EXPERIMENTAL STUDY OF RECYCLED ASPHALT MIXTURES WITH HIGH PERCENTAGES OF RECLAIMED ASPHALT PAVEMENT (RAP)

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ABSTRACT

This paper presents an experimental study to characterize the mechanical behaviour of bituminous mixtures containing high rates of RAP. Two semi-dense mixtures of 12 and 20 mm maximum aggregate size and containing 40 and 60% RAP, respectively (S-12 and S-20, in accordance with Spanish specifications), which were used for rehabilitation of a Spanish highway section, were evaluated. First, the effect of RAP variability on the recycled mixtures was analyzed. Their mechanical properties were then studied by determining the stiffness modulus and indirect tensile strength and applying a new direct tensile test, i.e. Fénix test, and the three-point bending beam test. Results show that high rates of recycled material can generally be incorporated into bituminous mixes by proper characterization and handling of RAP stockpiles.

INTRODUCTION

RAP rates between 10 and 30% are commonly used in bituminous mixes. According to several studies, with these rates bituminous mixtures perform similarly to conventional mixtures (*1, 2, 3, 4, 5, 6, 7, 8*). However, environmental restrictions are causing an increase in RAP content added to recycled mixtures used in bituminous pavement construction and rehabilitation. This has a beneficial effect from the economic point of view and makes pavement construction sustainable over time due to lower energy and natural resource consumption (*9,10*).

Laboratory and experimental field studies on mixtures containing large amounts of RAP show the feasibility of this technique (*11, 12, 13*). However, as its use in road construction and rehabilitation projects becomes more widespread, further research is necessary due to the damaging effect of traffic and climatic conditions on mixtures.

The FENIX Project (“Strategic Research on Safer and More Sustainable Roads”) is currently being undertaken in Spain. The FENIX Project is the greatest effort in research & development of road paving made in Europe. It is structured around the following main research lines: warm mixtures, perpetual pavements, recycling (cold and hot), by-products, safety and comfort, nanomaterials, low energy consumption plants and fluidized bed (*14*). Its main purpose is to create technical knowledge in order to develop construction technologies for safer, sustainable, environmentally-friendly road infrastructure. The following experimental study, which evaluates RAP variability and mechanically characterizes the properties of mixtures containing high rates of RAP, has been performed in the area of recycled asphalt mixtures within the FENIX project framework.

The aim of this work is to analyze the behaviour of mixtures with large RAP contents (specifically, 40 and 60%) and compare it with that of conventional mixtures.

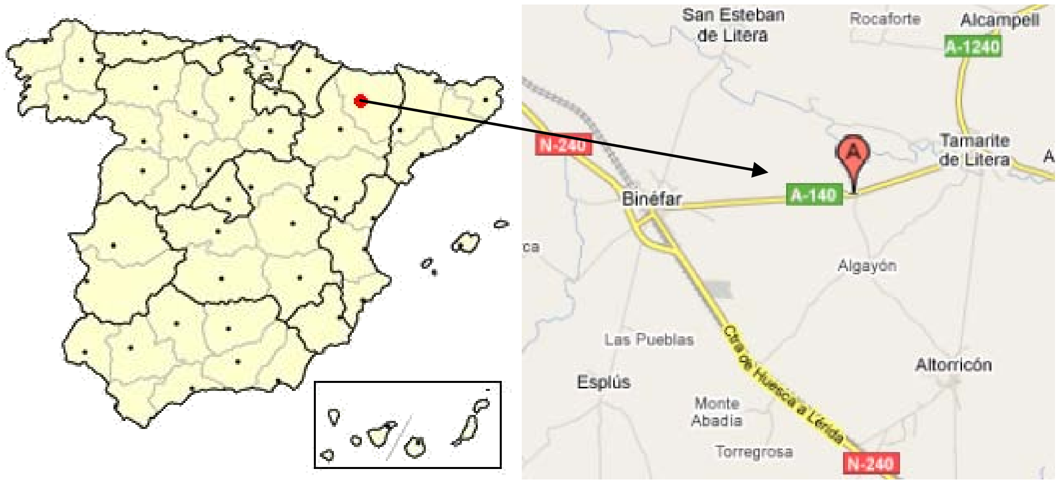
EXPERIMENTAL PROGRAM

Four tasks were carried out in cooperation with companies involved in the development area of recycled asphalt mixtures within the framework of the Fénix project:

- Proper selection of a rehabilitation project where mixtures containing high rates of RAP could be used.
- Determination of RAP characteristics (aggregate grading and binder content and characteristics).
- Design of job mix formulas for the recycled mixtures and the standard conventional mix.
- Evaluation of the effect of RAP variability on higher RAP mixes and their mechanical properties, and comparison of these properties with those of a conventional S-20 mixture containing 60/70 penetration binder.

Project selection

The selected project consisted in rehabilitating the pavement of a highway section located in Huesca, Spain, Figure 1. The top 80 mm of the asphalt mix was milled from the damaged pavement, and an 80 mm asphalt layer of S-20 recycled mixture containing 60% RAP (S20R60) was then laid. On top of this course, a 50 mm intermediate course of S-12 recycled mixture containing 40% RAP (S12R40) was placed, and finally a wearing course of gap-graded mixture prepared with a polymer-modified binder was laid.



(a) (b)

FIGURE 1 Spanish province where the selected project was conducted: (a) map of Spain and (b) A-140 highway.

