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RESEARCH ARTICLE

Performance Evaluation of Warm Mix Asphalt Mixtures with Recycled Asphalt Pavement

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Abstract

Warm mix asphalt (WMA) technology provides not only the production of asphalt pavement at a lower temperature than the temperature maintained in Hot Mix Asphalt (HMA) but also encourages the utilization of Recycled Asphalt Pavement (RAP) and therefore saves energy and nonrenewable resources as well as reduces emissions and fuel consumption. This paper describes the feasibility of utilizing four different WMA additives (organic, chemical, synthetic zeolite and natural zeolite) with different rates of RAP. Following the determination of optimum RAP content corresponding to each WMA additive, Marshall analysis, indirect tensile stiffness modulus and fatigue behavior of HMA and WMA involving RAP were analyzed and compared with control specimens. Hamburg wheel tracking device was also utilized to evaluate the permanent deformation characteristics of mixtures containing optimum RAP content.

Keywords

warm mix asphalt, recycled asphalt pavement, indirect tensile stiffness modulus, fatigue behavior, Hamburg wheel tracking device

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1 Introduction

During the last decade, implementation and development of Recycled Asphalt Pavements (RAP) has been discussed considerably. Recent studies have seemed to be searching for a solution to reduce crude oil consumption and accordingly its by-product which is used in asphalt scientifically known as bitumen [1]. From a global point of view in line with commissioning of eco-friendly technologies, the current recycling developments have been found secured and economically rational [2, 3]. The high cost associated with petroleum and raw material extraction, has justified scientists to search for new materials with the ability of combining durability and performance at low cost [4]. The utilization of RAP provides an economic method of construction of asphalt (cold recycled or hot mix asphalt (HMA)) pavements [5]. RAP contains both aggregate and bitumen, hence its use saves natural resources, money, and also it is eco friendly [6]. The rehabilitation of pavements with the utilization of recycling technologies has been found eligible over the last decade. Considering the continuous growth of data gained from experimental studies together with laboratory and field performance analyzes, it can be anticipated that recycling technologies will go on to be the most desirable rehabilitation technology [7]. The choice of rehabilitation technique should be based on energy conservation, economic consideration, engineering consideration, and environmental effects.

In last decade, ecological issues have been the most important points to be taken into account in road construction. Although HMA is widely used in road construction over the world, recent studies seek for alternative technologies which can be applied at lower temperatures. Most European countries have started to use these kinds of new technologies generally called Warm Mix Asphalt (WMA) [8]. The objective is to exhibit better or even equal referenced stability and durability which is reached by use of HMA [9].

The use of additives as modifying agents within bitumen has been found effective to reduce application temperatures. The current WMA additives implement two major principles to perform the mentioned task. The first principle is to reduce bitumen viscosity in order to improve workability, and the second one is to expand bitumen volume helping the aggregates coated by bitumen at lower temperatures [10, 11]. This fact results in facilitating coating of aggregates by bitumen at lower temperatures in comparison to conventional HMA applications [12].

Since WMA softening agents are added directly into the virgin bitumen, they quickly interact with bitumen derivatives to produce a new product with low viscosity and accordingly provide lower application temperatures. In addition to low viscosity and low application temperature, the advantages are coupled with the utilization of RAP into the new bitumen binder involving WMA additives. The statement "Besides, lowering of application temperatures, WMA technologies also facilitate the utilization of RAP materials" gains more significant value taking the economic benefits, environmental aspects, preservation of natural resources into account [5]. O'Sullivan and Wall reported that the use of RAP materials within WMA mixtures lowers the emission of greenhouse gases and accordingly causes less harmful effects to the environment [12]. Mallick et al. indicated that it is possible to use RAP materials within WMA mixtures [13].

WMA additives are categorized as organic, chemical and foaming additives. Organic additives are used to improve workability by reducing the viscosity of bitumen [14]. By lowering the viscosity, asphalt can be produced at lower temperatures compared to conventional HMA. Organic WMA additives are reported as resistance improvers against permanent deformation by composing crystallized structures after cooling [15]. There are various chemical additives objective to particular products at the market. Generally chemical additives are made up of emulsifying agents, plasticizers and polymers which all help for the enhancement of workability, adhesion, and compaction. Chemical additives are also utilized so as to process RAP materials within bitumen at lower application temperatures. The effective content of chemical additive used within the WMA mixtures is defined by the suggestion of manufacturer and based on literature review [16-19]. The utilization of water serving in WMA technologies is classified based on two major principles; most commonly the direct injection of water into the bitumen and secondly use of hydro-thermally crystallized minerals such as zeolites. Synthetic zeolite is a finely powdered hydrated sodium aluminum silicate that is hydro-thermally crystallized which holds 18–22% (by mass) of water. Theoretically, zeolite releases steamed water within the bitumen and causes a foaming effect which leads to the reduction of viscosity and increase of workability. This fact helps to facilitate coating of aggregates by bitumen [20].

In this research, RAP has been used (at contents of 10–50%) within both HMA and WMA mixtures. Each type of WMA mixture has been prepared with an optimum rate of WMA additive that is based on the recommendation of manufacturers (organic additive at a rate of 3%, chemical additive at a rate of 2% and two types of water containing additives at a rate of 5% by weight of the bitumen). The mechanical performances of the samples were evaluated by Marshall stability test. Following the determination of optimum RAP content regarding each mixture involving four different types of WMA additive, indirect tensile stiffness modulus (ITSM) and fatigue behavior of WMA and HMA containing optimum RAP content were analyzed and compared with control specimens. Hamburg wheel tracking device was also used to determine the rutting properties of mixtures involving optimum RAP content.

