Comparison of the Environmental Benefits of Cold Mix Asphalt and Its Application in Pavement Layers

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Abstract. Increasing CO_2 emissions and the importance of reducing the carbon footprint in transportation infrastructure are topics of growing interest in civil engineering. This paper examines the use of asphalt mix designs alternative to classic Hot Mix Asphalt (HMA) such as Warm Mix Asphalt (WMA) and Cold Mix Asphalt CMA) as sustainable solutions to mitigate environmental impacts and promote material reuse. The introduction stresses the importance of use in the transportation sector and highlights the potential for reducing CO_2 emissions and energy consumption by lowering processing temperatures [10]. The following paper analyzes asphalt technologies, exploring the merits and demerits of different solutions and assessing the suitability of recycled materials. It proceeds by quantifying the use of HMA, WMA and CMA at global, European, and Italian levels, highlighting the evolution of production techniques and their diffusion in different contexts.

In the conclusions, considerations are made on the environmental benefits and technical feasibility of WMA and CMA, emphasizing the importance of promoting the adoption of these solutions in transportation infrastructure for sustainable resource management and climate impact reduction.

The paper contributes to the debate on the use of sustainable materials in the construction industry by encouraging research and innovation in the design and implementation of greener transportation infrastructure.

Keywords: Warm Mix Asphalt (WMA) · Cold Mix Asphalt (CMA) · Transportation infrastructure · Environmental impact

1 Introduction

Road networks are the backbone of transportation infrastructure in most countries, allowing for the movement of goods and people across vast distances. In the UK, for example, road transport accounts for a staggering 91% of passenger travel and 67% of goods transport. Similarly, the figures for the European Union and the US are equally impressive, with 92% and 88% of passenger travel, respectively, and up to 48% of goods transport being conducted on roads [1]. It's clear that road transport is a vital component of the global economy, providing an essential link between producers, consumers, and

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suppliers. However, the environmental impact of road infrastructure is also significant, as green-house gas emissions and energy consumption associated with construction, maintenance, and use of roads contribute to climate change. In Italy, the situation is not different. In 2020, total passenger traffic amounted to 614.6 billion passenger-kilometers, representing a 36.4% decrease from the previous year. Of this total, an overwhelming 94.3% of passenger travel was conducted on roads, with only 4.2% taking place on rail, 1% by air, and 0.4% by sea. Private transportation, such as cars and motorcycles, accounted for most of the travel, growing from 79.8% in 2019 to 84.9% in 2020. In contrast, rail transport decreased from 5.9% in 2019 to 3.5% in 2020, while collective urban and extra-urban transport decreased from 11.5% to 10.1%, and air transport decreased from 2.3% to 1% [2]. Given the predominance of road transport in Italy and the significant environmental impact associated with it, it is critical to address these challenges by adopting innovative solutions that can reduce the carbon footprint and promote sustainability. One area of focus is the development of new technologies for asphalt mixes, such as Cold Mix Asphalt (CMA) and Warm Mix Asphalt (WMA), which can significantly reduce energy consumption and partially reduce greenhouse gas emissions compared to traditional asphalt.

Asphalt is a material widely used in the construction of transportation infrastructure such as roads, highways and airport runways. Its versatility, durability and strength make it an ideal choice for paving. How- ever, asphalt production and paving also have a significant impact on the environment, mainly due to greenhouse gas emissions and energy consumption associated with the extraction, processing and transportation of the materials. In the current global scenario of growing concern about climate change and resource sustainability, the construction industry is faced with the challenge of identifying and adopting innovative solutions to reduce the environmental impact associated with asphalt production and application. In this context, the research and development of new asphalt mix technologies that promote a more efficient use of resources and a reduction in pollutant emissions is a crucial challenge for the industry. The most used types of asphalt mixes are Hot mix asphalt (HMA), Warm mix asphalt (WMA), Cold Mix Asphalt (CMA). This article aims to analyze the different asphalt mix technologies currently available, highlighting their advantages and disadvantages, especially from an environmental perspective. In addition, the potential applications and implications of these technologies in the Italian context will be discussed.

2 HWA, WMA, CMA - Definition, Disadvantages and Advantages

Asphalt production technologies are mainly divided into three categories: Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA). These types differ in composition, chemical and physical characteristics and processing temperatures. The following will provide a general overview of the components and production and laying temperatures of each of these asphalt technologies.

