Sustainability and Cost Efficiency in Asphalt Production: A Comparison of Mixing Technologies and the Case Study in Sardinia (Italy)

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Abstract. The paper performs a comparative assessment of the industrial costs associated with the production of Warm Mix Asphalt (WMA), Warm Mix Asphalt enriched with Recycled Asphalt Pavement (RAP) material, and Hot Mix Asphalt (HMA). The objective is to identify the most cost-effective and environmentally sustainable solutions for road infrastructure. The operational and investment costs associated with each asphalt mixing technology were examined, paying particular attention to environmental aspects and the need to reduce costs through efficiency and innovations in production processes. The case study of Sardinia, an island in the middle of the Mediterranean Sea, provides a unique perspective for analyzing the influence of local variables such as material availability and climatic conditions on production decisions. This choice allowed the effectiveness of asphalt mixing technologies to be evaluated under well-defined boundary conditions, highlighting how WMA and WMA with RAP material can offer significant advantages in terms of lower emissions and reduced costs, especially when recycled material is widely available. The results underscore the importance of adopting innovative and environmentally friendly production practices, demonstrating how improvements in emissions can contribute significantly to lowering costs in the road construction sector. This study aims to provide crucial insights for decision makers, promoting the adoption of more sustainable and cost-effective asphalt production methodologies, with a specific focus on island contexts such as Sardinia.

Keywords: Pavements · Green Roads · Asphalt · HMA · WMA · RAP

1 Introduction

Road networks are the arteries of global economies, enabling the flow of goods and people, highlighting the importance of efficient and sustainable transportation infrastructure. Countries like Italy, the United Kingdom, as well as many European Union nations and the United States, depend heavily on road transport for most passenger and freight movements, underscoring the sector's central role in domestic and international

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O. Gervasi et al. (Eds.): ICCSA 2024 Workshops, LNCS 14824, pp. 133–149, 2024.
https://doi.org/10.1007/978-3-031-65332-2_9

trade [1]. The Italian transportation landscape, despite a significant decline in passenger miles traveled in 2020, continues to demonstrate an unwavering reliance on road transport [2, 3]. This resilience, even in the face of global challenges, underscores the need for sustainable infrastructure development, particularly in the face of environmental concerns. The construction and maintenance of road infrastructure, particularly through the use of asphalt, have significant environmental impacts, including greenhouse gas emissions and the consumption of large amounts of energy to produce the necessary materials.

In response to these challenges, the construction industry is exploring more sustainable practices, focusing on innovative asphalt technologies that promise to mitigate the environmental drawbacks traditionally associated with the industry, particularly that of road superstructure. Warm Mix Asphalt (WMA) has emerged as a major alternative to conventional Hot Mix Asphalt (HMA), offering the potential for lower energy consumption and reduced emissions. In addition, the integration of recycled asphalt pavement (RAP) into WMA and HMA formulations presents an attractive opportunity to further improve the sustainability of road construction by recycling existing materials and reducing the demand for virgin resources like land consumption.

This paper delves into a comparative analysis of HMA and WMA technologies, examining their industrial costs at elemental resources with and without the addition of RAP. The study is contextualized within the unique environmental and logistical framework of Sardinia, Italy, and provides a focused examination of how these asphalt technologies can be optimized to improve cost-effectiveness and environmental sustainability. By assessing the differences and potential benefits of these asphalt production methods, the research aims to shed light on the economic feasibility of more sustainable practices for future road construction and maintenance efforts. The goal is not only to assess the immediate impact of these technologies on cost and environmental sustainability, but also to envision the future of infrastructure development. The study focuses on the cost and production of individual types of asphalt mix, not going into the merits of the mechanical strength specifications of the materials, reserving the task of evaluating other key emission and cost items such as maintenance and paving operations for future study.

2 HMA, WMA, RAP – Definitions

In the context of asphalt production technologies, two categories can be distinguished: HMA and WMA [4]. The technologies may have different characteristics in terms of mix composition, thus different chemical and physical properties and processing temperatures, offering specific advantages and disadvantages that affect application effectiveness, sustainability and overall performance.

- Hot Mix Asphalt (HMA):

HMA represents the most traditional and widespread solution, characterized by the use of mineral aggregates and bituminous binders, occasionally enriched with additives aimed at improving performance. Aggregates, which constitute the predominant value of the total weight of HMA, are generally composed of crushed rock, gravel, sand, and

mineral powders. The bituminous binder, acting as a binder, gives the mixture considerable strength and durability. The production process of HMA requires the application of high temperatures, ranging from 150 to 180 °C for the aggregates and 160 to 175 °C for the bitumen, thus ensuring the production of a high-performance material that is ideal for withstanding heavy traffic and climatic adversity [5, 6].

