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Evaluation of Hot Asphalt Mixtures Containing Reclaimed Asphalt Pavements

Ahmed Ebrahim Abu El-Maaty, Abdulla Ebrahim El-Moher

Abstract*— *The conventional method of providing bituminous surfacing on flexible pavements require significant amount of energy for production of bituminous mix at hot mix plant. Due to economical reasons and the need for environmental conservatism, there has been an increasing shift towards the use of reclaimed asphalt pavement (RAP) materials in the pavement construction industry. Hot mix recycling is the process in which RAP materials are combined with new materials to produce hot mix asphalt mixtures. The amount of the added reclaimed asphalt depends on mineral materials and their homogeneity. The main objective of this paper is to investigate the use of a homogeneity reclaimed asphalt pavement in the pavement industry in Egypt evaluating the effects of partial and total replacements of aggregates by RAP on the mechanical and volumetric response of dense-graded HMA mixtures. Laboratory studies were carried out on asphalt mixes with RAP material and their performance was compared with virgin asphalt mixes. Various performance tests such as indirect tensile strength, resilient modulus, absorbed energy and wheel tracking test were carried out. In addition the effect of moisture damage or stripping on strength of RAP mixtures was investigated. Moreover an economic study was achieved to determine the saving in cost of materials due to using RAP in HMA. The laboratory results indicated that when properly designed, the asphalt mixes with RAP especially at 50% to 100% replacement ratio provided better performance compared to those of new conventional HMA mixtures. While cost analysis showed at least 45-64% savings in material cost related expenses.

Index Terms*— *Reclaimed asphalt pavement, Mechanical properties, Moisture Susceptibility, Indirect Tensile Strength, Marshall Stability, Rutting.

I. INTRODUCTION

The heating of bituminous binder, aggregates and production of huge quantities of HMA releases a significant amount of green house gases and harmful pollutants. The amount of emissions becomes twofold for every 10ºC increase in mix production temperature, and increasingly, higher temperature is actually being used for the production of HMA with modified binders. Also, there is a problem of the scarcity of aggregates, which forces transportation of materials from long distance. The use of diesel for running trucks leads to emission of pollutants. Therefore, an attempt has to be made to develop and adopt alternative technologies for road construction and maintenance to reduce consumption of fuel and aggregates [1&2]. Recycling of asphalt pavements is a technology developed to rehabilitate and/or replace pavement structures suffering from permanent deformation and evident structural damage.

In this context, according to Reyes et al. 2012 [3], the reclaimed asphalt pavement (RAP) is one of the most recycled materials in the world. The first data documented on the use of RAP for the construction of new roads date back to 1915 [4]. However, the actual development and rise of RAP usage occurred in the 1970's during the oil crisis, when the cost of the asphalt binder (or asphalt) as well as the aggregate shortages where high near the construction sites. Later, in 1997, with the Kyoto Protocol adaptation by parties and implementation in 2005, recycling received major attention and broader application in the road construction industry. RAP is considered to be one of the most important types of green asphalt pavement; pavement that minimizes environmental impacts through the reduction of energy consumption, natural resources and associated emissions while meeting all performance conditions and standards. In pursuit of sustainable development principles, sustainable development is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs [3 and 5].

In the US, the Federal Highway Administration (FHWA) reported that 73 of the 91 million metric tons of asphalt pavement removed each year during resurfacing and widening projects are reused as part of new roads, roadbeds, shoulders and embankments (FHWA 2002) [6]. The recycling of existing asphalt pavement materials produces new pavements with considerable savings in material, cost, and energy. Furthermore, mixtures containing reclaimed asphalt pavement (RAP) have been found to perform as well as virgin mixtures. The National Cooperation Highway Research Program (NCHRP) report provided basic concepts and recommendations concerning the components of mixtures, including new aggregate and RAP materials (NCHRP 2001)[7]. Several authors state that diverse methods for recycling of asphalt pavements are suitable including: hot recycling in plant, hot-recycling "in situ", cold-recycling "in situ", and others. Nevertheless, hot recycling is one of the most widely techniques used nowadays, where virgin materials and RAP are combined in different proportions and sizes [8]. Studies in Europe and the United States have concluded that over 80% of the recycled material is reused in the construction of roads, but regulations are still strict allowing inclusion of RAP in proportions ranging between 5 and 50% for production of new hot mix asphalt (HMA) mixtures [9]. Recent researches [2, 5, 10 and 11] have established that RAP replacement at proportions above 50% is feasible to produce new HMA mixtures, obtaining satisfactory results in the mechanical properties. Likewise, the susceptibility to moisture damage was low (tensile strength ratio (TSR) values close to 95%). In addition, the HMA mixtures with RAP replacement increased in 50% the indirect tensile strength (ITS) as compared to that of the HMA

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Ahmed Abu El-Maaty, Assoc. Prof., Department of Civil Engineering, Menoufia University , Shibeen Elkom City, Egypt.

Abdulla El-Moher, M.sc, Department of Civil Engineering, Alazhar University, Nasr City, Egypt.

mixtures fabricated with virgin materials. The energy dissipated during the ITS test also increased by 100% in the HMA mixtures with RAP replacement.

Some studies indicated that utilization of certain percentage of RAP increases the performance properties of mixes such as (Feipeng et al. 2009[12] and Saad et al. 2014 [13]) while some studies indicated that incorporating certain percentages of RAP there are no significant changes in the performance of mixes (Paul, 1996 [14]). Some researchers found that recycled mixes have good resistance to moisture damage at low RAP percentages whereas there is no significant increase in resistance to moisture damage with increase in RAP percentage in mix (Baron et al. 2012 [15]) and some studies stated that resistance to moisture damage significantly decreases with presence of RAP (Huang 2010 [16]). Some researchers found that presence of RAP increases the stiffness of the mix (Aravind et al. 2006 [17] and AL-Zubaidi et al. 2014 [18]) and decreases according to some studies (Huang, 2010 [16]). Similarly fatigue life increases according to (Tabakovi et al. 2010 [19]) and decreases according to (Mohammed et. al, 2003 [20]) and vary according to the temperature (Puttaguanta et al. 1997 [21]).Tensile strength increases (Sarsam et al. 2014 [22]) or similar to virgin mixes (Katman et al. 2012 [23]).

