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Durability of Hot Asphalt Mixtures Containing Reclaimed Asphalt Pavements

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Abstract

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. Now, flexible pavement, made of hot-mix asphalt (HMA) with the addition of the reclaimed asphalt pavement granules in the central asphalt mixing plant, is increasingly used. The amount of the added reclaimed asphalt pavement (RAP) depends on mineral materials and their homogeneity. This paper presents the physical properties of RAP and their influence on the durability performance of a binder asphalt pavement mix. A series of binder mixes containing varying percentages of RAP were designed and subjected to different moisture conditioning periods (1, 3 and 7 days) to investigate the moisture damage effect on RAP mixtures. A mix made from only virgin material was selected as the control mix. The effect of RAP on the durability of binder course mix was evaluated through a series of laboratory tests including Marshall test, indirect tensile strength test and the water sensitivity tests where many moisture damage indicators were obtained such as retained Marshall stability, Marshall quotient, durability index, tensile strength ratio, resilient modulus ratio and energy loss ratio. The results indicated that the additional of RAP especially at 50% content was beneficial in improving the durability performance and reducing the moisture susceptibility of the hot mix asphalt mixtures.

Keywords

Reclaimed Asphalt Pavement, Durability, Moisture Damage, Tensile Strength Ratio, Retained Marshall Stability, Energy Loss

Subject Areas: **Civil Engineering, Industrial Engineering**

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1. Introduction

Environmental factors such as temperature, air, and water can have a profound effect on the durability of asphalt concrete mixtures. In mild climatic conditions where good-quality aggregates and asphalt cement are available, the major contribution to the deterioration may be traffic loading, and the resultant distress manifests as fatigue cracking, rutting (permanent deformation), and raveling. However, when a severe climate is in question, these stresses increase with poor materials, under inadequate control, with traffic as well as with water which are key elements in the degradation of asphalt concrete pavements. Water causes loss of adhesion at the bitumen-aggregate interface. This premature failure of adhesion is commonly referred to as stripping in asphalt concrete pavements. The strength is impaired since the mixture ceases to act as a coherent structural unit. Loss of adhesion renders cohesive resistance of the interstitial bitumen body useless. Water may enter the interface through diffusion across bitumen films and access directly in partially coated aggregate. Water can cause stripping in five different mechanisms such as detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour [1] [2].

Asphalt paving mixtures are designed primarily for stability and durability [3]. The most serious consequence of stripping is loss of strength and integrity of the pavement. Stripping can take many surface forms during its progression. However, stripping in a particular area may be quite severe before any surface indicators are evident. Surface indicators may include rutting, shoving, and/or cracking. One of the major reasons for flexible pavement distress and the deterioration of highway serviceability is the low durability potential of the wearing and binder asphalt courses. The durability potential of bituminous mixtures may be defined as the resistance of the mixture to the continuous and combined damaging effects of water and temperatures. High durability potential usually implies that mechanical behavior of the mixture will endure for a long service life [4]. Long-term performance is an approximate synonym of durability, but there are several definitions of the word "durability" [5].

Durability: The safe performance of a structure or a portion of a structure for the designed life expectancy (ASTM recommended practice for increasing durability of building construction against water-induced damage (E241-77)).

Durability: The capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time (from ASTM recommended practice E632).

Serviceability: The capability of a building product, component, assembly or construction to perform the functions for which it is designed and constructed (from ASTM recommended practice E632).

1.1. Factors Affecting Moisture Susceptibility of Asphalt Pavement

Moisture damage in asphalt concrete pavement is affected by many factors [6].

a) The type of aggregate, both coarse and fine, must be examined carefully in evaluating the water damage of the mixture. Some aggregates such as granite, gravel and other siliceous type materials are sensitive to moisture and are prone to stripping when incorporated in asphalt concrete. Other aggregates such as limestone are less susceptible to moisture damage. In some cases, the majority of the stripping takes place in the coarse aggregate portion of the mixture. In some cases, the fine aggregate is more moisture sensitive and the most stripping occurs in that part of the mixture.

b) The second factor is the type of source of crude oil and refining process which is used to manufacture the asphalt cement. Most asphalt cements are relatively inert in regard to moisture damage. The asphalt cements, from one to another, do not show much difference in the degree of stripping. In other words, the source of asphalt cement is much less dominant than the type of aggregate.

c) The third factor is the asphalt concrete mixture properties. The air void level and the permeability of the mixture, which are influenced by the degree of compaction, asphalt cement and the aggregate gradation, are important since they control the level of water saturation and drainage. At high air void contents, above 6%, a given mixture can suffer a considerable degree of moisture damage. Exception is made for open graded mixtures where air void levels of 15% - 25% allow water to drain.

d) The asphalt film thickness has also an influence on the moisture susceptibility characteristics of HMA because it affects durability of the mixture. Thick films which are associated with black flexible mixtures are known to be durable. On the other hand, thin films which are associated with brownish, brittle mixtures tend to crack and ravel excessively, thus shortening the service life of the pavement. Mixtures with thick asphalt film are less susceptible to water damage than the mixtures with thin asphalt film since very little quantities of water can move through the mixture that contains thick asphalt film thicknesses.

e) Environmental conditions and traffic affect the amount of stripping which happens in a particular mixture. More moisture damage typically occurs in areas where there are considerable amount of rain and/or snowfall. Both the type of traffic and the volume are important variables. As the traffic becomes heavier and as the truck volume increases, the amount of stripping becomes greater.

1.2. Reclaimed Asphalt Pavement

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 10˚C 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 [7] [8]. 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-Ortiz *et al*. 2012 [9], 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 dated back to 1915 [10]. However, the actual development and rise of RAP usage occurred in the 1970's during the oil crisis. 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 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 [9] [11].