2 Experimental

2.1 Materials

50/70 penetration grade base bitumen was obtained from Izmir petroleum refinery of the TUPRAS. In order to characterize the properties of the base bitumen, conventional test such as: penetration, softening point, thin film oven test (TFOT), penetration and softening point after TFOT, etc. were performed [21–23]. These tests were conducted in conformity with the relevant test methods that are presented in Table 1.

Table 1 Properties of the base bitumen.

Test	Specification	Results	Specification Limits
Penetration (25ºC; 0.1 mm)	ASTM D5 EN 1426	55	50-70
Softening Point (ºC)	ASTM D36 EN 1427	49.1	46-54
Viscosity at (135ºC), Pa.s	ASTM D4402	0.413	-
Thin Film Oven Test (TFOT); (163ºC; 5 hr)	ASTM D1754 EN 12607-1		
Change of mass (%)		0.04	0.5 (max)
Retained penetration after TFOT (%)	ASTM D5 EN 1426	25	-
Softening Point difference after TFOT (ºC)	ASTM D36 EN 1427	5	7 (max)
Ductility (25ºC), cm	ASTM D113	100	-
Specific Gravity	ASTM D70	1.030	-
Flash Point (ºC)	ASTM D92 EN 22592	260+	230 (min)

Asphalt mixtures were produced with limestone aggregates that were procured from Dere Group/Izmir quarry. In order to find out the properties of the limestone aggregate used in this study, sieve analysis, specific gravity, Los Angeles abrasion resistance test, sodium sulfate soundness test, fine aggregate angularity test, and flat and elongated particles tests were conducted on limestone aggregates [24-30]. Aggregate gradation had been chosen in conformity with the Type-I wearing course of Turkish Specifications. The properties of the limestone aggregates were presented in Table 2.

Sasobit® is an organic WMA additive which is product of Sasol Wax Inc. It is a long-chain aliphatic polymethylene hydrocarbon produced from the Fischer-Tropsch (FT) chemical process with a melting temperature of 120°C. The longer chains help to keep the wax in solution, which reduces the viscosity of bitumen at typical asphalt production and compaction temperatures. Based on the literature, rates for Sasobit® ranged from 1.0% to 4.0% by weight of the bitumen [31–33]. In this research, Sasobit® content was chosen as 3.0%. The utilization of this content is based on a past research [12]. The researchers indicated that Sasobit® should be added at a rate of 3.0% by weight of bitumen for maximum effectiveness.

Table 2 The properties of limestone aggregates.

Test	Specification	Grading Passing (%)	Specification Limits
Sieve Size/No.	ASTM C 136		
¾”		100	100
½”		92	83–100
3/8”		73	70–90
No.4		44.2	40–55
No.10		31	25–38
No.40		12	10–20
No.80		8	6–15
No.200		5.3	4–10
Specific Gravity (Coarse Agg.)	ASTM C 127		
Bulk		2.704	–
SSD		2.717	–
Apparent		2.741	–
Specific Gravity (Fine Agg.)	ASTM C 128		
Bulk		2.691	–
SSD		2.709	–
Apparent		2.739	–
Specific Gravity (Filler)		2.732	–
Los Angeles Abrasion (%)	ASTM C 131	22.6	Max. 30
Flat and Elongated Particles (%)	ASTM D 4791	7.5	Max. 10
Sodium Sulfate Soundness (%)	ASTM C 88	1.47	Max. 10–20
Fine Aggregate Angularity	ASTM C 1252	47.85	Min. 40

Rediset® WMX is a chemical additive that uses a combination of cationic surfactants and organic additive based rheology modifier. Rediset® chemically modifies the bitumen and obtains active adhesion force which improves coating of aggregates with bitumen [17]. Rediset® can also encourage processing of asphalt mixture at lower temperatures. Researches indicate that the Rediset® should be used at rates of 1.5%, 2% and 3% by weight of the bitumen for better performance of mixture [16-19]. In this research, Rediset® content was chosen as 2.0% based on the recommendation of AkzoNobel [19].

Advera® is a water-containing WMA additive which is product of PQ Corporation. It is powdered synthetic zeolite that has been hydro-thermally crystallized. It contains about 18-21% water of crystallization which is released by increasing temperature above 85°C. The expansion of water causes foaming of bitumen. Austerman et al. and Estakhri et al. reported that the maximum rate of Advera® in base bitumen varies between 4% and 6% by weight of bitumen [32, 34]. In this research, Advera® content was chosen as 5% based on a past research made by PQ Corporation [34].

Natural zeolite can be considered as an alternative additive to water-containing WMA additive. The most abundant zeolite in Turkey is Clinoptilolite. The complex formula is $(Na_3K_3)(Al_6Si_{30}O_{72}).27H_2O$. It forms as white to reddish tabular monoclinic tectosilicate crystals with a Mohs hardness of 3.5-4.0 and a specific gravity of 2.1–2.2. Based on a past research made by Sengoz et al. the content of natural zeolite for this study has been chosen as 5% by weight of bitumen [20].

The RAP material to be utilized within the WMA and HMA mixtures was obtained from seven years old wearing course section of an asphalt pavement located on one of the main arterials in Izmir city.