When RAP is mixed with virgin mineral materials and virgin binder, partial blending of RAP binder occurs in the hot mix asphalt. Agencies limit the amount of RAP because the degree of blending between the RAP and the virgin materials is not known. The composition and properties of RAP HMA are improved, when weight by percent of all materials and their recycling technology are properly selected. The National Asphalt Pavement Association concluded that high RAP mixtures containing 30–40% RAP are possible to be produced; although the major restrictions towards producing quality RAP mixtures result from the extreme stiffness of the RAP binders. A disadvantage with using RAP materials is that RAP binders may force the producer to use a very soft binder within the mixture possibly resulting in workability issues in the mixture. Another problem affecting high percentage RAP mixtures is the amount of fine materials contained within the RAP mixture; this issue may be circumvented through fractioning RAP [15 &24]. Olard et al. 2008 [25] and Asmaa et al. 2013[26] assessed HMA mixtures with high recycling rates (i.e., >50% RAP replacement) for warm- and HMA-mixture production and stated that RAP foster positive environmental impacts, including that it:

- Can be done in an asphalt plant or in-place,
- Reuses existing materials thus eliminating disposal problems (saving or diminishing land requirements in populated countries),
- Saves costly materials and in some countries rare, hard to find good aggregates,
- Can correct both asphalt content and aggregate gradation of an existing HMA mixture, and
- Produces a stable pavement structure at a lower cost than that associated with conventional methods.

Based on the positive experiences and outcomes from global use of HMA mixtures with RAP inclusion, it can be inferred that relevant results could be obtained from application of this technology in developing countries, such as Egypt where approximately 4 million tons per year of reclaimed asphalt materials are not used. In this regard, research projects must be conducted and financial support gathered to advance in the development of feasible alternatives tending to be less invasive to the environment and practical in use for constructors and practitioners.

II. OBJECTIVES

The majority of HMA mixtures in Egypt are produced only from virgin materials although there are about 4 million tons per year of reclaimed asphalt materials, due to continuous pavement milling or scraping processes, are not used. Recently the world towards to use green asphalt and one of the important ways to use green asphalt is reclaimed asphalt pavement. The question now is: if these roads had been recycled, what is the effect of this on the behavior of the mechanical and volumetric properties as well as moisture susceptibility of the recycled HMA. Moreover, what is the suitable percentage of RAP which can be used to achieve the optimal performance and the maximum cost saving? The answers for these questions are the primary goal of this paper.

III. EXPERIMENTAL PROGRAM AND PROCEDURES

III.A. Materials

III.A.1. Natural Aggregates

Coarse aggregates (25/9.5) mm and (12.5/2.36) mm as well as breaking sand (pass 4.75 mm) from Amal breaker in Ataqa were used and resulted from dolomite aggregates, whereas natural sand (pass 4.75 mm) from socket in Kafer Dawood and dust cement from Helwan cement factories were used. The grading curve of the natural aggregates used is shown in Figure 1. The properties of natural aggregates are given in Table 1.

III.A.2. *Asphalt Cement*

Asphalt cement (AC 60/70) obtained from Victory Laboratory in Suez is used in this study. Table 2 summarizes the physical properties of this asphalt.

III.A.3. Recycling Asphalt Pavement

Reclaimed asphalt pavement (RAP) taken from Cairo to Alexandria agricultural road, at station [175 + 400], right direction was used. The specimen of the recycling asphalt

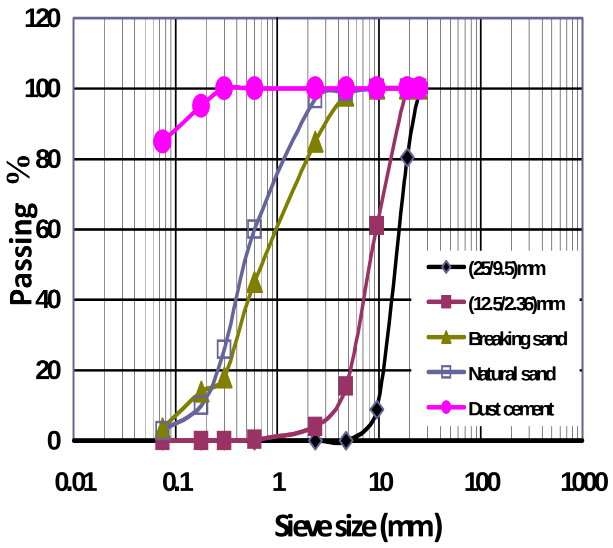

Fig. 1 Grading for natural aggregates

Table 1 Properties of natural aggregates

Description	Value	
	(25/9.5)mm	(12.5/2.36)mm
Volume weight	1.43 t/m3	1.45 t/m3
Specific gravity	2.56	2.54
% Absorption	1.88	1.94
Crushing factor	21.0 %	22.0 %

Table 2 Physical properties of asphalt

Test	Results	Specification limits
Penetration (25^{o}C, 0.1 mm)	63	60-70
Softening point (^{o}C)	50	46-54
Viscosity at (135^{o}C)- pas	0.51	-
Change of mass (%)	0.07	0.5(max)
Retained penetration (%)	51	50 (min)
Ductility (25^{o}C)- cm	117	-
Specific gravity	1.03	-
Flash point (^{o}C)	+260	230 (min)

pavement was taken by milling road about five centimeters by milling machine. By using extraction equipment, the specimen has 4.13 % of bitumen content. The specimen of the recycling asphalt pavement is shown in Figure 2.

Fig. 2 Reclaimed asphalt pavement

III.B. Mix Design

The mix design for virgin and RAP mixes was carried out according to Egyptian specifications by using 38% from (25/9.5) mm, 32% from (12.5/2.36) mm, 14% from breaking sand, 14% from natural sand and 2% from dust cement. Five dense graded mixtures of hot mix asphalt with recycled asphalt pavement percentages of 0%, 25%, 50%, 75%, and100% were designed based on Egyptian binder course (3D) specifications as shown in Figure 3.