The main advantages of HMA include high strength and durability, making it the preferred choice for road infrastructure under significant stress. The rapid installation process and ability to produce large volumes contribute to reduced construction time and costs. However, the production and laying of HMA involves high energy consumption and increased greenhouse gas emissions due to the high temperatures required. These aspects represent major disadvantages, to which are added safety risks for operators.

- Warm Mix Asphalt (WMA):

Warm Mix Asphalt is characterized by a similar composition to HMA, but is distinguished by the use of specific additives or modifications to the production process that allow it to be processed at lower temperatures, varying between 100 and 140 °C. These additives, capable of reducing the viscosity of the bitumen, facilitate the workability of the material, allowing significant energy savings and lower emission of harmful substances. WMA technology consists of several solutions, specific additives with organic or chemical components, each of which aims to decrease the temperature required for asphalt production and laying [6, 7].

The advantages of WMA lie in reduced energy consumption and emissions, improved workability, and the ability to extend the working season due to reduced production temperatures. These features not only promote less environmental impact but also greater safety for operators. Nonetheless, the relative newness of WMA results in a paucity of data on long-term durability and overall performance, as well as potential increases in cost and production time due to the use of additives. In addition, consideration must be given to the production chain of the latter, which are often produced by chemical processing and thus impact emissions.

Nevertheless, the study by Chehovits and Galehouse [8] shows that HMA production requires 275 MJ/t of energy, while WMA consumes 234 MJ/t, or 15 percent less. This comparison highlights the superior energy efficiency of WMA compared to HMA, offering an important perspective on the sustainability of different asphalt technologies.

- Recycled Asphalt Pavement (RAP):

A key aspect in the landscape of asphalt technologies is Recycled Asphalt Pavement (RAP), which consists of the recovery of milled material from pre-existing pavements. RAP can be incorporated into both HMA and WMA mixtures, helping to reduce the need for new aggregates and bituminous binders and promoting greater environmental sustainability. The added value of RAP in road construction is greatly recognized for its contribution to sustainability and cost reduction. The milling process that originates RAP results in milled material that can be used as a new resource, which can be granulometrically corrected and enriched with additives to meet the needs of new applications. As Oliveira et al. [9] point out, pavement quality is a key aspect of ensuring infrastructure functionality. If the implementation of RAP in maintenance operations lightens the environmental impact by avoiding the use of landfills, it allows the creation of renewed

asphalt mixtures, on the other hand, the integration of RAP presents challenges. Uncertainty about the percentages of use to be incorporated, reported by Bonfim [10], affects the workability and stiffness of the mixtures, with possible repercussions on fatigue and crack formation [11, 12]. This problem is due to the difficulty of regeneration and reactivation of oxidized bitumen, which results in higher stiffening than in virgin mixtures, from which arises a high susceptibility to fatigue cracking.

In accordance with L.F. Walubita, et al. [13] the design of flexible pavements is strongly influenced by fatigue durability, as the main cause of cracking in hot asphalt mixes, especially due to environmental conditions, significant traffic loads, but also due to own mineralogical composition of the aggregate, type of binder and precisely RAP incorporation [12, 14, 15].

Therefore, accurate evaluation of recycled material properties is essential to ensure pavement durability. Despite these obstacles, the increasing research and adoption in asphalt mixtures reflects a positive trend toward more efficient and responsible construction practices, promoting material reuse and recycling in the construction industry [14]. In conclusion, the choice between HMA and WMA, including considering the incorporation of recycled materials such as RAP, depends on a careful evaluation of project-specific requirements, including sustainability, safety, durability, and cost considerations. While HMA continues to be a solid option for demanding applications, WMA and the use of RAP are emerging as promising solutions to reduce environmental impact and improve working conditions while maintaining high standards of performance.

3 Trends in Asphalt Production in Europe – 2022

"Asphalt in Figures 2022" [5] is a detailed report presented by the European Asphalt Pavement Association (EAPA). The association represents manufacturers of asphalt mixtures and companies involved in asphalt road construction and maintenance in Europe. This report provides a comprehensive overview of key statistics and trends in the European asphalt industry for the year 2022, covering various aspects such as total production, reuse and recycling rates, applications in different road layers, and the introduction of technological innovations (Fig. 1).

Data compared to 2021 show a slightly decreasing trend in terms of annual production, but still close to the average of the last decade (Table 1).

