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A comparative environmental life cycle assessment of road asphalt pavement solutions made up of artificial aggregates

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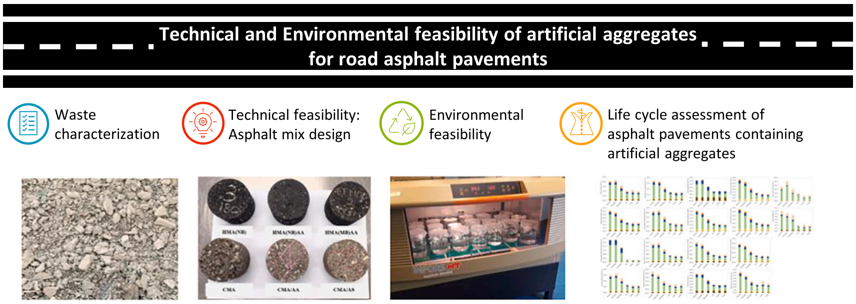
HIGHLIGHTS

- Suitability of artificial aggregates from municipal solid waste incineration for asphalt pavements
- Ecotoxicity of hot and cold asphalt mixtures containing artificial aggregates
- Environmental life cycle assessment of asphalt solutions for binder layers

GRAPHICAL ABSTRACT



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ABSTRACT

The construction and maintenance of road pavements entail detrimental impacts on the consumption of resources and damage to the natural environment but also make up an opportunity for the large-scale application of circular economy principles and innovative waste valorisation paths. The present study focuses on developing a comprehensive procedure to evaluate the technical and environmental sustainability of replacing high percentage of limestone aggregates with artificial aggregates from municipal solid waste incineration (MSWI) into hot or cold recycled asphalt mixtures for asphalt pavements.

The technical feasibility of the designed mixtures was investigated in terms of the main physical and mechanical properties of both the raw materials and the asphalt mixtures with content of artificial aggregates or sand in the range 25–40 % by mass. The environmental feasibility of the asphalt mixtures was evaluated through the SEM-EDS technique, the analysis of the eluate of the leaching test and the ecotoxicity for living organisms.

Afterwards, the life cycle assessment (LCA) was applied to detect the critical spots of the life cycle of 1 m^2 of a 6 cm-thick binder layer with high percentage of artificial aggregates or sand built and maintained through 30 years analysis period according to 18 impact category indicators.

The main results show that, recycling the artificial aggregates into hot asphalt mixtures has on average a negligible effect on the overall environmental performance of the life cycle, and appears to be detrimental only for the consumption of fossil resources due to the higher optimum bitumen content. Looking at the results for cold mixes, the introduction of the artificial aggregates has an effect on the predicted durability of the asphalt layers, which is maximized in the case of coarse artificial aggregates. Consequent environmental benefits regard the global warming potential, fossil resource scarcity and freshwater eutrophication indicators.

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1. Introduction

The construction and maintenance of road infrastructures, which is a fundamental mean to prompt the growth and competitiveness of the countries' economies, consumes millions of tons of materials each year, in particular of aggregates (Pourkhorshidi et al., 2020). Therefore, it entails at the same time a detrimental impact on the natural environment but also an opportunity for the large-scale application of the circular economy principles and innovative waste valorisation paths.

In the latest years, growing attention has been dedicated to the substitution of natural materials with waste flows such as the mineral solid residue of municipal solid waste incineration (MSWI), due to both the ever-increasing pressure on natural resources and the potential high value of the multiple products from MSWI (Allegrini et al., 2015). The initial composition of municipal solid waste varies from country to country according to the specific waste management policies, but mainly includes food, plastics, paper, metals, glass, and textiles (Silva et al., 2019). The preferred treatment of such waste is usually incineration, as it decreases its mass by 70 % and its volume by 90 % (Huang et al., 2020). The solid residue of MSWI can be further valorised through ferrous and non-ferrous scraps recovery; afterwards, the remaining mineral fraction can be either landfilled or further treated to produce artificial aggregates for the construction of buildings and infrastructures.

Most of the solid residue of MSWI is currently used as a supplementary cementitious material (Li et al., 2012; Tang et al., 2015), but its application as secondary artificial aggregate for asphalt-based road pavement materials has been growingly addressed as an effective way to valorise waste and provide benefits to the environment (Russo et al., 2022).

The most common asphalt-based material for road pavements is the hot mix asphalt (HMA), namely the asphalt mixture produced at high temperature (160–180 °C) into centralized plants to build the upper layers of road pavements (wearing, binder and base course). Several researchers focused on the evaluation of the mechanical properties and relative durability of road construction and maintenance solutions involving alternative recycled aggregates, including the mineral residue of MSWI (Gedik, 2020; Chen et al., 2022; Ou et al., 2022; Veropalumbo et al., 2022).

For example, Vaitkus et al. (2019) substituted the limestone sand (0–4 mm) fraction of the grading curve with the mineral solid residue of MSWI, corresponding to 26 % by mass of the aggregates, into an HMA for the base layer; compared to the conventional HMA, the HMA with the artificial sand from MSWI required 1.1 % higher optimum bitumen content and exhibited 40 % higher stiffness modulus at 20 °C and 3 % higher indirect tensile strength ratio (ITSR), indicating an improved stability towards prolonged contact with water.

Few scientists have evaluated the possibility using such artificial aggregates from MSWI in coarser size than sand and filler; among those, Ding et al. (2022) evaluated the influence of the porosity of artificial aggregates from MSWI (size 0–12.5 mm) on the composition and mechanical behaviour of a HMA using a 60/80 neat bitumen; they estimated that, for each additional 10 % of artificial aggregates from MSWI added to the mixture, the binder demand grew of about 0.9 %. Looking at the Marshall stability, freeze-thaw strength and tensile resistance, they observed a deterioration of the mechanical performance as the content of artificial aggregates increased, as opposed to the cracking resistance at low temperature, compared to a conventional HMA.

Aiming to support technically valid solutions with robust environmental assessments according to a standardized evaluation framework, researchers apply the life cycle assessment (LCA) models to asphalt-based road materials containing secondary aggregates in substitution of natural ones (Chen and Wang, 2018; Li et al., 2019; Oreto et al., 2021a; De Pascale et al., 2023).

Several studies focused on the quantification of the environmental benefits of different waste and industrial by-products through the analysis of leaching contaminants and LCA methodology to improve current waste management practices. For example, Cho et al. (2020) reviewed the potential leaching of harmful substances, such as heavy soluble salts and heavy metals, for 4 alternative management scenarios of the solid residue of MSWI: landfilling, use as aggregates for embankment fills, road subbases, hot mix asphalts (HMAs) and concrete. They highlighted that, when the solid residue of MSWI was either landfilled or in contact with soil and water, it was more likely to exceed the limit values for Cl, SO_4, Cu, Mo, Sb, and Se. Instead, when it was used as aggregate replacement into HMA and concrete, the leaching potential was significantly reduced via physical encapsulation in asphalt or stabilization through cement binder. Moreover, Allegrini et al. (2015) conducted LCA to compare 2 road construction scenarios using artificial aggregates from MSWI as aggregates substitute into HMAs and concrete; they observed that the concrete scenario had more than one order of magnitude higher human carcinogenic toxicity and three times higher freshwater ecotoxicity than the HMA scenario due to higher Cr and Cu releases during the carbonation of concrete specimens, which occurred with ageing.

Among the few studies who have applied the LCA to assess the sustainability of the life cycle of artificial aggregates from MSWI as a road construction material, most of them concern their use as a sub-base construction material that substitutes natural gravel (Birgisdottir et al., 2006; Margallo et al., 2014).

Looking at asphalt-based materials, Golestani et al. (2017) evaluated the environmental implications of substituting natural materials into HMA with a combination of reclaimed asphalt and artificial aggregates from MSWI. The results showed a reduction of the necessity of virgin fine aggregate and asphalt binder by 20 % and 19 %, and 15.5 % less greenhouse gas emission for a period of 20 years, compared to the traditional HMA. The study also underlined the need to approach innovative technologies (i.e., hot recycling of reclaimed asphalt pavement) to maximize the mechanical performance and address the sustainability of the whole life cycle, especially considering the incidence of the maintenance phase on the results of the LCA (Huang et al., 2021; Oreto et al., 2022).

As seen in the previous points, the artificial aggregates from MSWI have been introduced as aggregates substitute into HMAs often obtaining superior mechanical and environmental performance compared to conventional HMAs. Nevertheless, it should be pointed out that the subject of the LCA presents some novelties compared to what has been achieved so far in terms of recycling of the inert fraction from MSWI. In particular, the solid mineral residue of MSWI has been thoroughly and successfully analysed as coarse aggregates into cement concrete (Kim and Lee, 2011; Li et al., 2012; Tang et al., 2015), while hot asphalt mixtures usually include the MSWI residues as fine aggregates or sand (Vaitkus et al., 2019); no evidence has been found of cold recycled asphalt mixtures including this kind of artificial aggregate in any size.

Additionally, the scientific evidence addresses the utilisation of these artificial aggregates from MSWI in the asphalt layers of road pavements as the preferable valorisation path over their use as aggregates in concrete; however, to date, no study has been conducted to further compare the environmental benefits of recycling the solid residue of MSWI in the bitumen-bonded upper layers of a pavement using different aggregate sizes, as well as different technological solutions to extend the service life of the road pavement, like Styrene-Butadiene-Styrene (SBS) modified bitumen, and decrease the energy and virgin materials consumption in the asphalt mix production phase, like cold recycling technologies.

