A DETAILED ASSESSMENT OF GRAVE-EMULSION COMBINING TRIAL SECTION MONITORING AND LABORATORY TESTING

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ABSTRACT

Within the framework of a public-private cooperative research project, a reference section of grave-emulsion (GE) was laid in 2008. During its construction, various sensors and gauges were placed inside the layer in order to continuously record temperature, moisture content and deformations. In addition, special gauges were installed to record the strains in the GE under passing heavy vehicles. The section monitoring also includes deflection, radius of curvature and permanent deformation measurements, and core sampling. In the laboratory, several properties have been measured on both fresh and cured mixtures, as well as on samples cored from the site. The main material's properties considered are compaction degree, moisture content and stiffness modulus. Moreover, the extracted binder properties (penetration and softening temperature) have been evaluated. The section monitoring shows the satisfactory performance of the GE under traffic over the first 3 years and its rapid cohesion build-up. The GE strengthening effect has been accurately assessed. The response of the inlaid sensors and gauges provides an improved understanding of how the GE layer behaves, cures and consolidates. In the laboratory, a major issue is the material's accelerated curing. An adequate curing procedure has been defined for small specimens ; research goes on as regards larger ones. The main phenomena observed are the sharp increase in density, the initial increase then stability in stiffness and the binder hardening. All these results will contribute to improve behaviour modelling and pavement design.

Keywords : Grave-emulsion, Probes, Gauges, Deflection, Stiffness, Curing procedure

1 – INTRODUCTION

The peculiar features of the mixes containing bitumen emulsion require a specific design method [1], [2]. Besides, most of the testing procedures applicable for hot mixes do not account properly for cold, or warm, materials manufactured with emulsion. This is why the Union of the French Road Contractors (USIRF) and the Technical Network of the French Administration led by IFSTTAR have embarked in a joint research project aimed at defining a suitable design method based on pertinent tests.

The research programme has been established as a development of several previous projects carried out by both private and public sectors [3], [4], [5], [6], [7] and [8]. The main objective being an end-performance design method, the approach has essentially been based on correlating field observations and measurements with laboratory tests results carried out in parallel. To this end, full-scale trial sections were laid and monitored. As part of the joint public-private research project, a section of grave-emulsion was constructed, equipped with probes and gauges and monitored, whilst the material was thoroughly tested in the laboratory [9].

2 – BRIEF DESCRIPTION OF THE TRIAL SECTION

2.1 Pavement structure

The 270 m long section is located on RD44 departmental road near Rennes in French Brittany. The local climate is oceanic i.e. humid and mild. The existing pavement consists of 80 to 110 mm of bituminous materials (surface dressing and hot mix asphalt) lying on 370 to 500 mm of unbound materials (graded crushed stone over coarse single-sized “macadam”). The subgrade is mainly clayey. Ground water is abundant and not easy to drain (specific drainage works were carried out: reshaping of side ditches and installation of draining pipes). The traffic is medium-heavy (average daily number of heavy vehicles around 100).

The test section was overlaid with 110 mm of grave-emulsion (GE). A tack coat was spread ahead of the GE, except on the part of the section where the gauges had been placed). To date, the GE has been left unsealed.

2.2 Grave-emulsion composition

The aggregate, produced from hard massive rock (hornfels) is angular and presents a high internal friction angle. The 70/100 initial bitumen had the following characteristics :

- Penetration 82 dmm at 25 °C – Ring & Ball softening temperature : 44.9 °C – Asphaltenes : 11.2 %

It was cut with 3 % fluxing oil before being emulsified. The cationic coating emulsion was of C-60-BF-6 type (European classification). The 0/14 mm aggregate gradation is continuous, with 40 % passing the 2 mm sieve and around 10 % passing the 0.063 mm sieve. The residual binder content is 4.06 %. The total water content was 6.6 % at mixing time.

3 – SITE DATA COLLECTION

3.1 Meteorological data

A small meteorological station was mounted near the test section. It has recorded rainfall, wind speed and direction, air temperature, solar UV and atmospheric IR radiations.

3.2 Instruments installed in the GE layer

A short zone (approximately 12.5 m) was equipped with diverse probes and gauges, as shown in figure 1.

