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 reclaimed asphalt pavement (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 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 cracking and fatigue behaviour. Results show that high rates of recycled material can generally be incorporated into bituminous mixes by proper characterization and handling of RAP stockpiles.

Keywords:

Asphalt mixture; hot recycling; reclaimed asphalt pavement; variability analysis.

1. Introduction

RAP rates between 10 and 30% are commonly used in hot recycled bituminous mixes. According to several studies, with these rates bituminous mixtures perform similarly to conventional mixtures [1, 2, 3, 4, 5, 6]. 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 [7, 8].

Laboratory and experimental field studies on mixtures containing large amounts of RAP show the feasibility of this technique [9, 10, 11, 12]. 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 [13]. 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. These percentages were selected based on the Spanish General Technical Specifications for Highway Rehabilitation, which define and specify the design requirements of recycled mixtures with RAP contents between 10 and 50%. Therefore, the mixture with 40% RAP is within the specified acceptable range while the mixture with 60% RAP is outside this range.

The following tasks were carried out in cooperation with companies involved in the development of recycled asphalt mixtures within the framework of the FENIX Project:

- Proper selection of a rehabilitation project where mixtures containing high rates of RAP could be used.
- Milling of layers selected for rehabilitation.
- Mixing and homogenization of RAP obtained from milled layers.
- Analysis of RAP binder.
- RAP division into two fractions: 0/8 and 8/25 mm.
- RAP fraction characterization (binder content and gradation).
- Recycled and conventional mix design process according to Spanish Technical Specifications.
- Determination and comparison of the mechanical properties of recycled mixes and two conventional mixtures containing 60/70 and 13/22 penetration grade binders.
- Execution of the rehabilitation project.
- Analysis of RAP variability during layer construction: binder content and gradation.
- Analysis of recycled mixture variability during layer construction: binder content, gradation and mechanical and volumetric properties.
- Monitoring over time of the mechanical properties of recycled mixtures by core testing.

2. Project selection

The selected project consisted in rehabilitating the pavement of a section of highway A-140, located in Huesca, Spain. The section was 5.9 km long and the annual average daily traffic was 6980 with 8.5% of heavy vehicles. 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. Figure 1 shows the pavement structure before and after highway A-140 rehabilitation. Mixtures were made in a Double Barrel® drum mixer. Quality control of the recycled mixtures consisted in the monitoring of the conventional parameters, i.e. gradation, binder content and compaction temperature.

3. Experimental study

The experimental study was conducted in two stages:
The first stage consisted of the design of recycled and conventional laboratory mixes, as well as study and comparison of their mechanical properties. Two S-20 mixes without RAP and incorporating 60/70 and 13/22 penetration grade bitumen were chosen as control mixtures as they are the most widely used mixtures in the construction of base and binder layers for flexible pavements. 60/70 penetration grade binder is the most common bitumen in the above case, and 13/22 penetration grade binder was selected for the second control mixture because this bitumen is normally added to high modulus mixtures for maintenance use. At the end of the stage, the mechanical properties of the recycled mixtures were monitored by testing cores from the rehabilitated pavement after different service times.
The second stage consisted of studying the variability of RAP and properties of the recycled mixture during the project execution phase. To this end, binder content and gradation of RAP and recycled mixtures were analysed.

3.1. First stage

3.1.1. Recycled and conventional mixtures design

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 [14]. 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 gradation and the bitumen content for both RAP fractions.
The binder recovered from the RAP before fractioning had the following characteristics:

- Penetration grade of binder extracted at 25ºC (dmm)	5
- Softening point of aged binder (ºC)	87
- Asphaltenes (%)	44.6

Mixtures were designed by the Marshall method, according to the Spanish General Technical Specifications. Table 2 shows the gradations of the mixtures and grading envelopes for S20 and S12 mixes. As can be seen in Table 3, the new bitumen had a penetration grade of 200/300, the softer bitumen being used for the mixture with the highest RAP percentage. Table 3 also contains the properties of the designed mixtures and cited specifications.

3.1.2. Testing methods

This section describes the testing of laboratory specimens and cores extracted from the trial section of A-140 highway. The tests were selected according to the properties commonly evaluated in conventional mixtures, i.e. stiffness modulus, indirect tensile strength and fatigue resistance, which were not considered at the design stage and are currently specified in the new European standards for bituminous mixture mechanical behaviour. Furthermore, a test recently developed at the Road Research Laboratory of the Technical University of Catalonia (see below) was added to this testing series.

Stiffness test

The stiffness modulus was determined in accordance with UNE-EN 12697-26:2006 Annex C at a temperature of 20 ºC by the following expression:

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

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).

Fatigue test

Fatigue laws of the analyzed mixtures were found by a three-point bending beam test under controlled displacement, Figure 2. 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:

$$MD = \frac{T_c}{\varepsilon_c} \tag{3}$$

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

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:

$$\varepsilon = a \cdot N^{-b} \tag{4}$$

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.