2.2 Test methods

2.2.1 Conventional bitumen tests

The base bitumen and the bitumen samples containing organic, chemical, synthetic zeolite and natural zeolite additives were subjected to the following conventional bitumen tests; penetration, ring and ball softening point, thin film oven test (TFOT), penetration and softening point after TFOT as well as the storage stability test determined by the difference in softening point test results taken from the top and bottom of the tube [21-23]. In addition, the temperature susceptibility of the bitumen samples has been calculated in terms of penetration index (PI) using the results obtained from penetration and softening point tests [35]

The viscosity is defined as resistance of a fluid to flow and it affects the workability of the bitumen [36]. Brookfield viscometer was employed to inspect the mixing and compaction temperatures of the mixtures in according to ASTM D4402-06 [37]. The test was performed at 135°C and 160°C and the temperatures corresponding to bitumen viscosities 170±20 mPa.s and 280±30 mPa.s were chosen as mixing and compaction temperatures respectively.

2.2.2 Determining properties of RAP

One of the most important properties of asphalt mixtures is the bitumen content, because it has a sensitive impact on the quality and the price of the pavement. Many ways of asphalt bitumen measurements exist such as solvent extraction using trichloroethylene, solvent extraction using an alternative solvent, ignition oven, ignition oven and solvent combination [38]. In order to determine the bitumen content within the aged bituminous mixtures, ten batches (each of 1000 grams) of RAP were prepared and extraction test was performed on each of the batch with a laboratory type centrifuge extractor called Rota Test.

In order to characterize the properties of the old bitumen obtained from the extraction test, above mentioned conventional tests were performed. Besides, sieve analysis test were performed on the extracted aggregates.

2.2.3 Marshall stability and flow analysis

The main function of the base is to reduce the vertical compressive stress induced by traffic, in the sub-base and the subgrade, to a level at which no unacceptable deformation will occur in these layers [39]. The Marshall method has been applied on HMA and WMA samples involving different contents of RAP as well as on control samples in terms of stability, flow and air voids content so as to evaluate the effect of RAP [40].

2.2.4 Indirect tensile stiffness modulus test and indirect tensile fatigue test

Indirect tensile stiffness modulus test (ITSM) (BS DD 213) and indirect tensile fatigue test (BS DD ABF) were conducted on HMA and WMA samples as well as on mixtures involving optimum RAP content [41-44].

The indirect tensile fatigue test is one of the constant stress tests that characterize the fatigue behavior of the mixture [45]. In this study, the fatigue tests were performed in a controlled stress mode based on BS DD ABF standard [44]. The UTM was used for this purpose. A repeated dynamic compressive load was applied to specimens across the vertical cross-section along the depth of the specimen using two loading strips 12.5 mm in width. The resulting total deformation corresponding to the applied force was measured.

2.2.5. Rutting test

The loss of pavement serviceability is a common result from rutting which is defined as the formation of the longitudinal depressions under the wheel paths caused by the progressive movement of materials under traffic loading in the asphalt pavement layers [46]. The Hamburg wheel tracking device is designed to evaluate the rutting characteristics of bituminous mixtures by dint of aggregate structure, bitumen properties, moisture susceptibility and adhesion between bitumen and aggregates. The test is carefully contemplated to simulate bearing capacity of pavement under actual wheel tracks.

The working principle is to roll a steel wheel with a specified diameter over a bituminous mixture specimen with a standard thickness at a specified number of wheel passes. The test measures the depth of rut after the specified number of passes is reached. Various organizations may define their own specifications with different testing conditions such as specimen dimensions, wheel diameter, rolling length, applied load and temperature. Within this context, there are many devices designed to carry out the task under various conditions.

The test device used within the scope of this study, was an electronically powered device which rolls a steel wheel (capable of using rubber wheel) with a diameter of 203 mm and width of 50 mm over a well compacted specimen with dimensions of 430×280×50 mm. The device is capable of making about 50 passes in minute over the surface of specimen by rolling length of 230 mm. The applied load was chosen as 710 N by default as per BS EN 12697-22 standard test method [47]. Prior to compaction of the specimens, HMA and WMA mixtures were carefully mixed at their pre-defined mixing temperatures using a mixer capable of mixing adequate amount of materials at desired temperature. The Hamburg wheel tracking device comes with a roller compactor in order to compact mixtures within standard molds to fit in wheel tracking device frames. The roller compactor also makes it convenient to prepare specimens with desired thickness (50 mm) with specified air voids (4%). The amount of loose mix to reach the desired compacted bulk specific gravity corresponding to 4% air voids considering mold dimensions was calculated and poured into compaction molds.

After cooling the specimens at room temperature, the specimens were subjected to 30.000 passes of wheel tracks. For each mixture assessed in this study, two specimens of same mixture were prepared and tested for right and left wheels. The rut depth was measured and recorded for right and left wheels simultaneously by an electronic system at every 5.000 passes while the test was running.

3 Result and discussions

3.1 Conventional test results

Conventional properties of the bitumen prepared with organic, chemical, synthetic zeolite and natural zeolite additives are presented in Table 3.

As depicted in Table 3, the addition of the WMA additives decreases the penetration values and increases the softening point values.

