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A Review of Sustainability Asphalt Mixtures

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Abstract

Sustainability in asphalt mixtures refers to the use of environmentally friendly materials and practices in the construction and maintenance of roads and pavements. The purpose of this research is to review the waste materials that can be recycled and reused in the production of asphalt, as well as the technologies that have been created or underdeveloped to address environmental challenges related to asphalt mixtures. Warm Mix Asphalt (WMA) technology and reclaimed asphalt pavement (RAP) were evaluated with respect to their environmental and economic benefits and engineering performance as the main components of pavement sustainability. Rutting, moisture susceptibility, heat and fatigue cracking resistance were all examined as part of the performance evaluation. The study of the environmental impact of these technologies and materials was based on two major environmental effects: greenhouse gas emissions (GHGs) and energy consumption. Regardless, there are concerns over some aspects of warm-mix asphalt such as lower resistance to fatigue cracking, rutting and potential water-susceptibility problems, particularly with mixes prepared with water-based technologies.

1. Introduction

Global concerns over the gradual depletion of non-renewable natural resources and increasing damage to the environment from greenhouse gas emissions have created greater awareness, within the past two decades, for sustainable development practices in all spheres of human endeavor including the road construction industry. Within the construction industry, pavement construction and maintenance are known to be resource-intensive, sometimes with considerable negative environmental impacts. It is reported that in the United States (US) alone, over 320 million tons of raw materials are used in the construction, rehabilitation, and maintenance of the country's road network annually at a cost of over $150 billion [1].

Sustainability is the fulfillment of human needs and technological advancement with the least possible environmental and economic costs. Transportation is the primary need of human beings and developing sustainable transportation facilities is of main concern [2]. The construction industry consumes a large number of resources and energy, in contrast to other sectors of the contemporary economy. Having about 83.5% of total pavement, asphalt is the dominant element of road network assets in the United States. For having a sustainable pavement, it is vital to take environmental impacts, economic benefits, and performance into account.

From the environmental perspective, researchers have sought remedies to minimize air pollution as well as natural resource exploitation for asphalt. A study recorded a first-ever CO_2 reading more than 410 parts per million (ppm) by Mauna Loa [3]. Such a vast quantity requires all industrial sectors' attempts to lower the amount of greenhouse gas (GHG) emissions to tackle the accelerated catastrophic phenomenon of global warming. Asphalt pavement manufacture is an industrial section in which materials production, construction, service, maintenance and end-of-life are the phases that energy consumption and GHG emissions occur. Among them, materials production and construction are the major phases [4].

Materials production involves raw material procurement, transport of raw materials, and asphalt mixture manufacture [4]. In 2007, roughly 1.6 billion metric tons of asphalt was produced worldwide [5], which resulted in 14.4 × 10^6 m^3 of fuel, 1.28 × 10^4 GWh of electrical consumption and 46.08 million tons of CO_2 emissions, accounting for 0.15% of global CO_2 emissions.

The economy plays a crucial role in the industry, and any environmental enhancement should satisfy economic restrictions. Since road pavement is energy demanding and natural reserve consuming, any environmental improvement leads to certain economic advantages. Although it might be discouraging to have an initial cost increase due to environmental considerations, the long-term benefit assessment could justify it. Various aspects of asphalt mixture performance are the influential factors on life-cycle analysis (LCA) which decree the environmental-economical profitability. Better performance guarantees longer lifespan as well as higher serviceability, which, in turn, reduces reconstruction, maintenance, and rehabilitation costs. Additionally, less natural resources, including fuel, aggregate and asphalt binder are consumed in the long-term. Therefore, the optimal balance between engineering (performances), environmental, and economic aspects brings sustainability to pavement assets. The typical sustainability studies usually focus on three components: economic development, social development, and environmental protection [6].

The decrease in energy consumptions and GHG emissions, life cycle extension, and better serviceability can be achieved by the exploitation of waste materials, such as reclaimed asphalt pavement (RAP), and crumb rubber modifier (CRM) and/or adoption of warm mix asphalt (WMA) technologies. Therefore, in this research, WMA technologies RAP) employment and application of the most popular and approved waste materials (were evaluated regarding environmental, economic, and engineering performance.

2. Warm Mix Asphalt (WMA)

Warm mix asphalt mixtures (WMA) are those asphalt mixtures with lower mixing and compaction temperatures that are more environmentally-friendly compared to conventional hot mix asphalt (HMA) mixtures. The conventional HMA mixtures have a production temperature of 150–190 ∘ C while WMA mixtures can lead to a temperature reduction between 14–50 ∘ C depending on the used warm mix technology [7]. As the most important benefits of WMAs, they reduce fuel consumption and GHG emissions, improve working conditions for paving crews due to less harmful emissions, decrease binder aging, increase hauling distance, potentially increase the field densities (better compactability), and extend paving seasons.

However, compared to conventional HMA, a high change in pavement performance can be expected due to the reduction in production temperatures and modifications of binder characteristics. For example, although low binder oxidation may increase the pavement cracking resistance, it may decrease the moisture and rutting resistance [8]. There are also other technologies, namely half warm mix asphalt (HWMA), which can lower the production temperature to 60–100 ∘ C [9]. However, because of their poor performance, they have not drawn attention as WMAs. Production of WMA in world in (mil. tons per year) is shown in Figure (1) and also it shows that the highest use of WMA is in USA, and in Europe is about 10 times lower [10]. Figure (2) shows the classification of various application temperatures for asphalt concrete, from cold mix to hot mix. Warm mix asphalt mixtures are separated from the resulting mixture temperature and half warm asphalt mixtures [9].

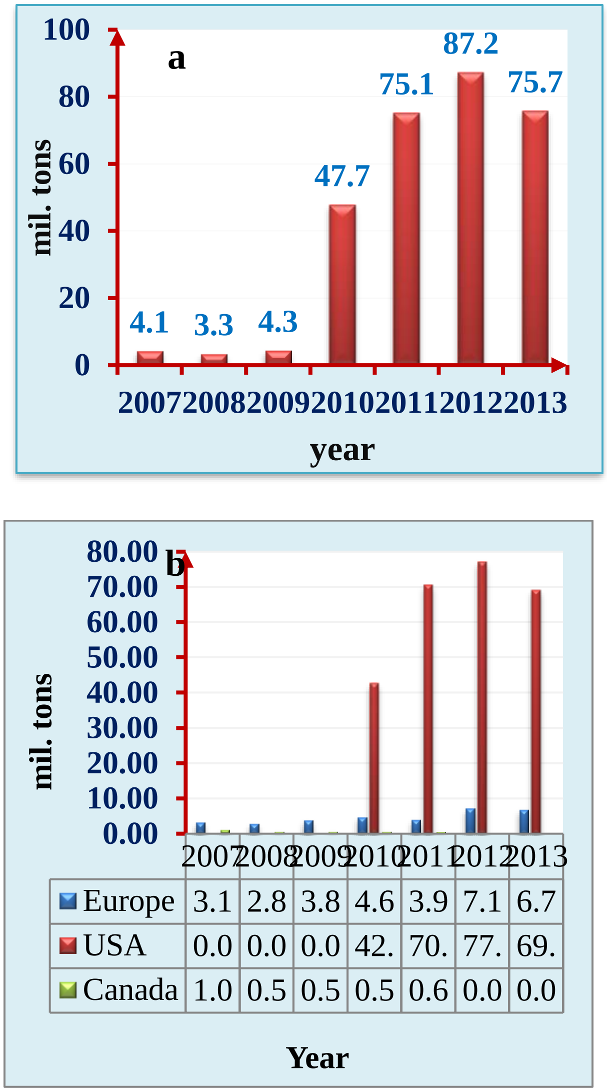


Figure (1): Production of WMA in world in mil. tons/year [10]

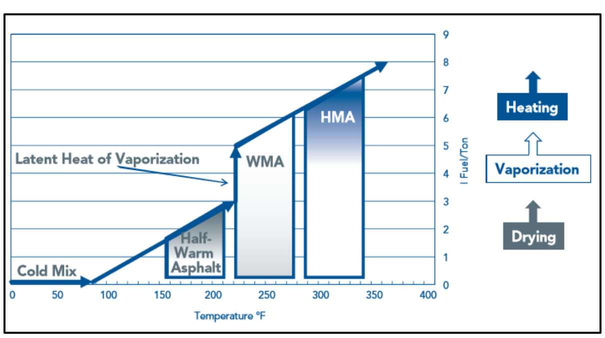


Figure (2): Classification by temperature range, temperatures, and fuel usage are approximations[9]

2.1 WMA Technologies

WMA technologies are divided into three main categories: (1) foaming (2) organic additives and (3) chemical additives, as illustrated in Table (1). Foaming involves using the introduction of water or water-containing additives into hot binder during production. Water then turns into bubbles that facilitate the flow of the binder and provide sufficient low viscosity to coat the aggregate at lower temperatures. Consequently, due to the bubble generation, the volume, and viscosity of binder increases and decreases, respectively. In general, the characteristic of the foamed binder is a function of source, date of production, and type of polymer modification (Newcomb et al., 2015). In case of binder properties, the results of NCHRP report 807 showed that although the increase in the water content results in higher expansion ratios (ER), it can reduce the rate of collapse (k-value), foam-ability index (FI), and bubble surface area index (SAI). Furthermore, increasing water content reduces workability and coat-ability of the foamed binders. The better workability and coat-ability can be achieved by applying higher mixing temperatures and foaming at the optimum water content, respectively [11].

Organic additives are waxes including Fischer-Tropsch wax, fatty acid amide, and Montan wax with melting temperatures (80–120 ◦ C) lower than the HMA production temperature and higher than in-service temperature. Having lower viscosity compared to the binder at similar temperatures, waxes can decrease the viscosity of binder once they substitute a small portion of the binder content, 2–4% of the weight of the binder [12].

Chemical additives are another category of WMA technology that improves the bonding between aggregates and binder, compaction, coating, and workability. They can be a surfactant, anti-stripping agents, polymers, or a combination of them [13–14].

