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# Characterization of Recycled Asphalt Pavement (RAP) for Use in Flexible Pavement

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**Abstract:** Due to economical reasons and the need for environmental conservatism, there has been an increasing shift towards the use of Recycled Asphalt Pavement (RAP) materials in the pavement construction industry. 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. 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 main objective of this paper is to investigate the use of a homogeneity reclaimed asphalt pavement in the pavement industry evaluating the effects of partial and total replacements of aggregates by RAP on the mechanical and durability performance of dense-graded HMA mixtures. The performance of RAP mixtures was evaluated through a series of laboratory tests including Marshall test, indirect tensile strength test, granule adhesion test and material test systems. 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. 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 where they minimized the environmental impacts through the reduction of energy consumption, improved the mechanical properties, durability performance and also stripping resistance.

**Keywords:** Recycled Asphalt Pavement, Mechanical Properties, Durability Performance, Tensile Strength, Material Test Systems

## Introduction

The heating of bituminous binder, aggregates and production of huge quantities of Hot Mix Asphalt (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 (Pradyumna *et al*., 2013; Vislavicius and Sivilevicius, 2013). 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), 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. 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 (Chen *et al*., 2009).

## Environmental Factors Affecting on HMA Performance

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 (Gorkem and Sengoz, 2009).

Asphalt paving mixtures are designed primarily for stability and durability (Ibrahim *et al*., 1998). 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 (Kanitpong and Bahia, 2006). Long-term performance is approximate synonym of durability, but there are several definitions of the word “durability”. Tow definitions of durability and a definition of a related concept, serviceability, which appear in standards prepared by ASTM committee E-6 on performance of building construction are (Nejad *et al*., 2012).

### *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).

## Recycled Asphalt Pavement

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). 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). 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 (Miro *et al*., 2011). 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 (Mengqi *et al*., 2012). Recent researches

(Celauro *et al*., 2010; Shirodkar *et al*., 2011) 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 and Amirkhanian, 2009; Sarsam and AL-Zubaidi 2014a) while some studies indicated that incorporating certain percentages of RAP there are no significant changes in the performance of mixes (Paul, 1996). 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 ) and some studies stated that resistance to moisture damage significantly decreases with presence of RAP (Huang *et al*., 2011). Some researchers found that presence of RAP increases the stiffness of the mix (Aravind and Das, 2006; AL-Zubaidi and Sarsam, 2014) and decreases according to some studies (Huang *et al*., 2011). Similarly fatigue life increases according to (Tabakovic *et al*., 2010) and decreases according to (Mohammed *et al*., 2003) and vary according to the temperature (Puttagunta *et al*., 1997). Tensile strength increases (Sarsam *and* AL-Janabi 2014b) or similar to virgin mixes (Katman *et al*., 2012). 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.

## Problem Statement and Objectives

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 this process on the mechanical and 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.

## Experimental Program and Procedures

### *Materials*

### *Natural Aggregates*

Coarse aggregates (25/9.5 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 Fig. 1. The properties of natural aggregates are given in Table 1.

### *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 according to ASTM specifications.

### *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 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 Fig. 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 (12.5mm/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 and 100% were designed based on Egyptian binder course (3d) specifications as shown in Fig. 3.

Table 1. Physical and mechanical properties of natural aggregates

| Description | Value (25/9.5) mm | Value (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 | Results | Specification limits |
|---|---|---|
| Penetration (25°C, 0.1 mm) | 63.00 | 60-70 |
| Softening point (°C) | 50.00 | 46-54 |
| Viscosity at (135°C)- pas | 0.51 | - |
| Change of mass (%) | 0.07 | 0.5(max) |
| Retained penetration (%) | 51.00 | 50 (min) |
| Ductility (25°C)- cm | 117.00 | - |
| Specific gravity | 1.03 | - |
| Flash point (°C) | +260.00 | 230 (min) |