As seen in Table 3, all WMA samples exhibit higher penetration index values (which is an indicator of reduced temperature susceptibility) compared to base bitumen. Besides among all the WMA additives, organic WMA additive exhibits the lowest temperature susceptibility. Asphalt mixtures containing bitumen with higher PI are more resistant to low temperature cracking as well as permanent deformation [48].

Table 3 Conventional properties of bitumen prepared with warm mix asphalt additives.

				Viscosity (mPa.s)		Thin Film Oven Test (TFOT)			Rollong Thin Film Oven Test (RTFOT)				
WMA Additive Types	Contents (%)	Pen. (0.1mm)	Softening Point (°C)	135 (°C)	160 (°C)	Loss of mass (%)	Retained Pen. (%)	Soft. Point diff. (°C)	Loss of mass (%)	Retained Pen. (%)	Soft. Point diff (°C)	Pen inex (PI)	Storage Stability (°C)
Natural Zeolite	0	55	49.1	412.5	137.5	0.04	25	5.0	-0.04	26	5.3	-1.20	-
	5	51	55.0	325.0	113.0	0.16	15	3.7	-0.17	17	3.7	0.02	2.0
Synthetic Zeolite	0	55	49.1	412.5	137.5	0.04	25	5.0	-0.04	26	5.3	-1.20	-
	5	52	56.0	312.5	112.5	0.16	16	4.1	-0.18	21	4.5	0.27	1.6
Organic	0	55	49.1	412.5	137.5	0.04	25	5.0	-0.04	26	5.3	-1.20	-
	3	37	69.3	287.5	75.0	0.7	13	4.0	-0.07	15	4.3	1.95	1.6
Chemical	0	55	49.1	412.5	137.5	0.04	25	5.0	-0.04	26	5.3	-1.20	-
	2	44	56.7	337.5	87.5	0.04	16	2.5	-0.07	17	2.5	0.04	0.5

Storage stability test indicates that, both natural and synthetic zeolite involving bitumen samples exhibit similar storage stability characteristics. Besides, the bitumen samples prepared with chemical additives are much more storage stable compared to other WMA samples.

As depicted in Table 3, the additives reduce the viscosity of bitumen which indicates that, all WMA additives increase the workability and make relatively reductions for mixing and compaction temperatures. The viscosity of results related to each WMA additive 135°C and 160°C are drawn at semi logarithmic figure and the temperatures corresponds to compaction and mixing range are also summarized in Table 4.

The addition of natural zeolite, synthetic zeolite, organic and chemical WMA additives reduce the mixing temperature by 6°C, 9°C, 13°C and 9°C respectively. Besides, the addition of mentioned additives reduce the compaction temperatures by 6°C, 7°C, 10°C and 8°C respectively.

Table 4 Mixing and compaction temperatures.

Additives	Contents (%)	Mixing Temp. (°C)	Compaction Temp. (°C)
Base Bitumen	0	156-163	143-149
Natural Zeolite	5	150-157	137-142
Synthetic zeolite	5	149-152	135-142
Organic	3	144-149	134-138
Chemical	2	148-153	133-142

3.2 Determining properties of RAP

Based on the extraction test results, the average bitumen content was determined as 4.30% based on ten batches of RAP samples. Conventional bitumen tests result conducted on the old bitumen is presented in Table 5.

Table 5 Properties of the old bitumen.

Test	Specification	Results
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	23
Softening Point (°C)	ASTM D36 EN 1427	72.9
Penetration Index (PI)		1.45
Viscosity at (135 °C)-Pa.s	ASTM D4402	0.563
Viscosity at (165 °C)-Pa.s	ASTM D4402	0.138
Thin Film Oven Test (TFOT) (163°C; 5 hr)	ASTM D1754 EN 12607-1	-
Change of Mass (%)		0.02
Retained Penetration (%)	ASTM D5 EN 1426	18
Softening Point Diff. after TFOT (°C)	ASTM D36 EN 1427	1.9

As RAP bitumen reacts and loses some of its components during the construction process (short term aging) and service life of the road (long term aging), its rheological behavior naturally differs from virgin materials. During aging process, bitumen is exposed to hot air at high temperatures ranging from 135°C to 160°C, resulting in a significant increase in viscosity. Besides, bitumen loses many of its oil components during construction and service resulting in a high proportion of asphaltenes in the blend, which leads to increased stiffness and viscosity.

Sieve analysis was performed on the extracted aggregates which are presented in Table 6. The mix gradation (10%, 20%, 30%, 40% and 50% of the RAP and 90%, 80%, 70%, 60% and 50% of new aggregate) must meet the requirements of Turkish Specifications related to the Type I Wearing Course construction.

Table 6 Sieve analysis results for extracted aggregates.

Sieve No	Cumulative Weight Passing (gr)	% Retained	% Pass
3/4”	13299	0	100
1/2”	13092	1.6	98.4
3/8”	11966	10.1	89.9
No.4	7197.5	45.9	54.1
No.10	4016	69.8	30.2
No.40	1792.5	86.5	13.5
No.80	1173	91.18	8.82
No.200	775	94.17	5.83

3.3 Marshall stability and flow analysis

The optimum bitumen content related to HMA and WMA including organic, chemical, synthetic zeolite and natural zeolite additives were determined (by the Marshall analysis) as 4.88%, 4.30%, 4.53%, 4.50% and 4.62% respectively.

Calculations of the rate of the new bitumen to be added into mixture with respect to the values are presented in Table 7.