Therefore, the present research aims at a comprehensive evaluation of different valorisation paths for the solid residue of MSWI sampled from the incinerator into asphalt mixtures for road pavements. In detail, the study explores the recycling of such artificial aggregates into both HMAs, using neat and modified bitumen, and cold-produced asphalt mixtures using coarse or sand size for a specific layer of the pavement structure interposed between the wearing and the base layers, namely the binder layer. The evaluation procedure, which is briefly summarized in Fig. 1, entails several points of view, including the prediction of the service life of the pavement according to fatigue and rutting accumulation laws and the calculation of multiple environmental impact indicators through LCA methodology. The presented framework has been applied to several scenarios consisting of an ordinary rehabilitation intervention of the upper layers of a rural road (i.e., wearing course and binder layer), where the artificial aggregates from MSWI are substituted to traditional limestone aggregates or limestone sand and combined or not with RAP milled from the old distressed pavement layers. The study intends to develop a ready-to-use checklist that can support the design of hot and cold asphalt mixtures with high rate of incorporation of artificial aggregates from MSWI, and eventually supporting the definition of the expected mechanical performance of the final mixture, setting up tailored technical specifications for asphalt mixtures incorporating this specific kind of artificial aggregates and communicating the expected improvement in terms of the main LCA indicators throughout the life cycle of the road pavement.

2. Materials and methods

2.1. Raw materials

2.1.1. Limestone aggregates

Virgin limestone aggregates extracted in a local cave (Campania region, Italy) and crushed in a dedicated facility up to the desired sizes were used to make up asphalt mixtures; several tests were performed on all the limestone aggregate sizes according to technical standards (EN 1097 series and EN 933 series) to assess the compliance of the main physical and mechanical features with local specifications for road construction aggregates (Città Metropolitana di Napoli, Capitolato Speciale d'Appalto, 2022). More on the results of the physical and mechanical characterization of the limestone aggregates used in the present study can be found in Table 1 in the Supplementary materials.

2.1.2. Reclaimed asphalt pavement

The Reclaimed Asphalt Pavement (RAP), namely the old and distressed asphalt pavement milled from the wearing and binder layer during ordinary or extraordinary maintenance works, was here reused into cold recycled asphalt mixtures for the binder layer of a flexible pavement; the RAP underwent several characterization steps to assess its feasibility in compliance with the environmental requirements of Italian Ministerial Decree no. 69 of 28/03/2018 (Italian Ministry for the Environment and the Protection of Land and Sea, 2018), and the technical specifications set by EN 13108–8 and UNI/TS 11688. In detail, two different RAP sizes were adopted and classified according to EN 13108-8: the first ranging from 0 to 8 mm particle diameter, designated as 8 RA 0/6, and the second with coarser particles, designated as 16 RA 0/10.

The detailed results of the characterization and size distribution of the RAP are shown respectively in Table 2 and Table 3 in the Supplementary Materials.

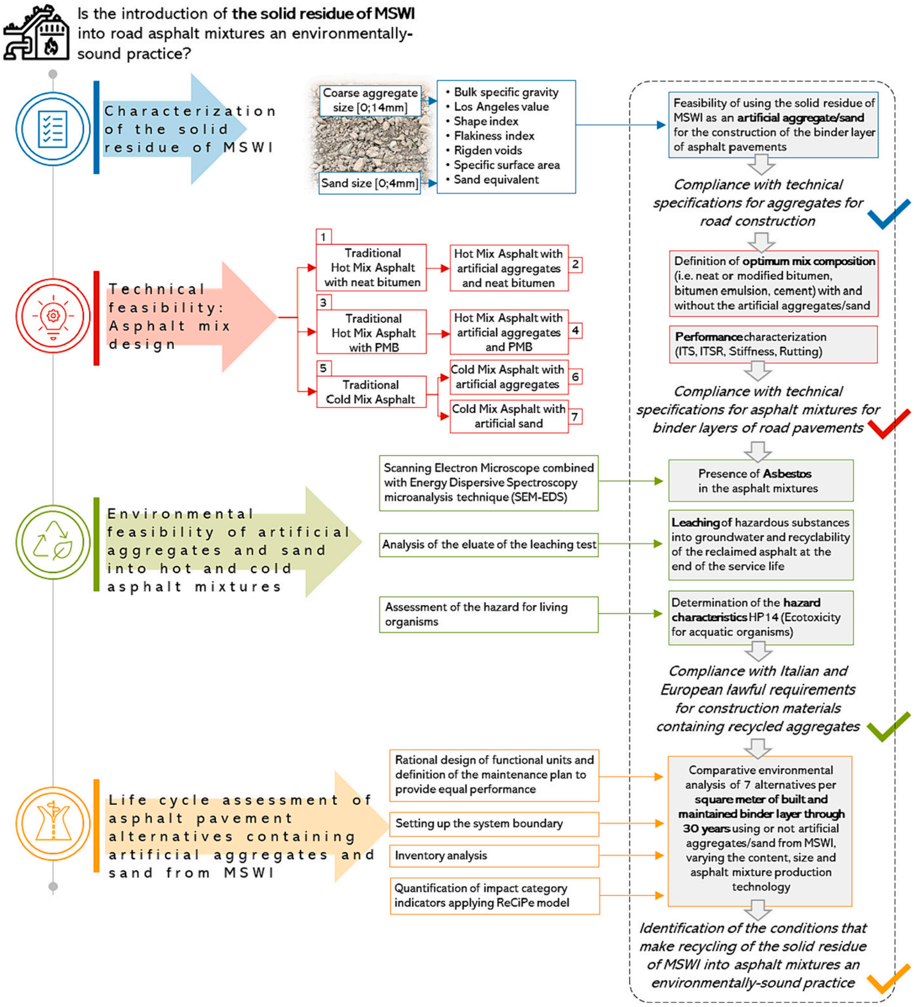


Fig. 1. Flow diagram of the research that validates an end-of-waste strategy for artificial aggregates from MSWI as secondary aggregates for asphalt mixtures for road pavements.

2.1.3. The artificial aggregates from MSWI

The solid waste originated within a local incinerator facility that burns approximately 732′000 t/year of non-hazardous mixed municipal solid waste that were previously sorted and shredded into a dedicated facility. After incineration, the solid residue is sieved through a 20 cm sieve to remove any larger pieces, sampled to check the leaching behaviour and classify the waste category and transferred to specialized recycling facilities. Here, the solid residues are left to cure for approximately 15 days, so that the carbonatation and drying processes occur, and then undergo ferrous and non-ferrous metals selection (7–18 % of the total mass). The remaining portion is mainly composed of a mineral fraction (50–75 % of the total initial mass), glass and ceramic fraction (15–30 %) and some residual unburnt organic matter (0.2–5 %).

In the present work, the untreated raw solid residue of MSWI sampled from the incinerator was delivered to the laboratory and left in the oven at 105 °C until reaching constant mass (<0.1 % mass variation between two subsequent checks) to make sure to remove any residual moisture. Pre-treatment was carried out to separate ferrous scrap that can cause swelling and expansion of the material from the prevalent mineral fraction using a magnet.

The remaining mineral fractions were subdivided into two different sizes and used in the present study: a) a coarser one, with aggregates size ranging from 0 to 14 mm diameter, used in substitution of the corresponding limestone aggregate size and regarded as artificial aggregates (AA), and b) a sand size, with particles diameter ranging from 0 to 4 mm, used in substitution of limestone sand and regarded as artificial sand (AS). The size distribution of the AA and AS is reported in Table 4 in the Supplementary materials.

Both mineral fractions were further subjected to the same physical and mechanical tests as conventional limestone aggregates (see Table 1 in the Supplementary Materials).

2.1.4. Binders

A commercial 50/70 penetration grade bitumen (NB) and a 5 % styrene-butadiene-styrene modified bitumen (MB) were adopted to blend HMAs. A commercial bitumen emulsion (BE) and pozzolanic cement were adopted in the case of CMAs; the main base properties of the NB, MB, BE and cement binders are reported in Table 5 in the Supplementary Materials.

2.2. Asphalt mixtures design and characterization

The present analysis focused on the environmental impact assessment of four competing asphalt mixture solutions for the binder layer of an asphalt pavement involving the use of the AA and AS, versus one conventional HMA made up of limestone aggregates and neat bitumen, a conventional HMA with limestone aggregates and modified bitumen and a conventional cold asphalt mixture recycled in-place using bitumen emulsion and cement. The seven asphalt mixtures are identified as follows:

- HMA(NB) is the reference conventional hot mix asphalt manufactured in-plant using limestone aggregates and NB;
- HMA(MB) is the reference conventional hot mix asphalt manufactured in-plant using limestone aggregates and MB;
- HMA(*NB*)AA is the hot-produced mixture made up of 60 % limestone aggregates and 40 % AA bonded with NB;
- HMA(*MB*)AA is the hot-produced mixture with the same aggregate size distribution as the HMA(*NB*)AA and MB in substitution of NB;
- CMA is an in-place recycled cold asphalt mixture made up of 74 % RAP and 26 % limestone aggregates bonded with BE, pozzolanic cement and water;
- CMA/AA is an in-place recycled cold asphalt mixture made up of 30 % RAP, 30 % AA and 40 % apportion of limestone aggregates with BE, pozzolanic cement and water addition;
- CMA/AS is an in-place recycled cold asphalt mixture made up of 53 % RAP, 25 % AS and 22 % apportion of limestone aggregates with BE, pozzolanic cement and water addition.

Table 1a summarizes the production type (i.e., in centralized asphalt production plant or recycled in place) and production temperature (for hot and cold mix asphalts) of the road construction materials.

Table 1b shows the mass composition of each asphalt mixture; in detail, the aggregate sizes were chosen to comply with the technical specifications applied by the road authority (Città Metropolitana di Napoli, Capitolato Speciale d'Appalto, 2022) for conventional binder layers for local roads subjected to high percentage of heavy traffic. Instead, the optimum binder content was chosen as follows: a) for hot-produced asphalts (i.e., HMA(NB), HMA(MB), HMA(*NB*)AA and HMA(*MB*)AA), following the mix design procedure of Superpave specifications (Asphalt Institute, 2001) and b) for cold-produced asphalts (i.e., CMA, CMA/AA and CMA/AS), applying an original experimental procedure developed by the authors to set the optimum content of BE, cement and water, which is thoroughly described in previous works (Oreto et al., 2021c).