Table (1): Products used in warm mix technologies [2]

WMA Technology	Additive Dosage	Mixing Temperature (0C)
Foaming Additive		
Aspha-min®	0.3% by total mass of the mixture	130-170 based on Binder Stiffness
ADVERA® WMA	0.25% by total mass of the mixture	130-170 based on Binder Stiffness
WAM-Foam®	No additive. It is a two-component binder system that introduces a soft and hard foamed binder at different stages during plant production.	110-120
LEA®	0.2-0.5% by weight of the binder	< 100
LEA, also EBE and EBT	0.2-0.5% by weight of the binder	< 100
ECOMAC	Unknown Quality & Quantity	Placed at above 45
LT Asphalt	0.5–1.0% of a hygroscopic filler	90
LEAB®	0.1% by weight of the binder	90
Organic Additives		
Sasobit®	0.8-3.0% by weight of asphalt	130-170 based on Binder Stiffness
Asphaltan-B®	2.5% by weight of asphalt	130-170 based on Binder Stiffness
Licomont BS 100®	3% by weight of asphalt mixture	130-170 based on Binder Stiffness
3E LT or Ecoflex	Unknown quantity	30-40 drop from HMA
Chemical Additives		
CECABASE RT®	0.2-0.4% by weight of asphalt	90-100
Evotherm®	Improve coating, workability, and adhesion at lower temperatures.	85-115
HyperTherm/QualiTherm	0.2-0.3 % by weight of the binder	120

Rediset WMX®	2% by weight of the mixture	120-130

Increases in the application of WMA mixtures during the past two decades makes them an essential asphalt technology for the 21st century. For example, in the United States, a dramatic increase in adoption of WMA technology (tripled) was observed from 2009–2011. The federal highway administration (FHWA) also reported that more than 40 states have used WMA mixtures to pave the roads and at least 14 state highway agencies have implemented specifications to use WMA mixtures [15]. As a part of NCHRP report 843, results of a survey about application of WMA technologies from 18 department of transportation (DOT) in United States revealed that foaming technologies (53.2%) were more popular than the other two technology (organic and chemical additives with 16.9% and 29.9%, respectively) [16]. However, this survey was conducted for the WMA mixtures with minimum 40 ∘ C reduction in the production temperatures compared to conventional HMAs. Additionally, among of the used additives, Evotherm with 23.4% was the most widely used additive, followed by Sasobit (16.9%), Astec DBG (15.6%), and Advera (10.4%). The other survey conducted by the national asphalt pavement association (NAPA) presented that about 77% of WMA used foaming technology, followed by chemical and organic additives (21.1% and 1.9%, respectively) in the U.S [2].

The main reason for the popularity of foaming technologies is that they have a lower production cost than other WMA technologies (see Table (2)). NAPA also reported that 31.2% (116.8 million tons) of the total produced asphalt mixture used in the United States was WMA in 2016. However, 68% of WMA was produced at HMA temperature [2]. Therefore, although it cannot be environmentally beneficial at all, some other advantages of WMA, such as better compactability, extended construction season, and hauling distance are still available.

Table (2): Production Cost of WMA [17]

Fuel Source	Price of Additive (USD per Ton)	Reduced Energy Costs (USD per Ton)			Increased Production Cost (USD per Ton		
		Oil Fuel (Iceland)	Diesel (HI, USA)	Natural Gas (IL, USA)	Oil Fuel (Iceland)	Diesel (HI, USA)	Natural Gas (IL, USA
WMA 20% (Sasobit)	1.3–2.6	1.3	1.7	0.6	0-1.3	-0.4-0.9	0.6-2
WMA 30%(Aspha-min	3.96	1.9	2.6	0.83	2.06	1.36	3.13
WMA 40% (Foam)	0.3	2.6	3.5	1.1	-2.3	-3.2	-0.8

2.2 Environmental Evaluation

Burning fossil fuels and heated binder are the two sources of GHG emissions during the production phase. Any production temperature decrease leads to cleaner production since less fuel is consumed and there is lowered binder temperature. WMA results in asphalt mixtures with 20–40% reduction in fossil fuel consumption in comparison to conventional HMA [17]. As shown in Table (3), WMA technologies are very effective in terms of the GHG emissions decrease. These results were extracted from the stack emissions tests for 15 projects worldwide and showed that although the reduction in carbon dioxide (CO_2), oxides of nitrogen (NOx), and carbon monoxide (CO) is significant, in some projects, an increase in sulfur dioxide (SO_2) was observed. Furthermore, as a part of NCHRP report 779, results of an investigation on stack emissions of three multi-technology projects in Michigan, Indiana, and New York States indicated that application of WMA results in a 20% reduction in CO2 emission compared to the corresponding HMA due to a 21% reduction in fuel usage [7]. However, there was an insignificant difference between the CO emissions for the WMA and the corresponding HMA mixtures. In the case of volatile organic compounds (VOC) emission, although a 50% reduction in VOC emissions was reported for a Michigan plant, the higher VOC emissions were observed for the New York project. The high variation in VOC emission can be justified by the difference between the burner design, fuel type, maintenance, and tuning of the studied plants. For NOx emission, results of this study showed a slight reduction while the significant reduction in SO_2 was observed for the only plants that used reclaimed oil as fuel. Temperature reduction and, consequently, less harmful gasses production provide a better working condition for workers, especially in the case of paving in a covered area like tunnels. Results of total organic matter (TOM) in breathing zones of paving crews for some projects indicated that the WMA mixtures have at least a 33% reduction in TOM compared to conventional HMA mixtures [7].

Table (3): Percentage of gas emissions reduction due to WMA from different countries' data [17]

Emission Component	**Oliveira et al.**	**Middleton and Forfylow**	**Vaitkus et al.**	**Powers**	**D'Angelo et Al., Capitão et al**	**McIver**	**Davidson and Pedlow**	**Larsen et al.**	**De Groot et al.**
CO_2	32	10.9	30-40	13.8	15-40	46	17.4	31.4	31
SO_2	24	-14.3	35	-	20-35	81	-17.2	-	-
VOC	-	-	50	31.9	50	30	20	-	-
CO	18	10.4	10-30	-	10-30	63	19.5	28.5	29
NOx	33	8.3	60-70	16.1	60-70	58	20	61.5	62
Dust	-	-	20-25	-	25-55	-	-	-	-

2.3 Economic Evaluation

Economic evaluation (cost vs. benefit) of each new technology is one of the main factors that control its acceptance into conventional practice. Compared to conventional HMA mixtures, the use of WMA mixtures have some certain economic costs and potential benefits. The type of WMA technology is the main factor that affects the costs of WMA mixtures because some WMA technologies require modification processes that makes initial costs increase. The initial cost for WMA technologies can be affected by some factors, such as modifications to the plant's control system, installation of mechanical equipment, additives, and mix design costs. Additionally, like other products, the initial cost is a function of the freight costs and can be varied during the times. For example, the primary water-injection foaming systems cost around $80,000 while their cost has reduced to $30,000 in the last decade [7]. It is reported that adding the WMA additive can increase the total cost of production by approximately $2.00 to $3.50/ton [18].

Furthermore, implementation of newly developed mix design specifications for WMA mixtures, such as NCHRP Report 691, may result in increasing mix design costs by $1500–$2000 due to conduct compactability, coating, and flow number tests [7,30]. However, the results of the cost analysis for some WMA technologies proved that the initial cost due to some plant modifications and equipment installation could be deprecated over 5–7 years and additive and mix design costs may be compensated by the following benefits of WMA [7]:

- Reduction in energy consumption at the plant;
- Increase in payments due to achieving higher in-place densities;
- Extended paving seasons; and
- The possibility of removing antistripping additives for some WMA additives.

Table (4) shows an example of the estimated costs and potential economic benefits for using WMA. This illustrates that the only energy savings could offset the cost of water-injection foaming systems. Another study also revealed that the implementation of foaming technologies could decrease the energy consumption up to 30–40%, while using Aspha-min and Sasobit can lead to energy reduction by 30% and 20%, respectively [19]. Superposing the reduced cost due to less energy consumption and price of WMA additive, there are increased production costs for Sasobit and Aspha-min (with the Asphamin having greater values), while foaming technology reduces them [19]. Additionally, results of a comprehensive study on the effect of WMA on the plant energy in the US revealed that, on average, a 27 ∘ C decrease in the mix production temperature results in burner fuel savings of 22%, which is equal to 1100 British Thermal Unit (Btu)/ ∘ F/ton in energy savings [7]. In general, it can be concluded that, regarding WMA technology and the additive dosage, the reduced energy consumption can be between 20% and 40%.

Table (4): A summary of cost and economic benefit for WMA technologies [7]

Cost and Potential Economic Benefits		WMA Type	
		Water Injection Foaming	Additive
Typical technology cost ($/ton)		$0.08	$2.50
Assumed temperature reduction (°C)		13	25
Typical energy savings ($/ton)	Natural Gas	$0.16	$0.31
	Recycled fuel oil (RFO)	$0.39	$0.79
Typical incentive/disincentive spec. savings ($/ton)	Density improvement	0 to $1.13	0 to $1.13
Possible savings from eliminated antistripping agent	Hydrated lime	0	0 to $1.50
	Liquid ASA	0	0 to $0.75

2.4 Performance

With respect to service, maintenance, and end-of-life phases weak performance might diminish the environmental and economic benefits of WMA technologies in production and construction phases. Some studies have focused simultaneously on both laboratory and field evaluations as well as mix design and best practices of WMA mixtures [20,21]. Moisture susceptibility, rutting, fatigue, and thermal cracking resistance are the main aspects of performance that have been evaluated for WMA mixtures. Moisture susceptibility is the main cause of premature distress formation. Incomplete drying of aggregate due to lower mixing temperature weakens the moisture damage resistance of the WMA [12]. However, some anti-striping agents, such as Zycotherm and polyamines, can act as WMA additives to solve the problem with moisture susceptibility [22]. From some trial projects in Europe, the results of the moisture susceptibility for WMA mixtures with different additives and virgin binders indicated that the WMA mixtures could show equal, or even better, adhesion compared to the HMA control mixtures [6]. Moreover, a study at the University of California, Davis reported no moisture damage for the saturated pavement sections tested under a heavy vehicle simulator (HVS) [23]. Another study (NCHRP report779) on the short-term performance of WMA pavements with less than 10 years old revealed that none of the field projects showed any sign of moisture damage [7]. In this study, cores were taken from the projects after 1–2 years of traffic. Furthermore, as a part of NCHRP Project 9–49, a recent web-survey from state DOTs and contractors in the US was accomplished to recognize WMA pavement moisture susceptibility based on the mix design, construction, production, or quality assurance (QA) data [8]. Results of this survey from the WMA pavements with ages of 3–8 years (short-term) revealed that no moisture-related distress had been observed for 90% of the states. However, it is important to note that the low percentage (10%) of moisture-related distress in this survey does not necessarily guarantee the long-term moisture damage resistance of the WMA pavements. Based on NCHRP report 83, results of the Hamburg wheel tracking (HWT) demonstrated that most of the WMA mixtures without an anti-stripping agent showed stripping inflection points (SIP) [16]. Therefore, application of anti-stripping agents can significantly reduce the stripping potential of WMA mixtures in a long-term period.