- Temperature and moisture probes

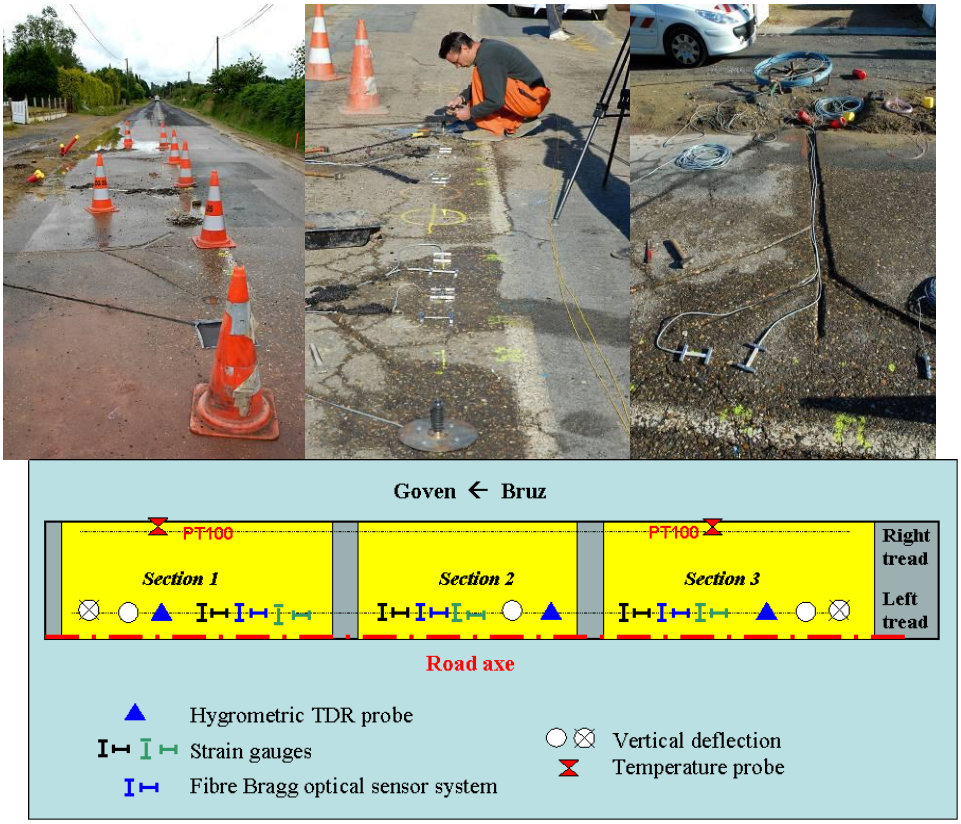

Figure 1 – Views of the gauges/probes zone (top) and layout of the sensors positions (bottom)

The GE layer temperature has been monitored by using PT 100 resistance-probes inserted at different depths (10, 40, 70 and 100 mm).

The monitoring of the GE layer moisture has been performed by the means of Time Domain Reflectometry (TDR) probes. The TDR technology basically allows to measure the volume occupied by moisture in a given material's volume. Electromagnetic wave impulses are generated and throughout two electrodes with integrated electronics. The wave travelling time through the electrode length depends on the material's dielectric properties, especially its moisture and voids contents.

- Deformation and strain gauges

The vertical deflections of the existing pavement surface have been measured with sensors anchored in it, the movements of which are evaluated in relation to a bench mark deeply anchored in the substratum and therefore assumed to be unaffected by passing loads. The deflections of the GE layer have been recorded with a novel type of sensor designed by the Administration Scientific and Technical Network, set at the interface between the existing pavement and the GE overlay [3].

In order to measure the strains in the GE, H-shaped resistive gauges (extensometers) have been placed in the lower part of the overlay. This instrumentation has been supplemented by an optical sensor system based on the optical fiber Bragg grating technology [10], that appears to be more reliable under extreme conditions (electromagnetic fields, permanent moistures, corrosive environment, etc).

4 – GE MANUFACTURE, LAYING, COMPACTION

The mixture was manufactured in a continuous cold-mix plant. It was laid full-width by finisher. It was then heavily compacted as follows : 4 passes of vibrating steel roller (VSR) + 16 passes of pneumatic-tyred roller (PTR) + 6 passes of VSR + 16 passes of PTR.