The mechanical properties of HMA and all WMA mixtures involving different rates (10–50%) of RAP in terms of stability, flow and voids are presented in Fig. 1, Fig. 2 and Fig. 3 respectively.

As illustrated in Fig. 1, all recycled asphalt mixtures involving HMA and all WMA additives provide adequate stability (min. 900 kg. related to wearing course specification). The stability values increase with the increase of RAP content for HMA and the mixtures prepared with organic, synthetic zeolite and natural zeolite. However, no significant variation is observed on the stability values above 30% RAP content addition for the mixtures involving chemical additive.

As presented in Fig. 2, the flow values decrease with increasing RAP content for HMA mixtures and the mixtures prepared with all WMA additives. As the flow values are indicator of deformation characteristic, the flow values are less than the specification limits (2 mm.). It is not favorable since it implies that the mix is very stiff and brittle. As depicted in Fig. 2, more than 20%, 30%, 40% and 50% RAP addition are below the specification limits of flow values for HMA and mixtures prepared with organic, chemical, both synthetic zeolite and natural zeolite respectively.

Table 7 Calculation of the percentage of the bitumen to be added in the mix based on RAP content for each of the additive.

Types of Mixture	RAP Content (%)	Pc (%) Total bitumen in the mix	Pa (%) Bitumen content of RAP	Pr (%) Bitumen content to be added into the mix
HMA	10	4.88	4.3	4.45
	20			4.02
	30			3.59
	40			3.16
	50			2.73
WMA + Organic Additive	10	4.3		3.87
	20			3.44
	30			3.01
	40			2.58
	50			2.15
WMA + Chemical Additive	10	4.53		4.10
	20			3.67
	30			3.24
	40			2.81
	50			2.38
WMA + Synthetic Zeolite	10	4.50		4.07
	20			3.64
	30			3.21
	40			2.78
	50			2.35
WMA + Natural Zeolite	10	4.62		4.19
	20			3.76
	30			3.33
	40			2.9
	50			2.47

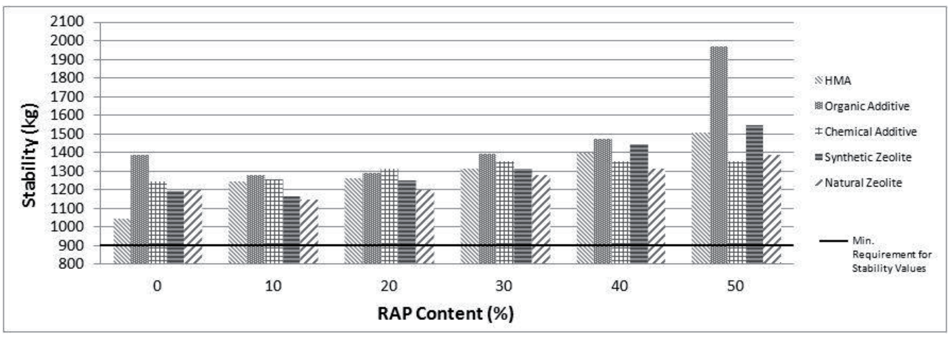

Fig. 1 Marshall stability values for RAP and control samples.

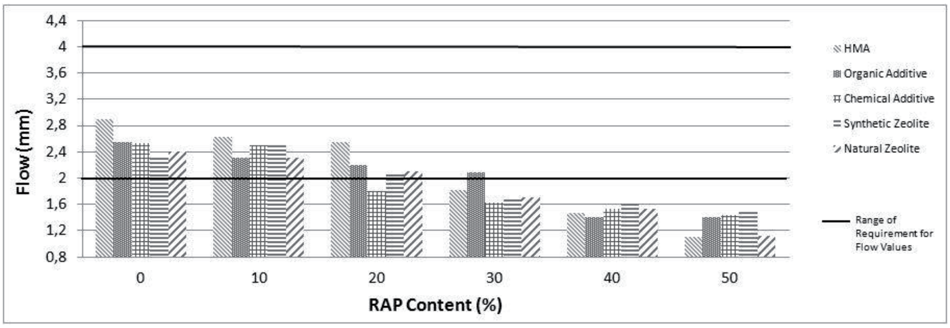

Fig. 2 Flow values for RAP and control samples.

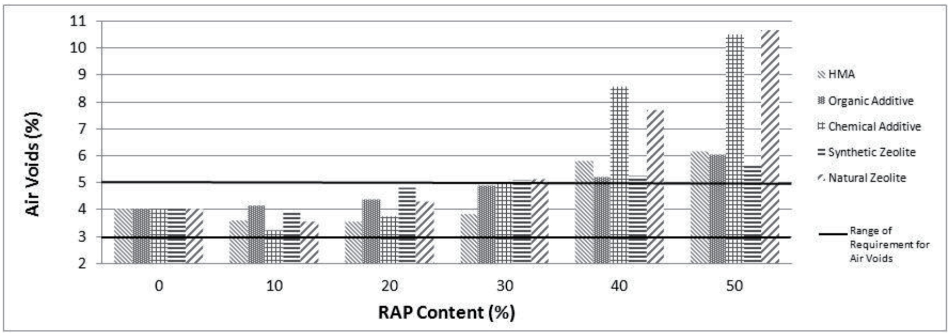

Fig. 3 Air void values for RAP and control samples.

