Mix Design of Polymer-Modified and Fiber-Reinforced Warm-Mix Asphalts with High Amount of Reclaimed Asphalt Pavement

Achieving Sustainable and High-Performing Pavements

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Sustainable materials management and recycling practices are strongly emphasized in a recent U.S. Environmental Protection Agency report (*1*). Transportation itself is one of the major consumers of energy globally, and it includes consumption from road construction and maintenance practices (*2*). Improvement in energy efficiency is therefore a key factor for promoting sustainable development. Throughout a roadway's service life, construction and maintenance account for only a small part of its energy use, the majority of which comes from road traffic. However, the energy spent during these phases is still quite important and is worth analyzing (*3*).

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Road authorities, municipalities, and state departments of transportation have been considering alternative greener methodologies in the production of asphalt concrete mixes. One of these methods is the use of reclaimed asphalt pavement (RAP) in newer construction projects. The use of RAP in asphalt mixtures has steadily increased in recent years (*4*). In the United States alone, almost 100 million tons of asphalt concrete are reclaimed each year, of which roughly 80% can be reused as RAP (*5*).

Another green option is warm-mix asphalt (WMA) technology, which allows asphalt mixes to be produced and placed at lower temperatures. High production temperatures are commonly needed by hot-mix asphalts (HMAs) to provide good workability during construction operations; to allow the asphalt binder, in a low-viscosity state, to coat the aggregate completely; and to achieve durability during traffic loadings and climate exposure. The decreased production temperatures of WMA result in reduced emissions from burning fuels for aggregate heating and in reduced fumes and odors generated at the plant and during construction operations compared with those of typical HMA. WMA technologies appear to allow the production of asphalt mixes by reducing the viscosity of the asphalt binder at a given temperature to coat the aggregates fully, similarly to HMA technologies.

Both the adoption of higher percentages of RAP and lower mixing–compaction temperatures in WMA generate a significant environmental benefit, but several drawbacks have been commonly acknowledged in relationship to performance. On a life-cycle basis, if recycled eco-friendly mixtures do not provide the same performance and durability, no long-term environmental or energy savings will be realized.

This paper presents a mix-design study of polymer-modified and fiber-reinforced WMA pavements with high RAP content. Durability was one of the main goals of the study.

BACKGROUND

Available literature on WMA is extensive, as the methodology has been widely adopted in several types of asphalt concrete, including dense-graded mixes, stone matrix, porous asphalt, and mastic asphalt since the 1990s in Europe. Data indicate that plant emissions are significantly lowered (*6*). Typical expected reductions are 20% to 40% for carbon dioxide and sulfur dioxide, almost 50% for volatile organic compounds, 10% to 30% for carbon monoxide, 60% to 70% for nitrous oxides, and 20% to 25% for dust (*7*). Paving-related benefits include the ability to pave in cooler temperatures and still obtain proper density, the ability to transport the mix longer distances and still retain good workability, the ability to compact the mixture with less effort, and benefits for the workers in reduced aerosols and fumes and polycyclic aromatic hydrocarbons compared with the use of HMA. Generally, WMA technologies that use some form of organic additive (mainly wax) to provide the lower temperature, as in the present research, show a substantial decrease in viscosity above the melting point of the wax and tend to increase the stiffness of the binder below the melting point (*8*). The type of additive must be carefully selected so that the melting point is higher than expected during in-service temperatures (otherwise permanent deformation may occur) and embrittlement of the asphalt at low temperatures is minimized. A National Asphalt Pavement Association publication presents more detailed information on many of these processes (*9*).

Studies highlighted that WMA mixes appear to provide performance as good as or better than that of HMA (*10*). The goal with WMA is to produce mixtures with similar strength, volumetric properties, and durability as HMA while using substantially reduced production temperatures. Lower production temperatures potentially improve pavement performance by reducing binder aging. For HMA mixtures with 1.0% binder absorption or less, the volumetric properties of WMA designed with the procedures developed under NCHRP Project 09-43 were essentially the same as those obtained from an HMA design (*11*). However, the compactability, moisture sensitivity, and rutting resistance of WMA may be significantly different from those of HMA. Volumetric properties will basically be very similar, but the stiffness of the warm mixture will probably be lower for as-constructed conditions.