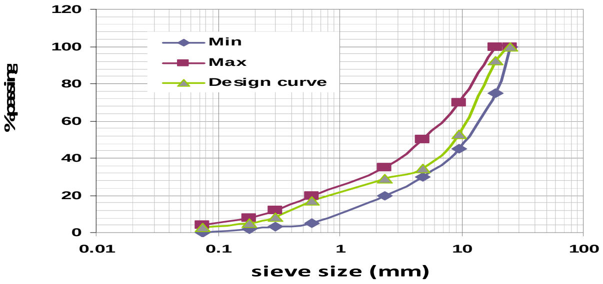

Fig. 3 Mix design of asphalt binder course (3d)

III.C. Experimental Program

III.C.1. HMA Mixtures Fabrication

Five different bitumen ratios (3.5%-5.5%) were prepared with increment of 0.5% to determine the optimum bitumen content for each RAP mixture. Marshall specimens prepared according to AASHTO T 245 were compacted at 75 blows per face using the Marshall compactor. The specimens were loaded to failure at a constant rate of compression of 1.65 mm/min. The ratio of stability to flow, stated as the Marshall quotient (MQ), and as an indication of the stiffness of the mixes was calculated. It is well recognized that the MQ is a measure of the materials resistance to shear stresses, permanent deformation and hence rutting. High MQ values indicate a high stiffness mix with a greater ability to spread the applied load and resistance to creep deformation. To determine the resistance of mixtures to moisture damage, the retained Marshall stability (RMS) was obtained by using the average stability in the following formula 1 [27]:

$$RMS = 100\ (MScond/MSuncond) \qquad (1)$$

where RMS is the retained Marshall stability, MScond is the average Marshall stability for conditioned specimens (kN) and MSuncond is the average Marshall stability for unconditioned specimens (kN). An index of retained stability can be used to measure the moisture susceptibility of the mix being tested.

III.C.2. Moisture Conditioning

The presence of water in an asphalt pavement is unavoidable. Several sources can lead to the presence of water in the pavement. Water can infiltrate the pavement from the surface via cracks in the surface of the pavement, via the interconnectivity of the air-void system or cracks, from the bottom due to an increase in the ground water level, or from the sides. Inadequate drying of aggregate during the mixing process can lead to the presence of water in the pavement as well. The moisture conditioning is used to evaluate the effects of water saturation of compacted bituminous mixtures in the laboratory. Yet almost all of studies aimed at a comparative measure of moisture damage, either via visual observations from field data or laboratory tests or via wet-versus-dry mechanical tests to give a so called moisture damage index parameter [28]. In this research, the moisture conditioning was used to evaluate the effects of water damage on the durability potential of compacted bituminous mixtures containing RAP in the laboratory. The hot-mix asphalt specimens conditioning was performed according to AASHTO T283 by immersing the specimens in water at 60±1°C for different treatment periods (1, 3 and 7 days) and then placing in water bath at 25°C for 2 hour.

III.C.3. Indirect Tensile Strength Test

The indirect tensile strength test according to (ASTM D 6931) was performed where cylindrical specimens were subjected to compressive loads, which act parallel to the vertical diametric plane by using the Marshall loading equipment. This type of loading produces a relatively uniform tensile stress, which acts perpendicular to the applied load plane, and the specimen usually fails by splitting along with the loaded plane. Five specimens with optimum bitumen content were prepared for each percentage of (RAP) mixture. The indirect tensile strength of the specimens was determined by the following equation 2:

$$ITS = \frac{2000 \times P}{\pi \times H \times D} \qquad (2)$$

Where: ITS is the indirect tensile strength (kPa); P the maximum load to failure (N); h is the specimen thickness (mm); and D is the specimen diameter (mm). The level and the extent of moisture damage, also called moisture susceptibility, depend on environmental, construction, and pavement design factors; internal structure distribution and the quality and type of materials used in the asphalt mixture. Moisture susceptibility of the compacted specimens was evaluated by tensile strength ratio (TSR) using equation 3.

$$TSR = \frac{ITS_{cond}}{ITS_{uncond}} \qquad (3)$$

Where: ITScond is the average indirect tensile strength of conditioned specimen while ITSuncond is the average indirect tensile strength of dry (unconditioned) specimen.

III.C.4.Wheel Trackers Test

Wheel tracker typically measures the rutting created by repeated passage of a wheel over prismatic asphalt concrete samples as shown in Figure 4. The HMA slap dimensions (length × width × thickness) of 300×250×50 mm were prepared compacted at optimum bitumen content for virgin as well as for each RAP mixture. The test was conducted as per AASHTO 324. A standard rolling wheel load of 700 ± 10 N was fitted with a solid rubber tire of outside diameter 200 mm under a temperature controlled cabinet with a range of 45°C ± 1.0°C was performed. The rutting was measured after 10000 passes of the standard load.

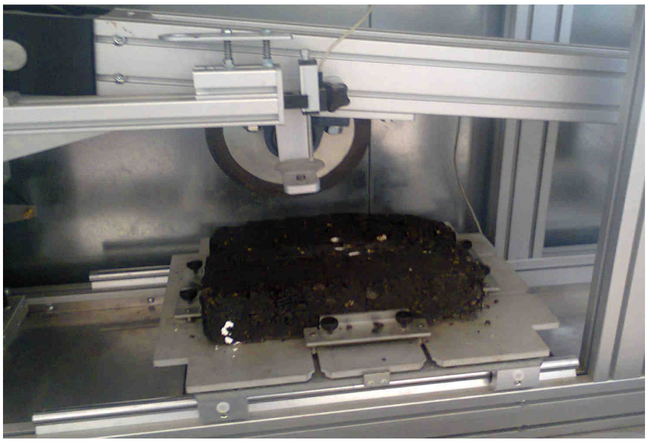

Fig. 4 Track wheel test

IV. RESULTS AND DISCUSSION

IV.A. Marshall Test Results

IV.A.1. Mechanical Properties

The mechanical properties include stability, flow and Marshall Quotient are shown in Table 3 where the Marshall mix design of HMA containing RAP and the corresponding optimum binder content (OBC) are illustrated. The results which are average of three samples show that the OBC varies due to the percentage of (RAP) where the lowest OBC value is provided at 50% RAP whereas, the highest value is obtained at 100% RAP. OBC increases by about 2% when RAP content increases from 0% to 25% and by about 22% when RAP content increases from 0% to 100%.