2.5 Rutting

Rutting performance of WMA mixtures have been evaluated under heavy loading conditions in some accelerated pavement testing (APT) facilities in the United States: the National Center for Asphalt Technology (NCAT) Test Track, the University of California Pavement Research Center (UCPRC), and MnROAD [24]. Results of these studies confirmed that rutting performance (structural response) of the WMA test sections were comparable to the companion HMA sections. Additionally, results of a survey in Europe demonstrated that the rutting performance of the variety of WMA technologies was equal or even better compared to corresponding HMA mixtures [6]. As one of significant findings from NCHRP report 779, the short-term field evaluation of rutting performance for 28 WMA projects revealed that the rutting performance of WMA pavements was comparable with that of the companion HMA pavement [7]. In this study, the companion HMA pavements were defined as those were like WMA pavements regarding pavement structure, climate, and traffic conditions. In another study, NCHRP Project 9-49A, investigation of the long-term rutting performance for WMA mixtures showed that most of the WMA and companion HMA pavement sections have comparable rutting [16]. Additionally, among of different WMA technologies (foaming, organic, and chemical additives), no statistical difference regarding rutting was observed. Most of the non-foaming WMA technologies had a positive effect on high-temperature rheological properties of asphalt binder [25].

2.6 Fatigue

In case of fatigue resistance, results of two laboratory studies showed that although the chemical additives and foamed mixtures have a lower fatigue resistance compared to conventional HMA [26], Sasobit as a wax additive can improve fatigue performance especially when the modified asphalt mixtures are compacted at lower temperature (100–115 ∘ C) [27,28]. Additionally, the laboratory evaluation of fatigue life for foamed WMA mixtures using four-point beam fatigue tests exhibited higher fatigue life compared to HMA mixtures [29]. Among different WMA technologies, results of laboratory studies have shown that chemical additives are more contributive on thermal cracking mainly due to the reduced stiffness while foamed and warm wax asphalt have a minor negative impact on it [30,31]. In terms of large-scale tests, evaluation of fatigue performance of WMA pavements using a heavy vehicle simulator (HVS) showed insignificant fatigue cracking for all test sections due to strong pavement structure [32]. Furthermore, in Florida State, an early field study (three years after construction) conducted by Sholar et al. [32] revealed that there was no statistically significant difference between fatigue performance of WMA and the companion HMA pavement sections. The laboratory and field evaluation of fatigue cracking in some projects across the Europe countries also exhibited that the fatigue performance of WMA mixtures was equal, or in some cases better, than the companion HMA mixtures [6].

2.7 Transverse and Longitudinal Cracking

In terms of transverse and longitudinal cracking, the analysis of long-term performance indicated that although the various WMA technologies had a comparable performance compared to the companion HMA pavements, among those technologies, the foaming and chemical WMA pavements showed better performance compared to the organically-modified WMA pavements due to a more noticeable effect of aging on organically-modified WMA pavements [16].

A summary of the recommended determinants and corresponding test methods and specifications for better evaluation of performance and engineering properties of WMA mixtures is shown in Table (5). Generally, as a result of the limited studies around the long-term performance of WMA mixtures, it seems that still many transportation agencies and pavement construction contractors are hesitant to employ these technologies due to the initial costs. However, the current WMA technologies are more environmental-friendly than conventional HMA, and they show a comparable performance with HMAs. For example, using life cycle assessment (LCA) to address both environmental and performance aspects of pavements, it is reported that the WMA mixtures are more environmentally friendly and economically competitive to conventional HMA [33–34].

Table (5): Recommended determinants for performance evaluation of WMA mixtures [7,16, 35]

Performance	Determinant Parameter	Specification
Moisture Susceptibility	Tensile strength ratio (TSR)	AASHTO T 283
Rutting	Rutting resistance index (RRI) Dynamic modulus (E*) at 30 ∘ C Creep compliance at 30 ∘ C Binder Performance Grade (PG) Multiple Stress Creep Recoveryparameter (Jnr)	Hamburg wheel tracking (HWT), AASHTO T 324 AASHTO TP 79 AASHTO T 322 AASHTO T 315 AASHTO TP70 and AASHTO MP19
transverse cracking	Fracture work density value at −10 ∘ C Dynamic modulus (E*) at −10 ∘ C Indirect tensile strength at 20 ∘ C Creep compliance at 0 ∘ C Vertical failure deformation at 20 ∘ C	Indirect tensile (IDT), AASHTO T 322 AASHTO TP 79 ASTM D6931 AASHTO T 322
Longitudinal cracking	Indirect tensile strength Vertical failure deformation at 20 ∘ C Horizontal failure strain from the IDT test at	IDT test at 20 ∘ C AASHTO T 322

20 ∘ C
Creep compliance at −10 ∘ C

3. Recycled Aggregate

The asphalt pavement production and construction need a substantial amount of energy and non-renewable materials. Therefore, use of recycled materials seems to be necessary to create a more sustainable future for asphalt concrete pavement construction. The well-known recycled aggregates that have been used in asphalt pavements can be categorized into three groups [36]:

- Existing pavement byproduct such as reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) materials;
- Construction and demolition (waste materials such as tiles and bricks; and
- The byproduct from industry, such as copper or steel slags.

Using all these recycled aggregates are environmentally beneficial as it deals with solid waste management. Nonetheless, they can have both positive and negative impacts on asphalt performance; the negative impacts are intensified with recycled aggregate (RA) percentage increase and most agencies and DOTs impose a threshold dosage. For more preservation of natural resource, researchers have been seeking solutions to increase the amount of RA that can substitute virgin aggregates with insignificant negative impacts on performance [2].

3.1 Reclaimed Asphalt Pavement (RAP)

Due to heavy traffic loads and environmental conditions that are not considered in the design of asphalt pavements, more and more asphalt pavements are failing prematurely, as a result overlaying or replacing failing pavements become a necessity. Overlaying a pavement is a simple process, where a new asphalt layer is added, the problem with overlaying is the nature of the asphalt mix materials, which will take the form of the lower layer and most distress will be reflected on it after opening road for traffic as shown in Figure (3). The best solution is to mill the surface of the old pavement to remove the affected part of the pavement as shown in Figure (4), then the question is what to do with the removed materials, either dump it in landfill or reuse it as construction materials, hence the use of reclaimed asphalt pavement (RAP) came into the picture with a promise of many economic and environmental benefits. The most recycled materials in the United States is asphalt pavement materials. Over 80% of asphalt pavement materials milled from roadways are reused. It can be mixed into new pavement or used as a sub-base or fill material. In 2012, American asphalt plants used an estimated 68.3 million tons of reclaimed asphalt pavement to produce new asphalt [37]. RAP was first used in 1973 with 3% allowed to replace virgin materials in an asphalt mix, and since then and due to the increase of cost of asphalt binder, higher percentages were allowed, reaching nowadays 20 to 30% and even 50% [38]. The asphalt industry is considered number-one recycler and in 2012 almost all (98%) contractors in the United States reported using RAP with estimated savings of $2.04 billion at $600 per ton for asphalt binder [38].

In asphalt pavement recycling, materials reclaimed from old pavement structures are reprocessed along with some new materials to produce asphalt mixtures meeting all normal specification requirements [39]. The percentage of RAP permitted in a recycled mix varies by agency as well as guidelines as to where the recycled mix can be used in the pavement structure. RAP is mixed with aggregate and asphalt binder to yield a recycled mix and there are different ways to complete the process and it is governed by the configuration of the hot mix plant. RAP is added directly to the mixer in a drum mix plant as shown in Figure (5). The inlet at which RAP is added to the drum mixer relies on the mixer type (parallel flow versus counter flow versus double barrel) and whether or not a separate coater is included in the drum mix operation [2]. Once the recycled mix has been produced, it is either delivered to the construction site to be placed and compacted or stored in silos for future delivery. No special techniques are needed to handle recycled mix. However, special care and consideration should be employed when compaction of the recycled mix, since the recycled mix temperature will be slightly lower than the conventional mix, to avoid overheating the mix at the plant [40].

