

# An Overview on Sustainable and Ecofriendly 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.

**Keywords:** Sustainability, Reclaimed asphalt pavement, Performance, Asphalt mixture, Warm Mix Asphalt

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## 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<sub>2</sub> 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  $14.4 \times 10^6$  m<sup>3</sup> of fuel,  $1.28 \times 10^4$  GWh of electrical consumption and 46.08 million tons of CO<sub>2</sub> emissions, accounting for 0.15% of global CO<sub>2</sub> emissions.

The economy is a vital aspect of the industry, and any efforts to improve the environment should align with economic constraints. Road pavement construction is resource-intensive and energy-consuming, so any environmental enhancements can lead to economic benefits. While initial costs may rise due to environmental considerations, a thorough long-term assessment can justify these investments. The performance of asphalt mixtures plays a pivotal role in the life-cycle analysis (LCA), influencing the balance between environmental benefits and economic gains. Enhanced performance ensures longer pavement lifespan and improved serviceability, ultimately reducing expenses related to reconstruction, maintenance, and rehabilitation. Moreover, long-term benefits include reduced consumption of natural resources such as fuel, aggregates, and asphalt binder. Achieving the optimal balance between engineering performance, environmental considerations, and economic factors contributes to the sustainability of pavement assets. Typical sustainability studies encompass economic development, social progress, and environmental protection as key components [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/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, 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].

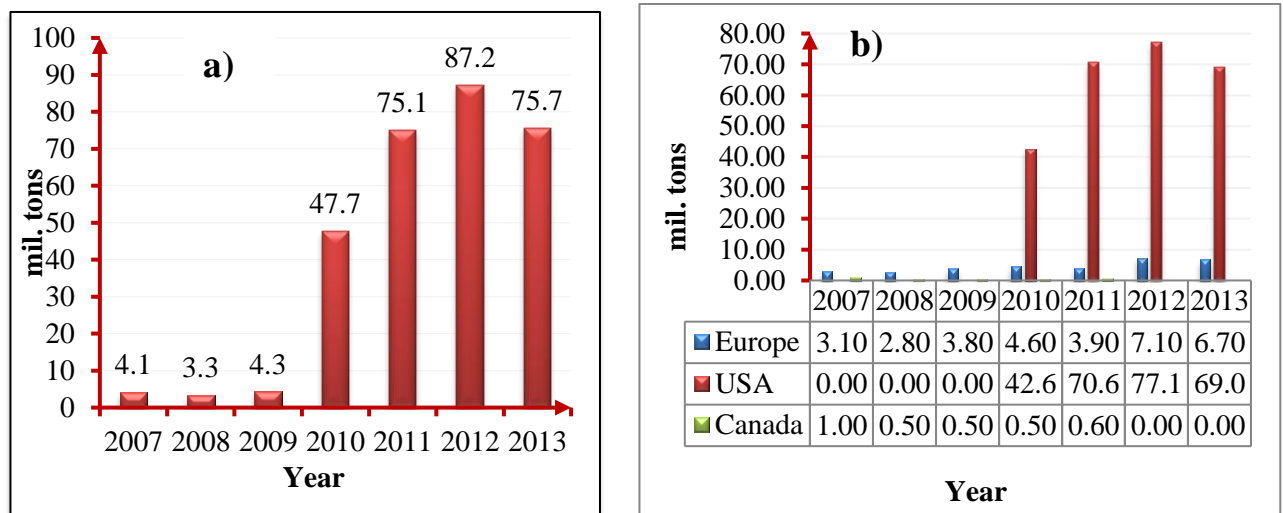


Figure (1): WMA Production in world in mil. tons/ year

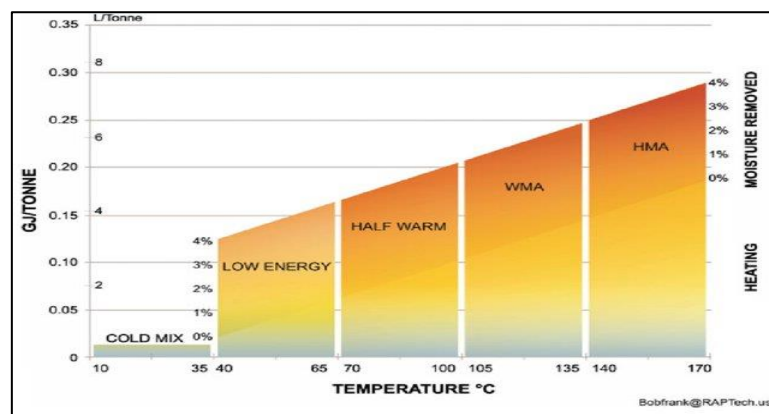


Figure (2): Classification of asphalt mixtures

## 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. Thus, 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. 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), foamability 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: Additives used in warm mix technologies

WMA Technology	Additive Dosage	Mixing Temperature (°C)
<b>Foaming Additive</b>		
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
<b>Organic Additives</b>		
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
<b>Chemical Additives</b>		
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

## 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 [15]. As shown in Table 2, 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<sub>2</sub>), oxides of nitrogen (NO<sub>x</sub>), and carbon monoxide (CO) is significant, in some projects, an increase in sulfur dioxide (SO<sub>2</sub>) 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 CO<sub>2</sub> emission compared to the corresponding HMA due to a 21% reduction in fuel usage [9]. 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 NO<sub>x</sub> emission, results of this study showed a slight reduction while the significant reduction in SO<sub>2</sub> 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 [9].