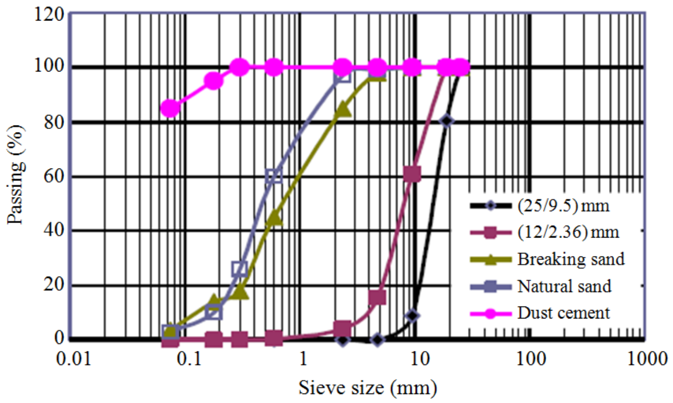


Fig.1. Grading for natural aggregates

Fig. 2. Specimen of the recycling asphalt pavement

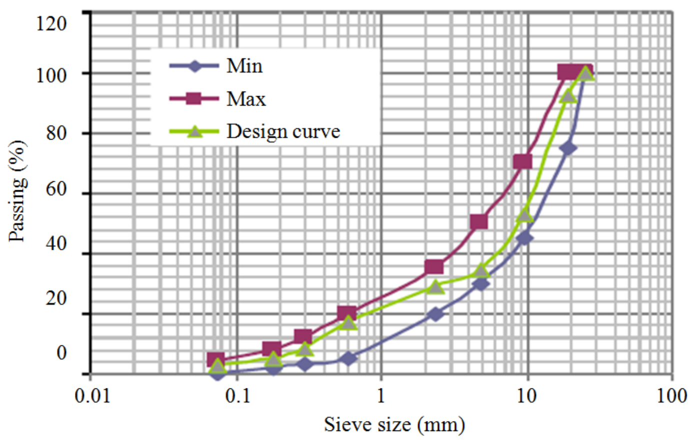


Fig. 3. Mix design of asphalt binder course (3d)

## Laboratory Tests

### *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 Equation 1 (Paul, 1996):

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

Where:

$RMS$ = The retained Marshall stability
$MS_{condis}$ = The average Marshall stability for conditioned specimens (kN)
$MS_{uncondis}$ = The average Marshall stability for unconditioned specimens (kN)

The index of retained stability can be used to measure the moisture susceptibility of the mix being tested.

### *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 (Ozen, 2011; Nejad *et al*., 2012). 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 h.

### *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:

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

Where:

$ITS$ = the indirect tensile strength (kPa)
$P$ = the maximum load to failure (N)
$h$ = the specimen thickness (mm)
$D$ = 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:

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

Where:

$IT_{Scondis}$ = The average indirect tensile strength of conditioned specimen
$IT_{Suncondis}$ = The average indirect tensile strength of dry (unconditioned) specimen

### *Granule Adhesion Test*

This test is intended to evaluate the abrasion resistance of the surface of the detectable warning/directional surface. The results of the test are used to determine how well the HMA sample retains its shape over its useful service life.

Fig. 4. Adhesion testing machine


Fig. 5. Five samples of adhesion testing machine

Fig. 6. Material test systems machine

The test machine is shown in Fig. 4. Five samples, for five RAP percentages, of approximately (200*50*50) mm dimensions as shown in Fig. 5 were prepared for this test. The test was performed according to ASTM D 4977. Each sample was placed under a wire brush weighted with 25 lb. The brush was then cycled 50 times back and forth across the surface. This creates surface wear which was measured to determine the level of abrasion resistance based on weight of the sample.

### *Material Test Systems (MTS)*

The material testing systems machine, that shown in Fig. 6, delivers a broad array of testing capabilities for both low and high force static and dynamic testing. By selecting from a variety of force capacities, servo valve flow ratings, pump capacities, software and accessories, the floor-standing 810 system can easily be configured to meet a specific material or component testing needs such as (tension, bend, durability, high cycle fatigue, low cycle fatigue compression, creep, fatigue crack growth, fracture toughness). In this study, the material testing systems machine was used to achieve a relationship between the axial load and corresponding axial displacement to evaluate the behavior of RAP mixtures under axial loads.

## Results and Discussion

### *Marshall Test Results*

The mechanical properties include stability; flow and Marshall Quotient are shown in Fig. 7-9 where the Marshall mix design of HMA containing RAP and the corresponding Optimum Binder Content (OBC) are illustrated. OBC for each RAP mixture are 4.5, 4.58, 4.13, 4.5 and 5.5% for RAP contents 0.0, 25, 50, 75 and 100% respectively. 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%.

The results shown in Fig. 7, 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 as shown in Fig. 8, 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. As shown in Fig. 9, 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 Fig. 10 to 12. 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.

### *Effect of Moisture Damage on Marshall Quotient*

As shown in Fig. 13, 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 3 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.

### *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 14 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 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.

### *Indirect Tensile Strength Test Results*

The results of Indirect Tensile Strength (ITS) of dry HMA mixtures for each RAP ratio are shown in Fig. 15.

