FORMULATING A RUTTING-RESISTANT HOT-MIX ASPHALT MATERIAL USING IN-SITU AND LABORATORY TESTS

Authors:
Neji J.
Professor – Ecole Nationale d'Ingénieurs de Tunis – BP 37, Le Belvedere 1002, Tunis, Tunisia, jamel.neji@enit.rnu.tn

Loulizi A.
Assistant Professor – Ecole Nationale d'Ingénieurs de Tunis – BP 37, Le Belvedere 1002, Tunis, Tunisia, amlouliz@vt.edu

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ABSTRACT

This paper investigates the main causes of hot-mix asphalt (HMA) rutting that are found on several sections of local freeways based on the results of a field assessment of an in-service freeway section. Field tests included deflection measurements and core laboratory analysis. The results of this field investigation made it possible to formulate an HMA mix using local materials that is thought to be more rut-resistant than the typically used, by the local highway authorities, HMA mix. The newly developed mix was then tested in a full scale pavement section and as expected its performance was by far better than that of the typical mix after the application of approximately 1-million equivalent 13-ton-single-axle load cycles. After its successful field testing, the newly formulated HMA mix, as well as other HMA mixes, was tested in the laboratory using a specially developed test that applies cyclic uniaxial loadings. The principle of the test consists in applying an axial haversine compressive stress to a cylindrical specimen and measuring the cyclic small deformation as well as the permanent deformation after the applications of several cycles. The performed test, which studies the viscoplastic behavior of HMA, is thought to be a good tool to study permanent deformation and complex modulus evolutions. The test showed the acceptable performance of the newly developed HMA mix. It is therefore recommended to develop a permanent deformation constitutive model using a larger experimental program with more different HMA mixes. Some of these HMA mixes could be made using local plastic (mainly polyethylene) waste material which is thought to enhance the rutting resistance of HMA.

Keywords: Hot-mix asphalt, rutting, constitutive model, flexible pavements.

INTRODUCTION

Ruts are uniform depressions in the wheel paths of a pavement. They are caused by plastic deformations in any or all of the pavement layers including the subgrade. The origins of these deformations are either one-dimensional compression and consolidation or plastic flow of mainly the HMA layer. The latter origin of rutting is manifested by a depression in the wheel paths with humps on either side of the depression. These depressions and humps cause discomfort to the driver because ruts tend to pull a vehicle towards the rut path and are very hazardous when they are filled with rain water as they cause hydroplaning. Lateral flow or the plastic movement of materials will occur in those mixtures with inadequate shear strength or by an insufficient amount of total voids in the HMA layer. Voids of an HMA mixture in the range of 2% or less right after construction are susceptible to lateral flow, because the low voids allow the asphalt to act as a lubricant rather than a binder especially during hot weather. Inadequate shear strength of HMA could be caused by several factors such as the use of soft asphalt with high thermal susceptibility, high asphalt content, high content of mineral filler, and improper shape and texture of aggregate particles (rounded, flat and elongated, and smooth texture) (Roberts et al., 1996).

HMA flow rutting usually occurs in freeways since their pavements are designed to be thick which minimizes the possibility for subgrade rutting (subgrade is not overstressed) and also due to the repeated heavy tire loads that cause high tangential stresses on the HMA surface layer. For this reason, research was initiated by assessing a 30-km local freeway section, which had shown severe HMA flow rutting, to identify the main causes that led to this type of distress. The in-situ assessment consisted on core extraction, deflection testing, rut-depth measurements, and consulting of construction documents such as the quality control forms and the daily construction log notebooks. The field assessment clearly showed the significant effect of the surface mix job-mix formula on the extent of rutting. Therefore, it was decided to run laboratory tests in order to formulate a new job-mix formula for the surface mix that would ultimately replace the classic formula used by the highway authorities. The formulation study was based on results of the Marshal Stability test, Duriez water sensitivity test, and behavior under the Gyratory compactor obtained on several HMA wearing surface mixes with different proportions of the used ingredients (filler percentage, binder content, sand content, etc.) The best performing HMA surface mix based on the laboratory test results was then tested as a full scale pavement section and as expected its performance, in terms of rut development, was by far better than that of the typical mix after the application of approximately 1-million equivalent 13-ton-single-axle loads. The proposed mix was then tested using a laboratory test that studies the viscoplastic behavior of HMA. Its performance under this test was deemed acceptable.

FIELD ASSESSMENT OF AN IN-SERVICE FREEWAY SECTION

The freeway section that was assessed as part of this research study opened to traffic in 1981. Originally the pavement design consisted on placing a drainage layer composed of sand 0/5 on the subgrade, followed by a 25-cm thick untreated aggregate subbase layer, followed by a 12-cm thick HMA base layer, on top of which a 7-cm thick HMA wearing surface was placed. However, as shown in Figure 1, in 1989, an 8-cm thick HMA overlay was placed on top of the original wearing surface.