Table 3 Mechanical properties of Marshall mixtures

RAP	Bit. ratio (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)	O.B.C
0.0%	3.5	996	2.8	345	4.5 %
	4	1150.56	3.2	359.55	
	4.5	1279.85	3.76	340.38	
	5	1232	3.9	315.89	
	5.5	1113.31	4	278.32	
25 %	3.25	1454.52	2.6	559.45	4.58 %
	3.75	1649.14	2.7	610.79	
	4.13	1398.13	2.9	482.115	
	4.5	1104.53	3.2	345.16	
	5	1005.51	3.6	279.31	
	5.5	974.21	3.8	256.37	
50 %	3.25	1053.37	2.3	457.99	4.13 %
	3.75	1648.85	2.6	634.17	
	4.13	1036.99	2.8	370.35	
	4.5	886.686	3	295.56	
	5	801.965	3.5	229.13	
	5.5	989.978	3.7	213.51	
75 %	3.25	1745.33	2	872.67	4.5 %
	3.75	1996.55	2.2	907.52	
	4.13	1362.7	2.4	567.79	
	4.5	990.216	2.6	380.85	
	5	978.69	2.7	362.47	
	5.5	1290.68	3	430.23	
100 %	4.13	1648.48	1.8	915.82	5.5 %
	4.5	2041.02	2.4	850.42	
	5	1806.83	2.8	645.29	
	5.5	1399.57	3.3	424.11	

The results shown in Table 3, illustrate that the percentage of RAP plays a significant role in mechanical properties of bituminous mixtures where 100% RAP mixture achieves the maximum stability. For flow value, it decreases with increasing the RAP ratio where all flow values are located within the required specifications range (from 2 to 4 mm according to Egyptian Code) except the mixture contains 100% RAP at 4.13 % bitumen content. Moreover, the Marshall quotient (MQ) of control mixture slightly increases at 3.5 % to 4% bitumen content, after that it slightly decreases at bitumen content up to 5.5%, while MQ of RAP mixtures increases then decreases significantly at a sharp rate by increasing the bitumen content. Based on the Marshall test results discussed previously, an optimum RAP content of 100% is recommended for obtaining the highest stability and Marshall Quotient. The variations of mechanical properties of RAP mixtures at the optimum bitumen content are shown in the Figures 5 to 7. It is observed that the addition of 100% RAP has a great impact on the stiffness of the mixture. It can be concluded that there is a significant improvement in the stiffness characteristics of HMA after adding RAP.

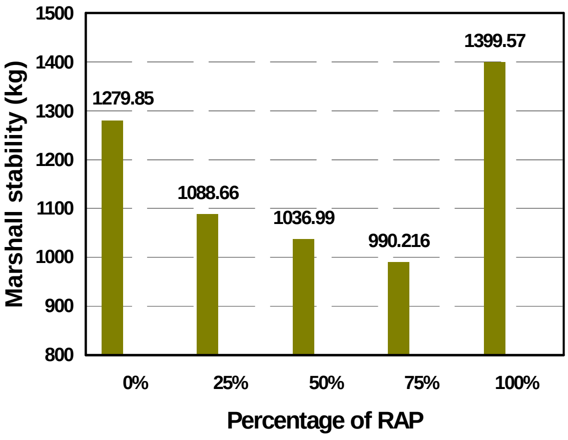

Fig. 5 Stability values at the optimum bitumen content

IV.A.2 Volumetric Properties

Fundamentally, mix design is meant to determine the volume of bitumen binder and aggregates necessary to produce a mixture with the desired properties. Since weight measurements are typically much easier, weights are taken and then converted to volume by using specific gravities [5, 18 and 23]. The important volumetric properties of bituminous mixtures that are to be considered include theoretical maximum specific gravity (Gt), bulk specific gravity of the mix (Gm), percentage air voids (Va), percentage volume of bitumen (Vb), percentage void in mineral aggregate (VMA) and percentage voids filled with bitumen (VFB). Test results have illustrated that the percentages of RAP plays an important role in volumetric properties of HMA. The variations of volumetric properties of RAP (average of three samples) are shown in Table 4.