Some studies debated about WMA exhibiting greater moisture sensitivity and moisture-induced adhesive failure than HMA (*12–14*), while others proved that WMA had similar to better fatigue performance with respect to HMA (*15, 16*); however, recent research showed that WMA additives have a significant effect on mixture fatigue life because of changes in the binder rheology (*17*). Additives also affect rutting resistance in WMA by decreasing the rutting potential with respect to the control HMA mix, especially at lower compaction temperatures (*14*). A green + green technology would be the inclusion of high percentages of RAP into WMA.

The term "higher percentages of RAP" is typically considered when the RAP levels used exceed 15% to 25%, which varies by country (*4, 18*). One of the main arguments against using higher percentages of RAP in asphalt mixes is that industry practitioners have an incomplete understanding of how RAP reacts with virgin materials, in particular, how the binder from RAP interacts with the virgin asphalt binder (*19*). Most studies have reported that adding RAP (in excess of 20%) results in an increase of the virgin binder performance grade (PG) by one grade (*4, 20*). In addition, recent research recommends that, if more than 20% RAP is used, a softer PG must be adopted (*21*). If RAP exceeds 30%, then blending charts must be checked to select the appropriate binder (*21*). RAP exhibits higher PG in relation to similar virgin PG because it has already experienced short- and long-term aging, which increases both the stiffness and viscosity of the binder. This increase is attributable to oxidation processes that transform resins and oils into asphaltenes. West conducted a survey on the restrictive factors that limited higher RAP content in asphalt mixes (*22*). Responders identified agency technical specifications for RAP as the main limiting factor; plant limitations and RAP variability appeared to have little to no effect on the usage of high RAP contents, while the need to meet volumetric properties received vague responses. In reference to performance, findings show that the use of RAP in lower amounts has little to no effect on a new pavement. Many researchers consider it proven that HMA mix designs with low RAP percentages (up to 15%) are not significantly affected by RAP variability (*23, 24*); however, higher RAP contents can significantly change the global performance of the mix. Copeland provided numerous suggestions and issues that need to be resolved when high RAP contents in asphalt mixtures are encountered (*25*). Among these are additional processing and quality control, RAP characterization, changes in the virgin binder grade, preparation of materials for mix design, blending of the virgin and RAP binders, and performance.

To date, researchers have spent a significant time studying the behavior of the asphalt concrete mixes that include RAP. Although the stiffness of RAP tends to increase resistance of an asphalt mix to rutting, it decreases the mix's resistance to thermal cracking (*26, 27*). Contradictory observations have been made about the effectiveness of RAP on fatigue performance of HMA; while some tests showed enhancement in fatigue resistance, others showed a reduction (*27*). The low-temperature fracture energy of the HMA decreased when 30% or more RAP was added compared with a control mix (*27*).

One of the major concerns when RAP is included in WMA is whether the RAP and new binders mix at the lower temperatures used in WMA. Some mixture design procedures suggested that the allowable RAP content of WMA mixtures would decrease as the production temperature decreased (*11*). Mogawer et al. investigated the performance of WMA-containing RAP and evaluated binder properties, workability, and mixture durability (*28*). The viscosity of the binder was reduced, and all the mixes enhanced workability but increased moisture susceptibility. Clumps in warm mixes with high percentages of RAP were observed on I-90 during a project of the Washington State Department of Transportation (*29*).

OBJECTIVE AND SCOPE

The objective of this study was to evaluate the performance of WMA containing high percentages of RAP through laboratory testing. Long-term performance was preferred as one of the main criteria for comparison through the use of fatigue and rutting testing.