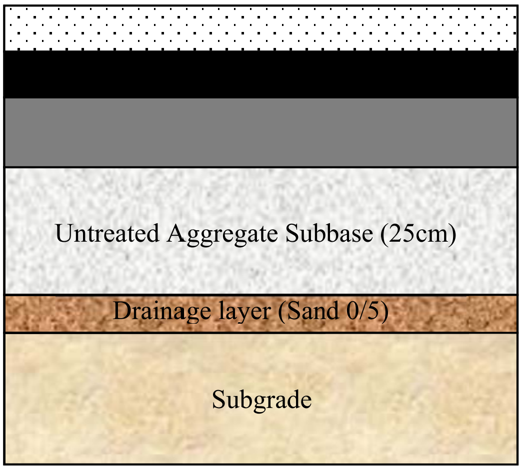


Figure 1 As-designed pavement cross-section

In 1991, only 2 years after the overlay placement, severe HMA flow rutting was observed mainly on the driving lane (right lane). To assess the causes of these defects, rut depths were first measured and then cores were extracted along the assessed pavement at different stations to measure the as-built thicknesses. Deflection measurements were performed using LACROIX deflectometer to verify the bearing capacity of the whole pavement cross-section. The LACROIX deflectometer measures the deflection at both edges of the road (inner edge and outer edge) caused by a 13-t single axle with dual tires. Construction documents, mainly the quality control forms, were consulted to verify the as-built ingredients of the HMA wearing surface mix. Nine cores were also extracted from one cross-section at station 15+200 to know the layers that are affected by the distress. Finally, samples from the subgrade were also collected to measure the bearing capacity using the California Bearing Ratio (CBR) test and to calculate its plasticity index (PI) from the measure Atterberg limits.

Figure 2 shows the results of the thickness measurements obtained from the cores extracted along the assessed pavement. From this figure, the variability in the construction of all the layers is noted. In fact, the thickness of the untreated aggregate subbase varied from 10 to 32cm with an average of 21cm and a standard deviation of 8.7cm which represents a coefficient of variation (COV) of 40.6%. For the HMA base layer, the thickness varied from 8 to 16cm with an average of 12cm and a standard deviation of 2.8cm, which represents a COV of 23.1%. For the wearing surface (original plus the overlay), the thickness varied from 6 to 16cm with an average of 11.4cm and a standard deviation of 3.8cm which represents a COV of 33.2%. Figure 3 shows the measured rut depths at different stations. Rut depths ranged from 2 to 6.5cm, which clearly shows the severity of the distress. By comparing figures 2and 3, no trend was found between the measured rut depth and the existing pavement thicknesses, which tends to indicate that the distress is not due to structural causes.

Figure 4 shows the results of the deflection measurements on the outer and inner edges of the driving lane. The figure shows the frequency of the recorded measurements for different deflection groups. Most of the measurements were less than 4×10^{-2} mm with all of them being under 50×10^{-2} mm, which indicates the good bearing capacity of the pavement section. In addition, testing of the subgrade material showed also its good bearing qualities as measured by its California Bearing Ratio (CBR) value of 19 and low plasticity index (PI) of 9. Therefore, these results indicate that the observed distress is not due to structural problems.