HMA is the traditional and still the most widely used type of asphalt mix; it is composed mainly of aggregates, bituminous binders and occasionally additives. Aggregates, which make up 80–90% of the weight of HMA, are generally composed of crushed rock, gravel, sand, and mineral powders. The bituminous binder acts as a bonding agent for

the aggregates, imparting strength and durability to the mixture. Sometimes, additives are introduced into HMA to improve mechanical properties, such as wear resistance and moisture resistance, or to reduce the viscosity of the bitumen, improving its workability during production and laying. Temperatures used in the production of HMA vary between 150 and 180 °C for aggregates and 160–175 °C for bitumen [4]. Various mixtures have been made of this type that are capable of giving the material superior or specific performance characteristics, as in the case of drainage or sound-absorbing asphalt mixes.

WMA has a similar composition to HMA, consisting mainly of aggregates, bituminous binders and additives. The main difference lies in the use of specific additives or modifications to the production process to allow processing at lower temperatures (between 100 and 140 °C). These additives, called viscosity-lowering agents, can be chemical compounds, organic or inorganic, that reduce the viscosity of the bitumen, allowing better workability of the material at lower temperatures. WMAs also include half-warm asphalt (HWMA), that is, when the maximum production temperature is below 100 °C (212 °F). There are various processes and products to achieve this reduction, but generally WMA technologies fall into four categories:

1. Water-based, nonadditive-based, and foam-based processes. Bitumen foam is formed by spraying water into heated bitumen or adding wet sand into the asphalt mixture.
2. Water-containing additives such as natural and synthetic zeolites, also based on foaming. Foam is formed by adding zeolite to the asphalt mixture during production;
3. Organic additives such as waxes and fatty acid amides. These organic waxes have longer chemical chains and a melting point of about 100 °C, reducing the viscosity of the binder and allowing the asphalt production and laying temperature to be lowered by 20–30 °C.
4. Chemical additives change the structure of the asphalt binder and reduce viscosity, allowing asphalt production and laying temperatures to be lowered by about 40 °C [3].

CMA is composed mainly of aggregates, such as crushed rock, slag and gravel, and binder materials such as bitumen emulsions or fluidized bitumen. The material is currently used for small repair and construction work, as it does not require a large investment in equipment. Unlike HMA and WMA, CMA uses water and solvents as additional components. Bitumen emulsion, containing about 60% bitumen and 40% water, is the most common binder in CMA, due to the use of an emulsifier that keeps the bitumen suspended in an aqueous medium. Cationic emulsions are the most used in road construction and maintenance. Aggregates in CMA are subjected to the same tests and limit values as those used in HMA. During the production of CMA, potable water is added to the mix to lubricate the aggregates and improve the workability and coverage of the aggregates.

2.1 Advantages and Disadvantages

- HMA is widely used around the world because of its many advantages, although it also has some disadvantages. HMA is valued for its high strength and durability, which make it suitable for withstanding heavy traffic and weather conditions. In addition, the laying process of HMA is quite rapid and the material can be produced in large quantities, allowing for a reduction in construction time and related costs. The spread of production facilities and the now-important knowledge about the material still make it the most chosen solution worldwide for road superstructures.
- However, the use of HMA also has disadvantages. Manufacturing and laying the material requires high temperatures, leading to significant energy consumption and higher greenhouse gas emissions. Work safety is a central issue these years; high temperatures pose significant risks to paving operators. In addition, except in the case of drainage asphalt, HMA is relatively impermeable and therefore capable of causing storm water drainage problems and increasing the risk of flooding in urban areas. Despite these drawbacks, HMA continues to be widely used worldwide for its reliability and performance in terms of strength and durability.
- The main advantages of Warm Mix Asphalt (WMA) include energy savings due to lower working temperatures, reduced emissions, reduced viscosity of the asphalt mix, resulting in better processability and lower cooling rate. In addition, at the plant level, it does not require major modifications to existing HMA production facilities [3]. The advantages of WMA undoubtedly include the ability to perform paving work in colder weather conditions, as the temperature of the newly produced mix is closer to that of the outdoor environment. This leads to an extension of the working season and an increase in material transport distance. Also due to the lower temperatures, the opening of traffic lanes can take place in a shorter time due to the shorter cooling period after the work is done, which can be particularly advantageous for work on roads with high traffic volume. The use of reduced temperatures in WMA compared to HMA can positively affect air quality on construction sites and reduce the risk of burns to operators.
- However, there are disadvantages related to the scarcity of research and the short service life of WMA. The physical and mechanical characteristics of WMA are worse than hot mix asphalt and vary depending on the technology used. In addition, the use of additives to improve the cohesive properties between the mineral materials and the bitumen results in increased costs and, in some cases, an extension of the asphalt mixing cycle.
- CMA, due to its low production and compaction temperature, offers many advantages, greater emission reduction than WMA, lower fuel consumption and better working conditions. The cold asphalt recycling process is energy efficient and particularly suitable on smoggy days. Compared with HMA, CMA reduces energy consumption by 60% and generates lower CO2 emissions, with 53.6 kg for HMA and 36.1 kg for CMA per ton produced. However, the possible addition of cement to CMA to increase its strength significantly increases CO2 emissions, which become comparable to those of HMA without cement. The economic benefits of CMA depend on the type of energy used, its cost, and potential pollution. Paving with CMA allows workability at lower temperatures, reducing road construction time.