No vibration was applied on the short zone containing the probes and gauges for fear of damaging them. The compaction procedure there consisted of 4 passes of smooth steel roller + 50 passes of PTR.

5 – RESULTS OF TESTS CONDUCTED ON THE FRESH MIXTURE (PLANT MANUFACTURED)

5.1 Cohesion build-up

Two types of test [11], [12] were carried out, in the field, on samples of GE taken in the augers of the finisher during the laying operation :

- The workability test, using the Nynas apparatus,
- The torque shearing test, using the device developed by the Saint-Brieuc Regional Laboratory.

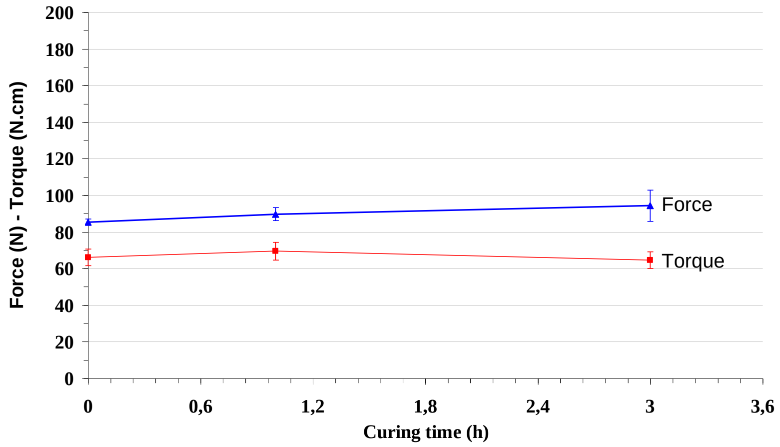

Figure 2 – GE sampled from the finisher's augers – Workability and shearing torque over time

The results are shown in figure 2. Both tests prove that the mixture cohesion remains practically constant for at least 3 hours after it was sampled. The low values of the force (workability test) and the torque indicate that this GE has a very good workability. These results are in line with the behaviour of the mixture observed in the field.

5.2 Compactability

A number of densification tests were carried out in different laboratories with Gyratory Shear Compactors (GSC), that gave consistent results. Of particular interest are the tests performed in the field, on GE samples taken for the finisher's augers, by using the IFSTTAR embarked GSC 2 (figure 3). The total voids at 20 gyrations amount to approximately 12 %. They decreased to 11 % after 200 gyrations. Water began to seep out of the specimen around 20 gyrations. At this point the voids were near 17 %, the value of the voids in place right after the mix compaction had been completed (as measured using the GPV nuclear densitometer).

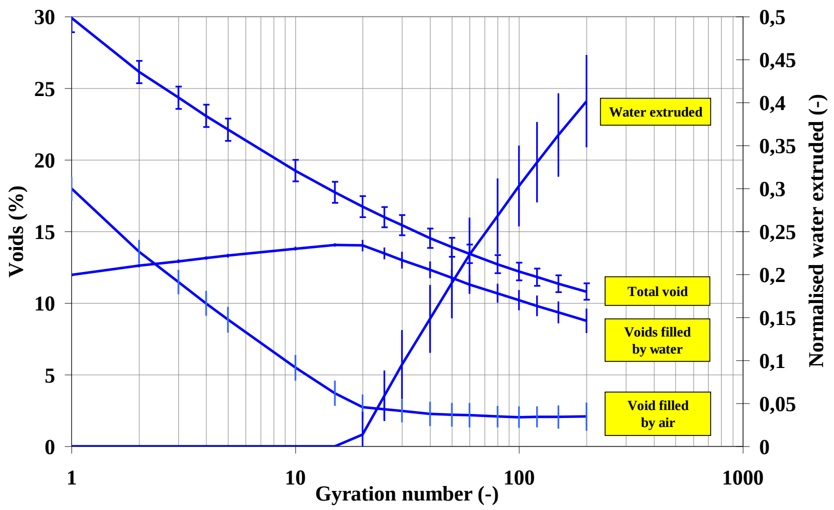

Figure 3 – Gyratory shear compactor densification (embarked GSC2)

6 – IN-PLACE RESULTS

6.1 General condition of the section

After three and a half years including four summers, the overall condition of the section is excellent. There is no permanent deformation. Only a few cracks begin to be visible on the old pavement, that can be attributed to the reflection of local degradations.

