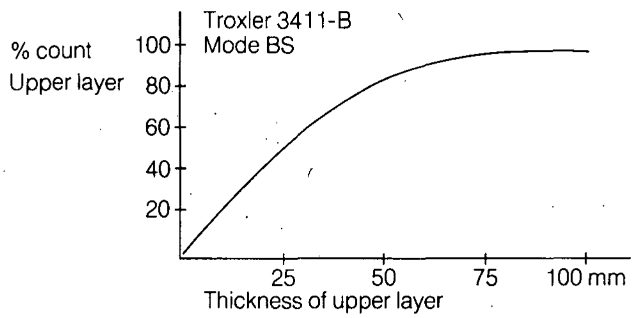


Figure VII

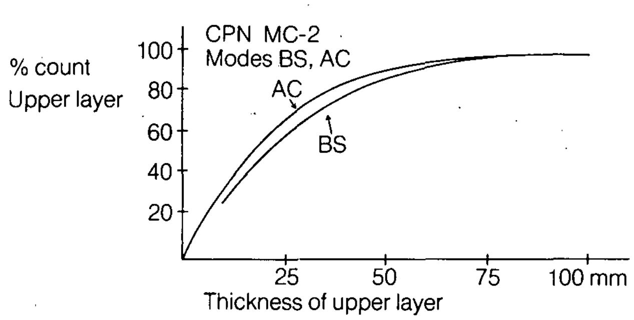


Table VIII shows the proportion of the count taken on the test material which must be considered, according to its thickness.

Table VIII – Value of count attributed to the upper LAYER (%)

Device and mode		Thickness of upper layer in mm 25.4	38.1	50.8	63.6
Troxler 3411B	BS	54	77	90	97
Troxler 2401	BS	75	92	96	100
CPN MC-2	AC	68	87	95	99
CPN MC-2	BS	62	77	90	97

For pavement 25.4 mm thick, with a Troxler 3411B, the count obtained represents 54% of the density of this layer and 46% of the density of the underlying material. Depending on the instrument model and the thickness of the test material, in some cases it is necessary to use a correction factor in computing the value of the test count.

7.0 Procedure for assessing the density of asphalt pavement

The theoretical and practical knowledge gained during research encouraged us to work out a new procedure for assessing the density of asphalt pavement. This procedure enabled us to cancel out the systematic errors in surface roughness and the mineral composition of the components.

In order to do this we first had to make changes in the program for processing the calibration data:

1. To take account of the attenuation coefficients of the limestone and granite blocks. These two blocks were made in Québec and their mineral composition is slightly different from that of the Troxler company blocks.
2. To cancel out the empirical correction of 25% of the surface error. This correction is valid when the instrument rests on a layer of granular material but certainly not on bituminous pavement.

The suggested procedure includes a number of operations to ensure accurate results. The steps to be followed are:

1. Determining the mineral components of the bituminous mix to be tested and their proportions. The composition of the materials used in every asphalt concrete plant is generally well known.
2. Recalculating a C_c calibration curve by data processing, taking account of the proportions of the components and of their attenuation coefficients.
3. Determining a C_{ch} calibration curve on the calibration blocks by putting water between the base of the device and the surface of the blocks when taking the count. The composition error must be taken into account when making the calculations.
4. Carrying out field tests with the instrument, using no correcting agent, and finding the density on the basis of the C_c curve.
5. Carefully inclining the instrument, adding water as the correcting agent, replacing the instrument in exactly the same spot, testing and calculating the density on the basis of the C_{ch} curve. It may be necessary to add water constantly if the surface slopes.
6. Calculating the amount of water between the base of the device and the pavement surface by computing the difference between the two measures.
7. Converting this amount into the density of the underlying material.
8. Adding this correction factor to the count found in the test done without a correcting agent.

The first three stages can be carried out at the beginning of the season in most cases. The other stages are field operations.

This method was tried out on seven sections in the summer of 1980. The results have not yet been completely analysed. However, with a summary analysis of the available results it can be concluded that the method is precise when the instrument used is accurate and precise and the procedure properly followed. It should be pointed out that the procedure includes a difference of two test counts and that the accuracy of the results depends directly on the accuracy of the device. According to our results, only one of our models displays this accuracy.

8.0 Conclusion

The experiments and research carried out in the field of bituminous concrete have shown that:

1. If one follows the instructions for using nuclear gauges now recommended by the manufacturers, results obtained are not accurate and vary from one model to the next. There are differences in the geometry and the accuracy of the various models.
2. The sand used as correcting agent presents difficulties in use and interpretation. The accuracy of the final result is increased in the case of a rough surface, but it may be reduced in the case of a smooth surface.
3. Water is a better correcting agent than sand since it adapts to all degrees of surface roughness.
4. A procedure has been devised to correct the surface error for each test. This procedure requires moisture calibration.
5. The two calibration curves must be adjusted for each type of mix in order to take the mineral composition into account.
6. The effect of gamma ray penetration on the upper layer is different for each model. This value must be interpreted in the case of thin layers.

The procedure established makes it possible to obtain a level of precision and accuracy comparable to that of coring. The advantage of this method is that it is mathematical and includes no empirical values. All the significant factors are quantified and considered in the calculations. However, calibration must be carried out under controlled conditions and the instruments must be precise.

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