As shown in Table 1b, the designed mixtures are characterized by variable rate of substitution of either coarse limestone aggregates (with the AA, size range 0–14 mm) or limestone sand (with the AS, size range 0–4 mm). Since the greater specific surface area of the AS significantly affects the optimum bitumen content of the final mixture (Vaitkus et al., 2019), the HMAs were made up using only the AA as a substitute for conventional limestone aggregates to prevent the final mixture from being too sensitive to rutting distress. Instead, the optimum BE content of CMAs was found to be less dependent on the porosity of the mineral fraction, therefore 2 alternative CMA solutions, one involving the AA and one with the AS, were provided.

The main volumetric and mechanical properties of the designed asphalt mixtures were investigated to assess the compliance with the technical specifications for road construction materials in the metropolitan area of Naples (Città Metropolitana di Napoli, Capitolato Speciale d'Appalto, 2022) and, at the same time, to allow predicting their durability, service life and relative maintenance program considering LCA application. The mechanical tests performed are as follows:

- Indirect tensile strength (ITS), i.e., the maximum tensile stress arising in the diametral plane of a cylindrical specimen due to a compressive loading, was evaluated according to EN 12697–23 at temperature of 10 °C and 25 °C as an indicator of the maximum heavy load bearable by the asphalt mixture averaged on 3 specimens;
- Indirect tensile strength ratio (ITSR), i.e., the percentage variation of the ITS between a specimen cured in air at room temperature and one immersed in a temperature-controlled water bath, was determined according to EN 12697–12 at 15 °C and 25 °C as an indicator of the weakening of the aggregate-bitumen bonding caused by protracted saturation of the mixture with water averaged on 3 specimens;
- Indirect tensile stiffness modulus (ITSM), i.e., the elastic stiffness of the asphalt mixture subjected to a compressive haversine loading wave induce horizontal diametral tensile deformation, was analysed according to Annex C of EN 12697–26 at 10, 20, 40 and 60 °C as an indicator of the load spreading ability averaged on 5 specimens;
- Rut depth (RD), i.e., the vertical displacement of a slab subjected to 10,000 cycles of a standard loaded wheel and immersed in water, was determined according to EN 12697–22 at 60 °C as an indicator of the susceptibility of the asphalt mixture to deform under repeated loading averaged on 2 slabs.

Table 1c shows the results of the mechanical characterization of the conventional asphalt mixture (HMA(NB), HMA(MB)), the reference cold asphalt mixture (CMA) and the asphalt mixtures containing the bottom artificial aggregates and sand (HMA(*NB*)AA, HMA(*MB*)AA, CMA/AA and CMA/AS). In detail, all the ITS values at 25 °C comply with the

Table 1
Main features of the asphalt mixtures under analysis: a) production type and mixing temperature, b) mix composition, c) main volumetric and mechanical features.

	Units	Mix IDs						
		HMA(NB)	HMA(MB)	HMA(*NB*)AA	HMA(*MB*)AA	CMA	CMA/AA	CMA/AS
a) Mix production type and mixing temperature								
Production type	–	in-plant	in-plant	in-plant	in-plant	in-place	in-place	in-place
Mixing temperature	°C	~170	~170	~170	~170	~25	~25	~25
b) Mix composition								
Limestone 10/31.5 mm	%	25	25	10	10	22		13
Limestone 6/12 mm	%	33	33	10	10			4
Limestone sand	%	38	38	34	34		37	
Limestone filler	%	4	4	6	6	4	3	5
Artificial aggregates	%			40	40		30	
Artificial sand								25
16 RA 0/10	%					20	10	16
8 RA 0/6	%					54	20	37
Neat Bitumen 50/70(1)	%	4.5		7.5				
Polymer Modified Bitumen(1)	%		4.3		6.5			
Bitumen emulsion(1)	%					5	4	4
Pozzolanic cement(1)	%					0.5	2.5	2
Water(1)	%					4	5	4
(1) Percentages by the total weight of the aggregates								
c) Volumetric and Mechanical features								
Air voids	%	4.0	4.0	4.0	4.0	9.0	9.0	9.0
ITS @10 °C	MPa	3.02	2.97	3.41	2.55	0.65	0.76	0.63
ITS @25 °C	MPa	1.42	1.40	1.3	1.26	0.42	0.52	0.48
ITSR @25 °C	%	97	100	112	100	98	111	94
ITSR @15 °C	%	95	100	118	111	92	101	90
ITSM @10 °C	MPa	6931	12,891	5441	7639	5773	6057	5484
ITSM @20 °C	MPa	3077	6825	2807	3806	2911	4010	3414
ITSM @40 °C	MPa	529	921	399	908	927	2436	2178
ITSM @60 °C	MPa	131	386	72	417	326	1757	1553
RD @60 °C	mm	19.22	3.88	18.34	3.06	4.67	2.20	1.62

specific range imposed by the technical specifications (Città Metropolitana di Napoli, Capitolato Speciale d'Appalto, 2022): [0.32 MPa; 0.55 MPa] for cold asphalt mixtures after curing, [0.72 MPa; 1.40 MPa] for HMAs with NB and [0.95 MPa; 1.70 MPa] for HMAs with MB. In general, the cold asphalt mixtures have on average 69 % lower ITS value compared to the hot asphalt mixtures, ranging from the minimum value equal to 0.42 MPa (CMA) to the maximum value equal to 0.52 MPa (CMA/AA). Looking at the percentage variation of ITS moving from 25 to 10 °C, the HMAs have higher thermal susceptivity compared to the CMAs, respectively increasing the tensile stress at failure by 125 % and by 44 % when moving from 25 to 10 °C.

All the mixtures also comply with the main moisture susceptibility requirement of ITSR above 90 % (Città Metropolitana di Napoli, Capitolato Speciale d'Appalto, 2022), meaning that the tensile resistance does not undergo excessive degradation when the moisture penetrates into the mix for a prolonged period of time.

Concerning the materials' stiffness (ITSM) in the temperature range [10; 60 °C], the contribution of the artificial aggregates into HMAs varies significantly when blended with MB or NB; for HMA(*MB*)AA, the ITSM variation with temperature is similar to that of HMA(MB), while the opposite happens for HMA(*NB*)AA, where the stiffness decrease with temperature is steeper compared to HMA(NB), dropping below 500 MPa at 40 °C and below 100 MPa at 60 °C.

Compared to the HMAs, most of the CMAs have similar or slightly lower stiffness at 10 and 20 °C, but significantly higher ITSM at 40 e 60 °C, especially for CMA/AA with 30 % AA and 2 % cement, suggesting a much lower susceptibility to rutting phenomenon compared to HMAs.

Looking in general at the CMAs, they exhibit a less temperature-dependant behaviour compared to HMAs because of the smaller amount of fresh bitumen and presence of cement binder in the cohesive matrix. Both AA and AS do not significantly affect the ITSM at 10 °C, but respectively increase the ITSM by 30, 150 and 400 % at 20, 40 e 60 °C compared to CMA.

Lastly, the rut depth after 10,000 cycles performed on an asphalt slab immersed in water at 60 °C identified the two mixtures that are more prone to rutting, namely HMA(NB) and HMA(*NB*)AA, which accumulated on average 18.8 mm, and those that are less prone to accumulate permanent deformations, namely HMA(MB), HMA(*MB*)AA, CMA, CMA/AA and CMA/AS, which showed rut depth in the range [1; 5 mm].

2.3. *Preliminary environmental feasibility assessment*

Once investigated the technical feasibility of using the artificial aggregates and artificial sand from MSWI for road flexible pavement applications, the designed asphalt mixtures underwent a series of preliminary environmental checks of compliance with existing Italian and EU regulations, as follows:

- presence of asbestos through SEM-EDS technique (compliance with Italian Ministerial Decree 06/09/1994);
- analysis of the eluate of the leaching test (EN 12457–2) to assess the potential release of contaminants into groundwater and compliance with Italian Ministerial Decree 5/2/1998;
- Ecotoxicological tests (OECD/OCDE 202 2004 and OECD/OCDE 201 2011) to assess the risk for living organisms once the mixtures are laid in place.

The samples were firstly subjected to qualitative-quantitative analysis by Scanning Electron Microscope combined with Energy Dispersive Spectroscopy microanalysis technique (SEM-EDS), applying the test method reported in Italian Ministerial Decree 06/09/1994 (G.U. n. 288 10/12/1994) Appendix 1 Method B to detect the presence of Asbestos. The samples were pretreated in a muffle at 500 °C, ground and homogenized. About 10 mg of powder of the ground sample was added to 200 mL of dispersing solution. The solution was then filtered through a polycarbonate membrane with pores size 0.4–0.8 μm and diameter 25 mm. A portion of the filter, previously air-dried, was transferred onto a double-sided carbon conductive disc. A layer of gold was applied to the stub using an Agar Sputter metallizer Coater 108 and subjected to observation with a SEM, model Prisma E by Thermo Fisher Scientific, combined with EDS analysis.

The SEM-EDS results showed that the concentration of asbestos in the analysed samples was always below the limit of quantification of the instrument (100 mg/kg), therefore excluding the presence of asbestos in the analysed samples.

The samples under examination were subjected to leaching tests according to EN 12457–2 standard. The EN 12457–2 standard establishes the leaching methodology for waste with a size smaller than 4 mm (with or without size reduction) characterized through a liquid/solid ratio equal to 10:1 on dry matter. The samples were ground, homogenized and passed through a sieve where applicable. Each sample of dry matter (dried in oven at 105 °C until constant mass) weighted 90 ± 5 g of dry matter. The leachate (deionized water) was added in such a way as to reach the 10:1 ratio previously described. The test was carried out at a controlled temperature of 20 ± 5 °C and stirring for 24 ± 0.5 h. At the end of the test, the sample was left to decant for 15 min and subsequently filtered and analysed.