6.2 Moisture content

Various measurements have shown that the GE moisture content decreased from its initial average value of 8 % (7-11 % range) to approximately 0.4 % in less than 2 months (of summer). It has then remained relatively stable around this low value, in spite of the continual humidity proper to the climate of Brittany and the fact that the GE has remained unsealed.

6.3 Air voids in the grave-emulsion

Three zones have been distinguished along the section:

- Zone 1 : PR 23+120 to PR 23+158 (based on a slight variation in subgrade response)
- Zone 2 : PR 23+15 to 23+120
- Zone 3 : (gauges and probes) PR 23-15 to 23+15

Site densities were measured using a GPV gamma-ray portable densitometer (figure 4). The voids contents measured with this device ranged from 16.5 to 17 % on the current section right after compaction completion. They sharply decreased to 12-13 % in a few days and then remained fairly stable with time. Voids in the gauges zone were initially higher (around 19.5 %) because of the lack of compacting vibration. They later decreased as sharply as those of the current section and reached the same level.

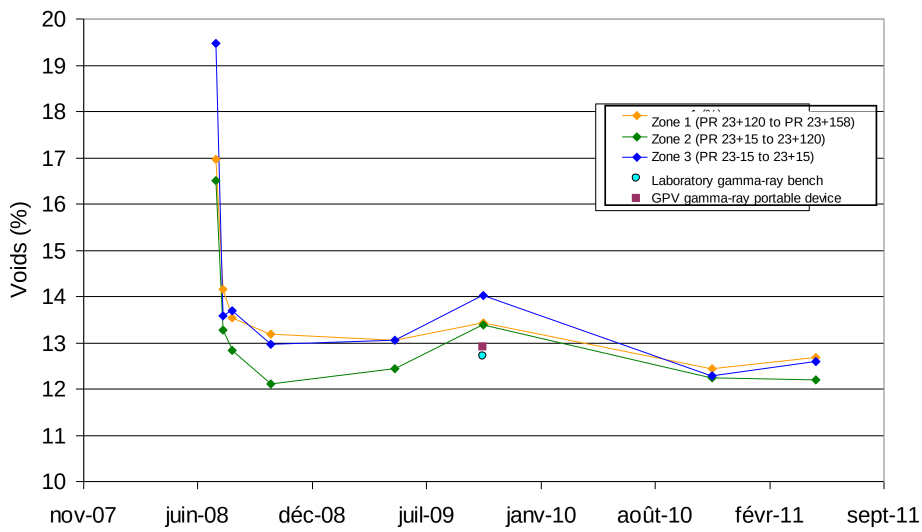

Figure 4 – RD 44 grave-emulsion – Variation of the voids over time

Voids contents were also measured on undisturbed samples (cores and slabs) of the GE, using laboratory gamma-ray benches. The voids measured in this way are systematically lower than those measured using the portable nuclear densitometer, e.g. :

~ 11.5 % at 3 months – 10.5 to 11.5 %* later on, with virtually no variation with time (latest results at 3 years)

** average of values obtained on several samples cored at the same time*

It is worth noting that the stable, medium-term, level of voids is close to the voids obtained after 200 gyrations of Gyratory Shear Compactor.

6.4 Temperature inside the GE layer

The probes installed in the GE record the temperature of the material at different depths. Figure 5 shows the monthly average temperature gradients over year 2009. The figures at level +3 cm correspond to the average air temperature. The temperature does not vary much with the depth, except in the very top of the layer. The lowest temperature profile is near 3 °C (january); the highest is slightly over 25 °C (july). The yearly average turns out very close to 15 °C, which is, by the way, the theoretical temperature specified for pavement design in France.