The WMA mixtures employed in the study were produced at mixing and compaction temperatures of 140°C and 110°C, respectively. Mixes also included 40% RAP and a specially developed compound of polymers, additives, and fibers, as further explained later. The usual control mix in this type of study is a standard HMA with the same percentage of RAP or no RAP; however, the authors decided to compare WMA mixtures with a polymer-modified HMA (named "control mix"). Eight mixes, including the control mix, were tested during the laboratory investigation. In particular, Mixes 1 to 5 were studied only as tentative laboratory mixes. Mix 6 was considered the best-performing mix according to laboratory evaluation, while Mix 7 had a different aggregate gradation. In fact, Mix 7 was collected directly at the plant site so that the gradation and asphalt binder content were slightly different from those of the laboratory-prepared mixes.

Maximizing the use of RAP and reducing the compaction temperature while maintaining performance comparable to polymer-modified HMA mixtures were the primary objective of the research activities performed. Both the control mix (polymer-modified asphalt) and WMA with high-RAP mixes had similar costs. However, the environmental burden and the effective costs of the mixes were not computed here because maximizing mechanical performance of recycled warm mixes by proving their effectiveness and long-term durability was the main goal.

TABLE 1 Gradation of Aggregates

Sieve Size (mm)	Passing (%) Virgin Aggregates	RAP
31.5	100	100
20	96.63	98.43
14	81.92	91.98
10	60.94	78.53
6.3	42.08	63.06
2	21.57	35.69
0.5	9.82	20.81
0.25	6.39	13.62
0.063	2.1	6.25

LABORATORY TESTING

Materials

One asphalt binder, with a penetration grade of 50/70 (in accordance with European Standard EN 12591), was selected in the study for WMA mixes (Mixes 1 to 7). A polymer-modified asphalt binder was adopted for the HMA control mix. The virgin aggregate selected in this study consisted of limestone with a nominal maximum size of 16 mm and natural sand. Table 1 presents the gradation of both the virgin aggregates and RAP.

Because a high percentage of RAP was adopted, several gradation analyses were conducted to evaluate RAP variability during sampling. Table 2 presents the gradations of the mixes. All the warm mixes showed practically the same gradation and asphalt binder content (i.e., 4.4% to 4.6%), although Mix 7 presented a gap in the 8- to 16-mm sieve size (as the sand fraction was lower in that mix). The asphalt binder content reported in Table 2 was evaluated after the extraction process; it consequently accounted for both the RAP and virgin asphalt binder. The asphalt binder content of the RAP was 4.38%.

Several combinations (compounds) containing additives and polymer were developed specifically for this study. Specific compounds included the following: styrene–butadiene–styrene (SBS), synthetic polyester fiber, cellulose fiber, paraffin polymer (wax), rejuvenator, adhesion promoters, and surfactants. SBS polymer and fibers were added to improve the mechanical performance of WMAs and mix stability; the paraffin polymer and surfactants were included to guarantee the proper workability at lower temperatures; and rejuvenator plus adhesion promoters, respectively, were added to revive the RAP-aged asphalt binder and provide the necessary bonding between aggregates (including the RAP aggregates) and the asphalt binder.

Mixes 1 to 7 were differentiated by the compound added. Table 3 shows the composition of the mixes.

Volumetric Analysis

Cylindrical WMA specimens were fabricated with the shear gyratory compactor. The mixing and compaction temperatures were 140°C and 110°C, respectively. WMAs were compacted at 120 gyrations, while the control polymer-modified mix was compacted at 200 gyrations and 155°C following national technical specifications. However, the volumetric properties were also computed at 10 and 200 gyrations for all the mixes for comparison purposes. The following parameters were calculated: maximum theoretical specific gravity (G_{mm}), bulk specific gravity of compacted mixture (G_{mb}), air void content (v), mixture