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 [15, 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 3.
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 5 and 6:

$$G_D = \frac{W_D}{h \cdot l} \tag{5}$$

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.

$$W_D = \int_0^{\Delta R} F \cdot du \tag{6}$$

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 7. Displacement at 50% of post-peak load, Δ_{mdp}, is also determined to evaluate the mixture ability to deform:

$$IRT = \frac{\frac{1}{2} \cdot F_{\max}}{\Delta_m} \tag{7}$$

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

3.2. Second stage

3.2.1. RAP and recycled mixture variability analysis

In this stage, the variability of binder content and aggregate gradation after extraction was analysed for both RAP fractions, 0/8 mm and 8/25 mm, on samples from mixtures prepared during the rehabilitation project. In addition, the effect of RAP on the variability of the recycled mixtures was studied and compared with that for mixtures without RAP.
Variability was determined from the mean deviations from mean values and the mean deviations from job mix formula values. These parameters were calculated by the following equations:

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

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

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

4. Data analysis and results

4.1. First stage: test result analysis

Figures 4 and 5 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, as well as the results for the control mixture specimens. Mean values are the average of six replicates in the specimen study and three replicates in the core analysis.
Laboratory specimens show that the stiffness moduli of the recycled mixtures are between the results obtained for the S20 standard mix with 60/70 and 13/22 penetration grade bitumens, although closer to the results for the high modulus mixture with 13/22 penetration grade

bitumen. Moreover, the average modulus of S12R40 mixtures is slightly lower than that of S20R60 mixtures. On the other hand, the density levels are very similar for all specimens.

The results for the cores indicate a slight increase in stiffness values over time, except for S12R40 mixtures between 12 and 24 months. Note that while densities are similar, the moduli increase but do not come close to the values recorded for the laboratory specimens.

Regarding indirect tensile strength, mixtures with RAP have very similar values, which are considerably higher than that of the conventional mixture with 60/70 penetration grade bitumen. Again, the strengths of the recycled mixtures are close to that of the high modulus mixture with 13/22 penetration grade bitumen.

Tests carried out on cores at 6 and 12 months show that indirect tensile strengths are similar and lower than the values for the recycled mixture laboratory specimens. No significant differences were found between core strengths at 6 and 12 months.

Figure 6 illustrates the fatigue laws of standard and recycled mixtures. Fatigue laws for recycled mixtures are very similar, the mixture with 60% RAP content having the highest dynamic modulus.

These results confirm that the fatigue behaviours of the recycled mixtures and the control mixture with 13/22 penetration grade bitumen are very similar since the slopes and ordinates of the fatigue laws, as well as the dynamic moduli, show close values, particularly the mixture with 60% RAP.

The results of Fénix test on specimens of conventional and recycled mixtures are shown in Figure 7. In the case of recycled mixtures, an increase in RAP content leads to higher tensile strengths (Fmax) and tensile stiffness indices, *IRT,* as well as less ability to deform, Δ_{mdp}. Again, the behaviours of these mixtures and the control mixture with 13/22 penetration grade bitumen are very much alike. However, the value of dissipated energy during the cracking process, G_D, is higher for recycled mixtures.

As in the previous test results, the cracking behaviour of the control mixture with 60/70 penetration grade bitumen and recycled mixtures is very different, and results show lower cracking resistance (Fmax), lower tensile stiffness index, *IRT,* and more ability to deform, as Δ_{mdp} indicates.

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 4. 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 cores with 40 than 60% RAP, showing a similar trend to that of laboratory specimens with 40 and 60% RAP.

4.2 Second stage: RAP and recycled mixture variability analysis

Figure 8 shows the results of RAP variability regarding the extraction of bitumen from RAP. Some values 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 (target value).

Deviations in RAP gradation are illustrated in Table 5 and represented in Figures 9 and 10. Table 5 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 9, 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 10. Therefore, this analysis shows that variability of asphalt content and particle size is higher in the coarser RAP fraction.

Figures 11 and 12 show the results obtained of the parameters indicated in equations (8) and (9) 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 11 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 12a 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 12b.

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 gradation and bitumen content. This confirms the recommendations of Don Brock [14], namely that variability of bitumen content and gradation is reduced by preparing mixtures with RAP separated and stockpiled into different material fractions.

5. Conclusions

El análisis de los resultados obtenidos a través de ensayos experimentales ha permitido llegar a las siguientes conclusiones.

Mechanical properties of laboratory specimens:

- The analysis of stiffness modulus and indirect tensile strength in laboratory specimens has a behaviour closer to that of a high modulus mixture and higher values than that of the conventional mixture with 60/70 penetration grade bitumen.
- Similar conclusions can be drawn from the analysis of dynamic modulus (fatigue tests) and IRT (Fenix test).
- Higher RAP contents lead to increased stiffness, as shown by the results for stiffness modulus, dynamic modulus and IRT.
- The fatigue laws of recycled mixtures and high modulus mixture are very similar. As stated in the preceding paragraph, the dynamic modulus increases with RAP content and gets closer to that of the high modulus mixture.
- In general terms, it was observed that the mechanical properties of recycled mixtures and high modulus mixture with 13/22 penetration grade bitumen are similar.

Mechanical properties of cores

- Stiffness modulus and *ITS* values for recycled mixtures cores are lower than those of the corresponding specimens, but differences between cores extracted after different service times (between 6 and 24 months) are not significant.

Effect of RAP on recycled mixture variability

- 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 less variability of bitumen content and gradation in the recycled mixtures.

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. Results show that recycled mixtures could behave in a similar way to that of conventional high modulus mixture. However, proper characterization and handling of RAP stockpiles is crucial to avoid excessive mix heterogeneity.

