Journal of Contemporary Technology and Applied Engineering (JCTAE)

Home Page: https://jctae.journals.ekb.eg/
Published by: Faculty of Engineering, Kafrelsheikh University

Volume: 4 **Issue:** 1 **Year:** 2025
Pages: 41– 52
DOI: 10.21608/jctae.2025.378642.1050

Print ISSN: 2812-5797
Online ISSN: 2812-5800

PERFORMANCE EVALUATION OF SUSTAINABLE AND ECOFRIENDLY ASPHALT MIXTURES BY USING WARM ASPHALT TECHNOLOGY

Received: 24-04-2025
Accepted: 29-05-2025

Mohamed Ashraf Elewa, Ahmed Mohamady Abdallah,
Hassan Darwish Hassanin

Construction Eng. and Utilities Dept., Faculty of Engineering, Zagazig University, Zagazig, 44519, Egypt.
*Corresponding author: M. A. Elewa (melewa@eng.zu.edu.eg), (https://orcid.org/0009-0000-5630-9291)

ABSTRACT. Studies on sustainable asphalt mixtures in Egypt have not been investigated extensively, and currently, no standards for their industrial application have been provided. This study examined the performance of sustainable asphalt mixtures containing reclaimed asphalt pavement (RAP) in hot and warm conditions. To achieve the study objective, an experimental program was designed for the asphalt mixtures using five ratios (0, 20, 40, 60, and 80%) of RAP and four different petroleum wax contents (0, 4.0, 6.0, and 8.0%) by weight of asphalt cement. Petroleum wax was used as an organic additive for bitumen binder to produce warm asphalt. Performance characterizations of the asphalt mixtures include stiffness, cracking resistance, and compressive strength. These characteristics were evaluated by Marshall, indirect tensile, and unconfined compression tests, respectively. Results show that the increase in the replacement percentage of RAP causes a decrease in the stability, flexibility, and cracking resistance of hot asphalt mixtures. Using petroleum wax decreases the penetration, the rotational viscosity, and the mixing and compaction temperatures of modified asphalt cement. This reduction in mixing temperature saves fuel costs in asphalt mixture production. Adding petroleum wax decreases the stiffness and increases the flexibility, the modulus of elasticity, and cracking resistance more than in the corresponding hot case. Also, it indicated that using RAP in hot and warm asphalt mixtures improves properties and meets performance requirements.

KEYWORDS: Sustainable; Asphalt mixtures; Marshall; Cracking Resistance.

1. INTRODUCTION

Hot mix asphalt (HMA) consists of asphalt cement and mineral aggregates, which which account for 90–95% by weight and 75–85% by volume of the HMA [1]. The physical and chemical characteristics of the aggregates in the mixture significantly influence the characteristics of HMA. In Egypt, only virgin ingredients are used to make hot asphalt mixtures. However, because of ongoing pavement milling or scraping operations, approximately 4 million tons of recycled asphalt materials are not utilized annually[2]. The goal of sustainability is to progress technology and meet human needs while minimizing negative effects on the environment and the economy. Humans have a basic need for transportation, hence creating sustainable transportation infrastructure is a top priority [3]. Over the past 20 years, there has been a global awareness of the need for sustainable development practices in all areas of human endeavor, including the road construction sector, due to growing environmental harm caused by greenhouse gas emissions and the slow depletion of non-renewable natural resources. It is well recognized in the construction business that pavement construction and maintenance require a lot of resources and can occasionally have detrimental effects on the environment [4]. The utilization of waste materials such as Reclaimed Asphalt Pavement (RAP) and warm mix asphalt (WMA) technologies facilitates a reduction in energy consumption and greenhouse gas emissions, extends life cycles, and enhances serviceability [5].

2. LITERATURE REVIEW

Reclaimed Asphalt Pavement (RAP) offers an eco-friendly and cost-effective alternative to virgin materials by reducing reliance on new aggregates and asphalt binder [6]. Research in Egypt demonstrated that asphalt mixtures with 50–100% RAP replacement, when optimally designed, outperformed conventional Hot Mix Asphalt (HMA) in mechanical properties and achieved 45–64% material cost savings [2]. While RAP enhances stiffness and high-temperature rutting resistance, higher replacement levels increase cracking risks, reduce stability and tensile strength, and elevate moisture sensitivity [4]. To mitigate these issues, Waste Engine Oil (WEO) is used as a rejuvenator, effectively softening aged binders to improve workability [7, 8]. A 15% WEO dosage is optimal, balancing rejuvenation benefits without compromising performance [9].

Warm Mix Asphalt (WMA) is an environmentally sustainable alternative to conventional Hot Mix Asphalt (HMA), produced and compacted at temperatures 14–50°C lower than HMA's typical 150–190°C range [10]. Key benefits include reduced fuel use, lower greenhouse gas emissions, safer working conditions, less binder aging, extended hauling distances, improved compaction potential, and the ability to pave in cooler weather. However, its lower production temperatures and modified binder properties may lead to differences in pavement performance compared to HMA, necessitating careful evaluation of durability and structural behavior.

Cracking in asphalt pavements arises from factors like poor mix design, heavy traffic, moisture damage, and binder deterioration [11]. The use of recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) intensifies these issues, as aged binders increase brittleness and stiffness, heightening susceptibility to fatigue, thermal, reflection, and top-down cracking [12]. To address this, researchers analyze fracture mechanics, focusing on fracture energy (Gf) to assess crack resistance. However, while Gf correlates with peak load and displacement, it alone cannot distinguish between mixtures with high strength/rapid failure versus low strength/gradual failure, limiting its utility as a standalone metric [13].

3. Study Objective

Research on sustainable asphalt mixtures in Egypt remains limited, and there are currently no established standards for their industrial application. This study examined the performance evaluation of sustainable and ecofriendly asphalt mixtures for the specific traffic conditions of Egypt, and it achieves a set of aims:

- Manufacturing warm asphalt mixture using petroleum wax as a warm additive and investigating its performance.
- Examining the performance of sustainabile asphalt mixtures containing reclaimed asphalt pavement (RAP) in hot and warm conditions.
- Investigating indices to evaluate cracking resistance of sustainable asphalt mixtures.

4. Materials and Methods

4.1. Natural Aggregate and Reclaimed Asphalt Pavement (RAP)

The study utilized natural aggregates (limestone coarse aggregates in two grades: 9.5 mm and 19 mm) and fine aggregates (crushed sand from Mania Crusher and natural sand from Abo-Shalaby, Sharkia Governorate). Limestone dust from Suez Governorate served as mineral filler. Reclaimed Asphalt Pavement (RAP) was sourced from Banha-Zagazig agricultural road (Sharkia, Egypt), with a binder content of 5.01% (determined via AASHTO T 164) [14]. A 15% waste engine oil (WEO) dosage (by aged binder mass) was used as a rejuvenator [9]. Material properties are detailed in Table 1, and Fig. 1 displays the components of the 4C mix samples.