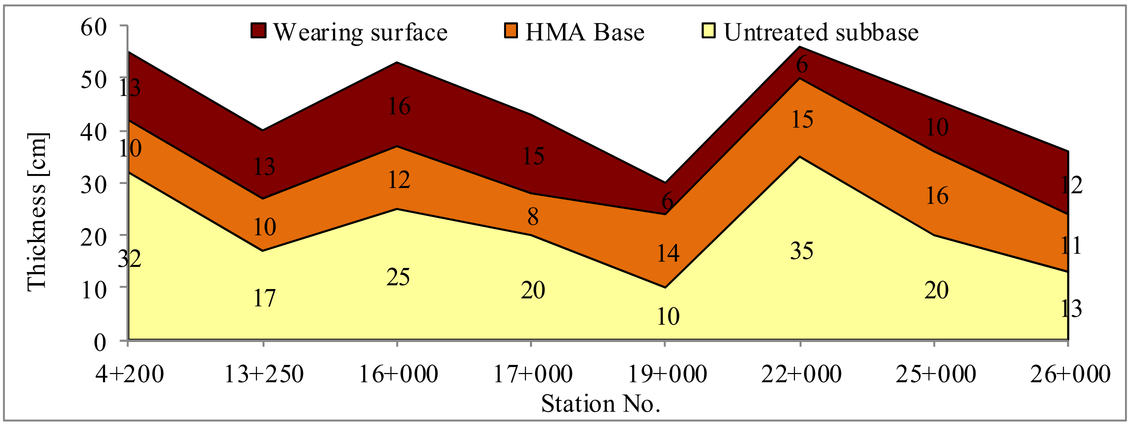


Figure 2. Measured layers' thicknesses at different stations

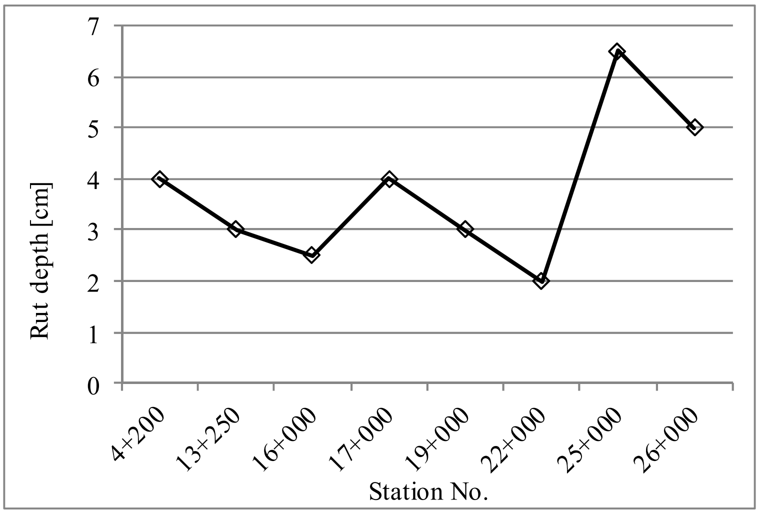


Figure 3. Measured rut depths at different stations

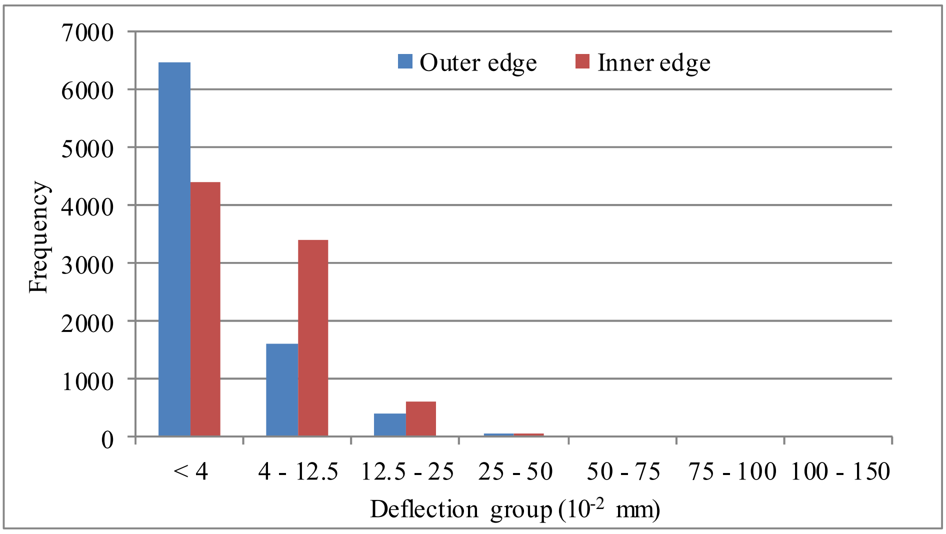
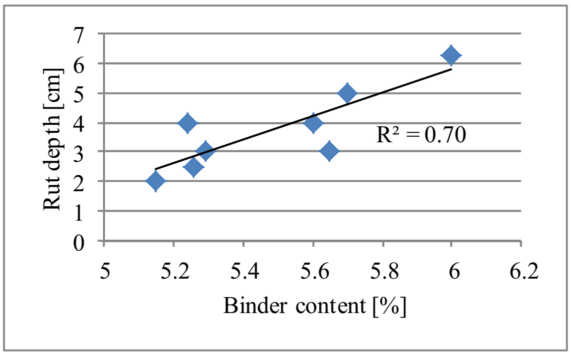


Figure 4. Deflection measurement results

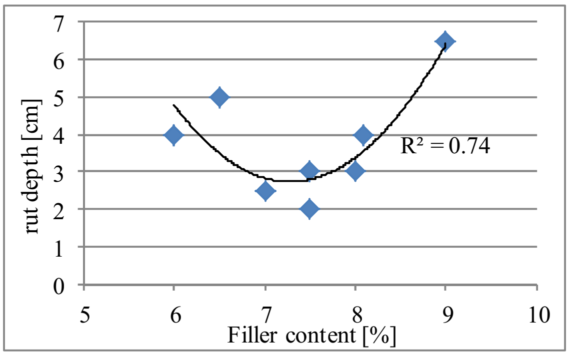
In order to identify which layers were affected by the ruts, a transverse profile was measured at station 15+200 using a transverse profilograph that uses ultrasonic sensors to measure the height of the pavement surface. Nine cores were then extracted along this profile. The extracted cores clearly indicated that the rutting occurred on the top surface layer and not the layers beneath it. Therefore, the ruts were developed in the overlay HMA mix and not in the original surface layer.