TABLE 2 Gradation of Mixes

Sieve Size (mm) or Property	Passing (%) by Mix 1	2	3	4	5	6	7	Control
31.5	100	100	100	100	100	100	100	100
20	98.4	97.4	96.4	96.3	95.3	98.9	92.4	193.04
16	93.4	92.3	91.8	92.4	90.4	94.2	80.3	83.9
14	85.6	83.7	80.4	83.3	82.6	87.3	68.3	78.3
10	71.3	70.1	71.3	69.9	70.7	70.4	45.8	67.5
8	63.4	62.3	60.7	61.2	63	62.3	36.8	62.7
6.3	51.7	50.4	51	50.1	52.4	53.7	30.6	57.7
4	43.7	42.1	40.3	41.5	44.3	42	25.4	43.4
2	32.3	30.6	31.6	30.6	32.4	31.1	20.1	28.7
1	24.6	23.6	22	22	22.9	23.9	15.5	23.3
0.5	17.9	17	16.5	16.3	16.7	18.1	11.5	18
0.4	15.7	15.1	15	14.6	15.4	16.3	10.4	15.5
0.25	11.9	11.2	10.9	10.7	11.2	12.6	8	10.4
0.125	8.3	8	7.9	8	8.6	8.4	5.6	6.5
0.075	6	6.1	6	5.8	6.2	6.2	4.5	4.8
0.063	5.5	5.3	5.5	5.3	5.8	5.6	4.2	4.6
RAP content (%)	40	40	40	40	40	40	40	20
Asphalt binder content (% by weight of the mix)	4.44	4.56	4.39	4.59	4.57	4.57	4.35	5.02

TABLE 3 Warm Mixes: Content of Additives and Polymers in Compounds

	Ingredient Presence by Mix[a]						
Ingredient	1	2	3	4	5	6	7
Synthetic fiber	N	N	Y	Y	Y	Y	Y
Cellulose fiber	Y	N	N	N	N	Y	Y
SBS	N	Y	Y	Y	Y	Y	Y
Paraffin polymer	Y	Y	Y	N	Y	Y	Y
Rejuvenator	Y	Y	Y	Y	Y	Y	Y
Surfactant	N	Y	Y	Y	Y	Y	Y
Adhesion promoter	Y	Y	Y	Y	Y	Y	Y

NOTE: Y = additive was included in the mix; N = additive was not included in the mix.
[a]The relative quantities of each ingredient were not made available because of industrial copyright.

workability (k), self-compaction (C_1), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). Although not universally adopted, the workability parameter (k) represents a measure of the rearrangement of the aggregate particles subjected to normal and shear stresses during the gyratory compaction and estimates the aptitude of a certain material to be compacted. The self-compaction parameter (C_1) represents the settlement of the material under its own weight and is represented by densification after the first gyration. Table 4 presents the results of the laboratory compaction phase.

Mix 1 exhibited the lowest void content (2.8% after 120 gyrations), which was mainly the result of the greatest amount of paraffin polymer (essentially wax) in the mix because the asphalt binder content was almost equal in all mixes. VMA and VFA values confirmed this assumption. Mix 2 showed increased void content because the paraffin content was reduced and the SBS polymer (reticulation action of the polymer) was added in the mix; workability was slightly improved because of the surfactant action. Mix 3 presented a greater void content relative to Mixes 1 and 2; paraffin and surfactant contents were the same as in Mix 2, but a synthetic fiber, able to retain the asphalt binder during mixing, was included. Mix 4 (high surfactant content) and Mix 5 (high paraffin content) registered an excessive void content and poor compaction ability and were therefore disregarded in further analyses; higher void contents were also the result of excessive fiber and lower rejuvenator contents. Mix 6 showed proper volumetric properties and was finally chosen as the optimal candidate for mechanical and long-term testing; the quantities of additives and polymers were accurately calibrated to provide proper compaction at lower temperature (paraffin and surfactant action) while a suitable void content (SBS and fibers features) was retained. Mix 7 showed high void content; however, the proper void content (between 4% and 5%) was achieved after a major compaction effort (i.e., 200 gyrations). Sometimes constructors prefer mixes able to be compacted at lower temperature with enhanced passes of the roller instead of an easily compactable mix that might then exhibit postcompaction problems or bleeding. Performance of the mixes is discussed further in the following sections.