The data show that Italy has seen the largest increase in production over the past three years, from 30 to 37.6 million tons produced by 2022, just behind Germany with 39.0 million tons and ahead of France with 30.7 million tons. These numbers reflect significant variations in asphalt production among different European countries, underscoring differences in the size of the road construction industry, infrastructure policies, and asphalt reuse and recycling practices.

Table 2 [5] presents the percentage distribution of hot and warm asphalt use in surface course (surface course), binder course (binder course), and base course (base course) applications for various countries in 2022. Data provide an important overview of how asphalt is used in road construction at the European level, reflecting the different construction needs and practices in different countries.

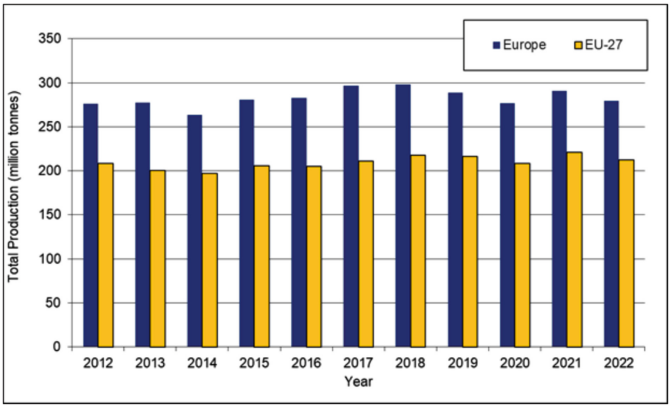

Fig. 1. Total production of HMA and WMA from 2011 to 2022 (Million tons) [5]

Table 1. Production of HMA and WMA from 2020 to 2022 (in million tonnes) [5]

Country	2022	2021	2020
Austria	6,5	7,3	7,4
Belgium	4,9*	4,627	4,34
Croatia	2,75	2,71	2,33
Czech Republic	6,8	7,2	6,7
Denmark	3,47	3,55	3,94
France	30,723	34,72	31,85
Germany	39	38	38
Great Britain	24,2	25,7	23
Hungary	4,47	4,919	4,847
Italy	37,6	37,6	30,1*
Netherlands	6,2	7,2	7,1
Norway	6,35	6,86	6,863
Poland	19,0*	19,0*	19,0*
Portugal	3,1	4	3,4
Slovakia	2,464699	2,371218	2,16435
Slovenia	2,06	2,1	1,88
Spain	17,1	18,9	17,1
Sweden	8,2*	8,2*	8,2*
Turkey	30,14	30,3	31,7

Table 2. Surface, binder and base courses - Application in surface-, binder- and base courses of total annual Hot and Warm Mix Asphalt production 2022 (%) [5]

Country	Surface course	Binder course	Base course
Austria	60	10	30
Belgium	53	0	47
Croatia	61	5	34
Czech Republic	55	22	23
Denmark	46	6	48
Estonia	63	5	32
Hungary	61	31	8
Norway	80	10	10
Portugal	68	18	14
Romania	28	25	47
Slovakia	70	19	11
Slovenia	55	6	39
Spain	75	19	6
Turkey	36	39	25

In Europe, the approach to asphalt use varies widely among countries depending on the road layers they intend to reinforce. In general, the percentage distribution of asphalt use in different road layers reflects each country's intervention priorities in terms of pavement rehabilitation, durability and performance, or in relation to new construction. Factors such as weather conditions, volume and type of traffic, as well as road maintenance strategies, can influence these choices. Regarding RAP utilization data, the report shows the following Table 3:

Also from the report reviewed in Italy, in 2022, 9.2 million tons of RAP were available for reuse by the asphalt industry. However, the table does not provide additional data on the specific percentages of how this recovered asphalt was actually used, so information on reuse and recycling in Italy for that year is lacking. In addition, the data are estimates of historical values with projections for that year.

