EFFECT OF MIXING TIME AND TEMPERATURE ON CRACKING RESISTANCE OF BITUMINOUS MIXTURES CONTAINING RECLAIMED ASPHALT PAVEMENT MATERIAL

Domingo Pérez Madrigal,

Ph.D. candidate, Dept. of Civil and Environmental Engineering,

Technical University of Catalonia, 08034 Barcelona, Spain

Andrea Iannone,

Graduate Student, Dept. of Civil and Environmental Engineering,

Politecnico di Milano, 20133 Milan, Italy

Adriana Martìnez, (corresponding author)

Associate Professor, Dept. of Civil and Environmental Engineering

Technical University of Catalonia, 08034 Barcelona, Spain

Phone +34934017273, Fax +34934017264

adriana.martinez@upc.edu

Filippo Giustozzi,

Assistant Professor, Dept. of Civil and Environmental Engineering,

Politecnico di Milano, 20133 Milan, Italy

Phone +390223996617, Fax +390223996602

filippo.giustozzi@polimi.it

Abstract

The use of reclaimed asphalt pavement (RAP) in bituminous mixtures is considerably increasing due to the environmental and economic benefits of recycled materials. However, stiffer mixes, usually resulting from RAP addition, have raised concern about long term properties of the pavement; a mechanical characterization of these mixes is thus needed. In this study, the effect of mixing condition on bituminous mixtures containing RAP was evaluated. Volumetric and mechanical properties were analysed. An experimental program, with the aim of measuring stiffness modulus, water sensitivity and cracking resistance, was conducted. Cracking resistance was evaluated according to the Fénix test since it has proved to be a convenient and effective method for characterizing cracking behaviour of bituminous mixtures at different temperatures.

Mixtures containing 20% or 40% of Reclaimed Asphalt Pavement (RAP) material were tested; virgin aggregates and RAP mixing temperatures as well as mixing time were varied and

34 comparisons with a reference mix were conducted to characterize fracture energy and mechanical

35 performance.

36

37 **Background**

38 In the last decades energy saving and preservation of the environment have acquired a major

39 importance in trying to curtail climate change. In roads construction this objective is pursued with

40 the increasing use of reclaimed asphalt pavement, also called RAP. The use of this material allows

41 an economization of energy, new fossil material and financial resources. However, it must be also

42 considered the need to develop a new pavement mixture without negatively impacting performance.

43 Since bituminous mixtures containing RAP are usually stiffer, it is recommended to investigate

44 their cracking resistance. As shown by Ozer and Al-Qadi (2009), low RAP percentages in the mix

45 (up to 20%) seem to have insignificant effects on the blended binders. Hence also cracking

46 resistance remains almost unchanged. However, when a higher amount of RAP is used, the effect of

47 the aged binder on the mix properties becomes significant.

48 One crucial parameter when addressing cracking resistance is the fracture energy, which is the

49 energy required to produce a unit surface area crack. In asphalt specimens, the load initially creates

50 an elastic strain that may trigger a fracture. If this happens the energy is then used to propagate the

51 cracking and deform the specimen. To evaluate fracture energy, different tests are available. The

52 semi-circular bending test or SCB test (EN 12697-44, 2011), and the disc-shaped compact tension

53 test or DC(T) test (ASTM D7313, 2013), are the most common. From both tests, similar parameters

54 can be obtained and both are commonly conducted during the mix-design phase to improve

55 cracking resistance of mixes. A new test, called Fénix, was developed by the Barcelona Tech with

56 the aim of characterising the cracking resistance of bituminous mixtures. The Fénix test is easily

57 feasible and overcomes the disadvantages of other tests, i.e. the arch effect in the SCB and the

58 specimen shaping in the DC(T) (Wagoner et al. 2005). Furthermore, it has been demonstrated that

59 the Fénix configuration is more reliable at higher temperature than the SCB (Pérez-Jiménez et al.

60 2013). Pérez-Jiménez et al. also obtained a correlation between the Fénix and fatigue law

61 parameters (2011) and demonstrated that this test can give an all-around characterisation of the

62 cracking resistance of a pavement.

63 At high RAP percentages, it is very difficult to know to what extent the aging of the RAP binder

64 affects the properties of the mixture; a blending between oxidized and virgin binder occurs but it is

65 very unlikely that this blending becomes complete (Mc Daniel et al., 2000). Some researchers found

66 that this inability of the aged binder to achieve full mobilization leads to "under-asphalted"

67 mixtures, with higher void content, reduced cracking resistance or lower resistance to water action

68 (Al-Qadi et al., 2007; Zaumanis and Mallik, 2015).

69 The degree of blending between RAP, binder and new aggregates has been studied by Huang et al.

70 (2005), who analyzed the coating obtained in the recycled mixture, subdividing it into layers, and

71 found that the outer layers were much softer than the inner ones, putting evident that the

72 combination of both bitumens was not uniform or complete. Others like Bowers et al. (2014) and

73 Marsac et al. (2014), also studied the efficiency of blending by means of different techniques, such

74 as gel permeation chromatography and infrared spectroscopy respectively. Both procedures also

75 confirmed that blending could be incomplete.

76 The greater or lesser degree of blending between the RAP bitumen and the new bitumen depends,

77 among other reasons, on the way in which the mixture is manufactured. Two manufacturing

78 processes are clearly differentiated: RAP can be incorporated into hot mix asphalt produced in a

79 batch plant up to a rate of approximately 20%. In this case, aggregates are usually overheated in the

80 dryer drum to get the energy required to dry and heat the RAP. For higher percentages of RAP, an

81 adapted asphalt plant is necessary in order to preheat RAP and facilitate the blending. Two key

82 variables are involved in the mixing process: the temperature of the mixture components and the

83 mixing time.