Now that the original thought that the defects are due to HMA mix problems and not structural ones is confirmed and to further deepen the research investigation, the effects of the ingredients of the HMA overlay mix on the flow rutting were investigated. One major contributor to the HMA flow rutting is the type of binder used for the mix. In fact, the overlay HMA mix was made using a binder with a penetration grade of 80/100, while the HMA original surface mix was made with a binder that has a penetration grade of 35/50. The soft binder significantly contributed to the observed HMA flow rutting and therefore it was recommended that this type of binder would not be used for future jobs. The quality control forms obtained from the contractor made it possible to know exactly the used ingredients of the overlay HMA mix at different stations. This made it possible to draw the measured rut depth at these station as a function of the percentage of different ingredients that are thought to affect the extent of HMA flow rutting, namely the binder content, the filler content and the sand 0/2 content. Figures 5a, 5b, and 5c show the effects of binder content, filler content, and sand 0/2 content on the measured rut depth, respectively. As expected, rut depth is found to increase with the increase in binder content or sand 0/2 content. On the other hand, filler content shows a different trend where its increase to an optimum value decreases the rut depth; then after this optimum value, the rut depth starts to increase. From Figure 5b, this optimum is found to be around 7.5%. This value needs to be further investigated.

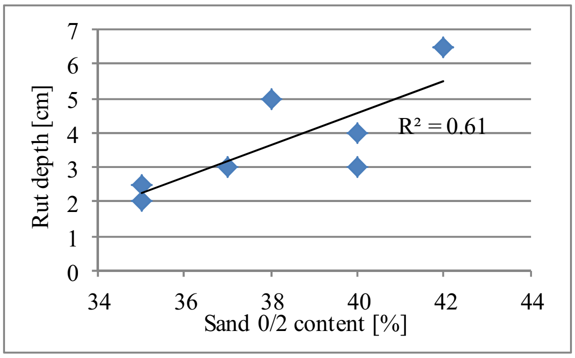
In addition, field density was measured using the extracted cores and the relative density with respect to density obtained using the Marshall procedure was calculated. Most of the measurements fell in the range of 97 to 99% with only one measurement less than the recommended value of 95%. This high density, which indicates small air void content, contributed also to the severe HMA flow rutting.



(a)



(b)



(c)

Figure 5. Effects of the ingredients content on the rut depth: (a) Binder content (b) filler content and (c) sand 0/2 content

FORMULATION OF A NEW WEARING SURFACE HMA MIX FOR LOCAL FREEWAYS

In the first part of this study, the significant effect of the wearing surface HMA job-mix formula on the flow rutting was demonstrated. For that reason, the objective of the second part of the study was to formulate, in the laboratory, a new HMA surface mix using local materials that can better resist HMA flow rutting. Table 1 shows the job mix formula for the control mix. Eight more mixes were then derived from the control mix by changing one ingredient at a time as shown by Figure 6. The binder was the same for all nine mixes as Asphalt 35/50 was the only product available for local highway authorities. Binder with lower penetration grades are not available and, as mentioned before, binders with higher penetration grades are very prone to HMA flow rutting especially with the hot summer weather encountered in the country. The sand 0/5 content was kept constant at 45%, but three contents for the 0/2 portion were tested namely, 28%, 30%, and 33%. Four different binder contents (4%, 4.5%, 5%, and 6%) were tested and 4 different filler contents, namely 5, 6, 7, and 8% were evaluated. The selection of the optimal ingredient content was based on achieving a relative density of less than 95.5% and a Marshall Stability value at 60°C of 1100 kg.

Table 1. Job-mix formula for the control mix

Ingredient	**Content (%)**
Crushed gravel 12/20	20
Crushed gravel 5/12	35
Crushed sand 0/5	45
Binder 35/50 content	5
Filler	6