In order to reduce the heterogeneity of the recycled mixtures, they were fabricated with two fractions of RAP, as recommended for recycled mixture preparation with higher RAP percentages (*15*). The RAP proportions and fractions used in S20R60 mixture were 15% and 0/8 mm RAP and 45% and 8/25mm RAP, and for S12R40 mixture, 20% and 0/8 mm RAP and 20% and 8/25mm RAP. Table 1 shows the RAP grading and the bitumen content for both RAP fractions. Mixtures were made in a Double Barrel® drum mixer.

TABLE 1 RAP Grading and Bitumen Content (after extraction)

RAP Fraction (mm)	0/8	8/25
Bitumen content (% by weight of mix)	5.7	3.2
Sieve size (mm)	Gradation (% Passing)	
25	100	100
20	100	96
12.5	100	77
8	99	59
4	91	35
2	67	24
0.5	33	14
0.25	21	9
0.125	15	8
0.063	8.8	4.6

The binder recovered from the RAP had the following characteristics:

- Penetration grade of binder extracted at 25ºC (dmm) 5
- Softening point of aged binder (ºC) 87
- Asphaltenes (%) 44.62

Binders used in S20R60 and S12R40 mixtures had rejuvenating agents and their penetrations grades were 250 and 200 (dmm), respectively.

An S-20 mixture incorporating 60/70 penetration bitumen and without RAP was used as the control mixture.

Job Mix Formula

Mixtures were designed by the Marshall method, Tables 2 and 3.

TABLE 2 Gradations of Tested Mixtures

Sieve Size	Gradation for each Mix Type (% Passing)		
(mm)	S 20R60	S 12R40	S 20
25	100	100	100
20	88	99	100
12.5	66	85	87.5
8	53	67	67.5
4	37	41	42.5
2	26	29	31
0.5	14	15	16
0.25	9	10	11
0.125	7	7.4	7.5
0.063	4.5	4.8	5

TABLE 3 Marshall Characteristics for Design of Tested Mixtures

Mix Type	S 20R60	S 12R40	S 20
New bitumen penetration (dmm)	250	200	60/70
New bitumen content (% by weight of mix)	2.11	2.72	4.5
Total bitumen content (% by weight of mix)	4.4	4.5	4.5
Density (g/cm^3)	2.449	2.418	2.426
Air voids (%)	3.8	4.4	3.4
Stability (kN)	17.5	15.6	15.1
Displacement (mm)	2.41	2.47	2.30
Marshall quotient (kN/mm)	7.26	6.31	6.57

Experimental Test

Stiffness Test

The stiffness modulus was determined in accordance with UNE-EN 12697-26:2006 Annex C at a temperature of 15 ºC by the following expression:

$$S_m = \frac{F(\nu + 0.27)}{z \cdot h} \quad (1)$$

where S_m = stiffness modulus (MPa); F = maximum value of applied vertical load (N); ν = Poisson coefficient; h = specimen thickness (mm); z = horizontal displacement (mm).

Indirect Tensile Test

In order to evaluate indirect tensile resistance of the mixtures, the European standard UNE-EN 12697-23:2004 test was used where temperature was 15ºC and velocity was 50 mm/min. The indirect tensile test consists in breaking cylindrical specimens by applying a compressive load along the vertical diameter. Assuming a virtually constant distribution of stress across the load application plane, indirect tensile resistance can be determined by the following expression:

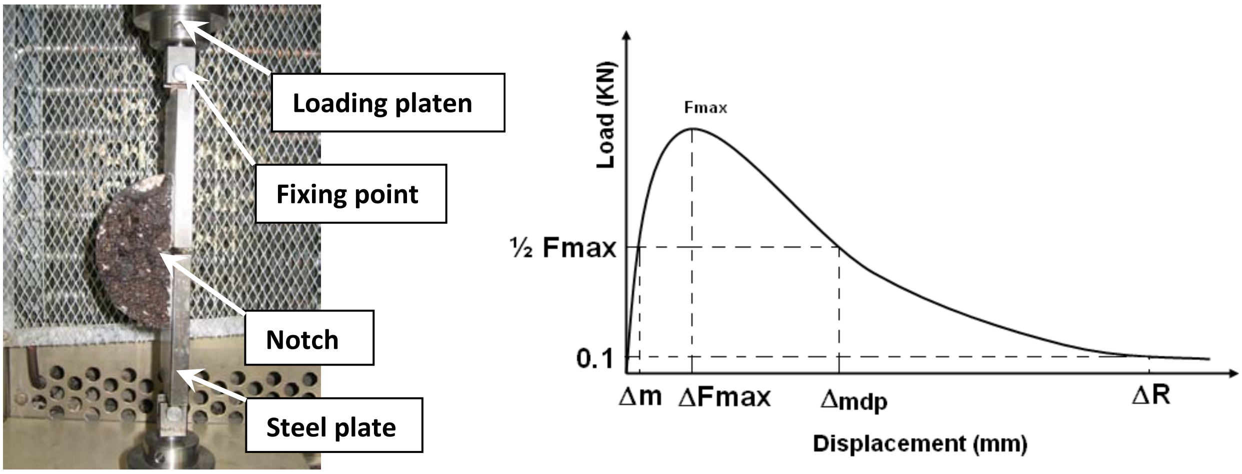
$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot h} \qquad (2)$$

where ITS = indirect tensile strength (MPa); P = applied load (N); D = specimen diameter (mm); h = specimen thickness (mm).

