Development and Uses of Hard-Grade Asphalt and of High-Modulus Asphalt Mixes in France

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Hard-grade paving asphalts, i.e., those having a penetration at 25°C lower than 25 mm/10, have experienced in France a significant development over the past 20 years. A brief review of the evolution of asphalts in France is provided, mentioning the current recommendations for the selection of asphalts and the rheological characteristics of the different hard asphalts produced in France. Data on the effect of rolling thin-film–oven and pressure-aging–vessel tests are given. Then high-modulus asphalt mixes are discussed. The different types of application of hot-mix asphalt concrete (HMAC) are indicated. Information is given about the composition of HMAC together with the current specifications in Association Française de Normalisation standards. Results are presented with respect to compactibility with the gyratory shear compactor, stiffness, resistance to rutting and to fatigue cracking, and about field performance. Two examples illustrate the potential economical benefit when making use of HMAC in new pavements instead of conventional base asphalt concrete.

Hard-grade paving asphalts, i.e. having a penetration at 25°C lower than 25 mm/10, have experienced in France a significant development over the past 20 years. They have been developed to provide technical solutions to the problem of mitigation of rutting of surface layers and to increase the rigidity of the base courses of asphalt pavements. The production of hard-grade asphalt in France was 39,000 tons in 1990, 77,000 in 1995, and reached 100,000 tons in 2000. This placed France in a leading position for the use of this type of binders according to the survey carried out by the Permanent International Association of Road Congresses (PIARC)—World Road Association in 1998. Though the general objectives guiding the use of hard asphalts were identified a long time ago, it took several years before methods of processing led to binders which exhibit the desired hardness together with good long-term performance in the field. The development of hard asphalts is also closely related to the parallel emergence of new asphalt mixtures designed especially for these binders in order to obtain the performances sought in pavements.

This paper is organized in two parts. The first one deals with hard asphalts and provides a short history of the evolution of paving asphalts in France, followed by a presentation of data on rheological characteristics and results of aging tests for the hard asphalts produced in France. The second part is devoted to the high-modulus asphalt mixtures. The uses of these pavement materials are presented. Indications are given on the composition of the mixes and on their main mechanical characteristics.

HARD ASPHALTS

Evolution of Asphalts in France in Brief

The 1960s: Early Stages and First Changes

Until the beginning of the 1960s in France, almost all paving asphalts were 80/100 and 180/220 penetration grade (PG). They were produced by direct distillation from heavy crudes imported from Central America. With a strong increase in heavy vehicle traffic at that time, the search for a higher rigidity and a better resistance of the asphalt mixes to plastic deformations (rutting) led to the use of harder asphalts. Production of 40/50 and 60/70 PG asphalts started in 1966 and the first 20/30 PG appeared in 1968 (*1*). The publication, by the French Road Directorate, in September 1969, of a directive for the construction of the surface courses in asphalt mixes, had a decisive role in this evolution. This directive introduced a climatic criterion for the choice of the asphalt, with the division of the French territory in three zones:

- Zone 1: Mediterranean type of climate characterized by mild winters and hot summers;
- Zone 2: Oceanic type of climate, characterized by both mild winters and summers; and
- Zone 3: Continental type of climate, characterized by cold winters and hot summers.

Recommendations made at the time for the choice of the asphalt are summarized in Table 1. In order to further increase the resistance to rutting of surface layers, the technique of air-blowing was used to reduce the thermal susceptibility of the asphalt, at the end of the 1960s, for the production of 40/50 PG asphalt with a high penetration index (*2*). If this proved to be effective with respect to rutting, on the other hand it led very quickly to extensive cracking at the pavement surface, which brought to the abandonment of this solution.

The explanation of this poor performance is to be linked to the effect of the manufacturing process on the structure of the asphalt. Air-blowing at high temperature produces a dehydrogenation of certain molecules followed by their reticulation. It results in an increase of the size of the naphteno–aromatic resins. If one refers to the separation of the components of the asphalt into saturated compounds, aromatics, resins, and asphaltenes, the proportion of asphaltenes increases, that of the resins and aromatics decreases, that of saturated coumpounds remains about constant. This results in an increase of the colloidal instability index:

$$IC = \frac{\text{asphaltenes + saturated}}{\text{aromatics + resins}}$$

TABLE 1 Recommendation for the Choice of Asphalt Grades in Surface Layers (1969 Road Directorate Directive)

	Zone 1	Zone 2	Zone 3
Altitude ≤ 500 m	40/50	40/50 or 60/70	60/70 or 80/100
Altitude > 500 m	60/70 or 80/100*	60/70 or 80/100	80/100

* if altitude >1000 m

This evolution of the structure of the asphalt, in which the asphaltene micelles are not any more completely peptized but are more or less flocculated, leads to a change in behavior from a "sol" type to a "gel" type. The penetration index (IP), which reflects the susceptibility to temperature, then reached values of +2 and more.

The 1970s: Consequences of the Oil Crises

The 1973 and 1979 oil crises deeply modified the French oil market with regard to both the volume of refined oil and the origin of the imported crudes. These crises involved the need for an adaptation of industry, with the closing of several refineries but also the construction of new and more powerful units of distillation. The development of the share of the crudes imported from the Middle East, less heavy than those from Central America, and the demand for 40/50 and 60/70 PG asphalts led to the generalization of the process of partial air-blowing for the production of these grades. This process was applied to rather soft bases which led to rather large chemical changes in the asphalts.

The 1980s: Impact of Specifications on the Evolution of Asphalt Processing Methods

The revision of the system of specification for paving asphalts, initiated at the beginning of the 1980s by the French Road Administration with participation of the oil industry and road contractors, has had an important impact on the processing methods. Earlier French specifications were primarily based on the penetration value (the other physical characteristics were only supplementing this information). In 1986, however, the ring and ball (R&B) softening point was introduced as a cornerstone of the new system of grading. The concern over the impact of aging on the field performance of the asphalt mixes led to a second development. A large experimental program involving 100 job sites made it possible to collect relevant data to assess representativeness of the rolling thin-film oven test (RTFOT) for simulation of aging during coating and laying. According to field performance of 35/50 and 50/70 PG asphalts used in wearing courses, specifications were fixed which limit hardening of the binder after RTFOT, with on the one hand a maximum increase in 9°C of the R&B softening point and on the other hand a minimal value of residual penetration (function of the paving grade). These requirements were adopted in 1990 by the asphalt producers and were introduced, in 1992, in the Association Française de Normalisation (AFNOR) standard for paving asphalts.

The 6°C interval for the R&B softening point for the definition of the width of each grade, as well as the requirements on the limitation of aging after RTFOT led the asphalt producers to adapt the methods of production.