Figure 2 [5] shows the percentage of recycled asphalt available in some European countries that has been reused to produce new asphalt mixtures, including HMA, WMA and cold mix asphalt (CMA). Recycled asphalt used as an unbound layer in civil engineering projects is also shown, in addition to its use in other unspecified applications or its landfilling. For the determination of these values, only the complete data provided by the countries (total quantities and percentages of use) were considered. The European countries considered in the study were Austria, Belgium, Croatia, Czech Republic, Denmark, France, Germany, Great Britain, Hungary, Norway, Romania, Slovenia, Spain and Turkey. In these countries, a total of 36.1 million tons of recycled asphalt was available, of which 76% was reused, 22% recycled into unbound road layers, and only 2%

Table 3. Re-use and Recycling of Reclaimed Asphalt in 2022 - [5]

Country	Total amount of site-won asphalt generated in 2022 in tonnes	Amount of reclaimed asphalt available to be used by the asphalt industry in 2022 in tonnes	% of available reclaimed asphalt used in						
			Hot and Warm Mix Asphalt Production	Half Warm Mix Asphalt Production	On-Site Cold Recycling **	Plant Cold Recycling **	Unbound Road Layers	Other Civil Engineering Applications	Put to Landfill /Other Applications/ Unknown
Austria	1.900.000	800.000	85	0	5	0	10	0	0
Belgium	1.684.000	1.025.000	100	0	0	0	0	0	0
Croatia	270.000	240.000	42	0	2	19	no data	no data	no data
Czech Republic	2.800.000	2.500.000	30	0	15	0	15	10	30
Denmark	1.306.000*	1.106.000	no data	no data	no data	no data	4	no data	no data
France	no data	7.340.000	45	no data	no data	no data	no data	no data	no data
Germany	14.800.000	12.876.000	87	0	0	0	13	0	0
Great Britain	5.814.442	no data	no data	no data	no data	no data	no data	no data	no data
Hungary	150.000	180.000	10	0	10	74	3	3	0
Ireland	500*	500*	45*	no data	no data	no data	no data	no data	no data
Italy	11.000.000*	9.200.000*	no data	no data	no data	no data	no data	no data	no data
Norway	>1.600.000	1.600.000	no data	no data	no data	no data	no data	no data	no data
Romania	34.000*	34.000*	0	0	95	0	5	0	0
Slovenia	305.000	51.000	58	0	9	0	14	9	10
Spain	1.900.000	2.000.000	66	~0	7	~0	24	0	3
Turkey	1.920.400	1.728.360	12	0	0	7	81	0	0

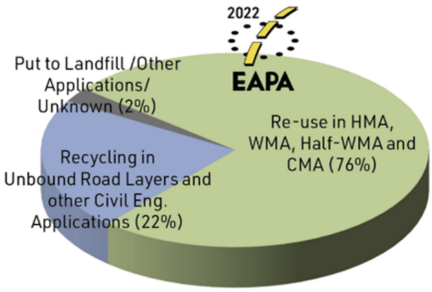

Fig. 2. Application of reclaimed asphalt in fourteen European countries providing data [5]

went to unknown applications or landfill. In conclusion, the report shows how the use of reclaimed asphalt, highlighted by data from various European countries, is significantly increasing toward reuse and recycling, with 76% of reclaimed asphalt reused in the production of new mixes and only 2% going to landfill or unknown uses. This orientation not only meets an environmental need, but also aligns with the goal of reducing industrial costs through efficient and innovative production processes.

4 Cost Analysis to 2024 to Produce HMA, WMA with and Without the Use of RAP - Case Study in Sardinia

The analysis of asphalt production costs is a crucial aspect in the evaluation of sustainable construction practices and material selection in the infrastructure sector. Focusing on Sardinia, an island that offers a unique and well-delineated geographic context, this

study aims to assess the economic impact resulting from the use of different types of asphalt, with material market prices updated to early 2024.

Sardinia's island status allows for the isolation of variables such as raw material availability and climatic conditions, providing an ideal scenario for analyzing the effectiveness of asphalt mixing technologies. In this well-defined context, the environmental benefits and economic advantages of using varying percentages of RAP material in specific mix designs for binder-type asphalt mixes can be observed. The use of WMA and HMA with RAP not only promotes the reduction of emissions and the use of resources already available in the area but can also result in a decrease in operating costs, which is particularly relevant in isolated settings where the burdens pertaining to transportation and logistics tend to be greater.

The objective is therefore twofold: on the one hand, to confirm the production efficiency and environmental sustainability of recycling and reuse techniques in the asphalt production process; on the other hand, to provide a replicable model, with the aim of promoting the adoption of innovative methodologies that can result in significant economic savings, in full compliance with environmental regulations.

The focus is therefore on mix design for an asphalt wearing course, exploring four distinct configurations: HMA with exclusively virgin material; HMA with 25% RAP; WMA with completely virgin material; and WMA with 25% RAP. This analysis will be conducted using a rigorous methodological approach, considering the elemental resource costs, as well as the benefits from the reduction in energy costs offered using WMA, and the land savings from the reduced supply of virgin material from quarries through the use of RAP.