Mechanical Properties

Mechanical characteristics of the mixes—except for Mixes 4 and 5, which exhibited poor volumetric performance—were evaluated by means of indirect tensile strength (ITS) and stiffness modulus (E^*). Stiffness is indeed a key material property that determines strains and displacements in pavement structures. The stiffness modulus was determined according to the European Standard EN 12697-26 (ANNEX-F). Three temperatures were tested: 10°C, 25°C, and 40°C. Controlled-strain mode and 5-μm deformation were adopted; these factors ensured, to the degree possible, that the response of the material was linear across the temperatures used in the study. Four loading frequencies were also tested: 0.5, 1, 2, and 4 Hz. Stiffness testing provided very important information about the linear viscoelastic behavior of a particular mix over a wide range of temperatures and loading frequencies (master curve).

TABLE 4 Volumetric Properties

	Volumetric Performance by Mix							
Property	1	2	3	4	5	6	7	Control
G_{mm} (kg/m^3)	2,581	2,581	2,581	2,581	2,581	2,578	2,590	2,537
G_{mb} (kg/m^3) @120 gyrations	2,508.7	2,474.2	2,444.7	2,422.4	2,423.1	2,463.7	2,400.9	2,454.7
G_{mb} (kg/m^3) @120 gyrations, SD	10.44	15.31	16.07	17.85	15.35	11.91	17.8	9.22
G_{mb} (kg/m^3) @10 gyrations	2,272	2,225	2,231	2,187	2,187	2,247	2,202	2,272
G_{mb} (kg/m^3) @200 gyrations	2,537	2,519	2,500	2,479	2,481	2,516	2,450	2,468
Void content (%) @120 gyrations	2.8	4.14	5.27	6.14	6.12	4.53	7.29	3.23
Void content (%) @120 gyrations, SD	0.4	0.58	0.64	0.69	0.59	0.52	0.7	0.35
Void content (%) @10 gyrations	12	13.8	13.6	15.2	15.3	12.8	15	10.4
Void content (%) @200 gyrations	1.7	2.4	3.1	3.9	3.9	2.4	5.4	2.8
k (workability)	8.8	9.1	8	8.5	8.6	8	7.3	6.8
C_1 (self-compaction) (%)	79.4	77.3	78.5	76.4	76.3	79.3	77.8	82.9
VMA (%)	13.72	15.20	15.79	17.04	16.98	15.57	17.53	15.31
VFA (%)	79.59	72.77	66.63	63.97	63.95	70.90	58.41	78.90

NOTE: SD = standard deviation.

In the new *Mechanistic–Empirical Pavement Design Guide,* the stiffness of an HMA at all temperatures and load frequencies is determined from a master curve constructed at a reference temperature (usually 25°C). Master curves are constructed on the principle of time–temperature superposition (*30*). Data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve, as a function of time, constructed in accordance with this methodology, describes the time dependency of the material. The amount of shifting (shift factor) at each temperature required to form the master curve describes the temperature susceptibility of the material. Commonly, the master curve of the modulus can be scientifically modeled by a sigmoidal function described as

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta+\gamma(\log t_r)}} \quad (1)$$

where

E^* = dynamic modulus,
t_r = reduced time of loading at reference temperature,
δ = lower asymptote of master curve,
α = difference between values of upper and lower asymptotes, and
β, γ = parameters describing shape of sigmoidal function.

E^* master curves of all mixtures were constructed at a reference temperature of 25°C (Figure 1). Table 5 presents E^* values for all mixes at different temperatures and load frequencies.

Mix 1, besides having poor volumetric and compaction characteristics, showed an excessive sensitivity to high temperatures; the greater amount of paraffin polymer made the material softer at temperatures near the melting point of the wax. This behavior is shown by the steep descending slope of the master curve. However, Mix 1 performed well at low temperatures, showing a nonbrittle behavior.