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Table 1
RAP gradation 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

Table 2
Gradations of tested mixtures

Sieve size (mm)	Gradation for each mix type (% passing)				
	S20R60	S12R40	S20 (B60/70 and B13/22)	Gradation specifications S20 Mixture	Gradation specifications S12 Mixture
25	100	100	100	100	100
20	88	99	87.5	80 - 95	100
12.5	66	85	71.5	64 - 79	80 - 95
8	53	67	58	50 - 66	60 - 75
4	37	41	42.5	35 - 50	35 - 50
2	26	29	31	24 - 38	24 - 38
0.5	14	15	16	11 - 21	11 - 21
0.25	9	10	11	7 - 15	7 - 15
0.125	7	7.4	7.5	5 - 10	5 - 10
0.063	4.5	4.8	5	3 - 7	3 - 7

Table 3
Marshall characteristics for design of tested mixtures

Mix type Bitumen grade	S20R60 B200/300	S12R40 B200/300	S20 B60/70	S20 B13/22	Specifications
New bitumen penetration (dmm)	250	200	63	17	-
New bitumen content (% by weight of mix)	2.11	2.72	4.5	4.5	≥ 60% total bitumen content
Total bitumen content (% by weight of mix)	4.4	4.5	4.5	4.5	> 4 binder layer > 3.5 base layer
Density (g/cm^3)	2.449	2.418	2.426	2.490	-
Air voids (%)	3.8	4.4	3.4	3.4	5-8 binder layer 6-9 base layer
Marshall stability (kN)	17.5	15.6	15.1	21.6	> 12.5
Marshall flow (mm)	2.41	2.47	2.30	2.9	2-3.5
Marshall quotient (kN/mm)	7.26	6.31	6.57	7.4	< 8

Table 4
Fenix test results at 20 ºC

Mixtures		Peak load	Displacement before Peak load at ½ F_{max}	Displacement peak load	Tensile stiffness index	Dissipated energy	Displacement 50% post peak load
		F_{max} (kN)	Δ_m (mm)	ΔF_{max} (mm)	I_{RT} (kN/mm)	G_D (J/m^2)	Δmdp (mm)
Specimens	S20R60	1.61	0.08	0.21	9.88	459	0.54
	S12R40	1.24	0.08	0.27	8.05	520	0.84
	S20 (B60/70)	0.54	0.05	0.25	6.00	248	1.07
	S20 (B13/22)	1.46	0.08	0.23	9.73	581	0.72
Cores 6 months	S20R60	0.91	0.15	0.27	6.20	446	0.95
	S12R40	0.87	0.14	0.20	6.36	510	0.82
Cores 12 months	S20R60	0.90	0.16	0.28	5.54	402	0.97
	S12R40	0.74	0.11	0.18	6.54	477	0.79

Table 5
Standard deviation RAP gradation

Sieve size (mm)	RAP 0/8 mm			RAP 8/25 mm		
	Target gradation (%)	Average gradation (%)	Standard deviation	Target gradation (%)	Average gradation (%)	Standard deviation
25	100	100	-	100	100	0.51
20	100	100	-	96	98	1.70
12.5	100	100	-	77	82	6.36
8	99	100	0.61	59	65	7.90
4	91	89	3.12	35	41	6.51
2	67	66	3.61	24	29	5.04
0.5	33	33	1.82	14	16	2.48
0.25	21	21	2.15	9	11	1.88
0.125	15	15	1.38	8	8	1.23
0.063	8.8	9	0.67	4.6	5	0.91
Nº extractions		18			18	