The possibility of obtaining a high point of cut was made possible by the use of structured packing internals in the vacuum distillation column. It became thus possible to eliminate fractions with a point of distillation under atmospheric pressure up to 550 °C. Contrary to the process of air-blowing which results, by reticulation, in an increase of the components which already have a large mass, direct distillation involves elimination of the saturated and naphteno-aromatic components of lower masses. This process is applicable only to the heavy crudes which already contain enough asphaltenes. The resulting hard asphalts have a penetration index less than 2 and are less susceptible to aging. Partial air-blowing remains used, in France, by one producer for the hardest grades.

Production of propane-precipitated asphalt, which is a process well adapted to the production of very hard grades, is only used in France in two refineries specializing in the production of lubricants. All in all, asphalts resulting from this process represent only approximately 5 percent of the French production of asphalts (*3*).

Current Recommendations for the Selection of Paving Asphalts

Recommendations for the choice of plain paving grades were redefined in 1994 in a technical guide issued by the Laboratoire Central des Ponts et Chaussées (LCPC) and the Societe d'Etudes Techniques des Routes et Autoroutes (*4*). As in the above-mentioned 1969 directive, three climatic zones are specified; however, they are based on average values of maximum daily temperatures in July and August and minimum daily temperatures in January and February observed over the past 30 years:

- Zone 1: Dominant oceanic climate ($T_{max} \leq 27°C$ and $T_{min} \geq 0°C$);
- Zone 2: Dominant southern climate ($T_{max} > 27°C$ and $T_{min} \geq 0°C$); and
- Zone 3: Dominant continental or mountainous climate ($T_{min} < 0°C$).

In order to relate France's climatic conditions to the SUPERPAVE approach, Figure 1 shows two maps of France for low and high temperatures with indication of the penetration grade (PG) for the asphalt binder.

For base asphalt concrete (AC), the grade most generally selected is 35/50 if not 50/70. For wearing courses, in the case of heavy traffic, the advised grades are indicated in Table 2 (in the case of less severe traffic conditions, one would accept a softer grade 50/70 instead of 35/50 and 70/100 above 1000 m).

The use of a harder grade is to be considered in the case of very demanding situations (important slow or channeled heavy traffic or high temperatures) or when there are constraints on how deep or high the pavement can be.

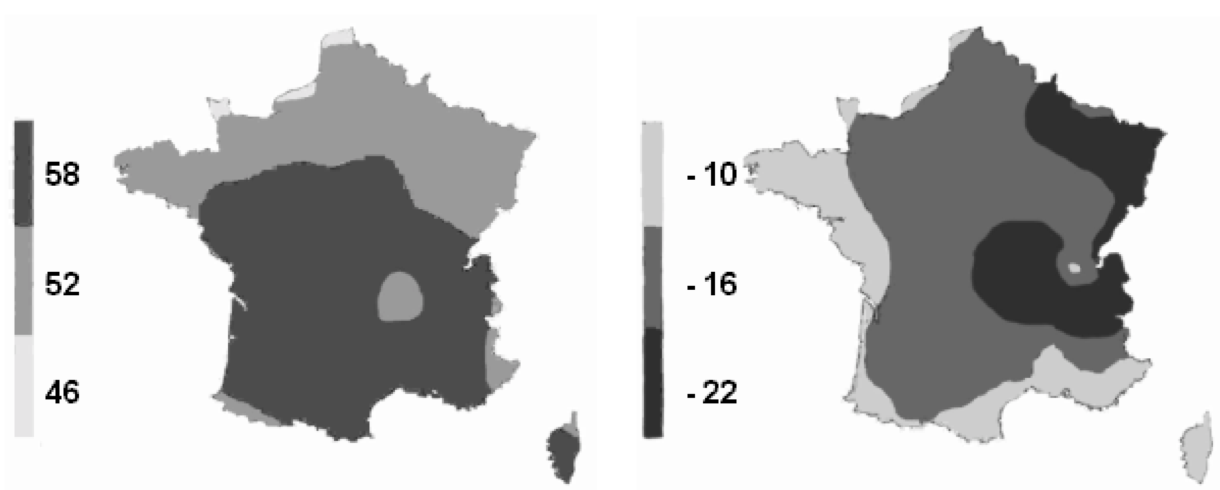

FIGURE 1 Maps of France PG pavement temperatures.

TABLE 2 Plain Asphalt Paving Grades for Wearing Courses in Cases of Heavy Traffic (1994 Recommendations for the French National Network)

Type of Climate	1	2	3
Altitude < 500 m	35/50	35/50	35/50
Altitude from 500–1000 m	50/70	50/70	50/70
Altitude > 1000 m	*of no concern*	50/70	70/100

Rheological Characteristics of Hard Asphalts

Hard asphalts are defined here like having a penetration less than 25 mm/10 at 25°C. There are three grades: 15/25, 10/20, and 5/10. Currently, grade 5/10 is at a trial stage, whereas the others have been marketed for several years. Typical characteristics of these hard asphalts are given in Table 3.

As an example, Figures 2 and 3 present the results of dynamic shear tests on four different PG, 10/20, 25/35, 35/50, and 50/70: master curves of the complex modulus G^* at 20°C (Figure 2) and the phase angle at 7.8 Hz.

Penetration at 25°C does not determine of course the rheological characteristics. Performances, for asphalts of the same PG, vary depending on the crude and the manufacturing process. Table 4, extracted from Glita and Conan (*5*), compares the rheological characteristics of seven 10/20 PG asphalts with, as a reference, those of a plain 35/50 asphalt. One notes that the modulus can vary, for the same test conditions, in a ratio from 1 to 2, and that the sensitivity to permanent deformation, as indicated by $G^*/\sin\delta$, is definitely different from one asphalt to another.

One can see from this table that the temperature for which the viscous and elastic components of the modulus are equal (phase angle equal to 45°) is definitely lower for the 35/50 asphalt than for 10/20 asphalts. The hard asphalts thus should have a lower capacity of healing than the softer 35/50 asphalt.

Brittleness at low temperature can be estimated from the temperature corresponding to the maximum of the viscous component G'' of the complex modulus, or by the value of the phase angle at low temperature, here at –10°C. Table 4 shows, according to these two criteria, that asphalts B, D, and E can be regarded as most fragile, whereas asphalts A, F, and G show characteristics similar to those of the 35/50 asphalt.

TABLE 3 Typical Hard Asphalt Characteristics (Before Aging)

Grade	15/25	10/20	5/10
R&B softening point (°C)	66	62 to 72	87
Pfeiffer IP	+0.2	+0.5	+1.0
Dynamic viscosity at 170°C (mm^2/s)	420	700	980
Complex modulus at 7.8 Hz, $\lvert E^*\rvert$, (MPa)			
Complex modulus at 0°C	425	700	980
Complex modulus at 10°C	180	300	570
Complex modulus at 20°C	70	110	300
Complex modulus at 60°C	0.4	0.7	7

NOTE: IP = penetration index; $\lvert E^*\rvert$ = complex Young modulus.