Table 2: Reduction in gas emissions percentage due to WMA

Emission Component	Oliveira et al.	Middleton and Forfylov	Vaitkus et al.	Powers	D'Angelo et al., Capitão et al.	McIver	Davidson and Pedlow	Larsen et al.	De Groot et al.
CO <sub>2</sub>	32	10.9	30-40	13.8	15-40	46	17.4	31.4	31
SO <sub>2</sub>	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
NO <sub>x</sub>	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 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 [9]. 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 [9], [16]. 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 depreciated over 5–7 years and additive and mix design costs may be compensated by the following benefits of WMA:

- 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 anti-stripping additives for some WMA additives.

## 2.4 Performance

Weak performance in the service, maintenance, and end-of-life phases can undermine the environmental and economic benefits of Warm Mix Asphalt (WMA) technologies during production and construction. Various studies have assessed WMA mixtures, considering laboratory and field evaluations, mix design, and best practices. Key performance aspects include moisture susceptibility, rutting, fatigue, and thermal cracking resistance. Moisture susceptibility, which leads to premature distress, is a primary concern, often caused by inadequate drying of aggregates due to lower mixing temperatures. Some additives like Zycotherm and polyamines can address this issue. Trials in Europe showed promising results with WMA mixtures, demonstrating equal or better adhesion compared to traditional Hot Mix Asphalt (HMA). Studies in the US also reported minimal moisture damage in short-term evaluations of WMA pavements. However, long-term moisture damage resistance is not guaranteed, highlighting the importance of anti-stripping agents to reduce the potential for stripping in WMA mixtures over time, as shown in Hamburg wheel tracking tests [17], [18].

## 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 [19]. 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 [15]. 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 [8]. 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 [7]. 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 [20].

## 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 [21], Sasobit as a wax additive can improve fatigue performance especially when the modified asphalt mixtures are compacted at lower temperature (100–115°C) [22]. 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 [23]. 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 [16], [24].

## 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 [7]. Table 3 showed that the indicators used for better evaluation of performance and engineering properties of WMA mixtures. 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[25], [26].

**Table 3: Indicators used for performance evaluation of WMA mixtures**

Performance	Determinant Parameter	Specification
Moisture Susceptibility	Tensile strength ratio (TSR)	AASHTO T 283
	Rutting resistance index (RRI)	Hamburg wheel tracking (HWT), AASHTO T 324
Rutting	Dynamic modulus ( $E^*$ ) at 30°C	AASHTO TP 79
	Creep compliance at 30°C	AASHTO T 322
	Binder Performance Grade (PG)	AASHTO T 315

	Multiple Stress Creep Recovery parameter (Jnr)	AASHTO TP70 and AASHTO MP19
transverse cracking	Fracture work density value at $-10^{\circ}\text{C}$	Indirect tensile (IDT), AASHTO T 322
	Dynamic modulus ( $E^*$ ) at $-10^{\circ}\text{C}$	AASHTO TP 79
	Indirect tensile strength at $20^{\circ}\text{C}$	ASTM D6931
	Creep compliance at $0^{\circ}\text{C}$	AASHTO T 322
	Vertical failure deformation at $20^{\circ}\text{C}$	
Longitudinal cracking	Indirect tensile strength	
	Vertical failure deformation at $20^{\circ}\text{C}$	IDT test at $20^{\circ}\text{C}$
	Horizontal failure strain from the IDT test at $20^{\circ}\text{C}$	AASHTO T 322
	Creep compliance at $-10^{\circ}\text{C}$	

### 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 [27]:

- 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].

#### 4. 3.1 Reclaimed Asphalt Pavement (RAP)

Due to heavy traffic loads and environmental conditions that are not considered in the design of asphalt pavements, 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-a. The best solution is to mill the surface of the old pavement as shown in Figure 3-b, 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 [28]. 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% [29]. 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 [29].

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 [30]. 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 4. 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 [31].