Note: RAP gradation after extraction

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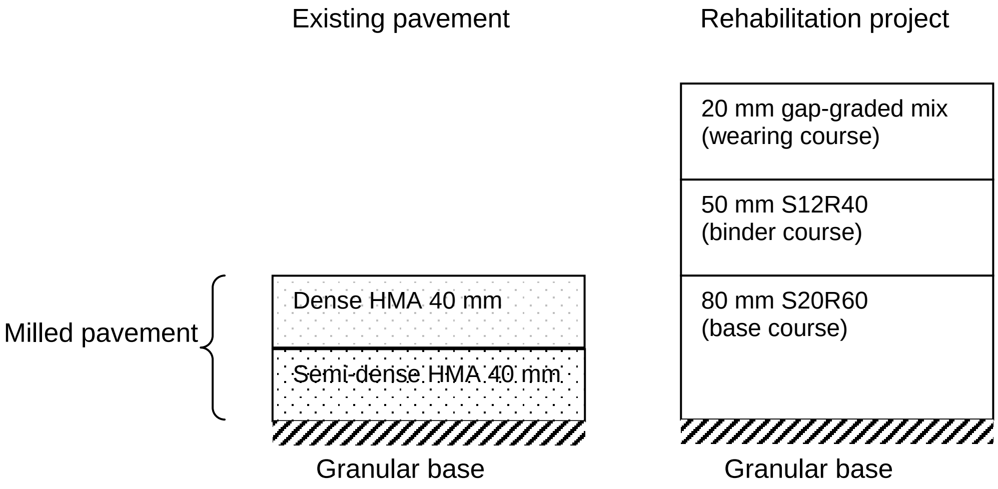
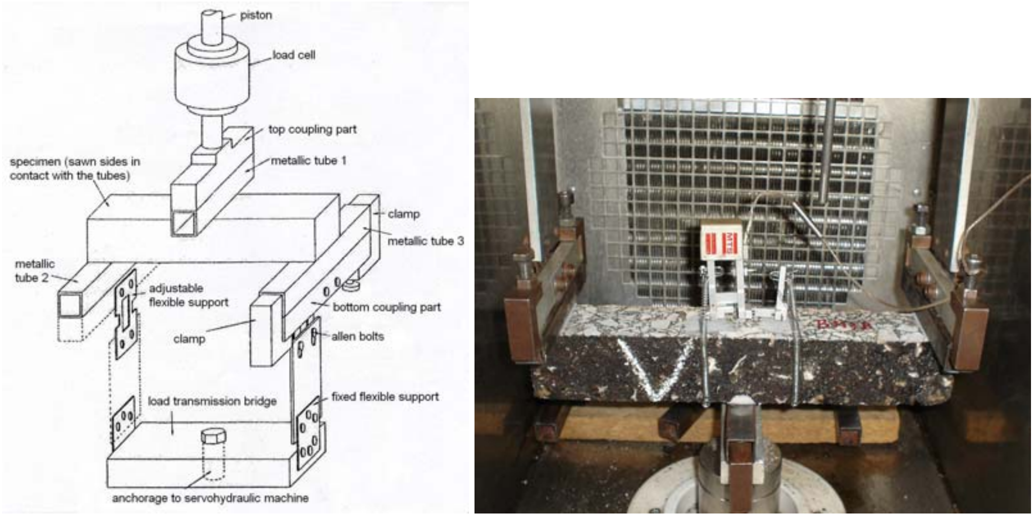
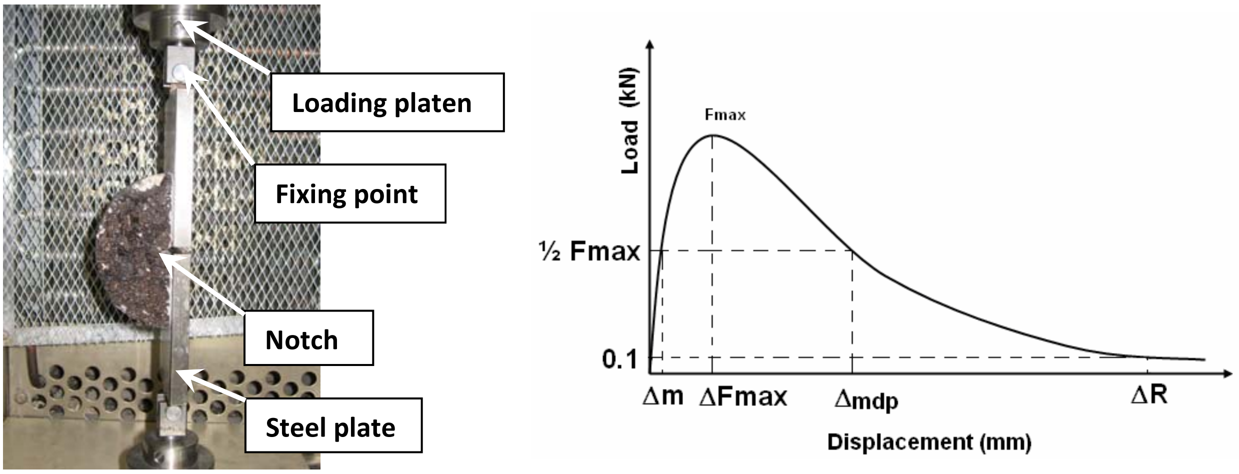


Fig.1. Pavement structure before and after highway A-140 rehabilitation



(a) **(b)**

Fig. 2. Anchoring devices for specimen fatigue testing: (a) scheme and (b) photo.



(a) **(b)**

Fig. 3. Fénix test: (a) test photo and (b) typical load vs. displacement output curve.