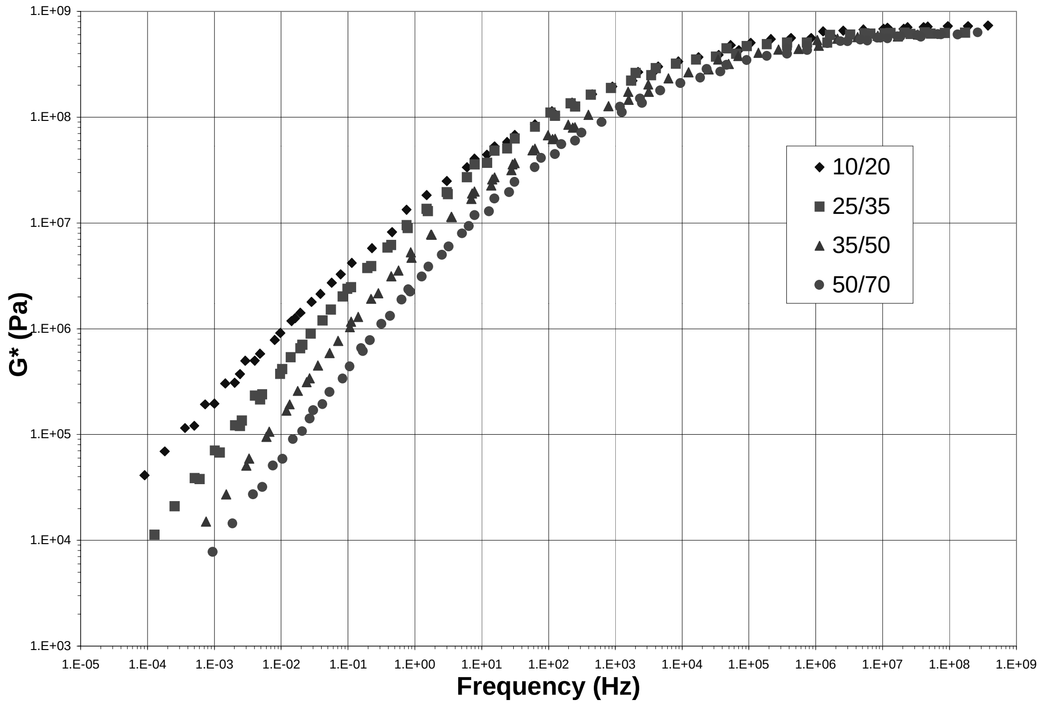

FIGURE 2 Master curves of complex modulus *G of four different asphalts: 10/20, 25/35, 35/50, and 50/70 penetration grades.**

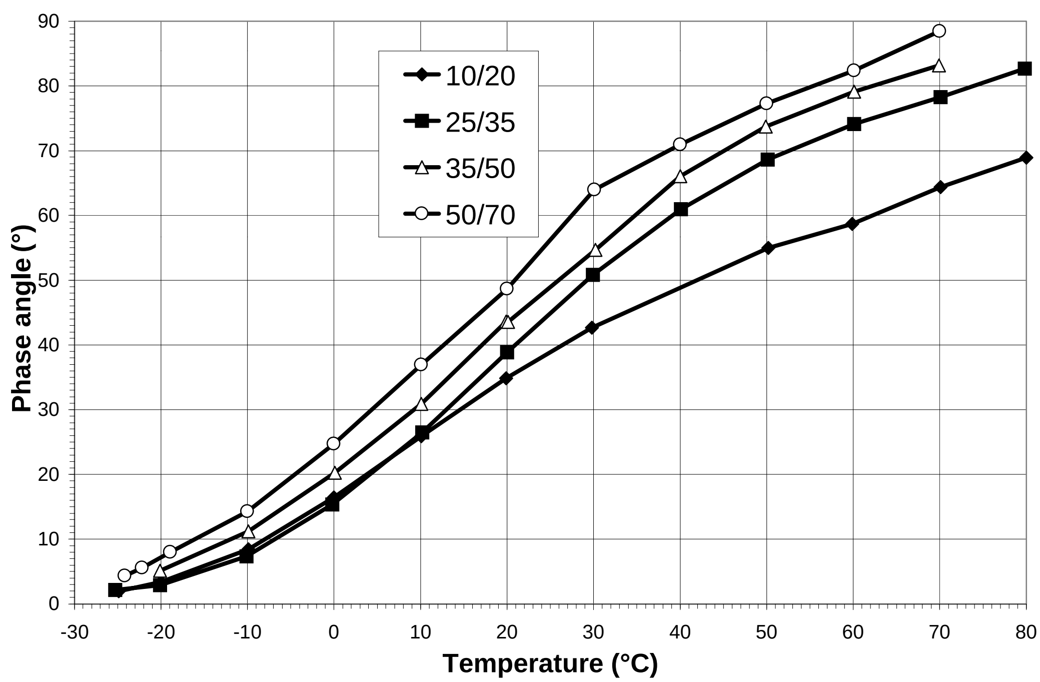

FIGURE 3 Variation of phase angle with temperature at 7.8 Hz for four different asphalts: 10/20, 25/35, 35/50, and 50/70 penetration grades.

TABLE 4 Rheological Characteristics of Seven 10/20 Asphalts and a 35/50 Asphalt

	35/50	A	B	C	D	E	F	G
$\lvert G^*\rvert$ (15°C; 10 Hz) (MPa)	34.5	53.7	88	88	83.7	71.1	43.7	47.3
$\lvert G^*\rvert / \sin\delta$ (60°C; 5 Hz) (MPa)	0.016	0.131	0.184	0.247	0.122	0.165	0.184	0.103
SR	3.55	4.3	3.64	3.94	3.3	3.58	4.53	4.1
T (°C) pour $G' = G''$	17	28	29	31	24	26	34	25
T (°C) pour G'' max	–10	–10	0	–5	0	–5	–15	–10
δδ (–10°C; 5 Hz)	12.2	11.6	7	9.1	6.5	8.3	12.7	11

NOTE: SR = standard deviation of the relaxation spectrum.

Table 5 gathers information included in the French “*Avis techniques*” (French technical assessments for innovative products issued by the “*Comité Français des Techniques Routières*, French Committee for Road Techniques). It presents hard asphalt characteristics, produced in France for use in high modulus AC. These values cannot be guaranteed because they are likely to vary with the origin of the crude oil.

