Rutting Behaviour of Wearing Course Mixtures in Severe Temperature and Loading Conditions

RUTTING BEHAVIOUR OF WEARING COURSE MIXTURES IN SEVERE TEMPERATURE AND LOADING CONDITIONS

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ABSTRACT
Following the construction of a major motorway pavement in Northern Africa, relevant rutting phenomena were observed after opening to traffic. Preliminary investigations showed that permanent deformations were limited to the upper wearing course layer which was designed according to set requirements.

In order to define the most appropriate rehabilitation strategy, investigations were carried out by focusing on the volumetric and mechanical properties of the employed wearing course mixture. Compaction properties were assessed by making use of a gyratory shear compactor and of a rubber-wheeled roller. Moreover, simulative wheel-tracking tests were carried out in severe temperature and loading conditions. Additional tests were performed on an alternative bituminous mixture containing polymer granules.

Based on the obtained results the possible causes of the above described distress phenomena were identified and the use of the alternative bituminous mixture as a technical solution to adopt for rehabilitation was considered.

KEY WORDS: wearing course, compaction, rutting, wheel-tracking, polymers.

1. INTRODUCTION

The need to provide an efficient transportation system capable of supporting the social and economic development of emerging Countries has recently led to the conception and construction of an impressive infrastructure network in Northern Africa. As a result of such an effort, Administrations, road engineers and Contractors are facing specific construction and performance-related problems which are essentially due to the availability of materials and technologies and to specific external constraints associated to environmental conditions and traffic characteristics. In particular, in the case of flexible pavements, major concerns have been raised with respect to surface rutting, identified as a potentially significant distress because of the very high temperatures and as a consequence of very high loads applied by heavy vehicles.

In such a context, the Authors recently addressed the subject of rutting in wearing courses as part of a forensic investigation which was performed on a section of the East-West Motorway in Algeria. As illustrated in the following paragraphs, following the observation of significant rutting in the early phases of the service life of the pavement, laboratory tests were carried out to understand the origin of permanent deformation phenomena and to validate the adoption of a specific rehabilitation solution.

2. CASE STUDY

2.1 East-West Motorway

The Algerian East-West Motorway (“Autoroute Est-Ouest”) was conceived to connect the Tunisian border, in the East, to the Moroccan border, in the West, with an extension of 1,216 kilometers. This infrastructure will be part of the “Autoroute Maghrébine”, which for 7,000 kilometers will span from the Atlantic coast of Mauritania to the eastern border of Libya.

The motorway section (lot M1) which was subjected to the forensic study described in this paper has an extension of 26 kilometers and connects the cities of Bouira and El Adjba. Construction activities were carried out from August 2005 to December 2009, and various sub-sections were progressively opened to traffic, starting in July 2007, depending upon actual advancement of construction operations.

As indicated in design documents, the pavement cross section of the motorway included the following layers (from top to bottom):

- wearing course constituted by a BB 0/14 bituminous mixture (“béton bitumineux” 0/14 mm), with a thickness of 6 cm;
- base course constituted by a GB 0/25 bituminous mixture (“grave bitume” 0/25 mm), with a thickness of 15 cm;
- foundation layer constituted by a GC 0/25 unbound granular material (“grave concassée” 0/25 mm), with a thickness of 30 cm.

During the progression of construction works, the BB 0/14 wearing course mixture was the subject of several mix design studies which were performed by Algerian laboratories selected by the National Highway Agency. The first design recipe officially approved by the Administration was used for the construction of the sub-section opened to traffic in July 2007 and indicated a target bitumen content equal to 6.03%. All the other sub-sections which were completed after July 2007 were built by referring to a second mix design, in which optimal bitumen content was set equal to 5.60%. Aggregate grading curves of the two studies were similar even though they were obtained by employing aggregates provided by different quarries. As prescribed by technical specifications [1], 40/50 penetration grade bitumen was employed throughout the project.