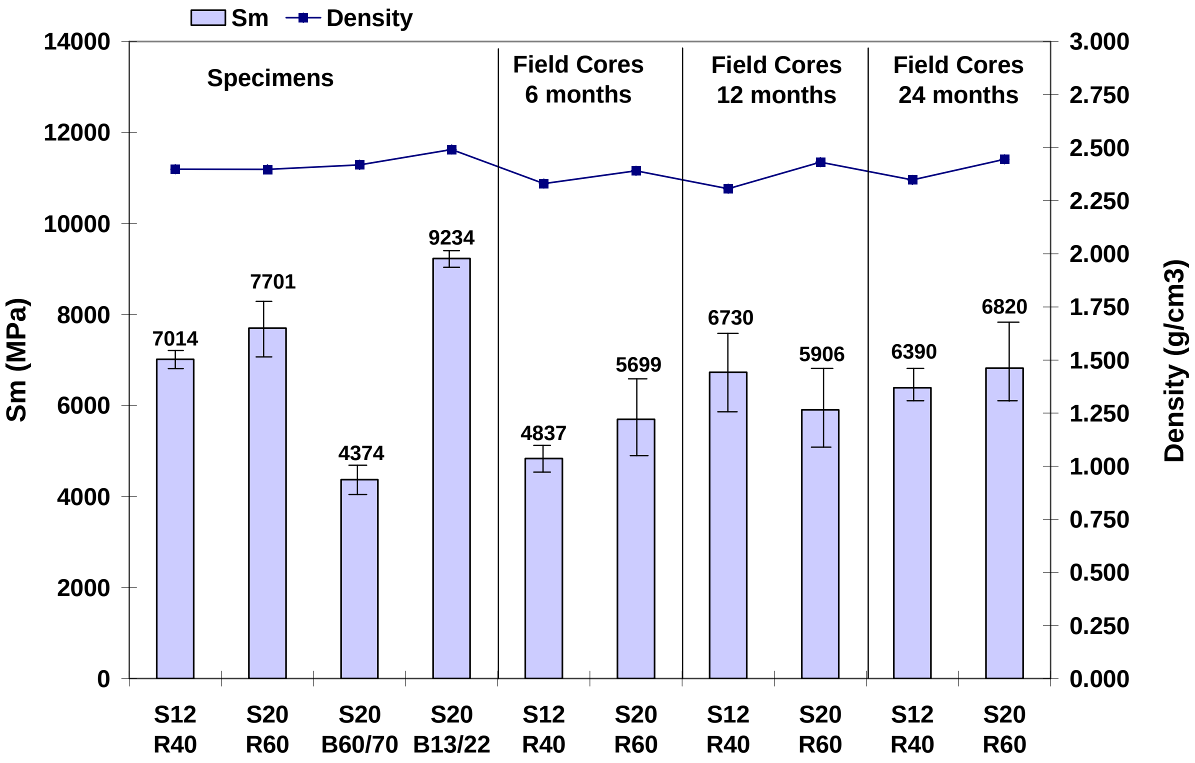


Fig. 4. Stiffness moduli and densities, specimens and field cores, at 20 ºC.

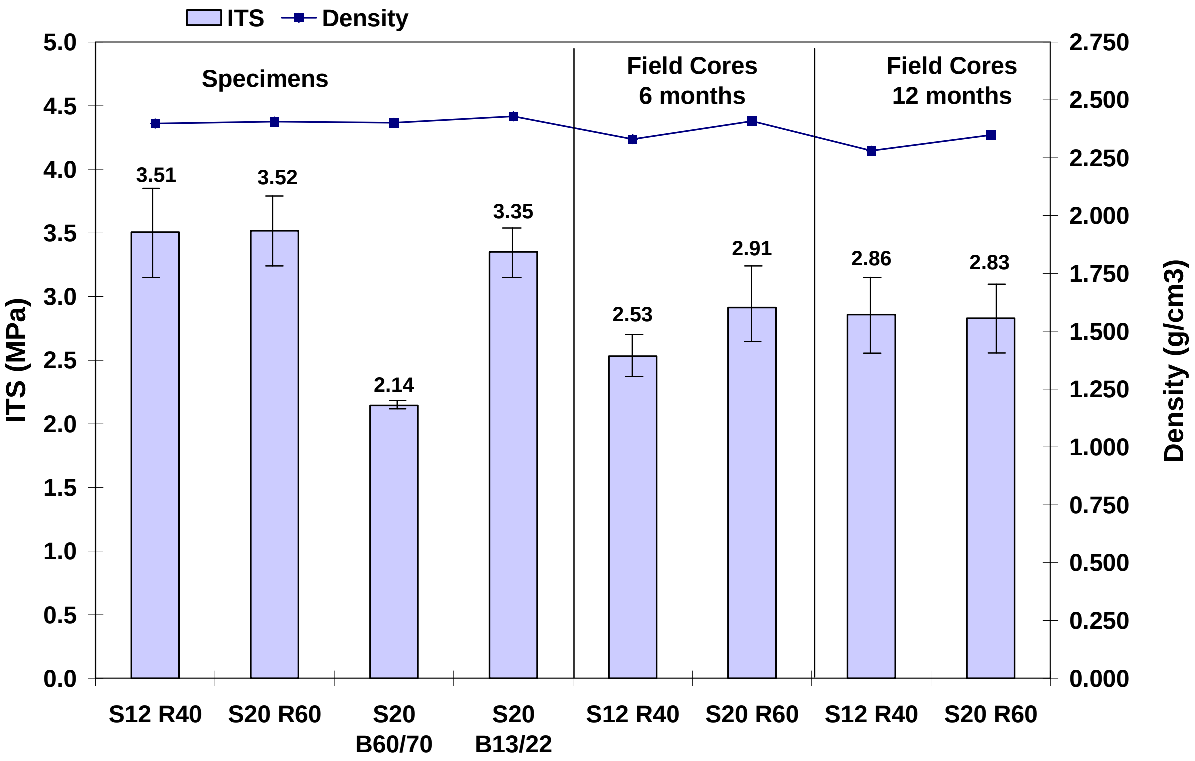


Fig 5. Indirect tensile strength and densities, specimens and field cores, at 15 ºC.