Table 3. 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 | 40.00 | 42.94 |
| 3 | 45.40 | 46.14 | 46.82 | 60.63 | 60.73 |
| 7 | 54.52 | 52.60 | 68.08 | 70.54 | 67.08 |

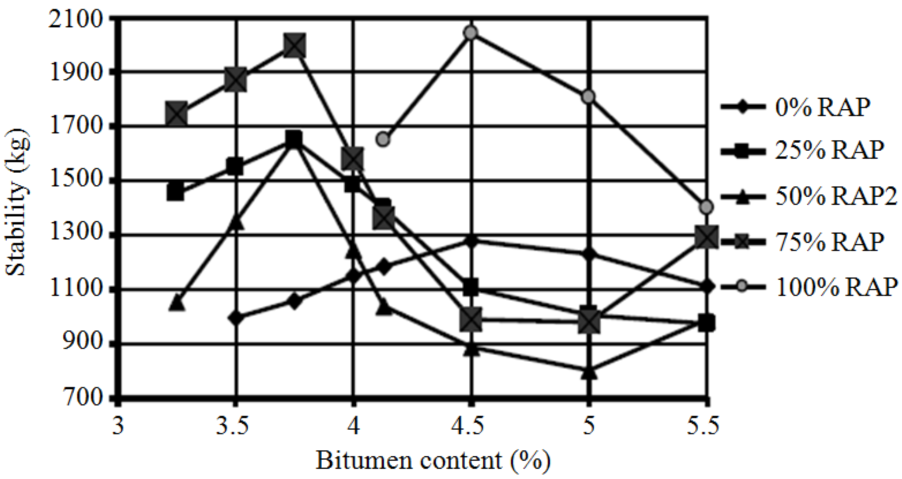


Fig. 7. Stability with different bitumen contents

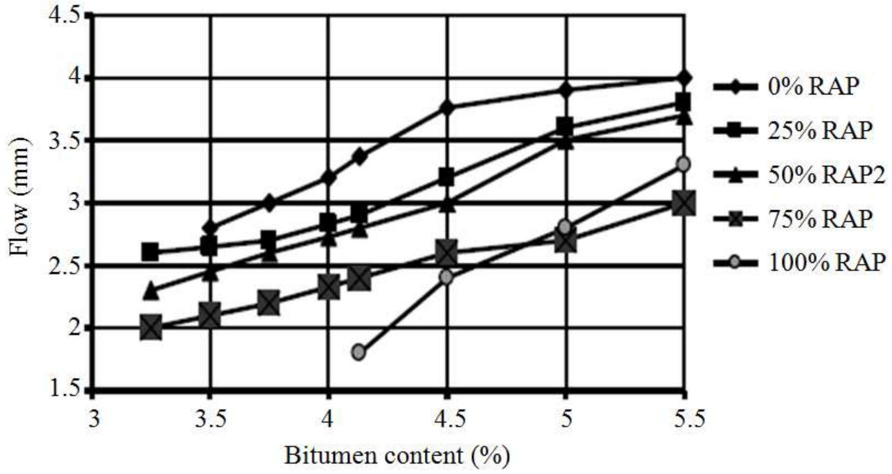


Fig. 8. Flow with different bitumen contents

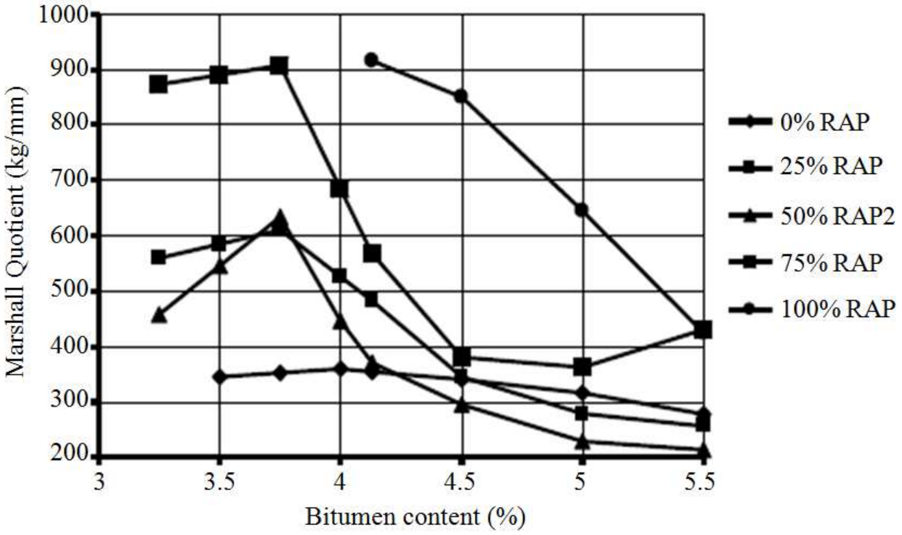


Fig. 9. Marshall Quotient with different bitumen contents

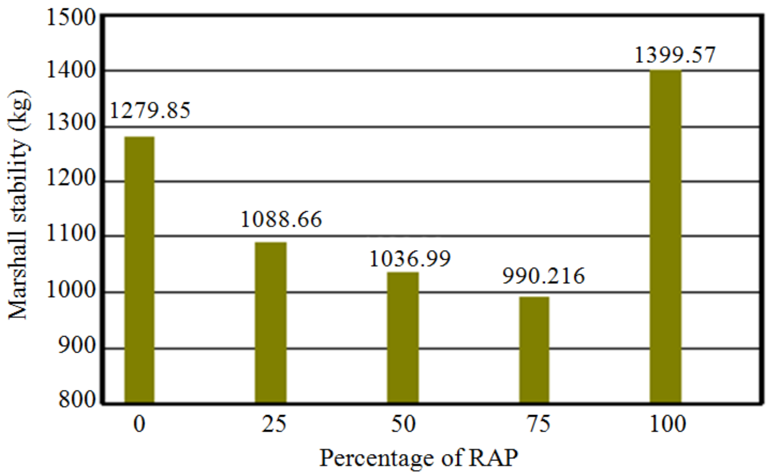


Fig.10. Stability values at the optimum bitumen content

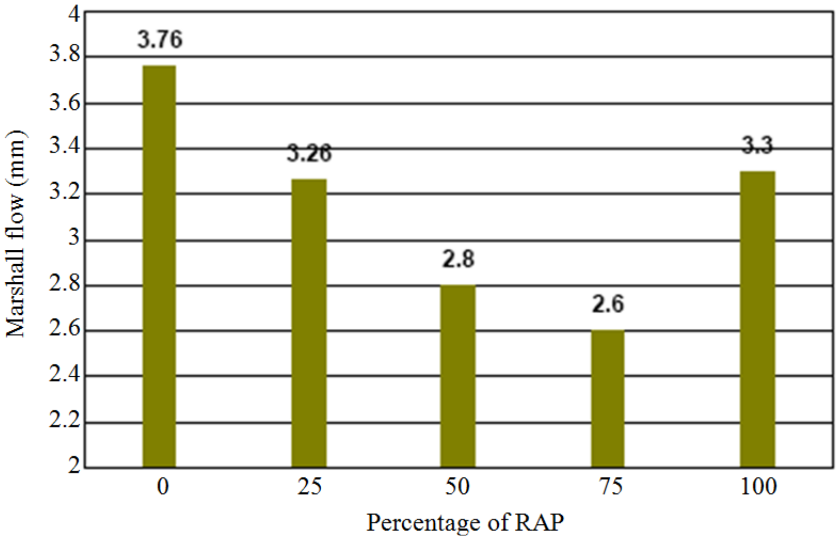


Fig. 11. Flow values at the optimum bitumen content

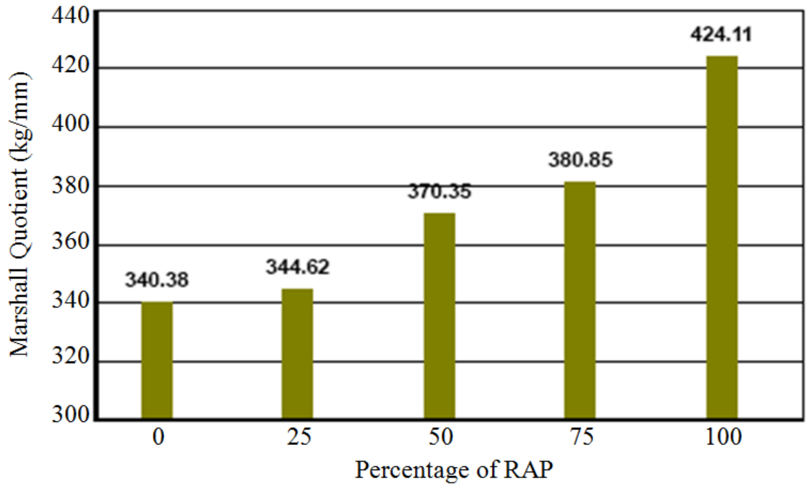


Fig. 12. Marshall Quotient values at the optimum bitumen content

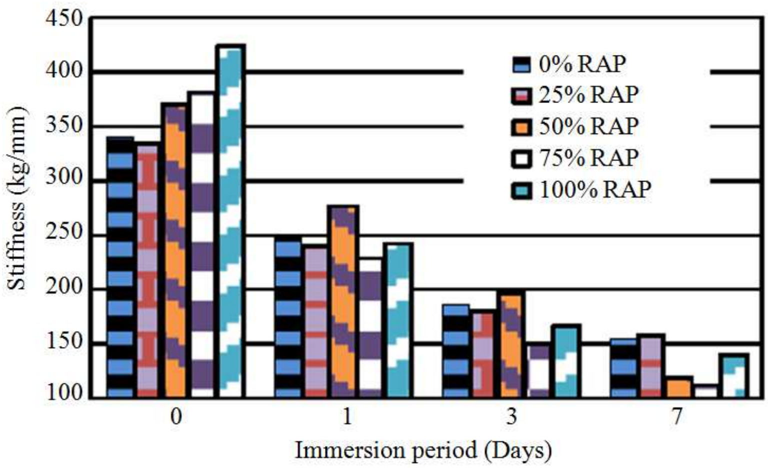


Fig. 13. Effect of immersion time on Marshall Quotient

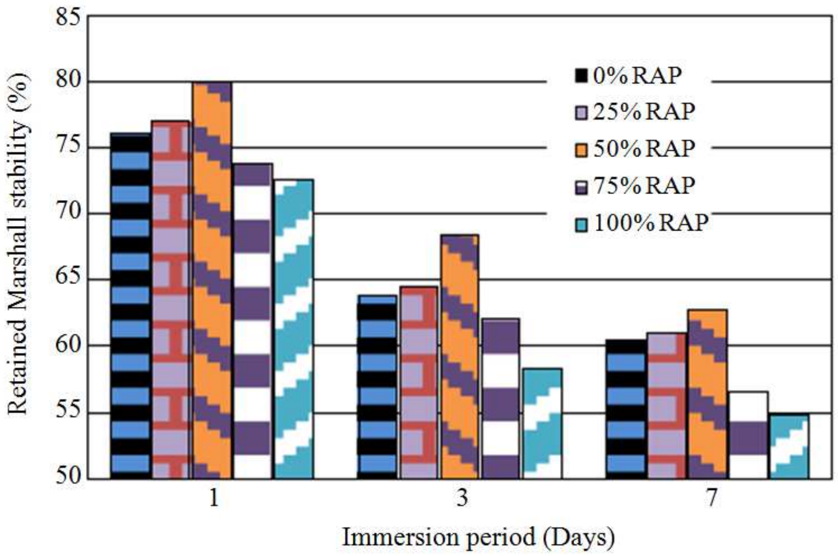


Fig.14. Retained Marshall stability of RAP mixtures

