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Original Paper

The economic potentials of reclaimed asphalt pavements (RAP) in urban road infrastructure: a case study of Yalova city

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ABSTRACT

Due to population growth and technological development, consumption is rapidly increasing all over the world. Waste materials are not disposed of properly, resulting in environmental and visual pollution, health problems and economic disadvantages. Although recycling of waste materials has been given more importance in recent years than in the past, 100% recycling is not possible. Recycling asphalt pavements, protecting natural resources and reusing waste materials are very important to avoid the landfills they create in nature. In addition, the economic benefits of RAP (Reclaimed Asphalt Pavement) cannot be neglected. In this study, the significance of asphalt pavement recycling in the world, recycling methods and economic benefits are highlighted. In addition, the average annual amount of asphalt pavement excavated in Yalova was determined and the approximate cost of using different percentages of RAP was performed. For the construction of 1 km of asphalt pavement, the road construction costs were evaluated and compared using 30%, 50% and 70% RAP. Based on the findings, 6%, 11% and 15% of the initial costs could be saved, respectively. Although 70% RAP usage increased the recycling cost by 12%, it decreased the bitumen use by 7.2%, the aggregate use by 10.6%, and the operation cost by 11.1%.

I. INTRODUCTION

In recent years, there has been a significant increase in consumption worldwide, driven by the development of production technologies and growing human needs. Consequently, the production of waste materials has also increased. Globally, approximately 2.01 billion tons of municipal solid waste is generated annually, with at least 33 percent of this waste being improperly managed from an environmental standpoint [1]. The World Bank Group projects that waste generation will nearly double to reach 3.40 billion tons worldwide by 2050, with a particularly substantial increase expected in low and middle-income countries like Türkiye, nearly tripling compared to the present [2]. In order to prevent environmental damage caused by waste and to incorporate them into the economy, it is crucial to implement recycling methods across various sectors for our future well-being. Transportation and highway engineering have emerged as key areas where recycling methods have gained considerable importance in recent years. Hot mix asphalt layers, particularly the top layers, experience deterioration over time due to various factors. In some cases, pavements become completely unserviceable, leading to undesirable scenarios. It is imperative to address potential deformations before the end of the pavement's projected lifespan to ensure its longevity and functionality. To ensure a comfortable and safe driving surface, it may be necessary to modify the road profile and remove the existing pavement. However, with the right application method, the removed asphalt pavement waste can be recycled and reused. There are several available methods for pavement recycling. The

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Asphalt Recycling and Reclaiming Association (ARRA) categorizes them into five main groups: Cold Planning (CP), Hot In-Plant Recycling (HIPR), Hot In-Place Recycling (HIR), Full Depth Reclamation (FDR), and Cold Recycling (CR) [3]. Among these methods, HIPR is the most commonly used, involving the mixing of Reclaimed Asphalt Pavement (RAP) with new materials and the addition of additives if necessary. Another method is HIR, which involves the addition of pure asphalt and/or aggregate, mixing the materials with a recycling or rejuvenating agent without removing them from the pavement site [4]. The benefits of utilizing RAP extend beyond environmental protection and include reducing the consumption of new materials, minimizing transportation needs, saving energy, improving mixing properties, and, most importantly, achieving economic gains [5]. The objective of this study is to draw attention to the amount of waste generated globally, particularly asphalt waste, and highlight the benefits of utilizing these wastes in the construction of new roads. The aim is to emphasize the advantages that can be achieved by incorporating RAP into road construction, focusing on the economic benefits and sustainability aspects in Yalova City. Firstly, the annual quantity of excavated asphalt pavement in Yalova was determined. Subsequently, a cost-benefit analysis was conducted to investigate the economic implications associated with recycling the determined amount at specific rates. In the conclusion, the study not only highlights the benefits of employing RAP in Yalova but also emphasizes global research efforts and initiatives focused on recycling natural resources. Furthermore, the positive effects of RAP usage on the environment are presented. While there is significant emphasis on the use of Reclaimed Asphalt Pavement (RAP) in America and Europe, there have been relatively few studies conducted in Turkey. Therefore, this study will serve as a valuable resource, particularly in terms of literature review, for future research on this subject.

II. FINANCIAL SYNOPSIS OF THE RAP MARKET

2.1 Market Sizing for Recycling Asphalt

Various types of waste materials, such as Construction and Demolition Waste (CDW), steel slags, plastics, crumb rubber, glass, and RAP, have been successfully recycled in construction of pavement [1]. RAP, in particular, has been utilized in asphalt mixes since 1915 [6] , establishing itself as one of the most extensively recycled construction products worldwide, with an approximate recycling rate of 88% [7]. Additionally, according to The Federal Highway Administration (FHWA), asphalt concrete is the most recycled material worldwide [8]. The National Asphalt Pavement Association (NAPA) further asserts that the majority of reclaimed asphalt is either reused or recycled, solidifying asphalt pavement as the most recycled material [9]. In 2019, approximately 140 million tons of RAP were used in asphalt pavements [10]. In 2020, this figure amounted to 125 million tons (with the USA accounting for 88 million tons in 2019 and 85 million tons in 2020) [11].