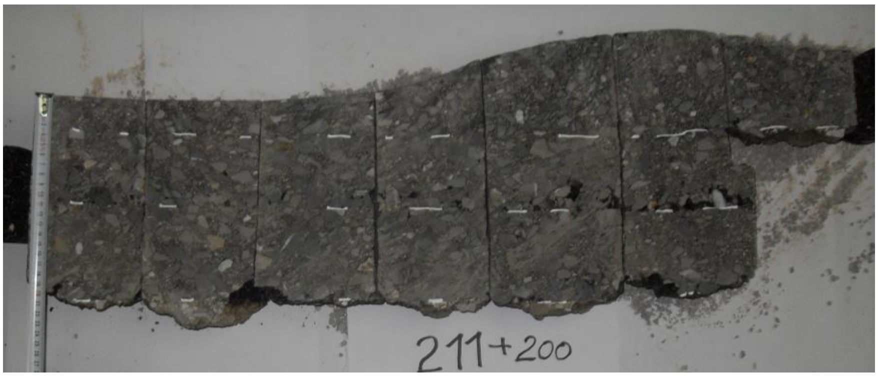
Quality control of the BB 0/14 mixture yielded results which were in large part coherent with specifications and mix design studies. However, during the construction of the motorway section, it was reported that the softening point of bitumen, required to be within the 47-60°C range, was characterized by a high degree of variability, with values very often close to the lower acceptance limit.

2.2 Observed rutting phenomena

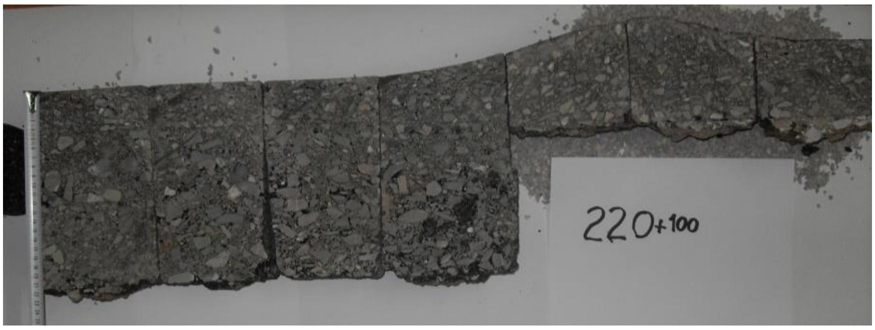
Almost immediately after opening to traffic of the first subsection, rutting phenomena were observed on both carriageways. These were reported to be mainly concentrated along the slow lane in uphill stretches in the direction of Algiers. A topographical survey was therefore carried out in selected sections of the motorway in order to assess their level of severity. Moreover, cores were taken from the pavement and the thickness of the layers was checked to identify those which were actually involved in the accumulation of permanent deformation. Based on these preliminary observations, it was concluded that only the BB 0/14 wearing course was affected by the phenomenon and that the distress would be monitored in time with further topographical measurements in order to detect its evolution under the effects of repeated traffic loading.

Regardless of the fact that for all the other sub-sections the reference recipe was changed (reducing bitumen content to 5.60%), even in those portions of the motorway rutting occurred after they were opened to traffic.

Topographical measurements showed that in all sub-sections rutting tended to significantly progress in time, reaching rut depths of the order of 5-6 cm. Moreover, it was confirmed that only the surface layer was responsible for the creation of ruts. This is clearly shown in Photographs 1 and 2, which were taken from cores extracted from the pavement in October 2009. They refer to two transverse sections (“A” and “B”) which had been under traffic respectively for 28 months (including 3 Summer seasons) and 8 months (including just one Summer). In both cases it can be seen that rut formation led to a significant reduction of the thickness of the wearing course under the loading tracks, associated to an impressive lateral flow of the mixture. It is also apparent that interfaces between the various layers remained almost undeformed.



Photograph 1 Cores taken from transverse section A (28 months traffic)



Photograph 2 Cores taken from transverse section B (8 months traffic)

3. INVESTIGATION ON THE BB 0/14 MIXTURE

Experimental investigations focused on the BB 0/14 wearing course mixture produced in a continuous-type mixing plant according to the second job-mix formula approved by the Road Administration (5.60% target bitumen content). Sampling was carried out at the construction site and the material was thereafter transferred to the laboratory. Testing included the evaluation of composition, a two-stage compaction study and wheel-tracking tests.