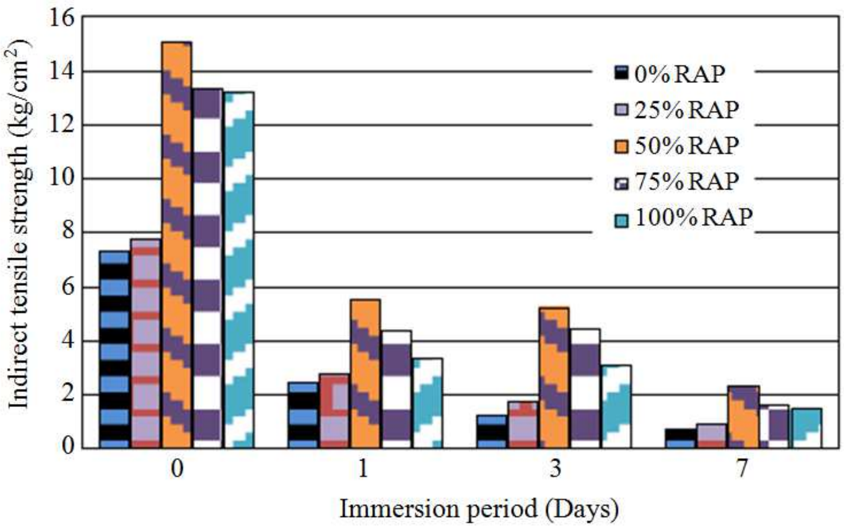


Fig. 15. Tensile strength for dry and conditioned mixtures

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.

### *Effect of Stripping on Indirect Tensile Strength*

The indirect tensile 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 15 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.

### *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 and Amirkhanian, 2009) 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 16 illustrates tensile strength ratio for both control and RAP mixtures. It can be illustrated that only mixtures containing 25 and 50% RAP provide the highest 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.

### *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. 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 (Katman *et al*., 2012):

$$Mr = P\frac{\mu + 0.2732}{h\delta} \quad (4)$$

Where:

$Mr$ = the modulus of resilience (MPa)
$P$ = the maximum load applied (N)
$h$ = sample thickness (mm)
$\delta$ = recoverable horizontal deformation (mm)
$\mu$ = the Poisson's ratio (assumed as 0.35)

The resilient modulus is considered 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 Fig. 17 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.

### *Granule Adhesion Test Results*

From Fig. 18, it can be obtained that the presence of RAP in HMA mixtures increases the adhesive bond strength of particle which leads to decreasing the percent of weight loss. The lowest percent weight loss is achieved at 100% RAP content where it is lower than the percent loss of control mix by about 76.53%. For HMA mixtures containing 25, 50 and 75% RAP content, the weight losses are lower that the weight loss of control mixture by 16.24, 32.85, 52.71% respectively. This result indicates that the mixtures containing RAP provides well performance over its useful service life compared with the control mixture.