84 Clearly the higher the temperature at which the RAP is exposed, the greater the aging that the RAP

85 could further undergo, especially when exceeding 100°C (Yu et al., 2016). On the other hand, when

86   RAP is incorporated at ambient temperature, increasing the mixing time favors both the total drying

87   of RAP and the homogenous heating between the components of the mixture, resulting in a higher

88   quality recycled mixture (Howard et al., 2009). Some studies investigated the temperature evolution

89   and the amount of RAP binder transfer during the mixing of the overheated new aggregates and

90   RAP; results showed that either a longer mixing time or higher overheated new aggregates is

91   necessary when high RAP contents are to be used, as stated by Zhang et al. (2015).

92   For these reasons, the purpose of this study is to evaluate the mechanical properties of a mixture

93   recycled with 20% and 40% of RAP, considering different manufacturing alternatives, simulating

94   the effect of two variables: the temperature of the aggregates and RAP, and the mixing time.

Experimental Plan and Methodology

96   The aim of this study was to verify the effect of 1) mixing time and 2) temperature on bituminous

97   mixtures, especially those containing RAP. The same mixing energy was applied through a

98   mechanical mixer. Different combinations of temperatures were tested to evaluate their influence on

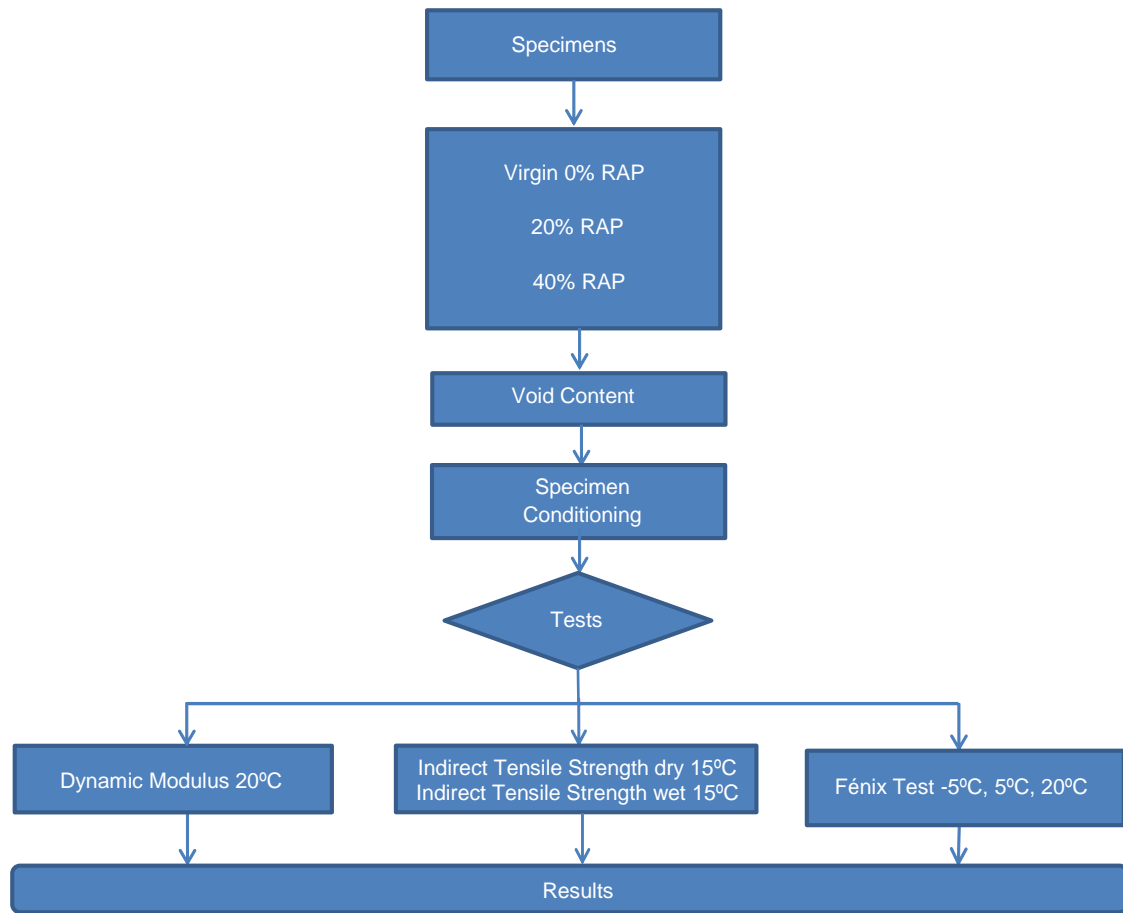99   aged and virgin bitumen, and their blending (Figure 1).

100

Figure 1. Experimental plan

102　The effect of these parameters was studied on mixtures containing 20% and 40% of RAP and the

103　results were compared with a reference virgin mix.

104　Void content was first calculated according to EN 12697-6 (2012) and the dynamic modulus was

105　sequentially tested (EN 12697-26, 2012). Indirect tensile strength was evaluated and sensitivity to

106　water (EN 12697-23, 2004; EN 12697-12, 2009) of the mixes was assessed. Finally, the Fénix test

107　was executed at three different temperatures.