Composition tests showed that average binder content of the mixture (EN 12697-39), equal to 5.64%, was very close to the design value (5.60%) and to values recorded during quality control operations. Aggregate gradation (EN 933-1), of the continuous type, satisfied specification limits (Figure 1).

3.1 Compaction study

The preliminary stage of the compaction study was performed by making use of a gyratory shear compactor (600 kPa vertical pressure, 1.25° deviation angle, 30 rpm gyration speed). Compaction temperature was set at 150°C coherently with normal practice followed on site by the Contractor. The number of gyrations was set equal to 200 in order to have a full assessment of the compaction properties of the mixture as explicitly required by EN 12697-31. Since maximum diameter of the aggregates contained in the mixture was equal to 20 mm, moulds with an inner diameter of 100 mm were employed.

Gyratory-compacted specimens were subjected to full volumetric characterization. Based on obtained results, compaction curves were then represented in the form of percent compaction (C) as a function of the number of gyrations (N) in the semi-logarithmic plane. A linear model was fitted to the data recorded in the first 100 gyrations ($C = C_1+k_C \cdot \log N$), for the assessment of self-compaction (C_1) and workability (k_C). The linear model was also used to calculate percent compaction at any given number of gyrations without the need of preparing additional specimens.

Table 1 contains average values of the considered parameters derived from three replicates. Results include percent compaction calculated at 100 gyrations (C_{100}), which is often used both in mix design and in quality control as a reference for the evaluation of the effectiveness of field compaction.

Table 1 Results of the preliminary compaction study of the BB 0/14 mixture

Theoretical maximum density (TMD, g/cm^3)	2.476
Bulk density (D, g/cm^3)	2.457
Percent voids at 200 gyrations (%v, %)	0.8
Voids in the mineral aggregate at 200 gyrations (VMA, %)	13.5
Voids filled with bitumen at 200 gyrations (VFB, %)	94.3
Self-compaction (C_1, %)	79.2
Workability (k_C, %/logN)	10.0
Compaction at 100 gyrations (C_{100}, %)	98.5

It can be observed that indeed, as required by EN 12697-31, the BB 0/14 mixture reaches at 200 gyrations a state of compaction which is quite close to limiting conditions, with a percentage of residual voids smaller than 1%. If compared to typical values of wearing course mixtures, self-compaction and workability parameters (C_1 and k_C), respectively equal to 79.2 and 10.0, are remarkably high. This leads to an early densification of the mixture which in fact at 100 gyrations reaches 98.5% compaction. This is due to the combined effects caused by quantity and rheology of the binder (and of the filler-bitumen mastic) and by the packing characteristics of aggregates.

The second stage of the compaction study was based on the preparation of roller-compacted slabs (EN 12697-33, large size device). It was considered that slabs should necessarily mimic compaction obtained during construction, for which an average void content of 4.5% (95.5% compaction) was recorded. Such a value corresponds to 97% of the reference compaction value (C_{100}) obtained during the first stage of the laboratory investigation (Table 1). Thus, variability of field compaction was taken into account by defining an admissible range of slab density, corresponding to 95-99% of the reference density of gyratory specimens. This assumption, coherent with field data, is compatible with uncertainties associated to the volumetrics of roller-compacted slabs.

Table 2 contains the results of volumetric tests carried out on four slabs prepared at the same compaction temperature adopted for gyratory specimens (150°C). It should be noticed that the mixture is characterized by very high VFB values (average equal to 75.7%).