As part of this assessment, the financial and environmental impacts of adopting variable percentages of RAP will be highlighted, providing a detailed comparison of different mixing techniques. Particular attention will be paid to the relationship between cost reductions from the use of recycled material taking into account that the mixtures considered, can be produced in most conventional asphalt plants.

4.1 The Production Facility

The plant under study in this study is configured as a batch-type asphalt production system, specifically a mixing tower, widely recognized for the high quality of the final product. The choice of a batch plant ensures greater quality control of the material produced, although it involves higher initial and operating costs than continuous plants.

Production begins with the selection and withdrawal of lithic aggregates from on-site deposits, followed by the drying and heating, hot reclassification, and weighing stages. These preparatory operations are crucial to ensure that the mix meets the required technical specifications. Next, bitumen, filler and any additives are fed and dosed into the production process, finally converging at the mixing stage, where all elements are amalgamated in the mixer. From here, the finished product is transferred to storage silos awaiting transport to the site of use by truck.

The detailed production cycle follows a well-defined path, from the collection of aggregates, which are characterized by various moisture levels and at room temperature, to their processing.

The drying and heating phase takes place in a rotating cylinder, where a burner generates the necessary heat. The aggregates advance in countercurrent to the hot gases, optimizing the heat exchange process. An innovative burner-dryer system ensures the high efficiency of the process, minimizing emissions and improving combustion efficiency.

The mixing tower, the centerpiece of the plant, handles the handling of hot and dried aggregates until they are mixed with bitumen and additives. This area of the plant is distinguished by its discontinuous functionality, allowing accurate weighing and batching of the components, which are essential to ensure the final quality of the asphalt mix.

The burner integrated in the plant under review, presents advanced technical characteristics, configuring itself as a closed and pressurized modulating type system, with automatic electrogas ignition. Its maximum capacity is 19,600,000 kcal/h (22.7 MW), with an LPG gas flow rate of 890 Nm3/h. The supply pressure is maintained at optimum levels, with 0.6 bar at the gas ramp inlet and 0.5 bar at the burner inlet, thus ensuring a constant and adequate flow for the effective operation of the plant.

A distinctive feature of this plant is the use of liquid LPG as fuel, which is regasified through specific regasifiers. These not only power the burner but also provide the energy needed to maintain the optimal temperature in the bitumen tanks, which are heated through an electrical system. This configuration not only highlights the efficiency and technological innovation of the plant but also emphasizes an approach aimed at optimizing energy consumption and reducing environmental impact. The use of LPG, in fact, allows cleaner combustion than other fossil fuels, with lower emissions of pollutants. The impact of aggregate moisture on energy consumption within the asphalt production process is a significant variable. In this regard, a strategic measure was adopted to optimize the energy efficiency of the plant by covering the aggregate piles with special canopies. This solution makes it possible to protect the materials from the weather, particularly rainfall, while ensuring that a low moisture level is maintained in the aggregates.

The presence of sheds that isolate the aggregate piles has a twofold advantage: on the one hand, it reduces the amount of energy required to dry the aggregates, contributing to a significant decrease in energy consumption; on the other hand, it ensures greater stability and predictability in the production process, facilitating the control of production variables and ensuring a final product of consistent quality. Then, being a support point for a photovoltaic plant, they allow to close the circle and the supply chain, providing sufficient energy input to make the production plant autonomous.

In summary, the plant analyzed represents an advanced example of asphalt production technology, where attention to operational details and the choice of cutting-edge technological solutions contribute to obtaining a high-quality product, in full compliance with the criteria of energy efficiency and environmental sustainability.

4.2 Mix Design

The development of innovative mix designs for asphalt production is a key aspect in the development of more sustainable and efficient paving techniques. The Table 4 illustrates a series of experimental mix designs, tested in the plant under consideration, that aim to optimize material use, recycling, and environmental impact reduction in the context of

road pavement wearing course production. These mix designs include both standard formulations HMA and WMA without the use of recycled material, and advanced versions that incorporate RAP to promote recycling in the road construction industry.