108   The Fénix test is commonly used to calculate the dissipated energy during the cracking formation.

109   The evaluation of this energy is an effective way of estimating cracking resistance of asphalt

110   mixtures. The half of a cylindrical specimen, 63.5 mm thick with a diameter of 101.6 mm prepared

111   by Marshall or gyratory compaction, is subjected to a tensile stress at a constant displacement

112   velocity (1 mm/min). The test temperature is controlled. In the middle of the flat face of the

113   specimen, a 6 mm deep notch is made. Then, the specimen is glued to two steel plates with epoxy

114   resin. The plates are attached to a loading platen with a hinge, so that they can make a small rotation

115   (Figure 2).

116   Load and displacement data were recorded throughout the test to calculate the parameters involved

117   in the cracking process. The dissipated energy during cracking, G_D, is calculated by Equations 1 and

118   2.

119
$$G_D = \frac{W_D}{hl} \tag{1}$$

120   where G_D is the dissipated energy during test (J/m^2), W_D is the dissipated work (kN · mm), h is the
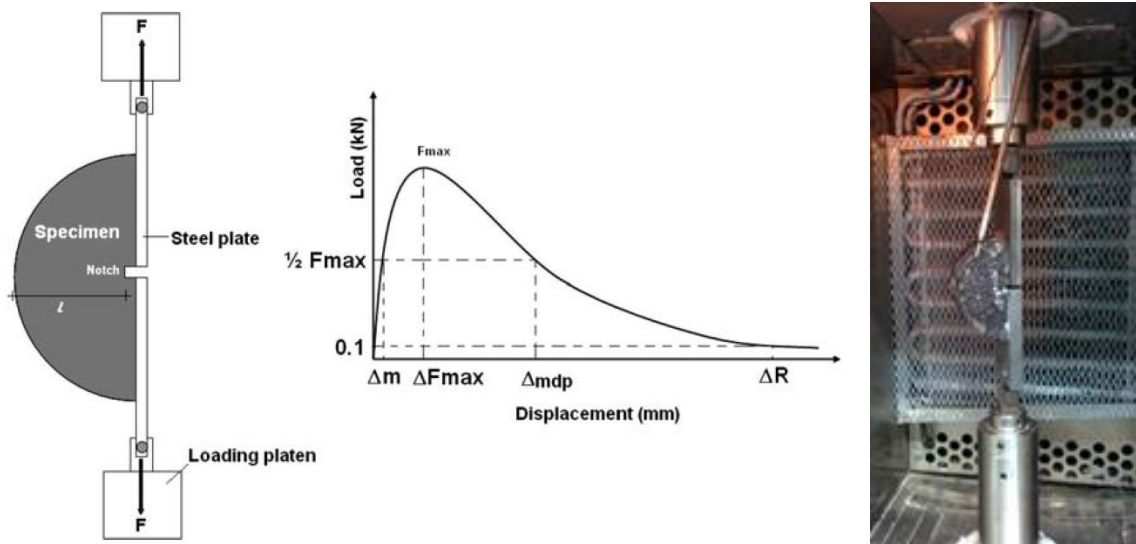

Figure 2. Typical load vs. displacement output curve and Fénix experimental set up

121   specimen thickness (m), and l represents the initial ligament length (m).

122
$$W_D = \int_0^{\Delta R} F du \tag{2}$$

123   where F is the applied load (kN), u is the vertical actuator displacement (mm), and ΔR is the

124   displacement at $F = 0.1$ kN post peak load (mm) (considered as a residual value).

125   Other mechanical parameters such as peak load (F_{max}), displacement at peak load (ΔF_{max}) and

126   displacement at 50% of post peak load (Δ_{mdp}) are determined from the load–displacement curve, as

127   shown in Figure 2.

128   In previous studies (Pérez-Jiménez et al., 2010), the repeatability of the Fénix test was assessed by

129   coefficient of variation values (COV). For dissipated energy, G_D, and maximum tensile load, F_{max},

130   COV mean values of 15% and 8.5% were obtained, respectively. Based on COV values for

131   dissipated energy, the Fénix test seems to have good repeatability in comparison with other tests

132   like DC(T), and SCB tests (Wagoner et al., 2005).

133   **Materials**

134   For this study ten different mixtures were prepared (Table 1). A control mixture without RAP was

135   also analyzed. Five out of ten mixtures included 20% of RAP and were mixed varying the mixing

136   temperatures and mixing time.

	Name	Aggregate Temperature [°C]	RAP Temperature [°C]	Mixing Time [min]	Number of compaction blows (Marshall hammer)
0% RAP	Virgin	160	-	2	75
		160	-	2	50
20% RAP	Mix 1	160	110	2.5	75
		160	110	2.5	50
	Mix 2	160	20	2.5	75
		160	20	2.5	50
	Mix 3	160	20	3.5	75
		160	20	3.5	50
	Mix 4	200	20	2.5	75
		200	20	2.5	50
	Mix 5	200	20	3.5	75
		200	20	3.5	50
40% RAP	Mix 1	160	110	2.5	75
		160	110	2.5	50
	Mix 2	160	20	2.5	75
		160	20	2.5	50
	Mix 3	160	20	3.5	75
		160	20	3.5	50
	Mix 4	200	20	2.5	75
		200	20	2.5	50
	Mix 5	200	20	3.5	75
		200	20	3.5	50

137

138 **Table 1.** Summary of the mixes

139 RAP was used at 110°C or at 20°C, while the aggregates were heated at 160°C or overheated at

140 200°C, with the aim of simulating the manufacturing processes explained in previous sections. Both

141 temperatures participate to determine the final mixing temperature; thus, after mixing RAP,

142 aggregates, bitumen and filler, the temperature of the mixture was measured with a laser

143 thermometer. The mixing time was 2.5 minutes and 3.5 minutes.