4.2. Asphalt Cement and Warm Additive

The study employed 60/70 penetration grade asphalt cement, commonly used in Egyptian road construction. Penetration and rotational viscosity tests are used to measure the physical properties of virgin and modified asphalt cement samples. Viscosity is a critical rheological property of fluids [15] and used for determining workability and mixing/compaction temperatures, was measured using a Brookfield viscometer (ASTM D4402–06) [16]. Properties of the asphalt cement used are shown in **Error! Reference source not found.**2. Petroleum wax was used as organic additives for modifying asphalt cement to produce warm mixture. Petroleum wax was obtained from AMOC – Alexandria Minerals Oil Company-Egypt. The petroleum wax has a melting temperature of about 62 °C. The physical characteristic of petroleum wax is represented in Table 3. Petroleum wax can be decrease the viscosity of binder once they substitute a small portion of the binder content, based on the available literatures, dosage rates for wax ranged from 2.0% to 10.0% by weight of the asphalt cement [17].

5. Asphalt Concrete Mix Design

The laboratory testing program evaluated asphalt mixtures using three methods: Marshall Testing for mechanical properties, Indirect Tensile Test to assess cracking resistance and fracture energy and Unconfined Compression Test for compressive strength and elasticity modulus evaluation. Mixes were designed via the Marshall Mix method [18], incorporating Reclaimed Asphalt Pavement (RAP) at 0%, 20%, 40%, 60%, and 80% replacement of natural aggregates. Petroleum wax (2–10% by asphalt cement weight) was added as a warm-mix additive (WMA) to virgin bitumen. The study aimed to determine the feasibility of combining RAP and wax-modified asphalt cement at optimal binder content, identifying performance trends for sustainable, eco-friendly asphalt solutions.

5.1. AGGREGATE BLENDING AND SAMPLE PREPARATION

Mix designs for virgin and RAP mixes followed Egyptian specifications (see Fig. (2)), using 20% Grade 2 (19 mm), 28% Grade 1 (9.5 mm), 37% crushed sand, 11% natural sand, and 4% limestone filler. Five dense-graded hot mixes with 0%, 20%, 40%, 60%, and 80% RAP were prepared per Egyptian 4C wearing course standards [19]. RAP was heated at 146°C for 2 hours [20], Natural aggregates and binder were heated separately at 170°C for 1 hour [9]. Modified binder with petroleum wax (2–10% by asphalt cement weight) was added to create warm mixes. Meanwhile, the 15% WEO (by aged binder mass) was mixed directly with heated RAP to reactivate aged binder before adding natural aggregates and virgin/modified binder [21, 9]. This process aimed to balance sustainability (via high RAP and WEO) with performance (using wax for workability and Egyptian standards for durability). The prepared samples were cured at room temperature for 24 hours prior to further testing.

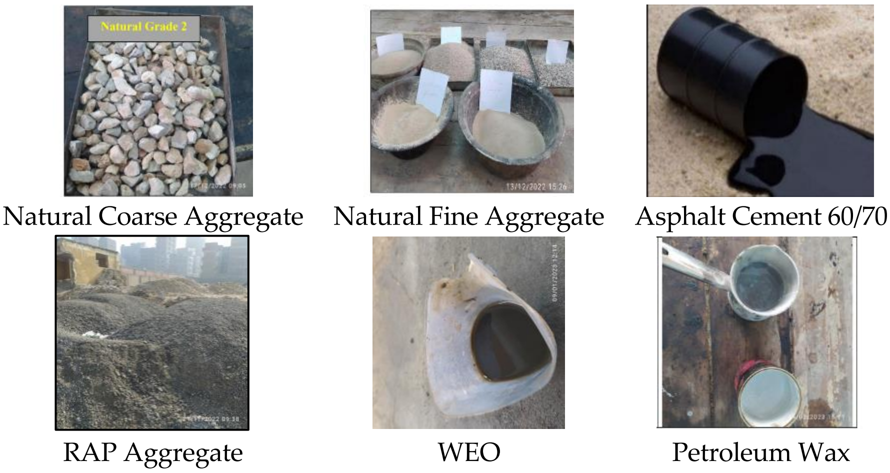


Fig. 1. Primary Materials Used in this Study to Prepare 4C Mix Samples

Table 1. Properties of Aggregates

Property	Coarse aggregate			Fine aggregate		Criteria	Method
	Grade2	Grade1	RAP	NA	RAP		
Bulk SG	2.668	2.618	2.631	2.64	2.65	-	ASTM C127/ C128
Bulk SSD SG	2.767	2.772	2.752	-	-	-	ASTM C127/ C128
Apparent SG	2.707	2.673	2.675	-	-	-	ASTM C127/ C128
Water absorption (%)	1.341	2.127	1.662	-	-	< 5	ASTM C127/ C128
Water disintegrate (%)	0.10	0.105	0.386	-	-	-	ASTM C127/ C128
Los Angeles abrasion (%)	19.79	22.86	20.16	-	-	< 45	ASTM DC-131

Table 2. Physical Characteristics of Asphalt Cement

Property	Value	Criteria	Unit	Standard
Penetration at 25 ⁰C	64	60-70	0.1 mm	AASHTO T 49, ASTM D 5
Rotational Viscosity at 135⁰C	512	> 320	cP	AASHTOTP48, ASTM 4402
Softening Point	48	45-55	⁰C	AASHTO, T53-09, ASTM D36-06
Specific gravity	1.02	-	gm/cm3	ASTM D 70

Table 3. Physical Properties of Petroleum Wax

Property	Test Value	Unit	Method
Density @ 15 ⁰C;	0.827	gm	ASTM D4052
Kinematic viscosity @ 100 ⁰C	5.12	Cst.	ASTM D445
Flash point	245	⁰C	ASTM D9320
Penetration @ 25 ⁰C	18	0.1 mm	ASTM D1321
Oil content	0.48	%	ASTM D721
Congealing point	62	⁰C	ASTM D938

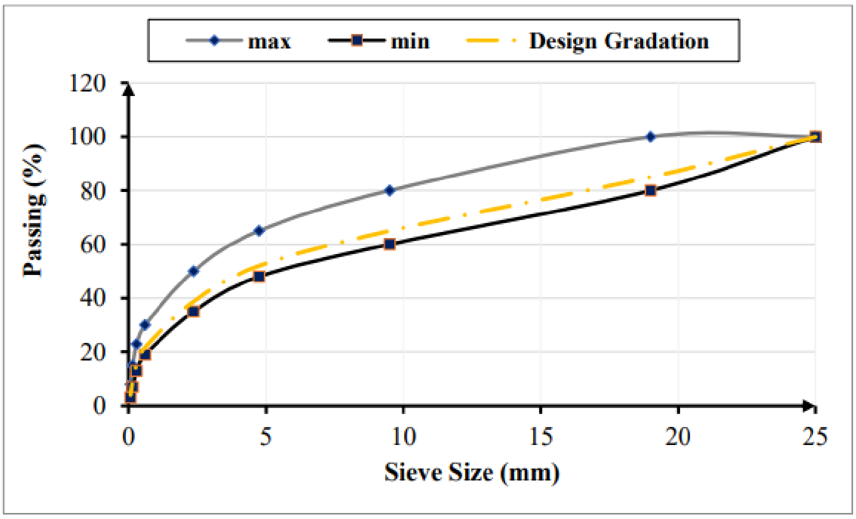


Fig. 2. Design Gradation and Standard Limits of Gradation (4C)

5.2. MECHANICAL PROPERTIES

Stability and flow are critical performance indicators for asphalt mixtures. Stability ensures resistance to traffic loads, requiring a minimum of 1100 kgf for heavy-traffic surface layers, while the flow must stay within 2–4 mm to meet wearing course specifications. These indicators, tested per ASTM D6927 [22], validate mixture durability and compliance with design standards, balancing load-bearing capacity and flexibility.