In the US, the Federal Highway Administration (FHWA) reported that 73 of the 91 million metric tons of asphalt pavement was removed each year during resurfacing and widening projects were reused as part of new roads, roadbeds, shoulders and embankments (FHWA 2002) [12]. 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) [13]. 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 [14]. 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 [15]. Recent researches [8] [11] [16] [17] 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 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 (Xiao *et al*., 2009, [18] and Sarsam and AL-Zubaidi, 2014, [19]) while some studies indicated that incorporating certain percentages of RAP there are no significant changes in the performance of mixes (Paul, 1996, [20]). 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 (Colbert and You, 2012, [21]) and some studies stated that resistance to moisture damage significantly decreases with presence of RAP (Huang, 2010, [22]). Some researchers found that presence of RAP increases the stiffness of the mix (Aravind and Das, 2006, [23] and AL-Zubaidi and Sarsam, 2014, [24]) and decreases according to some studies (Huang, 2010 [22]). Similarly fatigue life increases according to (Tabakovič *et al*., 2010, [25]) and decreases according to (Mohammed *et al*., 2003, [26]) and vary according to the temperature (Puttagunta *et al*., 1997, [27]). Tensile strength increases (Sarsam *et al*., 2014, [28]) or similar to virgin mixes (Katman *et al*., 2012, [29]). 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.

1.3. Problem Statement and Objectives

Maintenance of roads in Egypt costs annually high percentage of the total road construction costs or in other words, in the futures, the maintenance cost will have equaled the construction cost of new roads. Roads in Egypt usually show excessive failures of an early stage of pavement life. Some factors contributing to the early failures are excessively high temperature and humidity. On highways and urban roads, damaged spots can be seen after the seasonal rains, which may cause stripping due to the properties of local aggregates. Moreover, the severe water damage problems in Egypt are due to the high water table. The rising of the water table is accelerated due to its huge coastal locations on red and white seas as well as on the River Nile. Therefore, the road network is facing a lot of durability problems including stripping, raveling and pothole formation. On the other side, recently all worlds toward to use green asphalt and one of the important ways to use green asphalt are reclaimed asphalt pavement. For example, Egypt produces approximately 4 million tons per year of reclaimed asphalt pavement that are not used. The question now is, if these RAP materials had been recycled in the HMA mixtures, what is be the effect of moisture damage on the durability performance of asphalt mixtures, and what is the suitable percentage of RAP which can be used in the mix to get the maximum advantages. The answers for these questions are the primary goal of this research.

2. Research Methodology

Moisture damage in asphalt mixtures refers to loss in their strength and durability due to the presence of water. 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. In order to assess the moisture destruction in HMA mixtures containing RAP, the current study bears out an analytical approach based on experimental methodology depicted in **Figure 1**.

3. Experimental Program and Procedures

3.1. Materials

3.1.1. 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 2**. The properties of natural aggregates are given in **Table 1**.

3.1.2. 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.

3.1.3. 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 pavement was taken by milling road about five

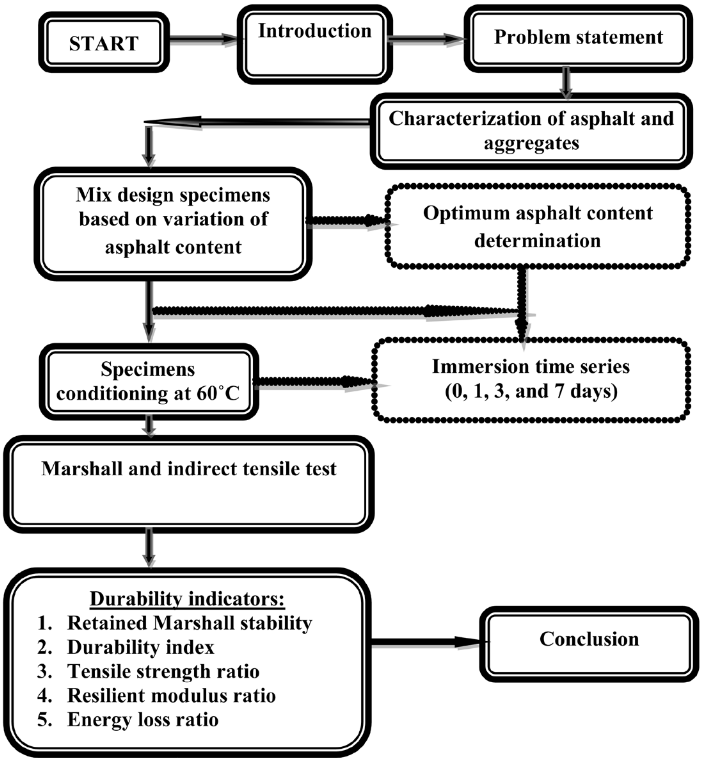

Figure 1. Research procedure flowchart.

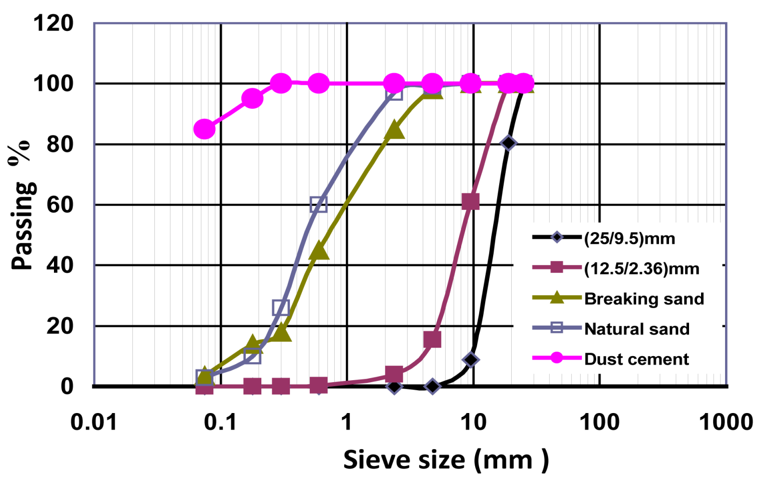

Figure 2. Grading for natural aggregates.