Influence of Aging

The incidence of aging, as simulated by the RTFOT for the phases of coating and laying of the asphalt mix, then with the pressure-aging vessel (PAV) for field evolution in the pavement, was studied on various 10/20, 35/50, and 50/70 paving asphalts by the Regional Laboratory of Bridges and Roads of Aix en Provence. It considered composition, the traditional empirical characteristics (penetrability, R&B softening point, Fraass temperature), and the rheological behavior from bending beam rheometer (BBR) tests.

From the point of view of the change in the composition of the asphalt, if one considers the n-heptane asphaltenes content, the increase in asphaltenes after aging tests is all the more larger since the grade of the asphalt is soft. After RTFOT + 20 h of PAV, the ranges are from 50 to 80 percent for 50/70 asphalts, from 40 to 65 percent for 35/50, and from 15 to 35 percent for 10/20 grade. Iatroscan chromatography, which provides a global analysis without preliminary separation of asphaltenes, gives a more complete image of the evolution of the generic components of the asphalt. The change is qualitatively comparable for the various grades, namely:

- The proportion of saturated remains about constant;
- The proportion of aromatics varies little after RTFOT, but the decrease is important after RTFOT + PAV and results in a transformation into resins; and
- The proportion of asphaltenes increases slightly, much less than the change observed with the n-heptane precipitation method (the difference comes from the fact that certain resins are dragged by the solvent in one case while in the other case they are precipitated).

With respect to the rheological behavior at low temperature, the BBR test shows little influence of RTFOT on the temperatures of iso-modulus 300 MPa and m = 0.300. On the other hand, the effect of RTFOT + PAV is important. For the hard asphalts tested, the magnitude of the changes is comparable with that observed on softer grades 35/50 and 50/70, namely a rise in 2°C to 3°C for the temperature of iso-modulus 300 MPa and 4°C to 7°C for the temperature of iso-slope m = 0.300.

TABLE 5 Data on Hard Asphalts Produced in France for High-Modulus AC

Avis Technique	26	96	76	22	72	42	40
Asphalt Before Aging							
Penetration (0.1 mm) at 25°C	16	21	21	12	13	13	16
R&B (°C)	63.5	66	68	72	66	65	71
IP (LCPC)	+0.7	+1	+1.3	+0.4	+0.4	–0.2	+0.5
Fraass temperature (°C)	–6	–8	–6	–5	–6	+3	–3
Modulus E (MPa) (7.8 Hz; 25°C)	54	40	34	60	56	61	66
Phase angle (°) (7.8 Hz; 25°C)	37	39	38	35	29	34	—
Modulus E (MPa) (7.8 Hz; 60°C)	0.6	0.6	0.5	0.9	0.9	0.6	1
Phase angle (°) (7.8 Hz; 60°C)	64	62	63	62	64	64	59
Modulus E (MPa) (250 Hz; 60°C)	6	6	5	8	9	7	10
Phase angle (°) (250 Hz; 60°C)	63	56	57	59	60	67	61
Asphalt After RTFOT							
Penetration at 25°C	11	17	18		7/13		
Residual Penetration (%)	69	83	86				
R&B (°C)	75	72	74		62/76		
Increase in R&B (°C)	11.5	6	6				
Fraass temperature (°C)	–4	–6	–6		0/+4		
Increase in Fraass temperature (°C)	+2	+2	0				
Modulus E (MPa) (7.8 Hz; 25°C)	71	39	39				
Phase angle (°) (7.8 Hz; 25°C)	28	35	36				
Modulus E (MPa) (7.8 Hz; 60°C)	1.2	0.72	0.7				
Phase angle (°) (7.8 Hz; 60°C)	60	58	58				
Modulus E (MPa) (250 Hz; 60°C)	10	6	6				
Phase angle (°) (250 Hz; 60°C)	53	54	54		47		

NOTE: LCPC = Laboratoire Central des Ponts et Chaussées.

Tests carried out on two 10/20 asphalts with an initial R&B softening point of 64°C showed, after RTFOT + PAV, a hardening slightly less than for the softer asphalts but nevertheless important: the increase in R&B is 11°C to 13°C, residual penetrability is 45 to 53 percent. The R&B temperatures on aged asphalt exceed here the threshold value of 71°C, which had been correlated with the observation of surface cracking of wearing courses attributed to thermal fatigue. However, these correlations were made on asphalt mixes with 35/50 and 50/70 asphalts (*6*) and cannot be extrapolated directly to the harder grades.

Practical Indications for Use of Hard Asphalts

The higher viscosity of hard grade asphalts necessitates raising the coating temperature; for 10/20 asphalts it will be around 170°C to 180°C. Laying of the mix must be carried out between

150°C and 170°C, approximately, and compaction must in general be carried out at a temperature higher than 140°C. Hence, to achieve correct compaction thin lifts should not be laid when the ambient temperature is low.

HIGH-MODULUS AC

Interest created by the use of hard asphalts—i.e., of grade lower than 25—is reflected by the diversity of the uses which have developed since 1980. The corresponding pavement materials are now standardized under the names of *“enrobé à module élevé* (EME)*”*, for use in base course, and of *“béton bitumineux à module élevé* (BBME)*”*, for use in binder and wearing courses. (Alternatives to the use of hard-grade plain asphalt were also developed during the same period, such as adding asphaltite or polyethylene to 35/50 asphalts, but these solutions will not be developed in this paper.)

Field of Application of Hot-Mix Asphalt Concrete

The first applications of hot-mix asphalt concrete (HMAC) in 1980 involved reinforcement or rehabilitation projects operating with depth constraints. In urban areas, in particular, buried pipes, curbs, and other thresholds frequently limit the depth of possible excavation.

This problem led road contractors to seek pavement materials having a higher modulus than traditional AC in order to produce thinner layers while having a high fatigue resistance so that the solution offers the same service life without premature structural maintenance operation.

The first material of this kind appeared in 1980 patented under the name of GBTHP (“*Grave Bitume à Très Hautes Performances*”). The first applications on state roads began in 1981 as base courses in reinforcement after or without milling or partial excavation of the old pavement (*7*). However, the number of applications became really significant only after 1985—that is, 4 to 5 years after the very first applications.

The oil crises were also a factor which stimulated the search for solutions reducing the quantity of asphalt while maintaining the performance criteria for the pavement. Thus, HMAC was used not only in rehabilitation works, but also in base courses for new pavements, resulting in an economic benefit over traditional solutions using 35/50 or 50/70 grades. It was also imagined to take benefit from the performance of hard asphalts to allow the use of local aggregates with a weak crushing index. The use of HMAC in base courses of new pavements initially appeared on toll motorways. The 1994 edition of *SCETAUROUTE’s Manual of Pavement Design for Motorways* (*8*) considers the use of HMAC in base course on an unbound subbase, or in full-depth asphalt pavements (subbase and base courses in HMAC). The new 1998 edition of the Road Directorate’s catalogue of new pavements also considers this use of HMAC (*9*).