Fénix Test

A new direct tensile test, the Fénix test, has recently been developed by the Road Research Laboratory of the Technical University of Catalonia to determine the cracking resistance of bituminous mixes by mainly evaluating the dissipated energy during the cracking process, G_D, together with stiffness and displacement parameters, IRT and Δ_{mdp}, respectively (*16*).

The Fénix test consists in subjecting one half of a cylindrical specimen prepared by Marshall or gyratory compaction to a tensile stress at a constant displacement velocity (1 mm/min) and specific temperature. A 6 mm-deep notch is made in the middle of its flat side where two steel plates are fixed. Each plate is attached to a loading platen so that they can rotate about fixing points, as illustrated in Figure 2.



(a) **(b)**

FIGURE 2 Fénix test: (a) test photo and (b) typical load vs. displacement output curve.

Load and displacement data are recorded throughout the test to calculate the parameters involved in the cracking process.

Dissipated energy during cracking, G_D, is determined by Equations 3 and 4:

$$G_D = \frac{W_D}{h \cdot l} \quad (3)$$

where G_D = dissipated energy during test application, J/m^2; W_D= dissipated work during test application, area under load-displacement curve, kN-mm; h= specimen thickness, m; l= initial ligament length, m.

$$W_D = \int_0^{\Delta R} F \cdot du \quad (4)$$

where F= Load, kN; u= displacement, mm; ΔR= displacement at F = 0.1 kN post- peak curve, mm.

The tensile stiffness index, *IRT*, is calculated by Equation 5. Displacement at 50% of post-peak load, Δ_{mdp}, is also determined to evaluate the mixture ability to deform:

$$IRT = \frac{\frac{1}{2} \cdot F_{\max}}{\Delta_m} \quad (5)$$

where *IRT* = tensile stiffness index, kN/mm; F_{max}= peak load, kN; Δ_m= displacement before peak load at ½ F_{max}, mm.

Fatigue Test

Fatigue laws of the analyzed mixtures were found by a three-point bending beam test under controlled displacement, Figure 3. This test consists in subjecting a prismatic specimen to a time-varying displacement, according to a sinusoidal function described in European Standard UNE-EN 12697-24:2006.

The dynamic modulus at a specified cycle is defined as the quotient between the cyclic amplitude of the stress function and the cyclic amplitude of the strain function:

$$MD = \frac{T_c}{\varepsilon_c} \quad (6)$$

where *MD* = dynamic modulus; T_c = cyclic amplitude of the stress function; ε_c = cyclic amplitude of the strain function.

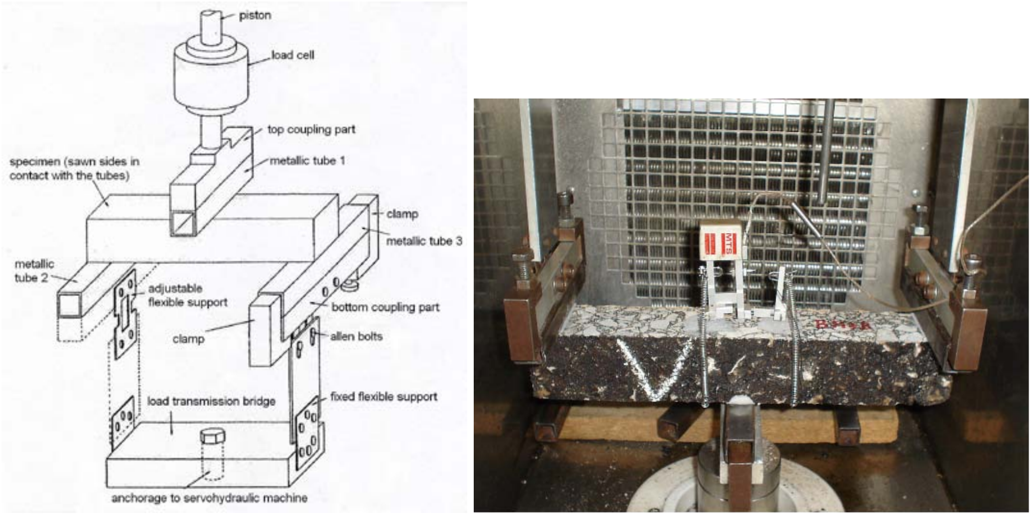


FIGURE 3: Anchoring devices for specimen testing: (a) scheme and (b) photo.

The fatigue law under controlled displacement is obtained from the following pairs of values: half of the cyclic amplitude of the strain function at cycle 200 and the total number of cycles applied to reduce the applied load to 50%. The fatigue law is expressed by the following kind of equation:

$$\varepsilon = a \cdot N^{-b} \qquad (7)$$

where ε = half of the cyclic amplitude of the strain function at cycle 200; N = total number of cycles; a and b = coefficients of the strain fatigue law.

DATA ANALYSIS AND RESULTS

RAP Variability Analysis

Some test results of the extraction of bitumen from RAP show greater dispersion for the coarser RAP fraction. However, in general RAP binder contents were found to be approximately the same as those in the job mix formula, Figure 4.

Deviations in RAP gradation are illustrated in Table 4 and represented in Figures 5 and 6. Table 4 shows that the largest standard deviations from the job mix formula occur for 2, 4, 8 and 12.5 mm sieves, namely, the coarser RAP fraction, i.e. 8/25 mm. Furthermore, for this coarser RAP fraction, a finer gradation on average was observed, Figure 5, as found by Solaimanian and Tahmoressi in one single RAP fraction (*17*). On the other hand, the 0/8 mm fraction met on average the job mix formula as reflected by the lower variation of its gradation, Figure 6. Therefore, this analysis shows that variability of asphalt content and particle size is higher in the coarser RAP fraction.