Figure (3): Overlaying over Distressed Asphalt Pavement [40]

Figure (4): Milling of Asphalt Pavements [40]

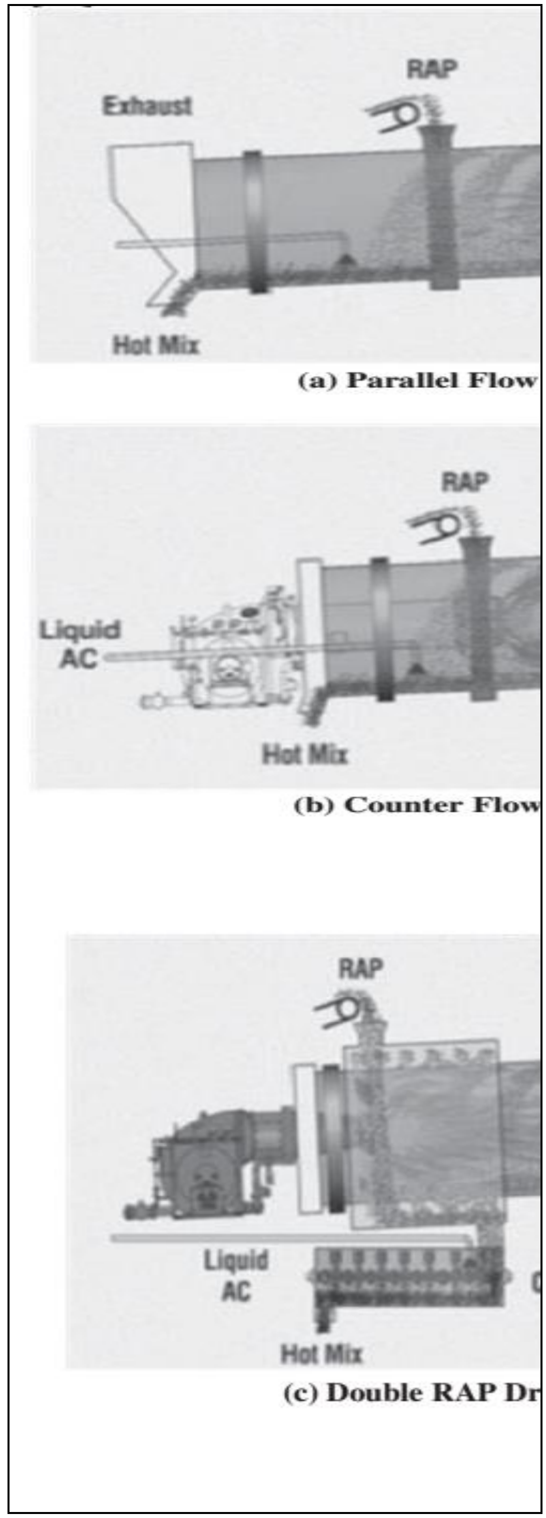


Figure (5): Different Types of Asphalt Mixing Drums [40]

Although the amount of available, and the use of, RAP materials is a function of construction activities at all levels, the National Asphalt Pavement Association (NAPA) reported that usage of RAP in asphalt mixtures reached 76.9 million tons in 2016 in the United States, which shows a 3.6% and 37% increase in using of RAP in 2015 and 2009, respectively (Figure 6). Additionally, in

Europe, reusing RAP in asphalt mixture production started more than 40 years ago, and currently it has an increasing trend in many European countries. Table (6) shows the percentage of total available RAP materials that have been used in the production of HMA, WMA, HWMA, and cold recycling for some European countries from 2007–2017 [63]. Additionally, based on the average value of total used RAP for each year, the trend of using RAP in the production of different types of asphalt mixtures is upward, but has a low slope (see Figure 7).

However, some obstructions limit the use of RAP material to make high-quality asphalt mixtures with most environmental and economic benefits [2]:

- High variability in RAP due to different RAP sources;
- Demolition and milling processes; and
- Aged asphalt binder of RAP.

Table (6): Total percentage of RAP used to hot and warm recycling for European countries during 2007–2017 [2, 41]

Country	% of Available RAP Used in Asphalt Mixture										
	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007
Austria	60	40	45	-	98	98	95	88	90	-	25
Belgium	95	81	64	72	61	61	65	57	57	55	50
Czech Republic	34	47	52	46	43	52	49	50	50	55	85
Denmark	67	65	100	54	83	77	80	56	55	59	57
France	70	70	90	64	64	62	45	40	41	25	15
Germany	85	87	28	90	90	87	84	82	82	82	82
Hungary	95	90	100	90	90	100	100	27	66	44	-
Italy	23	50	50	20	20	20	20	20	20	20	20
Netherlands	82	82	80	85	76	95	98	75	74	83.5	90
Norway	31	37	38	23	26	21	18	40	24	21	34
Slovakia	98	98	99	99	95	95	94	93	-	-	-
Slovenia	39	43	100	25	46	50	50	50	100	100	60
Spain	83	68	96	100	93	77	83	81	66	70	60
Sweden	-	93	95	90	90	85	80	80	95	95	95
Turkey	15	4	2	6	4	7	23	19	3	2	-
Average	64	64	69	62	65	66	66	57	59	55	56

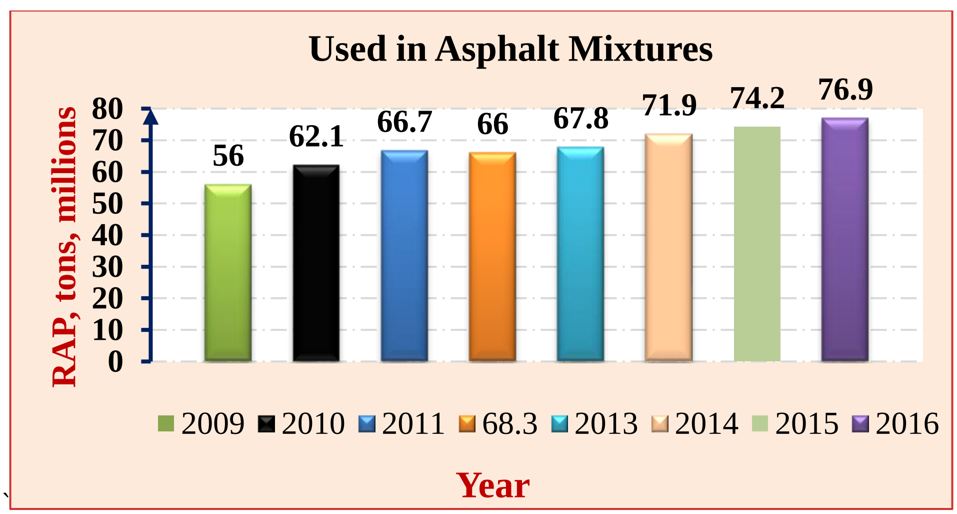


Figure (6): Summary of RAP usage data in the U.S during 2009–2016 [2]

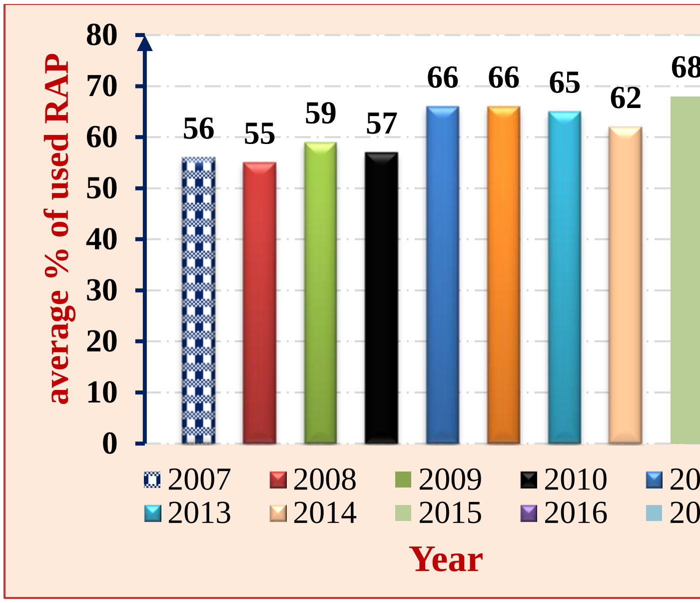


Figure (7): Change in average of using RAP in production of asphalt mixtures in Europe from 2007–2017[2]

3.2 Limitations of RAP use

To understand the limitations of high RAP usage in plant production, NAPA [2, 41] conducted a voluntary survey on asphalt mixture producers, representing 238 companies with 1,158 production plants in the United States, specification limits (38.5%), RAP availability (18.5%), asphalt plant capabilities (15.4%), volumetric requirements (13.8%), and mixture performance (6.2%) the most common inputs from the groups are shown in Figure (8).

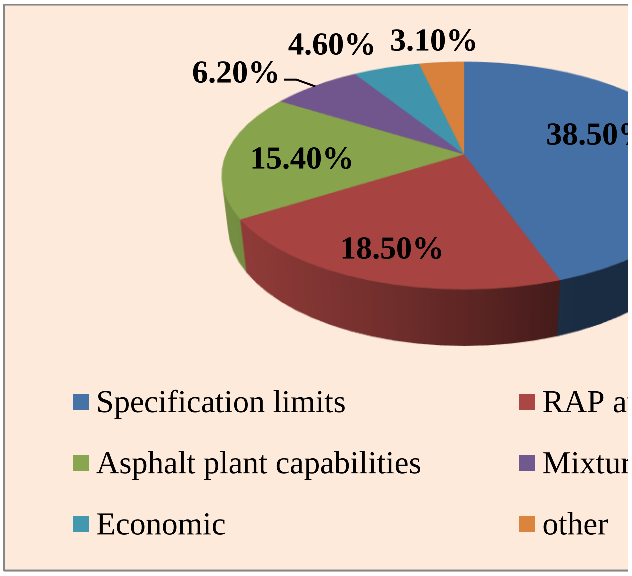


Figure (8): Reported factors limiting the use of RAP (NAPA 2017) [2, 41]

3.3 Environmental Evaluation

Before production, preparation of raw materials including aggregate and asphalt binder also demands energy that should be looked into when conventional virgin aggregate and/or asphalt binder are replaced by other materials. Generally, the following factors have significant effects on the environmental impact of asphalt mixture production using RAP: moisture content, HMA discharge temperature, RAP content, transport process, and quality of RAP [42–43].

Currently, there are two approaches to add RAP to virgin materials for asphalt mixture production. In the first approach, RAP is added cold to the overheated virgin materials in the drum mixer. Although as an advantage, this approach can be easily implemented in an asphalt plant, it needs a higher temperature for virgin materials and a longer mixing time especially at a high percentage of RAP.

On the other hand, the second approach is adding preheating RAP materials to the asphalt mixture. The preheating process can be usually done using a parallel drum and, therefore, it increases the cost of production because using a parallel drum requires high investment for modification of plant. Compared to the virgin aggregates, RAP materials have higher moisture content because milling of the old pavements needs water [43,44].