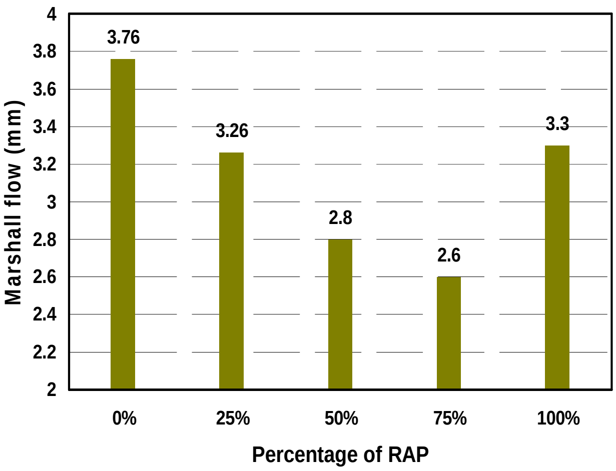

Fig. 6 Flow values at the optimum bitumen content

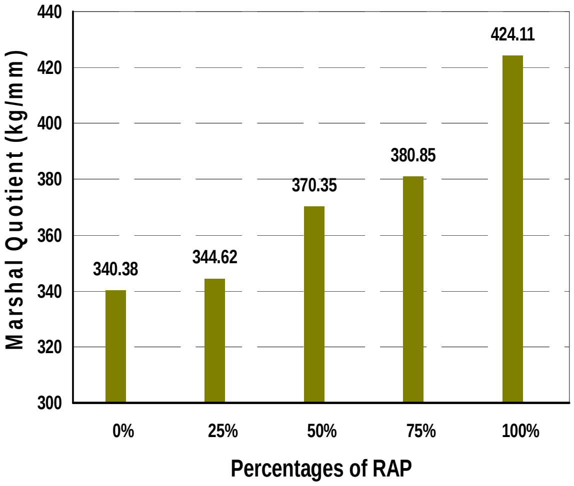

Fig. 7 Marshall Quotient values at the optimum bitumen content

Excessive air voids in the mixture would result in cracking due to insufficient bitumen binders to coat on the aggregates, while too low air void may induce more plastic flow (rutting) and bitumen bleeding. As shown in Table 4, up to 3.85% bitumen content, the adding of 25%RAP provides the highest air voids while 50% RAP gets the lowest value. With increasing bitumen content from 4% to 5.5%, the control mixture provides the lowest air voids. However, all air voids of RAP mixtures are located within the Egyptian specification range of 3% to 8% except the mixture of 25% RAP at bitumen ratio less than 3.85%. Moreover, it is observed that the addition of RAP has a great impact on the VMA and VFB of the mixture where 25% RAP provides the highest VMA and the lowest VFB while the control mixture gets the lowest VMA and highest VFB especially after 4% bitumen content.

The volumetric properties due to adding RAP in HMA at the optimum bitumen content are shown in Figures 8 to 10. From results, it can be indicated that the RAP mixtures show higher air voids (except the mixture of 100% RAP), while the voids filled with bitumen of RAP mixtures are less than the control mix (except at mixture of 100% RAP). Moreover, the voids in mineral aggregates increase obviously after adding RAP especially at 25% RAP. All VMA values are located within the Egyptian specification range except the value of control mixture, while the VFB values at 25, 50 and 100% RAP don't achieve the AASHTOO specification.

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Table 4 Volumetric properties of Marshall mixtures

RAP (%)	Bit. %	Theo GS (Gt)	Bulk GS (Gm)	Air voids (Va) %	Bit. Vol. (Vb) %	VMA (%)	VFB (%)
0.0%	3.5	2.54	2.35	7.33	8.11	15.43	52.50
	4	2.52	2.39	5.31	9.40	14.71	63.88
	4.5	2.50	2.41	3.77	10.67	14.44	73.86
	5	2.48	2.43	2.36	11.95	14.31	83.45
	5.5	2.47	2.42	2.00	13.10	15.10	86.71
25 %	3.25	2.48	2.20	11.3	7.04	18.41	38.20
	3.75	2.47	2.25	8.62	8.31	16.93	49.09
	4.13	2.45	2.30	6.03	9.37	15.40	60.80
	4.5	2.44	2.30	5.59	10.20	15.79	64.57
	5	2.42	2.28	6.02	11.21	17.23	65.02
	5.5	2.41	2.26	5.96	12.26	18.22	67.27
50 %	3.25	2.50	2.32	7.39	7.42	14.81	50.08
	3.75	2.49	2.34	5.73	8.65	14.38	60.13
	4.13	2.47	2.34	5.53	9.50	15.02	63.19
	4.5	2.46	2.33	5.46	10.30	15.76	65.34
	5	2.44	2.31	5.24	11.40	16.64	68.48
	5.5	2.43	2.30	5.18	12.46	17.65	70.60
75 %	3.25	2.53	2.34	7.26	7.49	14.75	50.77
	3.75	2.51	2.35	6.25	8.68	14.93	58.1
	4.13	2.50	2.37	5.19	9.61	14.81	64.90
	4.5	2.48	2.36	5	10.44	15.44	67.59
	5	2.46	2.35	4.63	11.57	16.19	71.41
	5.5	2.45	2.34	4.55	12.63	17.20	73.52
100 %	4.13	2.43	2.31	5.013	9.39	14.40	65.19
	4.5	2.42	2.31	4.46	10.24	14.70	69.63
	5	2.40	2.32	3.39	11.43	14.82	77.10
	5.5	2.39	2.31	3.13	12.52	15.66	79.96

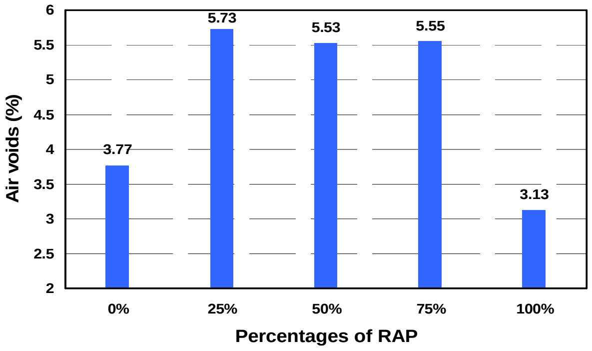

Fig. 8 Air voids at the optimum bitumen content

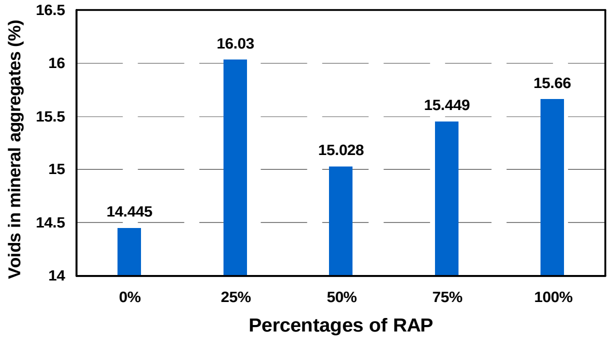

Fig. 9 Voids in mineral aggregate

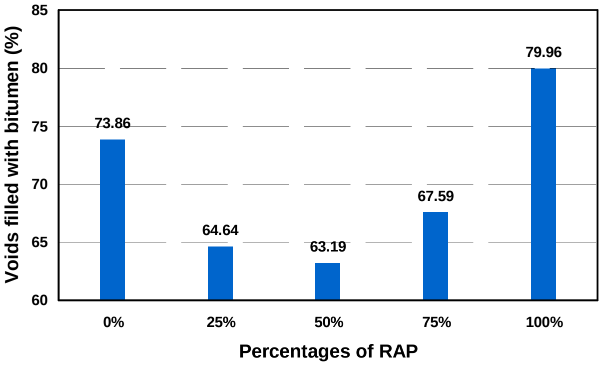

Fig. 10 Voids filled with bitumen

IV.B. Indirect Tensile Strength Test Results

The results of indirect tensile strength (ITS) for each RAP ratio which are average of three samples are shown in Figure 11. It is noticed that the adding of RAP in HMA improves the tensile strength values compared with control mixture by about 6, 106, 82 and 81 % for 25%, 50%, 75% and 100% RAP ratios respectively. The highest value is achieved at 50% RAP content. Thus, it can be concluded that, the mixture containing 50% RAP gains desired strength other than studied mixtures.