144 Similarly, five mixtures with 40% of RAP were prepared. For each specific combination of mixing

145 time and temperature, six specimens were realized with 50 blows and other six specimens with 75

146 blows of a Marshall impact compactor (EN 12697-30, 2013).

147 Mixes gradation was developed for a binder layer of the pavement; nominal maximum aggregate

148 size was 22 mm. The gradation of the RAP (before and after the bitumen extraction) was studied to

149 identify the amount of virgin aggregates to be added to fall within the limit curves. The sieve size

150 gradations are showed in Figure 3.

151
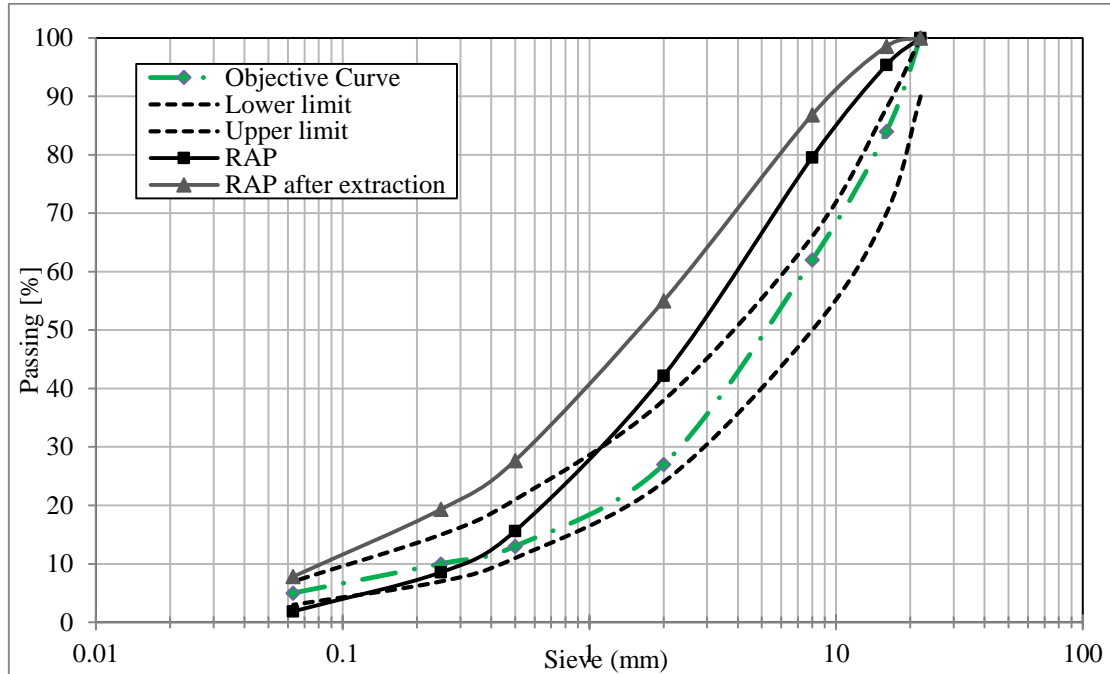
153 **Figure 3.** Gradations of materials

154 The virgin binder used for the specimens without RAP is 50/70 dmm pen grade bitumen. Instead,

155 70/100 dmm pen grade bitumen was used for specimens containing RAP. It was, in fact, expected

156 that the blending between the aged RAP bitumen and the virgin softer binder resulted in a similar

157 performance to the 50/70 dmm. The amount of binder and main physical characteristics are shown

158 in Table 2.

	Penetration (EN 1426) (dmm)	Softening Point (EN 1427) (°C)	Bitumen Extracted (%)	Bitumen in the mix (%)
50/70 pen grade	51	50.9		4.25
70/100 pen grade	84	47		4.25
RAP binder	7	87	3.5	4.25