Every year, approximately 1.5 billion tons of asphalt concrete are produced worldwide, consuming 1.425 billion tons of aggregate and 75 million tons of bitumen [12, 13]. Highways experience deterioration over time due to various factors such as traffic, climate change, poor design, inadequate maintenance, and weak soil. This deterioration results in a decrease in serviceability, which negatively impacts comfort and economic parameters. In more severe cases, pavements become completely unserviceable and require excavation and replacement with new ones. However, it is possible to recycle the removed asphalt pavements and transform them into economic value. Similarly, as shown in Figure 1, Türkiye produces an average of 37.9 million tons of asphalt annually, indicating that the cost of asphalt production amounts to approximately $34.5 billion* per year. By recycling only 1% of these excavation wastes, several benefits can be achieved. Specifically, 379 thousand tons less excavated asphalt pavement waste will be generated, 360 thousand tons less aggregate will be used, and an average of 19 thousand tons less bitumen will be consumed. This not only helps in preserving natural resources but also significantly reduces environmental pollution.

Recycling asphalt pavements is a widely adopted practice in Europe and America, with countries like the United States, France, and Germany leading the way in this regard [14]. In the United States, asphalt and asphalt pavements are among the most commonly recycled materials [15].

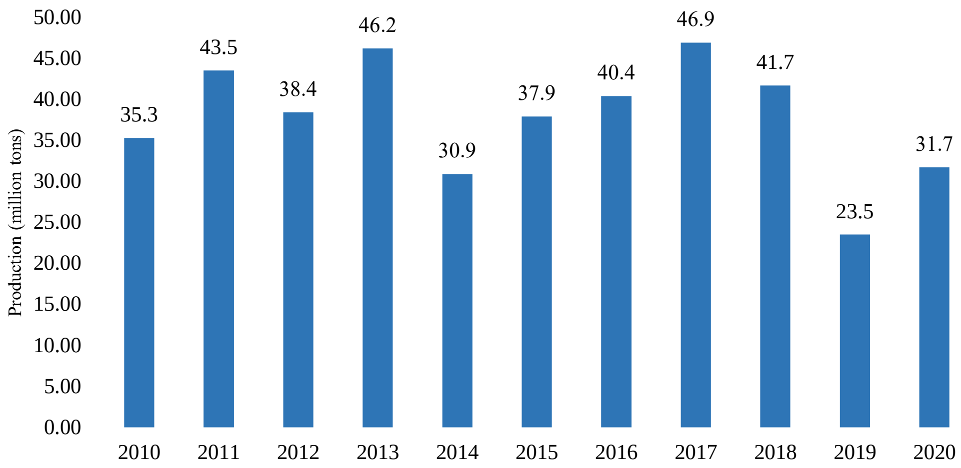

Figure 1. The total production of asphalt in Türkiye during the period of 2010-2020 [10], [11], [16]–[24]

*wearing course asphalt production cost is $91/tons [25]

Furthermore, according to NAPA, the majority of reclaimed asphalt in the United States is reused or recycled, making asphalt pavements the most extensively recycled material in the country [9, 26]. Additionally, EAPA reported that in 2020, 82.2 million tons of RAP and 1.05 million tons of recycled asphalt shingles (RAS) were utilized in the production of 370 million tons of new asphalt pavement mixes in the United States.

Table 1 presents the global quantities of reclaimed asphalt between 2010 and 2020. In the United States, in particular, an average of 74.6 million tons of reclaimed asphalt is generated annually, with 90-95% of this asphalt being effectively utilized in high-performance mixtures such as warm and hot mixes. Among European countries, several nations, including Germany, Italy, and France, demonstrate substantial amounts of reclaimed asphalt. Regarding Türkiye, as indicated once again in

Table 1, an average of 2.3 million tons of asphalt waste is removed annually over an eleven-year period.

Table 1. All available reclaimed asphalt in the World (in tons) [10], [11], [16]–[24]

Country	2010	2011	2012	2013	2014
Austria	500,000	550,000	750,000	750,000	1,500,000
Belgium	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
Croatia	75,000	No data	No data	No data	170,000
Czech Rep.	1,650,000	1,500,000	1,400,000	1,450,000	1,600,000
Denmark	350,000	600,000	580,000	790,000	1,300,000
Finland	1,000,000	1,000,000	1,000,000	860,000	1,000,000
France	7,080,000	7,080,000	6,500,000	6,900,000	7,000,000
Germany	14,000,000	14,000,000	11,500,000	11,500,000	10,900,000
Great Britain	4,000,000	4,500,000	4,500,000	4,500,000*	3,350,000
Hungary	44,580	64,882	100,777	88,000	20,000
Italy	11,000,000	11,000,000	10,000,000	10,000,000	No data
Norway	750,000	726,000	787,689	686,268	834,410
Romania	40,000	13,000	20,000	22,000	20,000
Slovakia	No data	No data	33,000	26,000	30,000
Slovenia	26,160	10,000	10,000	26,000	40,000
Spain	1,590,000	1,350,000	368,000	205,000	390,000
Switzerland	1,450,000	1,750,000	1,575,000	1,370,000	1,000,000
Türkiye	2,420,000	2,809,000	3,816,000	1,200,000	2,340,000
USA	66,500,000	71,400,000	64,000,000	69,000,000	68,700,000
TOTAL	**113,975,740**	**119,852,882**	**108,440,466**	**110,873,268**	**101,697,410**