5.3. INDIRECT TENSILE STRENGTH (ITS) TEST

The Indirect Tensile Strength (ITS) test, conducted per ASTM D6931, evaluated asphalt mixtures using cylindrical specimens loaded at 50 mm/min along the vertical diameter via Marshall equipment at 25 ⁰C [23]. It was used to assess cracking resistance, determine fracture energy and cracking tolerance index, calculated via Eqs. (1)– (4) [24-26].

$$ITS = \frac{2000 * P}{\pi * t * D} \quad \text{Eq. (1)}$$

Where ITS is indirect tensile strength in kPa, P the maximum load to failure in N, t is the specimen height before a test in mm and D is the specimen diameter in mm.

$$G_f = \frac{W_f}{V_s} \quad \text{Eq. (2)}$$

Where Wf is the fracture work in joule (Wf is the total area under the curve), Vs is volume of specimen and FE=Gf is the fracture energy in J/m².

$$CT_{Index} = \frac{t * G_f * L75}{62 * |m_{75}| * D} \quad \text{Eq. (3)}$$

$$|m_{75}| = \left| \frac{P85 - P65}{l65 - l85} \right| \quad \text{Eq. (4)}$$

Where CT_{Index} is cracking tolerance index, L65, L75, L85 are displacements corresponding to 65%, 75% and 85% of peak load at the post-peak region in mm, P65, P85 are 65% and 85% of peak loads in kN, m75 is slope corresponding to 75% of peak load in the post-peak region in N/m, CRI is cracking resistance index.

5.4. COMPRESSIVE STRENGTH TEST OF BITUMINOUS MIXTURES

The Unconfined Compressive Strength (UCS) test, conducted per ASTM D1074-02 [27], evaluates compressive strength and Young's modulus of bituminous mixtures using cylindrical specimens

(101.6 mm diameter × 101.6 mm height) prepared as per ASTM D6926 at 25 ⁰C [28]. Specimens were loaded at 5.08 mm/min perpendicular to the diametric plane. Compressive strength was calculated using Equation (5). Young's Modulus (static modulus of elasticity) was derived from stress (load/area) and strain (height change/original height). The tangent modulus method (at a fixed percentage of ultimate strength) was applied, calculated via Equation (9). Mathematical expressions for these parameters are detailed in Equations (5)– (9) [29, 30]:

$$\mathbf{UCS} = \frac{P_{max}}{A_c} \quad \text{Eq. (5)}$$

$$\mathbf{AC} = \frac{A0}{100-\varepsilon v} \quad \text{Eq. (6)}$$

$$A_0 = 0.25\ \pi\ D^2 \quad \text{Eq. (7)}$$

$$\varepsilon v = (\delta v/h)*100 \quad \text{Eq. (8)}$$

$$E = 100 * \frac{\Delta\sigma}{\Delta\varepsilon v} \quad \text{Eq. (9)}$$

σ is compressive strength (kg/cm²), P is load (kg), Ac is area corrected of specimen (cm²), A0 is initial area of specimen (cm²), D is specimen diameter (cm), εv is vertical strain (%), δv is length change of specimen, h is specimen height and E is elastic modulus (kg/cm²).

6. RESULTS AND DISCUSSIONS

6.1. EFFECT OF ADDING PETROLEUM WAX ON CHARACTERISTICS OF ASPHALT CEMENT

The study evaluated asphalt cement modified with petroleum wax (2–10% by weight) through penetration, rotational viscosity, and mixing/compaction temperature. Fig. (3-a) illustrates the relation between percentage of petroleum wax and penetration value of Asphalt Cement at 25ᵒC. The figure shows that penetration decreases with the percentages of petroleum wax increases. This decrease is between 63 to 26 (0.1mm) as the percentages of petroleum wax from 0% to 10%. This decrease is due to that penetration of petroleum wax is 1.8mm lower than that of the virgin asphalt sample, which is consistent with the findings of (J. Oner et al., 2015) [31].

Fig. (3-b) demonstrates the impact of petroleum wax content on the rotational viscosity of asphalt binder at 135°C. It shows the rotational viscosity of virgin asphalt is 420 cp at 135 oC, whereas the rotational viscosity of modified asphalt by adding 2, 4, 6, 8 and 10 % of wax was reduced by 16.67, 25.7, 36.36, 45 and 51.58 % respectively. This decrease in rotational viscosity at the same temperature is due to the lower viscosity of the petroleum wax than that viscosity of the virgin asphalt cement, which is consistent with the findings of (J. Oner et al., 2015) [31].

Mixing and compaction temperatures for asphalt were determined based on viscosity thresholds; 0.17 ± 0.02 Pa.s (mixing) and 0.28 ± 0.03 Pa.s (compaction). Fig. (4) shows relation between heating temperature and rotational viscosity of virgin asphalt and modified asphalt at 135˚C and 170˚C [31]. The temperature that corresponds to compaction and mixing range is also summarized in Table (4). The figure shows that temperature of mixing and compaction of asphalt binder decreases with the percentages of petroleum wax increases. Decreasing in temperature of mixing and compaction of modified asphalt due to a decreasing viscosity of the petroleum wax and is highly sensitive to temperature. This reduction in mixing temperature saving fuel cost usage in asphalt mixture production.

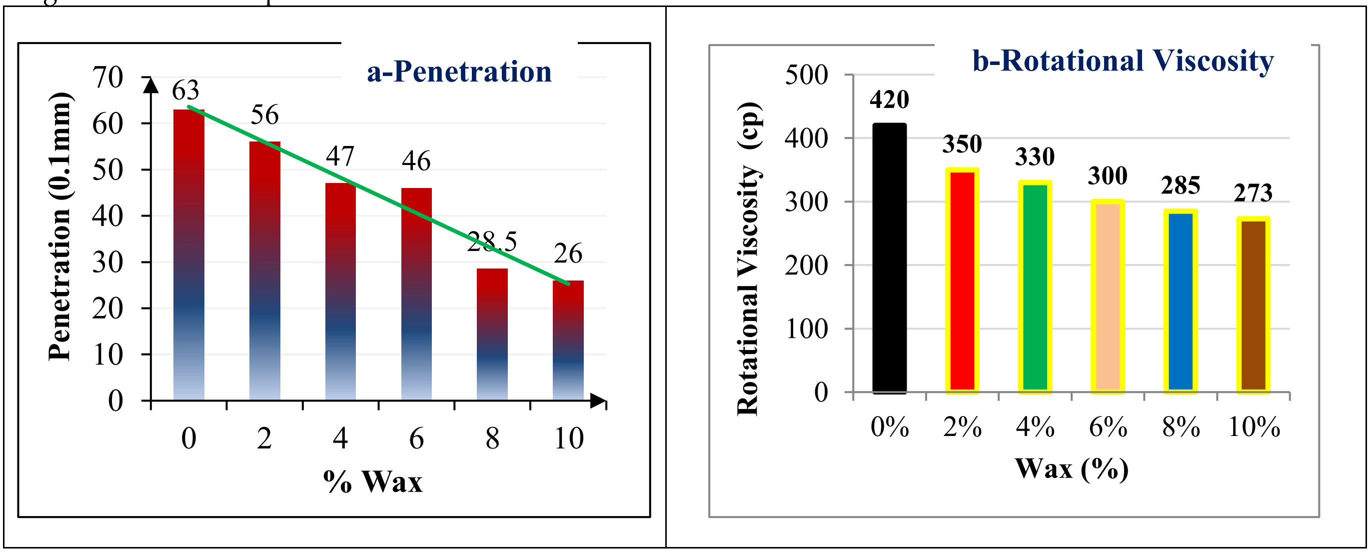


Fig. 3. Influence of Wax Content on the Penetration and Rotational viscosity of binder