Table 2 Volumetric characteristics of BB 0/14 roller-compacted slabs

ID slab	T1	T2	T3	T4	Mean
Bulk density (D, g/cm3)	2.358	2.393	2.352	2.406	2.377
Percent voids (%v, %)	4.8	3.3	5.0	2.9	4.0
Compaction (C, %)	95.2	96.7	95.0	97.1	96.0
Voids in the mineral aggregate (VMA, %)	17.0	15.7	17.2	15.3	16.3
Voids filled with bitumen (VFB, %)	71.9	78.8	70.9	81.4	75.7
Percent of the effective C_{100} (C/C_{100}, %)	96.7	98.1	96.4	98.6	97.5

3.2 Wheel-tracking tests

Roller-compacted slabs were subjected to wheel-tracking tests performed according to EN 12697-22. Severe environmental and loading conditions met on site were simulated by carrying out tests at 60°C with a maximum number of applied loading cycles equal to 30,000 [2]. Vertical permanent strain in the wheel path was measured in 15 control points after 1,000, 3,000, 10,000 and 30,000 cycles. Corresponding results are listed in Table 3.

Table 3 Results of wheel-tracking tests (mixture BB 0/14)

ID Slab	B1	B2	B3	B4	Mean
Permanent strain at 1,000 cycles (%)	3.4	3.9	3.7	4.9	4.0
Permanent strain at 3,000 cycles (%)	4.7	4.9	5.0	6.6	5.3
Permanent strain at 10,000 cycles (%)	5.9	6.6	5.9	8.7	6.8
Permanent strain at 30,000 cycles (%)	7.7	8.0	7.3	10.1	8.3

4. INVESTIGATION ON AN ALTERNATIVE MIXTURE

Observations made on site (paragraph 2) and results obtained in the tests carried out on the BB 0/14 (paragraph 3) clearly indicated that it was necessary to remove the existing wearing course from the pavement and to substitute it with a mixture less susceptible to rutting. However, because of the logistic constraints of the project, it was considered unpractical to try to optimize the composition of a new mixture by employing aggregates and bitumen different from those already available locally. Thus, based on the positive performance records which have been reported in literature [3,4], the use of polymers to be added directly in the mixing plant was considered as a valid solution to the problem.

A first validation of the proposed solution was performed by considering, as a candidate wearing course mixture, the EMA 0/10 (“enrobé à module amélioré”, 0/10 mm) produced by another Contractor and laid on a nearby section of the motorway (lot M2), were reportedly no rutting had occurred.

The mixture, designed according to different specifications, contained 0.4% anti-rutting polymer granules (by weight of the aggregates), with a target bitumen content equal to 5.6%. It was sampled from site and thereafter subjected to the same tests carried out on the BB 0/14 (paragraph 3).

Unfortunately, no data was available on the volumetric properties of the field-compacted mixture. Thus, roller-compacted slabs were considered representative of field conditions when satisfying the same criterion defined for BB 0/14 (95-99% of the reference gyratory density). Since the presence of polymers in the mixture significantly increases viscosity and affects self-compaction and workability, compaction temperature in the laboratory was conveniently increased and set equal to 170°C.

Results of composition tests showed that the EMA 0/10 had a slightly lower binder content (5.46%) and a finer and more discontinuous aggregate gradation than BB 0/14 (Figure 1).

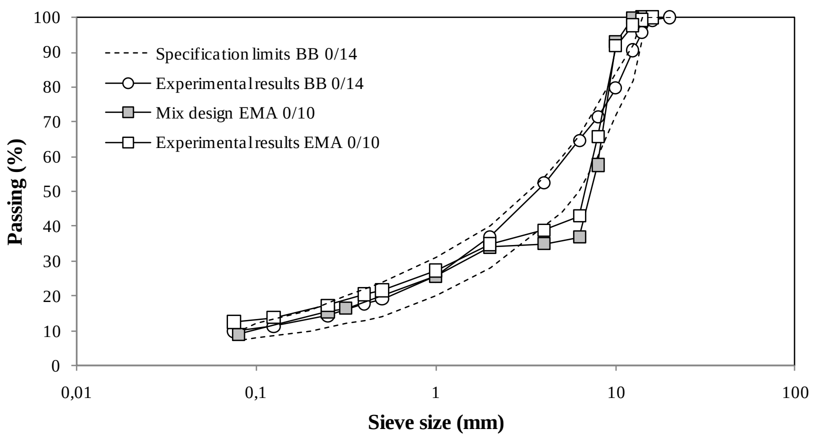


Figure 1 Aggregate size distribution of the bituminous mixtures

Results obtained in the tests carried out as part of the compaction study are shown in Tables 4 and 5. It was thus observed that despite the higher compaction temperature (170 vs. 150°C) the EMA 0/10, as a result of different packing characteristics of the aggregates and of a more viscous behavior of the binding mastic, reached with both laboratory equipment a slightly lower compaction level when compared to BB 0/14. The average difference in void content was equal to 0.5% in the case of gyratory specimens and to 1.0% in the case of roller-compacted slabs. Self-compaction and workability parameters derived from compaction curves were also very similar.