*(Continue to **Table 1**)*

Country	2015	2016	2017	2018	2019	2020
Austria	1,350,000	1,400,000	1,650,000	1,900,000	1,800,000	1,260,000
Belgium	1,553,994	1,240,000	1,030	1,687,000	1,637,000	1,981,500
Croatia	No data	80,000	No data	200,000	210,000	240,000
Czech Rep.	2,000,000	1,800,000	2,600,000	2,700,000	2,800,000	2,500,000
Denmark	1,300,000	1,150,000	1,165,000	1,185,000	1,255,000	1,160,000
Finland	1,160,000	1,150,000	1,200,000	1,300,000	1,500,000	No data
France	7,000,000	6,370,000	6,400,000	7,817,000	8,074,000	6,042,000
Germany	11,000,000	12,000,000	13,000,000	13,000,000	13,400,000	11,600,000
Great Britain	3,500,000	3,250,000	3,400,000	6,100,000	6,050,000	4,973,106
Hungary	180,000	109,000	120,000	200,000	105,000	140,000
Italy	9,000,000	9,000,000	9,000,000	9,000,000	9,500,000	9,500,000
Norway	932,049	1,112,000	No data	1,004,000	1,173,000	840,000
Romania	No data	No data	No data	No data	612,500	No data
Slovakia	75,000	54,000	50,000	150,966	165,600	135,846
Slovenia	37,000	56,000	84,000	106,200	150,000	170,000
Spain	410,000	490,000	494,000	1,165,000	1,486,000	1,900,000
Switzerland	No data	No data	No data	No data	1,650,000	No data
Türkiye	1,520,000	3,551,167	2,570,589	1,965,000	1,038,000	2,143,354
USA	69,700,000	74,200,000	72,500,000	91,700, 000	88,000,000	85,000,000
TOTAL	**110,718,043**	**117,012,167**	**114,234,619**	**141,180,166**	**140,606,100**	**129,585,806**

As indicated in Table 2, among European countries, Italy and France rank highest in terms of the utilization of recycled asphalt in road construction, following Germany. RAP are commonly employed in the production of warm and hot mixed asphalt roads [11, 27]. Notably, Finland and Ireland achieved a remarkable 100% rate of reusing RAP in high-quality asphalt in 2020. In the United States, a substantial 85 million tons of asphalt pavement waste is utilized in the production of hot and warm mix asphalt, reaching an impressive rate of 93% by 2020. In Türkiye, the amount of reclaimed asphalt pavement utilized in 2020 reached 2,143,354 tons. According to EAPA, only 2% of this amount was used for hot and warm mix asphalt, while the remaining 98% was employed for unbound layers [11].

RAP has been the subject of numerous studies; however, only a few have compared the cost of recycled and virgin mixtures. An Illinois-based study evaluated the life-cycle cost and environmental impact of four pavement sections, each consisting of asphalt mixes with different RAP content: 0%, 30%, 40%, and 50%. The analysis conducted over a 45-year period demonstrated a significant cost reduction of up to $94,000 per mile, even with higher RAP content [14].

Table 2. Amount of available reclaimed asphalt in the World (in tons) and where to use in [11]

	Amount of reclaimed asphalt available to be used by the asphalt industry in 2020	Hot and warm mix asphalt production	Half warm mix asphalt production	On-Site cold recycling	Plant cold recycling	Unbound road layers	Other civil eng. apps	Put to landfill/ Other Apps/ Unknown
Austria	1,260,000	70				30		
Belgium	1,981,500	47	no data	no data	no data	no data	no data	no data
Croatia	240,000	33	0	0	2	no data	no data	no data
Czech Rep.	2,500,000	15	no data	25	no data	25	7	28
Denmark	1,160,000	85	no data	no data	no data	15	no data	no data
Finland	1,600,000*	100	0	0	0	0	0	0
France	6,042,000	76	10	no data	no data	no data	no data	no data
Germany	11,600,000	84	0	0	0	16	0	0
Great Britain	4,973,106	37	0	10	0	63		no data
Hungary	140,000	95	0	0	3	2	0	0
Ireland	220,000	100	0	0	0	0	0	0
Italy	9,500,000	25				75		
Norway	840,000	35	0	0	0	65	0	0
Romania	10,425*	0	0	100	0	0	0	0
Slovakia	135,846	53	0	30	0	17	0	0
Slovenia	170,000	29	0	10	1	25	10	25
Spain	1,900,000	72.7	0.2	0.2	0	24	3	0
Türkiye	2,143,354	2	0	0	0	98	0	0
USA	85,000,000	93	0	0	0.4	6.2	0.3	0