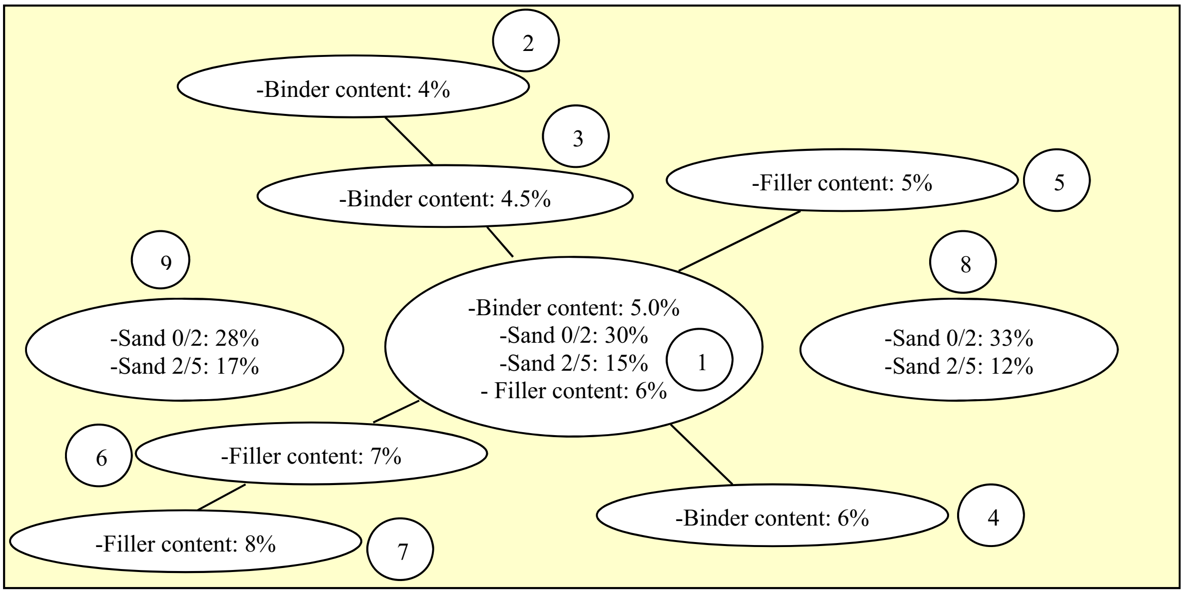


Figure 6. Tested HMA wearing surface formulas

Figures 7, 8, and 9 show the effect of changing the filler content, the binder content, and the sand 0/2 content on the relative density and Marshall Stability value. In these figures, the white interval indicates the range in the ingredient content that leads to satisfactory results. Therefore, the filler content should be between 5.3 and 5.9%, the binder content should be in the range of 4.6 to 4.9%, and the sand 0/2 content should be less than be less than 28%. It appears from these findings that among the nine tested formulas, the formula that meets the best compromise between the relative density and Marshall Stability is formula No. 9. Therefore, it was decided to keep this formula, but with a decrease in the binder content to 4.7%, for further testing. Results of the performed test on this selected mix are shown in Table 2.