Therefore, using this approach, the better control of RAP moisture content can be achieved. A study reported an increase in energy consumption up to 14% and 17% could be observed when 15–30% and more than 45% RAP, respectively, were used in new asphalt mixtures [45]. However, the other studies stated that producing asphalt binder consumes 3,110,090 MJ of energy and releases of 226,870 kg of GHG and replacing 50% of RAP as binder replacement can result in 17–28% reduction of energy consumption as well as emissions [46,47].

Using 10–20% RAP in the HMA mixtures, ***Giani et al.*** [43] indicated that there was 6.8% and 6.4% reduction for greenhouse gasses (ton $CO2_{eq}$) and the single score endpoint impact, respectively, for a 15 years lifespan analysis. Furthermore, 40% reduction in emission of the CO2e was reported when 75% RAP was in a production of HMA mixtures. The comparison between GHG emissions for virgin and 20% RAP mixtures (Figure (9)) revealed that adding RAP can result in averagely 8.3% reduction in air pollutant parameters such as carbon monoxide (CO), oxides of sulfur (SOx), oxides of nitrogen (NOx), volatile organic compound (VOC), and particulate matter (PM) [47].

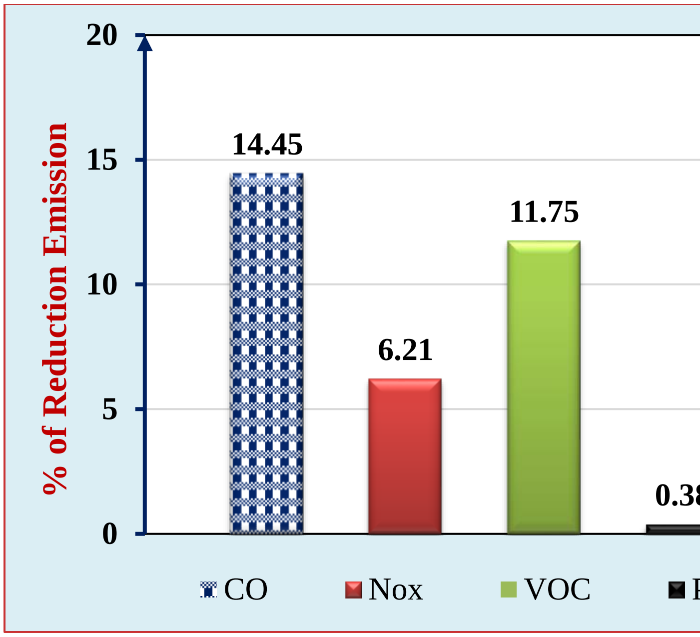


Figure (9): Percentage of reduction in the emission of air pollutants for using 20% RAP [47]

Adding up the energy and emissions due to plant production, transportation, and construction, which are equal for conventional mixtures and those containing RAP, as well as road maintenance, Figures (10, 11) illustrate the total energy consumptions and emissions per km per lane for different RAP percentage. In Figure (11), Carbon dioxide equivalent (CO2eq) is a global warming potential (GWP) unit to measure the environmental impact of one ton of different other greenhouse gases compared to the impact of one ton of CO_2. It can be observed that there is a reduction in both energy consumptions and emissions with RAP content increase. Based on the midpoint (climate change and fossil depletion) and endpoint (human health, ecosystem diversity, resource availability) environmental impacts, results of a study revealed that adding 15% RAP to HMA or WMA mixtures could result in 13–14% reduction on the most of midpoint and endpoint impacts [42]. Moreover, a decreasing trend of environmental impacts (midpoint, endpoint, and cumulative energy demand) was observed as the rate of using RAP increased [48].

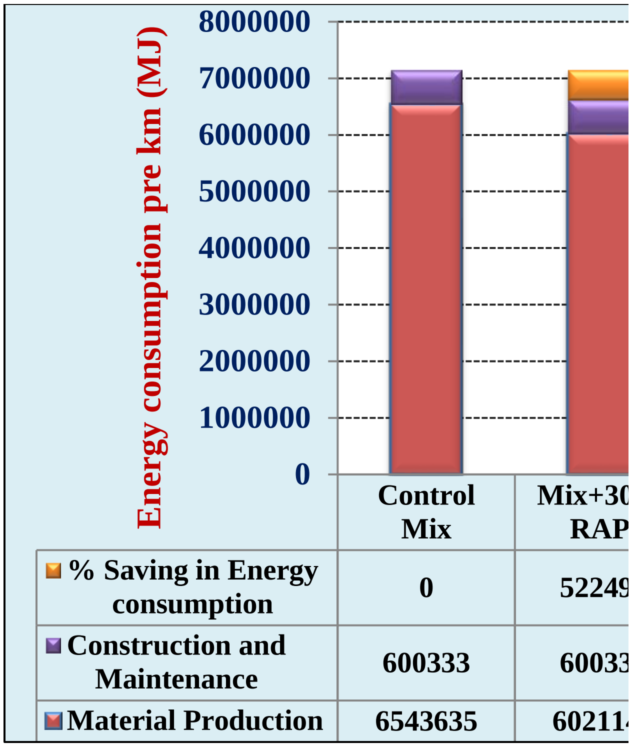


Figure (10): Energy consumption for different RAP content [47]

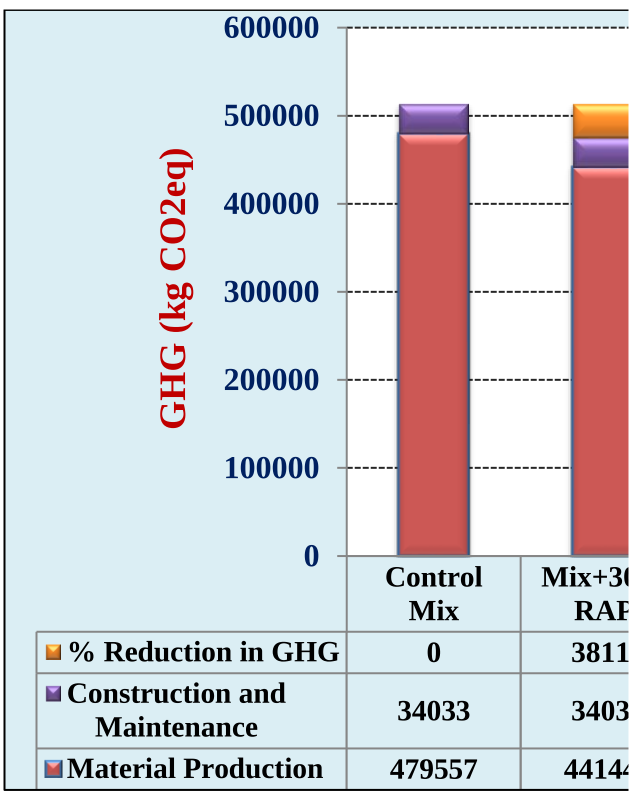


Figure (11): GHG emissions for different RAP content [47]

Applying LCA analysis based upon three performance breakdown scenarios of 100%, 85%, and 70% compared to conventional HMA for mixtures containing RAP, Figures (12, 13) show the trend of how environmental benefits, including energy consumption and GHG emissions reduction, set off with decreased performance. It can be observed that, for all RAP contents, the performance level of 70% demands greater energy and produces higher CO_2 than the control mixture. It can be concluded that the performance is a critical factor in assessing the environmental benefits of using RAP materials in asphalt mixtures.

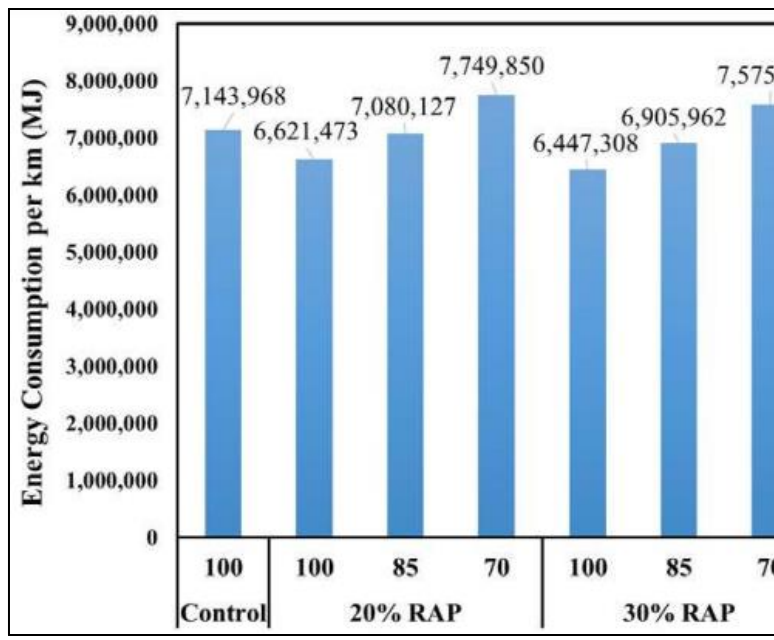


Figure (12): Energy consumption for different RAP content at different performance scenarios [47]

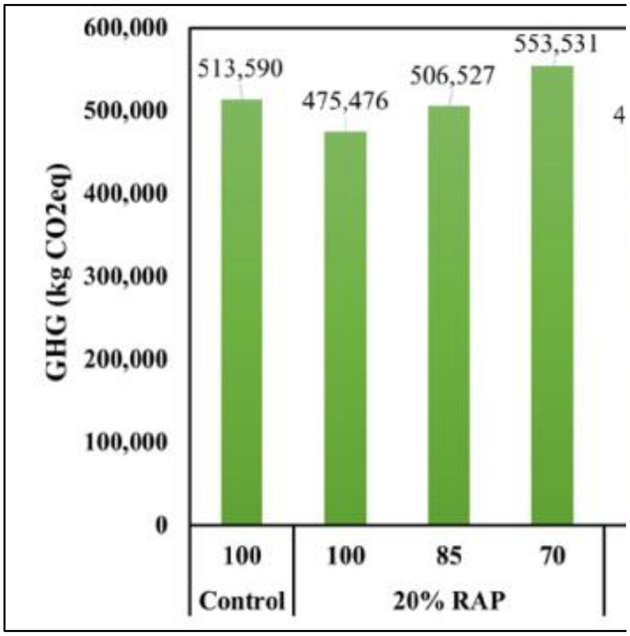


Figure (13): Greenhouse gas emissions for different RAP content at different performance scenarios [47]

3.4 Economic Evaluation

Using reclaimed asphalt materials have significant economical advantages, but these come true only if similar performance to conventional asphalt is ensured. The most expensive and economically variable material in an asphalt mixture is the asphalt binder [49]. By using the RAP material in surface and intermediate layers, can make the pavement construction very economical as the expensive virgin binder will be replaced by less expensive binder from RAP. The consumption of natural aggregates is also reduced by using aggregates obtained from RAP. This will also result in huge economical saving considering the reduction in aggregate requirement and cost of transporting the material. Although there is an additional cost associated with the milling operation and rejuvenators. Studies have suggested that total cost can be reduced up to 35% by using RAP content at 50% [14]. The cost benefits of using high RAP mixtures depend on a numbers of factors which can be material cost, plant efficiency, government incentives etc. Thus it becomes very important to carry out the economic reassessment before choosing the recycling methodology. It will also be very important to lay down standard protocols for reclamation, transportation, storage, mixing and compaction of RAP material so that it is economically feasible.