IV.C. Resilient Modulus of RAP Mixtures

Material's resilient modulus is actually an estimate of its modulus of elasticity. In recent years, there has been a change in philosophy in asphalt pavement design from the more empirical approach to the mechanistic approach based on elastic theory.

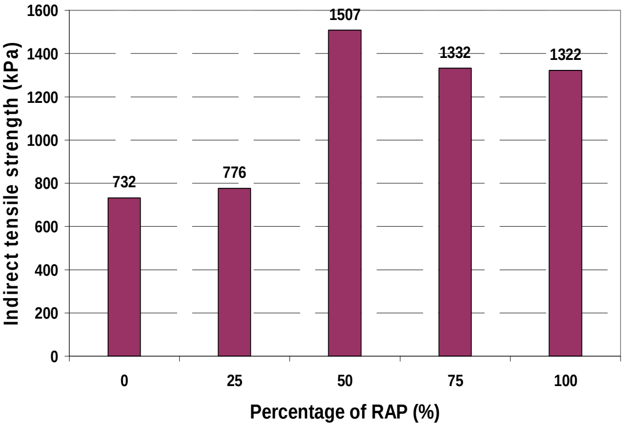

Fig. 11 Indirect tensile strengths of RAP mixtures

Resilient modulus of asphalt mixtures is the most popular form of stress–strain measurement used to evaluate elastic properties. It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as elastic [29]. For this purpose, the repeated loading indirect tensile test on compacted bituminous mixtures was performed as per ASTM D 7329. The resilience modulus (Mr) can be calculated using the maximum load applied and the horizontal elastic tensile deformation as shown in the following equation 4 [29]:

$$Mr = p\frac{\mu + 0.2732}{h\delta} \qquad (4)$$

Where: Mr is the modulus of resilience (MPa); p: the maximum load applied (N); h: sample thickness (mm); δ: recoverable horizontal deformation (mm) and μ: Poisson’s ratio (assumed as 0.35). The results which are average of three samples are shown in Figure 12 which illustrates that the resilient modulus increases with increasing the percentage of RAP in the mixture due to the stiffer of the RAP mixture that leads to better resistance against permanent deformations. The highest value of Mr is achieved at 100% RAP by increasing ratio of about 216% compared with control mixture. The result of resilient modulus agrees to the result of the Marshall quotient.

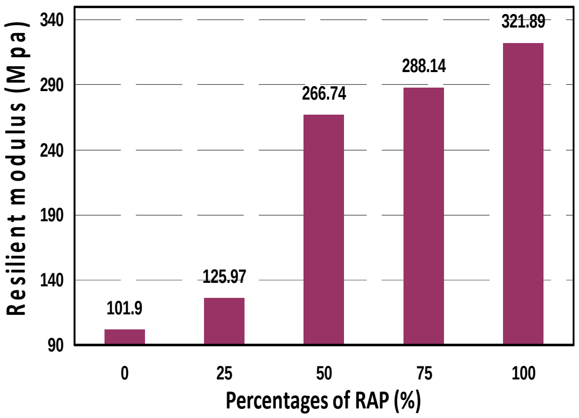

Fig. 12 Resilient modulus of RAP mixtures

IV.D. Absorbed Energy

An object initiates a micro-crack for some reasons the tiny crack tends to propagate to increase its crack surface. The propagation needs a certain amount of energy to balance the energy equilibrium, and this portion of energy is defined as the absorbing energy (the area under the load displacement curve in the indirect tensile strength test. Absorbed energy is a promising indicator for evaluating fracture performance of asphalt concrete [15, 23 & 25]. Equation (5) was used to calculate the absorbed energy at failure for specimens containing various percentages of RAP based on the indirect tensile strength test.

$$E = 0.5Pd / t \qquad (5)$$

Where: E is energy (N); P is ultimate load at failure (N); d is vertical deformation at the ultimate load (mm); t is specimen thickness (mm). Figure 13 shows that the absorbed energy increases by increasing the percentages of RAP in the mixture due to stiffness of the mixture containing RAP. The all results are average of three samples.

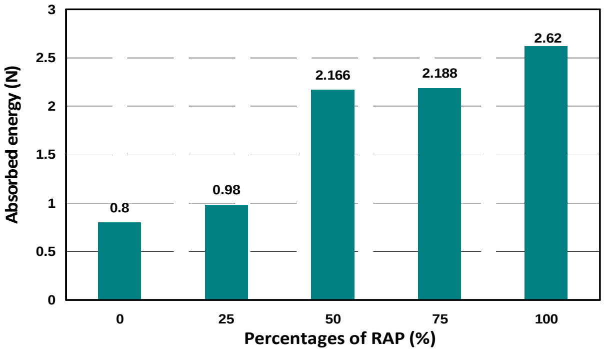

Fig. 13 Absorbed energy of RAP mixtures

IV.E. Track Wheel Test Results

The wheel tracker test is used to measure the rutting due to repeated passages of a standard wheel. Figure 14 illustrates the great influence of adding RAP with increased ratios on the rutting resistance of HMA where the rutting depth of control mixture reaches to 8.17 mm after 10,000 load passages, whereas for 100 % RAP mixture, the rutting depth reaches to 2.45 mm only. The results which are average of three samples are shown in Figure 15. An improvement in rutting resistance is observed as RAP content increased from 0% to 100%. The lowest rutting depth value is achieved at 100% RAP content (2.45mm) where it is lower than the rutting depth of control mixture (8.17mm) by about 70%. With considering that none of the mixtures reaches to the criterion of failure (12.5mm).