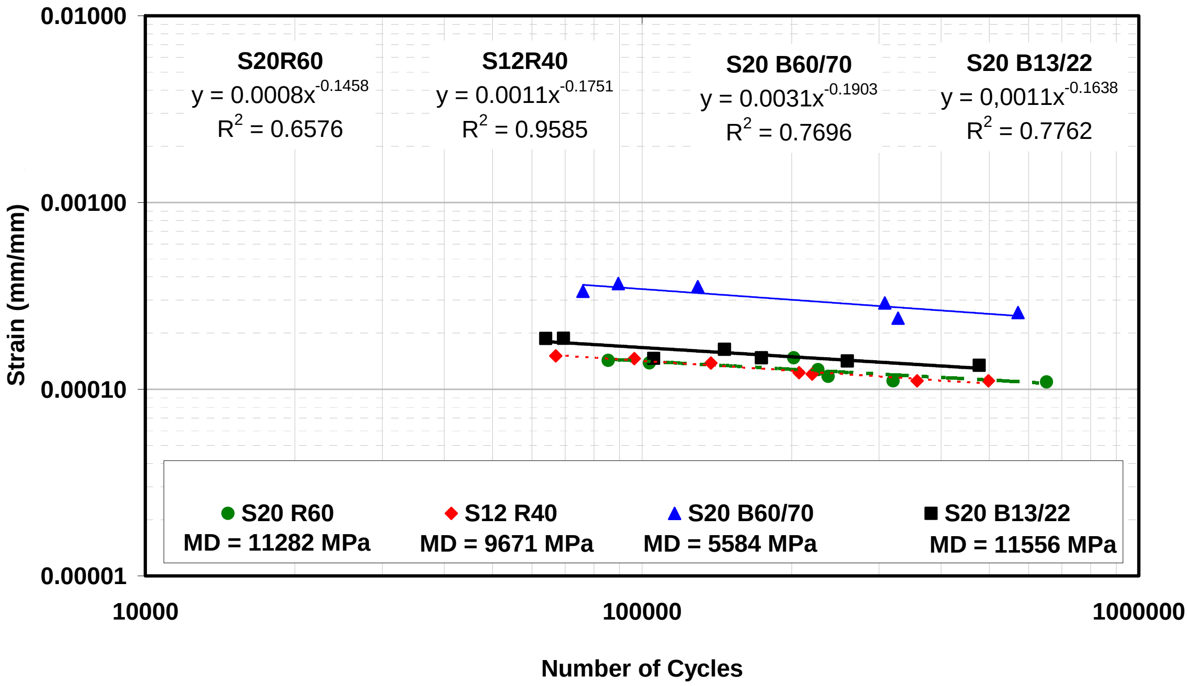
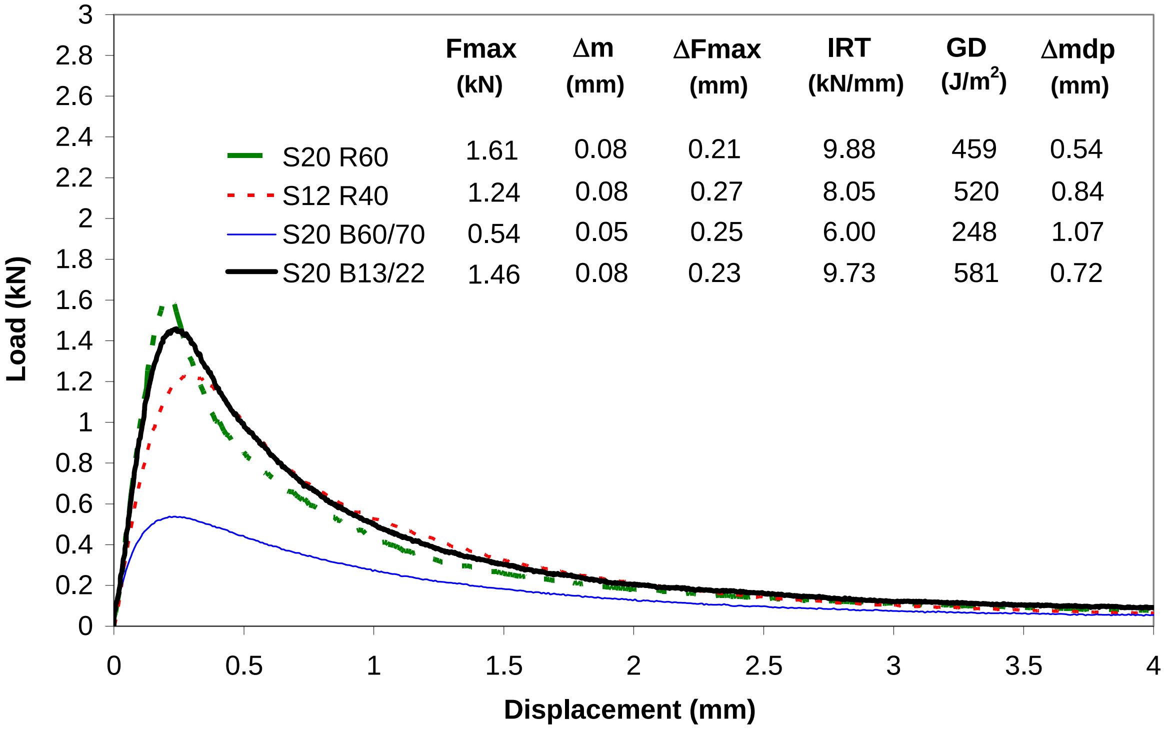


Fig. 6. Fatigue laws at 20 ºC.