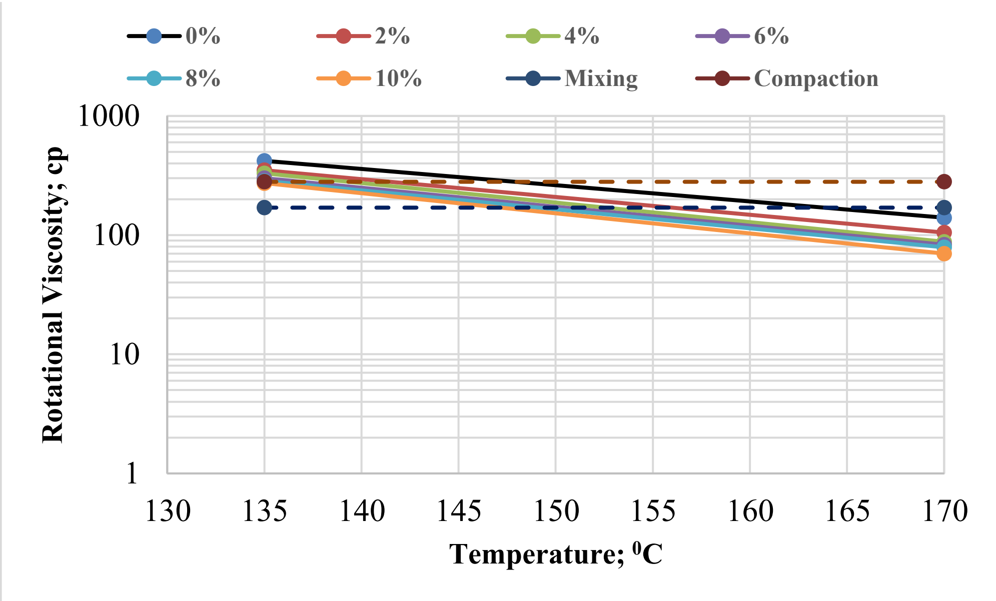


Fig. 4. Effect of Wax content on Mixing and Compaction Temperatures of Asphalt Binder

Table 4. Table (4): Results of Mixing and Compaction Temperatures

Item	Wax (%)	Mixing Temperature (⁰C)		Compaction Temperature (⁰C)	
		range	average	range	average
Virgin bitumen	0	158-166	162	145-149	147
Modified Asphalt Binder	2*	150- 160	155	142-144	143
	4	144-148	146	139-141	140
	6	138-145	141	136-140	138
	8	137-143	140	132-138	135
	10*	136-143	139	131-138	134

Note; * neglect these percentages in prepared of mixes

6.2. Performance Evaluation of Asphalt Mixtures

6.2.1. Mechanical Properties Evaluation

The objective from this section determines the feasibility of utilizing petroleum wax as WMA additive with mixtures containing different percentages of RAP at optimum asphalt cement content. The asphalt concrete samples including WMA additive and different percentages of RAP were prepared taken into the mixing and compaction temperatures into consideration. The mechanical properties of different RAP percentages with all mixtures in terms of stability, flow, stiffness and flexibility are presented in Fig. (5).

Fig. (5) presents the mechanical properties of asphalt mixtures containing Reclaimed Asphalt Pavement (RAP) at optimum asphalt content. Optimum Asphalt Content (OAC %) values range from 5.27% to 5.40%, meeting the criteria of 3-7%. This indicates consistent binder content in all mixes. Stability decreases as RAP content increases, from 1200 kg for R0 to 940 kg for R80. Mixtures R20, R40, and R60 meet the minimum stability criterion of >1100 kg. [19], but R80 does not. Flow values (2.85-3.20 mm) are within the acceptable range of 2-4 mm, indicating good deformation resistance for all mixes, this finding is in agreement with (El Hmrawey et al., 2015 and Julide Oner et al., 2015) [31, 32]. Marshall Stiffness decreases as RAP content increases, from 367 kg/mm for R0 to 303 kg/mm for R80. All values meet the minimum stiffness criterion.

Stability decreases with an increase in wax content of all mixtures. The mixture containing 40% RAP has maximum stability and occurs at 4% wax. Flow increases with an increase in wax content, staying within Egyptian specifications. Highest stiffness occurred at 6% wax for most RAP mixes. Fig. (5) shows a new parameter that indicates the flexibility of the asphalt mix [9]. It was calculated using the following formula: (Marshall stability × Marshall flow)/2. The flexibility of the mixtures containing different RAP content is similar to that of the common mix at zero wax. The customary effect of an increase in wax content, which usually results in a fall, followed by a rise, in the flexibility can be observed for asphalt mixtures at all levels of the RAP. Results showed that maximum flexibility is a mixture containing 40% RAP and is achieved at all percentages of wax.

6.2.2. Cracking Resistance Evaluation

The purpose of the ITS test is measuring load and displacement to determine the ultimate tensile strength and the cracking parameter of bituminous mixtures. Fig. (6) presents the load-displacement relationships of both control mix (R0) and mixtures containing 20%, 40%, 60%, and 80% percentages of RAP at different percentages of wax content. From Fig. (6), the Virgin mixture needs a higher peak load and higher FE values than RAP mixtures and it reversal of the results of the Al-Qadi [33]. An increase in RAP content decreases the peak load and FE of the sustainable asphalt mixture. This may be waste engine oil (WEO), which restores and softens the aged binder, enhances the workability of recycled mixes, and makes them more flexible. An increase in wax content increases the ductility of the sustainable asphalt mixture. This trend of R40 is similar to the behavior of R0 in the elastic and plastic regions at all percentages of wax