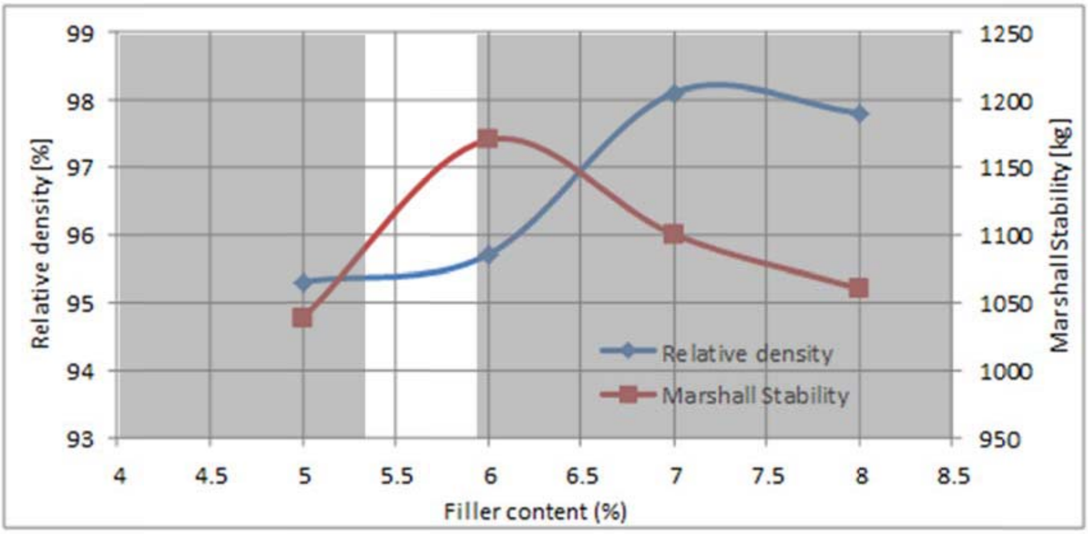


Figure 7. Effect of filler content on HMA performance

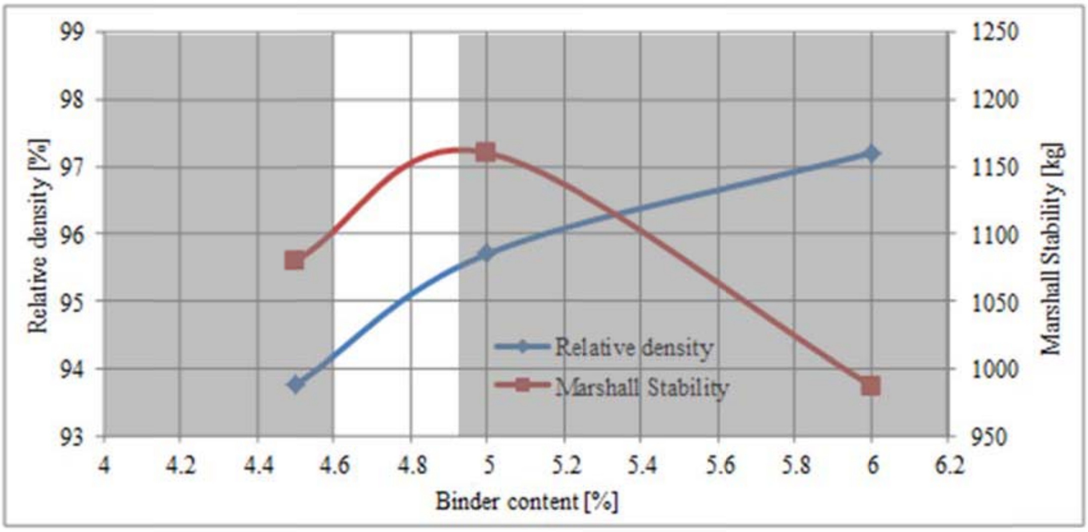


Figure 8. Effect of binder content on HMA performance

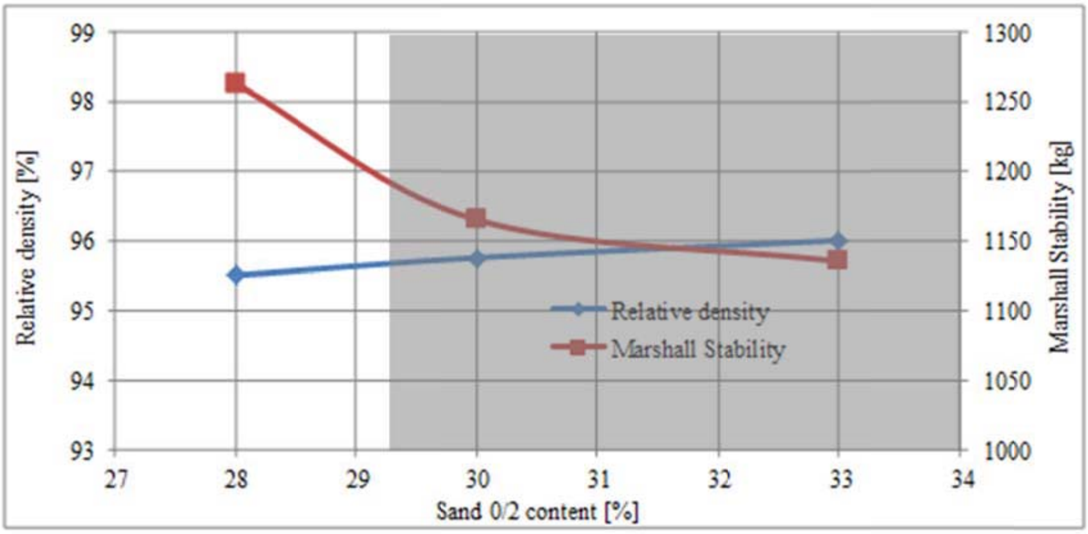


Figure 9. Effect of sand 0/2 content on HMA performance

Table 2. Results of the performed tests on the selected HMA wearing surface mix

Test	Result
Relative density	94.6%
Marshall Stability	1336kg
Marshall flow	24/10mm
Gyratory compactor	k_1=4.71, C_1=75.39 et C10<89%
Duriez Test	92%

These results appear to meet the objective of the research study, but they remain insufficient to predict the long-term behavior in real field conditions. Therefore, a full-scale pavement section was constructed to validate its long-term performance under real truck loadings.

FULL-SCALE PAVEMENT TESTING

A full-scale pavement section was constructed using the proposed formula. The 150-m long section was built in a National road with equivalent annual average daily truck traffic (AADTT) of 1000. Another 150-m section was constructed using the surface mix commonly used by the highway authority. The 300-m test sections were chosen along a straight section of the road and away from critical points (intersection, high point, etc.) to make sure that both testing sections receive the same load at the same speed. Traffic count sensors were installed right before the sections to count truck traffic over time. This truck counts were then converted to cumulative equivalent 13-ton-single axle loads, which is the reference load used by the highway authorities. Rut depths were measured periodically on both sections. Figure 10 shows the results of this analysis. From this figure, it is clear that the newly developed mix performance is by far better than that of the typical mix after the application of approximately 1-million 13-ton-equivalent single-axle loads (ESALs). In fact the maximum measured rut depth was 0.9cm for the proposed mix test section while it reached 1.5cm for the section with the typical surface mix. Also, the rut in the proposed wearing surface mix test section seems to reach a plateau around 1cm, while the rut in the typical wearing surface test section appears to keep its increase.