**there is no data about total amount of site-won asphalt generated*

RAP has been the subject of numerous studies; however, only a few have compared the cost of recycled and virgin mixtures. An Illinois-based study evaluated the life-cycle cost and environmental impact of four pavement sections, each consisting of asphalt mixes with different RAP content: 0%, 30%, 40%, and 50%. The analysis conducted over a 45-year period demonstrated a significant cost reduction of up to $94,000 per mile, even with higher RAP content [14]. Another case study focused on a 20% RAP content and performed a cost analysis, revealing a cost reduction of 14% compared to conventional materials [28]. Researchers also discovered that a mixture containing 40% RAP resulted in a 29% reduction in greenhouse gas emissions and a 26.2% decrease in life-cycle costs compared to a mixture without RAP additives [29]. Similar to various other examples worldwide, the idea of reusing asphalt pavements has gained prominence in Türkiye in recent years, driven by the crucial need for resource sustainability. The initial studies were conducted by ISFALT in 1996, where pavements excavated by the General Directorate of Highways (GDH) from the Çobançeşme-TEM connection road were applied at a 25% rate in a project in Bağcılar. However, certain issues arose during this application, requiring extensive laboratory testing. Recycling production of asphalt pavements gained momentum and significance from 2005 following partial trials conducted in 2001 [30]. Table 3 provides examples of recycling applications implemented in Türkiye.

Table 3. Recycling practices applied in Türkiye [31]

Region	Road Name	Firm	Application Layer	Recycle Type
GDH, 17th Regional Directorate	Sakarya Bridge Junction-Gümüşova Highway*	Gülsan	Binder, Bituminous Base	Cold in-Plant
DH, 3rd Regional Directorate	Şereflikoçhisar Aksaray-Ereğli road junction*	Fernas	Bituminous Base	Cold in-Plant
DH, 4th Regional Directorate	Bala road junction-Kulu road junction*	Fermak	Bituminous Base	Cold in-Plant
GDH, 9th Regional Directorate	Şanlıurfa Viranşehir Kızıltepe-Silopi Road*	Seza-DemyolACS	Binder, Bituminous Base	Cold in-Plant
GDH, 4th Regional Directorate	Ankara Kızılcahamam**	No data	All HMA Layers	Cold in-Place

2.2. European Green Deal and Circular Economy

Since our world is facing many problems such as climate change and environmental pollution, the European Union Commission has taken action on this issue. On December 11, 2019, the EU Commission released the European Green Deal which aims to make inhabited geography sensitive and harmless to the climate, environment, and nature until 2050 [32]. The concept of sustainability is key to achieving this goal. Sustainability creates and preserves conditions in which people and nature can exist in productive harmony, allowing present and future generations to fulfill their social, economic, and other needs [33]. Supporting biodiversity and public health, reducing carbon emissions and pollution, and preparing for a sustainable urban future not only benefit the global environment but also provide economic advantages. The three golden rules of sustainability—reduce, reuse, and recycle—can be applied to the asphalt industry [34].

Considering the impact of asphalt recycling on energy consumption, emissions, and the economy, it is concluded that studies on sustainable pavements should focus on minimizing energy usage and maximizing recycling efforts through the use of rapidly developing technology. This is essential to protect the environment and create a livable world for future generations [34]. Improving the performance of asphalt pavement materials is necessary to reduce energy consumption, greenhouse gas emissions, and associated costs for service, maintenance, and end-of-life projects. RAP materials offer an effective way to preserve natural resources and prevent the disposal of hazardous waste that harms the environment.

The long-term use of fuel, aggregate, and asphalt can be reduced by incorporating RAP. This leads to a reduction in greenhouse gas emissions, improved service quality, and support for sustainable practices. The greenhouse gas emissions and energy consumption levels associated with different percentages of RAP usage are illustrated in Figure 2 [35].

With a 50% RAP usage, greenhouse gas (CO_2) emissions decreased from 479,557 kg/km to 416,033 kg/km. Additionally, the amount of energy consumption, which was 6,543,635 MJ/km without the use of RAP material, was reduced to 5,672,810 MJ/km when 50% RAP was used. To achieve this reduction, it is crucial to recycle waste materials and prevent their accumulation in nature. Therefore, there should be an increase in RAP usage and recycling rates.

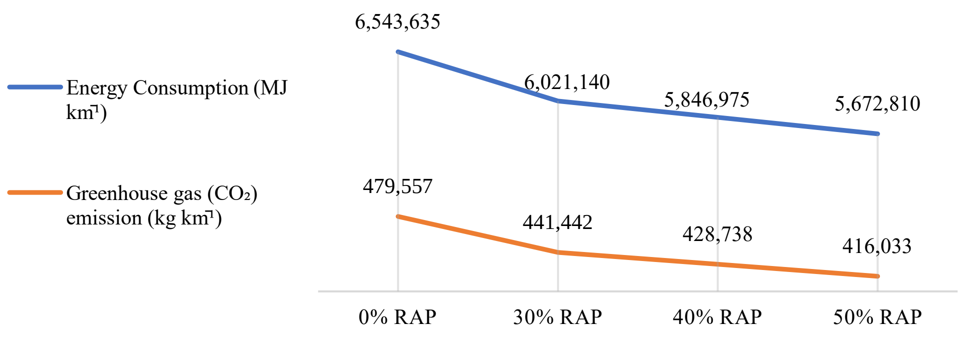

Figure 2. Greenhouse gas-CO2 emissions and energy consumption amounts due to using different RAP materials [35]