Table 4. Mix design considered for analysis

Type	Mix Design	RAP	Sand 0–4	Sand 4–8	Filler	Bitumen 50/70 [% on dosage]	Additive [% on bitumen]	Additive type
HMA	Asphalt wearing course 0/8	0,00%	50,00%	50,00%	2,00%	6,50%	0,00%	
WMA	Asphalt wearing course 0/8	0,00%	40,00%	60,00%	3,00%	6,00%	1,20%	Additive for WMA
HMA - RAP	Asphalt wearing course 0/8	25,00%	30,00%	45,00%	1,00%	4,90%	0,98%	Additive for HMA with RAP
WMA - RAP	Asphalt wearing course 0/8	25,00%	30,00%	45,00%	1,00%	4,90%	0,98%	Additive for WMA with RAP

For each mix design, these percentages of aggregates, RAP, filler, bitumen and additives are calculated relative to a predetermined total mass of 1 ton of aggregate material, allowing for effective standardization in formulations. The calculation of RAP and aggregate percentages relates directly to the total ton of aggregate material, allowing precise allocation of resources within the mix. For example, a 25% presence of RAP indicates the inclusion of 250 kg of recycled material for every ton of aggregate. Similarly, the amount of filler is defined as a fixed percentage of the total mass, providing a constant measure of this critical component for the volumetric stability of the asphalt mix. Conversely, the percentage of bitumen is expressed as a function of aggregate weight (aggregates + RAP), emphasizing the importance of adequate saturation of the mix to ensure optimal adhesion and mechanical properties. Finally, the additive is calculated as a percentage of the bitumen used, emphasizing its role in modifying specific chemical and physical properties of the mix, such as workability at low temperatures or regenerative capacity against aged bitumen from RAP.

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aim to optimize material use, recycling and environmental impact reduction in the context of road pavement wearing course production. For the various mixtures, the use of various specific additives designed to optimize the properties required in the cases evaluated was considered.

Additive for WMA - NO RAP

This additive aims to reduce the temperatures required for asphalt mix production, paving and compaction, offering significant benefits in terms of energy savings and reduced air emissions. At the same time, it contributes to improved adhesion between aggregates and bitumen, thereby increasing the quality and durability of the final material.

The recommended dosage of the additive varies between 0.2% and 0.5% by weight of bitumen, depending on the specific operating conditions and the type of mix to be produced. Determining the optimum percentage of additive, however, requires laboratory testing to tailor use to the particular characteristics of production. Composed of a mixture of amine derivatives and specific additives, this additive is in liquid form with a yellow-brown color. Its physical properties include a density at 25 °C ranging from 0.95 to 1.05 g/cm^3 and a viscosity at 25 °C ranging from 150 to 250 cP. Safety of use is ensured by a flash point above 105 °C and a pour point below -5 °C.

The use of this additive in the WMA production process involves specific procedures both in the laboratory and in the plant, with the recommendation that the mixing temperature be maintained between 130 and 140 °C and that samples be conditioned to the suitable compaction temperature for about 2 h before compaction. The mixture should be spread and rolled at the optimum compaction temperature, usually between 100 and 120 °C, depending on the type of bitumen used and weather conditions.

Additive for HMA/RAP

The additive is particularly effective in handling mixtures with recycled material and makes it possible to optimize the mixing process, ensuring optimal integration of aggregates and recycled bitumen.

The recommended dosage varies from 0.2% to 0.4% on RAP weight, depending on specific production requirements, such as operating conditions and the type of mix to be made. Its formula, based on a mixture of amine derivatives and mineral oils, ensures effective dispersion within the bituminous mixture, promoting adhesion between the aggregates and the binder and improving the strength and durability of the finished product.

During application, both in the laboratory and in the plant, it is crucial to keep mixing temperatures controlled (150–160 °C) to ensure activation of the additive and its complete integration into the mix. Reclaimed asphalt mix should be dry and used at room temperature or preheated to 80 °C, to facilitate mixing and optimize the effect of the additive.

Additive for WMA/RAP

The additive is distinguished by its ability to significantly lower the temperatures required for production, paving and compaction of asphalt mixes, thus contributing to significant energy savings and reduced emissions to the atmosphere.

The recommended dosage ranges between 0.08% and 0.13% on RAP weight, although under certain operating conditions an increase up to 0.4% can be considered to handle special challenges such as high RAP rates or long transport times. Determining the optimal additive percentage requires specific laboratory and plant tests to adjust for production variables.

The additive has a composition based on amine derivatives and mineral oils, characterized by a yellow-brown liquid appearance, specific density and viscosity, and flash and creep points that attest to its safety and ease of handling. Regarding practical use, during mixing steps, it is recommended to maintain temperatures between 130 and 160 °C, ensuring that the RAP is dry to optimize the effectiveness of the additive. The introduction of this additive into WMA production processes with high RAP percentages stands as a significant advancement in the field of sustainable asphalting, offering a practical solution to improve the quality and environmental sustainability of road pavements.