160 **Table 2.** Properties of the binders

Preliminary Results

The void content was estimated for all the specimens. Figure 4 shows that increasing the amount of RAP generally results in greater void content with 40% RAP mixes exhibiting up to 7.4% of voids due to compaction difficulties. Longer mixing times generally decrease the content of voids because the degree of blending between virgin and oxidized binders was improved and compaction was thus facilitated. Higher RAP temperatures led to a reduced viscosity in the binder and, therefore, better aggregate flow during compaction.
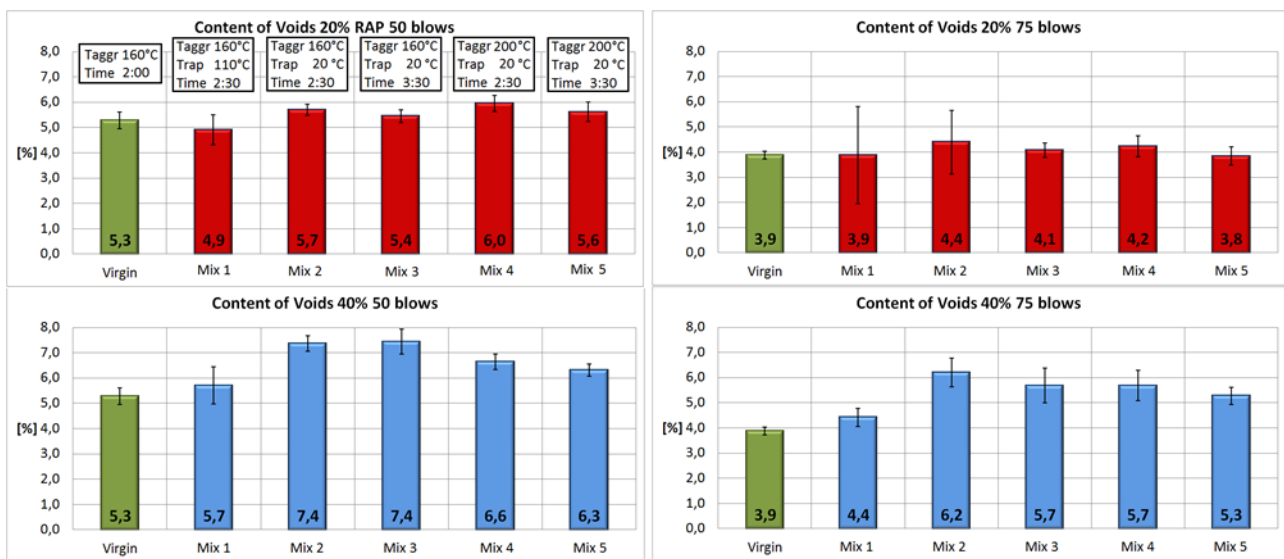
Figure 4. Void content of the mixtures

Dynamic modulus of 75-blow specimens was evaluated at $20 \pm 0.5°C$. As expected, the stiffness modulus was improved as the content of RAP increased.

If RAP is not heated (i.e.; used at 20°C), the oxidized binder does not blend with the virgin binder and stiffness is reduced. Increasing mixing temperature provided an improved blending; this led to greater modulus (Figure 5). This is even more evident in specimens with 40% RAP. Heating RAP up to 110°C provided a double modulus respect to the virgin mix without RAP.
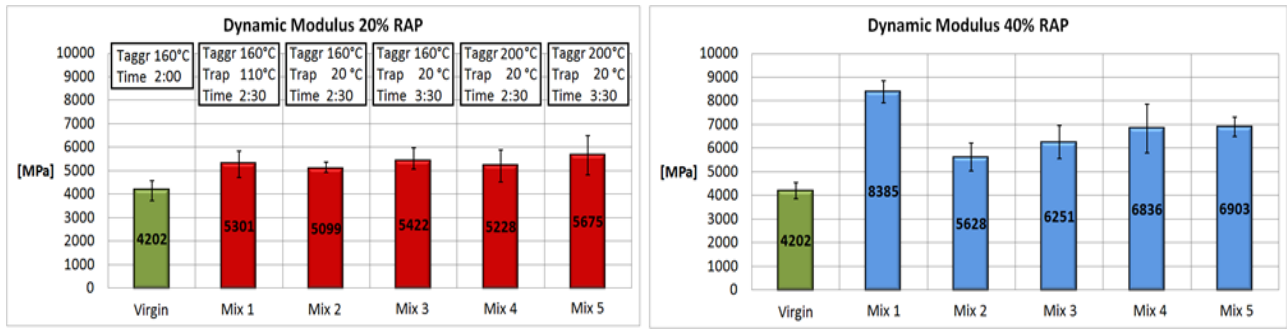
178

Figure 5. Dynamic Modulus of the mixtures

Increasing the mixing time provided greater stiffness due to improved degree of blending (when RAP was heated), lower void content and greater homogeneity.

50-blow specimens were used to analyze the indirect tensile strength (Figure 6). Each mix was tested at different conditions, dry and wet, to evaluate water damage according to EN 12697-12 (2009); the test was conducted at 15°C. The Indirect Tensile Strength Ratio (ITSR) index was thus calculated as the ratio between the ITS_{wet} and the ITS_{dry}.
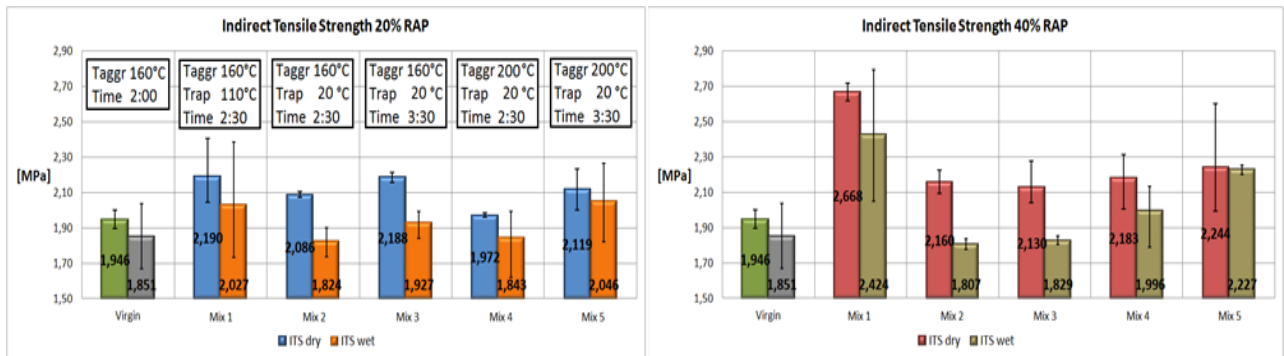