	Fmax (kN)	Δm (mm)	ΔFmax (mm)	IRT (kN/mm)	GD (J/m^2)	Δmdp (mm)
S20 R60	1.61	0.08	0.21	9.88	459	0.54
S12 R40	1.24	0.08	0.27	8.05	520	0.84
S20 B60/70	0.54	0.05	0.25	6.00	248	1.07
S20 B13/22	1.46	0.08	0.23	9.73	581	0.72

Fig. 7. Fénix test results on specimens at 20 ºC.

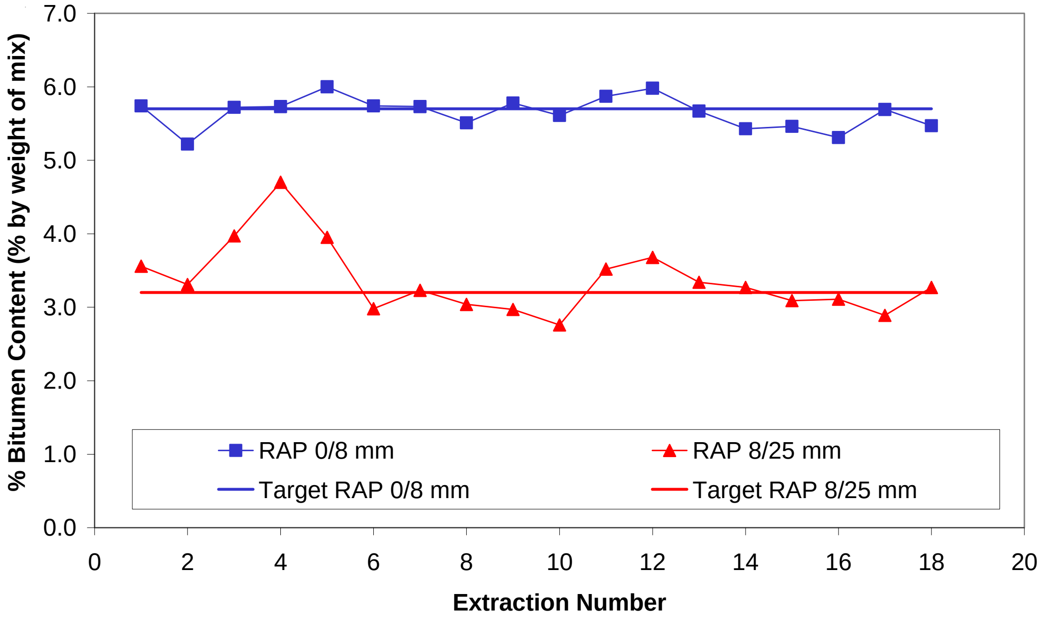


Fig. 8. Control chart for RAP asphalt content.

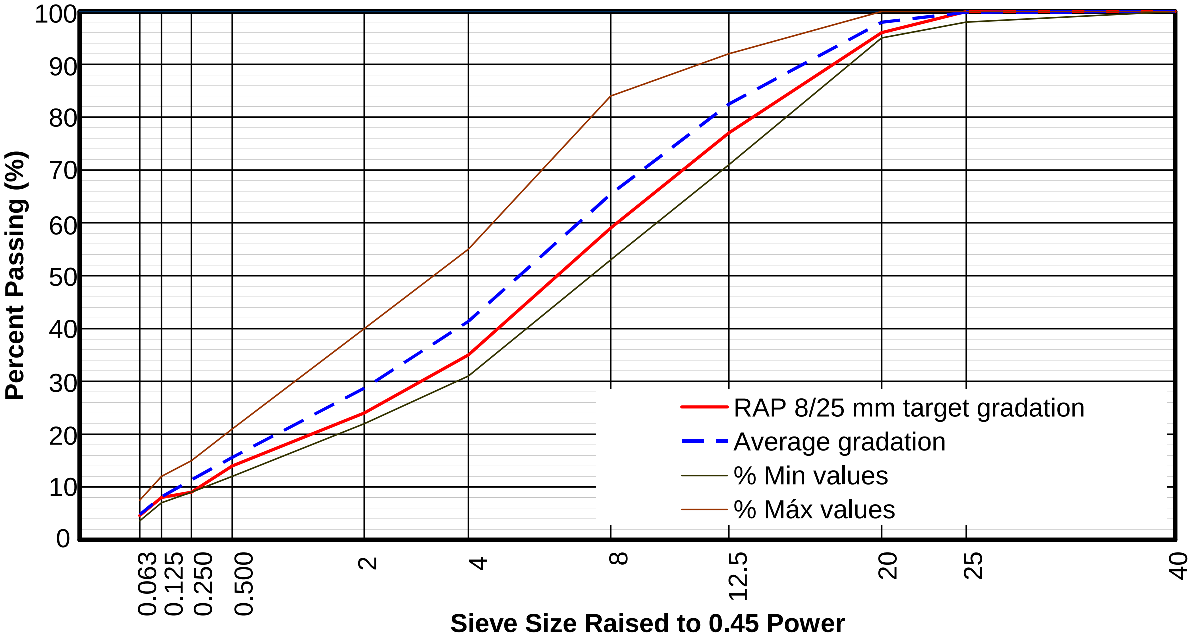


Fig. 9. Control gradations from 8/25 RAP extraction.