Table 1. Physical and mechanical properties of natural aggregates.

Description	Value	
	(25/9.5) mm	(12.5/2.36) mm
Volume weight	1.43 t/m^3	1.45 t/m^3
Specific gravity	2.56	2.54
% Absorption	1.88	1.94
Crushing factor	21.0%	22.0%

Table 2. Physical properties of asphalt.

Test	Specification	Results	Specification limits
Penetration (25˚C, 0.1 mm)	ASTM D5 EN 1426	63	60 - 70
Softening point (˚C)	ASTM D36 EN 1427	50	46 - 54
Viscosity at (135˚C)-pas	ASTM D4 402	0.51	-
Change of mass (%)	ASTM D1754	0.07	0.5 (max)
Retained penetration (%)	ASTM D5 EN 1426	51	50 (min)
Ductility (25˚C)-cm	ASTM D113	117	-
Specific gravity	ASTM D70	1.03	-
Flash point (˚C)	ASTM D92 EN 2592	+260	230 (min)

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 3**.

3.2. 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 mm/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 4**.

3.3. Laboratory Tests

3.3.1. 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) [20]:

$$RMS = 100\left(MS_{cond} / MS_{uncond}\right) \tag{1}$$

where RMS is the retained Marshall stability, MS_{cond} is the average Marshall stability for conditioned specimens (kN) and MS_{uncond} 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.

3.3.2. 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 [2] [5] [30]. 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˚C ± 1˚C for different treatment periods (1, 3 and 7 days) and then placing in water bath at 25˚C for 2 hour.

Figure 3. Specimen of the recycling asphalt pavement.

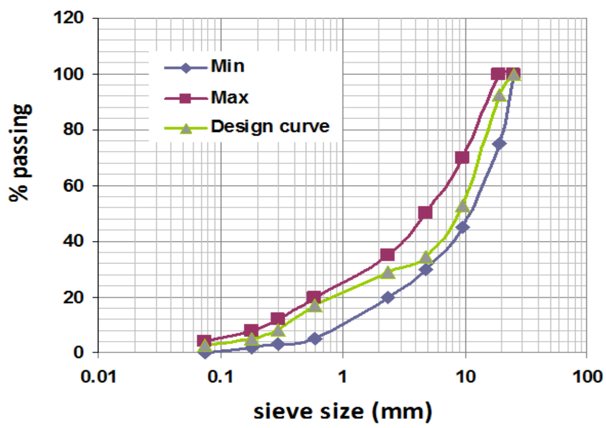

Figure 4. Mix design of asphalt binder course (3d).

3.3.3. Indirect Tensile Strength Test

The stripping resistance of asphalt mixtures is evaluated by the decrease in the loss of the indirect tensile strength (ITS). 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):

$$\boldsymbol{ITS} = \frac{\boldsymbol{2P}}{\boldsymbol{\pi HD}}\,\mathbf{N/mm^2}\ ITS = \frac{2000\times P}{\pi\times H\times D} \tag{2}$$

where *ITS* is the indirect tensile strength (kPa); *P* is 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).

$$RMS = 100\left(MS_{cond}/MS_{uncond}\right) \tag{3}$$

where ITS_{cond} is the average indirect tensile strength of conditioned specimen while ITS_{uncond} is the average indirect tensile strength of dry (unconditioned) specimen.

3.3.4. Durability Index (DI)

Durability index is the method to predict and control moisture damage in asphalt mixtures, whereas the evaluation of moisture damage in asphalt mixture is based on the ratio of mechanical properties of wet condition to the value of unconditioning specimens. Specifically, the term durability as used in this research is the asphalt mixture ability to resist breaking down on the water immersion. In this research, the use of the ratio of retained Marshall stability is analyzed to develop a method of predicting and controlling moisture damage in asphalt mixtures. Durability index (DI) is defined as the average strength loss area enclosed between the durability curves and it is calculated according to the following Equation (4).

$$\mathrm{DI} = \left(\frac{1}{2tn}\right)\sum_{t=0}^{n-1}\left(s_i - s_{i+1}\right)*\left[2tn - \left(t_{i+1} - t\right)\right] \tag{4}$$

where s_{i+1} is percent retained strength at time t_{i+1}; s_i is percent retained strength at time t_i; t_i, t_{i+1} is immersion time calculated from beginning of test.

4. Results and Discussion

4.1. Marshall Test Results

After obtaining the optimum asphalt content for each percentage of RAP, Marshall specimens of 4 inch diameter and 2.5 inch depth were prepared again according to Marshall method of mix design (ASTM D1559). Specimens tested for Marshall stability and flow after being soaked in hot water for 0, 1, 3 and 7 days at 60˚C. As shown in **Table 3**, the Marshall stability for all RAP mixtures decreases and the flow increases by increasing the immersion period. Moreover, with increasing RAP ratio up to 75%, the Marshall stability slightly decreases more than control mixture, while increases obviously at 100% RAP ratio. For Marshall flow, the RAP percent-

Table 3. Effect of conditioning on Marshall stability and flow.