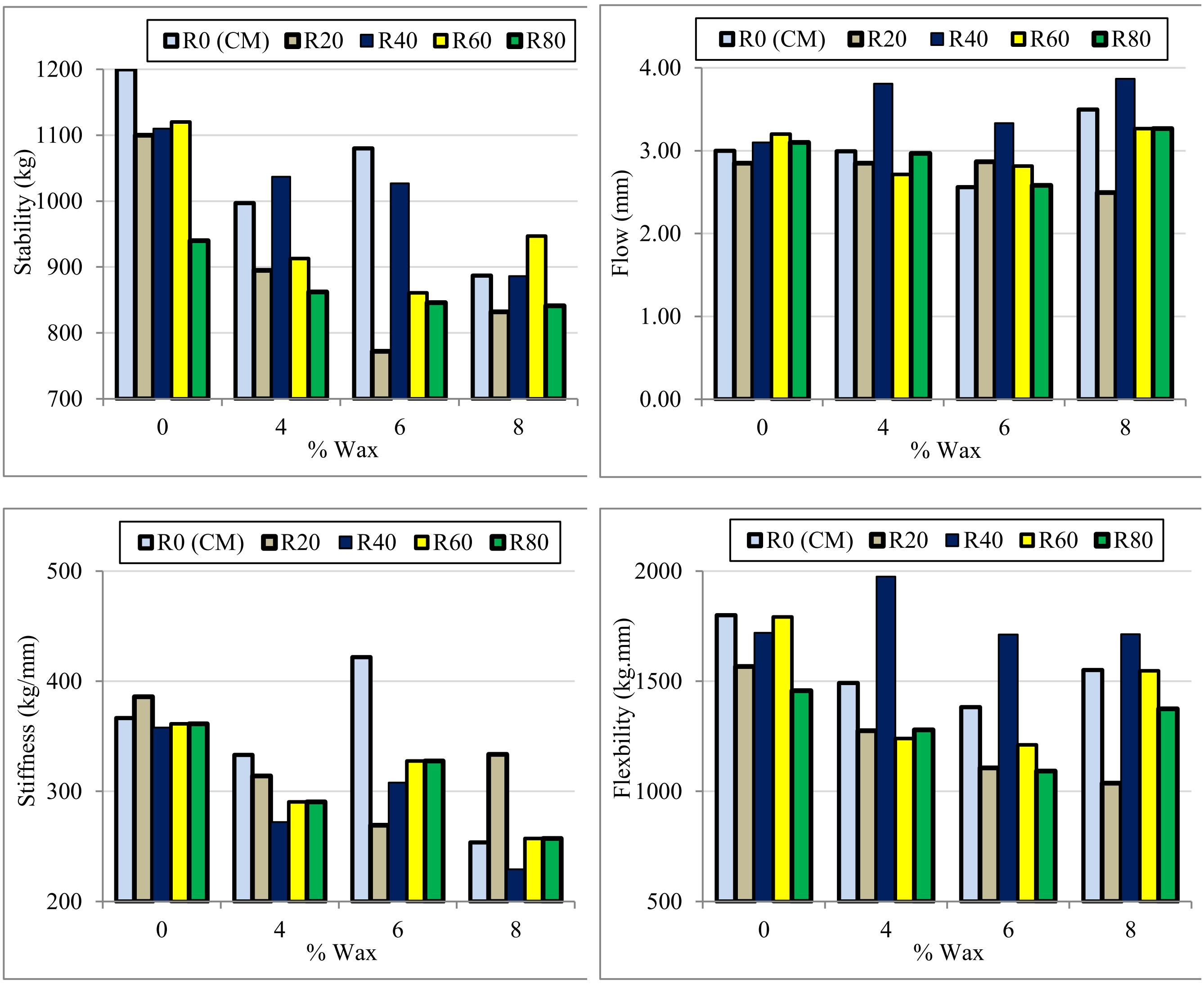


Fig. 5. Influence of Wax Content on the Mechanical Properties; Stability, Flow, Stiffness and Flexibility