- However, CMA with the technologies currently in use has some limitations: it does not achieve the required strength and stability, which limits its use mainly to rural roads with low traffic density and low axle loads. Moisture damage is a major problem, as water used in preparation reduces the adhesion between binder and aggregates, causing deformation and cracking. In addition, CMA requires a longer curing time to reach full strength, putting it at a disadvantage compared to HMA and WMA (Fig. 1 and Table 1).

Table 1. Comparative table of asphalt mixes: design, production temperature, advantages and vanishing points of Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA)

Mix Design	Production Temperature	Advantages	Disadvantages
HMA	150° - 180° C	• Superior mixture performance • Lower initial cost • Dedicated and widespread production facilities	• High production temperature • High emissions • High energy consumption
WMA	90° - 140° C	• Low production temperature • Energy savings • Better working conditions • Longer transport distance • Less plant wear and deterioration • Less binder aging	• Lower mixture performance than HMA • Higher initial cost due to the use of additives • Poor aggregate coating and bonding • Absence of regulations on use in several countries
CMA	10° - 40° C	• Lower fuel consumption • Production at room temperature • Reduced energy consumption • Low emissions • Longer transport distance	• Lower strength and stability • Limited mainly to rural roads • Moisture and adhesion problems • Slower curing • Absence of regulations on use in several countries

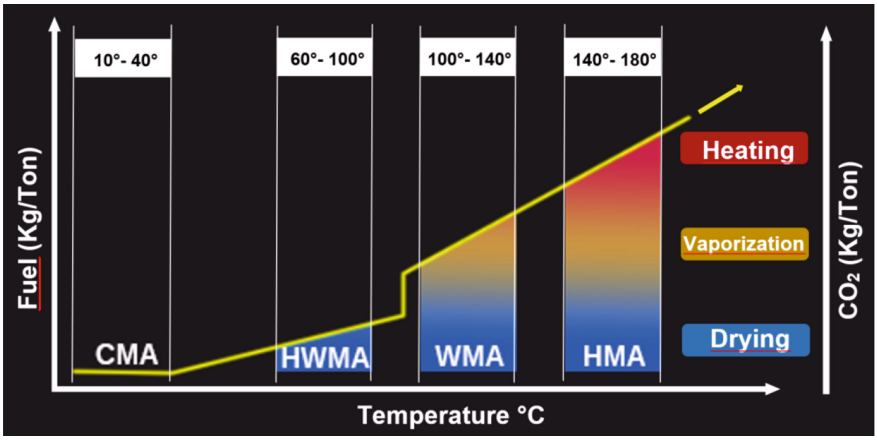
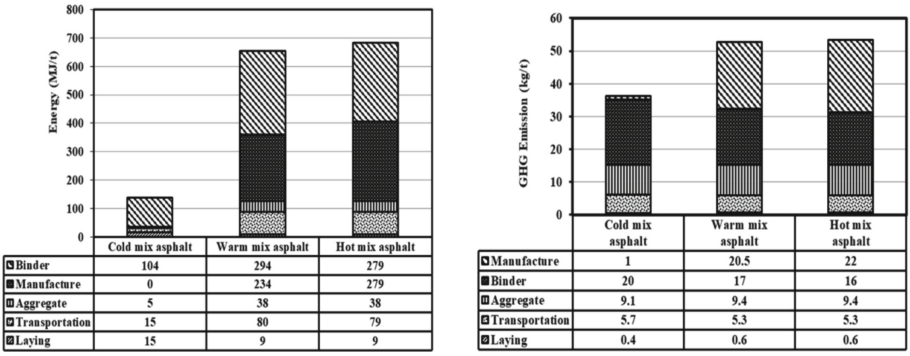


Fig. 1. Type of mixes with their manufacture temperature and fuel consumption per ton.