RAP (%)	Condition period (days)	Stability (kg)	Flow (mm)
0%	0	1279.86	3.76
	1	973.462	3.9
	3	817.70	4.4
	7	773.93	5
25%	0	1088.66	3.26
	1	837.833	3.5
	3	701.42	3.9
	7	664.84	4.2
50%	0	1036.99	2.8
	1	829.385	3
	3	708.99	3.6
	7	650.089	5.5
75%	0	990.216	2.6
	1	731.17	3.2
	3	614.72	4.1
	7	560.85	5
100%	0	1399.57	3.3
	1	1016.37	4.2
	3	815.949	4.9
	7	767.804	5.5

tages has not obvious effect on it. This result may be due to the water that can damage the structural integrity of the asphalt aggregate interface and the less adhesive forces caused by the increase in the viscosity of the asphalt concrete to reach the bad workable and compaction condition. The mechanisms are generally starting with the water that can cause the loss of cohesion (strength) and stiffness of the asphalt; secondly, the water attacks the adhesive bond between the asphalt and the aggregate in the mixture (stripping). This result agrees with [14] [18] [22] [25].

4.1.1. Effect of Stripping on Marshall Quotient

As shown in **Figure 5**, the Marshall quotient (stiffness) decreases by the increase of immersion period. The RAP content in HMA mixtures has a slight effect on the Marshall quotient. This influence may be due to the decrease of workability, which decreases the asphalt coating of the aggregate grains and the filling of the micro pores with asphalt; and thus the density of the mixture are decreased which allows the flows to be increased.

Table 4 shows the effect of stripping on the variation ratio of stiffness for all mixtures. It can be noticed that, after immersing period for one day, the mixture containing 50% RAP achieves the minimum loss of Marshall quotient where this variation is less than it for the control mix by about 4.9%. After immersion periods of 3 and 7 days, the minimum stiffness losses are obtained at control mixture and 25% RAP mixture respectively.

4.1.2. Retained Marshall Stability

The 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 6** shows the relationship between immersion periods of RAP mixtures and RMS values. 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

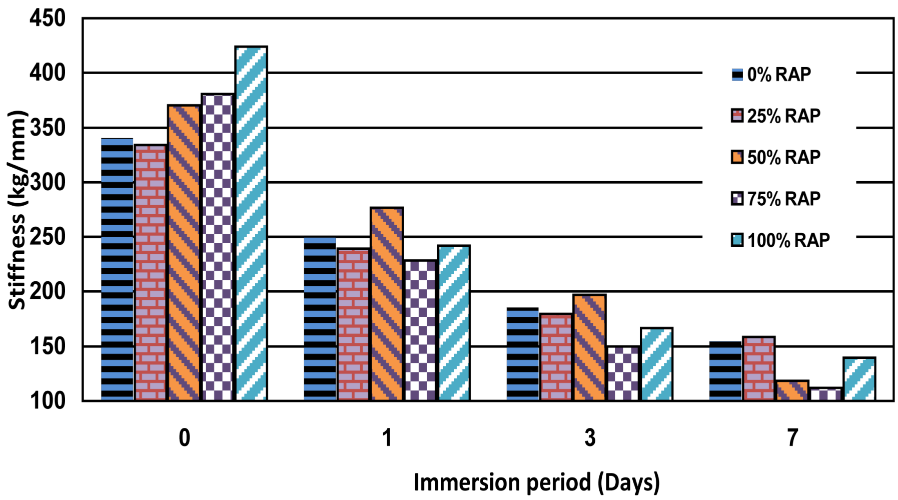

Figure 5. Effect of immersion time on Marshall quotient.

Table 4. Effect of conditioning on the ratio of mixtures stiffness loss.

Conditioning periods (days)	RAP content (%)				
	0	25	50	75	100
1	26.66	28.31	25.35	40	42.94
3	45.40	46.14	46.82	60.63	60.73
7	54.52	52.60	68.08	70.54	67.08

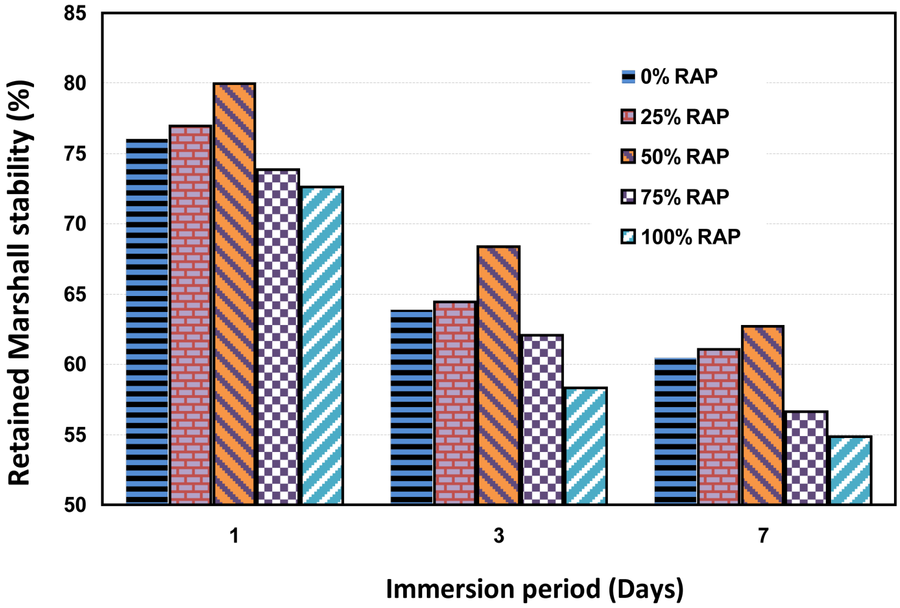

Figure 6. Retained Marshall stability of RAP mixtures.