The increased cost of bitumen and ban on mining of natural aggregates push to find alternate construction material such as RAP. RAP replacement level up to 100% can curtail cost per ton of asphalt by 50 to 70% as shown in Figure (14) [50].

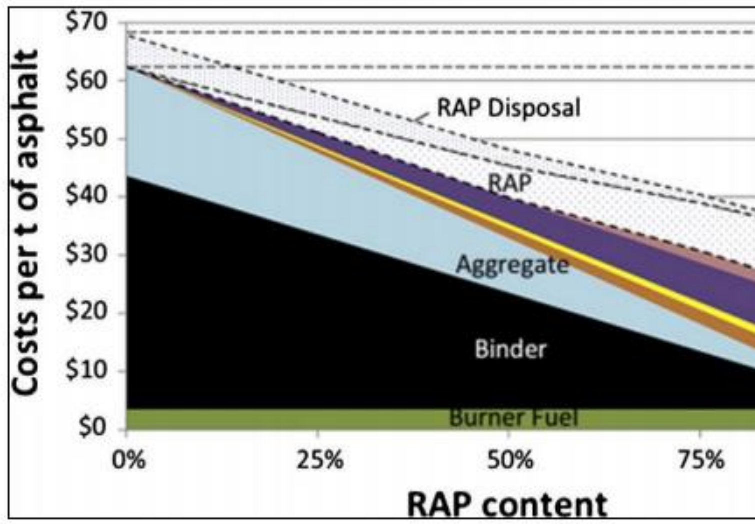


Figure (14): Cost of construction v/s percent RAP content [50]

Table (7) shows how recovered binder from 20% and 40% of RAP can reduce the amount of total as well as virgin binder needed based on Superpave mix design [51]. Doubling RAP content leads to approximately twice the reduction in virgin binder content. Therefore, not only does the introduction of RAP decrease the amount of virgin aggregate in asphalt mixtures, but it also lessens the most valuable component of them, i.e., asphalt binder.

With modern asphalt plant design, better RAP processing, and blend controls, more RAP can be introduced into pavement construction without compromising product quality. This makes the asphalt industry consider RAP as valuable as virgin aggregate and asphalt, even which can utilize 100% RAP in producing a good quality mix. An increasing the amount of RAP by 10% provides a considerable saving by reducing the cost of collecting and processing to approximately one fifth of the raw materials.

Table (7): Effect of RAP on virgin and total binder contents [51]

RAP Content (%)	Total needed Binder (%)	Virgin Binder (%)	Recovered Binder (%)	Reduced Virgin Binder (%)
0	5.9	5.9	0	0
20	5.7	4.8	0.9	15.8
40	5.65	3.8	1.85	32.7

One study reported that using 20–50% of RAP materials in HMA results in saving between 14 to 34% in material and production costs [52]. Additionally, the saving percentages of 15% and 16% were reported by FEDERAL HIGHWAY ADMINISTRATION (FHWA) and the U.S. Corps of Engineers, respectively, due to using RAP materials in asphalt mixtures [59]. Table (8) shows the percentage of material cost saving in different regions of the US as well as total saving based on the different percentage of RAP in the mixture. For example, between 1979 and 2002, the Florida Department of Transportation reported that reusing of RAP in the production of HMA mixtures could result in $224 million saving which is equal to two-thirds of its annual resurfacing budget [53]. Additionally, the cost-benefit of using RAP in HMA mixtures for some plants was investigated by Franke and Ksaibati [54]. Results of this study showed that there was a remarkable amount of savings ($40.87 per ton) in the application of RAP in hot mix asphalt. Amount of savings due to the use of RAP in asphalt mixtures for 2015–2017 construction season in the United States is shown in Table (9) [53]. This indicates that the using of RAP resulted in a reduction of the asphalt mixture production costs approximately $6.6 billion in compared to the use of all virgin materials during the 2015–2017 construction seasons.

Table (8): Typical cost savings in different regions of the US and material cost savings [53]

Region	Average Saving (%)
South Central	10–13
North Central	20
Southwest	4–18
Northwest	24–26

% of RAP	Cost/ton	Saving $/ton	Saving (%)
0	11.9	-	-
20	10.26	1.64	14
30	9.44	2.46	21
40	8.62	3.28	28
50	7.8	4.1	34

Table (9): Saving in materials due to using RAP in the U.S[53]

Material	Material Quantity, Million Tons			Aggregate Cost Savings ($ Billion)			Asphalt Binder Cost Savings ($ Billion)			Total Cost Savings ($ Billion)		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
RAP	74.2	76.9	76.2	0.663	0.713	0.734	1.787	$1.333	1.393	2.450	2.046	2.127

The economic benefits of recycling have been enhanced by new methods that allow using increased amounts of RAP in asphalt mixtures. It is appropriately done; RAP mixtures can provide the same or better properties and performance than virgin asphalt mixtures. A typical section for one kilometer length, 12m width, and 0.05m thickness from a 2013 (Cairo–Alexandria) agricultural road project is analyzed. The details of economic analysis by using national asphalt pavement association (NAPA) method are shown in Table (10). It can be observed that the adding of RAP has a great influence on saving money where the savings in material cost increase by about 23.70%, 45.64%, 62.98% and 64.84% for RAP content of 25, 50, 75 and 100% respectively by Abu El-Maaty and El-Moher [55].

Table (10): Economic analysis on using RAP in HMA [55]

RAP Content (%)	Total cost (L.E)	Cost Saving (%)
0	370486	-
25	4.282660	23.70
50	201367	45.64
75	137156	62.98
100	130259	64.84

3.5 Performance

The effect of RAP material percentage on the performance of asphalt mixtures has been investigated by many researchers. In the case of rutting performance, it was described as an improvement by using RAP due to harder asphalt binder [56]. Although this improvement largely depends on the RAP properties and content, it has been reported that adding 25–30% RAP can result in a double increase on rutting resistance. The soft binder or rejuvenators are usually used to improve the fracture toughness of mixtures containing RAP by countering the stiffness of RAP. However, the acceptable rutting performance has been found for mixtures containing RAP with rejuvenators at the optimum content [57].

There is an inconsistency in case of fatigue performance. Although the fatigue resistance behavior can be improved due to the stiffer nature of a RAP mixture, this is only true in constant strain testing condition, and there is no evidence for the consistent level of improvement [58]. This inconsistency gets worse at a higher percentage of RAP materials [59] due to the stiffer nature of the recycled mixtures (the thermal resistance of mixtures decreases). A summary of some laboratory studies on the effect of increasing of RAP on the performance of asphalt mixtures is shown in Table 11. In this Table, "mixed" effect refers to observation of both increase and decrease on the corresponding performance parameter. It can be seen that although increasing percentages of RAP results in better rutting resistance and higher stiffness, it increases low-temperature cracking potential. Mixed results can be found for cracking potential at intermediate temperatures and moisture sensitivity

Table (11): Effect of increasing RAP on mixture performance [2]

Performance	Testing Parameter	Effect			
		Same	Increase	Decrease	Mixed
Stiffness	Dynamic Modulus (E*)		√		√
	Phase Angle			√	
Rutting	Deflection	√		√	
	Creep Stiffness				√
	Creep Flow Time		√		
Moisture Susceptibility	Moisture Sensitivity	√	√		

	Toughness Index			√	
Cracking	Fatigue	√	√	√	√
	Reflective		√		
	Thermal	√	√		

Abu El-Maaty and El-Moher [55] investigated the use of a reclaimed asphalt pavement in the pavement industry in Egypt evaluating the effects of partial and total replacements of aggregates by RAP on the mechanical and volumetric response of dense-graded HMA mixtures. The laboratory results indicated that when properly designed, the asphalt mixes with RAP especially at 50%to 100% replacement ratio provided better performance compared to those of new conventional HMA mixtures. While cost analysis showed at least 45-64% savings in material cost related expenses. Performance Indicators of RAP Mixtures are shown in Table (12).

Table (12): Performance Indicators of RAP Mixtures [55]

% of RAP	**0**	**25**	**50**	**75**	**100**
Marshall Quotient QS; kg/mm	340.48	344.62	370.35	380.85	424.11
Indirect Tensile Strength ITS; kpa	732	776	1507	1332	1322
Resilient modulus MR; Mpa	101.9	125.97	266.74	288.14	321.89
Absorbed Energy; N	0.8	0.98	2.166	2.188	2.62
Rutting Depth; mm	8.17	7.35	5.39	3.57	2.45

3.6 Permanent Deformation (Rutting)

Rutting is one of the main distresses in asphalt pavements; it is defined as the depression under the wheel path and can be clearly observed after a rainfall. Rutting is one of the essential parameter in design and evaluation of asphalt pavements, and it occurs mainly in the first 5-7 years of an asphalt pavement life. Pradyumna et al. [60] evaluated rutting resistance on mixes with 20% RAP, they utilized a Wheel Tracking Device (WTD) with an application of 20,000 passes of the rolling wheel at 45 °C. The result showed that mixes with RAP exhibited lower rutting depths than virgin mixes. Thus, the addition of RAP improved the rutting resistance of an asphalt mix, since mixes with RAP become stronger and stiffer when compared to virgin mixes leading to better resistance to permanent deformation.