III. A CASE STUDY OF YALOVA CITY

Yalova, which is the smallest city in Türkiye in terms of surface area, has experienced a rapid increase in population due to immigration in recent years. When examining the geographical region of Yalova with a population of 276,050, it can be observed that the coastal areas, surrounded by the Marmara Sea, are flat, while the inland consists of elevated lands and maquis vegetation [36, 37]. The city is connected to surrounding provinces and districts through asphalt paved roads, and regular sea bus and ferryboat trips are organized to Istanbul due to its coastal location. Additionally, there has been significant development in freight transportation for national and international logistics, resulting in heavy vehicle traffic on the asphalt paved roads in these regions. Although Yalova lacks an airport, transportation is facilitated through the Yalova coach station, providing access to Istanbul Sabiha Gökçen Airport and Istanbul Airport. Asphalt pavement is extensively used for passenger and freight transport. However, the excavated asphalt pavement is not recycled and reused; instead, it is treated as waste material in various areas. This study aims to evaluate the feasibility of recycling asphalt in Yalova based on information obtained from Yalova Municipality and Yalova Special Provincial Administration.

3.1 Road Network and Construction Activities

In Yalova, four types of road surfaces are used: HMA (Hot Mix Asphalt) pavement, ICBP (Interlocking Concrete Block Pavement), chip seal, and dirt roads (unpaved roads). Among the surfaced roads, 65% are HMA and 5% are chip seal, with a total road length of 849,589 meters. On average, 10,000 tons of HMA are produced annually, with a production cost of $618,672.7. The annual average cost of road maintenance and repair for 5,000 tons of HMA is $281,214.8. Approximately 4,800 tons of excavated asphalt pavement waste are used annually in the construction of new stabilized roads, as part of the Granular Base Course and over the filling, as a fine material. Figure 3 illustrates the road construction, including 14,234 meters of chip seal, 3,846 meters of HMA, 143,026 meters of ICBP, and 14,011 meters of stabilized roads. Under the Special Provincial Administration, 1,232 tons of asphalt pavements are maintained and repaired at a cost of $35433.1. On average, 1,250 tons of asphalt pavement are excavated by the Special Provincial Administration. The waste materials are either taken to designated dumping areas as requested by the village headmen or used in areas within the villages where materials are needed.

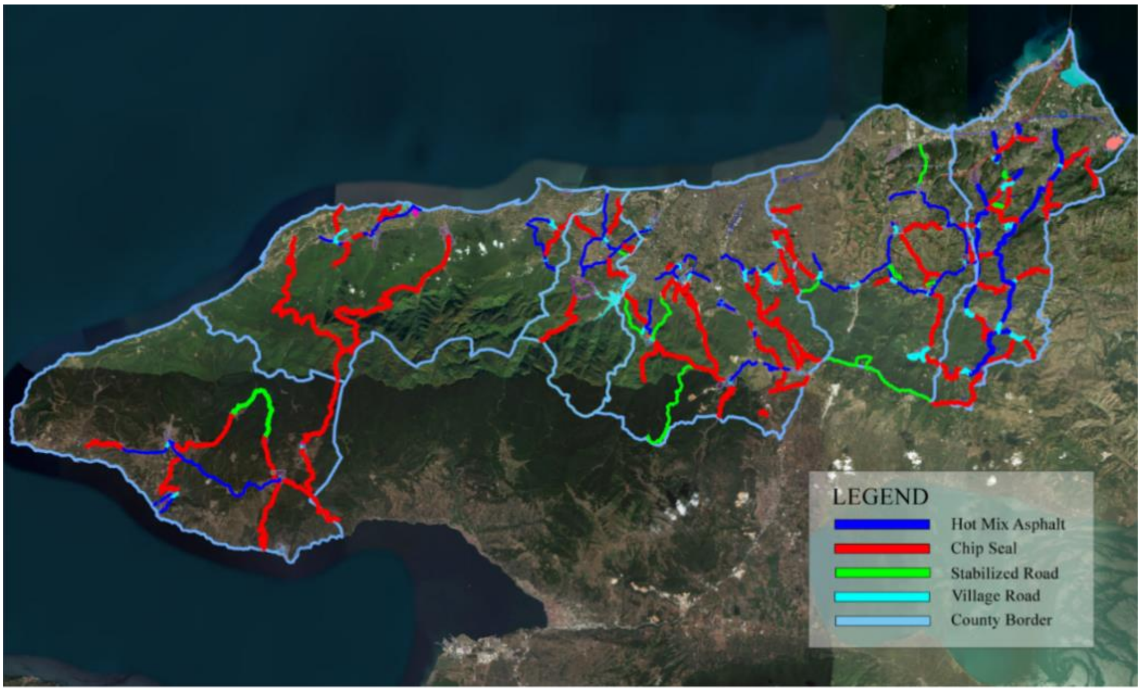

Figure 3. Distribution of Road Types under the Responsibility of Yalova Special Provincial Administration

3.2 Cost-Benefit Analysis

In this section, a cost-benefit analysis has been conducted for the implementation of a 1 km asphalt road in Yalova, considering the use of RAP instead of virgin aggregate. The analysis focuses on evaluating the cost and environmental benefits and opportunities associated with this approach.