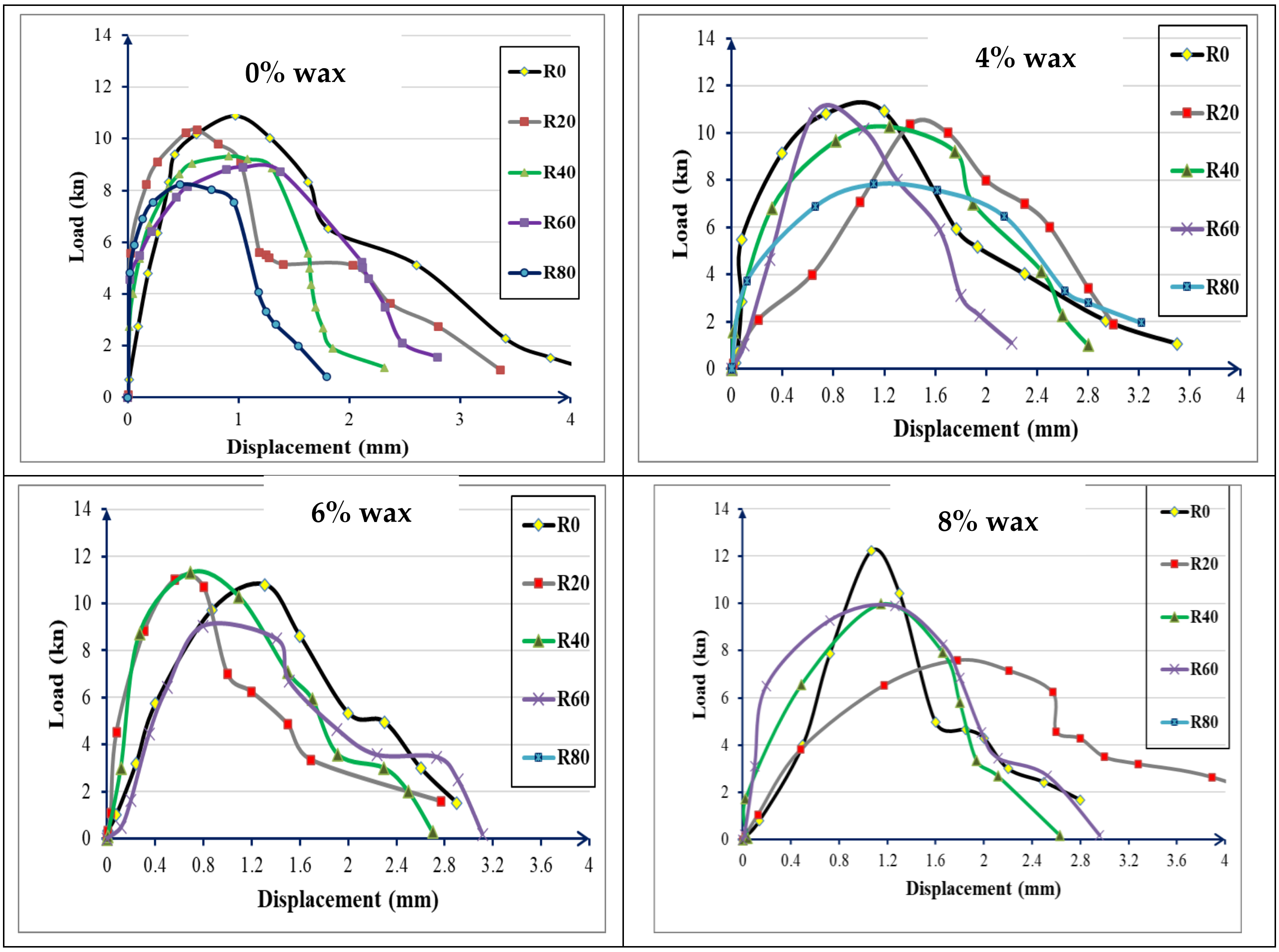


Fig. 6. Load-Displacement Curves

Fig. (7) presents the influence of RAP and wax content on cracking parameters; ITS, ΔD, FE, and CT index of asphalt mixtures. The ITS of mixtures containing RAP decreases with the increase in RAP percentages, which is in line with the findings of other researchers who have observed a reduction in the tensile strength of asphalt mixtures with higher RAP content (Azzam et al., 2016) [34]. It shows that the ITS values for mixes containing 40% RAP are nearest to the ITS values for the control mix (R0). Higher RAP percentages mean more aged binder, reducing overall mix flexibility. This aged binder is typically more brittle and less able to form strong, cohesive bonds. Vertical displacement (ΔD) of mixtures incorporating RAP decreases with increased RAP percentages. The figure shows that the ITS values of common mixes increase with the percentage of petroleum wax. The maximum ITS value of the modified mixture containing 40% RAP content was achieved at 4 % wax. Also, the ITS values of modified mixtures containing 60 and 80% RAP decrease with increased petroleum wax. The ΔD values of all mixes increase with the percentage of petroleum wax. Fracture energy (FE) of mixtures containing RAP decreases with the increase in RAP percentages, indicating a reduction in the ability of the mixtures to absorb energy before failure. This is consistent with the findings of previous studies, which have reported that incorporating RAP reduces the fracture energy of asphalt mixtures (Weimin Song et al., 2023) [35]. FE values of common mixes decrease as the percentage of petroleum wax increases. FE of mixtures containing different percentages of RAP decreases with the increase in wax percentages. The maximum FE value of common and modified mixes containing 40% RAP content was achieved at 4 % wax. Thus, it can be concluded that the common mix and modified mixture containing 40% RAP gain the desired strength, unlike the studied RAP mixtures. CT Index values of common mixtures decrease with an increase in wax content. The CT Index values of mixtures containing different percentages of RAP decrease with the increase in wax percentages. The CT Index of the mixture containing 20 and 40% RAP values is higher than that of other RAP mixtures at all wax percentages. The CT Index values of all RAP mixtures and the common mixture are lowest at 8% wax. Thus, it can be concluded that the petroleum wax increases the ductility of asphalt mixtures

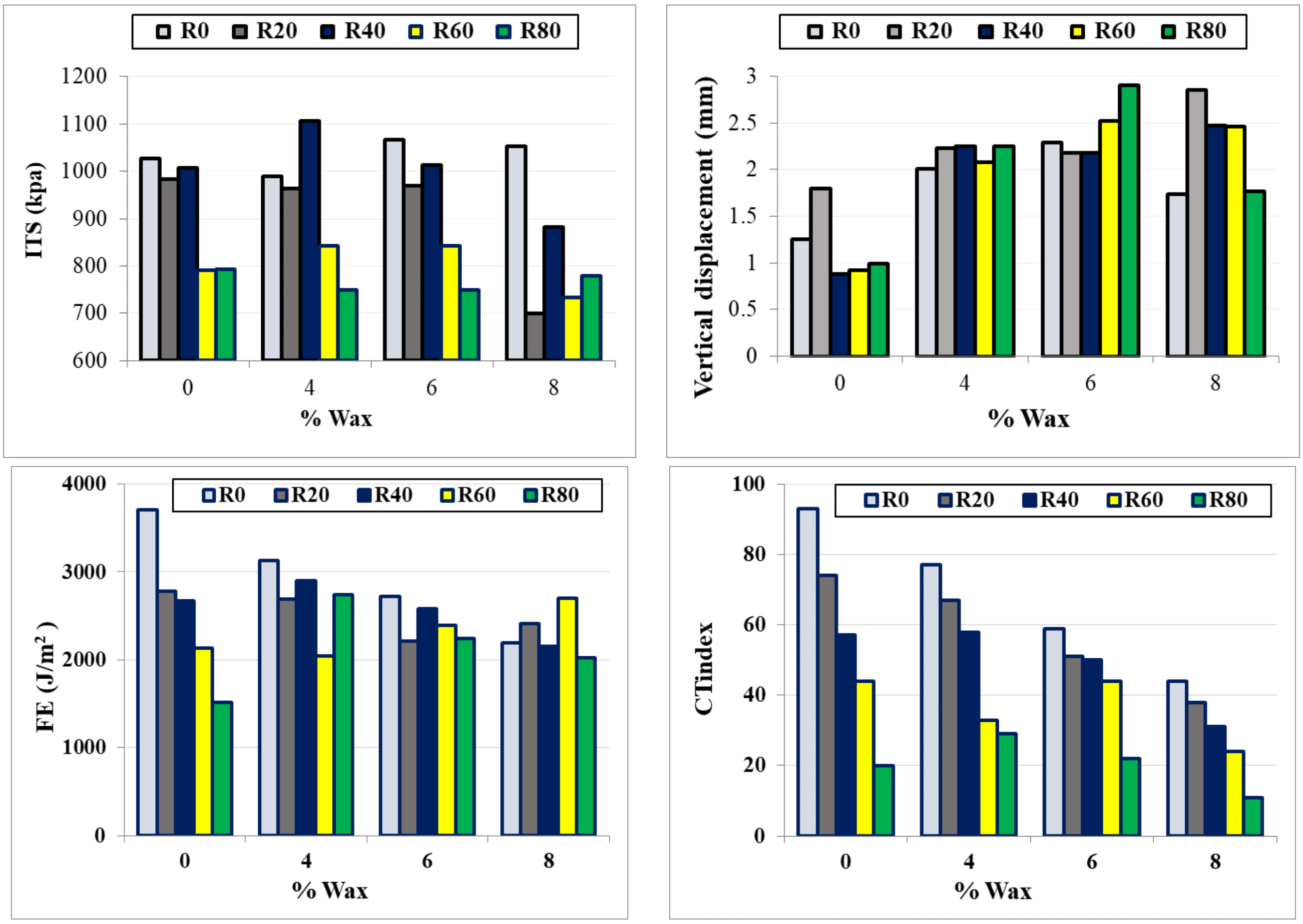


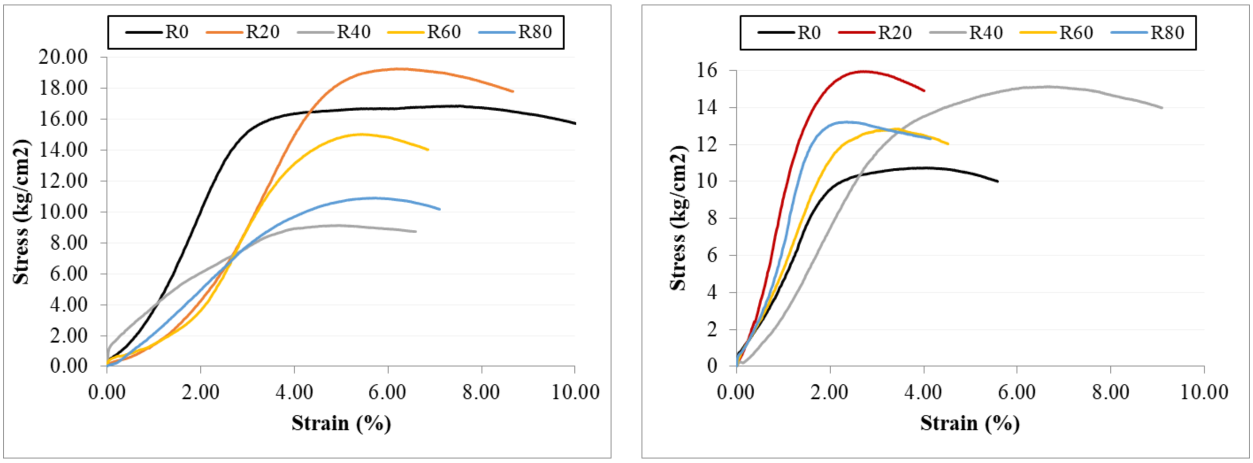
Fig. 7. Influence of Wax Content on Cracking Parametres; ITS, ΔD, FE and CT index