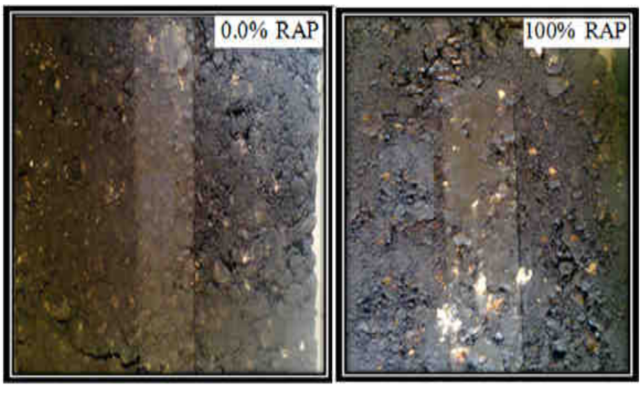

Fig. 14 Rutting depths after track wheel test

V. MOISTURE DAMAGE

Moisture damage can be defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture. Moisture can damage HMA in two ways: (1) loss of bond between asphalt cement or mastic and fine and coarse aggregate or (2) weakening of mastic due to the presence of moisture. There are six contributing factors that have been attributed to causing moisture damage in HMA: detachment, displacement, spontaneous emulsification, pore-pressure–induced damage, hydraulic scour, and environmental effects. Not one of the above factors necessarily works alone in damaging an HMA pavement, as they can work in a combination of the processes. A loss of the adhesive bond between aggregate and asphalt can lead to stripping and raveling, while a loss of cohesion can lead to a weakened pavement that is susceptible to premature cracking and pore pressure damage [4, 9, 16 and 27]. In order to combat this stripping in HMA mixtures that containing RAP, a proper mix design is essential.

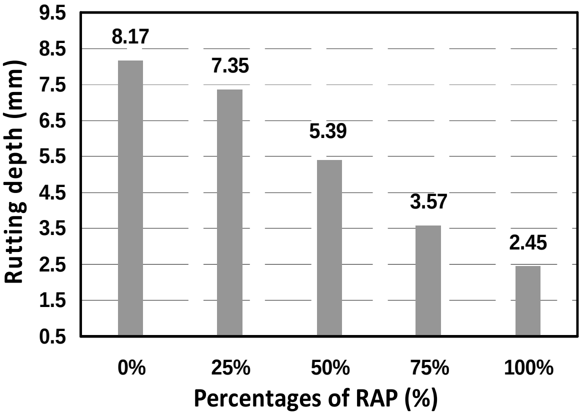

Fig. 15 Rutting depths of RAP mixtures

V.A. Retained Marshall Stability

The index of retained Marshall stability (RMS) can be used as an indicator of durability potential. The durability potential of bituminous mixtures may be defined as the resistance of the mixture to the continuous and combined damaging effects of water. High durability potential usually implies that the mechanical behavior of the mixture will endure for a long service life. This test is conducted as per ASTM D 1075 specifications. Figure 16 shows the relationship between immersion periods of RAP mixtures and RMS. The results are average of three samples. It can be observed that by increasing the immersion period the durability potential reduces. The highest RMS is obtained at 50% RAP ratio while 100% RAP mixtures obtain the lowest RMS for all studied immersion periods. The RMS of RAP mixtures up to 50% are located within the Egyptian specification limits (more than 75%). This result means that adding of 50% RAP to HMA provides better durability and longer service life for the pavement.

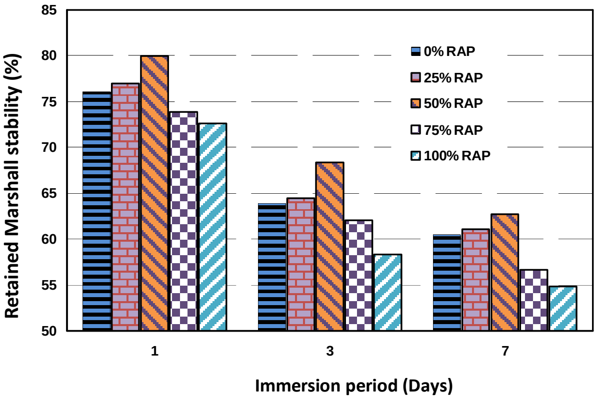

Fig. 16 Retained Marshall stability of RAP mixtures

V.B. Tensile Strength Ratio

Tensile strength ratio (TSR) is used to predict the moisture susceptibility of the mixtures. This test is conducted as per ASTM D 4867 specifications. The prepared samples were divided into two subsets, one subset is maintained dry while the other subset is partially saturated with water conditioned. The potential for moisture damage is indicated by the ratio of the tensile strength of the wet subset to that of the dry subset. According to previous researches such as Feipeng et al. 2009[12], a TSR of 0.8 after 1 day has typically been utilized as a minimum acceptable value for hot mix asphalt. Mixtures with tensile strength ratios less than 0.8 are moisture susceptible and mixtures with ratios greater than 0.8 are relatively resistant to moisture damage. Figure 17 illustrates tensile strength ratio for both control and RAP mixtures. It can be illustrated that only mixtures containing 25% and 50% RAP provide higher TSR than control mixture after 1 day conditioning whereas all TSR values are not located within the specification. After 3 or 7 days, the moisture susceptibility of HMA is improved for all RAP mixtures compared with control mixture. The highest TSR is obtained at 50% RAP ratio thus, the adding of 50% RAP to the mixture can enhances the moisture susceptibility for all studied conditioning periods.

V.C. Comparison between moisture damage indicators

Moisture damage is signified by loss of strength or durability in an asphalt pavement due to the effects of moisture and may be measured by the asphalt mixture's loss of mechanical properties.