Simge Group [13] conducted a study to examine the economic benefits of recycling the removed asphalt pavement waste and utilizing it in new pavements. Table 4 presents the results, indicating the gain rates for different RAP percentages: 6.7% for 30% RAP, 12.4% for 50% RAP, and 16.9% for 70% RAP. The cost comparisons were made by separately considering the parameters of *"Aggregate, Bitumen, Operating Expenses, and Recycling Expenses,"* and the differences and earnings ratios were evaluated. Also, considering the presence of bitumen in RAP, it is anticipated that incorporating RAP at rates of 30%, 50%, and 70% in the bitumen mixture, as indicated in the table, will result in respective increases of 4.2%, 8.2%, and 12%. In the first stage of the study, the annual amounts of excavated and constructed asphalt pavements in Yalova were determined. In the second stage, assuming the construction of a 1 km asphalt road, the initial construction cost was calculated without utilizing RAP material in this scenario. Subsequently, cost calculations were performed for using 30% RAP, 50% RAP, and 70% RAP on this 1 km road, respectively. Finally, a cost-benefit analysis was conducted to compare the different scenarios.

Table 4. Cost comparison asphalt production cost with and without using RAP [13]

Cost factors		**Without recycling**	**With recycling**		
		Aggregate Usage Rate	Reclaimed Asphalt Usage Rate		
		100%	30%	50%	70%
	Values mentioned on the chart are used as indicators of the content rates of unit cost				
Aggregate	Quarrying	3.7	2.6	1.8	1.1
	Back transport	3.4	2.4	1.7	1.0
	Crushing	3.1	2.2	1.5	0.9
	Carrying	5.1	3.5	2.5	1.5
	Total	15.2	10.6	7.6	4.6
	Difference		-30.0%	-50.0%	-70.0%
Bitumen	Bitumen Rate	5.0%	4.17%	3.70%	3.60%
	Bitumen	56.3	54.0	51.7	49.6
	Transport	0.8	0.8	0.8	0.7
	Heating	2.8	2.7	2.6	2.5
	Total	60.0	57.5	55.1	52.8
	Difference		-4.2%	-8.2%	-12.0%
Operating expenses	Electric	5.6	3.9	2.8	1.9
	Aggregate Heating cost of Asphalt Plant	11.3	7.9	5.5	3.9
	Labor Cost	5.6	5.6	5.6	5.6
	Total	22.5	17.5	13.9	11.4
	Difference		-22.5%	-38.3%	-49.3%
Cost For Reclamation	Electricity	0.0	1.3	2.2	3.1
	Aggregate heating costs	0.0	3.6	6.0	8.4
	Scrapping of Asphalt	1.1	1.1	1.1	1.1
	Transportation of Scrapped Asphalt	0.8	0.8	0.8	0.8
	Handling of Scrapped Asphalt	0.3	0.3	0.3	0.3
	Crushing and Screening of Scrapped Asphalt	0.0	0.6	0.6	0.6
	Total	2.3	7.7	11.0	14.3
	Difference		243.1%	388.4%	533.8%
	Total	**100**	**93.3**	**87.6**	**83.1**
			6.7%	**12.4%**	**16.9%**

IV. RESULTS AND DISCUSSIONS

Considering the components of HMA production costs without the use of RAP, as shown in Figure 4, the recovery costs of 2.3% are not associated with the utilization of RAP. This value solely represents the expenses related to scraping, transportation, and unloading of the removed pavement. When using 30% RAP, an increase of 1.3% in electricity costs, 3.6% in aggregate heating costs, and 0.6% in the crushing-sieving process of the removed asphalt pavement were observed as recovery costs. However, the reductions in aggregate and bitumen production, as well as operating costs, result in an overall gain of 6.9%. With 50% RAP material, an average gain of 12.4% was achieved, along with a 2.2% increase in electricity costs, a 6.0% increase in aggregate heating costs, and a 0.6% increase in the crushing-sieving process of the removed asphalt pavement. Nevertheless, the reductions in aggregate and bitumen production, as well as operating costs, make it economically beneficial when considering the total benefit.

Using 70% RAP material, an increase of 3.1% in electricity costs, an 8.4% increase in aggregate heating costs, and a 0.6% increase in the crushing-sieving process of the removed asphalt pavement were observed as recovery costs. However, the reductions in aggregate production, bitumen production, and operating costs result in a significant profit of 16.9% when considering the total benefit. Based on the research conducted by Yalova Municipality and Special Provincial Administration, it is determined that an average of 6,000 tons of asphalt pavement is excavated annually.