As the quantities of SBS and fibers were increased and the paraffin content decreased (Mixes 2 and 3), the master curves exhibited an improvement through the rise of the lower asymptote and the reduction in the relative distance between the upper and lower asymptotes: the smaller is the distance between the asymptotes, the steadier is the stiffness during temperature changes (seasonal variations during the service life, for instance). This relationship leads to a theoretically ideal steady stiffness independent of the operational in-service temperatures; polymer-modified asphalts, one of which the control mix was, get closer to this hypothetical behavior. Mixes 6 and 7 both performed well, providing greater stiffness values in all temperature domains; however, Mix 7 presented a nonoptimal behavior, with a rapid stiffness increase at lower temperatures, which may cause susceptibility to thermal cracking. In particular, Mix 6 (high content of SBS and fibers) performed better overall despite the major amount of paraffin polymer it contained (similar to the quantity adopted for Mix 1).

The ITS testing was conducted on cylindrical specimens in accordance with European Standard EN 12697-23. Results are summarized in Table 6.

Again, Mix 1 showed the poorest performance, with the lowest strength value. Whenever SBS and fiber content were high (Mixes 3 and 6), tensile strength increased. The use of SBS alone (i.e., Mix 2) did not provide great improvements in strength. Mix 6 was very close to the control mix (polymer-modified mix).

Results from the mechanical analyses highlighted that good workability and compaction at low temperature (WMA) can be achieved without reducing the structural performance of material, even for high percentages of RAP, if the specific additives are correctly proportioned.

Long-Term Performance

The long-term performance of the mixes was analyzed by means of fatigue and rutting testing. Fatigue resistance was tested in accordance with European Standard EN 12697-24. A cylindrical specimen compacted with the gyratory shear compactor was subjected, in indirect tensile configuration, to a constant cyclic load (stress-controlled mode).

The stress was 500 kPa, test temperature 25°C, and load frequency 2 Hz. Failure of the specimens was established when the

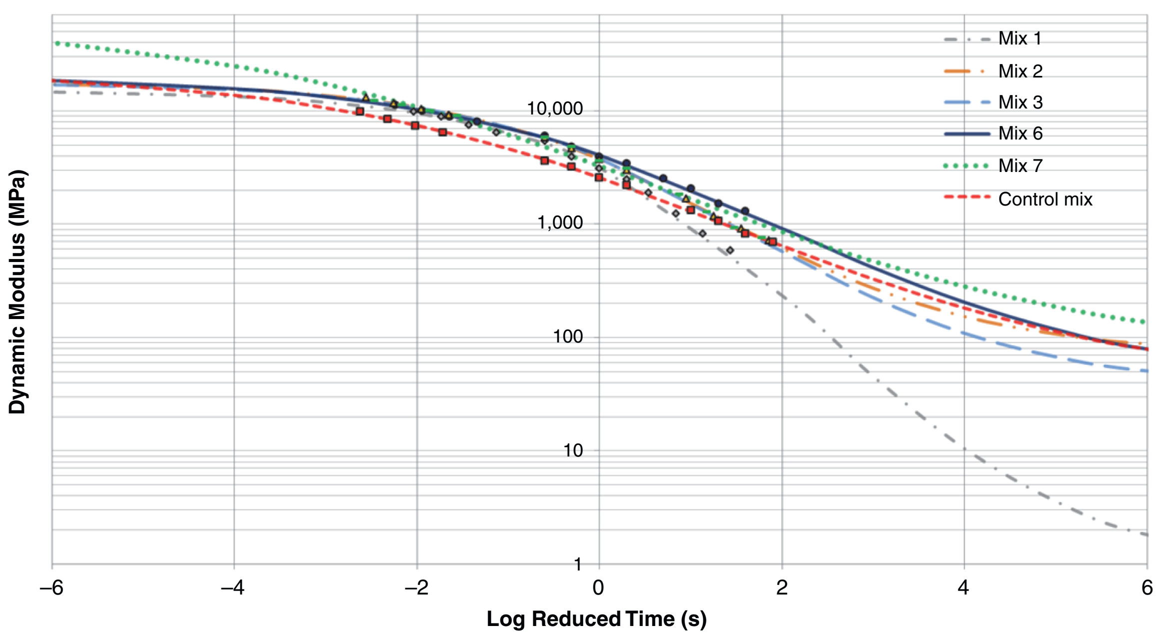

FIGURE 1 Master curves (T_{ref} = 25°C).