The analytical results found are summarized in Table 6 in the Supplementary materials; the results are compliant with the limits of attachment 3 of the Ministerial Decree 5/2/1998 as amended by Ministerial Decree 3/4/2006 n° 186 for non-hazardous waste subjected to simplified recovery procedures. Therefore, both the hot and cold asphalt mixtures here designed using the AA and the AS in substitution of limestone are non-hazardous and fully recyclable once the built pavement has reached the end of its service life, just like it usually happens with traditional asphalt mixes. Consequently, the same end-of-life scenario (reuse or, eventually, landfilling) can be assumed for both the traditional asphalt mixtures and the asphalt mixtures containing the AA and the AS.

Further on, all the mixtures containing the AA and AS were subjected to ecotoxicity tests. Indeed, waste classified as “mirror entries” (i.e., wastes potentially classified as hazardous if containing hazardous substances above a specific level) on the European List of Waste (LoW, European Commission, 2000) require assessment of their specific Hazard Properties (HP). In this context, “Ecotoxicity” (i.e., HP 14) is acknowledged as the HP most frequently resulting from wastes classified as hazardous (Maggi et al., 2022).

The objective of ecotoxicity studies is to determine the acute toxicity of the sample to organism *Daphnia magna* (crustacean) and growth inhibition of Pseudochirkneriella subcapitata (green algae) for the purpose of assessment of the hazard characteristic HP14 “Ecotoxic”, applying the methods set out in the Regulation (EC) 440/2008 and by the OECD Guidelines.

Given the complexity of the matrix, the OECD was used as a preparation method for ecotoxicological tests 23 “Guidance Document on Aquatic Toxicity testing of difficult substances and mixtures” according to what envisaged by the ECHA Guideline – Guidance on the application of the CLP criteria – July 2017 – Annex IV and as reported in the SNPA Guidelines, approved with the Italian Directorial Decree n. 47/2021, for poorly soluble substances.

In particular, to determine the EC50, namely the concentration with toxic effect for 50 % of organisms, a solution with a concentration equal to 100 mg/L was prepared by weighing 100 mg of sample (ground to 1 mm where possible) for each litre of aqueous solution. The solutions were prepared in a glass container at a temperature between 20 and 23 °C by continuous stirring with an orbital stirrer at a speed of 100 rpm. The contact time between sample and liquid was 7 days. At the end of the dissolution period, the solution was decanted to allow the deposition of the insolubilized sample. The aqueous fraction of the solution was taken and used for the exposure.

For the algal growth inhibition test, three replicates for each concentration containing the solutions to be tested (39, 63, 100, 160, 256 mg/L) and six replicates containing algal medium only (negative control) were inoculated with a known volume of a culture in exponential growth in order to have an initial cell concentration of 10,000 cells/mL. The flasks thus prepared were incubated under controlled conditions for a continuous period of 72 h and kept in agitation in a climatic chamber. At the end of the exposure period, cell density was measured using an electronic cell counter. Growth inhibition was determined in comparison to the control culture.

For the acute toxicity test with *Daphnia magna*, four replicates were prepared containing the solutions to be tested (39, 63, 100,160 and 256 mg/L) and four replicates containing only the reconstituted water (negative control). In each replica, 5 daphnids were introduced aged <24 h. The beakers thus prepared were incubated under controlled conditions inside a climatic chamber. After 24 and after 48 h from the beginning of the exposure, immobilization was recorded and the results were analysed to calculate the EC50 value.

Table 2 shows the results of the ecotoxicity tests; for both the acute toxicity on *Daphnia magna* and the algal growth inhibition test, the EC50 value must be higher than 100 mg/L, the limit set out in the EU Regulation 1272/2008 and subsequent amendments in order to classify a mixture dangerous for acute or chronic toxicity for the aquatic environment.

As shown in Table 2, all the mixtures under analysis satisfy the ecotoxicity requirements with EC50s higher than 100 mg/L, therefore they do not pose a threat to living organisms subjected to a prolonged exposure. In detail, the concentration that inhibits the algal growth for 50 % of the organisms is above the limit of quantification (250 mg/L) for all the analysed mixtures. The concentration with toxic effects for 50 % of *Daphnia magna* is above 250 mg/L for HMA(*NB*)AA and equals 171, 102 and 174 mg/L for HMA(*MB*)AA, CMA/AA and CMA/AS, respectively. Considering the mass fraction of artificial aggregates/sand in each asphalt mixture (see Table 1b), significantly different values of EC50 for *Daphnia magna* are detected in correspondence to similar AA and AS content; therefore, it can be assumed that the EC50 for *Daphnia magna* is not only affected by the mass content of either the AA and the AS in the sample, but rather by the whole composition of the asphalt mixture, including all the inert fractions, binders and additives (i.e., bitumen, polymers for bitumen modification, fluxing agents and cement).

In conclusion, all the asphalt mixtures containing the AA and the AS, object of the present study, did not overcome the concentration limits imposed by both Italian and European regulations in terms of Asbestos content, leaching of hazardous substances, recyclability at the end of the service life and ecotoxicity for living organisms; therefore, they can be used as a road construction material and no specific precaution is required compared to traditional hot and cold asphalt mixtures.

2.4. *Life cycle assessment*

Once investigated the technical and environmental feasibility of the construction materials themselves, a LCA was applied to a local case study to detect and quantify the possible benefits and drawbacks of using the asphalt mixtures containing the AA and the AS to build and maintain the binder layer of a road pavement for 30 y, with a focus on all the phases of the life cycle of a pavement system.

Table 2
Results of the ecotoxicity tests carried out on the hot and cold asphalt mixtures containing the AA and AS.

Test	Unit	Method	HMA (*NB*) AA	HMA (*MB*) AA	CMA/AA	CMA/AS
Acute toxicity on Daphnia EC50	mg/L	OECD/OCDE 202 2004	>250	171	102	174
Algal growth EC50	mg/L	OECD/OCDE 201 2011	>250	>250	>250	>250

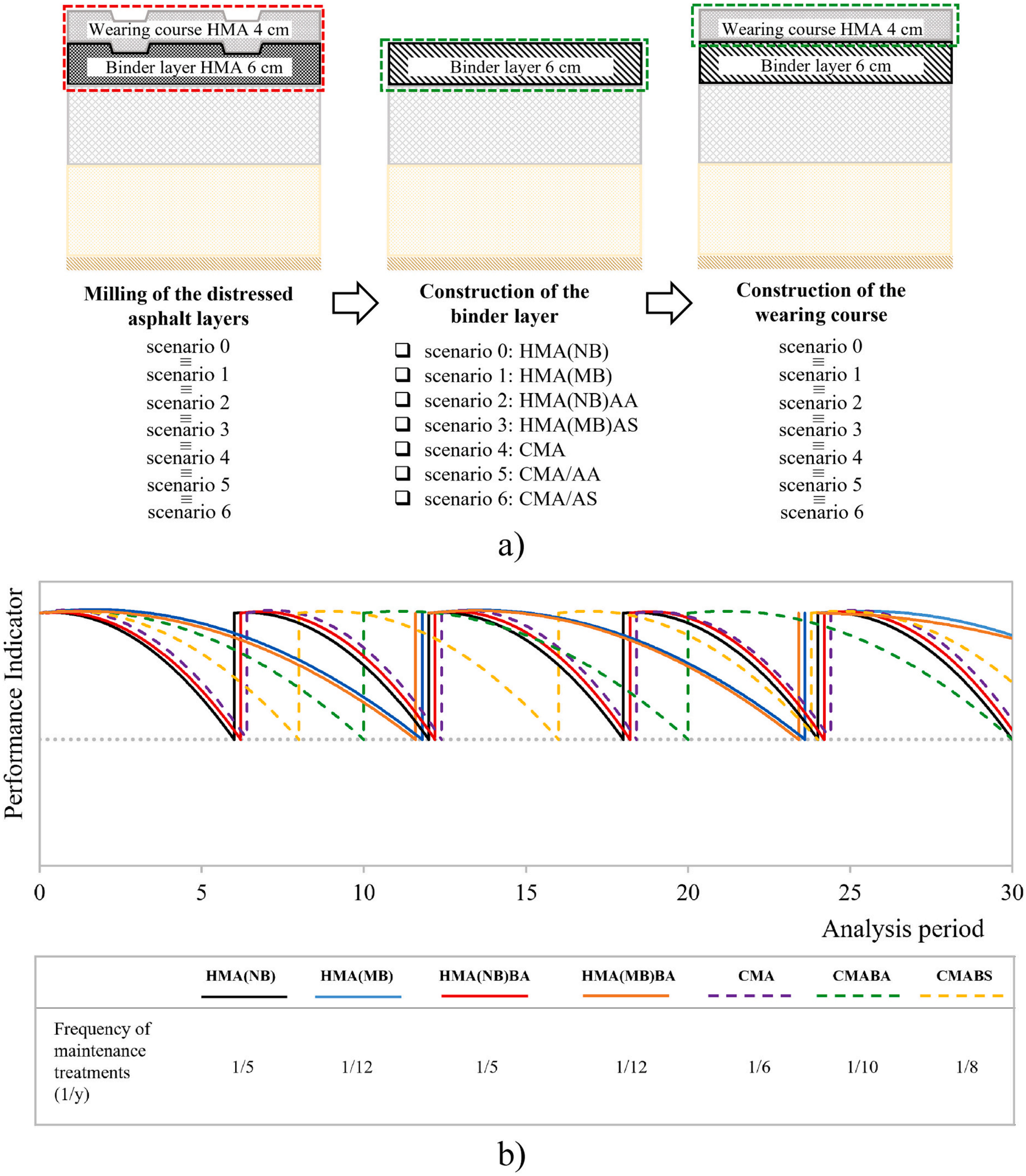
The LCA framework (ISO 14040) was applied as an internationally recognized life cycle-based environmental impact assessment procedure aimed at quantifying several indicators of environmental problems and concerns over different stages of the life cycle of a product system, including the global warming potential, stratospheric ozone depletion, ecotoxicity, human toxicity, resources depletion and more. According to ISO 14040, 3 main steps should be carried out: the goal and scope definition, the life cycle inventory (LCI) and the life cycle impact assessment (LCIA), each one subjected to a thorough interpretation phase.