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.

4.1.3. Durability Index (DI)

The durability values are taken from the retained Marshall stability at 0.0% to 100% RAP content and drawn as shown in the **Figures 7-11**. The durability index was calculated according to Equation (4) for each RAP content and illustrated in **Table 5**.

Table 5 shows that the mixtures containing RAP contents of 75% and 100% obtain higher total durability index values (34.24% and 36.62% respectively) compared with control mixtures. Thus it can be concluded that the mixture containing 50% RAP is the best mixture to endure for a long service life and the mixture containing 100% RAP is the worst mixture to resistance moisture damage.

4.2. Indirect Tensile Strength Test Results

The indirect tensile (ITS) test measures the change in tensile strength value resulted after saturation and accelerating water conditioning of compacted HMA in the laboratory. The results used to predict long-term stripping susceptibility of bituminous mixtures. **Figure 12** shows the RAP mixtures that tested in tensile strength equipment before and after the conditioning period of 7 days. **Figure 13** illustrates the effect of immersion period on ITS values where it can be noticed that, after immersion periods of 1, 3 and 7 days, the mixtures containing 50%, 75% and 100% RAP obviously provide higher ITS compared with the control mixture. Thus it can be concluded that the RAP addition by 50% to HMA mixtures provides the maximum improvement in tensile strength after all studied conditioning periods.

4.2.1. 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 Xiao *et al.* 2009 [18], 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 14** illustrates tensile

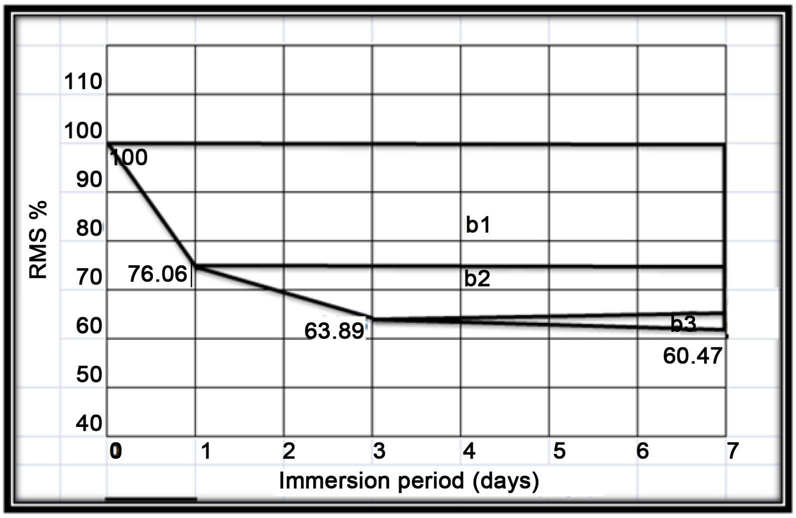

Figure 7. Durability index curve at 0% RAP.

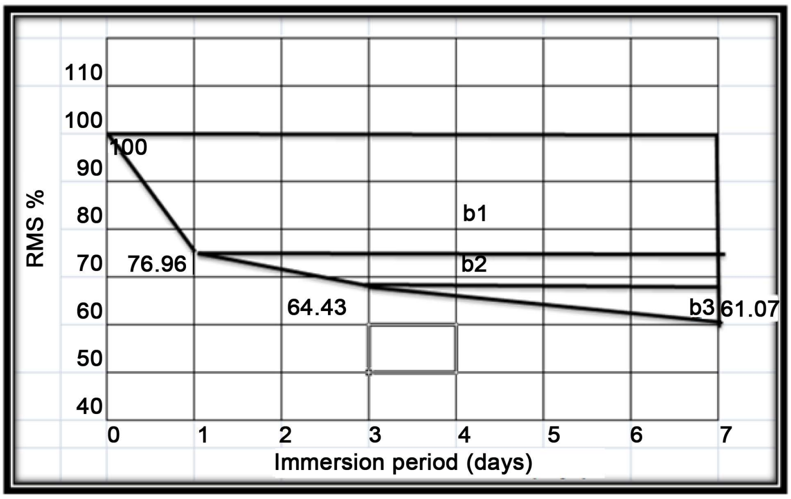

Figure 8. Durability index curve at 25% RAP.

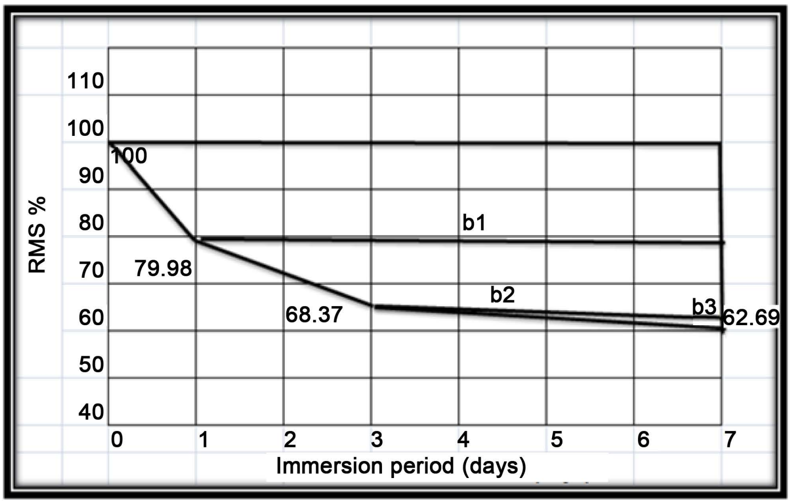

Figure 9. Durability index curve at 50% RAP.