According to a study by Chehovits and Galehouse (2010), the production of HMA requires 275 MJ/t (megajoules per ton) of energy, while WMA consumes 234 MJ/t, or 15% less than HMA. In the case of CMA, no aggregate heating is required, so energy consumption is reduced to only 14 MJ/t, making it about 95% more efficient than HMA and WMA [4].

Regarding energy consumption per ton of installed material, CMA and the cold in-situ recycling process are more efficient than HMA and hot in-situ recycling. The cold in-situ recycling method is the most energy efficient because it requires less binder and the aggregates are recovered directly on site. To produce one ton of installed material, HMA requires 680 MJ of energy, while CMA and cold in-situ recycling consume 2/3 and 1/5, respectively [5]. This indicates that CMA is more efficient than HMA. The total energy consumption in making the different types of asphalt mixes varies according to the techniques used and the individual components involved (Fig. 2).



	Cold mix asphalt	Warm mix asphalt	Hot mix asphalt
Binder	104	294	279
Manufacture	0	234	279
Aggregate	5	38	38
Transportation	15	80	79
Laying	15	9	9

	Cold mix asphalt	Warm mix asphalt	Hot mix asphalt
Manufacture	1	20.5	22
Binder	20	17	16
Aggregate	9.1	9.4	9.4
Transportation	5.7	5.3	5.3
Laying	0.4	0.6	0.6

Fig. 2. Total energy and GHG emissions use for different asphalt mixes.

The table highlights important differences in the energy required to produce CMA, WMA, and HMA. Regarding the binder, CMA requires significantly less energy (104 MJ/t) than WMA (294 MJ/t) and HMA (279 MJ/t). In addition, CMA requires no additional energy for production, whereas WMA and HMA require 234 and 279 MJ/t, respectively.

For transportation, CMA is more energy efficient, requiring only 15 MJ/t, compared to WMA (80 MJ/t) and HMA (79 MJ/t).

Examining the emission data, the authors see that the most significant difference is found in the production stage. CMA has significantly lower emissions than WMA and HMA in the production phase (1 kg/t for CMA, 20.5 kg/t for WMA, and 22 kg/t for HMA). However, at the transport stage, emissions are slightly higher for CMA (5.7 kg/t) than for WMA (5.3 kg/t) and HMA (5.3 kg/t). In the laying phase, the differences between the three materials are minimal, with values ranging from 0.4 kg/t to 0.6 kg/t. This higher emission related to transport may be because CMA is produced at lower temperatures than WMA and HMA and can be transported more easily via properly packed bags over a longer distance while maintaining the proper temperature and ensuring proper laying. In addition, the availability of CMA production facilities of good mechanical properties could be limited locally, requiring the material to be transported from more distant facilities. This results in increased transportation distances and, consequently, emissions.

3 Trends in Asphalt Production in Europe and the United States from 2011 to 2021

In a recent study conducted based on data collected through 2021, the European asphalt industry was analyzed, looking at aspects such as production, asphalt types, applications, binders, reuse and recycling rates, number of companies, and production sites (Fig. 3).

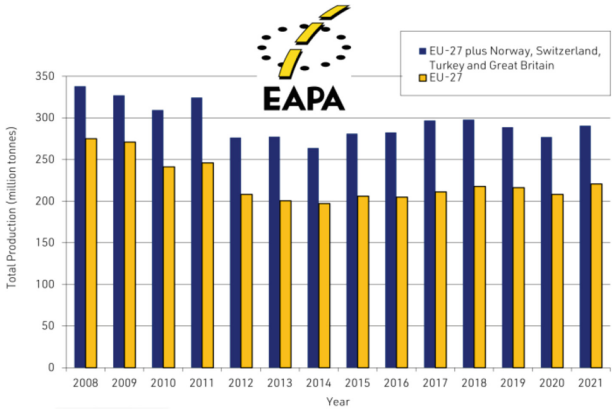


Fig. 3. Total production of HMA and WMA from 2011 to 2021 (Million tons) [5]

This information was obtained through input from members of the European Asphalt Pavement Association (EAPA) and represents the most reliable and up-to-date figures available for the asphalt industry.

In some cases, data from some countries were not available ("no data" - //) and considered zero in the calculation of the totals. In other situations, some countries did not provide data for a particular year, but it was possible to estimate them based on time series of data provided in previous years.