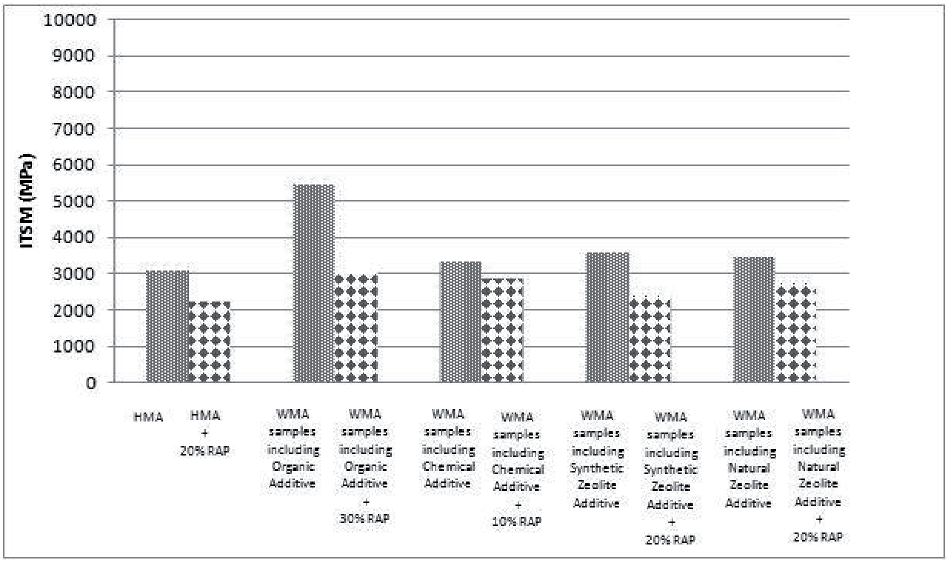

Fig. 4 ITSM values of HMA mixture and WMA mixtures as well as mixtures including optimum RAP content at 25°C.

Therefore, it can be concluded that the 20% RAP content with HMA, 30% RAP content with organic additive, 10% RAP content with chemical additive, 20% RAP content for both synthetic zeolite and natural zeolite additive can be accepted as an optimum RAP content based on the specification limits of flow and stability values.

As illustrated in Fig. 3, as RAP contents increase, the voids increase as well for HMA and all specimens involving WMA additives. Besides, the concluded optimum RAP contents for HMA and each WMA additive satisfy the specification limits of air voids value (3%-5%).

3.4 Indirect Tensile Stiffness Modulus Test and Indirect Tensile Fatigue Test Results

The ITSM values regarding HMA and WMA mixtures and the WMA mixtures involving optimum RAP contents are depicted in Fig. 4.

As presented in Fig. 4, the utilization of RAP materials obviously decreases ITSM values in comparison with the control mixtures. This evidence is accountable considering the fact that the aged RAP materials which are counted as responsive materials to fatigue cracking effect the bond between the bitumen and aggregate. Mixtures containing organic WMA additive demonstrated the highest values among other test samples. Other than

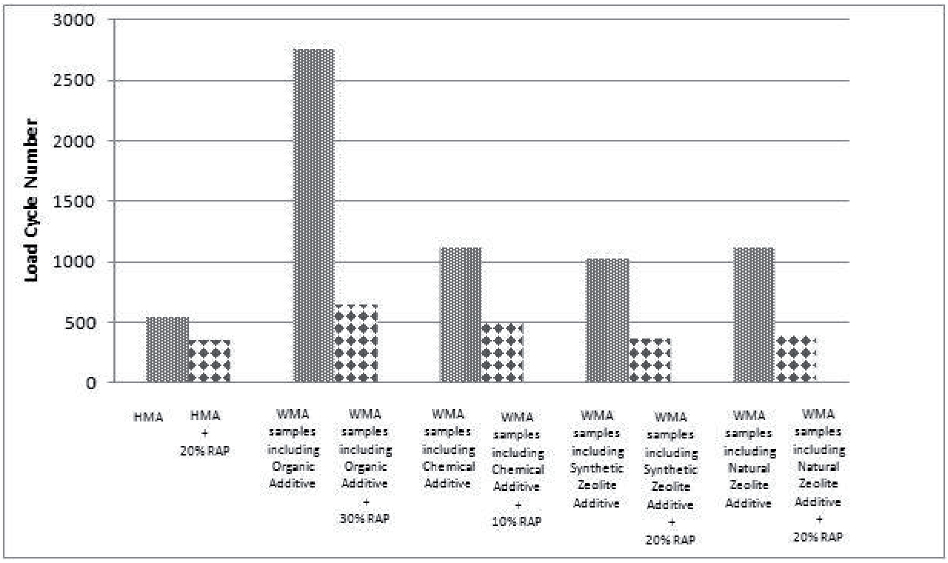

Fig. 5 Load cycle numbers of HMA mixture and WMA mixtures as well as mixtures including optimum RAP content at 25°C.