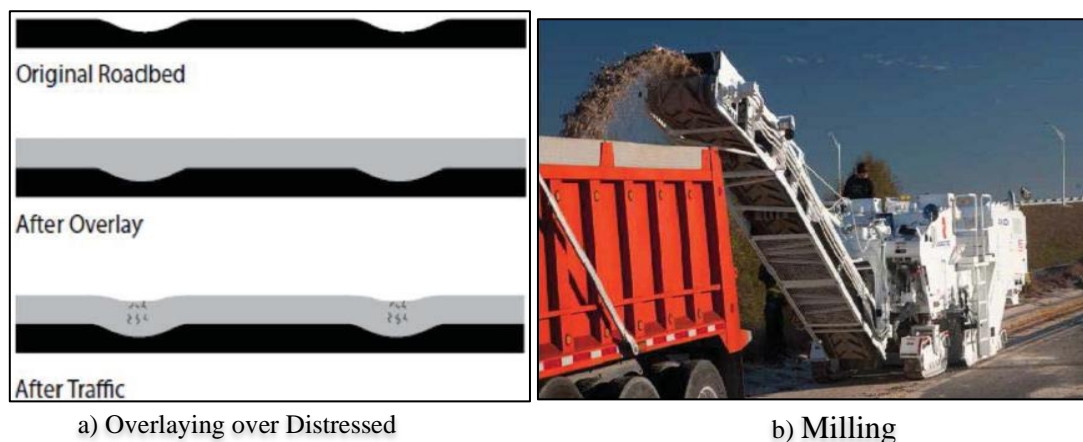


Figure 3: Overlaying over Distressed and Milling of Asphalt Pavement

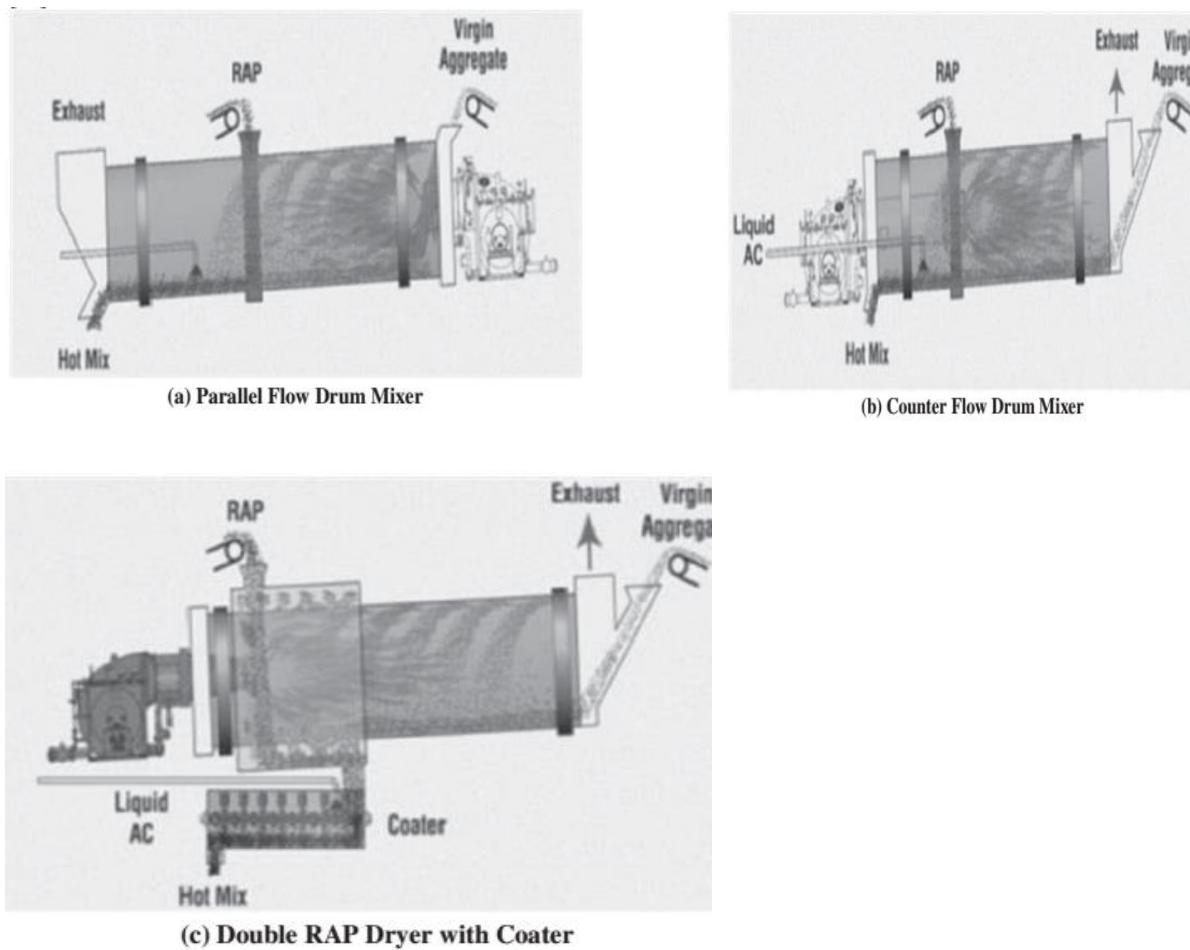


Figure 4: Different Types of Asphalt Mixing Drums

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 5). 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. 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 as shown in Figure 6.

### 3.2 Limitations of RAP use

To understand the limitations of high RAP usage in plant production, NAPA 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 7.