Table 2. Total production of HMA and WMA from 2011 to 2021 (Million tons) [6]

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
EU-27	246.1	208.2	200.5	197.1	206.0	204.9	211.2	217.6	216.2	208.3	220.7
Europe	324.3	276.4	277.3	263.7	280.9	282.5	296.7	297.9	288.9	276.9	290.6
USA	332.0	326.9	318.1	319.0	331.0	340.0	344.0	353.0	382.0	370.0	392.0
South Africa	5.7	5.7	5.5	5.4	4.8	4.8	4.1	4.2	4.1	2.3	2.8

The Table n. 2 shows the total production of HMA and WMA in millions of tons from 2011 to 2021 in four different geographic areas: the 27-country European Union (EU-27), Europe including Britain, Norway, Switzerland, and Turkey, the United States of America (U.S.), and South Africa. Analyzing the data, some trends and variations over time can be seen for each geographic area. In the EU-27, total asphalt production increased from 246.1 million tons in 2011 to 220.7 million tons in 2021. An initial decline is observed until 2014, followed by a recovery between 2015 and 2018 and a slight decrease in 2019 and 2020. In 2021, production increased from the previous year, but remains below the 2011 level. As for Europe including the above-mentioned countries, production decreased from 324.3 million tons in 2011 to 290.6 million tons in 2021. The trend is similar to that of the EU-27, with an initial decline until 2014, a recovery between 2015 and 2018, and a decline in 2019 and 2020. Again, there is an increase in production in 2021, but we are still below 2011 levels.

In the United States, asphalt production has increased overall over the time interval under consideration, from 332 million tons in 2011 to 392 million tons in 2021. Growth has not been steady, with a decline between 2011 and 2013, followed by a substantial increase between 2014 and 2019. There was a slight decline in 2020, but production increased in 2021, reaching its peak over the entire period.

The decline was particularly noticeable between 2019 and 2020, with a decrease of nearly 50%. HMA and WMA production in the geographic areas that were involved in the study showed different trends over the period 2011–2021, with an overall decrease in Europe and South Africa and an increase in the United States. Tied to these variations is economic, political, and infrastructural factors that may have changed asphalt demand and subsequent production in these years.

Over the period 2011–2021, the factors behind these fluctuations can certainly be attributed to various reasons of which the first is related to the global economic crisis of 2008, capable of having a significant impact on the world economy for several years.

The decline in asphalt production in Europe between 2011 and 2014 may be due in part to the austerity policies adopted in many European countries, with reduced investment in public infrastructure. In the United States, the economy recovered faster after the 2008 crisis than in Europe, which may have led to increased demand for asphalt for new superstructure, explaining the increase in production between 2014 and 2019. From 2019 onward, it is evident how any change is due to the influence of the COVID-19 epidemic on the entire global economy and industrial production. With the restrictive measures imposed, disruptions in supply chains were inevitable, resulting in a reduction of asphalt produced.

The data show that, especially in South Africa, there was a significant decline. Political instability and resulting conflicts have slowed the post-pandemic economic recovery, which will be reflected in future data. As a final but main point of interest in the paper, it is evident that in recent years there has been an increasing focus on environmental sustainability and the use of environmentally friendly as well as reusable materials and technologies in the construction sector, particularly in road paving. The study and subsequent use of mix designs including Reclaimed Asphalt Pavement (RAP) and waste products from other processes to improve the performance and mechanical properties of recycled materials has allowed for less use of virgin and newly produced material. Particularly in Europe, where many countries are investing in green infrastructure projects and using alternative materials (Table 3).

Table 3. Total production of HMA and WMA from 2011 to 2021 (in million tonnes) – Europe

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Austria	8.0	7.2	7.0	7.2	7.2	7.4	7.4	7.5	7.5	7.4	7.3
Czech R	5.8	5.6	5.4	6.4	8.0	6.7	7.4	7.9	6.8	6.7	7.2
Finland	5.0	4.5	4.5	4.7	5.4	5.9	6.4	6.1	5.5	7.6	6.1
France	39.2	35.3	35.4	31.9	31.5	33.6	33.7	35.0	35.8	31.9	34.7
Germany	50.0	41.0	41.0	39.0	39.0	41.0	42.0	41.0	40.0	38.0	38.0
Great Britain	22.4	18.5	19.2	20.6	21.9	22.0	22.7	22.9	25.2	23.0	25.7
Greece	2.3	1.6	2.7	2.7*	2.5*	2.3*	2.3*	2.3*	2.3*	2.3*	2.3*
Hungary	2.3	2.5	2.7	3.8	3.9	2.8	2.6	4.7	5.0	4.8	4.9
Italy	28.0	23.2	22.3	22.3	23.1	23.1	23.7	26.0	30.1	30.1*	37.6
Netherlands	9.6	9.2	9.7	9.0	8.0	8.2	8.1	7.9	7.7	7.1	7.2
Norway	6.7	6.3	6.4	7.0	6.9	7.2	7.8	7.5	7.7	6.9	6.9
Poland	26.5	21.1	18.2	16.5	18.5	19.0*	19.0*	19.0*	19.0*	19.0*	19.0*
Portugal	6.4	6.4*	6.4*	6.4*	6.4*	6.2*	6.2*	6.2*	3.1	3.4	4.0
Romania	3.6	3.2	4.1	4.5	4.5*	4.5*	4.5*	4.5*	1.7	1.0	1.0*
Spain	29.3	19.5	13.2	14.5	16.4	13.1	15.2	16.0	18.8	17.1	18.9