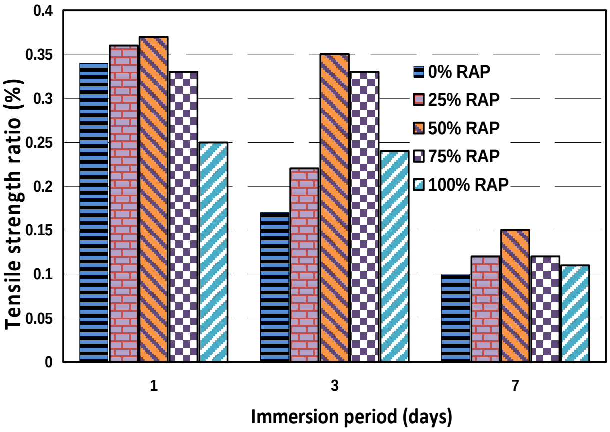

Fig. 17 Tensile strength ratio of RAP mixtures

To quantify the effect of conditioning process on moisture susceptibility of RAP mixtures, two parameters have been used in this study. These are retained Marshall Stability (RMS) and tensile strength ratio (TSR). Table 5 that illustrates the increasing (positive) or decreasing (negative) variations in each RMS and TSR values of RAP mixtures compared with the corresponding values of control mixtures with variations of RAP ratio and immersion period. It can be observed that with increasing RAP content up to 50%, a positive variation in both moisture damage indicators is occurred for all conditioning periods. With increasing the RAP content more than 50%, a negative variation in RMS value is obtained while the positive variation in TSR value is appeared with increasing both of RAP content and immersion period. Moreover, it can be noticed that the retained stability is less affected by the RAP content as well as conditioning period compared with the tensile strength ratio which is more sensitive to moisture susceptibility due to variation in RAP content and conditioning period.

Table 5 Variations in moisture damage indicators of RAP mixtures

%RAP	After 1 days		After 3 days		After 7 days	
	RMS	TSR	RMS	TSR	RMS	TSR
25	+1	+6	+0.8	+29	+0.9	+20
50	+5	+9	+7	+106	+3.6	+50
75	-3	-3	-3	+94	-6.4	+20
100	-4.4	-26	-9	-29	-9.3	+10

VI. THE ECONOMICALLY VIABLE

In addition to the environmental benefits of using RAP in HMA, it reduces the material cost of mixtures. The reuse of materials provides an opportunity to stabilize construction prices, which may fluctuate as the economy and demand for raw materials change. The economic benefits of recycling have been enhanced by new methods that allow using increased amounts of RAP in asphalt mixtures. It is appropriately done; RAP mixtures can provide the same or better properties and performance than virgin asphalt mixtures. A typical section for one kilometer length, 12m width, and 0.05m depth from a 2013 (Cairo–Alexandria) agricultural road project is analyzed. The details of economic analysis by using national asphalt pavement association (NAPA) [30] method are shown in Table 6. It can be observed that the adding of RAP has a great influence on saving money where the savings in material cost increase by about 23.70%, 45.64%, 62.98% and 64.84% for RAP content of 25, 50, 75 and 100% respectively.

Table 6 Economic analysis on using RAP in HMA

RAP (%)	Density (t/m3)	weight (ton)	cost (L.E/ton)	Total cost (L.E)	Cost savings (%)
0	2.385	1431	258.90	370485.9	
25	2.246	1347.6	209.75	282659.1	23.70
50	2.471	1482.6	135.82	201366.7	45.64
75	2.28	1368	100.26	137155.6	62.98
100	2.30	1380	94.39	130258.2	64.84

VII. CONCLUSIONS

The reclaimed asphalt pavement (RAP) is one of the most recycled materials in the world. In Egypt, there are about 4 million tons per year of reclaimed asphalt materials are not used. The main objectives of this study were to evaluate the adding of RAP on the mechanical and volumetric properties as well as stripping tendency of HMA mixtures. Based on the laboratory test results, the following conclusions were drawn:

1. The optimum bitumen content at adding (0, 25, 50, 75, 100%) RAP were (4.5, 4.58, 4.13, 4.5, 5.5) respectively. Optimum bitumen content was increased by about 1.7% when RAP content was increased from 0% to 25% and by about 22% when RAP content increases from 0% to 100%.

2. There was a significant improvement in mechanical properties of mixture after adding RAP where the stability was decreased by about 15, 19 and 22.6 % for 25, 50 and 75 % RAP content respectively, and was increased by about 10% for 100% RAP content. While the flow values were decreased by about 31% for 75% RAP content and the Marshall Quotient values as a measure of stiffness resistance were increased by about 25% for 100% RAP content.
3. The adding of RAP had a great influence on improving the indirect tensile strength where the highest value was achieved at 50% RAP content by increasing ratio about 106% compared with control mixtures. Moreover, the RAP addition improved the resilient modulus, absorbed energy and rutting resistance of the mixtures by about 216%, 194% and 70% respectively.
4. There is a significant effect on volumetric properties of mixture after adding RAP. Air voids, void in mineral aggregate and voids filled with bitumen increased by increasing of RAP ratio. The highest air voids and void in mineral aggregate values were achieved at 25% RAP content, while the highest voids filled with bitumen value was achieved at 50% RAP content.
5. The highest retained Marshall stability that used as an indicator of HMA durability potential is obtained at 50% RAP ratio while 100% RAP mixtures obtain the lowest value for all studied immersion periods. For tensile strength ratio that used as indicator of moisture susceptibility, mixtures containing 25% and 50% RAP provided higher values than control mixture after 1 day conditioning while after 3 or 7 days, the moisture

susceptibility of HMA was improved for all RAP mixtures.

6. Generally, it could be said that the RAP is one of the most important types of green asphalt pavement that all world towards to use it where it minimizes the environmental impacts through the reduction of energy consumption, improves the properties and stripping resistance of HMA and reduces the cost of construction materials by 50% at least.
7. Based on the findings of the study, it is concluded that it is possible to design acceptable-quality bituminous mixes with RAP that meets the required volumetric, mechanical properties and desired performance criteria.

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Ahmed Ebrahim Abu El-Maaty is associate professor in the department of Civil Engineering, Faculty of Engineering, Minoufiya University, Egypt. He received his Master of Science degree in 2004 and obtained his Ph.D. in 2007 with major in civil engineering from Minoufiya University, Egypt. His fields of interest include pavement structure and highway geometric design, consistency of soil reinforcement, concrete pavement, finite elements analysis, fundamentals of geotechnical engineering and traffic performance analysis. He has published numerous refereed articles in professional journals/proceedings.

Abdulla Ebrahim El-Moher, M.sc, Civil Engineering Dept. Alazhar University, Nasr City, Egypt. He works at Arab Contractors Company.