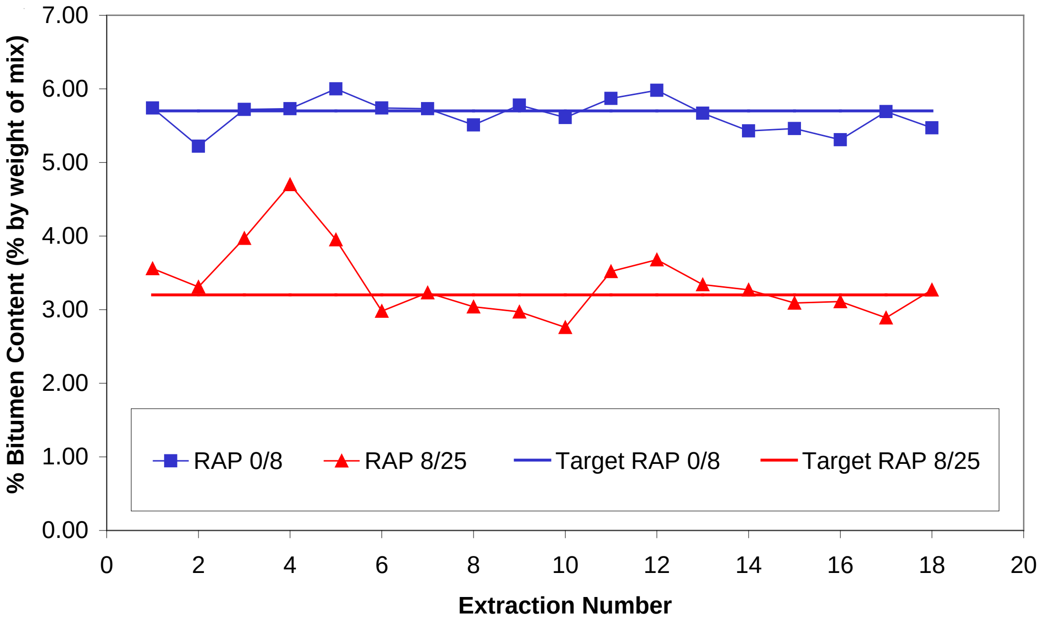


FIGURE 4: Control chart for RAP asphalt content.

TABLE 4 Standard Deviation From Job Mix Formula RAP Gradation for S 20R60 and S12R40 mixtures

Sieve Size (mm)	RAP 0/8		RAP 8/25	
	Target Gradation (%)	Standard Deviation	Target Gradation (%)	Standard Deviation
25	100	-	100	0.51
20	100	-	96	1.70
12.5	100	-	77	6.36
8	99	0.61	59	7.90
4	91	3.12	35	6.51
2	67	3.61	24	5.04
0.5	33	1.82	14	2.48
0.25	21	2.15	9	1.88
0.125	15	1.38	8	1.23
0.063	8.8	0.67	4.6	0.91

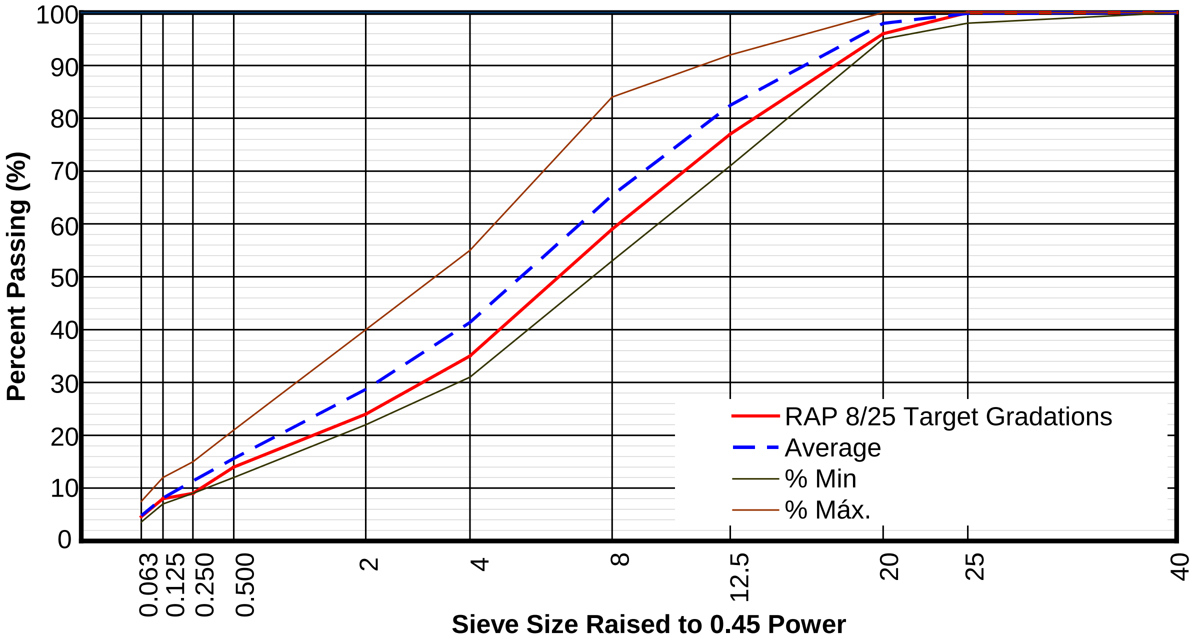


FIGURE 5 Control gradations from 8/25 RAP extraction.