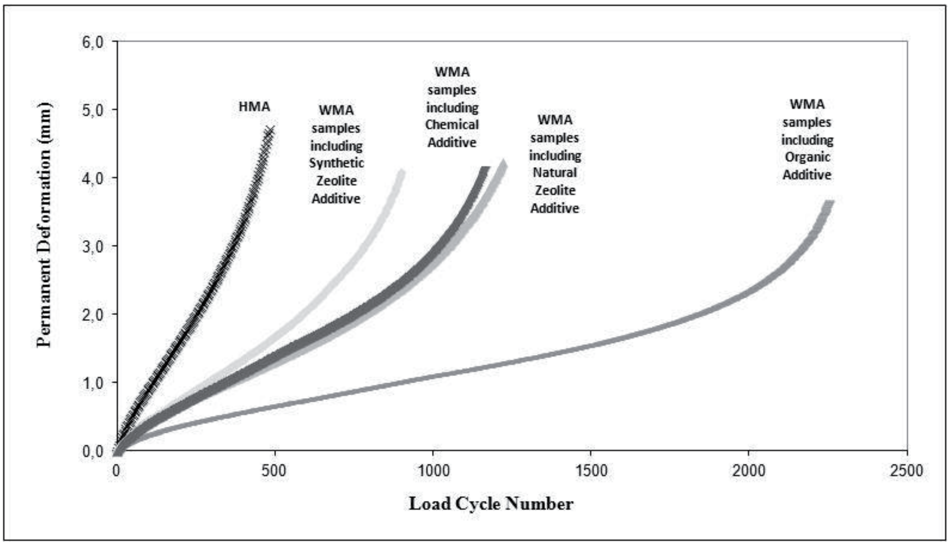

Fig. 6 Permanent deformations corresponding load cycle numbers of HMA mixture and WMA mixtures.

organic WMA additive, all WMA additives could partly compensate the side effects of using RAP. Although the utilization of 30% RAP significantly decreased the ITSM value of sample including the organic WMA additive, this mixture yielded the highest ITSM value among the other mixtures involving RAP. Mixtures involving synthetic zeolite, natural zeolite and chemical additives come after the organic WMA mixtures respectively.

The graphs of load cycle numbers for HMA and WMA mixtures with and without RAP materials, which caused the specimens to be cracked in the fatigue test are shown in Fig. 5.

As depicted in Fig. 5, the load cycle numbers of WMA mixtures are more than the load cycle numbers of HMA mixture. When comparing the effect of each WMA additive, the mixture containing organic WMA additive could tolerate more repetition of loads than other mixtures. Chemical and synthetic WMA additives as well as natural zeolite have demonstrated the same performance in terms of load cycle numbers as presented in Fig. 5. The utilization of RAP materials considerably decreased the tolerance of all mixtures against fatigue phenomena. A significant variation in load cycle numbers was recorded in the mixture involving organic WMA additive in comparison with the 30% of RAP involving organic WMA additive. The tolerance of samples against fatigue loads almost halved in case of other WMA additives involving optimum RAP contents.

The deformation of the specimens was monitored through linear variable–differential transducers (LVDTs) during the indirect tensile fatigue test. Fig. 6 and Fig. 7 demonstrate the graphs for the load cycle numbers corresponding permanent deformation for mixtures without RAP and mixtures involving RAP materials respectively.

The comparison of HMA and WMA mixtures in order to find out the efficiency of different kind of WMA additives is made possible by the graph depicted in Fig. 6. All WMA additives considerably increased the load cycle number of samples for a referenced deformation. The organic additive involving WMA specimens tolerated about fourth times more cycling in

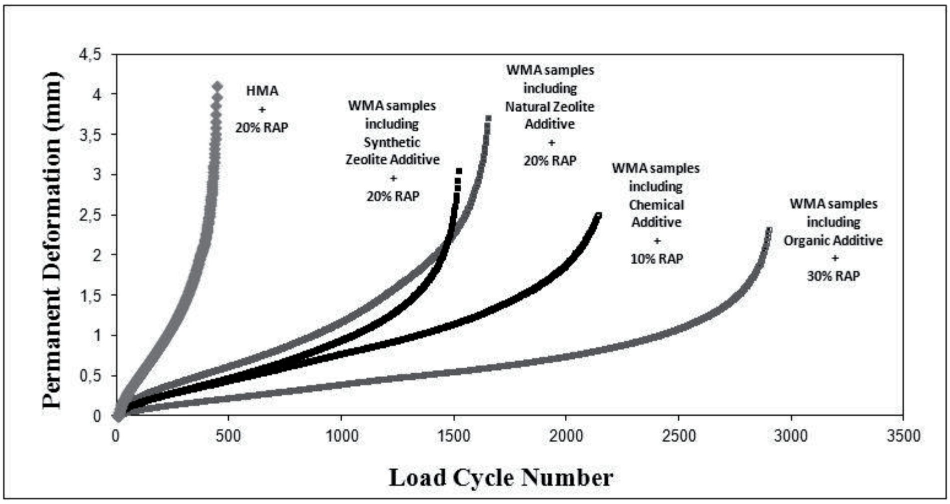

Fig. 7 Permanent deformations corresponding load cycle numbers of mixtures including optimum RAP contents.