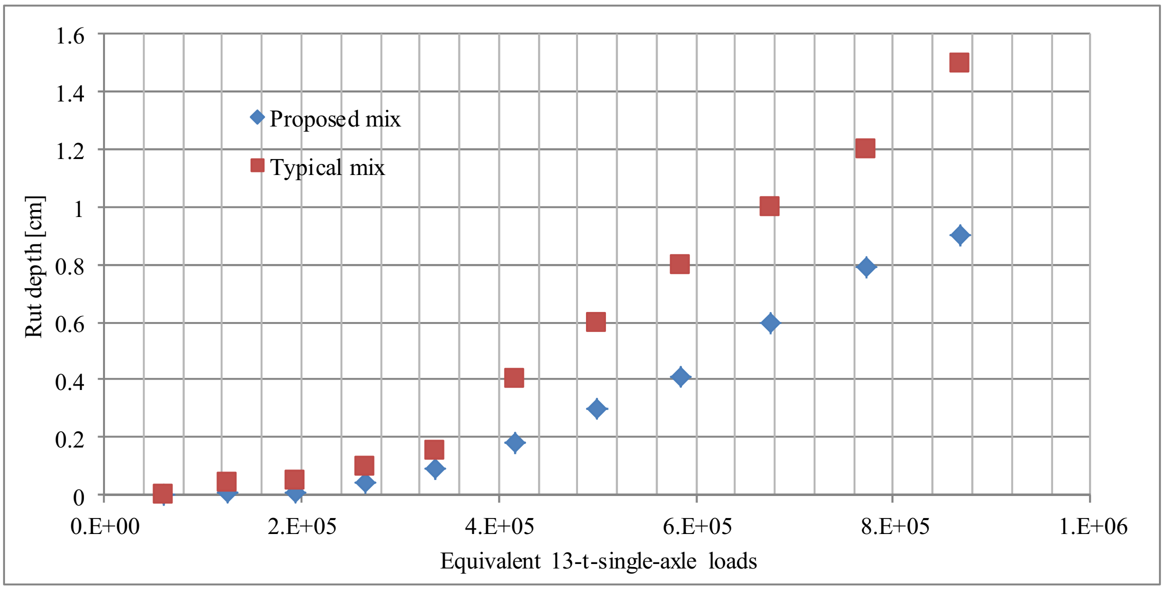


Figure 10. Measured rut depth as a function of 13-t ESALs in both sections

LABORATORY TESTING

After its successful field testing, the newly formulated HMA mix was tested in the laboratory using a specially developed test that applies cyclic uniaxial loadings. The principle of the test consists on applying an axial haversine compressive stress to a cylindrical specimen and measuring the cyclic small strain as well as the permanent strain after the applications of several cycles (Neifar and De Benedetto, 2000). The haversine compression load is applied for a time t_1, followed by a rest period (No stress) with duration t_2. This loading and unloading sequences are then repeated using different durations. For example, the first cyclic loading duration is 30s, the second cyclic loading duration is 100s, the third cyclic loading duration is 1000s, and so on. On the other hand, the rest periods are 12 minutes, 18minutes, and 51 minutes, and so on. These resting durations are chosen in order to obtain a "quasi" stabilisation of permanent strain.

Seven HMA mixes were then prepared based on the proposed mix by varying the %voids (energy of compaction), the binder content, and the filler content as shown by Table 3. The mixes were labelled as HMA mixes E1 to E7. Figure 11 shows the obtained results of the performed test on all tested mixes. From this figure, it is noted that mix E4 performed the best, which was expected sine this mix had the lowest binder content (4%), an optimum % voids of 4%, and a good filler content of 6%. In addition, the complex modulus master curve was constructed for the proposed mix and the results are shown in Figure 12.

Table 3. Prepared HMA mixes for laboratory permanent deformation test

HMA Mix Label	Sand content (%)	Filler content (%)	Crushed gravel 5/12 (%)	Crushed gravel 12/20 (%)	Binder content (%)	% voids
E1	39	6	35	20	4.7	5
E2	38	8	34	20	4.7	3.5
E3	40	5	35	20	4.7	4.5
E4	39	6	35	20	4	4
E5	39	6	35	20	5	2
E6	39	6	35	20	4.7	3.5
E7	39	6	35	20	4.7	6.5