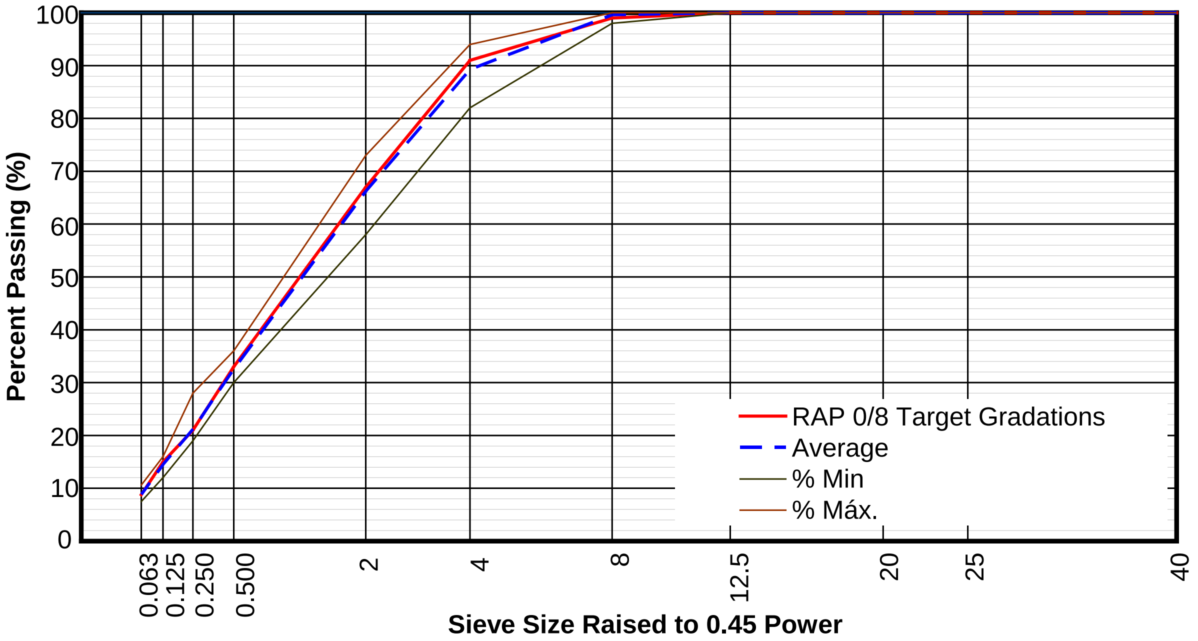


FIGURE 6 Control gradations from 0/8 RAP extraction.

Effect of RAP on Recycled Mixtures Variability

Recycled mixtures variability was determined from the mean deviations from mean values and mean deviation from job mix formula values. These parameters were calculated by the following equations:

$$D = \frac{1}{n}\sum_{i=1}^{n}\left|X_i - \overline{X}\right| \quad (8)$$

$$D_{TF} = \frac{1}{n}\sum_{i=1}^{n}\left|X_i - X_{TF}\right| \quad (9)$$

where D = mean deviation (%); D_{TF} =mean deviation from target formula; X_i = individual value; $\overline{X}$ = mean value; X_{TF} = target formula value

Figures 7 and 8 show the results obtained of the parameters indicated in previous equations for the mixture bitumen content and gradation, respectively. Values of the mean deviations of mixtures without RAP, as summarized in these figures, were obtained from Solaimanian and Tahmoressi's work because of the large number of samples used (*17*).

Results in Figure 7 show a greater mean deviation of bitumen content for the mixtures with the largest RAP proportion, i.e. S20R60, and the largest coarse fraction percentage, i.e. 8/25 mm (45%). The mean deviations of S12R40 mixture are lower than those of S20R60 and similar to the mean deviation from the job mix formula obtained in mixtures without RAP.

Figure 8*a* shows a greater mean deviation from the job mix formula for the 8 mm sieve of recycled mixtures than for the 10 mm sieve used for mixtures without RAP. However, for the 0.063 mm sieve, the statistic values calculated reveal variability similar to that observed for mixtures without RAP, Figure 8*b*.

This analysis shows that the increase in RAP content and the use of a coarser RAP fraction, as the case of S20R60, have an influence on the variability of mixture grading and bitumen content. This confirms the recommendations of Don Brock (*15*), namely that variability of bitumen content and gradation is reduced by preparing mixtures with RAP separated and stockpiled into different material fractions.