186

Figure 6. Indirect tensile strength of the mixtures at 15°C

Increased water damage is shown by ITSR lower values. ITSR value ranged from 84% (Mix 2, 40% RAP, 2.5 minutes of mixing, $T_{agg} = 160°C$, $T_{RAP} = 20°C$) to 99% (Mix 5, 40% RAP, 3.5 minutes of mixing, $T_{agg} = 200°C$, $T_{RAP} = 20°C$). As demonstrated by Iwanski Chomicz-Kowalska (2012), tensile strength grows as the percentage of blended and oxidized binder increases. Generally, tensile strength is higher as the percentage of RAP in the mixes increases. The tensile strength and the water susceptibility did not seem to be greatly influenced by the mixing time. A better blending, depending on higher RAP heating temperatures, provided better mechanical performance and

195   resistance to water damage (Figure 7). This could be noted in Mix 1, Mix 4 and Mix 5 where

196   aggregates were overheated or RAP was preheated.
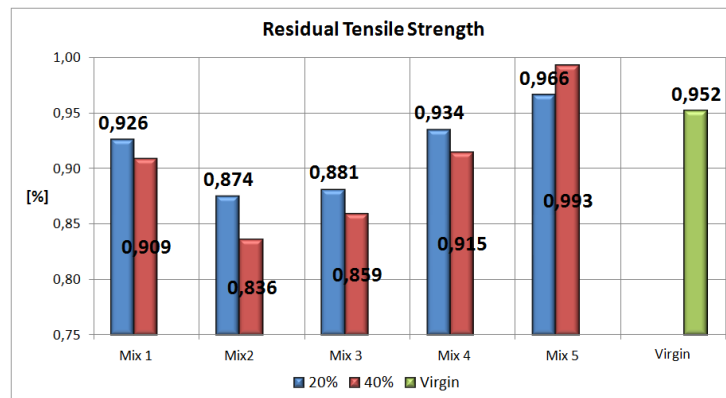
Figure 7. Indirect tensile strength ratio of the mixtures

Fracture Energy

200   As a matter of fact, RAP binder is commonly stiffer than the virgin binder due to aging processes.

201   Low-temperature fracture, fracture energy and fatigue cracking should therefore be analyzed.

202   Figure 8 shows the results of Fénix test on the reference mixtures at three different temperatures.
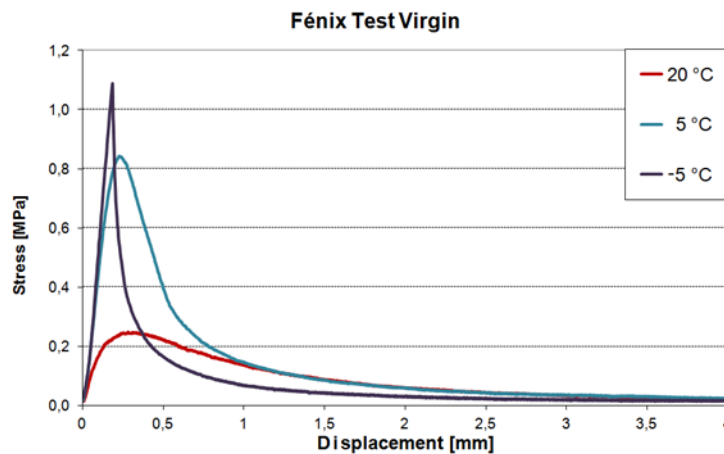
Figure 8. Fénix test at three different temperatures

205   Prior to fracture, the work effectuated by the load is principally stored as elastic strain energy. Upon

206   fracture, the energy is spent in propagating the crack and irreversibly deforming the material. As the

207   test temperature decreases the behavior of the material becomes more brittle. The slope of the

208   elastic initial segment is increased while Δ_{mdp} (displacement at 50% post-peak load) is considerably

209   decreased.

210   The highest values of G_D (fracture energy) were obtained at 5°C for 20% RAP mixes; however,

211   adding 40% RAP resulted in a shift of the fracture energy peak at higher temperature (Figure 9).

212   This could be related to an increased amount of less-ductile bitumen (i.e.; oxidized binder from

213   RAP) into the mixes. The greatest fracture energy was provided by the reference virgin mix; all

214   other mixtures broke at lower energy since the blended bitumen is weaker due to aging.
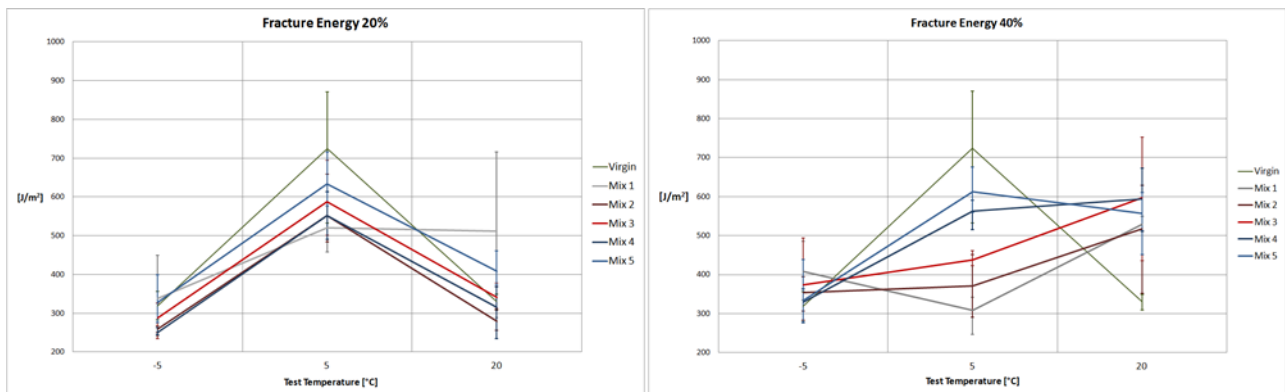
215