TABLE 5 Stiffness Modulus of Mixes

Frequency	Stiffness (MPa) Average	SD	Frequency	Stiffness (MPa) Average	SD
Mix 1			Mix 6		
4 Hz			4 Hz		
10°C	9,906.0	1,158.9	10°C	11,264.0	620.7
25°C	5,412.0	1,014.8	25°C	5,984.3	396.4
40°C	1,882.7	403.4	40°C	2,502.0	272.8
2 Hz			2 Hz		
10°C	8,862.3	1,213.8	10°C	9,973.7	378.1
25°C	3,906.0	507.7	25°C	4,846.3	163.7
40°C	1,230.7	319.9	40°C	2,061.3	138.7
1 Hz			1 Hz		
10°C	7,476.3	1,247.5	10°C	8,866.7	289.2
25°C	3,092.3	493.0	25°C	3,931.7	122.7
40°C	818.3	158.2	40°C	1,518.0	72.3
0.5 Hz			0.5 Hz		
10°C	6,437.7	1,347.8	10°C	8,058.7	336.5
25°C	2,497.7	428.3	25°C	3,437.7	116.0
40°C	589.7	184.7	40°C	1,310.3	68.3
Mix 2			Mix 7		
4 Hz			4 Hz		
10°C	13,031.0	493.8	10°C	11,623.6	1,303.0
25°C	5,796.0	563.1	25°C	4,613.8	596.0
40°C	1,678.7	113.7	40°C	2,345.8	421.3
2 Hz			2 Hz		
10°C	11,637.3	762.3	10°C	9,960.0	835.6
25°C	4,650.0	379.3	25°C	3,681.0	522.4
40°C	1,166.3	66.5	40°C	1,765.3	322.4
1 Hz			1 Hz		
10°C	10,397.3	539.7	10°C	9,076.8	843.7
25°C	3,714.7	127.4	25°C	3,090.0	475.0
40°C	909.3	42.8	40°C	1,359.0	297.2
0.5 Hz			0.5 Hz		
10°C	9,153.3	598.6	10°C	8,287.3	896.6
25°C	3,006.0	181.2	25°C	2,606.0	334.9
40°C	722.7	29.0	40°C	1,099.8	237.6
Mix 3			Control Mix		
4 Hz			4 Hz		
10°C	12,242.67	427.48	10°C	9,814.5	831.1
25°C	5,819.67	547.85	25°C	3,613.3	399.1
40°C	1,830.33	514.17	40°C	1,314.0	248.8
2 Hz			2 Hz		
10°C	11,350.67	452.49	10°C	8,397.8	791.4
25°C	4,776.67	380.86	25°C	3,190.0	339.4
40°C	1,275.00	153.52	40°C	1,061.3	201.9
1 Hz			1 Hz		
10°C	10,051.33	358.00	10°C	7,320.3	658.5
25°C	3,622.33	276.62	25°C	2,546.0	262.1
40°C	928.00	111.10	40°C	821.5	139.0
0.5 Hz			0.5 Hz		
10°C	9,015.00	254.21	10°C	6,422.8	646.8
25°C	3,089.00	199.26	25°C	2,191.5	251.9
40°C	749.33	84.42	40°C	695.8	139.6

stiffness modulus decreased by 50% of its initial value. The numbers of cycles to failure are summarized in Table 7.