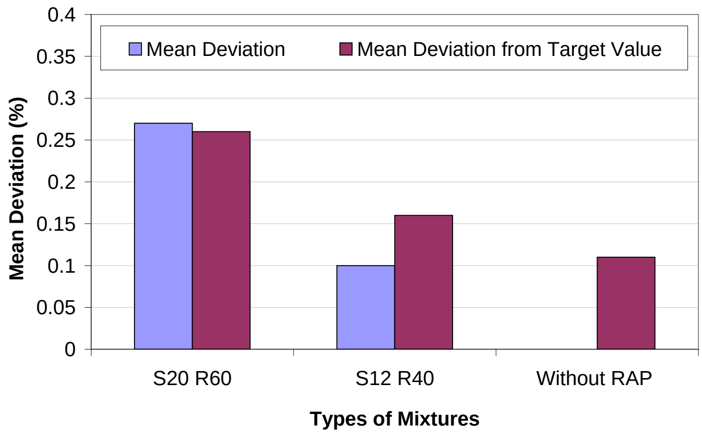
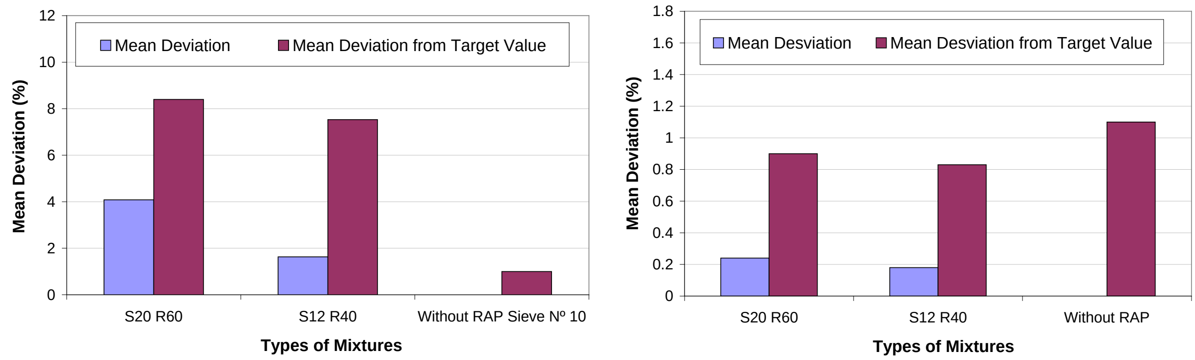


FIGURE 7 Mean deviations from job mix formula target gradation for bitumen content.



(a) **(b)**

FIGURE 8 Mean deviations from job mix formula target gradation: (a) 8 mm sieve and (b) 0.063 mm sieve.

Experimental Test Result Analysis

Figures 9 and 10 present the mean values of stiffness modulus and indirect tensile resistance obtained for specimens and cores of the recycled mixtures used in the rehabilitation of A-140 highway.

Specimens of the mixture with the largest RAP content, i.e. S20R60, have a higher stiffness modulus than that of the standard mixture containing 60/70 penetration binder. The average modulus of S12R40 mixtures is slightly lower than that of S20R60 mixture. All specimens have similar density levels.

The results for the cores extracted after 6-month service time show slightly lower average density levels than those observed for laboratory specimens. The stiffness modulus values for all recycled mixtures were very similar but slightly lower than those for specimens.

Stiffness moduli of S12R40 and S20R60 mixtures obtained from the cores after 12 and 24-month service times are slightly higher than those from the 6-month core, while density levels were similar.

The indirect tensile test yielded very similar values for specimens of both recycled mixtures but higher than those found for S20 mixture containing 60/70 binder. The ITS values for 6-month cores are considerably lower than those obtained for the recycled mixtures but very similar to those for 12-month cores.

The results of the above test show that there may be some factors of the construction phase affecting the strength and density values obtained during the design of recycled mixtures, such as laying temperature, compaction energy, etc.

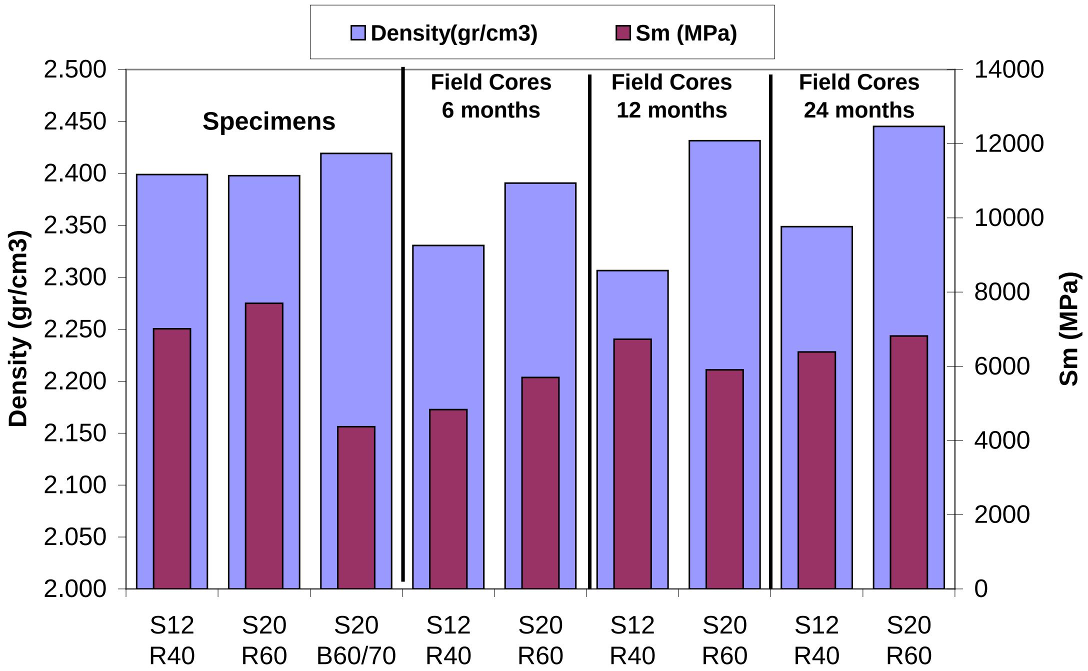


FIGURE 9 Stiffness moduli and densities, specimens and field cores.