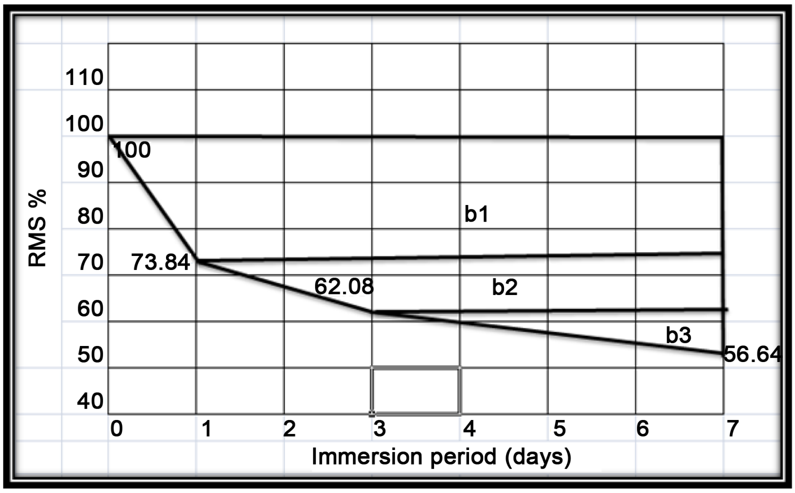

Figure 10. Durability index curve at 75% RAP.

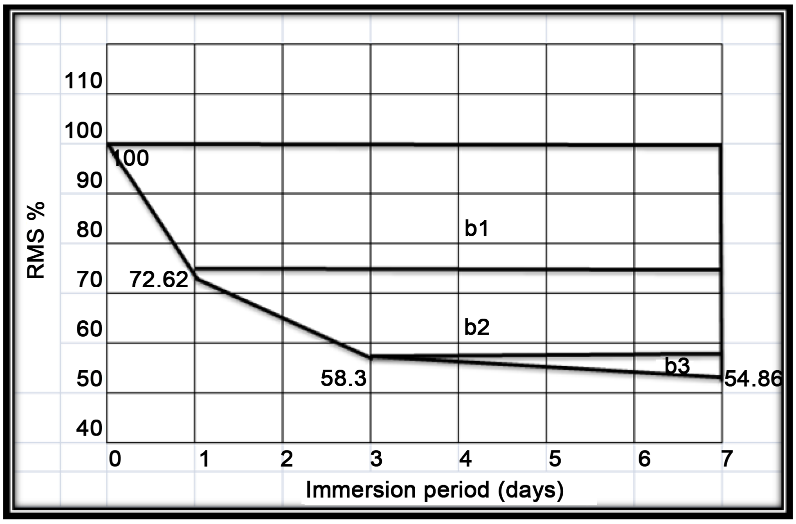

Figure 11. Durability index curve at 100% RAP.

Figure 12. Effect of stripping on RAP mixtures after ITS test.

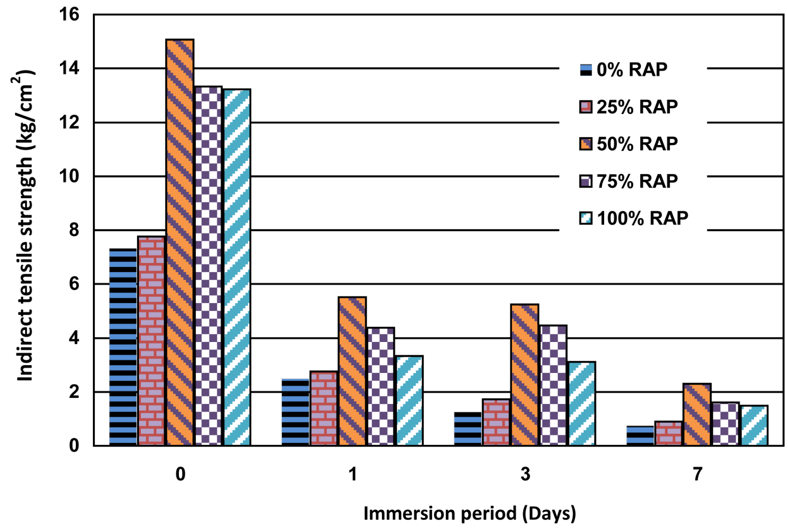

Figure 13. Effect of conditioning on indirect tensile strength.

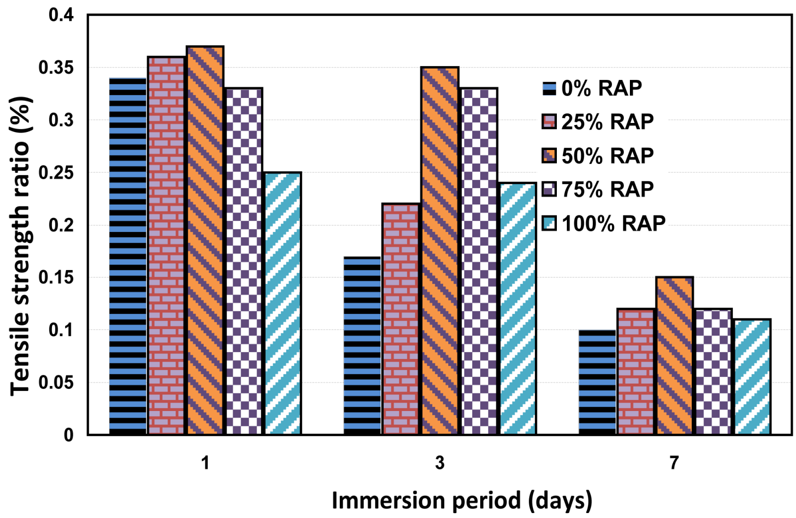

Figure 14. Tensile strength ratio of RAP mixtures.