6.2.3. Compressive Strength and Modulus of Elasticity Evaluation

The purpose of the UCS test is measuring stress and strain, determining ultimate compressive strength and determining the Modulus of Elasticity of bituminous mixtures. Fig. (8) shows the stress and strain curves for all the asphalt mixtures at optimum asphalt content. In hot case, the Fig. (8-a) shows that the R20 has the higher strength (stress) than R0. Obviously, the curves show that the R0 and R20 are more ductile than other mixes. The R40, R60 and R80 have a ductile mix but lower strength. Whereas, Fig. (8-b) shows that adding warm additive increases the ductility but lower strength of some mixtures. In warm case, The R40 is more ductile and higher strength than the corresponding in Hot Case.

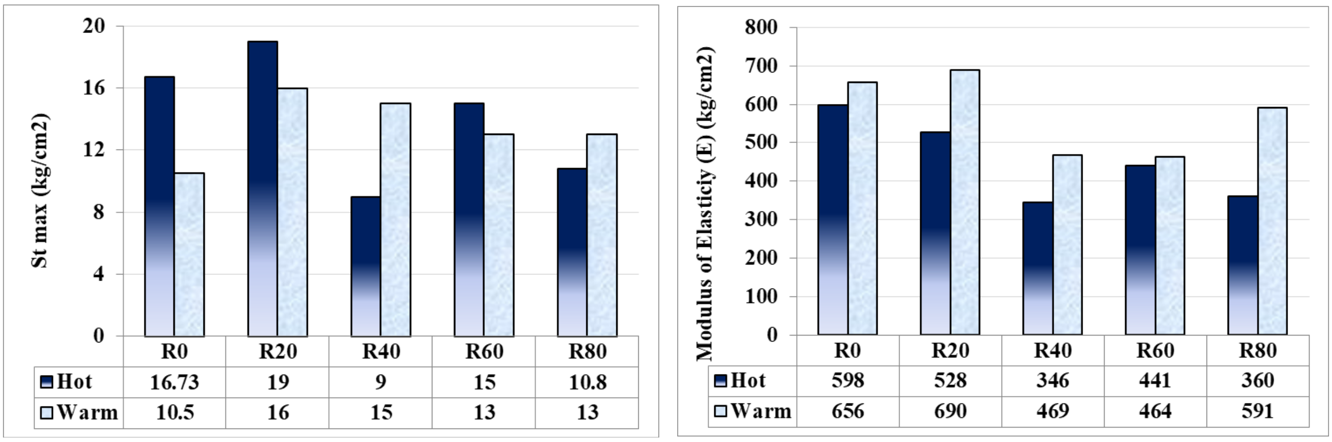
Fig. (9-a) presents ultimate UCS for all the asphalt mixtures at optimum asphalt content. The UCS values for all the warm mixtures were close, but comparatively lower than the value obtained for hot mixtures. In the hot case, the UCS value of R0 is 16.73 kg/cm^2 and this finding is in agreement with Arief Setiawan et al [30]. The UCS value for mix containing 20% RAP content higher than the value obtained for R0 by 13.57%, but the UCS values for mixes containing 40% to 80% of RAP are lower than the value obtained for R0. In warm case, the UCS values for R0, R20, and R60 are lower than the values obtained than the corresponding in Hot Case. As well as, the UCS values for mixes containing 40% and 80% of RAP are higher than the corresponding in Hot Case. These results indicated that the using RAP aggregates instead of natural aggregates in hot and warm case are successful.

Fig. (9-b) illustrates the Modulus of Elasticity values for all the asphalt mixtures at optimum asphalt content. In the hot case, the Modulus of Elasticity of R0 has the higher value of the other mixes. The Modulus of Elasticity values for mixes containing RAP decreases with increases percentages of RAP, it because of are lower ductility of R0. Also, Fig. (9-b) shows that adding warm additive increases the ductility and the Modulus of Elasticity values than the corresponding in Hot Case.



a) Hot Mixtures b) Warm Mixtures

Fig. 8. Effect of RAP Content on Stress and Strain Curves



a) Compressive Strength b) Modulus of Elasticity

Fig. 9. Influence of RAP Content on Compressive Strength and Modulus of Elasticity

7. Conclusions

In Egypt, studies on Sustainble asphalt mixtures have not yet been investigated extensively, and currently, no standards for their industrial application have been provided. This study was examined the performance evaluation of sustainable and ecofriendly asphalt mixtures for the specific traffic conditions of Egypt.

In the following, the main conclusions from the performance evaluation tests are presented:

- Adding RAP to hot asphalt mixtures decreases the stability, flexibility and cracking resistance.
- Using petroleum wax decreases the penetration, the rotational viscosity and the mixing and compaction temperatures of modified asphalt cement. This reduction in mixing temperature saves fuel cost usage in asphalt mixture production.
- Adding petroleum wax decreases the stiffness and increases the flexibility, the modulus of elasticity, and cracking resistance more than the corresponding hot case.
- Maximum ITS value of modified mixture containing 40% RAP content achieved at 4 % wax.
- The UCS values for all the warm mixtures were close, but comparatively lower than the value obtained for hot mixtures. the UCS values for mixes containing 40% and 80% of RAP are higher than the corresponding in Hot Case. Adding warm additive increases the ductility and the Modulus of Elasticity values than the corresponding in Hot Case.
- These results indicated that the using RAP aggregates instead of natural aggregates in hot and warm cases are successful.

References

[1] M. Arabani, A.R. Azarhoosh, The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures, Constr. Build. Mater. 35 (2012) 1–7. https://doi.org/10.1016/j.conbuildmat.2012.02.036.

[2] S. El Hmrawey, A.E.A. El Maaty, A.I. Elmohr, Durability of Hot Asphalt Mixtures Containing Reclaimed Asphalt Pavements, OALib 02 (2015) 1–18. https://doi.org/10.4236/oalib.1101508.

[3] B.A. Williams, J.R. Willis, J. Shacat, Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2019, Natl. Asph. Pavement Assoc. (2020) 48.

[4] H. Al Dughaishi, J. Al Lawati, M. Bilema, A.M. Babalghaith, N.S. Mashaan, N.I.M. Yusoff, A. Milad, Encouraging Sustainable Use of RAP Materials for Pavement Construction in Oman: A Review, Recycling 7 (2022) 1–15. https://doi.org/10.3390/recycling7030035.

[5] M. Bilema, M.Y. Aman, N.A. Hassan, Z. Al-Saffar, N.S. Mashaan, Z.A. Memon, A. Milad, N.I.M. Yusoff, Effects of waste frying oil and crumb rubber on the characteristics of a reclaimed asphalt pavement binder, Materials (Basel). 14 (2021) 1–18. https://doi.org/10.3390/ma14133482.