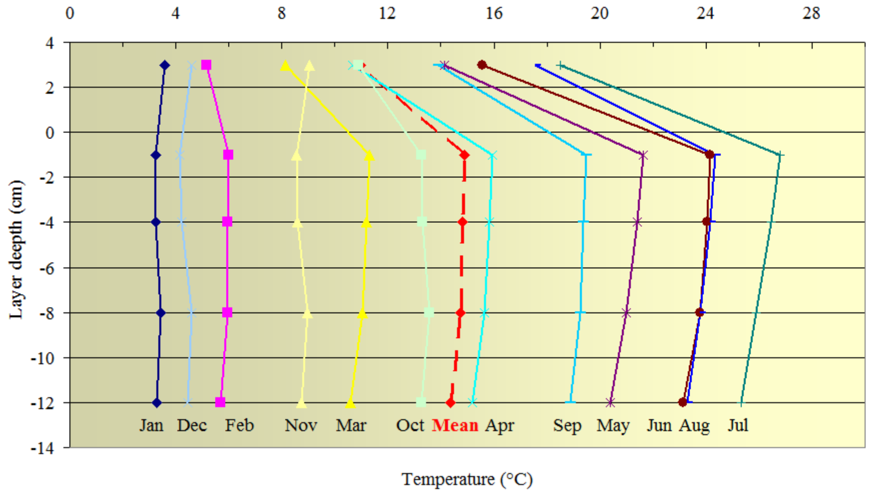

Figure 5 – RD 44 grave-emulsion – Temperature inside the layer over one year

6.5 Deflections

Falling Weight Deflectometer (FWD) data was obtained on a segment of zone 3 (figure 6). The first deflection basin was recorded one month before the pavement was overlaid with the GE. The FWD was then operated twice a year, the first measurement taking place one week after the overlay. The subsequent deflection basins reflect the increase in the GE stiffness that results from the material's consolidation and curing, combined with the binder hardening. On the other hand, an increase in deflection level can be observed between spring and fall, in 2009 as well as in 2010. It is assumed that it is due partly to the softening of the subgrade at this particular location, resulting from water ingress during the winter season (the moisture content of the GE remains fairly constant and low over the years). A slight decrease in the GE stiffness has also been observed after the first winter season.

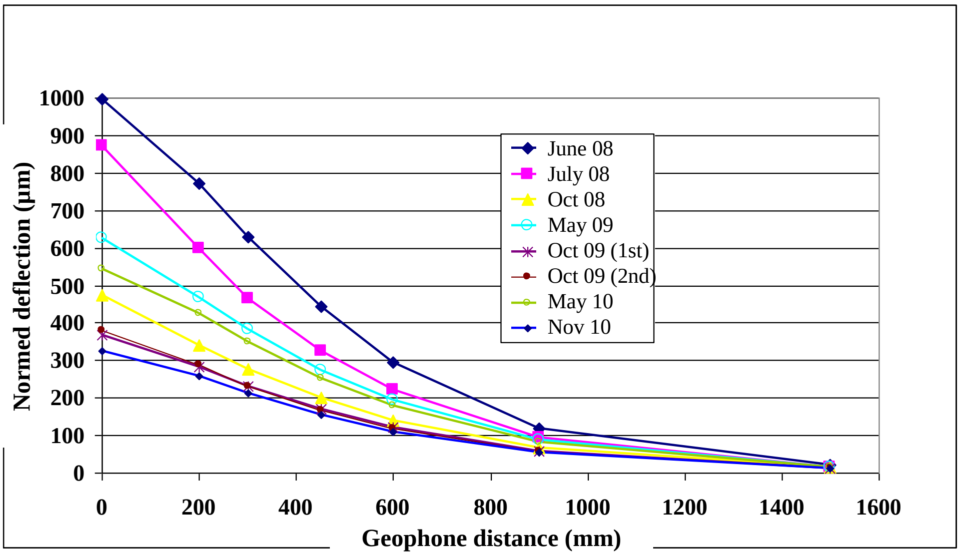

Figure 6 – Influence of time on Falling Weight Densitometer basins (gauges/probes zone)

6.6 Longitudinal strains

Longitudinal strains under passing loads (13 tons axle) have been recorded through the gauges installed in the GE. Figure 7 illustrates the strains measured in one of the gauges. Two points are of particular interest :

- the overall decrease in strain over time, which indicates the increase in the GE's stiffness,
- the seasonal increase in strain, that could be attributed to the subgrade soil softening during the winter period.