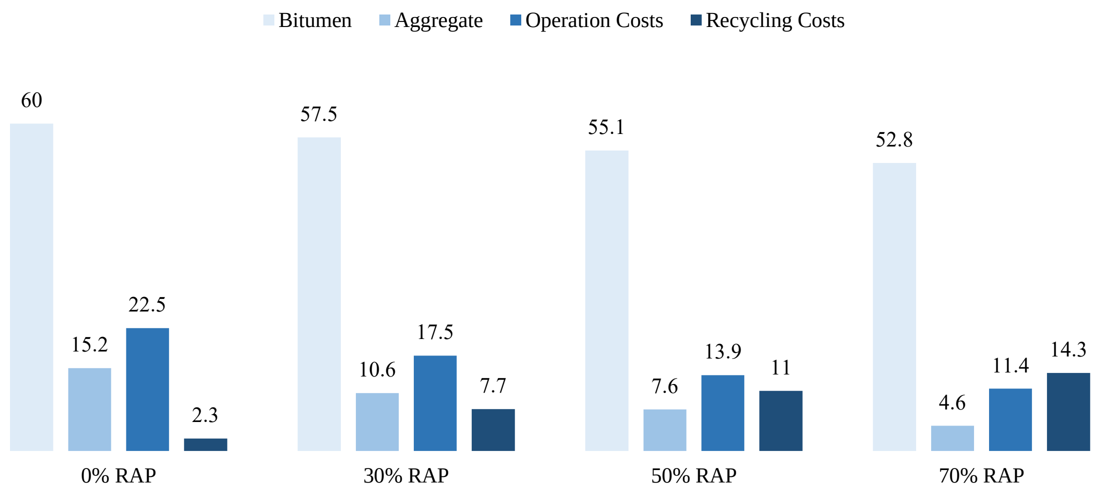

Figure 4. Cost components depending on the use of RAP at different rates (%)

As shown in Table 5, it is estimated that by recycling 30%, 50%, and 70% of the excavated asphalt pavement, gains of $4,341.1 to $25,549.6 can be achieved for 1,800, 3,000, and 4,200 tons of RAP, respectively. Apart from the financial benefits, recycling waste materials will protect the environment by preventing the creation of waste sites, reduce the use of natural resources, and significantly decrease greenhouse gas emissions associated with production and transportation. Cost-benefit analyses have been conducted in Table 6 and Table 7, considering the use of RAP at rates of 30%, 50%, and 70%, respectively. These analyses only include on-site production costs, and additional costs per ton, such as transportation, paving, compaction (labor), should be taken into account. Labor costs for paving and compaction, depending on the distance from the site, are typically around $1.7-$2.8 per ton. Moreover, expenses related to drainage works and horizontal and vertical marking should also be added.

Table 5. Comparison of recycling costs of asphalt pavements excavated in Yalova

Annual Average Amount of Asphalt Pavement Excavated (tons)	RAP Usage Rate (%)	RAP Amount (tons)	Initial Cost without using RAP ($)	Initial Cost with using RAP ($)	Profit ($)	Profit (%)
6000	30	1,800	64,791.9	60,450.8	4,341.1	6.7
6000	50	3,000	107,986.5	94,596.2	13,390.3	12.4
6000	70	4,200	151,181.1	125,631.5	25,549.6	16.9

Table 6. Asphalt pavement road construction cost without recycling for 1 km

Pavement Courses	Layer Thickness (m)	Density (tons m^{-3})	Road width (m)	Road length (m)	Amount (m^3)	Unit Cost ($)	Total Cost ($)
Excavation	0.15	1.60	7.00	1,000	1,050	3.4	3,543.3
PMB	0.15	1.60	7.00	1,000	1,050	5.6	5,905.5
						Subtotal	9,448.8
Wearing Course	0.05	2.40	7.00	1,000	840	36	30,236.2
Binder Course	0.08	2.40	7.00	1,000	1,344	33.2	44,598.4
						Subtotal	74,834.6
						TOTAL	84,283.5
Unit cost (per 1 m^2)							**12.04**

According to Table 6, the construction cost of a 1 km asphalt road is approximately $84,283.5. In this section, the use of RAP in the wearing and binder courses and the resulting savings in asphalt road costs were evaluated. It was planned to use 70% RAP in the wearing and binder courses, and as shown in Table 7, a cost saving was determined. Consequently, the total cost, which was $84,283.5, decreased by 15% to $71,636.4. By performing the same assessments, the use of 30% and 50% RAP in the wearing and binder courses was planned, and the cost saving was calculated. The total cost decreased by 6% from $84,283.5 to $75,004 with the use of 30% RAP, and it decreased by 11% from $84,283.5 to $79,269.5 with the use of 50% RAP. The increase in the utilization percentage of RAP to levels of 50-70% can potentially introduce challenges related to strength and durability [38, 39]. However, considering in terms of cost-effectiveness, environmental impact, and human well-being, usage of RAP in low-traffic volume road construction or as road maintenance material can still be advantageous along with a balance between the potential drawbacks and overall benefits [39].