2.4.1. Goal and scope of the analysis

The goal and scope definition phase aims to provide important details for the subsequent LCA phases, such as the functional unit and the system boundary to which the analysis is applied.

In the present work, the functional unit is 1 m^2 of built and maintained binder layer of an asphalt pavement of a rural road in the metropolitan area of the city of Naples (Italy) over an analysis period equal to 30 y.

The 7 designed asphalt mixtures were regarded as the alternative solutions to be adopted for 7 alternative road pavement maintenance scenarios triggered by the achievement of a vertical displacement on the pavement surface, namely the rut depth, equal to 20 mm and/or the achievement of an accumulated fatigue damage equal to the value 0.25 (Miner, 1945), according to the current maintenance approach of the local road authority. The 7 alternatives, regarded as maintenance



	HMA(NB)	HMA(MB)	HMA(NB)BA	HMA(MB)BA	CMA	CMABA	CMABS
Frequency of maintenance treatments (1/y)	1/5	1/12	1/5	1/12	1/6	1/10	1/8

Fig. 2. Ordinary maintenance activities applied to the functional units: a) graphical representation and b) qualitative plot of pavement performance decay versus time in 30 y analysis period.

scenarios (from 0, HMA(NB) to 6, CMA/AS), consisted of the milling of the existing distressed wearing course and binder layer and reconstruction of both the binder layer (using the six alternatives including or not the recycled AA and AS into hot and cold-produced asphalt mixtures) and the wearing course (conventional HMA), as depicted in Fig. 2a. The milling and reconstruction of the wearing course have been placed outside the boundary of the LCA because their durability does not depend on the structural capacity of the pavement, but rather it is related to its roughness deterioration rate, which calls for a fixed replacement frequency, equal to 3 y.

Regarding the maintenance phase, innovative solutions could have higher production-related impacts compared to a conventional alternative but, due to lower maintenance frequency and longer service life, lower impacts over its complete life cycle. In that case, a LCA that assumes that both alternatives have the same maintenance frequency would miss the benefits of the innovative material and there would be little incentive to use and develop such innovative materials in road engineering (Oreto et al., 2021b; Liljenström et al., 2022).

When competing pavement solutions are expected to have different service lives, several approaches can be applied to detect and communicate benefits in terms of life cycle impacts through competitive equilibria between the solutions (Praticò et al., 2023). In the case of asphalt pavements, the current practice suggests to: a) compare asphalt layers with different thickness and the same service life, or b) compare asphalt layers with the same thickness but different maintenance program within the same period of analysis. In the latter case, which is the approach applied within the present work, the current approach to pavement management and maintenance planning applied by the reference road authority was considered to schedule the maintenance activities.

Therefore, the service life of the alternatives was determined analytically through the application of fatigue (trigger model by Francken and Verstraeten, 1974, and upheaval model by Marchionna et al., 1989) and rutting (BRRC model by Verstraeten et al., 1977, Verstraeten et al., 1982 and Francken and Clauwaert, 1987) accumulation laws based on the stress-strain state of a pavement loaded by the ESAL (equivalent standard axle load) and modelled as a homogeneous, isotropic and linear elastic multilayer (De Jong et al., 1973), where the linear constitutive law is represented by the ITSM. A complete overview of the boundary conditions (service life, bearing capacity of the subgrade, elastic moduli of the subbase, base and wearing layers, operational temperature and temperature distribution during the seasons, road category, annual average daily traffic, traffic spectrum and distribution etc.) applied during the pavement design phase is detailed in Table 7 in the Supplementary Materials. The geometry of the pavement envisages an 18 cm thick base layer, a 6 cm thick binder layer and a 4 cm thick wearing course. In order to keep the accumulated fatigue damage calculated according to Miner's law (Miner, 1945) below the limit threshold value of 0.25 and the rut depth below 2 cm, a series of repeated maintenance treatments were planned, involving the milling of the wearing and binder layers and their reconstruction.

In detail, Fig. 2b shows the qualitative decay curve of the pavement using the alternative binder layer materials object of the study, as well as the frequency of the maintenance treatments taken into account when performing the LCA in the 30 y analysis period. In detail, the scenario 0 matches the current maintenance practice of the local road managing authority, namely milling and replacing the wearing and binder layers with a conventional HMA(NB) respectively every 3 and 6 years. Concerning the scenarios that account for a residual value of the layer at the end of the analysis period, the impacts from the last maintenance treatment applied to the pavement have been allocated to the functional unit considering the concept of salvage value (Babashamsi et al., 2016).

2.4.2. *System boundary and life cycle inventory analysis*

The second phase of LCA is the LCI. All the main phases of the life cycle are broken down into activities or unit processes; the inventory consists of a list of input flows (i.e., flows of materials and energy from the natural environment into the system under analysis and land use) and output flows (i.e., flows of waste and pollutants released into air, water and soil) for each unit process of the life cycle. Data are collected from primary and secondary sources; primary data are directly measured or collected data representative of activities at a specific facility or set of facilities, while secondary data are not directly collected, measured, or estimated, but rather sourced from a third-party life-cycle-inventory database (Allacker et al., 2013). Before moving on to the construction of the LCI, all the phases of the life cycle included in the system boundary have been thoroughly identified and broken down into unit processes (see Fig. 3). An overview of the primary and secondary data sources to build the LCI is shown respectively in Table 8 and Table 9 in the Supplementary Materials.

2.4.2.1. *Production of primary raw materials.* The primary raw materials that make up the hot asphalt mixtures include the natural limestone aggregates, the neat and modified bitumen; in the case of cold recycled mixtures, the natural aggregates, modified bitumen emulsion and Portland cement are produced in the respective industrial facilities and then supplied to the asphalt plant. The limestone aggregates production includes rock mining, transportation by dumpers to the crushing units, multiple crushing and sieving processes connected by conveyor belts that produce progressively finer aggregates. In the present analysis, the data regarding the production of 1 t of limestone aggregates, sand and filler have been gathered from Ecoinvent 3 database (Wernet et al., 2016).

The life cycle inventory data to produce 1 kg of neat bitumen, modified bitumen and bitumen emulsion have been extracted from the European Bitumen Association (European Bitumen Association, 2012; European Bitumen Association, 2021) inventory database, which collects the average European data for petroleum refining, storage and subsequent processing to obtain modified bitumen and bitumen emulsion. Lastly, the inventory data to produce 1 kg of Portland cement have been gathered from Ecoinvent 3 database.

2.4.2.2. *Recovery and recycling of the solid residue of MSWI.* The life cycle of the artificial aggregates/sand is modelled on a reference incinerator located in southern Italy, which produced 59,759.54 t of waste in year 2021.

The handling of the residue of MSWI takes place using 2 wheel loaders and 1 excavator. The power of the handling vehicles varies slightly according to the model, but it is included in the range 187–271 kW and the working time of each equipment is approximately equal to 0.078 h/t.

Waste is loaded into hook lift trucks with a maximum capacity of 30 t and transported for 50 km to the recycling facility.

The incoming waste is stored in special areas of the recycling facility for about 15 days so that the natural carbonatation and drying phase takes place in order to make their processing more effective.

After that, the solid waste undergoes a series of sequential treatments aimed at recovering their exploitable fractions (the ferrous and non-ferrous metal fraction and inert fraction):

- Ferrous metals recovery: initially, waste is screened to remove any large ferrous and non-ferrous material. The material, deprived of any coarse metal fractions, is sent to the first treatment phase which consists of removing calamitable ferrous metals using magnetic tapes. The selected ferrous metals are then further treated to remove any inert adhered residues;
- Non-ferrous metals recovery: the iron-free materials are subjected to a screening phase in rotating tunnel screens equipped with one or more grids to divide the material into different sizes. The fractions leaving the rotating screen are subjected to the separation of non-