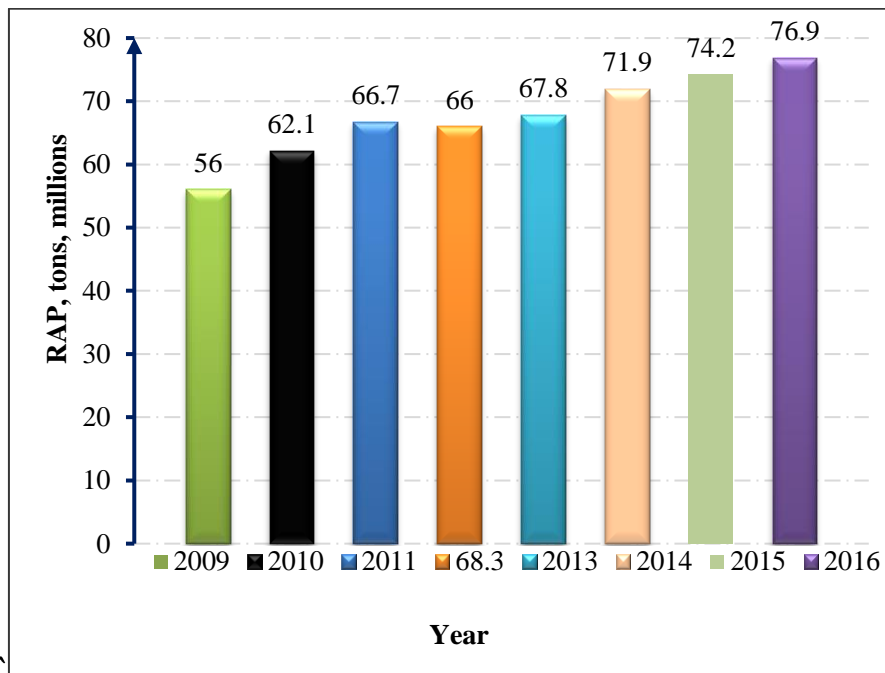


Figure 5: Summary of RAP usage data in the U.S during 2009–2016 <sup>[2]</sup>

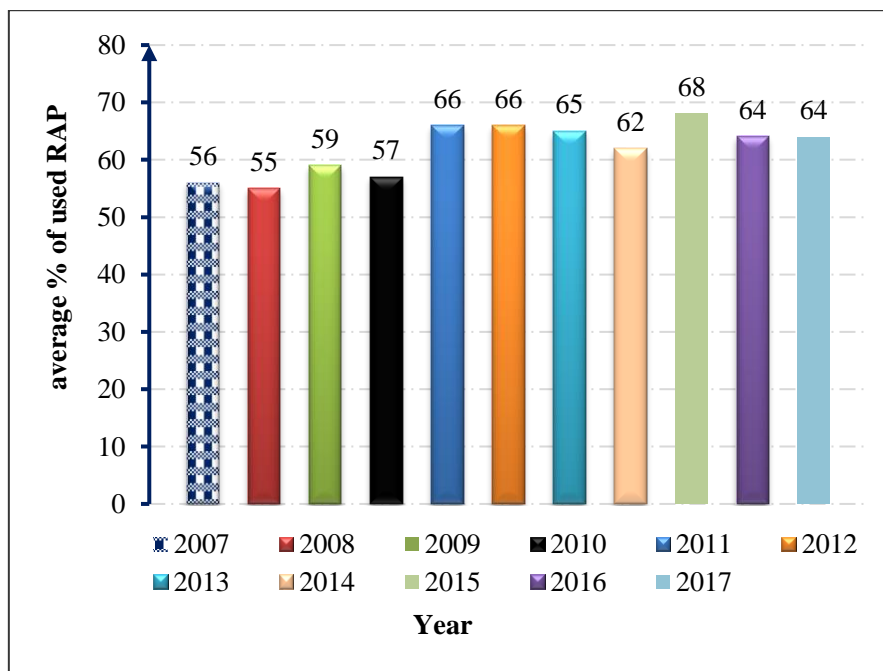


Figure 6: Change in average of using RAP in production of asphalt mixtures in Europe from 2007–2017

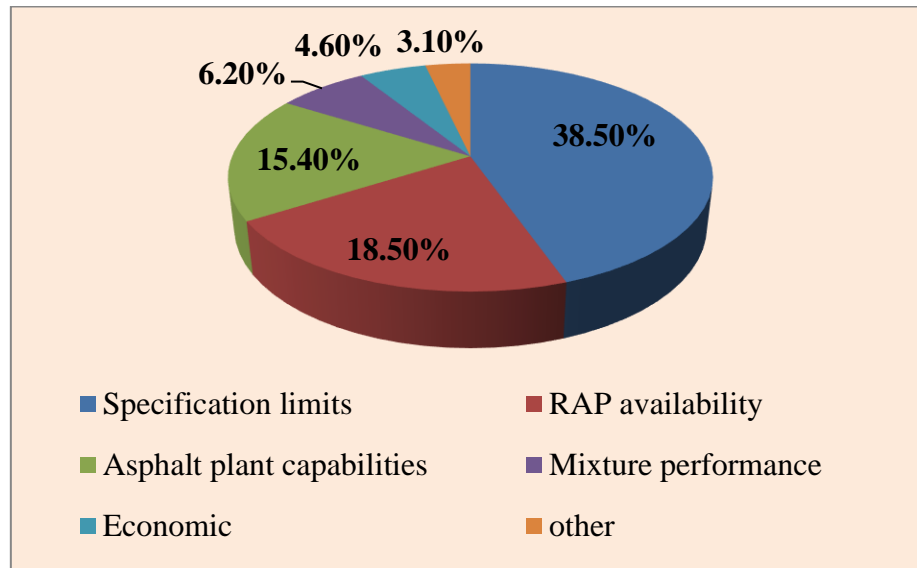


Figure 7: Reported factors limiting the use of RAP (NAPA 2017)

### 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 [33].

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 [34]. 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 [35]. 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 [36].