Table 7. Asphalt pavement road construction cost with 30%,50% and 70% RAP for 1 km

Pavement Courses	Layer Thickness (m)	Density (tons m^{-3})	Road width (m)	Road length (m)	Amount (m^3)	Total Cost based on RAP usage ($) 30%	50%	70%
Excavation	0.15	1.60	7.00	1,000	1,050	3,543.3	3,543.3	3,543.3
PMB	0.15	1.60	7.00	1,000	1,050	5,905.5	5,905.5	5,905.5
					Subtotal	9,448.8	84,000	9,448.8
Pavement Courses	**Layer Thickness (m)**	**Density (tons m^{-3})**	**Road width (m)**	**Road length (m)**	**Amount (tons)**	**Total Cost based on RAP usage ($)* 30%**	**50%**	**70%**
Wearing	0.05	2.40	7.00	1,000	840	28,210.3	26,487.0	25,126.3
Binder	0.08	2.40	7.00	1,000	1,344	41,610.3	39,068.3	37,061.3
					Subtotal	69,820.7	65,555.2	62,187.6
					TOTAL	79,269.5	75,004.0	71,636.4
Unit cost (per 1m^2)						**11.3**	**10.7**	**10.2**

**As mentioned before, for the calculations of asphalt production costs were decreased by 6.7% for 30% RAP, 12.4% for 50% RAP and 16.9% for 70% RAP.*

V. CONCLUSIONS

In this study, a cost-benefit analysis was conducted for the construction of a 1 km asphalt road in Yalova. The analysis focused on the benefits and opportunities of using RAP instead of virgin aggregate in asphalt pavements, considering cost and environmental factors. Based on the findings:

- It was observed that total production costs decreased by 6% to $5,013.9 for 30% RAP usage, by 11% to $9,279.4 for 50% RAP usage, and by 15% to $12,647 for 70% RAP usage. These cost reductions indicate that recycling asphalt pavements can be a viable alternative for new road construction.
- Although energy consumption was not specifically addressed in this study for Yalova, references were made to existing literature. As previously mentioned in Figure 2, a study showed a decrease of approximately 7.6% in CO2 emissions, amounting to 63,524 kg per km, with the use of 50% RAP. Additionally, the use of 50% RAP resulted in an energy consumption reduction of 870,825 MJ per km. Despite the increase in recovery costs, the overall cost analysis favors the expansion of RAP usage due to the significant decrease in total production costs resulting from reductions in aggregate and bitumen production, as well as operating costs.
- Detailed life cycle cost analysis should be conducted to further explore the use of RAP in Yalova. To promote the recycling and reusability of pavement materials nationwide in Türkiye, an integrated management system could be established for recycling asphalt roads, which are classified as utilizable and recyclable waste. The government can incentivize municipalities and private entities to utilize RAP. Legislation must be enacted to mandate the use of recycled materials, and detailed regulations should be developed.
- The use of recycling methods and RAP in asphalt pavements not only helps preserve natural resources and prevent environmental damage but also offers significant financial gains. Non-recycled asphalt pavement waste poses significant harm to the environment when left untreated. Therefore, promoting the recycling and reusability of asphalt pavements is crucial not only in Türkiye but also worldwide. Taking steps to support the goals of the European Green Deal can contribute to creating a more sustainable world.

VI. RECOMMENDATIONS

- Conduct further research on different percentages of RAP usage: Although the study focused on 30%, 50%, and 70% RAP usage, it would be beneficial to explore the effects of other percentages as well. This can help identify the optimal balance between cost reduction and environmental benefits in asphalt pavement construction.
- Evaluate the long-term durability of RAP: While the cost-benefit analysis indicates the potential advantages of using RAP, it is important to assess the long-term performance and durability of asphalt pavements incorporating recycled materials. Longitudinal studies and field trials can provide valuable insights into the structural integrity and maintenance requirements of RAP-based road surfaces.
- Assess the feasibility of RAP in different geographical regions: The study focused on Yalova, but it would be valuable to evaluate the applicability of RAP in other regions of Türkiye or even in different countries. Factors such as climate, traffic patterns, and aggregate availability can influence the performance and cost-effectiveness of RAP, making it essential to assess its viability in diverse contexts.

- Investigate alternative recycling methods and technologies: While the study focused on RAP usage, it would be worthwhile to explore other innovative recycling methods and technologies for asphalt pavements. Technologies such as warm mix asphalt and cold recycling techniques have shown promising results in terms of cost savings and environmental benefits. Assessing their suitability and potential implementation can broaden the range of sustainable options.
- Promote collaboration and knowledge-sharing among stakeholders: To accelerate the adoption of sustainable practices in road construction, fostering collaboration among government agencies, research institutions, industry stakeholders, and environmental organizations is crucial. Sharing best practices, lessons learned, and success stories can facilitate the widespread implementation of recycling methods and encourage the development of standardized guidelines and specifications.

These suggestions aim to expand the scope of future research and provide a broader perspective on utilizing recycled materials in asphalt pavement construction beyond the findings and limitations mentioned in the article.

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