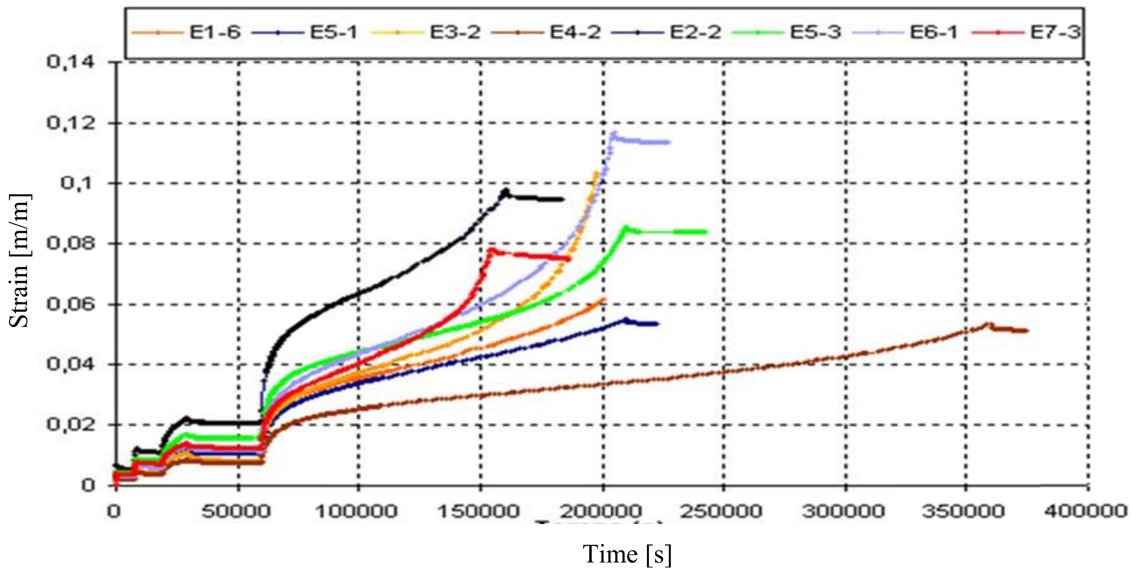


Figure 11. Permanent strain test results

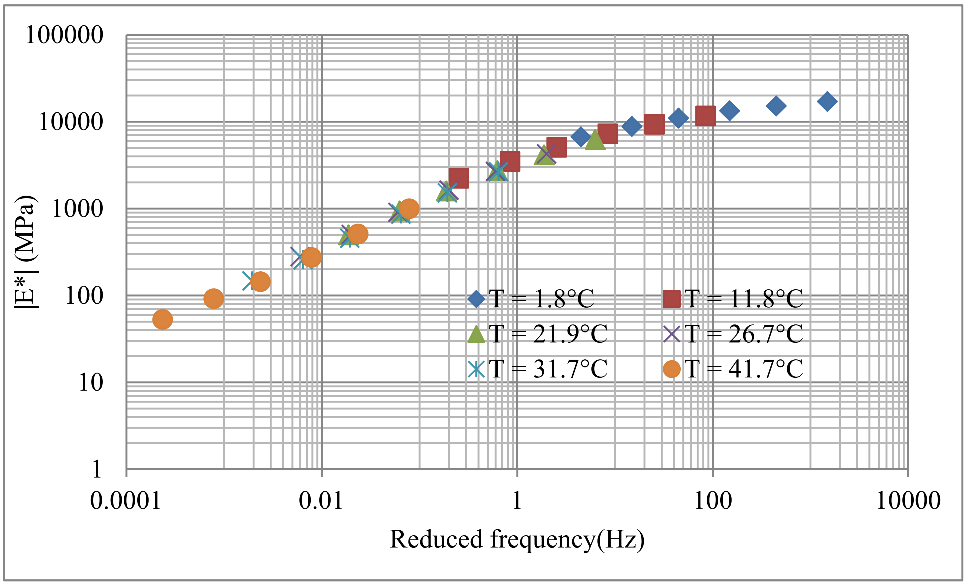


Figure 12. Complex modulus master curve for the proposed mix at a reference temperature of 21.9°C

CONCLUSIONS AND RECOMMENDATIONS

Several field and laboratory tests made it possible to formulate a new HMA surface mix for local use in the construction of freeway pavements. Performance of the proposed mix was tested using a full-scale pavement section under real truck loadings and in the laboratory using a permanent strain cyclic test. From these tested the following conclusions and recommendations could be drawn:

- HMA flow rutting increases when using higher grade penetration binders
- HMA flow rutting increases with an increase in either binder content or sand 0/2content.
- There is an optimal value for the filler content in an HMA mix for which the rutting potential is lowest
- Air-voids in the range of 4% are essential for reducing HMA flow rutting. Lesser air-void contents increase the HMA rutting potential.
- It is recommended to develop a permanent deformation constitutive model using a larger experimental program with more different HMA mixes.
- Some of the recommended HMA mixes could be made using local plastic (mainly polyethylene) waste material which is thought to enhance the rutting resistance of HMA (Calkins, 2009).

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