Abu El-Maaty and El-Moher [55] suggested that mixes with RAP, especially at 50% to 100%, when properly designed showed better performance compared to those of virgin mixes. Mixes with RAP showed improvement in the indirect tensile strength where the highest value was achieved at 50% RAP content exhibited a 106% increase when compared to control mixes. Additionally, the increase in RAP content enhanced the resilient modulus, absorbed energy, and rutting by about 216%, 194% and 70% respectively.

3.7 Fatigue Cracking

Fatigue cracking starts from the bottom of the asphalt layer where the tensile stress and strain is high due to repeated loading and it propagates to the surface layer as one or few longitudinal parallel cracks. These cracks increase and connect with other cracks and form a net, which is called alligator cracking. Tabakovic´ et al. [61] conducted laboratory tests on asphalt mixes with RAP and results showed an improvement in all mechanical properties, especially mixes with 30% RAP performed better than control mixes with no RAP in Fatigue tests. In particular, it was found that the mixes containing up to 30% RAP, displayed improved fatigue resistance relative to the control mix manufactured from virgin materials.

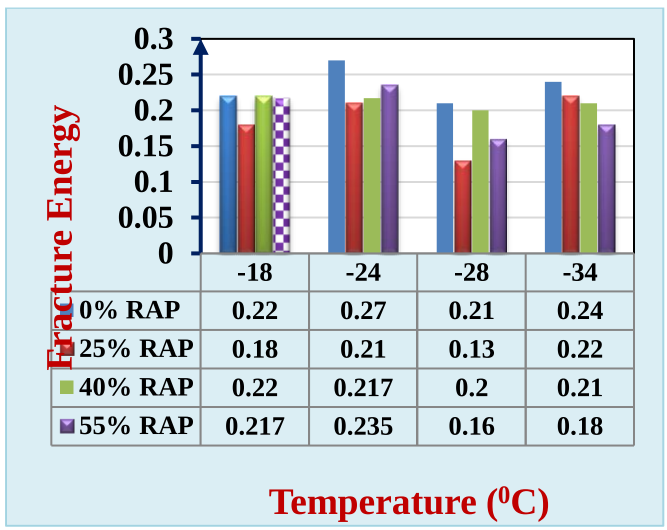
Ajideh et al. [62] investigated asphalt mixes that contained 50% RAP. They developed scanning laser detection technology, which could scan tested samples and capable of capturing cracks and exhibits a strong correlation with the results from the conventional and energy-based approaches. Based on their results, they argued that the 50% RAP mix could be environmental and economic beneficial and exhibit good performance.

Pradyumna et al. [60] observed an improvement in the fatigue life with increase of RAP content in an asphalt mix. It was found that by adding 20% RAP, fatigue life increased by 67.2% compared to a virgin mix.

A study by ***Sunil et al.*** [63] on fatigue life of mixes with different RAP contents found that the increase of RAP reduced fatigue resistance of these mixes. Fatigue tests were conducted at three stress ratios (60%, 70% and 80%), as shown in Figure 6, the number of cycle to failure reduced with increase of the percentages of RAP but still met the design requirements.

3.8 Thermal Cracking

Thermal cracking defined as an isolated crack that runs perpendicular to traffic, it occurs at high load combined with cold temperatures at which the asphalt pavement becomes very stiff and brittle and breaks. Low temperature testing of laboratory mixes with up to 55% RAP, found that the creep stiffness measured by the Indirect Tensile Test (IDT) increased along with RAP content and that the addition of RAP significantly reduced crack resistance. Also, the increase of RAP in mixes lowered the fracture energy measured by the Semi-Circular Bend Fracture Test (SCBT). Thus, the increase in RAP content led to a drop in fracture resistance at cold temperatures [64].Taha et al. [65] explored thermal cracking resistance of mixes containing RAP. It was found that at lower temperatures, the mix containing a lower RAP content was stiffer resulting in higher creep compliance and indirect tensile strength values. In a similar study, Solanki et al. [66] argued that mixes with RAP showed a slight increase in IDT strengths but were not enough to cause larger increases in thermal stress. Results from SCBT Tests showed that with the increase of RAP, the fracture energy decreased and the fracture toughness increased in these mixes as illustrated in Figure (15). Furthermore, all tested mixes did not meet the fracture toughness or energy minimum recommended levels.



	-18	-24	-28	-34
0% RAP	0.22	0.27	0.21	0.24
25% RAP	0.18	0.21	0.13	0.22
40% RAP	0.22	0.217	0.2	0.21
55% RAP	0.217	0.235	0.16	0.18

Figure (15): SCBT Tests Results for Different Percentages of RAP [66]

4. Conclusions

In this paper, the research works on the utilization of wastes materials as a substitute to virgin aggregates and asphalt binder, as well as warm mix asphalt WMA) technologies, were reviewed from the standpoint of sustainability (environmental, economic, and engineering performance aspects). Waste management, GHG emissions, and energy consumption that lead to more environmentally-friendly products were addressed.

From the literature, it was found that there are few negative impacts associated with the use of warm additives in asphalt mixtures, which are as follows:

- Reduced durability: The use of warm additives may reduce the durability of asphalt mixtures, as the lower mixing and compaction temperatures may result in less effective bonding between the aggregate and asphalt binder. This can lead to reduced resistance to rutting, cracking, and other types of pavement distress.
- Reduced workability: While warm additives can improve the workability of asphalt mixtures, there is a risk that they may also reduce workability if not used properly. This can result in issues with compaction and density, which can affect the long-term performance of the pavement.
- Increased sensitivity to moisture: Warm mix asphalt (WMA) mixtures containing warm additives may be more sensitive to moisture than hot mix asphalt (HMA) mixtures. This can result in reduced durability and performance in wet conditions.

Also, there are a few potential negative effects associated with using recycled asphalt pavement (RAP) in asphalt mixtures, which are as follows:

- Reduced durability: RAP typically contains old, oxidized asphalt binder that has been exposed to the elements for years. When this aged binder is incorporated into new asphalt mixtures, it can reduce the overall durability and performance of the mix. This is because the old binder may be more brittle and less flexible than fresh binder, which can lead to cracking and other types of distress in the pavement.
- Reduced workability: RAP can also have a negative impact on the workability of asphalt mixtures. This is because the old binder in RAP tends to be stiffer and more viscous than fresh binder, which can make it more difficult to mix and compact the asphalt mixture. This can lead to issues with density and stability, which can affect the long-term performance of the pavement.
- Environmental concerns: While the use of RAP can be environmentally beneficial in terms of reducing the amount of waste sent to landfills, there are also potential environmental concerns associated with its use. For example, RAP may contain contaminants such as asbestos or lead that can pose health risks if not properly handled and disposed of.

5. Future Study

- Studying is to produce a sustainable warm asphalt mixture by using Egyptian petroleum wax and investigating its performance.
- Investigating sustainable warm asphalt mixtures containing high percentages of RAP.
- Identifying a parameter to assess the cracking resistance of RAP asphalt mixtures
- Evaluating of Bitumen and Warm Asphalt Mixtures Modified with by product additives (as Fly Ash and Silica Fume) and waste materials as iron powder
- Modeling of pavement section on a finite element program to predict pavement behavior.
- Improving the Warm Mixture sensitivity to moisture by product additives (as Fly Ash and Silica Fume) and waste materials as iron powder.
- Improving durability and workability of RAP mixes by using rejuvenators

References

[1] Husam Al., Jawad Al., Munder B., Ali M., Nuha S., Nur I.and Abdalrhman M., Encouraging Sustainable Use of RAP Materials for Pavement Construction in Oman: A Review, Recycling, MDPI, 2022.

[2] Hansen, K.R.; Copeland, A. Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage, National Asphalt Pavement Association: Lanham, MD, USA, 2017; No. IS 138(7e).

[3] Kahn, B. We Just Breached the 410 Parts Per Million Threshold, Climate Central, Archived News, 2019.

[4] Wang, T.; Xiao, F.; Zhu, X.; Huang, B.; Wang, J.; Amirkhanian, S. Energy consumption and environmental impact

of rubberized asphalt pavement. J. Clean. Prod. 2018, 180, 139–158.

[5] Jialin Z., Taiwo S., Qinglong Y.,and Hongjun J., Maximizing the Application of RAP in Asphalt Concrete Pavements and Its Long-Term Performance: A Review, Polymers, MDPI, 2022, 14, 4736.

[6] Daniela L., Joao S. and Gilberto M., Environmental performance evaluation of warm mix asphalt with recycled concrete aggregate for road pavements, INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING, 2021.

[7] West, R.; Rodezno, C.; Julian, G.; Prowell, B.; Frank, B.; Osborn, L.V.; Kriech, T. Field Performance of Warm Mix Asphalt Technologies; NCHRP Report 779; Transportation Research Board: Washington, DC, USA, 2014.

[8] Kenneth A., Yaw A., Warm-Mix Asphalt and Pavement Sustainability: A Review, Open Journal of Civil Engineering, 2016, 6, 84-93.

[9] Bugra Sinmez., "Asphalt and Asphalt Mixes. " University of South Florida, College of Engineering, Civil and Environmental Engineering, CGN 6933-903., 2018.

[10] Gandu Srikanth, Rajiv Kumar, Rohit Vasudeva , A Review on Warm Mix Asphalt", Proceedings of National Conference: Advanced Structures, Materials And Methodology in Civil Engineering (ASMMCE – 2018), 03 - 04th November, 2018.

[11] Newcomb, D.E.; Arambula, E.; Yin, F.; Zhang, J.; Bhasin, A.; Li, W.; Arega, Z. Properties of Foamed Asphalt for Warm Mix Asphalt Applications; Transportation Research Board: Washington, DC, USA, 2015; No. Project 09-53.

[12] Rubio, M.C.; Martínez, G.; Baena, L.; Moreno, F. Warm Mix Asphalt: An overview. J. Clean. Prod. 2012.