Using 10–20% RAP in the HMA mixtures, [34] indicated that there was 6.8% and 6.4% reduction for greenhouse gasses (ton CO<sub>2e</sub>) and the single score endpoint impact, respectively, for a 15 years lifespan analysis. Furthermore, 40% reduction in emission of the CO<sub>2e</sub> was reported when 75% RAP was in a production of HMA mixtures. The comparison between GHG emissions for virgin and 20% RAP mixtures revealed that adding RAP can result in averagely 8.3% reduction in air pollutant parameters such as carbon monoxide (CO), oxides of sulfur (SO<sub>x</sub>), oxides of

nitrogen (NO<sub>x</sub>), volatile organic compound (VOC), and particulate matter (PM) as shown in Figure 8 [36].

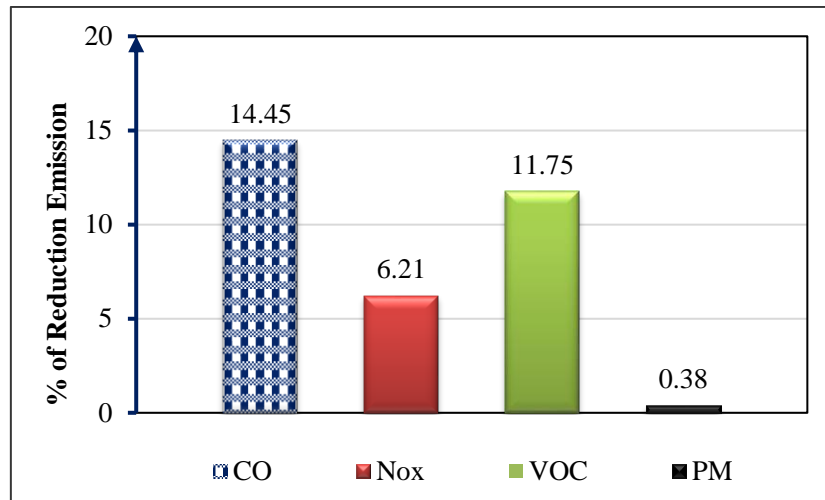


Figure 8: Reduction in the emission percentage of air pollutants for using 20% RAP

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 9 and 10 illustrate the total energy consumptions and emissions per km per lane for different RAP percentage. In Figure 10, showed Carbon dioxide equivalent (CO<sub>2</sub>eq) 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<sub>2</sub>. 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 was observed as the rate of using RAP increased [37].