Interesting variations were observed in the case of those volumetric properties of the roller-compacted slabs which are related to the internal structure of the mixtures (VMA and VFB). In fact, even though average VMA values were quite similar (16.3% for BB 0/14, 16.8% for EMA 0/10), VFB values were significantly different (75.7% for BB 0/14, 70.7% for EMA 0/10).

Table 4 Results of the preliminary compaction study of the EMA 0/10 mixture

Theoretical maximum density (TMD, g/cm^3)	2.492
Bulk density (D, g/cm^3)	2.469
Percent voids at 200 gyrations (%v, %)	0.9
Voids in the mineral aggregate at 200 gyrations (VMA, %)	13.3
Voids filled with bitumen at 200 gyrations (VFB, %)	93.3
Self-compaction (C_1, %)	79.1
Workability (k_C, %/logN)	9.7
Compaction at 100 gyrations (C_{100}, %)	98.0

Table 5.Volumetric characteristics of EMA 0/10 roller-compacted slabs

ID slab	E1	E2	E3	E4	Mean
Bulk density (D, g/cm3)	2.336	2.387	2.368	2.352	2.361
Percent voids (%v, %)	6.2	4.2	4.4	5.0	5.0
Compaction (C, %)	93.8	95.8	95.6	95.0	95.0
Voids in the mineral aggregate (VMA, %)	18.0	16.2	16.3	16.8	16.8
Voids filled with bitumen (VFB, %)	65.3	74.0	73.1	70.3	70.7
Percent of the effective C_{100} (C/C_{100}, %)	95.7	97.7	97.6	96.9	97.0

Table 6 Results of wheel-tracking tests (mixture EMA 0/10)

ID Slab	E1	E2	E3	E4	Mean
Permanent strain at 1,000 cycles (%)	0.9	1.4	1.1	0.8	1.0
Permanent strain at 3,000 cycles (%)	1.1	1.8	1.4	1.1	1.4
Permanent strain at 10,000 cycles (%)	1.4	2.1	1.6	1.3	1.6
Permanent strain at 30,000 cycles (%)	1.4	2.1	1.8	1.5	1.7

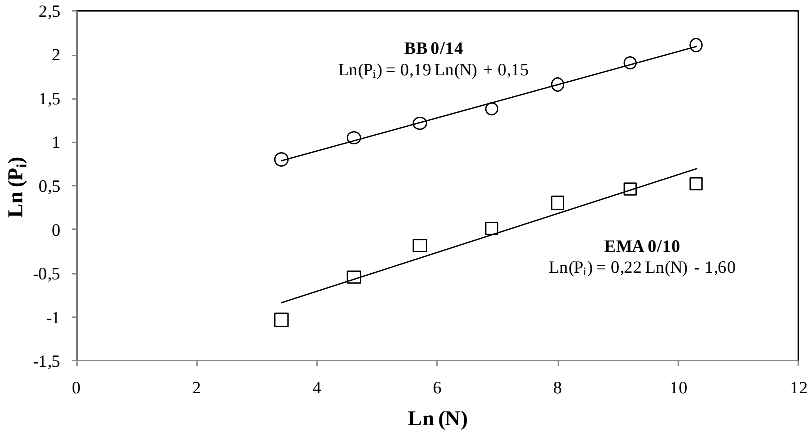


Figure 2 Rutting curves of the bituminous mixtures

Results of wheel-tracking tests carried out on EMA 0/10 slabs are given in Table 6. Listed permanent strain values indicate that such a mixture exhibited a higher resistance to rutting than BB 0/14, with significantly lower strains at every number of loading cycles. This can also be seen in Figure 2, where rutting curves of the mixtures have been represented as suggested by EN 12697-22:

$$\mathrm{Ln}(P_i) = a \cdot \mathrm{Ln}(N) + b \qquad \text{(eq.1)}$$

where P_i is vertical permanent strain, N is the number of loading cycles, a and b are regression coefficients.