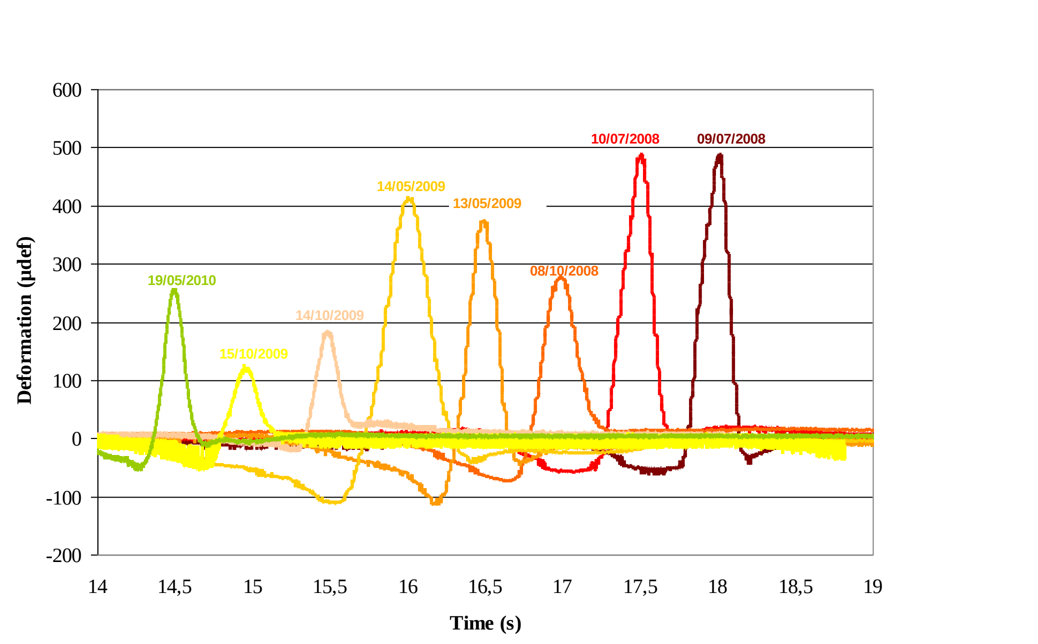

Figure 7 – Longitudinal strains in the GE layer – Variation over one year

7 – LABORATORY RESULTS

7.1 Tests conducted on mixtures manufactured in the laboratory

All manufactures were carried out using small laboratory mixers (single vertical shaft or twin-shaft pugmill following as closely as possible the feeding/spaying/ mixing procedure used with the site plant).

7.1.1 Unconfined compressive strength and water sensitivity (Duriez test)

The results of this test obtained by the different laboratories are consistent. Two moulding procedures were used for the preparation of the mixture specimens :

- standard procedure : "normal" moulding force (120 kN)
- modified procedure : reduced moulding force (40 kN)

Table 1 shows typical results of one laboratory.

Table 1 : Unconfined compressive strength (UCS) and water sensitivity (Duriez test) results

Moulding procedure	Standard (120 kN)	Modified (40 kN)
Voids (geometric method)	10.7 %	16.9 %
Voids (hydrostatic method)	10.4 %	-
UCS at 18°C after 14 days air 18°C – 50 % HR	4.7 MPa	2.7 MPa
UCS at 18°C after 7 days air 18°C + 7 days immersion 18°C	2.9 MPa	1.65 MPa
Retained strength after immersion/ Dry strength	0.62	0.61
Moisture content :		
- manufacture	6.6 %	6.6 %
- after removal from the mould	2.5 %	4.8 %
- after 7 days air 18°C – 50 % HR	0.3 %	0.6 %
- after 14 days air 18°C – 50 % HR	0.6 %	0.3 %
- after 7 days air + 7 days immersion	2.7 %	5.9 %

The modified procedure turns out to give a level of voids close to that obtained in place right after the compaction has been completed. On the other hand, the standard procedure brings about voids that are of the same order of magnitude as those measured in the field after the GE has reached its "stable" state. It is also pointed out that the water sensitivity ratio (retained strength after immersion over dry strength) is the same for both procedures.