216   **Figure 9.** Fracture energy of the mixes at different temperatures

217   For what concerns the Δ_{mdp}, Figure 10 shows that at higher temperatures the behavior of the

218   mixtures becomes more ductile. Once again the values of the displacement of the virgin mixture are

219   the highest. It is worthwhile to notice that the virgin bitumen had a lower penetration (more ductile)

220   than the one used in the mixtures with RAP (more fragile). This means that the aged bitumen in

221   RAP substantially affects the good properties of the virgin one. Figure 10 also shows that a higher

222   percentage of RAP reduces the capability of the mixtures to resist once the fracture is triggered.

223   Analyses about the effect of mixing time and temperature on fracture energy are provided in the

224   following section.

Influence of Mixing Time and Temperature

226   The fracture energy was influenced not only by the test temperature but also by the compaction

227   temperature (i.e.; the temperature resulting after mixing the components). The experimental results

228   highlighted that a higher mixing temperature should bring to a higher G_D. When RAP is used at

229   ambient temperature (20°C), overheating the virgin aggregates to 200°C improves the resistance of

230   the mixture. This excess in heat allows the two materials to collaborate without compromising the

231   good properties of the virgin binder. In colder mixtures (T_{agg} = 160°C, T_{RAP} = 20°C), RAP behaves

232   as a *"black rock"* (Al-Qadi et al., 2009) and its binder does not really participate to the final

233   mechanical characterization. Particular attention should be paid to the mixtures with RAP heated to

234   110°C; in this case the better blending considerably changed the stiffness of the mixture and led to a

235   deterioration of the ductile properties of the virgin binder. This trend is confirmed in the mixtures

236   with more RAP, in which the behavior of the mixtures considerably changes with the temperature.
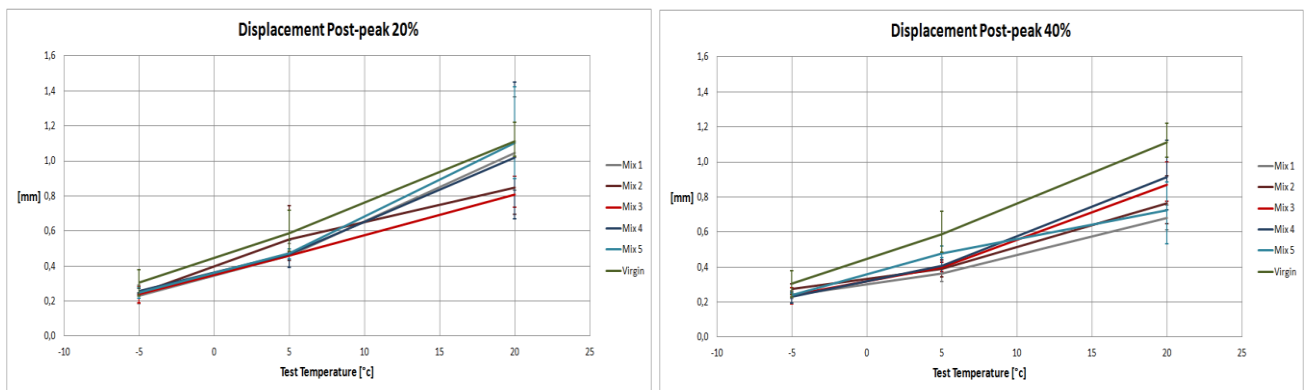
237   **Figure 10.** Displacement at 50% post-peak load of all mixtures

238   A compromise between collaborating binders and high blending degree should be pursued in order

239   to have the best mechanical performance.

240   In addition, increasing the mixing time has a beneficial effect on G_D, which rises, improving the

241   fracture resistance of the material. The advantageous effect of a longer mixing time is tangible in

242   each mix and for all RAP percentages. A well-mixed compound has a more homogeneous

243   distribution of the aggregates and a good level of blending between the binders.

244   ## Conclusions

245   On the basis of the performed tests the following conclusions about the stiffness and the cracking

246   resistance of RAP pavement mixes can be drawn.

247   • The void content is higher in all the mixtures that contain RAP for constant compaction

248   energy. The aged bitumen has a greater viscosity that reduces the workability of the mixture

249   during compaction. Results have also highlighted that an increase of mixing temperature

implies a diminishment of voids. Increasing the mixing time makes the mix more homogenous and the same void reduction can be observed.

- Stiffness, measured by the dynamic modulus test, revealed that including RAP provides stiffer mixes. Preheating the RAP makes the oxidized binder to collaborate with the virgin bitumen, with a consequently higher stiffness. The lowest modulus was found in the specimens with RAP at 20°C, probably because the aged bitumen blended in a significant lower degree. An intermediate behavior was obtained by heating the aggregates to a higher temperature.

- Indirect Tensile Strength was higher for all RAP mixes, especially 40% RAP mixes. However, lower mixing temperature and time increased the damage caused by the water (ITSR).

- Fénix tests highlighted that fracture energy is maximum at intermediate temperature (5°C), although including greater RAP rates shifted the fracture energy peak toward higher temperatures. Greater mixing temperature seemed to have a positive effect on fracture energy, as long as RAP is not heated to a high temperature. Longer mixing times slightly increase fracture resistance; however, this could be caused by a reduced void content.