[13] Shishehbor, M.; Pouranian, M.R.; Imaninasab, R. Evaluating the adhesion properties of crude oil fractions on mineral aggregates at different temperatures through reactive molecular dynamics. Pet. Sci. Technol. 2018, 36, 2084–2090.

[14] Shishehbor, M.; Pouranian, M.R.; Ramezani, M.G. Molecular investigations on the interactions of graphene, crude oil fractions and mineral aggregates at low, medium and high temperatures. Pet. Sci. Technol. 2019, 1–8.

[15] Federal Highway Administration (FHWA). Warm Mix Asphalt Technologies and Research, 2019.

[16] National Academies of Sciences, Engineering, and Medicine (NASEM). Long-Term Field Performance of Warm Mix Asphalt Technologies; The National Academies Press: Washington, DC, USA, 2017.

[17] Anda L., Adrian C., Raluca B., Florin B. and Ciprian C., Environmental Impact Assessment of Different Warm Mix Asphalts, Sustainability, MDPI, 2021, 13, 11869.

[18] Bennert, T. Evaluation of Warm Asphalt Technology—Feasibility Study; NJDOT Project, 1; New Jersey Department of Transportation Bureau of Research and Technology: Trenton, NJ, USA, 2008.

[19] Kristjánsdóttir, Ó.; Muench, S.; Michael, L.; Burke, G. Assessing potential for warm-mix asphalt technology adoption. Transp. Res. Rec. J. Transp. Res. Board 2007, 2040, 91–99.

[20] Martin, A.E.; Arambula, E.; Yin, F.; Park, E.S. Validation of Guidelines for Evaluating the Moisture Susceptibility of WMA Technologies; Transportation Research Board: Washington, DC, USA, 2016; No. Project 09-49B

[21] Bonaquist, R.F. Mix Design Practices for Warm Mix Asphalt; Transportation Research Board: Washington, DC, USA, 2011; Volume 691.

[22] Oliveira, J.R.M.; Silva, H.M.R.D.; Abreu, L.P.F.; Fernandes, S.R.M. Use of a warm mix asphalt additive to reduce the production temperatures and to improve

the performance of asphalt rubber mixtures. J. Clean. Prod. 2013, 41, 15–22.

[23] Jones, D.; Wu, R.; Tsai, B.W.; Harvey, J.T. Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing and Phase 1 and Phase 2 Forensic Assessments: No. UCPRC-RR-2009-02; University of California Pavement Research Center: UC Davis, UC Berkley, July 2009.

[24] West, R.; Timm, D.; Willis, R.; Powell, B.; Tran, N.; Watson, D.; Sakhaeifar, M.; Brown, R.; Robbins, M.; Vargas-Nordcbeck, A.; et al. Phase IV NCAT Pavement Test Track Findings; Auburn University: Auburn, AL, USA, 2012.

[25] Xiao, F.; Punith, V.S.; Amirkhanian, S.N. Effects of non-foaming WMA additives on asphalt binders at high performance temperatures. Fuel 2012, 94, 144–155

[26] Ghabchi, R.; Singh, D.; Zaman, M. Laboratory evaluation of stiffness, low-temperature cracking, rutting, moisture damage, and fatigue performance of WMA mixes. Road Mater. Pavement Des. 2015, 16, 334–357.

[27] Jamshidi, A.; Hamzah, M.O.; You, Z. Performance of Warm Mix Asphalt containing Sasobit®: State-of-the-Art. Constr. Build. Mater. 2013, 38, 530–553.

[28] Notani, M.A.; Moghadas Nejad, F.; Khodaii, A.; Hajikarimi, P. Evaluating fatigue resistance of toner-modified asphalt binders using the linear amplitude sweep test. Road Mater. Pavement Des. 2018, 1–14.

[29] Goh, S.W.; You, Z. Moisture damage and fatigue cracking of foamed warm mix asphalt using a simple laboratory setup. In Transportation and Development Institute Congress 2011: Integrated Transportation and Development for a Better Tomorrow; American Society of Civil Engineering (ASCE): Reston, Virginia, USA, 2011; pp. 762–771.

[30] Das, P.K.; Tasdemir, Y.; Birgisson, B. Low temperature cracking performance of WMA with the use of the Superpave indirect tensile test. Constr. Build. Mater. 2012, 30, 643–649.

[31] Hill, B.; Behnia, B.; Hakimzadeh, S.; Buttlar, W.G.; Reis, H. Evaluation of low-temperature cracking performance of warm-mix asphalt mixtures. Transp. Res. Rec. 2012, 2294, 81–88.

[32] Sholar, G.; Nash, T.; Musselman, J.; Upshaw, P. FDOT's Experience with Warm Mix Asphalt; Report No. 09-527; Florida Department of Transportation: Gainesville, FL, USA, 2009.

[33] Mazumder, M.; Sriraman, V.; Kim, H.H.; Lee, S.J. Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA). Int. J. Pavement Res. Technol. 2016, 9, 190–201.

[34] Leng, Z.; Al-Qadi, I.L.; Cao, R. Life-cycle economic and environmental assessment of warm stone mastic asphalt. Transp. A Transp. Sci. 2018, 14, 562–575.

[35] Wen, H. Use of fracture work density obtained from indirect tensile testing for the mix design and development of a fatigue model. Int. J. Pavement Eng. 2013, 14, 561–568.

[36] Horvath, A. Earlier Faculty Research Title Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements, 2019.

[37] FHWA (2012). User Guidelines for Waste and Byproduct Materials in Pavement Construction. Federal Highway Administration, USA, 2012.

[38] Ishraq Hameed Naser, A review of RAP and its use in pavement engineering, Global Journal of Engineering and Technology Advances, 2021, 07(01), 073–084.

[39] Rismawansyah, M. Ihsan, ''Aging Simulation of Hot Mix Asphalt Mixtures Utilizing Reclaimed Asphalt Pavement'', Proceedings of the 2nd Makassar International Conference on Civil Engineering, 2015.

[40] Ahmad M. Abu Abdo, ''Utilizing Reclaimed Asphalt Pavement (RAP) Materials in New

Pavements'', the International Journal of Thermal & Environmental Engineering, 2016.

[41] M Rathore, M Zaumanis and V Haritonovs ''Asphalt Recycling Technologies: A Review on Limitations and Benefits'', Conf. Series: Materials Science and Engineering, 2019.

[42] Pala Gireesh kumar, A Comprehensive Review on the Replacement of Virgin Material using Reclaimed Asphalt Pavement (RAP) Material in Flexible Pavements, IOP Conf. Series: Materials Science and Engineering, 2020.

[43] Giani, M.I.; Dotelli, G.; Brandini, N.; Zampori, L. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. Resour. Conserv. Recycl. 2015, 104, 224–238.

[44] Anthonissen, J.; Braet, J. Life cycle assessment of bituminous pavements produced at various temperatures in the Belgium context. Transp. Res. Part D Transp. Environ. 2015, 41, 306–317.

[45] Anthonissen, J.; Braet, J. Review and environmental impact assessment of green technologies for base courses in bituminous pavements. Environ. Impact Assess. Rev. 2016, 60, 139–147.

[46] Leyssens, D.; Verstappen, B.; Huybrechts, D. Best Available Techniques for Asphalt Plants [Beste Beschikbare Technieken voor asfaltcentrales]. BBT-kenniscentrum VITO, Mol. 2013.

[47] Aurangzeb, Q.; Al-Qadi, I.L.; Ozer, H.; Yang, R. Hybrid life cycle assessment for asphalt mixtures with high RAP content. Resour. Conserv. Recycl. 2014, 83, 77–86.

[48] Giulia T. , Piergiorgio T.and Cesare S., The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review, Materials, MDPI, 2020, 13, 4052

[49] Oliveira, J.R.M.; Silva, H.M.R.D.; Abreu, L.P.F.; Fernandes, S.R.M. Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures. J. Clean. Prod. 2013, 41, 15–22.

[50] A Sharma, G D Ransinchung1, P Kumar, and D S N V A Kumar, ''Design Mixture of RAP-HMA Pavements: A Review'', Conf. Series: Materials Science and Engineering, 2021.

[51] Al-Qadi, I.L.; Carpenter, S.H.; Roberts, G.; Ozer, H.; Aurangzeb, Q.; Elseifi, M.; Trepanier, J. Determination of Usable Residual Asphalt Binder in RAP; Research Report ICT-09-031; Illinois Center for Transportation (ICT): Rantoul, IL, USA, 2009.

[52] Kandhal, P.S.; Mallick, R.B. Pavement Recycling Guidelines for State and Local Governments: Participant's Reference Book; National Center for Asphalt Technology: Auburn, AL, USA, Report Number FHWA-SA-98-042

[53] Horvath, A. Earlier Faculty Research Title Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements, 2019.

[54] Franke, R.; Ksaibati, K. A methodology for cost-benefit analysis of recycled asphalt pavement (RAP) in various highway applications. Int. J. Pavement Eng. 2015.

[55] Abu El-Maaty, A.E. and A.E. El-Moher (2015). Evaluation of Hot Asphalt Mixtures Containing Reclaimed Asphalt Pavements. International Journal of Engineering and Advanced Technology (IJEAT), (4), pp. 197-206.

[56] Huang, B.; Li, G.; Vukosavljevic, D.; Shu, X.; Egan, B.K. Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. Transp. Res. Rec. 2005, 1929, 37–45.

[57] McDaniel, R.S.; Shah, A.; Huber, G. Investigation of Low-and High-Temperature Properties of Plant-Produced RAP Mixtures; 2012; No. FHWA-HRT-11-058.

[58] Al-Qadi, I.L.; Elseifi, M.; Carpenter, S.H. Reclaimed Asphalt Pavement—A Literature Review; Federal Highway

Administration, IL, USA (March 2007), Report No.: FHWA-ICT-07-001.

[59] Huang, B.; Zhang, Z.; Kingery, W.; Zuo, G. Fatigue crack characteristics of HMA mixtures containing RAP. In Proceedings of the Fifth International RILEM Conference on Reflective Cracking in Pavements, Limoges, France, 5–7 May 2004; RILEM Publications SARL: Paris, France, 2004; pp. 631–638.