7.1.2 Stiffness modulus

Various tests were carried out by the laboratories involved, using different test methods, as well as diverse types of specimens. Examples of the results obtained are as follows:

Example 1 : Specimens : GSC-moulded (h : 150 mm - ∅ : 160 mm), cured 14 days at 35°C – 20 % Relative Humidity (HR)
Voids : mean 14.5 %
Modulus : Sinusoidal axial compression
Mean 3,510 MPa at 15°C – 10 Hz

Example 2 : Specimens : GSC-moulded (h : 150 mm - ∅ 160 mm), cured at 35°C – 20 % HR, then sawed and cored (h : 50 mm - ∅ 100 mm)
Voids : mean 11.2 %
Modulus : Diametral load pulses (ITSM)
- mean 2,500 MPa at 10°C – 124 ms (14 days curing)
- mean 3,200 MPa at 10°C – 124 ms (28 days curing)

Example 3 : The specimens were prepared and tested following the same protocol as in example 2. The results are given in table 2. Three sets of specimens were made, each at a different level of compaction (A, B, C).

Table 2 : Indirect tensile stiffness modulus of RD 44 GE – Versus curing time and mix voids

Set	Curing time 35 °C – 20 % HR	7 days		14 days		28 days	
A	Voids Modulus 10°C – 124 ms (MPa)	sawing not feasible		A14	12.9 % 1,980	A28	13.6 % 2,540
B	Voids Modulus 10°C – 124 ms (MPa)	B7	11.4 % 1,600	B14	11.5 % 3,050	B28	11.2 % 3,640
C	Voids Modulus 10°C – 124 ms (MPa)	C7	8.1 % 2,160	C14	9.3 % 3,820	-	

The major influence of the compaction is proved by these results, which also allow the increase in stiffness over the curing time to be quantified.

Besides, two-point sinusoidal bending tests were carried out on trapezoidal specimens sawn in laboratory-made and-cured slabs (table 3) :

Table 3 : Complex modulus (two-point bending) and voids of RD 44 GE

Slab curing protocol	Voids (mean)	Modulus 15 °C – 10 Hz
60 days 18°C – 50 % HR	15.3 %	1,520 MPa
14 days 35°C – 20 % HR + 60 days 18°C	16.4 %	1,380 MPa
Ditto	17.2 %	1,690 MPa

The complex moduli measured according to this method are considerably lower than those exposed above. Two reasons way help explain this difference: the difficulty of completely curing slabs, due to their large volume and the occurrence of microscopic damages caused by the sawing of the specimens.

The possible relations between moduli measured on laboratory-made and-cured mixtures with moduli measured on field samples are discussed below.

7.2 Tests conducted on field samples (cores and slabs)

Two types of samples were taken from the grave-emulsion : cores and slabs. The modulus was measured directly on the cores, using the diametral pulses method. On the other hand, test specimens were extracted from the slabs, either by coring cylinders or sawing trapezoidal specimens. Owing to diverse constraints, the modulus tests were carried out several months later. In the meantime, cores and slabs were kept sealed at ambient temperature. The binder was extracted from the slabs at the time of modulus test and characterized.

7.2.1 Indirect tensile modulus

The voids, moduli (diametral pulses method) and binder characteristics are given in table 4 :

Table 4 : Voids, Stiffness modulus and binder characteristics measured on field samples

Field sampling		Voids (mean)	Modulus 10°C – 124 ms		Extrated binder	
Type	**Age (date)**		**Age at time of test**	**Mean value**	**Pen (dmm)**	**R&B (°C)**
3 cores	3 months (06/10/08)	11.5 %	5 months	3,250 MPa	n.m.	n.m.
Slab	10 months (15/05/09)	11.0 %	15 months	3,080 MPa	35	55.0
Slab	15 months (14/10/09)		17 months	3,070 MPa	31	55.8
			19 months	3,530 MPa	n.m.	n.m.
Slab	23 months (19/05/10)	10.9 %	24 months	3,990 MPa	28	57.8
Slab	29 months (16/11/10)	11.5 %	30 months	3,840 MPa	26	58.0
			31 months	4,230 MPa	n.m.	n.m.