(*continued*)

Table 3. (*continued*)

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Sweden	8.1	7.7	7.6	8.5	8.2	8.2*	8.2*	8.2*	8.2*	8.2*	8.2*
Turkey	43.5	38.4	46.2	30.9	37.9	40.4	46.9	41.7	32.7	31.7	30.3

The data presented show the total production in millions of tons of asphalt mix for various European countries from 2011 to 2021.

Focusing on Italy, production increased from 28.0 million tons in 2011 to 37.6 million tons in 2021, showing significant growth. Between 2011 and 2016, Italian production was rather stable, hovering around 22–23 million tons. However, from 2017 onward, there has been a gradual increase, culminating in the highest value in 2021.

Comparing Italy with other major European countries such as France, Germany, Spain and Great Britain, we see that Germany maintained the highest production during the period analyzed, fluctuating between 38 and 50 million tons. France, after an initial decline, showed some stability between 31.5 and 35.8 million tons, while Spain saw a substantial decrease in production, from 29.3 million tons in 2011 to 18.9 in 2021. Great Britain, on the other hand, showed growth in production, rising from 22.4 million tons in 2011 to 25.7 in 2021.

In summary, Italy showed significant growth in asphalt production between 2011 and 2021, while other major European countries such as France and Britain showed some stability or moderate growth. Germany remained the largest producer among the listed countries, while Spain showed a considerable decline in production over the years.

Taking an example in relation to the French case, in terms of the road network, excluding vicinities (chemins ruraux) France has 1,028,260 km of roads (61.27% urban and 38.73% suburban)[7] compared to 167,565 km of Italian roads.[8].

Between 1990 and 2019, about 15,000 km of new roads were built in Italy,[9] a number that is not particularly large; several possible reasons can be hypothesized for greater asphalt production than in France, despite the fact that the French road network is much more extensive. One possible reason could be related to the need for maintenance of existing roads and the possible poor quality of materials and construction techniques used in the past. If Italy's infrastructure requires more frequent maintenance due to age, deterioration, or poor quality of materials and/or placements, this could explain the higher production of asphalt mix in the country, even though the road network is less extensive than in France. It should also be considered that other countries such as France may have adopted alternative materials for road paving than asphalt, making more extensive use of different solutions, such as cementitious conglomerate for rigid pavements not widespread in Italy except in some northern regions.

In Italy, 90% of the asphalt used is asphalt concrete (asphalt concrete EN 13108–1), while 1% is stone mastic asphalt EN 13108–5 and 9% is porous asphalt EN 13108–7. The data shows that Italy makes extensive use of stone mastic asphalt (asphalt concrete), the most common and widely used type of asphalt throughout the world capable of adapting to temperature variations and traffic stresses without significant damage. However, the use of modified asphalt mixes shows that Italy is also adopting alternative solutions to

improve road pavement characteristics. The former allows greater resistance to wear and deformation, and the latter is used to improve road safety due to its permeable structure that allows better water drainage.

Table 4. Total production WMA from 2013 to 2021 (in million tonnes)

Paese	2013	2014	2015	2016	2017	2018	2019	2020	2021
Croatia	0	0,04	0,06	0,06	–	–	–	0,075	0,08
France	3,55	4,023	4,552	4,324	3,824	3,728	4,305	4,058	6,52
Great Britain	1	<1,000	<1,000	–	<0,300	<1,000	<1,000	>1,000	1,000*
Hungary	0,02	0,038	0,07	0,208	0,21	0	0,18	0,35	0
Netherlands	0,06	0,133	0,1	0,100*	0,06	–	–	–	–
Norway	0,38	0,54	0,592	0,502	0,869	1,339	1,74	1,851	1,754
Spain	0,086	0,14	0,14	0,06	0,2	0,18	0,38	0,5	0,65
Switzerland	0,87	0,388	//	//	//	//	0,5	//	//
USA	69	103	109	106	133	143	150	169	85

The previous Table n. 4 shows WMA production in different countries from 2013 to 2021, in millions of tons. France shows a significant increase in WMA production, rising from 3.55 million tons in 2013 to 6.52 million tons in 2021, highlighting the country's growing commitment to promoting more sustainable materials and solutions for road infrastructure.