[6] C.H. &Laurent P. Nam Tran,Adam Taylor,Pamela Turner, Effect of rejuvenator on performance characteristics of high RAP mixture, Road Mater. Pavement Des. 18 (2017). https://doi.org/https://doi.org/10.1080/14680629.2016.1266757.

[7] H. Li, B. Dong, W. Wang, G. Zhao, P. Guo, Q. Ma, Effect of waste engine oil and waste cooking oil on performance improvement of aged asphalt, Appl. Sci. 9 (2019). https://doi.org/10.3390/app9091767.

[8] M. Chen, B. Leng, S. Wu, Y. Sang, Physical, chemical and rheological properties of waste edible vegetable oil rejuvenated asphalt binders, Constr. Build. Mater. 66 (2014) 286–298. https://doi.org/10.1016/j.conbuildmat.2014.05.033.

[9] M.Z.H. Khan, S. Koting, H.Y.B. Katman, M.R. Ibrahim, A.M. Babalghaith, O. Asqool, Performance of high content reclaimed asphalt pavement (RAP) in asphaltic mix with crumb rubber modifier and waste engine oil as rejuvenator, Appl. Sci. 11 (2021). https://doi.org/10.3390/app11115226.

[10] National Academies of Sciences, Engineering, and Medicine; Field Performance of Warm Mix Asphalt Technologies, Washington, DC Natl. Acad. Press. (2014) 240. https://doi.org/https://doi.org/10.17226/22272.

[11] F. Kaseer, F. Yin, E. Arámbula-Mercado, A. Epps Martin, Stiffness characterization of asphalt mixtures with high recycled material content and recycling agents, Transp. Res. Rec. 2633 (2017) 58–68. https://doi.org/10.3141/2633-08.

[12] J.L. Imad L. Al-Qadi, Hasan Ozer, T.K. Ahmad El Khatib, Punit Singhvi, and B.D. José Rivera-Perez, Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS, 2015.

[13] S. Pirmohammad, M.R. Ayatollahi, Fracture Behavior of Asphalt Materials, 2020. https://doi.org/https://doi.org/10.1007/978-3-030-39974-0.

[14] ASTM D2172, Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures. ASTM International, West Conshohocken, PA, USA, 2018.

[15] J.A.P.C. Luciano Pivoto Specht, Oleg Khatchatourian, Lélio Antônio Teixeira Brito, Modeling of asphalt-rubber rotational viscosity by statistical analysis and neural networks, Mater. Res. 10 (2007) 69–74. https://doi.org/https://doi.org/10.1590/S1516-14392007000100015.

[16] A. D4402-06, Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer, West Conshohocken, PA, USA, 2002.

[17] Z. Magdy, A. Manal, M. Ahmed, H. Hassan, Study of Warm Mix Asphalt Production, M.SC thesis, Faculty of Engineering, Zagazig University, (2016).

[18] AASHTO-T245, Standard Method of Test for Resistance to Plastic Flow of Asphalt Mixtures Using Marshall Apparatus, 444 North Capitol Street NW, 2015.

[19] E.C. of P. for R. and U.R. Works, Road Materials and Their tests, Egypt, 2021.

[20] A.A. Mamun, H.I. Al-Abdul Wahhab, Evaluation of Waste Engine Oil-Rejuvenated Asphalt Concrete Mixtures with High RAP Content, Adv. Mater. Sci. Eng. 2018 (2018). https://doi.org/10.1155/2018/7386256.

[21] M. Zaumanis, R.B. Mallick, R. Frank, Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications, Constr. Build. Mater. 69 (2014) 159–166. https://doi.org/10.1016/j.conbuildmat.2014.07.035.

[22] ASTM D6927, Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, ASTM International, West Conshohocken, PA., Am. Soc. Test. Mater. i (2015) 1–7. https://doi.org/10.1520/D6927-15.2.

[23] S. Properties, B. Paving, M. Specimens, I. Road, P. Materials, A. Concrete, P. Mixtures, U.M. Apparatus, B. Mixtures, Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures 1, (2011) 3–7. https://doi.org/10.1520/D6931-12.2.

[24] ASTM D8225-19, Standard Test Method For Determination Of Cracking Tolerance Index Of Asphalt Mixture Using The Indirect Tensile Cracking Test At Intermediate Temperature, ASTM Int. (2019).

[25] B.P. Das, A.K. Siddagangaiah, Identification of parameter to assess cracking resistance of asphalt mixtures subjected to aging and moisture conditioning, J. Traffic Transp. Eng. (English Ed. 9 (2022) 293–304. https://doi.org/10.1016/j.jtte.2021.02.004.

[26] Astm D8225-19, Determ. Crack. Toler. Index Asph. Mix. Using Indirect Tensile Crack. Test Intermed. Temp. (2019) 1–17. https://doi.org/10.1520/XXXXX-XX.

[27] B. Statements, T. Size, O. Bituminous, P. Mixtures, Standard Test Method for Compressive Strength of Bituminous Mixtures 1, (1996) 5–8.

[28] I. Road, P. Materials, A. Mixtures, Standard Practice for Preparation of Bituminous Specimens Using Marshall, i (n.d.) 1–6. https://doi.org/10.1520/D6926-10.1.5.

[29] P. Measurements, P. Measurements, W. Pore, P. Measurements, T. Compression, W. Pore, P. Measurements, R.C. Specimens, Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and, (2004).

[30] C. Paper, A. Setiawan, U. Tadulako, L.B. Suparma, U.G. Mada, Developing the elastic modulus measurement of asphalt concrete using the compressive strength test Developing the elastic modulus measurement of asphalt concrete using the compressive strength test Arief Setiawan , Latif Budi Suparma , and Agus Taufik Mul, (2017). https://doi.org/10.1063/1.5011541.

[31] J. Oner and B. Sengoz, "utilization of recycled asphalt concrete with warm Mix Asphalt and cost-benefit analysis," PLoS One, vol. 10, no. 1, pp. 1–18, 2015, doi: 10.1371/journal.pone.0116180

[32] S. El Hmrawey, A. E. A. El Maaty, and A. I. Elmohr, "Durability of Hot Asphalt Mixtures Containing Reclaimed Asphalt Pavements," OALib, vol. 02, no. 05, pp. 1–18, 2015, doi: 10.4236/oalib.1101508.

[33] Al-Qadi et al., "Testing Protocols to Ensure Mix Performance w/ High RAP and RAS," Illinois Cent. Transp., no. 1, p. 209, 2015

[34] A. Alkhalil, L. Radwan, and M. Elmitiny, "the Effects of (RAP) on the Laboratory Performances of Hot Mix Asphalts," J. Al-Azhar Univ. Eng. Sect., vol. 11, no. 38, pp. 53–58, 2016, doi: 10.21608/auej.2016.19493.

[35] W. Song, X. Zou, H. Wu, and F. Yang, "Energy evolution in fracture process of hot mix asphalt containing reclaimed asphalt pavement and rejuvenator," Theor. Appl. Fract. Mech., vol. 124, no. January, p. 103809, 2023, doi: 10.1016/j.tafmec.2023.103809.