### *Material Test Systems*

Samples of HMA containing RAP were placed in Material Test System (MTS) as shown in Fig. 19. Figure 20 from (a) to (e) illustrates the relationship between the effective load and corresponding axial displacement for RAP mixtures with content from 0.0 to 100% respectively.

From Fig. 20, it can be noticed that the maximum failure loads or the mixture capacities are about 25, 27.5, 34, 11 and 17.5 kN with corresponding axial displacements about 1.8, 2, 2.2, 1.8 and 3 mm for 0.0, 25, 50, 57 and 100% RAP respectively. Thus, the mixture of 50% RAP achieves the maximum capacity while 75% RAP mixture provides the lowest failure load.

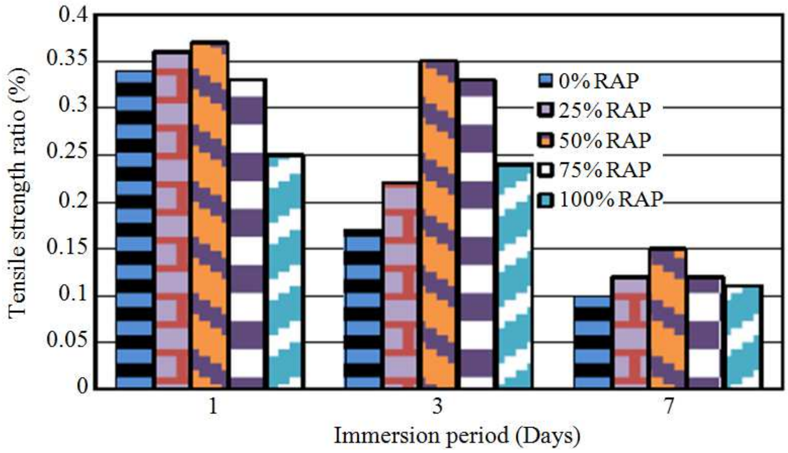


Fig. 16. Tensile strength ratio of RAP mixtures

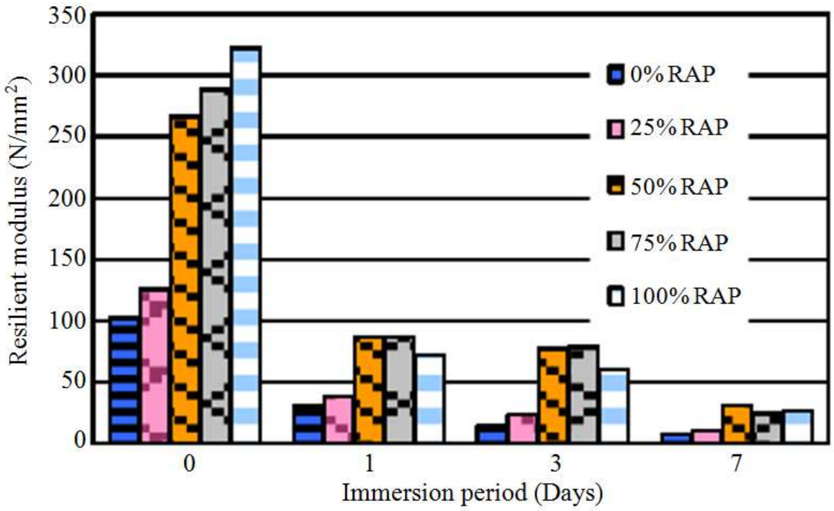


Fig. 17. Resilient modulus of RAP mixtures

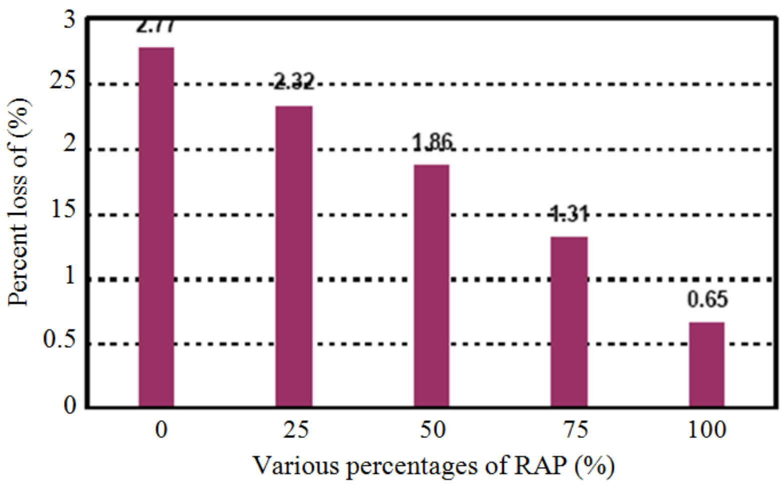


Fig. 18. Percent loss of weight for all of RAP mixtures

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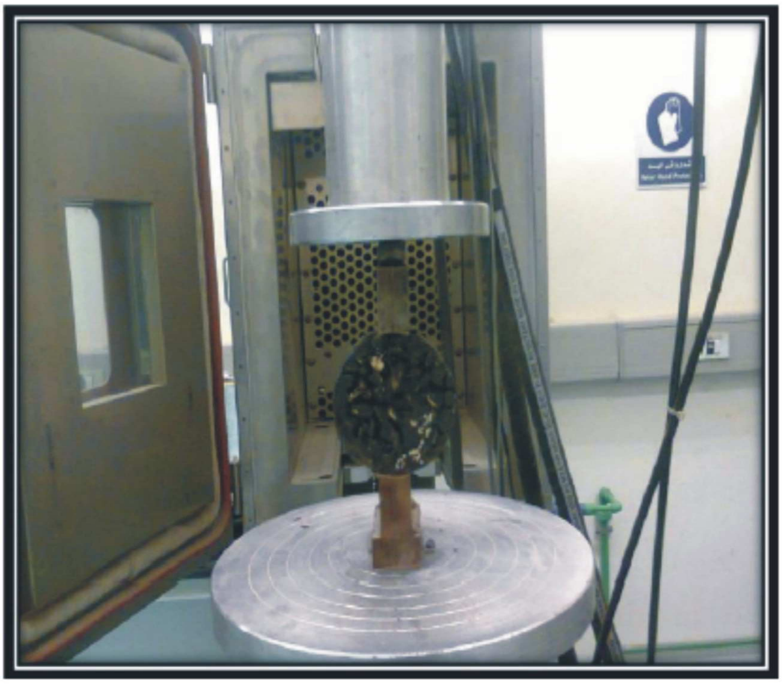
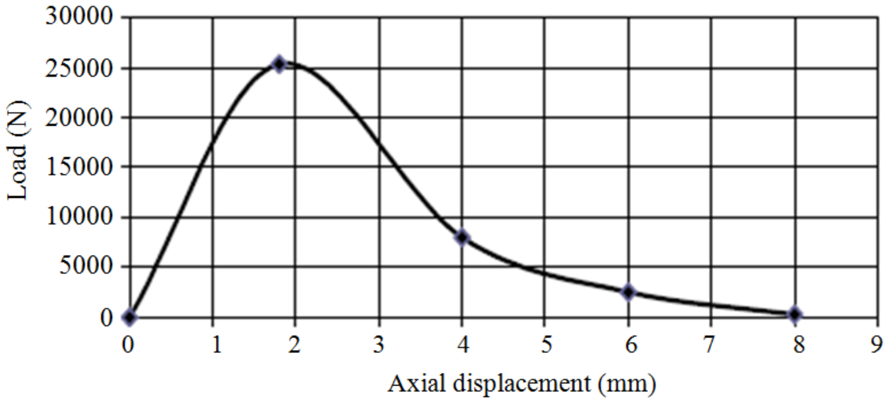
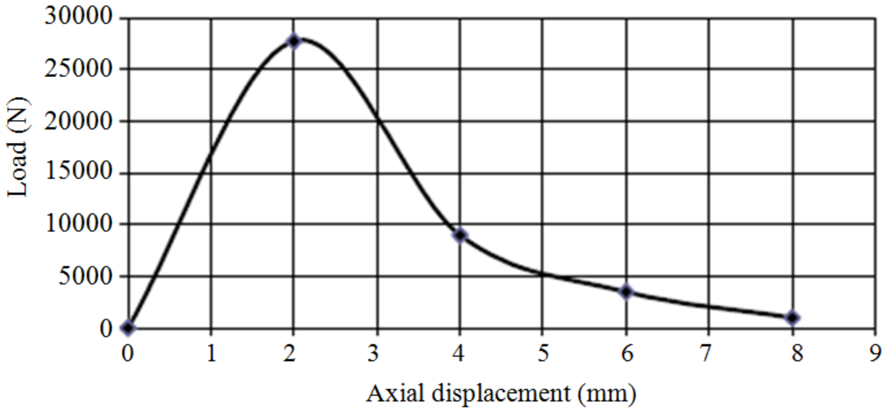