The United States had considerable warm mix asphalt production, increasing from 69 million tons in 2013 to 85 million tons in 2021, although a decrease from the peak of 169 million tons in 2020 is noted likely because of Covid19 and the recovering economy.

WMA production in Italy is not included in the table to underscore how its use is more than rare, making it necessary to emphasize how the adoption of this more sustainable technology could help reduce the environmental impact of Italy's road infrastructure.[8] The table shows that several countries are increasing WMA production, signaling a growing focus on sustainability in the road paving sector. The uptake of this technology varies widely among countries, suggesting the need for further efforts to promote greener solutions globally.

Regarding the production of CMA, EAPA's data in Europe shows considerable variation between countries and over time. France is the largest producer, peaking at 2,220,000 tons in 2021 [7]. Spain saw a decrease in production, from 200,000 tons in 2011 to 83,000 tons in 2021. On Italy there is no data, highlighting how the technology is used only for partial repairs of wear layers. It is important to evaluate and continue studying CMAs as solutions for the future, as they can generate less environmental impact than traditional bituminous mixtures.

4 Asphalt Production Scenarios in Italy: Energy Analysis and CO2 Emission Reduction

Different scenarios related to asphalt production in Italy will be analyzed below. The table presents five scenarios with different percentages of HMA, WMA and CMA, showing the total energy consumption and energy savings compared to the exclusive use of HMA from total asphalt production data in 2021 and on the energy consumption values for each type (Table 5).

Table 5. Five scenarios with different percentages of HMA, WMA, CMA - Energy

Values	Description	Unit
37,6	Total production 2021	Million tonnes
275	Energy for HMA	MJ/t
234	Energy for WMA	MJ/t
14	Energy for CMA	MJ/t

	% HMA	% WMA	% CMA	HMA (MJ)	WMA (MJ)	CMA (MJ)	Total (MJ)	Saving (MJ)
1	100%	0%	0%	10.340.000.000	-	-	10.340.000.000	-
2	70%	30%	0%	7.238.000.000	2.639.520.000	-	9.877.520.000	462.480.000
3	50%	30%	20%	5.170.000.000	2.639.520.000	105.280.000	7.914.800.000	2.425.200.000
4	40%	40%	20%	4.136.000.000	3.519.360.000	105.280.000	7.760.640.000	2.579.360.000
5	30%	50%	20%	3.102.000.000	4.399.200.000	105.280.000	7.606.480.000	2.733.520.000

The data in the table show the energy consumption to produce HMA, WMA and CMA by combining the percentage use of the various technologies in different scenarios. The first is the current figure with only HMA, the total energy consumption is 10,340,000,000 MJ. In the third scenario, combining 50% HMA, 30% WMA and 20% CMA, the total energy consumption drops to 7,914,800,000 MJ, a saving of 2,425,200,000 MJ compared to the first scenario. The adoption of WMA and CMA can lead to significant reductions in energy consumption compared with the exclusive use of HMA.

Regarding CO_2 emissions, according to the data provided, the production of 1 ton of HMA and CMA results in emissions of 53.6 and 36.1 kg of CO_2, respectively. However, the addition of cement to CMA can significantly increase CO_2 emissions. The addition of 2% cement in CMA results in CO_2 emissions like those of HMA without cement (Table 6).

Table 6. Four scenarios with different percentages of HMA, WMA, CMA – GHG emissions

Emissions CO_2 HMA (kg/t)	Emissions CO_2 WMA (kg/t)	Emissions CO_2 CMA (kg/t)
53,6	52,8	36,1

	% HMA	% WMA	% CMA	Emissions CO_2 HMA (kg/t)	Emissions CO2 WMA (kg/t)	Emissions CO_2 CMA (kg/t)	Emission CO_2 Total (kg/t)
1	70%	20%	10%	37,52	10,56	3,61	**51,69**
2	60%	25%	15%	32,16	13,2	5,415	**50,775**
3	50%	30%	20%	26,8	15,84	7,22	**49,86**
4	40%	35%	25%	21,44	18,48	9,025	**48,945**

The table shows a gradual reduction in CO2 emissions as the percentages of WMA and CMA increase relative to HMA. However, the reduction in emissions is not significant, from 51.69 kg/t in the first scenario to 48.945 kg/t in the fourth scenario. The explanation lies in the limited impact of WMA technologies in particular and CMA on overall emissions. The production process of WMA requires less thermal energy than HMA, but maintains similar orders of magnitude so that replacing HMA with WMA may only partially reduce emissions; the use of CMA may not offer the same performance in terms of durability and mechanical strength as HMA and WMA, limiting its adoption in some applications; and finally, the possible addition of cement or additives to the latter may cause an increase in CO2 emissions.