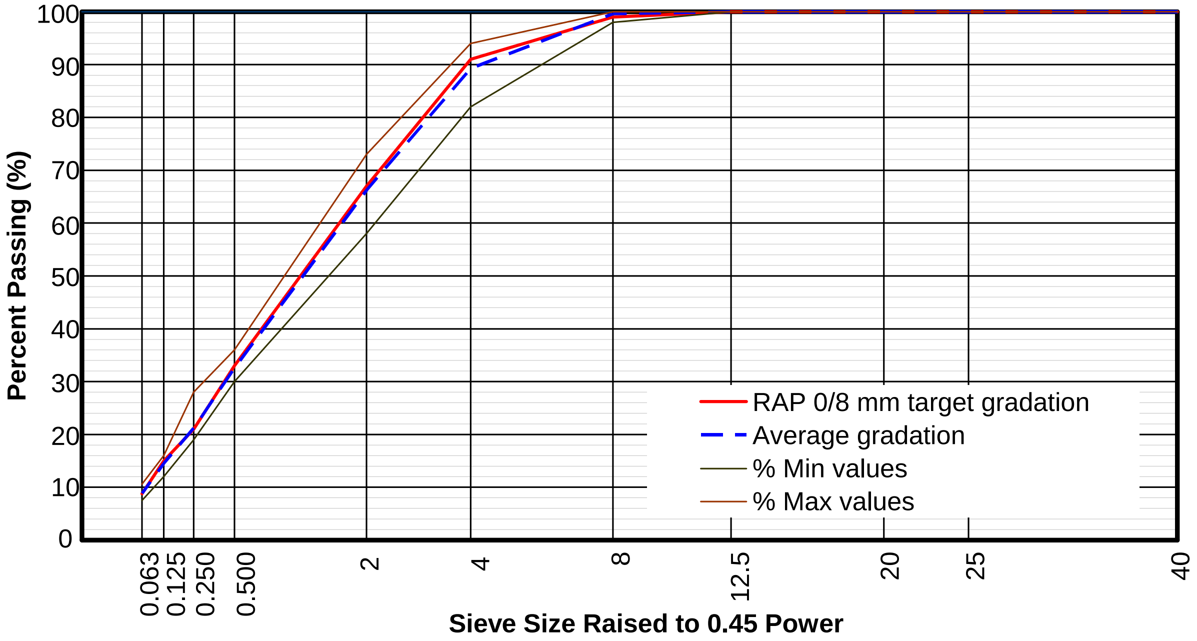


Fig. 10. Control gradations from 0/8 RAP extraction.

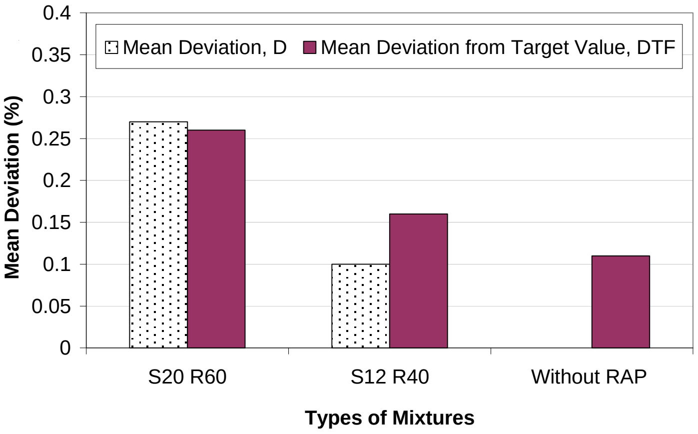
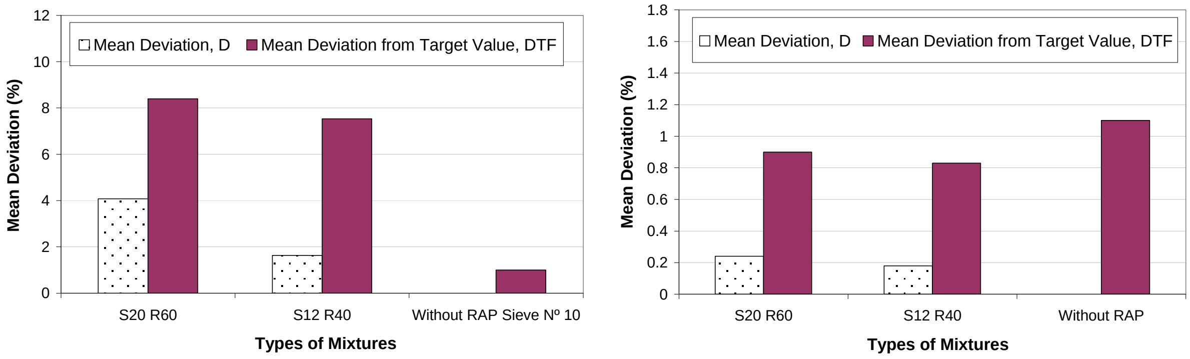


Fig. 11. Mean deviations from job mix formula for bitumen content.



(a) (b)

Fig. 12. Mean deviations from job mix formula target gradation: (a) 8 mm sieve and (b) 0.063 mm sieve.