Even though technical specifications did not indicate limiting values of permanent deformation, results at 30,000 loading cycles were compared with requirements which are set by the French standard (NF P 98-141) for wearing course mixtures of the BBME (béton bitumineux à module élevé) type. The standard refers to three different classes of mixtures (1, 2 and 3), of increasing rutting resistance, for which the maximum strain is set at 10, 7.5 and 5%.

It was thus observed that the BB 0/14 mixture has an average rutting performance which is comparable to BBME mixtures of the less performing class (class 1), while the EMA 0/10 mixture exhibits a response under repeated loading which is compatible with requirements set for class 3, characterized by the best resistance to rutting.

Figure 3 provides a synthetic illustration of the correlations between volumetric and mechanical properties of the slabs subjected to testing.

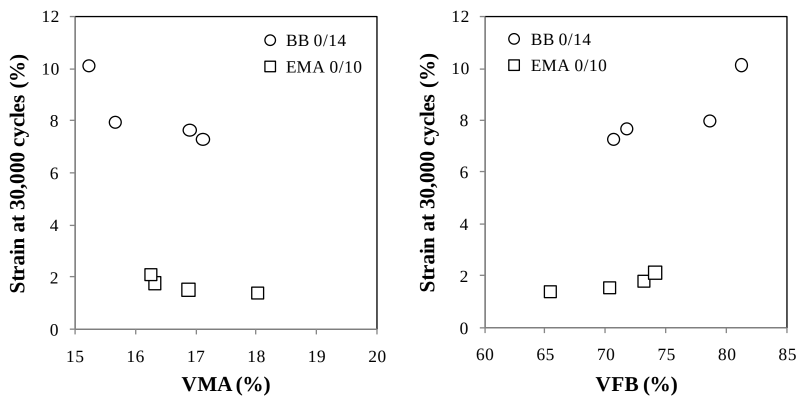


Figure 3 Correlations between volumetric and mechanical properties

For both bituminous mixtures, vertical strain at 30,000 cycles increases as the VFB is increased (i.e. as the bituminous binding mastic absorbs increasing portions of the applied loads), regardless of the fact that VMA is correspondingly reduced (i.e. as a closer aggregate packing is achieved). However, the strain level achieved by the two mixtures is clearly different because of their different aggregate structure and binder rheology.

These observations clearly indicate that in both cases permanent deformation is associated to viscous flow of the binding mastic rather than to post-compaction phenomena. Accordingly, it is convenient to adopt a binder characterized by enhanced stiffness properties at high temperatures in order to reduce the severity of rutting.

4. CONCLUSIONS

Results of tests performed on the BB 0/14 wearing course mixture employed on lot M1 of the Algerian East-West Motorway showed that the significant rutting phenomena observed in the field are certainly due to viscous flow of the bituminous binding mastic. Such an interpretation is coherent with the volumetrics of the mixture and with bitumen type (40/50 penetration grade). In such a context it is interesting to consider the recommendations of the Algerian Ministry of Public Works [5], which suggest the use of stiffer 20/30 penetration binders in the case of infrastructures subjected to high traffic volumes and located in the geographical area of lot M1.

Laboratory results obtained by testing an alternative wearing course mixture (EMA 0/10) also indicated that the use of polymer granules added to the mixing plant may indeed enhance rutting resistance, compensating for deficiencies of the available bitumen without compromising the volumetric properties of the resulting mixture. This may require the adjustment of aggregate gradation, which may be of the discontinuous type, and of binder content, which should be conveniently limited in order not to overfill the mixture. For such a purpose, the use of performance-related tests (e.g. wheel-tracking) is strongly recommended as part of mix design procedures.

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