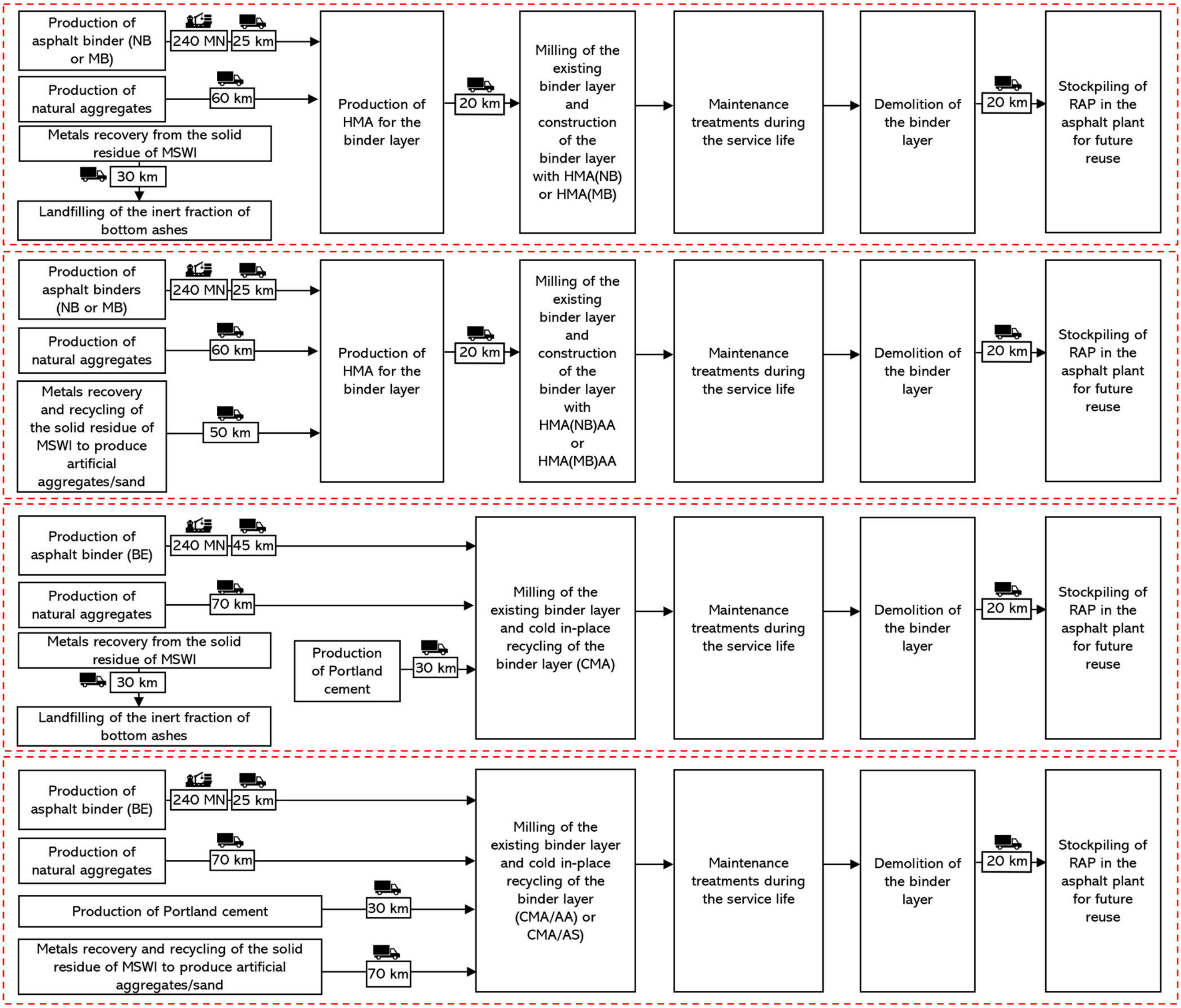


Fig. 3. Overview of the main phase of the life cycle of HMA(NB), HMA(MB), HMA(*NB*)AA, HMA(*MB*)AA, CMA, CMA/AA and CMA/AS. The dashed red lines represent the system boundary for each analysed scenario.

ferrous metals from the inert fraction, by means of magnetic induction separators.

- Inert fractions recovery: the inert coarse fraction usually undergoes a washing treatment to separate other foreign fractions, after which it is left to cure in a dedicated storage area so that the chemical maturation of the product takes place, i.e. the transformation of calcium hydroxide into carbonate of calcium, with consequent absorption of atmospheric CO_2, evaporation of water and pH reduction. After the curing phase, the inert fraction is further screened to obtain different aggregate sizes to meet the physical characteristics required by the technical standards and therefore be compliant for the production of construction materials, among which aggregates for cement production, road embankments and asphalt mixtures.

2.4.2.3. Landfilling of the solid residue of MSWI in the non-recycling scenarios. In the case of HMA(NB) and CMA, the analysis is conducted under the hypothesis that the inert residue of MSWI after the ferrous and non-ferrous recovery is transported by road to the nearest landfill (50 km away) and disposed of. The landfilling of inert waste was modelled according to the corresponding process in the Ecoinvent 3 database, as shown in Table 9 in the Supplementary materials.

2.4.2.4. Production, laying and compaction of HMAs. All the hot asphalt mixtures for the binder layer of an asphalt pavement (HMA(NB), HMA (MB), HMA(*NB*)AA, and HMA(*MB*)AA), were produced in a centralized batch plant using the same operating conditions in terms of mixing temperature and residence time for all the hot mixes, equal to 170 ± 5 °C and 1 min/m^3, respectively. The following data were acquired through direct surveys at a local asphalt plant: 1) the electricity consumption per ton of hot asphalt mixture produced, equal to 4.37 kWh/t, needed to store and feed the hot bitumen and mix the aggregates, filler, and bitumen for the production of the hot asphalt mixture, 2) the natural gas consumption per ton of asphalt mixture produced, equal to 8.79 m^3/t, used at the drum dryer to heat the aggregates at the mixing temperature, and 3) the productivity of a wheel loader, equal to 60 m^3/h and powered by diesel fuel, that handles the aggregates from the stockpiles to the plant feeding system. All the input and output inventory flows were then selected for the corresponding operations from the Ecoinvent 3 database. The amount of hot asphalt mixtures produced at the asphalt plant was estimated based on the thickness of each layer.

Concerning the construction of the hot asphalt layers, the boundary of the construction operations includes the milling of the existing deteriorated pavement and transportation of the RAP to the asphalt plant for future reuse. The hot asphalt layers are constructed using the paving and the roller machines, which work in series to lay and compact the asphalt layer; direct surveys allowed for the estimation of the productivity of the construction of a 6 cm-thick binder layer, which equals 205 t/d. In addition, the emissions to air of 16 mg/kg of NMVOC, 40 mg/kg of PM10, and 2 mg/kg of PM2.5 were considered during hot asphalt mixture production, as reported in tier 2 emission factors by the United States Environmental Protection Agency (McDonald et al., 2004) for the process "asphalt paving with hot mix asphalt".

2.4.2.5. CMAs in situ recycling and pavement construction. Contrary to what happens with HMAs, the cold binder layers are mixed directly in place using the RAP milled from the pavement surface, the natural aggregates and/or the AA and AS. Cold in-place recycling requires a train of machinery, as follows: (i) a diesel-powered motor grader that smooths and prepares the surface before placing the binder layer; (ii) a diesel-powered pulvimixer that mixes in place the RAP, natural/recycled aggregates, cement, water, and bitumen emulsion (each one of them supplied from the production facility to the construction site), (iii) two large pneumatic tire rollers and a large vibratory steel wheel roller that provide the desired density and iv) the tankers that supply water and bitumen emulsion. The reclaimed asphalt that is not recycled according to each cold mix composition shown in Table 1b is stockpiled in the asphalt plant for future reuse The productivity of all the equipment is listed in Table 8 in the Supplementary Materials.

2.4.2.6. Maintenance phase. In the present analysis, the maintenance program of each binder layer accounts for all the preventive maintenance activities applied in 30 years. The maintenance treatment of the binder layer consists of its milling and reconstruction using the original materials. The frequency, and therefore the number of preventive maintenance treatment applied in 30 years, is shown in Fig. 2b.

2.4.2.7. End of life phase. Once the asphalt pavement has reached the end of its service life, it is demolished (through a milling machine with a productivity of 150 t/h), hauled to the nearest asphalt plant, and stockpiled for future reuse. The inventory flows associated with the milling of RAP were estimated using data from Ecoinvent 3 database. Input and output flows associated to the stockpiling and future treatments aimed at reuse were not accounted for in the present analysis.

2.4.2.8. Transportation of materials. The distance travelled by road transportation vehicles has been surveyed directly (see Fig. 3 and Table 8 in the Supplementary Materials), when known, or estimated using "market" processes from Ecoinvent 3 database, which include the flows from both production and transport processes as the average of a specific geographic area.

2.4.3. Impact assessment methodology

The LCIA phase converts the long list of input and output flows of the LCI into a limited number of impact category indicators, each of them representing the measure of a specific environmental problem. Among the impact assessment methods, the Hierarchical ReCiPe method (Huijbregts et al., 2016) addresses multiple environmental concerns through 18 midpoint indicators. The midpoint level refers to the middle stage of the cause–effect chain that begins with the input and output flows and ends with the damage on the human health, ecosystems, and resource availability. In this study, the indicators assessed according to the Hierarchical ReCiPe method were adopted to compare the solutions under analysis using SimaPro 9.5® software (PRé Sustainability, 2023).

The list of selected midpoint indicators of the ReCiPe method includes the main following indicators: Global warming (GWP, kg CO_2 eq), fine particulate matter formation (PM, kg PM2.5 eq), marine eutrophication (ME, kg N eq), freshwater ecotoxicity (F-ECO, kg 1,4-DCB eq), human carcinogenic toxicity (CT, kg 1,4-DCB eq) and fossil resource scarcity (FR, kg oil eq). The rationale for the selection of such indicators lies in the willing to narrow the discussion by addressing 3 main topics through intermediate measures of: a) fossil resources use and main environmental effect (FR and GWP), b) damage to human health (PM and CT) and c) damage to ecosystems (F-ECO and ME).

3. Results and discussion

The results of the present study are presented below. In detail, taking into account the composition of the asphalt mixtures for the binder layer (HMA(NB), HMA(MB), HMA(*NB*)AA, HMA(*MB*)AA, CMA, CMA/AA, CMA/AS) and the type and timing of the maintenance activities planned by the road authority to restore the roughness of the pavement surface and prevent degradation of the structural layers, a thorough discussion of the LCA results is carried out.

3.1. Impact assessment indicators

The output of the LCA was expressed using 6 impact category indicators, each of which summarizes the effect of multiple flows of materials, energy, pollutants and waste on as many environmental categories under an equivalent unit of measurement. The complete list of indicators for the 7 alternatives under analysis is given in Table 10 in the Supplementary Materials. Aiming to draw useful considerations about the environmental soundness of using artificial aggregates and sand from MSWI into road pavement bound-materials, 6 indicators, namely the GWP, PM, F-ECO, CT, ME and FR, were selected, broken down into the main processes of the life cycle and shown in Fig. 4. The percentage variation of the 18 impact indicators with respect to the maximum value is shown in Fig. 5.