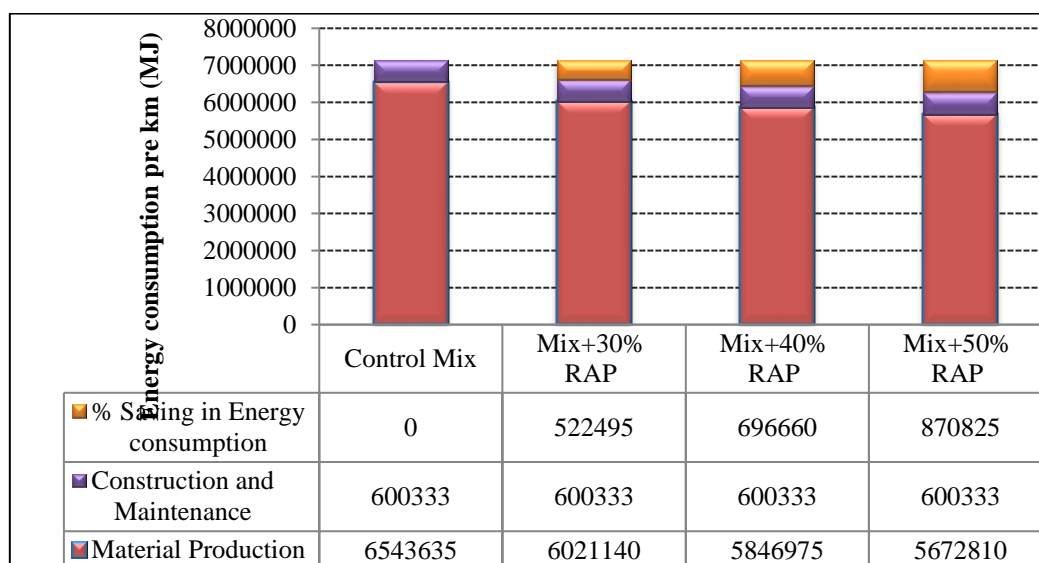


Figure 9: Energy consumption for different RAP content

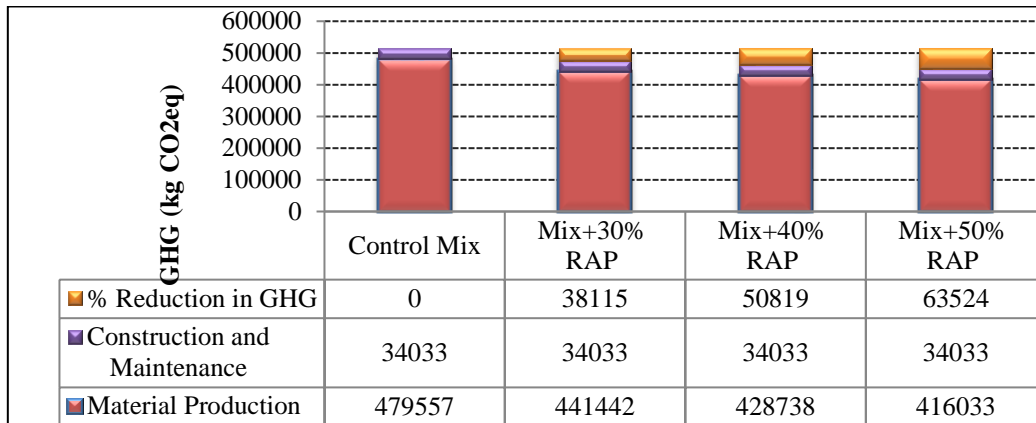


Figure 10: GHG emissions for different RAP content

### 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 [18]. 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 11[38].

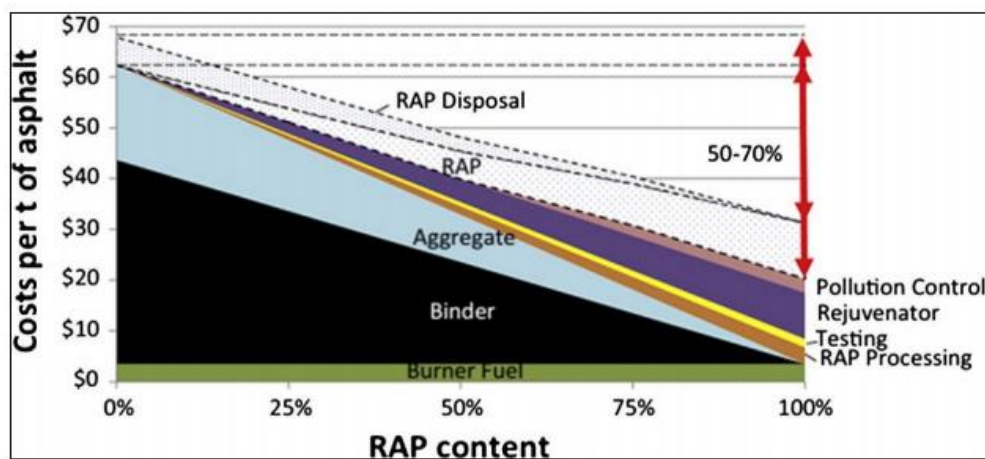


Figure 11: Cost of construction v/s percent RAP content

Table 4 displayed 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 [39]. 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[27].

**Table 4: Effect of RAP on virgin and total binder contents**

RAP (%)	Content	Total Binder (%)	needed 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

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 5. 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 [40].

**Table 5: Economic analysis on using RAP in HMA `**

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 [41]. 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 [42]. 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. This inconsistency gets worse at a higher percentage of RAP materials due to the stiffer nature of the recycled mixtures (the thermal resistance of mixtures decreases) [43]. A summary of some laboratory studies on the effect of increasing of RAP on the performance of asphalt mixtures is shown in Table 6. In this Table 6, “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 [2], [44].

**Table 6: Influence of increasing RAP on mixture performance**

Performance	Testing Parameter	Effect			
		Same	Increase	Decrease	Mixed
Stiffness	Dynamic Modulus (E*)		✓		✓
	Phase Angle			✓	
	Deflection	✓		✓	
Rutting	Creep Stiffness				✓
	Creep Time Flow		✓		
Moisture Susceptibility	Moisture Sensitivity	✓	✓		
	Toughness Index			✓	
Cracking	Fatigue	✓	✓	✓	✓
	Reflective		✓		
	Thermal	✓	✓		

#### 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.

The use of warm additives in asphalt mixtures can have several effects:

- 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. 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. 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 several effects associated with using recycled asphalt pavement (RAP) in asphalt mixtures, which are as follows:

- RAP 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. 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. 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.