To reduce the risk of rutting, HMAC has very often been combined with very thin AC (VTAC) (*Béton Bitumineux Très Mince, BBTM*) as a wearing course. This solution for heavily trafficked pavements benefits from the advantages both techniques:

- The low voids content and high stiffness of HMAC provides protection to the base course and great resistance to rutting; and
- The high surface texture due to the discontinuous grading of VTAC provides high and durable skid resistance.

Because of the hardness of the asphalt and of the low voids content of these mixtures, a wearing course is necessary to get enough surface texture and to ensure the thermal protection of the HMAC base layer.

During the 1980s, the road contractors prompted the production of these hard binders and developed AC mixes to answer the above-mentioned objectives. Specific productions of asphalt not calling upon the old process of blowing (because of the sensitivity to thermal cracking) were started. Because of the level of development reached by HMAC, its diversification among all major road contractors, and the experience gained in pavement construction, it was decided to codify this technique in an AFNOR standard, published in October 1992, under reference NF P 98-140 (*10*).

Characteristics of HMAC

The basic idea of HMAC was to design a mix with a very hard grade asphalt at a high binder content, around 6 percent (ratio by weight of the asphalt to the aggregate), comparable with that of AC used in wearing courses. The hard grade of the asphalt confers a higher modulus to the mix which allows, with equal thickness, to reduce the stresses transmitted to the subgrade; enrichment of the asphalt content makes it possible to increase the compactness of the mix and its resistance to fatigue.

Mix are designed in order to permit laying of lifts 7 to 15 cm thick. Figure 4 shows a typical continuous grading curve for a 0/14 mm HMAC.

Because of the higher binder content, as compared to traditional base AC, HMAC will exhibit lower air voids content for the same number of gyrations in the gyratory shear compaction test, as shown by Figure 5.

The standard distinguishes two classes of performance for HMAC:

- EME 2, corresponding to the first generation of these materials; and
- EME 1, introduced only since 1988, with a reduced asphalt content close to that of traditional base AC. Since these materials exhibit lower durability and resistance to fatigue, they are rather used for the layers subjected to compression, their advantage being resistance to rutting. Their use has, however, hardly developed.

Table 6 summarizes the performance requirements fixed by standard NF P 98-140 for the two classes of HMAC and, by comparison, that of a traditional base AC ("*grave-bitume*" of class 2 of French AFNOR standard NF P 98-138).

As seen from Table 6, for EME2 the requirement for the binder content is a minimum richness factor *K*, of 3.4. This *K* factor is defined by the following equations:

$$K = \frac{TL}{\alpha \sqrt[5]{\Sigma}}$$

where

TL = binder content (ratio by weight of asphalt to aggregate)
α = 2.65/*Gse* (*Gse* effective specific gravity of aggregate)

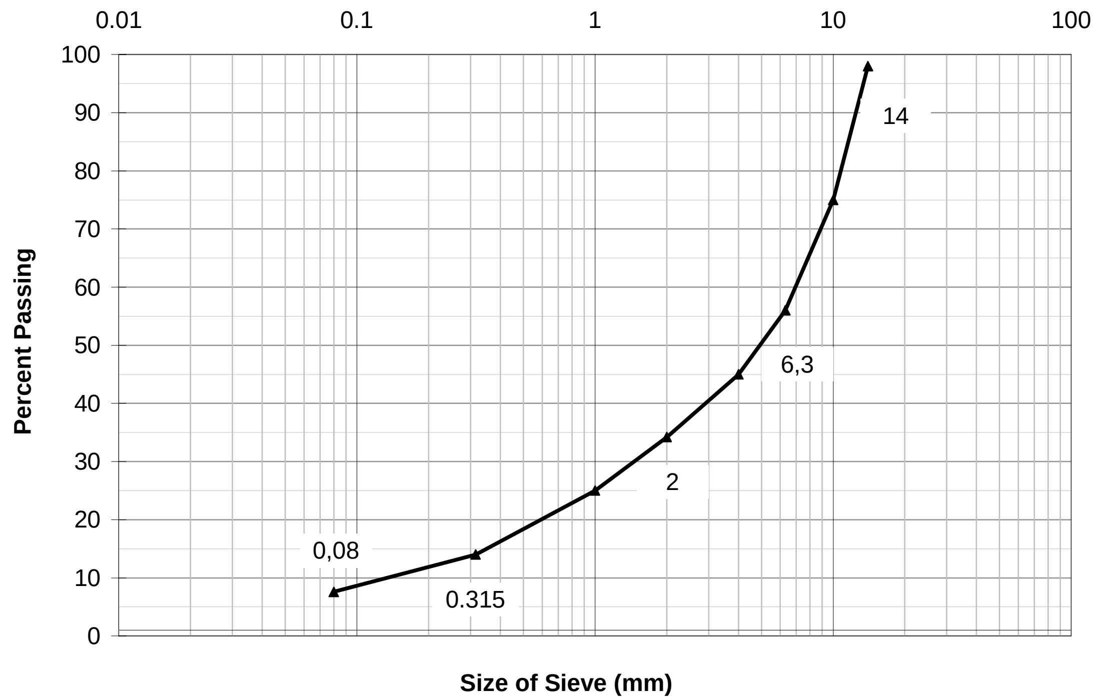

FIGURE 4 Sieve analysis = typical grading for a 10/14mm HMAC with 6.2 percent asphalt content.

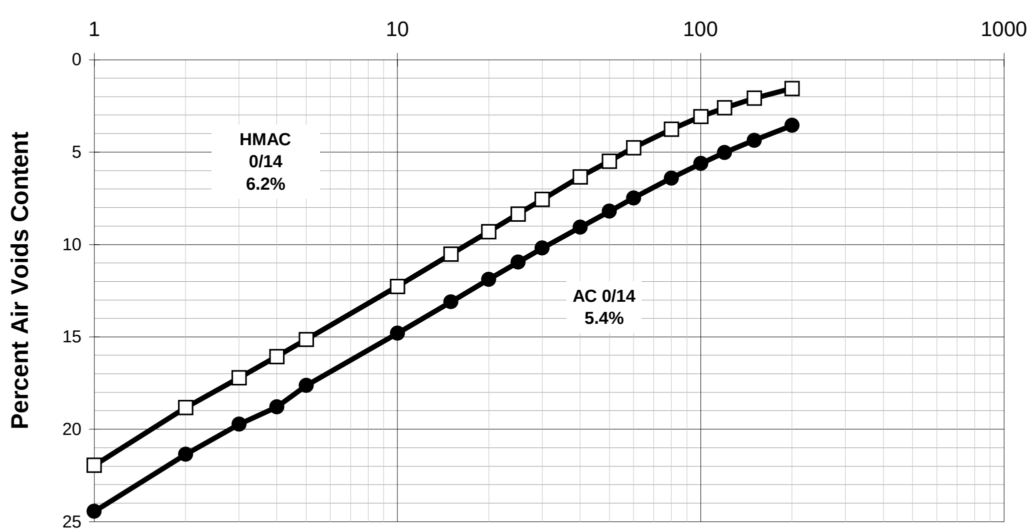

FIGURE 5 Gyratory shear compaction tests: comparison between HMAC and a traditional base asphalt concrete.

$$100\Sigma = 0.25G + 2.3S + 12s + 135f$$

G = % > 6.3 mm
S = % between 6.3 and 0.315 mm
s = % between 0.315 and 0.08 mm
f = % < 0.08 mm

Hence the asphalt content depends on the gradation of the mix. For a 0/14 mm HMAC this leads to a minimum binder content by weight (with respect to the aggregate weight) of about 5.7 percent.