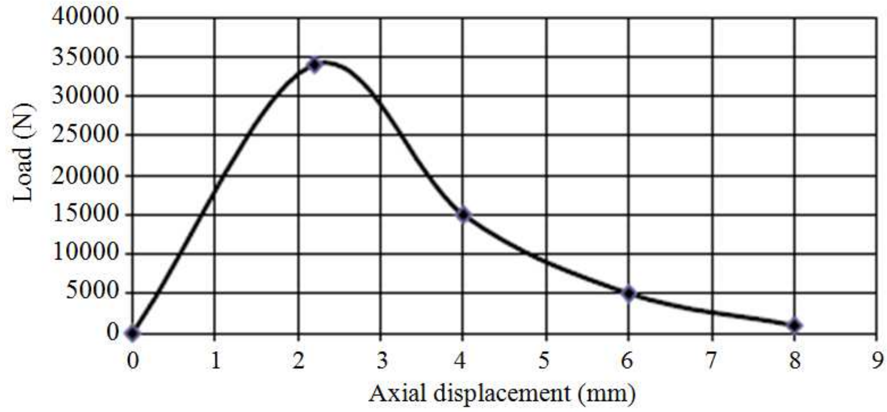
Fig. 19. HMA sample in MTS machine



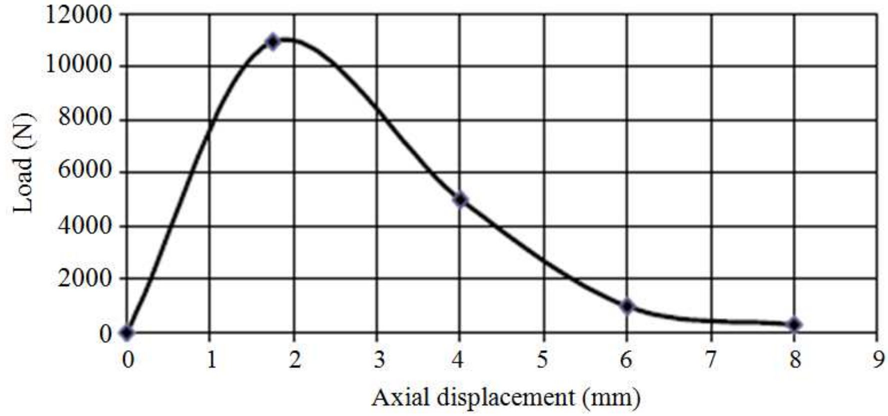

(a)



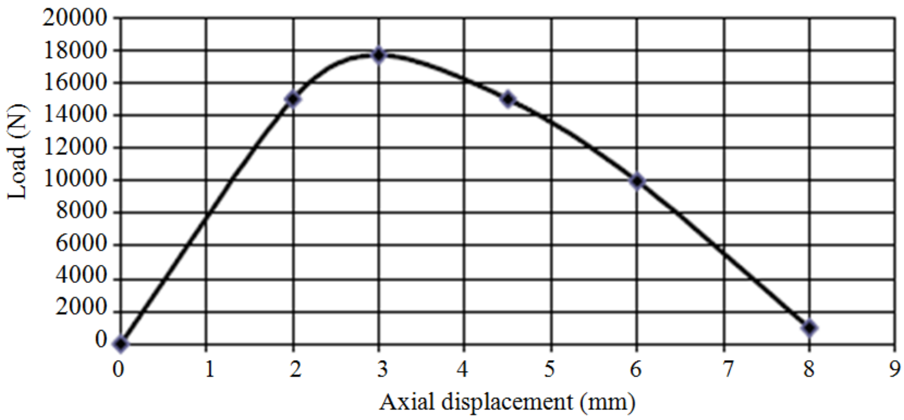

(b)




(c)




(d)




(e)

Fig. 20. Load versus axial displacement for all of RAP mixtures (a) Control mixture (0.0% RAP) (b) 25% RAP (c) 50% RAP (d) 75% RAP (e) 100% RAP

## Conclusion

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. Moreover, many highways in Egypt have been exposing to premature failures that decrease the performance and service life of pavements. The main objectives of this study were to evaluate the adding of RAP on the mechanical and durability performance of HMA mixtures to resist the different types of failures. Based on the laboratory test results, the following conclusions were drawn:

- 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
- 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 enhances the moisture susceptibility for all studied conditioning periods
- 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 provides the maximum stripping resistance was 50%
- The presence of RAP increased the adhesive bond strength of particle which leads to decreasing the percent of weight loss. The lowest percent weight loss was achieved at 100% RAP content. Thus, the mixtures containing RAP provided well performance over its useful service life compared with the control mixture. Moreover, mixture of 50% RAP achieved the maximum capacity while 75% RAP mixture provided the lowest failure load
- 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 mechanical properties, durability performance and stripping resistance of HMA

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## Author's Contributions

**Ahmed Abu El-Maaty:** Organized the manuscript, provided technical consultancy about the obtained results, participated in analyzing the data and discussing the results, contributed to the writing of the manuscript.

**Abdulla Elmohr:** Participated in performing necessary tests and conducting and analyzing the obtained results, contributed to the writing of the manuscript.

## Ethics

This manuscript in its current form has not been published elsewhere; however there are some points of similarity were published in preliminary versions. So there are no ethical issues know to authors that may arise after the publication of this manuscript.

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