Rutting was evaluated only on selected mixes in accordance with European Standard EN 12697-22, namely Mixes 6, 7, and the control mix (Figure 2). Two slabs were compacted for each mix with a roller compactor and tested with a wheel-tracking device (pneumatic-tire pressure was 600 ± 30 kPa). Compaction was performed at 110°C ± 5°C, and the test temperature was 60°C; the failure criterion was 10,000 load cycles or a rut depth of 20 mm, whichever occurred first. The following parameters were registered as requested by the standard: $RD_{5,000}$ and $RD_{10,000}$ were the rut depths after 5,000 and 10,000 load cycles, respectively; $PRD_{10,000}$ was the proportional rut depth for the material under test at 10,000 cycles; WTS_{air} was the wheel-tracking slope, calculated as the average rate at which the rut depth increases with repeated passes of a loaded wheel, $WTS = (RD_{10,000} - RD_{5,000})/5$.

TABLE 6 Indirect Tensile Strength of Mixes

Mix	ITS (MPa) Average	SD	Mix	ITS (MPa) Average	SD
1	1.16	0.17	6	1.48	0.07
2	1.32	0.15	7	1.24	0.05
3	1.53	0.05	Control	1.49	0.01

As a validation of previous results, Mix 1 had the worst performance over the long term, providing about half the fatigue life as the other mixes. Again, Mixes 2 and 3 presented comparable performance, as their mix compositions were very similar. Mix 6 had the greatest fatigue life, but the data had a high standard deviation. However, resistance to fatigue analysis should be improved by further testing of the mixes at, for instance, different levels of stress.

All the mixes performed well with respect to rutting because the permanent deformation was less than 2 mm after 10,000 cycles. However, Mix 7, with less paraffin and surfactant content, provided the best performance; better high-temperature behavior was indeed identified during analysis of stiffness and the master curve. In particular, even if Mix 6 had greater SBS and fiber content, Mix 7 had better rutting resistance, showing that a substantial presence of binder viscosity modifiers (such as waxes) is therefore comparable to the reinforcement provided by the polymer modification and the fibers.

CONCLUSIONS

Volumetric, mechanical, and long-term performance of seven WMA mixes with high RAP content and a polymer-modified mix were investigated. Polymers, additives, and fiber content were properly altered for an accurate balance of compactability capabilities at lower temperatures and resistance to loads. On the bases of the materials and procedures used in this work, the following can be concluded:

1. The addition of paraffin polymer (mainly waxes) and surfactants helps reduce viscosity of the binder and facilitate compaction at lower temperature; however, an excessive amount can cause a large reduction in void content, poor mechanical performance, greater thermal susceptibility, short fatigue life, and reduced rutting resistance.
2. SBS polymer and reinforcing fibers, in addition to paraffin polymer, combine to permit good compaction at lower temperature, improved mechanical characteristics, and long-term performance.
3. The proper calibration of additives, polymer, and fibers into WMA with high RAP percentages provides comparable performance to polymer-modifier HMA.
4. Thermal susceptibility of WMA with high percentages of RAP can be limited by adding SBS polymer and cellulose–synthetic fibers.
5. The results presented here need further investigation, especially on long-term performance measurements and binder aging, before WMA with high percentages of RAP can be widely adopted.

TABLE 7 Long-Term Performance: Fatigue and Rutting Behavior

Mix	Fatigue Resistance (number of cycles to failure)		Rutting Potential by Parameter			
	Average	SD	$RD_{5,000}$ (mm)	$RD_{10,000}$ (mm)	$PRD_{10,000}$ (%)	WTS_{air} (mm/10^3 cycles)
1	1,114	159.39	na	na	na	na
2	2,690	838.22	na	na	na	na
3	2,519	947.90	na	na	na	na
6	4,758	1,773.42	1.666	1.787	3.6	0.024
7	1,606	265.47	0.889	1.0265	2	0.028
Control	2,909	377.05	1.718	2.002	4	0.057

NOTE: RD = rut depth; PRD = proportional rut depth; WTS = wheel-tracking slope; na = not applicable.

(a) (b) (c)

FIGURE 2 Rut testing on (*a*) Mix 6, (*b*) Mix 7, and (*c*) control mix.

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