Stiffness

The use of hard asphalt as a binder increases the stiffness of the asphalt mix. This is illustrated by Figure 6, which presents the master curves of the complex modulus *E** determined for a traditional dense asphalt mix made with a 50/70 PG asphalt, a HMAC and the same dense asphalt mix made this time with an Ethylen-Vinyle-Acetate (EVA) modified asphalt.

Resistance to Rutting

It has been known for a long time that there is a narrow correlation, at service temperatures, between the modulus of the binder and that of the asphalt mix and that the increase in modulus of the binder is accompanied by a reduction of the sensitivity to permanent deformations (*11*). This good resistance of HMAC can be judged from the results with the LCPC wheel-tracking rutting tester at 60°C (standard NF P 98-253-1), which is used to fix the French specifications with respect to rutting. A series of tests were carried out to determine the influence of the binder on the performance of asphalt mixes having the same aggregate skeleton. The tests involved 10/20 and 50/70 PG, multigrade-type asphalt, polymer-modified asphalts with 4 percent Styrene-Butadiene-Styrene or 7 percent EVA, and the addition of polyethylene or fibers. Results obtained with the

TABLE 6 Performance Requirements Fixed by Standard NF P 98-140 for HMAC and Comparison with a Base AC "Grave-Bitume" of Class 2

	EME 1	**EME 2**	**GB 2**
Granularity and average thickness of lifts	0/10 6 to 10 cm 0/14 7 to 12 cm 0/20 10 to 15 cm	0/10 6 to 10 cm 0/14 7 to12 cm 0/20 10 to 15 cm	0/14 8 to 12 cm 0/20 10 to 15 cm
Minimum richness factor for asphalt content (*K*)	≥2.5	≥3.4	≥2.5
Binder content for 0/14 grading	≥4.2 pph	≥5.7 pph	≥4.2 pph
Duriez test (*r*/*R*)	≥0.70	≥0.75	≥0.65
Wheel-tracking rutting test (60°C, 30,000 cycles)	≤7.5 %	≤7.5 %	≤7.5 %
Modulus (MPa) (15°C, 10 Hz)	≥14,000	≥14,000	≥9,000
Fatigue test ε_6 (10^{-6}) (15°C, 25 Hz)	≥100	≥130	≥80
Max voids content (%)	≤10	≤6	≤11

NOTE: EME = enrobé à module élevé, GB = grave-bitume.

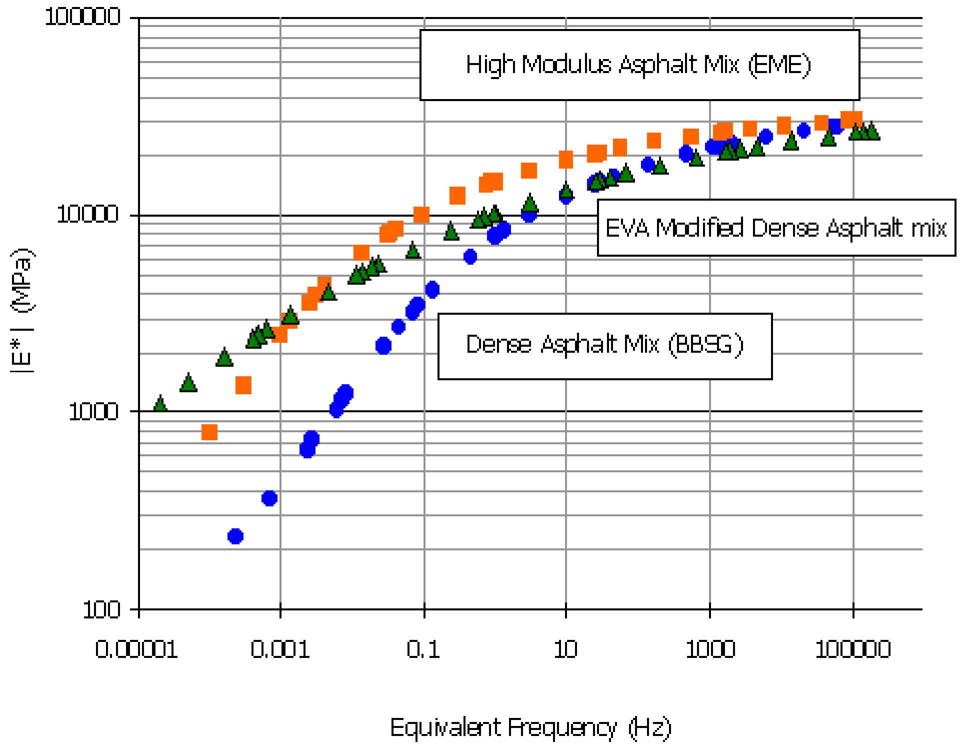

FIGURE 6 Complex modulus master curves on three different asphalt mixes (BBSG = Béton Bitumineaux Semi-Grenu).