Table 5. Durability index values for RAP mixtures.

Area code	Immersion periods (days)	(RAP) Variations				
		0%	25%	50%	75%	100%
b1	0 to 1	22.23	21.39	18.59	24.29	25.42
b2	1 to 3	8.69	8.95	8.29	8.4	10.22
b3	3 to 7	0.977	0.96	1.62	1.55	0.98
	Total durability index (%)	31.90%	31.30%	28.5%	34.24%	36.62%

strength ratio for both control and RAP mixtures. 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 enhance the moisture susceptibility for all studied conditioning periods.

4.2.2. Resilient Modulus Ratio

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. 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 (5) [29]:

$$Mr = p\frac{\mu + 0.2732}{h\delta} \quad \boldsymbol{M_R} = \frac{\boldsymbol{p(0.27+\nu)}}{\boldsymbol{\Delta \mathrm{Ut}}} \tag{5}$$

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 resilient modulus is considered as a qualitative test to estimates the severity of moisture damage, whereas a quantitative test measures a strength parameter. The ratio of Mr of conditioned mixture to Mr of dry mixture, stated as the resilient modulus ratio. The results of ITS which are average of three samples are shown in **Figure 15** which illustrates that the mixtures containing 50%, 75% and 100% RAP provide obviously higher increase in resilient modulus compared with control mix. Moreover, the condoning periods (from 1 to 7 days) have a great and approximate similar influence on reducing the resilient modulus values. The highest Mr value is achieved at 100% RAP content for dry mixtures while the maximum value is obtained at 50% and 75% RAP contents for wet mixtures. From **Figure 16**, it can be observed that the adding of RAP to HMA improves the moisture damage resistance

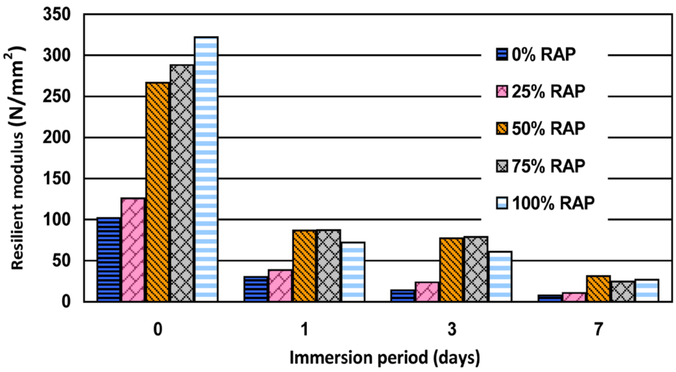

Figure 15. Resilient modulus of RAP mixtures.

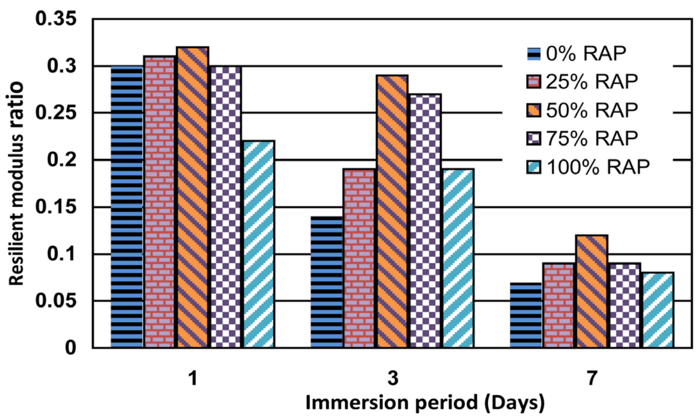

Figure 16. Resilient modulus ratio.

by increasing resilient modulus ratio at all studied condoning periods. The best RAP ratio that provides the maximum stripping resistance at all immersion periods is 50% where the maximum resilient modulus ratio is achieved. This result agrees to the results of retained Marshall stability, durability index and tensile strength ratio.

4.2.3. Absorbed Energy Ratio

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 (6) was used to calculate the absorbed energy at failure for specimens containing various percentages of RAP based on the indirect tensile strength test.

$$E = 0.5Pd/t \tag{6}$$

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 17** shows that at RAP content (≥50%), the mixtures provide higher absorbed energy compared with control mixtures where the absorbed energy increases by increasing RAP content in dry mixtures while the highest absorbed energy value is achieved at 50% RAP content in conditioned mixtures for all periods. For dry mixtures, the highest absorbed energy value is achieved at 100% RAP content. All results are average of three samples.

Energy loss ratio is proposed as an indicator of the effects of moisture damage on the fracture resistance of asphalt mixtures which calculated as the ratio of absorbed energy of conditioned mixture to absorbed energy of dry mixture. From **Figure 18**, it can be noticed that the maximum energy loss ratio after 1, 3 and 7 days is achieved at 50% RAP content whereas the mixtures containing 75 and 100% RAP contents provide energy loss ratio less than the control mix after 1 and 7 conditioning days. It means that the mixture containing 50% is the best mixture for fracture moisture damage resistance of asphalt mixtures. This result agrees to the results of retained Marshall stability, durability index, tensile strength ratio and resilient modulus ratio.