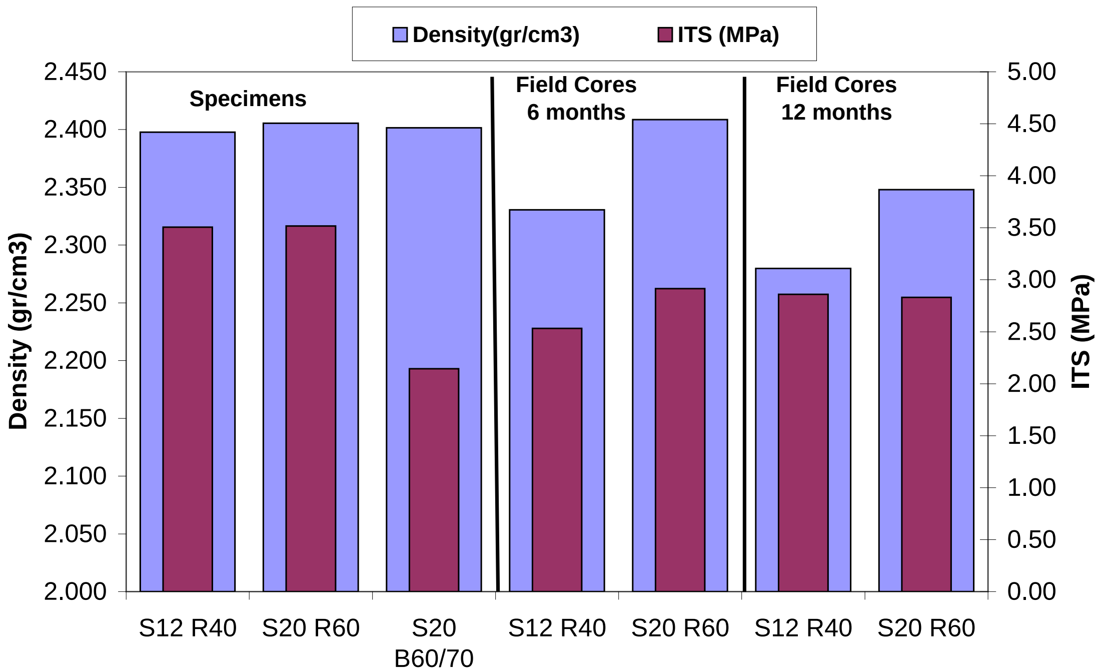


FIGURE 10 Indirect tensile strength and densities, specimens and field cores.

The results of Fénix test on specimens of conventional and recycled mixtures are shown in Figure 11. It can be observed a more fragile behaviour in recycled mixtures as RAP content increases, showing higher loads, F_{max}, and stiffness, IRT, values with regard to conventional mixtures. Furthermore, values of displacement at 50% post-peak load, Δ_{mdp}, are lower with increasing RAP content.

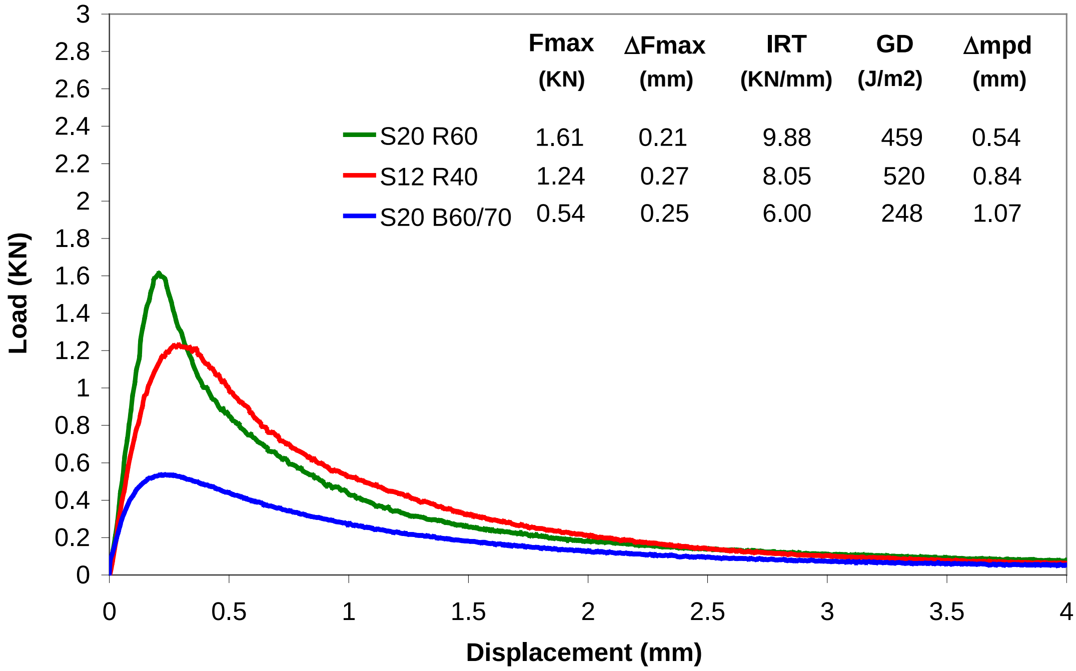


FIGURE 11 Fénix test results on specimens at 20 ºC.

The average values of the parameters obtained from specimens and cores by the Fénix test for the standard and recycled mixtures are listed in Table 5. This table shows that F_{max} and IRT values for 6 and 12-month cores of recycled mixtures are very similar and lower than those of the specimens, just like the results obtained for stiffness and ITS tests.

Values of dissipated energy during cracking, G_D, are higher for the recycled mixture with 40% RAP content. Both recycled mixtures have higher G_D values than the standard mixture containing 60/70 binder. In the case of cores, values are slightly lower than those obtained for specimens.