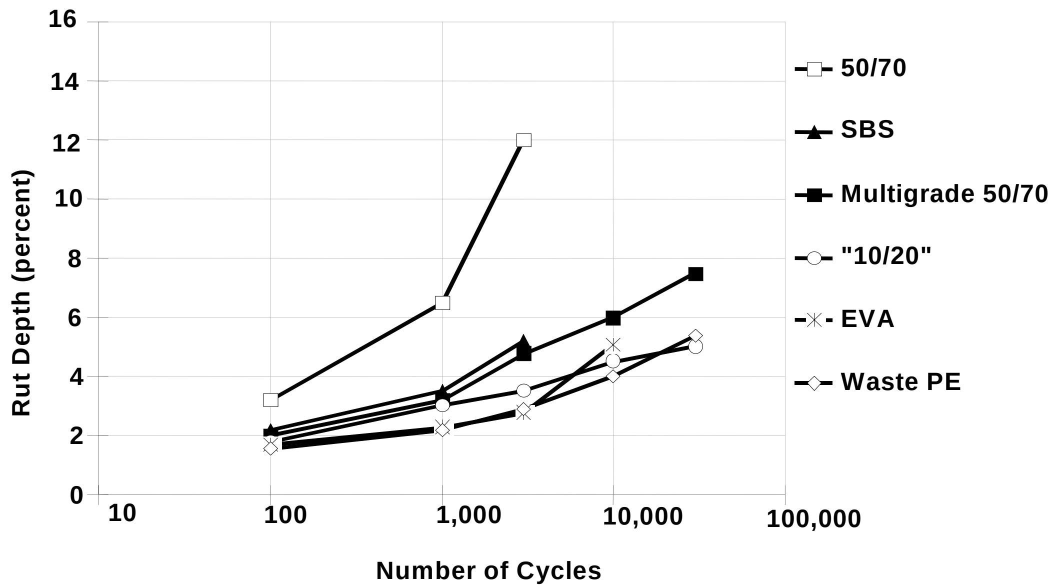

FIGURE 7 Wheel-tracking test results showing the influence of the asphalt binder on the resistance to rutting of similar AC mixes (PE = polyethylene).

FIGURE 8 View of LCPC's accelerated pavement testing facility.

LCPC wheel-tracking rutting tester are shown in Figure 7. The assessments from these laboratory tests have been confirmed by experiments with LCPC's accelerated loading test facility (Figure 8). These full-scale experiments confirmed the very good behavior of HMAC + VTAC in resistance to rutting and in durability of surface macrotexture (*12, 13*).

Resistance to Fatigue

Resistance to fatigue cracking is assessed by the two-point bending test on trapezoidal samples with controlled displacement imposed at the top of the beam. The higher asphalt content together with the lower air voids content in HMAC as compared to traditional base AC provide a better resistance to fatigue as indicated by the increase in the strain for which failure as reached after 10^6 cycles. The HMAC standard requires a minimum value of 130 10^{-6} for ε_6 for EME2 when the requirement is only 80 10^{-6} with a traditional base such as AC GB2 (see Table 6). A typical example of fatigue curves is shown by Figure 9. The mean value of the slope of the fatigue curve found over 16 different HMACs was –1/6 (with values ranging from a minimum of –1/7.5 to a maximum of –1/5.2). The mean value is –1/5 for traditional base AC.

Pavement Design with HMAC

The French pavement design method (*4*) can be described as a rational approach which makes use of a mechanical model together with the results of complex modulus and of two-point bending fatigue tests. Taking into account certain simplifications of the model and the approximate character of the fatigue laboratory test, the calculation of the working strains $\varepsilon_{t,ad}(N)$ uses a shift factor k_c which is derived from an adjustment between model predictions and monitoring of in-service pavements.

$\varepsilon_{t,ad}(N) = \varepsilon_6 f(N) k_c$

where N stands for the number of load cycles to failure and ε_6 is the applied strain at failure after a million cycles in the two-point bending fatigue test.

For the traditional techniques, which have been under a long period of observation (i.e., traditional pavement structures have sustained traffic for at least as long as the project service life), the shift factor was determined by consideration of a representative set of monitored pavements. In the case of the introduction of a new technique like HMAC, design of such pavements was made possible by using the results of accelerated loading tests. To this end, LCPC carried out a series of three experiments between 1990 and 1994 in cooperation with the toll-motorways companies association. Each trial ring comprised four relatively thin asphaltic base layers (8 to 12 cm) resting on an untreated subbase. The results of these experiments (development of cracking versus the number of load cycles) were analyzed in a manner relating the behavior of the various sectors (*14*). From these experiments it was concluded that a lower shift factor should be used for HMAC than for pavements with traditional base AC (respectively 1 and 1.3). However, because of the large difference in fatigue resistance, the working strain of HMAC will still be larger. Combining k_c and ε_6 values from Table 6 gives for traditional base; AC GB2, $\varepsilon_{t,ad}(N) = 104f(N)$; and for HMAC, $\varepsilon_{t,ad}(N) = 130f(N)$.

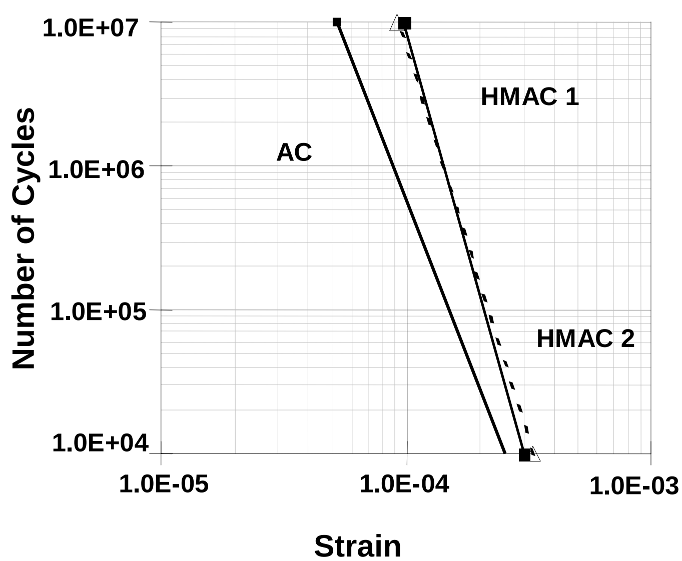

FIGURE 9 Two-point bending fatigue tests (one traditional base AC, two HMACs having the same composition but different hard asphalt).

Illustration of the Possible Economic Gain with the Use of HMAC

The potential saving in the cost of a new pavement when using HMAC as compared to a traditional base concrete solution, can be illustrated by the following examples.

The first one is taken from the 1997 SCETAUROUTE's catalogue. Table 7 presents a comparison for flexible pavements between a HMAC solution as a base layer and a traditional base AC. With the HMAC solution, the reduction in thickness represents 33 percent of the total thickness of the asphaltic layers. If one considers now the asphalt quantities, because of the higher binder content and the lower voids content of the HMAC, the difference between the two solutions is reduced to approximately 24 percent.

The second example presented in Table 8 is related to full-depth asphalt pavements; it is taken from the 1998 French Road Directorate catalogue (*9*). Here the reduction in total thickness of the pavement is 25 percent, which represents about the same reduction in the quantity of aggregate; the reduction in the asphalt quantity is only 4.5 percent. The French Road Administration has preferred to adopt a binder layer to provide protection to the HMAC base course.

Assessment of Performance of HMAC Pavements

In 1997, an assessment of the performance of HMAC pavements built since the beginning of the 1980s was published (*15*). This report covered the use of over 10 million tons of asphalt mix at 47 sites, with pavements from 2 to 14 years old. The conclusions can be summarized as follows:

- For pavements between 2 and 6 years of age, there were no or only minor degradations,
- For pavements between 6 and 10 years old, the percentage of cases presenting cracks grew but the gravity of cracking was low to moderate,
- For the oldest sites, the cracking was similarly moderate and did not require maintenance.