4.3 Quantities and Costs

As part of optimized asphalt mix production research, the determination of the proportions between the different components of the mix design is based on a rigorous quantitative approach, which is critical to ensuring the desired performance of the final material. For each mix design, the percentages of aggregates, RAP, filler, bitumen and additives are calculated relative to a predetermined total mass of 1 ton of aggregate material, allowing for effective standardization in formulations. The calculation of RAP and aggregate percentages relates directly to the total ton of aggregate material, allowing precise allocation of resources within the mix. For example, a 25% presence of RAP indicates the inclusion of 250 kg of recycled material for every ton of aggregate. Similarly, the amount of filler is defined as a fixed percentage of the total mass, providing a constant measure of this critical component for the volumetric stability of the asphalt mix. Conversely, the percentage of bitumen is expressed as a function of aggregate weight (aggregates + RAP), emphasizing the importance of adequate saturation of the mix to ensure optimal adhesion and mechanical properties (Tables 5 and 6).

The costs highlighted in the table reflect the average costs incurred for the purchase of materials used in asphalt mixes, calculated by a company in Oristano, Sardinia, Italy. These prices, which include not only aggregates and bitumen but also specialized additives, are inclusive of transportation costs, which are essential in an insular geographic context where logistics greatly affect final costs. Bitumen, being a material strongly influenced by market fluctuations, is accounted for as an average value to facilitate financial planning in response to global price dynamics and the complexities of import operations (Table 7).

Incorporating RAP into HMA and WMA mixtures results in a reduction in overall cost per ton, which underscores the economic value of reusing materials in the road construction industry. Differences in sand costs between HMA and WMA mixtures could reflect variations in particle size properties or quality of materials used, suggesting optimization of compositions according to production thermal characteristics.

Although the addition of additives results in a marginal increase in total cost in WMA variants, this is balanced by the decrease in bitumen cost. This highlights the potential

Table 5. Amount of mixture

Type	HMA	WMA	HMA - RAP	WMA - RAP
Mix Design	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8
RAP [kg]	0	0	250	250
Sand 0–4 [kg]	500	400	300	300
Sand 4–8 [kg]	500	600	450	450
Filler [kg]	20	30	10	10
Bitumen 50/70 [kg]	65	60	49	49
Additive [kg]	0	0,72	0,4802	0,4802
Additive type		Additive for WMA	Additive for HMA with RAP	Additive for WMA with RAP
Tot [kg]	1085	1090,72	1059,48	1059,48

Table 6. Unit costs elementary resources

Elemental materials	UM	€/UM
RAP	ton	6,50 €
Sand 0–4	ton	15,00 €
Sand 0–8	ton	12,00 €
Filler	ton	53,00 €
Bitumen 50/70	ton	640,00 €
Additive for WMA	ton	4.170,00 €
Additive for HMA with RAP	ton	4.570,00 €
Additive for WMA with RAP	ton	4.820,00 €
LPG - Gas	KG	0,45 €

of additives to increase process efficiency and contribute to wider energy savings and emission reductions.

The cost per kg of material remains essentially unchanged between HMAs and WMAs, implying that the reduction in production temperatures for WMAs does not substantially affect material costs. The cost per ton data reveal marginal savings among the different mix designs, highlighting how operational decisions can be driven by environmental and process performance factors as well as economic considerations.

Taken together, this information underscores the importance of an integrated approach that considers environmental sustainability, technical performance, and economic factors in the decision-making process for mix design selection in infrastructure projects,

Table 7. Cost Comparison and Environmental Impact of Asphalt Mix Designs with and without RAP

Type	HMA	WMA	HMA - RAP	WMA - RAP
Mix Design	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8
RAP [€]	– €	– €	1,63 €	1,63 €
Sand 0–4 [€]	7,50 €	6,00 €	4,50 €	4,50 €
Sand 4–8 [€]	6,00 €	7,20 €	5,40 €	5,40 €
Filler [€]	1,06 €	1,59 €	0,53 €	0,53 €
Bitumen 50/70 [€]	41,60 €	38,40 €	31,36 €	31,36 €
Additive [€]	– €	3,00 €	2,19 €	2,31 €
Additive type		**Additive for WMA**	**Additive for HMA with RAP**	**Additive for WMA with RAP**
Tot [kg]	1085,00	1090,72	1059,48	1059,48
Tot [€]	56,16 €	56,19 €	45,61 €	45,73 €
[€]/kg	0,052 €	0,052 €	0,043 €	0,043 €
€/ton	51,76 €	51,52 €	43,05 €	43,16 €

especially in a framework of long-term financial sustainability for companies in the sector. As part of experiments conducted to evaluate the winter performance of asphalt mix designs, an average aggregate moisture content of 6% was found during the cold season. On a sample of 1,000 tons of material produced for the four mix designs previously discussed, it was observed that energy consumption varies with mix type and outdoor thermal conditions, specifically in an ambient temperature range of 10° to 15° Celsius.