Finally, it was observed that bituminous mixtures containing RAP provide a stiffer behavior that could potentially turn into cracking occurring. Overheating the aggregates without preheating RAP and extending mixing time have proven to be good expedients to improve the cracking resistance of the mixtures.

References

Al-Qadi, I., Carpenter, S., Roberts, G., Ozer, H., and Aurangzeb, Q. (2009) "Investigation of working binder in Hot-Mix asphalt containing recycled asphalt pavement". *88th Annual Meeting Transportation Research Board.*

Al-Qadi, I.; Elseifi, M. y Carpenter, S. (2007) "Reclaimed asphalt pavement: a literature review". FHWA-ICT-07-001. Illinois Center for Transportation, Chicago.

ASTM D7313–13. (2013) Standard test method for determining fracture energy of asphalt-aggregate mixtures using the disk-shaped compact tension geometry.

Bowers, B., Huang, B., Shu, X., and Miller, B. (2014). "Investigation of reclaimed asphalt pavement blending efficiency through GPC and FTIR". *Construction and Building Materials* 50, 517-523.

EN 12697-12 standard. (2009) Bituminous mixtures. Test methods for hot mix asphalt. Determination of the water sensitivity of bituminous specimens.

EN 12697-12 standard. (2009) Bituminous mixtures. Test methods for hot mix asphalt. Determination of the water sensitivity of bituminous specimens.

EN 12697-23 standard. (2004) Bituminous mixtures. Test methods for hot mix asphalt. Determination of the indirect tensile strength of bituminous specimens.

EN 12697-26 standard. (2012) Bituminous mixtures. Test methods for hot mix asphalt. Stiffness.

EN 12697-30 standard. (2013) Bituminous mixtures. Test methods for hot mix asphalt. Specimen preparation by impact compactor.

EN 12697-44 standard. (2011) Bituminous mixtures. Test methods for hot mix asphalt. Crack propagation by semi-circular bending test.

EN 12697-6 standard. (2012) Bituminous mixtures. Test methods for hot mix asphalt. Determination of bulk density of bituminous specimens.

Howard, I. L., Cooley, A. L.Jr., and Doyle, J. D. (2009). "Laboratory testing and economic analysis of high RAP warm mixed asphalt" (Report Number FWHA/MS-DOT-RD-09-200). Jackson: Mississippi Department of Transportation.

Huang B.; Li, G.; Vukosavlievic, D. and Shu, X. (2005). "Laboratory investigation of mixing HMA with RAP". Transportation Research Record 1929. 37–45.

Iwanski, M., and Chomicz-Kowalska, A. (2012) "Experimental study of water and frost resistance of foamed bitumen mixes in the cold recycling technology". *Eurasphalt and Eurobitume Congress*.

301 Marsac, P., Piérard, N., Porot, L., Van den Bergh, W., Grenfell, J., Mouillet, V., Pouget, S.,

302 Besamusca, J., Farcas, F., Gabet, T., and Hugener, M. (2014). "Potential and limits of FTIR

303 methods for reclaimed asphalt characterization". Materials and Structures, 47, 1273-1286.

304 McDaniel, R., Soleymani, H., Anderson, M., Turner, P. and Peterson, R. (2000). "Recommended

305 use of reclaimed asphalt pavement in the Superpave mix design method". National Cooperative

306 Highway Research Program, Washington, D.C.

307 Ozer, H., Al-Qadi, I., Carpenter, S.H., Aurangzeb1, Q., Roberts, G.L., and Trepanier, J. (2009)

308 "Evaluation of rap impact on hot-mix asphalt design and performance". *Journal of the Association*

309 *of Asphalt Paving Technologists*, 78, 317-348.

310 Pérez-Jiménez, F., Botella, R., Moon, K., and Marasteanu, M. (2013). "Effect of load application

311 rate and temperature on the fracture energy of asphalt mixtures; Fénix and semi-circular bending

312 tests". *Construction and Building Materials,* 48, 1067-1071.

313 Pérez-Jiménez, F., Valdés, G., Botella, R., Miró, R., and Martínez, A. (2011). "Approach to fatigue

314 performance using fénix test for asphalt mixtures". *Construction and Building Materials,* 26, 372-

315 380.

316 Pérez-Jiménez, F., Valdés, G., Miró, R., Martínez, A., and Botella, R. (2010) "Fénix test:

317 Development of a new test procedure for evaluating cracking resistance in bituminous mixtures".

318 *Transportation Research Record,* 2181, 36-43.

319 Wagoner, M., Buttlar, W. and Paulino, G. (2005) "Disk-shaped compact tension test for asphalt

320 concrete fracture". Experimental Mechanics, 45, No. 3, 270–277.

321 Yu, B., Gu, X., Wu, M., and Ni, F. (2016). "Application of a high percentage of reclaimed asphalt

322 pavement in an asphalt mixture: blending process and performance investigation". Road Materials

323 and Pavement Design, (online).

324 Zaumanis, M., and Mallick, R.B. (2015). "Review of very high-content reclaimed asphalt use in

325 plant produced pavements: State of the Art". International Journal of Pavement Engineering, 16, 1,

326 39–55.

327   Zhang, K., Wen, H., and Hobbs, A. (2015) "Laboratory tests and numerical simulations of mixing

328   superheated virgin aggregate with reclaimed asphalt pavement materials". Transportation Research

329   Record, 206, 62-71.