TABLE 7 Comparison Between HMAC and Traditional AC Solution for Flexible Pavements (1997 SCETAUROUTE's *Manual*)

	Flexible pavement **Traffic: 600 HV/day, 4% increase/year, 15-year design** **Subgrade modulus: 120 MPa**	
	Traditional AC solution	HMAC solution
	Wearing course: 2.5 cm *BBTM* Binder course: 6 cm *BBL* Base course: 13 cm *GB3* Subbase: 20 cm unbound gravel	Wearing course: 2.5 cm *BBTM* Base course: 12 cm *EME2* Subbase: 20 cm unbound gravel
Difference in thickness of asphalt layers	7 cm (33%)	
Difference in asphalt quantity	–24%	
Difference in aggregate	–33%	

BBTM: béton bitumineux très mince (VTAC)
BBL: béton bitumineux de liaison (AC for binder layers)
GB3: grave-bitume class3 (base AC)
EME2: enrobé à module élevé class 2 (HMAC for base layers)

TABLE 8 Comparison of HMAC and Traditional AC Solution for Full-Depth Asphalt Pavement (1998 Road Directorate's Catalogue)

	Full-depth asphalt pavement Traffic: 20 million ESALs (130 kN) Subgrade modulus: 120 MPa	
	Traditional AC solution	**HMAC solution**
	Wearing course: 2.5 cm *BBTM* Binder course: 6 cm *BBL* Base course: 14 cm *GB2* Subbase: 14 cm *GB2*	Wearing course: 2.5 cm *BBTM* Binder course: 6 cm *BBME* Base course: 9 cm *EME2* Subbase: 10 cm *EME2*
Difference in thickness of asphalt layers	–9 cm (25%)	
Difference in asphalt quantity	–4.5%	
Difference in aggregate	–24%	

BBTM = béton bitumineax trés mince (VTAC)
BBL = béton bitumineax de liaison (AC for binder layers)
GB2 = grave bitume class 2 (traditional AC for base layers)
EME2 = enrobé à module élevé class 2 (HMAC for base layers)
BBME = béton bitumineux à module élevé (HMAC for binder layer)

Transverse cracks were found in two cases only, which shows that thermal cracking is, in the French climatic context, a marginal phenomenon with these hard asphalts used in base course.

Low-Temperature Cracking

It is interesting to report here the extreme case of a trial section with a high-modulus AC made with a very hard asphalt. Initial characteristics were a penetration of 5/10 mm, a R&B softening point of 88°C which led to a Young modulus for the HMAC of 21,600 MPa (direct tension test at 15°C and 0.02 s). Tests on the recovered binder from a core taken from the pavement gave a softening point of 93.5°C, and BBR's temperatures $T_{m = 0.300}$ = +1.7°C and $T_{G = 300}$ = –5.7°C (T_m is the temperature when the slope m of the creep curve = 0.300; T_G is the temperature when the sheer modulus G = 300 MPa). Cracking was observed after the first winter, with minimum recorded temperatures of –10°C to –13°C.

HMAC for Surface Courses

The search for a solution for thick wearing courses, offering a good resistance to rutting, led to the definition of another kind of high modulus AC, the "*Bétons Bitumineux à Module Elevé,*" BBME, codified since 1993 in French AFNOR standard NF P 98-141. These materials can also be used in binder courses, too.

These mixes generally have a continuous grading of 0/10 or 0/14. The minimum richness factor for the 0/10 mixes is 3.5, which corresponds to an asphalt content of the order of 5.6 percent (by weight of aggregate) for aggregate with a density equal to 2.75.

The performance requirement for resistance to rutting is, in the case of heavy traffic, less than 5 percent rutting after 30,000 cycles for wearing courses and less that 7.5 percent rutting after 30,000 cycles for binder courses when the wearing course thickness is less than 5 cm.

The use of hard asphalt in the wearing course, which is the layer most exposed to temperature variations and thermal shocks, should be considered cautiously because of the risks of low-temperature cracking or thermal fatigue. In order to limit this risk, a proposal has been made to improve the performance of hard asphalt at low temperature by a modification with polymers. Table 9 presents the characteristics at low temperature of a plain 20/30 PG asphalt and of a hard asphalt modified by reticulation with a styrene-butadiene polymer. This product currently is in an experimental phase.

CONCLUSIONS

Hard asphalts, produced in France for nearly 20 years, have offered for the French climatic context very interesting technical solutions for rutting mitigation of asphalt pavements and for construction of stiff asphaltic base layers. Field performance has indicated no susceptibility to low temperature or thermal fatigue cracking. On the contrary, poor performance had been observed in the past with asphalts produced by air blowing; the search for very high IP values by means of air blowing is detrimental to durability.

The mechanical properties of the hard asphalts are strongly dependent on manufacturing process because this directly influences the composition and the colloidal structure of the asphalts. The rheological tests showed in particular that the results (modulus, phase angle) can vary within a broad interval for asphalts having the same PG at 25°C. This can result in significant differences in behavior at low temperature. Research appears to be still necessary, however, to better assess behavior at failure in order to identify the predominant factors linked to the composition of these asphalts.

To benefit from the qualities of these hard asphalts, it is necessary to have an adequate design for the mix. This cannot just be a simple substitution of the binder. It is worthwhile stressing that, in the concept of HMAC developed in France, these base materials are designed

TABLE 9 Low Temperature Characteristics of Plain 20/30 Asphalt and Styrene-Butadiene–Reticulated Hard Asphalt

	SB Reticulated Hard Asphalt	20/30 Plain Asphalt
Penetration (0.1 mm) at 25°C	27	25
Fraass temperature (°C)	–15	–10
Direct tensile test (5°C, 100 mm/min) Strain at failure (%) Energy at 400 percent strain (J/cm^2) at failure (J/cm^2)	 600 23 37	 fragile
Temperature G′′ (°C) (5 Hz) max	–7	–1
*G** (MPa) (–10°C; 5 Hz)	355	463
Phase angle (°) (–10°C; 5 Hz)	9.6	6.3
Temperature *G** (°C) (7.8 Hz) = 133.3 MPa	5.5	10

with a higher binder content and a lower air voids content. Such provisions are intended to compensate for problems with fatigue, the lower capacity of the hard-grade asphalts for healing as compared to the softer traditional grades.

Hard asphalts have mainly been used in base and binder courses with a surfacing which ensures a certain thermal protection. There is much less experience with HMAC in thick wearing courses, and questions remain with respect to the behavior at low temperature. A solution may be in a complementary modification with polymers or in multigrade-type asphalts.

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ADDITIONAL RESOURCES

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