5. Conclusions

Many highways in Egypt have been exposing to premature failures that decrease the performance and service life of pavements. Many surface deterioration indicators in flexible pavement may be occurred including rutting, shoving, and/or cracking. One of the major reasons for flexible pavement distress and the deterioration of highway serviceability is the low durability potential of the wearing and binder asphalt courses. The durability potential of bituminous mixtures may be defined as the resistance of the mixture to the continuous and combined damaging effects of water and temperatures. The reclaimed asphalt pavement (RAP) is one of the most recycled

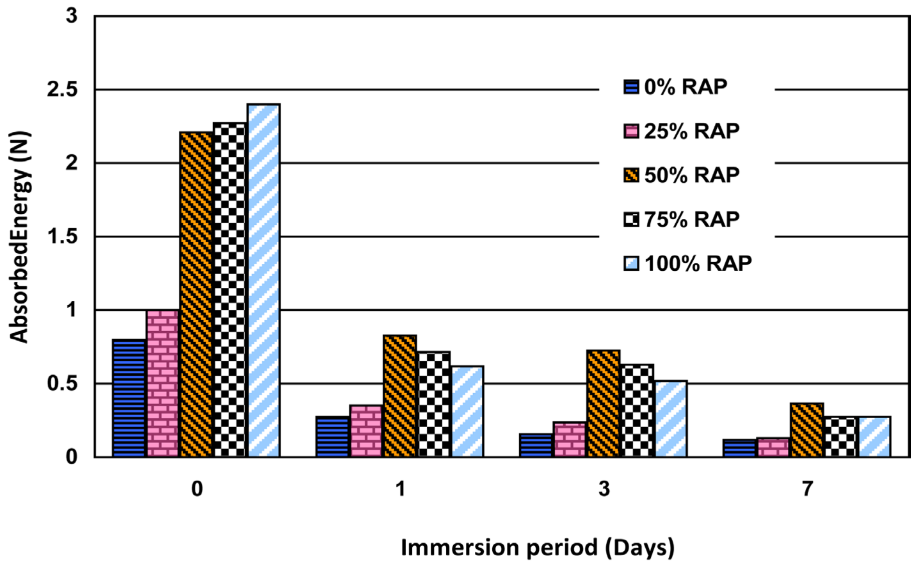

Figure 17. Absorbed energy after different immersion periods.

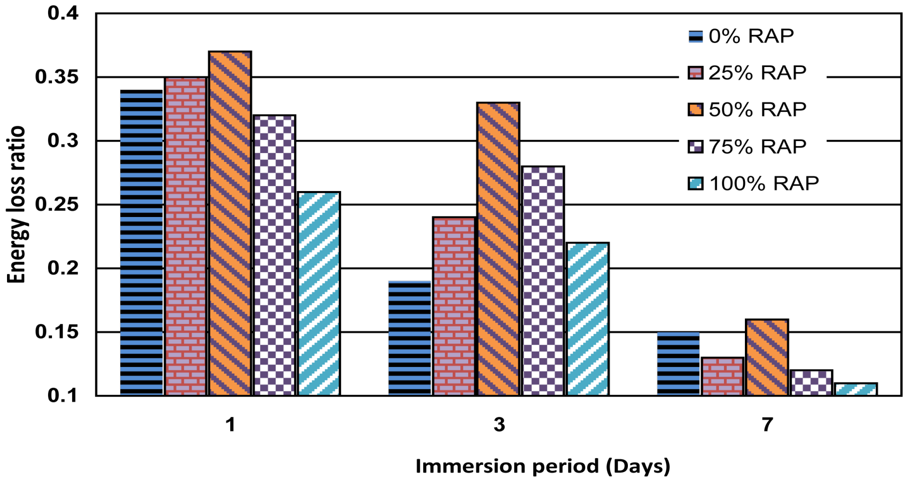

Figure 18. Absorbed energy ratio of RAP mixtures.

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 durability of HMA mixtures. Based on the laboratory test results, the following conclusions were drawn:

1. There was a significant effect on Marshall stability after adding RAP to asphalt mixtures 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 for Marshall flow, the RAP percentages had not obvious effect on it. After immersing period for one day, the mixture containing 50% RAP achieved the minimum loss of Marshall quotient (mixture stiffness) where this variation was less than it for the control mix by about 4.9%. After immersion periods of 3 and 7 days, the minimum stiffness losses were obtained at control mixture and 25% RAP mixture respectively.

2. The mixtures containing RAP contents of 75% and 100% obtained higher total durability index values (34.24% and 36.62% respectively) compared with control mixtures. While mixtures of 25 and 50% RAP content achieved lower durability index (31.30% and 28.5% respectively). The mixture containing 50% RAP was the best mixture to endure for a long service life.

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. The tensile strength ratio of conditioned HMA was improved for all RAP mixtures compared with control mixture. The highest TSR was obtained at 50% RAP ratio, thus the adding of 50% RAP to the mixture could enhance the moisture susceptibility for all studied conditioning periods.

4. The mixtures containing 50%, 75% and 100% RAP provided higher increase in resilient modulus compared with control mix where the highest value was achieved at 100% RAP content for dry mixtures while at 50% and 75% RAP contents for wet mixtures. The adding of RAP improved the moisture damage resistance of HMA by increasing resilient modulus ratio at all studied condoning periods. The best RAP ratio that provided the maximum stripping resistance was 50%.

5. At RAP content (≥50%), the mixtures provided higher absorbed energy compared with control mixtures where the absorbed energy increased by increasing RAP content in dry mixtures while the highest absorbed energy value was achieved at 50% RAP content in conditioned mixtures. The maximum energy loss ratio after conditioning periods of 1, 3 and 7 days was achieved at 50% RAP content whereas the mixtures containing 75 and 100% RAP contents provided energy loss ratio less than the control mix after 1 and 7 days.

6. The mixture containing 50% RAP content provided the best durability indicators for all studied conditioning periods such as retained Marshall stability, durability index, tensile strength ratio, resilient modulus ratio and fracture moisture damage resistance.

7. 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, durability performance and stripping resistance of HMA.

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