In the first place, looking at the results for the conventional solution with HMA(NB), the maintenance phase accounts for >70 % of the overall life cycle impacts, which is consistent with most LCA applications (Liljenström et al., 2022); the total GWP, equal to 49.9 kg CO_2 eq/m^2 is also consistent with literature data (i.e., 55.3 kg CO_2 eq/m^2 by Siverio Lima et al. (2021)), considering the variability in the boundary conditions of the analysis (layer thickness, road category, traffic, bearing capacity of the subgrade etc.). The incidence of the main phases of the life cycle on the impact category indicators is strictly connected with the inventory flows; the raw materials production phase accounts for 5.9 %, 7.6 % and 14.9 % of respectively the GWP, CT and FR of the whole life cycle. In detail, 88 % of the GWP indicator is linked to CO_2 emissions to air during the extraction and processing of crude oil (1.35 kg CO_2 eq/m^2) and natural aggregates (0.93 kg CO_2 eq/m^2), 93 % of the CT indicator is due to Chromium VI dispersion in air, soil and water due to engine operation (burning of fossil fuels like coal and oil) of industrial manufacturing facilities and equipment, and 82 % of the FR indicator results from crude oil consumption both as a raw material (bitumen) or used as an energy resource. The asphalt mixture production phase accounts for a slightly significant contribution to the impact category indicators, averaging 2.8 % of the overall impacts of the life cycle, up to 7.9 % of the GWP indicator. The construction of the asphalt pavement contributes significantly to the PM indicator (17.4 %), which is almost entirely (94 %) due to $PM_{2.5}$ emissions from construction equipment and asphalt fumes, and accounts for 2.8 % of the ME indicator, which is caused by nutrients over-enrichment of marine water bodies caused by the atmospheric deposition of chemicals like ammonium and nitrates emitted by construction equipment operation. Lastly, the transportation of raw and finished materials has a relevant impact on all the category indicators, accounting for around 19.2 % of the marine, freshwater and terrestrial ecotoxicity indicators due to the atmospheric emissions of metals, like zinc, copper and antimony, from combustion engines.

Comparing the CMA to the HMA(NB), all the impact indicators decrease on average by 56 %, which is in line with previous results from other works discussing the environmental performance of cold in-place recycling compared to traditional hot mix asphalt (Offenbacker et al.,

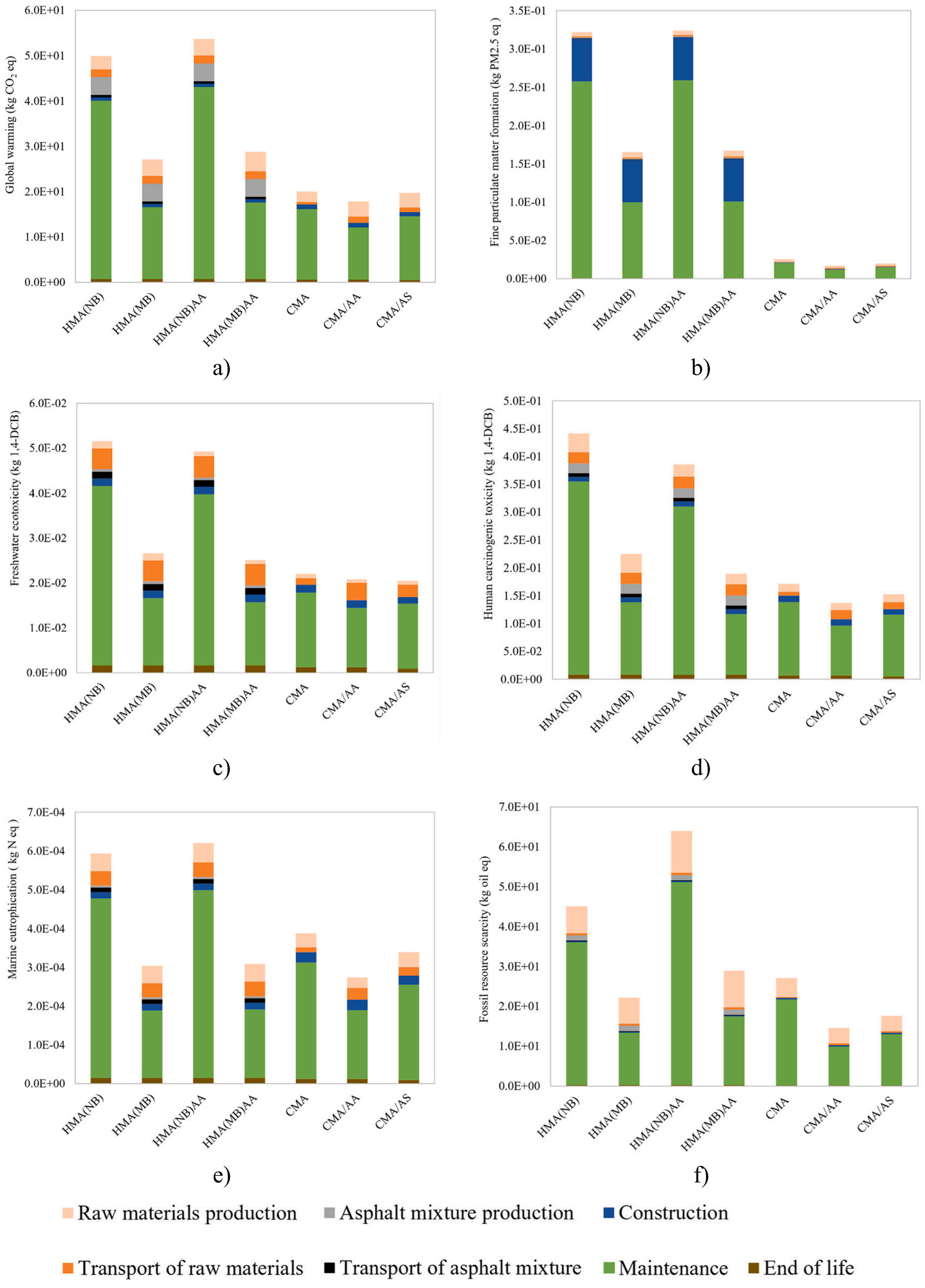


Fig. 4. Impact assessment indicators of the solutions under analysis: a) global warming (GWP), b) fine particulate matter formation (PM), c) freshwater ecotoxicity (F-ECO), d) human carcinogenic toxicity (CT), e) marine eutrophication (ME) and f) fossil resource scarcity (FR).

2021). The reduction of the environmental burden can be explained, on the one hand, with the avoided impacts from hot asphalt mixture production and transportation to the construction site and, on the other hand, with the avoided impacts from natural aggregates production. In detail, the positive balance in terms of GWP (-1.8 kg CO$_2$ eq/m^2) at the raw materials production and supply stages results from the avoided

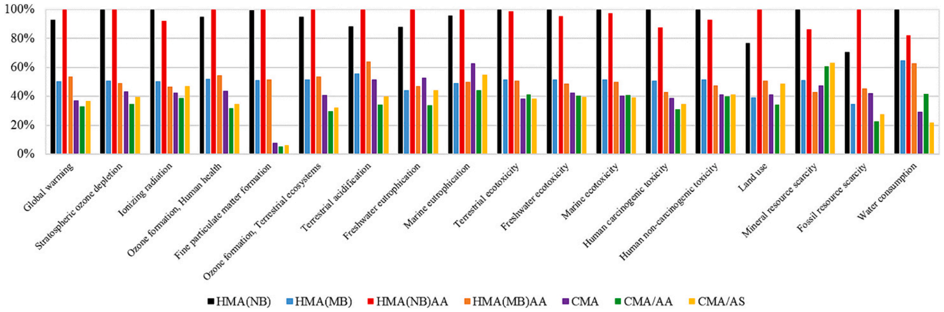


Fig. 5. Percentage variation of the impact category indicators of the 7 alternatives under analysis.

impacts from natural aggregates production (−0.6 kg CO_2 eq/m^2) and the additional impacts from the production and supply of cement binder (+0.4 kg CO_2 eq/m^2). Other remarkable aspects concern the reduction of 57, 46 and 29 % of respectively the CT, FECO and FR indicator during the extraction and processing of raw materials. Looking at the construction of the asphalt pavement, the CMA entails additional impacts during the operation of the equipment involved in the recycling train (grader, pulvimixer, rollers, tankers) compared to the traditional hot mix asphalt construction (i.e., +0.4 kg CO_2 eq/m^2 for the GWP, +0.5 kg 1,4-DCB/m^2 for the TECO and + 0.2 kg oil eq/m^2 for the FR indicator) but avoids the impacts from the end of life stage (transportation and stockpiling of asphalt waste) proportionally to the share of RAP reused in the mixture. The impact indicators of the overall construction phase decrease on average by 17 % compared to HMA(NB), with the maximum variation for the PM indicator (92 %). The greatest contribution to the PM indicator is attributed to the construction process with hot mix asphalt, for which the US EPA accounts for direct emissions into air of NMVOC, PM10 and PM2.5, other than all the emissions from combustion engines of the construction equipment. Instead, no data regarding any direct emissions from cold in-place recycling were considered in the analysis for the following reasons: a) bitumen emulsion is handled at low temperature, therefore no emissions from the volatile fractions of bitumen are expected, and b) the mixing of cold asphalt takes place in presence of a certain moisture content, which contributes to limit dust formation. Lastly, the impact of the maintenance phase depends on the "cradle to site" of the CMA (from raw materials production to pavement construction) repeated for the number of interventions (milling and rebuilding using the same material) envisioned by the maintenance program; comparing the maintenance phase of the CMA to that of the HMA(NB), the impact indicators of the maintenance phase decrease on average by 56 %, reaching −23.8 kg CO_2 eq/m^2 (GWP), −172.5 g NOx eq/m^2 (OFT and OFH) and − 14.4 kg oil eq/m^2 (FR).