5 Conclusions

Different alternatives to the production of classic HMA were analyzed in terms of environmental impact and energy efficiency. From the results obtained, the use of WMA and CMA with the technologies considered was shown to generate significant energy savings compared to the exclusive use of HMA. However, in terms of CO2 emission reduction, the changes were not of a significant order of magnitude. The push on the study and subsequent use of more sustainable production technologies remains critical to responsible and sustainable resource management and the reduction of atmospheric

emissions and thus climate impact. The use of technical solutions such as WMA and CMA are just one step in the right direction to reduce the environmental impact of the asphalt industry.

Research and innovation are essential for a sustainable future and a more environmentally friendly asphalt industry. So, efforts related to research and development of increasingly less impactful materials must be constant, particularly in relation to those capable of improving performance characteristics over traditional ones by focusing on the recovery of waste materials from other production processes.

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References

1. Jain, S., Singh, B.: Cold mix asphalt: an overview. J. Clean. Prod. **280** 124378 (2021). https://doi.org/10.1016/j.jclepro.2020.124378
2. Gibbons, S., Lyytikäinen, T., Overman, H.G., Sanchis-Guarner, R.: New road infrastructure: the effects on firms. J. Urban Econ. **110,** 35–50 (2019). https://doi.org/10.1016/j.jue.2019.01.002
3. Dossier ANFIA.pdf
4. Quaderni tecnici volume 5 - Anas
5. Vaitkus, A., Čygas, D., Laurinavičius, A., Vorobjovas, V., Per-veneckas, Z.: Influence of warm mix asphalt technology on asphalt physical and mechanical properties. Constr. Build. Mater. **112**, 800–806 (2016)
6. Chehovits, J., Galehouse, L.: Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements. In: Proceedings on the 1st International Conference of Pavement Preservation, pp. 27–42 (2010)
7. Brown, S., Needham, D.: A study of cement modified bitumen emulsion mixtures. Asphalt Paving Technol. **69**, 92–121 (2000)
8. Asphalt in figures 2021 - EAPA European Asphalt Pavement Association
9. SeA, R.: La rete stradale in Europa e nel mondo: confronti Italia-Francia, Strade & Autostrade. https://www.stradeeautostrade.it/traffico-smart-mobility/la-rete-stradale-in-europa-e-nel-mondo-confronti-italia-francia/
10. Documento strategico mobilità stradale 2022–2026 - MIT.pdf. https://www.mit.gov.it/nfsmitgov/files/media/notizia/2022-07/Documento_strategico_mobilit%C3%A0_stradale.pdf
11. Mashaan, N.S., Chegenizadeh, A., Nikraz, H., Rezagholilou, A.: Investigating the engineering properties of asphalt binder modified with waste plastic polymer. Ain Shams Eng. J. **12**(2), 1569-1574 (2021)
12. Cheraghian, G., et al.: Warm mix asphalt technology: an up to date review. J. Clean. Prod. **268**, 122128, set (2020). https://doi.org/10.1016/j.jclepro.2020.122128
13. Catani, A.: Siteb: MERCATO BITUME ITALIA 2021. https://www.siteb.it/sitebNew/siteb-mercato-bitume-italia-2021/
14. Asi, I., Assa'ad, A.: Effect of Jordanian oil shale fly ash on asphalt mixes. J. Mater. Civ. Eng. **17**(5), 553–559 (2005)

15. Chegenizadeh, A., Tufilli, A., Arumdani, I.S., Budihardjo, M.A., Dadras, E., Nikraz, E.H.: Mechanical Properties of cold mix asphalt (CMA) mixed with recycled asphalt pavement. Infrastructures, **7**(4), 4 (2022). https://doi.org/10.3390/infrastructures7040045
16. Milad, A., et al.: A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: towards a sustainable asphalt pavement. Int. J. Environ. Res. Public. Health, **19**(22), fasc, 14863 (2022). https://doi.org/10.3390/ijerph192214863