#### 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

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### References

- [1] H. Al Dughaisi *et al.*, “Encouraging Sustainable Use of RAP Materials for Pavement Construction in Oman: A Review,” *Recycling*, vol. 7, no. 3, pp. 1–15, 2022, doi: 10.3390/recycling7030035.
- [2] B. A. Williams, J. Richard Willis, and J. Shacat, “Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage 2021 Information Series 138,” *12th Annu. Asph. Pavement Ind. Surv.*, vol. 2019, no. September, p. 51, 2022, doi: 10.13140/RG.2.2.21946.82888.
- [3] Brian Kahn, “We Just Breached the 410 PPM Threshold for CO<sub>2</sub>,” *Clim. Cent. Arch. News*, 2019.
- [4] T. Wang, F. Xiao, X. Zhu, B. Huang, J. Wang, and S. Amirkhanian, “Energy consumption and environmental impact of rubberized asphalt pavement,” *J. Clean. Prod.*, vol. 180, pp. 139–158, 2018, doi: 10.1016/j.jclepro.2018.01.086.
- [5] J. Zhang, T. Sesay, Q. You, and H. Jing, “Maximizing the Application of RAP in Asphalt Concrete Pavements and Its Long-Term Performance: A Review,” *Polymers (Basel)*, vol. 14, no. 21, 2022, doi: 10.3390/polym14214736.
- [6] D. L. V. Araujo, J. Santos, and G. Martinez-Arguelles, “Environmental performance evaluation of warm mix asphalt with recycled concrete aggregate for road pavements,” *Int. J. Pavement Eng.*, pp. 1–14, 2022, doi: 10.1080/10298436.2022.2064999.
- [7] brian prowell and bob frank Randy west, Carolina rodezno, grant Julian, “Field Performance of Warm Mix Asphalt Technologies,” *TRB’s Natl. Coop. Highw. Res. Progr. Rep. 779*, 2014, doi: 10.17226/22272.
- [8] K. A. Tutu and Y. A. Tuffour, “Warm-Mix Asphalt and Pavement Sustainability: A Review,” *Open J. Civ. Eng.*, vol. 06, no. 02, pp. 84–93, 2016, doi: 10.4236/ojce.2016.62008.
- [9] M. Zaumanis, “Warm mix asphalt,” *Green Energy Technol.*, vol. 204, no. October, pp. 309–334, 2014, doi: 10.1007/978-3-662-44719-2\_10.
- [10] G. Srikanth, R. Kumar, and R. Vasudeva, “A Review on Warm Mix Asphalt,” *Natl. Conf. Adv. Struct. Mater. Methodol. Civ. Eng.*, no. November, pp. 525–533, 2018.
- [11] Z. A. D. Newcomb, E. Arambula, Fan Yin, Jun Zhang, A. Bhasin, Wei Li, “Properties of Foamed Asphalt for Warm Mix Asphalt Applications,” *Mater. Sci. Eng. NCHRP Rep.*,

2015.

- [12] M. C. Rubio, G. Martínez, L. Baena, and F. Moreno, "Warm Mix Asphalt: An overview," *J. Clean. Prod.*, vol. 24, pp. 76–84, 2012, doi: 10.1016/j.jclepro.2011.11.053.
- [13] M. Shishehbor, M. R. Pouranian, and R. Imaninasab, "Evaluating the adhesion properties of crude oil fractions on mineral aggregates at different temperatures through reactive molecular dynamics," *Pet. Sci. Technol.*, vol. 36, no. 24, pp. 2084–2090, 2018, doi: 10.1080/10916466.2018.1531032.
- [14] M. R. P. and M. G. R. Mehdi Shishehbor, "Molecular investigations on the interactions of graphene, crude oil fractions and mineral aggregates at low, medium and high temperatures," *Pet. Sci. Technol.*, vol. 37, no. 7, 2019, doi: <https://doi.org/10.1080/10916466.2019.1566254>.
- [15] A. L. Belc, A. Ciutina, R. Buzatu, F. Belc, and C. Costescu, "Environmental impact assessment of different warm mix asphalts," *Sustain.*, vol. 13, no. 21, 2021, doi: 10.3390/su132111869.
- [16] P. K. Das, Y. Tasdemir, and B. Birgisson, "Low temperature cracking performance of WMA with the use of the Superpave indirect tensile test," *Constr. Build. Mater.*, vol. 30, pp. 643–649, 2012, doi: 10.1016/j.conbuildmat.2011.12.013.
- [17] F. Y. and E. S. P. Amy Epps Martin, Edith Arambula, "Validation of Guidelines for Evaluating the Moisture Susceptibility of WMA Technologies," *Transp. Res. Board Washington, DC, USA*, 2016.
- [18] J. R. M. Oliveira, H. M. R. D. Silva, L. P. F. Abreu, and S. R. M. Fernandes, "Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures," *J. Clean. Prod.*, vol. 41, pp. 15–22, 2013, doi: 10.1016/j.jclepro.2012.09.047.
- [19] R. West *et al.*, "NCAT Draft Report 18-04 PHASE VI ( 2015-2018 ) NCAT TEST TRACK FINDINGS By Randy West David Timm Buzz Powell Michael Heitzman Nam Tran Carolina Rodezno Don Watson Fabricio Leiva Adriana Vargas October 2018," no. October, 2018.
- [20] F. Xiao, V. S. Punith, and S. N. Amirkhanian, "Effects of non-foaming WMA additives on asphalt binders at high performance temperatures," *Fuel*, vol. 94, pp. 144–155, 2012, doi: 10.1016/j.fuel.2011.09.017.
- [21] D. S. and M. Z. Rouzbeh Ghabchi, "Laboratory evaluation of stiffness, low-temperature cracking, rutting, moisture damage, and fatigue performance of WMA mixes," *Road Mater. Pavement Des.*, vol. 16, no. 2, 2015, doi: <https://doi.org/10.1080/14680629.2014.1000943>.
- [22] A. Jamshidi, M. O. Hamzah, and Z. You, "Performance of Warm Mix Asphalt containing Sasobit®: State-of-the-art," *Constr. Build. Mater.*, vol. 38, pp. 530–553, 2013, doi: 10.1016/j.conbuildmat.2012.08.015.