For mix design HMAs, the average gas consumption stands at 3.7 Nm^3/ton, while for WMAs there is a significant reduction in consumption to 3.1 Nm^3/ton. This decrease reflects the inherent energy efficiency of WMA production processes, which operate at lower temperatures than conventional HMAs, confirming the hypothesis that WMA technologies can result in tangible energy savings.

The gas consumption figure is critical in calculating the economic and environmental impact of asphalt production. Lower consumption, such as that found for WMAs, implies less use of fossil resources and thus a reduced operating cost, and is also associated with lower emissions of greenhouse gases and air pollutants.

From the data evaluated from the examined plant and considering a purchase cost of bulk LPG used to fuel the burner of €0.45/kg, the following values were estimated (Table 8):

This table provides a detailed comparison of the costs associated with the production of different types of mix designs of asphalt wearing course mixes. The data refer to the

Table 8. Cost and Efficiency Analysis of 0/8 Asphalt Wearing Course Mixes

Type	HMA	WMA	HMA - RAP	WMA - RAP
Mix Design	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8	Asphalt wearing course 0/8
Tot [€]	56,16 €	56,19 €	45,61 €	45,73 €
€/kg	0,052 €	0,052 €	0,043 €	0,043 €
€/ton	51,76 €	51,52 €	43,05 €	43,16 €
GPL	3,70 €	3,10 €	3,70 €	3,10 €
GPL [€]	4,33 €	3,63 €	4,33 €	3,63 €
Tot [€]	**60,49 €**	**59,82 €**	**49,94 €**	**49,36 €**

standard Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) mixes, as well as their variants incorporating Reclaimed Asphalt Pavement (RAP).

A total cost analysis reveals that the price difference between HMA and WMA mixes is minimal, suggesting that despite the energy savings offered by WMAs due to lower processing temperatures, the introduction of specific additives for these mixes increases their cost. Indeed, while LPG (used as an indicator of energy consumption) for WMA is lower than for HMA, the additional cost of additives brings total costs to comparable levels between the two types of mixes.

However, the most significant distinction emerges when considering RAP-containing variants. Both types of mix designs with RAP (both HMA and WMA) show a significant cost reduction compared to mixes without RAP, with a decrease of about €10 per ton. This saving highlights the economic benefit of using recycled material, which reduces the need for new aggregates and bitumen-resources that are typically more expensive.

In summary, the analysis indicates that the use of RAP in asphalt mixes can be an important cost reduction strategy for the road construction industry. While the adoption of WMA technologies is often justified by environmental sustainability considerations, the real cost savings, according to the data reported, are achieved through the incorporation of recycled materials, emphasizing the relevance of recycling in the financial optimization of asphalt production.

5 Conclusions

Examination of the costs associated with asphalt mix production highlights crucial considerations for the road construction industry, especially from the perspective of economic and environmental sustainability. The minimal variation in total costs between HMA and WMA, despite the lower energy consumption of the latter, highlights how the adoption of specific additives can significantly influence the production cost structure. This observation underscores the importance of balancing sustainability goals with the economic management of the production process.

On the other hand, the presence of RAP in asphalt mixtures marks a net cost saving, reducing the need for new materials and enhancing the recovery of existing resources.

The analysis confirms that incorporating RAP is a practical strategy for lowering costs, with the additional potential to minimize the carbon footprint of road operations.

The conclusions emerging from the study confirm that the asphalt industry is at a crossroads, where technological innovation and material reuse can not only coexist but, in fact, can enhance each other. Adoption of WMA production practices and efficient use of RAP appear to be viable paths toward greater environmental sustainability and economic savings. This is of particular relevance in geographically isolated settings such as Sardinia, where logistics and material import costs can place a significant burden on firms' cost structures.

Finally, the implications of these findings extend far beyond the local context of the island, offering insights for the global debate on the future of road infrastructure and the adoption of more sustainable construction methods. The challenge for decision makers, designers, and road builders will be to integrate this knowledge into construction and maintenance strategies that not only improve the quality and durability of infrastructure but also its compatibility with the environment and the circular economy.

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