** n.m.: not measured*

- The voids percentage has reached a stable level (11 to 11.5 %) in a short time.
- The modulus of the GE has risen rapidly (in the course of one summer) to a comparatively high level of stiffness.
- A slight decrease in stiffness has been recorded after the first winter season. Its cause remains to be investigated.
- The stiffness then tends to stabilize at a higher level (near 4,000 MPa).
- The binder steadily hardens over time, a phenomenon systematically observed on grave-emulsions [5], [7].
- On two slabs (sampled 14/10/09 and 16/11/10) cylindrical specimens were cored, tested, then kept at 20°C without any sealing and retested. It turns out that one or two months of exposition of these cylinders to air cause a very significant increase in mixture stiffness. This demonstrates that field samples must be carefully protected as long as they are stored before being tested.

7.2.2 Complex modulus

The modulus of the GE was measured on trapezoidal specimens sawed from slabs cut in the field, using the two-point sinusoidal bending method (figure 8). After 2 summers, the complex modulus seems to have reached a plateau. However, the level of the complex modulus at 15°C – 10 Hz is significantly lower than the ITSM moduli at 10°C – 124 ms (see 7.1.1), when it is generally accepted that they should not differ much.

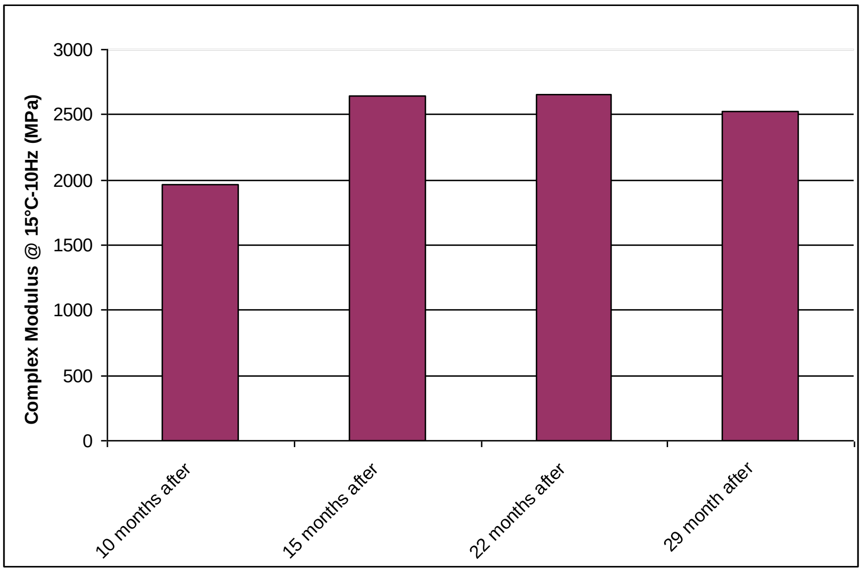

Figure 8 – GE RD 44 – Complex modulus at 15°C – 10 Hz measured on field samples at different ages

8 – THE ISSUE OF ACCELERATED CURING

Previous research [2], [7], [8] has shown that a fairly good correlation can be made between accelerated curing during 14 days at 35°C – 20 % HR and field curing over a period of time including 2 summers. This correlation is valid only if two conditions are fulfilled :

- the climate prevailing in the region considered is temperate,
- the specimens cured are small (for example cylinders made with a small gyratory compactor : height 80 m, diameter 100 or 150 mm).

The comparison of laboratory curing to field curing shows that the accelerated curing protocols applied in the present research appear to be not sufficient to simulate medium term field curing (1 to 3 summers, depending to the actual weather and the mixture response). Proper curing of GSC specimens (h : 150 mm, ∅ : 160 mm) requires more than 14 days at 35°C – 20 % HR. Thorough curing of slabs for rutting stiffness modulus or fatigue tests, is particularly difficult, because of the volume of material involved. Further research is under way to define more appropriate curing protocols.

9 – CONCLUSION

The present research program has not yet been fully completed, as the trial section monitoring is to go on for two more years. Nevertheless, tangible results have already been obtained regarding the grave-emulsion behaviour, in terms of cohesion build-up, stiffness modulus, binder hardening. Suitable test procedures have been defined. However, some questions remain for accelerated curing, which should be answered when the additional research under way will be finalized.

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