Under the Fenix test conditions, the results confirm that cracking propagation in the recycled mixtures studied requires more dissipated energy than in the conventional mixture.

TABLE 5 Fenix Test Results at 20 ºC

Mixtures		Peak Load F_{max} (kN)	Displacement Peak Load ΔF_{max} (mm)	Tensile Stiffness Index I_{RT} (kN/mm)	Dissipated Energy G_D (J/m^2)	Displacement 50% Post Peak Load Δmdp (mm)
Specimens	S 20 R60	1.61	0.21	9.88	459	0.54
	S 12R40	1.24	0.27	8.05	520	0.84
	S20 B 60/70	0.54	0.25	6.00	248	1.07
Cores 6 months	S 20 R60	0.91	0.27	6.20	446	0.95
	S 12R40	0.87	0.20	6.36	510	0.82
Cores 12 months	S 20 R60	0.90	0.28	5.54	402	0.97
	S 12R40	0.74	0.18	6.54	477	0.79

Figure 12 illustrates the fatigue laws of standard and recycled mixtures. The latter have very similar deformation values for the same number of cycles, although the mixture with 60% RAP content shows a higher dynamic modulus. The standard mixture has a lower dynamic modulus and a greater ability to deform.

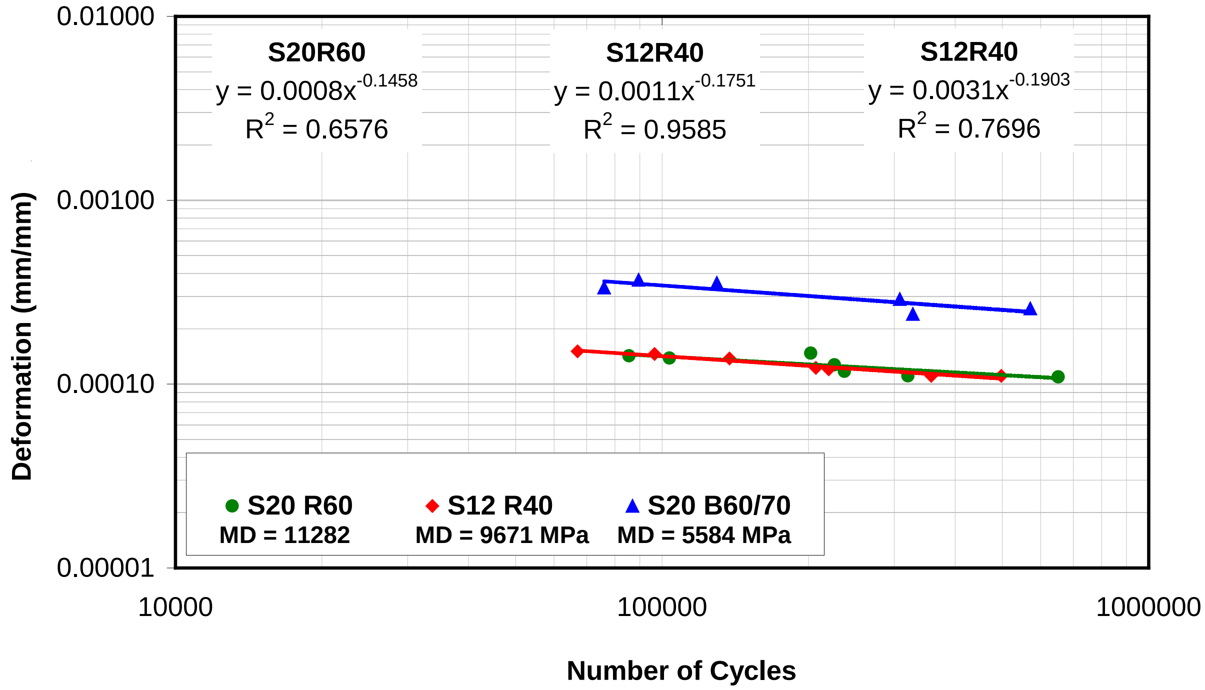


FIGURE 12 Fatigue Laws.

CONCLUSIONS

The analysis performed on RAP samples reveals a certain degree of variability in RAP binder content and gradation, being higher in the coarse RAP fraction. As a consequence, dividing RAP into several fractions and using higher percentages of fine RAP fraction results in greater control over bitumen content and gradation of recycled mixtures.

Stiffness modulus and ITS values for specimens of the recycled mixtures are higher than those for the standard mixture. Cores have lower values than specimens, but differences between cores extracted after different service times are not significant.

Fénix test allows distinguishing between more fragile or more ductile mixture behaviour through the analysis of stiffness and displacement parameters, IRT and Δ_{mdp}, respectively. Results obtained indicate that recycled mixtures showed higher IRT, as well as higher stiffness, Sm, and dynamic modulus, MD. Besides, it was also observed that recycled mixtures presented lower displacement at 50% post-peak load (Δ_{mdp}), just like the deformation level of fatigue laws regarding to the same parameters of the standard mixture.

No significant differences are found between the fatigue laws of the two recycled mixtures. Nevertheless, their ability to deform at the same number of cycles is lower than that of the standard mixture, and their dynamic moduli are higher, particularly that of the mixture with the highest RAP content.

The evaluation of properties of the recycled mixtures analyzed in this study shows that it is possible to use up to 60% RAP content in mix preparation. However, proper characterization and handling of RAP stockpiles is crucial to avoid excessive mix heterogeneity.

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