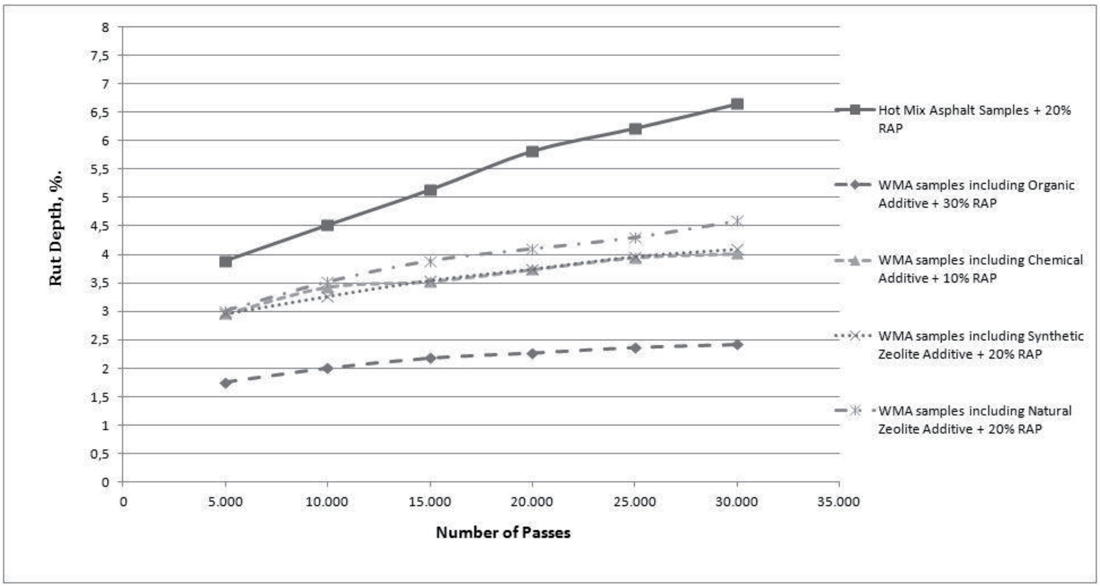

Fig. 8 The rut depth percent values corresponding number of passes for mixtures including optimum RAP content.

comparison to HMA mixtures. By use of other WMA additives tested within the scope of this study such as chemical WMA additive, natural and synthetic zeolites as WMA additives, the specimens could withstand two times more cycling but cracked at lower deformation strains comparing to HMA control specimens.

As it can be seen in Fig. 7, the RAP materials increased the number of cycling together with lowering the permanent deformation. Utilization of 30% RAP within organic WMA mixture shifted the load cycle number by about 600 cycle numbers. As presented in Fig. 7, among all the mixtures involving RAP, the organic WMA mixture demonstrated a singular performance. Natural zeolite, chemical additive and synthetic zeolite WMA additives showed similar performance in terms of load cycling.

3.5 Rutting test results

The Hamburg wheel tracking test was performed in accordance with BS EN 12697-22 standard [47]. The rut depths are presented in Fig. 8.

Results are given as percent values indicating the ratio of actual rut depth over the total thickness of tested specimen (50 mm). The real rut depths (mm) can be calculated by halving the percent values. The rut depths of HMA and WMA mixtures involving optimum RAP contents were determined at each 5.000 passes initiating at 5.000 and ending at 30.000.

As expected the rut depth values typically increase with increase in the number of passes. Based on each number of passes, all WMA mixtures exhibit better performance than HMA mixture in terms of rut depth. The resistance of mixtures against rutting susceptibility is significantly improved by the utilization of organic WMA additive together with 30% RAP content.

4 Conclusions and recommendations

Lowering asphalt production emissions in the plant and compaction emissions in the field are the most important benefits of utilization of WMA. The properties of bitumen are improved by means of organic, chemical, synthetic zeolite WMA additives and natural zeolite. These results have been reached by the conventional test methods such as penetration, softening point, rotational viscosity, TFOT test results. Besides, the utilization of organic, chemical, synthetic zeolite and natural zeolite additives help in the reduction of viscosity values which are in return decreases mixing and compaction temperature leading to the reduction of energy costs as well as emissions.

Marshall Stability values related to RAP mixtures have been found higher than the control mixtures. Based on the utilized aggregate, 20%, 30%, 10% and 20% can be accepted as an optimum RAP contents related to HMA samples, organic, chemical, both synthetic zeolite and natural zeolite additives respectively. The other properties of samples including optimum RAP content for HMA mixtures and each WMA additive are also within specification limits in terms of flow, air void level.

The utilization of WMA additives significantly improves fatigue performance of bituminous mixtures. However, implementation of RAP materials adversely affects fatigue characteristics. Considering the impact of RAP on fatigue performance it can be said that even if the Marshall characteristics of mixtures containing RAP materials remain within the acceptable limits, the fatigue characteristics of these mixtures must be taken into account separately. Among the additives used within the scope of the study, the organic WMA additive is an appropriate additive that can be used as rejuvenator agent in road rehabilitation with RAP materials.

The deformation of the specimens involving all WMA additives monitored during the indirect tensile fatigue test demonstrates that the additives considerably increase the load cycle number of samples for a referenced deformation compared to HMA mixtures. Besides, the addition of RAP significantly improves the deformation characteristics of the WMA samples. The variation is much more promising with organic WMA additive.

In the light of findings from rutting test, it is possible to consider that the WMA additives used within the scope of this study improve resistance to rutting characteristics of bituminous mixtures. Organic and chemical additives have structural modification effects on bituminous mixtures since the zeolites also behave as filler particles. For a specified number of passes (15.000 passes e.g.), the mixtures involving organic additive exhibit the lowest rut depth percentage. This result is attributable to crystallized structure arising from the modification effect of organic WMA additive.

Overall, WMA mixtures prepared with additives used in this study perform better than HMA mixtures in terms of fatigue and rutting characteristics. Beside modification effects of WMA additives, the lower amount of aging due to lower application temperatures play an important role in total assessment of these innovative technologies.

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