- [23] Shu Wei Goh and Zhanping You, "Moisture Damage and Fatigue Cracking of Foamed Warm Mix Asphalt Using a Simple Laboratory Setup," *Transp. Dev. Inst. Congr.*, 2011, doi: [https://doi.org/10.1061/41167\(398\)73](https://doi.org/10.1061/41167(398)73).
- [24] B. Hill, B. Behnia, S. Hakimzadeh, W. Buttlar, and H. Reis, "Evaluation of low-temperature cracking performance of warm-mix asphalt mixtures," *Transp. Res. Rec.*, no. 2294, pp. 81–88, 2012, doi: 10.3141/2294-09.
- [25] M. Mazumder, V. Sriraman, H. H. Kim, and S. J. Lee, "Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA)," *Int. J. Pavement Res. Technol.*, vol. 9, no. 3, pp. 190–201, 2016, doi: 10.1016/j.ijprt.2016.06.001.
- [26] R. C. Zhen Leng, Imad L. Al-Qadi, "Life-cycle economic and environmental assessment of warm stone mastic asphalt," *Transp. A Transp. Sci.*, vol. 14, no. 7, 2018.
- [27] A. Horvath, "Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements," *Transp. Res. Part B Methodol.*, vol. 37, no. 1–25, p. 2010, 2003.
- [28] FHWA, "User Guidelines for Waste and Byproduct Materials in Pavement Construction," *Fed. Highw. Adm.*, no. FHWA-RD-97-148, 2012.
- [29] Ishraq Hameed Naser, "A review of RAP and its use in pavement engineering," *Glob. J. Eng. Technol. Adv.*, vol. 7, no. 1, pp. 073–084, 2021, doi: 10.30574/gjeta.2021.7.1.0043.
- [30] M. I. Mukrim, "Aging Simulation of Hot Mix Asphalt Mixtures Utilizing Aging Simulation of Hot Mix Asphalt Mixtures Utilizing," no. August 2015, 2020, doi: 10.13140/RG.2.2.20120.42249.
- [31] J. Oner and B. Sengoz, "Research article 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] M. Rathore, M. Zaumanis, and V. Haritonovs, "Asphalt Recycling Technologies: A Review on Limitations and Benefits," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 660, no. 1, 2019, doi: 10.1088/1757-899X/660/1/012046.
- [33] P. Gireesh Kumar, "A Comprehensive Review on the Replacement of Virgin Material using Reclaimed Asphalt Pavement (RAP) Material in Flexible Pavements," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1006, no. 1, 2020, doi: 10.1088/1757-899X/1006/1/012041.
- [34] E. K. Anastasiou, A. Liapis, and I. Papayianni, "Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials," *Resour. Conserv. Recycl.*, vol. 101, pp. 1–8, 2015, doi: 10.1016/j.resconrec.2015.05.009.
- [35] J. Anthonissen, W. Van den bergh, and J. Braet, "Review and environmental impact assessment of green technologies for base courses in bituminous pavements," *Environ. Impact Assess. Rev.*, vol. 60, pp. 139–147, 2016, doi: 10.1016/j.eiar.2016.04.005.

- [36] R. Y. Qazi Aurangzeb, Imad L. Al-Qadi, Hasan Ozer, "Hybrid life cycle assessment for asphalt mixtures with high RAP content," *Resour. Conserv. Recycl.*, vol. 83, pp. 77–86, 2014.
- [37] G. Tarsi, P. Tataranni, and C. Sangiorgi, "The challenges of using reclaimed asphalt pavement for new asphalt mixtures: A review," *Materials (Basel)*, vol. 13, no. 18, 2020, doi: 10.3390/ma13184052.
- [38] A. Sharma, G. D. Ransinchung, P. Kumar, and D. S. N. V. A. Kumar, "Design Mixture of RAP-HMA Pavements: A Review," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1075, no. 1, p. 012025, 2021, doi: 10.1088/1757-899x/1075/1/012025.
- [39] I. L. Al-Qadi *et al.*, "Determination of Usable Residual Asphalt Binder in RAP," *Illinois Cent. Transp.*, no. 09, p. 64, 2009.
- [40] 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.
- [41] B. Huang, G. Li, D. Vukosavljevic, X. Shu, and B. K. Egan, "Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement," *Transp. Res. Rec.*, no. 1929, pp. 37–45, 2005, doi: 10.3141/1929-05.
- [42] R. McDaniel, A. Shah, and G. Huber, "Investigation of Low and High-Temperature Properties of Plant-Produced RAP Mixtures. McLean, VA: Federal Highway Administration," *Fhwa, Usdot*, vol. 11, no. 1, p. 107, 2012.
- [43] A. Basueny, A. Carter, D. Perraton, and M. Vaillancourt, "Laboratory evaluation of complex modulus and fatigue resistance of asphalt mixtures with RAP," *RILEM Bookseries*, vol. 11, pp. 521–532, 2016, doi: 10.1007/978-94-017-7342-3\_42.
- [44] T. A. Pradyumna, A. Mittal, and P. K. Jain, "Characterization of Reclaimed Asphalt Pavement (RAP) for Use in Bituminous Road Construction," *Procedia - Soc. Behav. Sci.*, vol. 104, pp. 1149–1157, 2013, doi: 10.1016/j.sbspro.2013.11.211.