Moving on to the impact of recycling the solid residue of MSWI as an artificial aggregate into hot asphalt mixtures using a neat bitumen 50/70 (HMA(*NB*)AA), the composition of the mixture that complies with the main tender specifications and ensure the same service life as the traditional HMA(NB) entails additional 3.7 kg/m^2 of bitumen, and saves 55.0 kg/m^2 of limestone with an uptake of 51.4 kg/m^2 of solid waste (which undergo a recovery process) for a 6-cm thick binder layer. Comparing HMA(*NB*)AA to HMA(NB), the changes at the raw material production stage overall negatively affect the GWP (+7.6 %) and the FR indicators (+40 %), but also entail a reduction of the IR, F-ECO, CT, MR and W indicators, respectively by 7.8, 4.5, 12.7, 13.7 and 17.9 %, being these the most sensitive to changes at the stage of extraction and processing of limestone and to the avoided impacts from landfilling of the solid residue of MSWI.

Designed to keep the same uptake capacity as the HMA(*NB*)AA but improve the overall mechanical performance of the mixture (+6 years of service life compared to HMA(NB)) and lower the bitumen content (−1.2 kg/m^2 compared to HMA(*NB*)AA), the HMA(*MB*)AA solution shows comparable mechanical performance (equal durability) and slightly worse environmental performance (mainly because of the greater optimum bitumen content, which entails +2.7 kg/m^2 of SBS-modified bitumen) compared to the HMA(MB). All the impact indicators on average decrease by 45.9 and 47.2 % compared to HMA(NB) and HMA(*NB*)AA, respectively. Nevertheless, the impact indicators of the HMA(*MB*)AA increase on average by 1.9 % compared to those of HMA(MB), with the maximum increase corresponding to the A, LU and FR indicators (respectively +14.8, 29.5 and 30.9 %) and the maximum decrease corresponding to the IR, CT and MR indicators (respectively −7.9, 15.7 and 15.9 %). Looking at the raw materials production stage, the use of modified bitumen entails a significant increase of GWP and TECO indicators, respectively equal to 1.3 kg CO_2 eq/m^2 and 120 g 1,4-DCB/m^2 compared to the corresponding stage of the life cycle of HMA (*NB*)AA; the additional burdens of MB regard the production and supply of SBS polymer and the high shear milling at 175 °C to produce the polymer modified bitumen. The negative aspects at the production stage are overall compensated by the benefits obtained throughout the life cycle with a lower frequency of maintenance, which translates into an overall reduction of all the impact category indicators associated to the maintenance stage by half compared to both HMA(NB) and HMA(*NB*) AA, but does not entail additional benefits when comparing the HMA (*MB*)AA to the HMA(MB).

Moving on to the cold recycled mixtures where the RAP is combined in turn with the artificial aggregates and artificial sand (CMA/AA and CMA/AS), all the impact indicators decrease on average by 13.2 and 8.0 % respectively comparing CMA/AA and CMA/AS to CMA, by 28.8 and 22.0 % respectively comparing CMA/AA and CMA/AS to HMA(MB), and by 62.4 and 59.1 % respectively comparing CMA/AA and CMA/AS to HMA(NB). In particular, recycling the artificial aggregates from MSWI into cold asphalt mixtures produces an overall better environmental compliance than hot recycling, being all the impact indicators of the cold solutions 61.3 and by 25.6 % lower than those of HMA(*NB*)AA and HMA(*MB*)AA, respectively.

Three key stages of the life cycle are affected when comparing the LCA results to those of the CMA: a) the raw materials production stage, in terms of avoided impacts from limestone aggregates production and landfilling of waste from MSWI and additional impacts from greater content of either bitumen emulsion, cement binder and water, b) the construction stage, in terms of recycling rate of the reclaimed asphalt produced at the yard and avoided impacts from landfilling of the reclaimed asphalt that is not recycled in place, and c) the maintenance stage, which mainly depends on the expected service life before any maintenance activity is performed on the binder layer during the period of analysis (30 y).

The CMA/AA solution maximizes the amount of AA (30 %), while the CMA/AS maximizes the RAP (53 %) in combination with the AS. Most of the impact indicators at the inert production stage (limestone processing and recycling of the residue from MSWI) are not significantly different comparing the CMA/AA to the CMA/AS (±5 %), except for FE and ME indicators due to high emissions of P and N equivalents from the industrial recovery of the solid residue of MSWI, which shows 40 %

increase for CMA/AA compared to CMA/AS. Looking at the binder production (bitumen emulsion and cement), the substitution of limestone with artificial aggregates and sand, just like in the case of hot asphalt mixtures, often causes an increase in the binder demand needed to reach the desired mix performance: for cold asphalt mixtures, that is the case of cement (+2 % and + 1.5 % respectively for CMA/AA and CMA/AS compared to CMA) but not of the bitumen emulsion (−1 % for both CMA/AA and CMA/AS compared to CMA). Indeed, cement production largely affects the GWP (+1.4 and + 1.0 kg CO_2 eq/m^2 for CMA/AA and CMA/AS compared to CMA) and the TECO (+1.9 and + 1.4 kg 1,4-DCB/m^2) mainly because of the SO_2, NO_x, CO and heavy metals emissions during plant operation.

The mentioned gaps at the raw material production stage between CMA/AA, CMA/AS and CMA are more than compensated at the maintenance stage through increased time between the maintenance activities (+4 and + 2 years for CMA/AA and CMA/AS compared to both CMA and HMA(NB)); therefore, all the impact indicators of the maintenance stage decrease on average by 26.8 and 14.0 % comparing CMA/AA and CMA/AS to CMA, and by 68.8 and 62.3 % comparing CMA/AA and CMA/AS to HMA(NB), respectively. Despite the greater maintenance frequency, the same goes when comparing the impacts from the maintenance stage of the CMA/AA and the CMA/AS to those of the HMA (MB), which decrease on average by 19.6 and 2.3 %.

3.2. *Synthetic checklist to use artificial aggregates and sand from MSWI into asphalt mixtures*

When approaching new valorisation paths for alternative and marginal waste materials, multiple aspects that surround the sphere of sustainability should be adequately deepened before a safe and environmentally-sound recycling chain can be set up. Indeed, following ready-to-use sheets based on previous thorough definition of the sustainability aspects, both from a technical and environmental point of view, can support the design of hot and cold asphalt mixtures with high rate of incorporation of the solid residue of MSWI recycled as an artificial mineral component, eventually helping to set up policies and tailored technical specifications and communicating the expected improvement in terms of the main impact indicators throughout the life cycle of the pavement, with consideration of the geographical context in which the specific project is carried out.

Table 3 summarizes the results of the present study carried out using the AA and AS from MSWI in 2 different sizes and introduced into hot and cold asphalt mixtures, using percentage in the range between 25 % and 40 %. As mentioned above, the sheet is made up of 4 stages, not

Table 3
Final checklist for high rate of MSWI residue recycling (≥25 %) into asphalt mixtures for a 6-cm thick binder layer based on the results of the research.

Operative steps	Hot asphalt mixtures		Cold asphalt mixtures	
	AA - Aggregate size (0–14 mm)	AS - Sand size (0–4 mm)	AA - Aggregate size (0–14 mm)	AS - Sand size (0–4 mm)
Characterization of raw waste	• BA have greater specific gravity and lower fragmentation resistance than the limestone • BS have greater specific surface and Rigden voids than the limestone sand and filler			
Technical feasibility of asphalt mixtures	• The optimum bitumen content is greater when artificial aggregates are used in substitution of natural ones. • Using a polymer modified bitumen instead of a neat bitumen causes a 1 % decrease of the optimum bitumen content. • The ITS and ITSR at 25 °C are compliant with the main Italian tender specifications. • The stiffness modulus of HMA(*NB*) AA is greater than that of HMA (NB); the gap is greater as the temperature increases. Comparable stiffness is detected between HMA(MB) and HMA(*MB*) AA, except for low temperatures (10 °C) • The use of a modified bitumen makes the mixture less sensitive to rutting.	Not investigated as the specific surface of the BS is 6 times that of limestone sand/ filler, calling for a bitumen content higher than 7.5 % by mass of the aggregates	• Using the AA into cold in-place recycled asphalt mixtures maximizes all the static (ITS) and dynamic (ITSM, RD) mechanical performance of the cold recycled mixture. • The greater ITS suggests the embrittlement of the mixture, which may lead to a decrease of the fatigue resistance when the binder layer is subjected to tensile stress state. • The improvement of the high temperature stiffness and rutting tendency has a huge influence on the durability of the pavement layer and the predicted frequency of maintenance.	• Using the BS into cold in-place recycled asphalt mixtures improves the mechanical performance of the mixture compared to CMA, especially in terms of ITSM at 60 °C and accumulation of rut at 60 °C. • The improvement of the high temperature stiffness and rutting tendency has a non-negligible influence on the durability of the pavement layer and the predicted frequency of maintenance.
Environmental feasibility and recyclability of asphalt mixtures	• Asbestos not present • Leaching thresholds of Ministerial Decree 5/2/1998 are satisfied • Ecotoxicity thresholds are satisfied: EC50 for *Daphnia magna* and algal growth is always above 170 mg/L		• Asbestos not present • Leaching thresholds of Ministerial Decree 5/2/1998 are satisfied • Ecotoxicity thresholds are satisfied: EC50 for algal growth is above 250 mg/L and EC50 for *Daphnia magna* is above 100 mg/L	• Asbestos not present • Leaching thresholds of Ministerial Decree 5/2/1998 are satisfied • Ecotoxicity thresholds are satisfied: EC50 for algal growth is above 250 mg/L and EC50 for *Daphnia magna* is above 170 mg/L
Life cycle impacts of asphalt mixtures	• Comparing HMA(*NB*)AA vs HMA (NB): a non-negligible positive effect on FE, CT and MR indicators, a negative effect on the FR indicator and a non-negligible effect on the remaining indicators (variation ≤10 %). • Comparing HMA(*MB*)AA vs HMA (NB): the impact indicators decrease on average by 33 % • Comparing HMA(*MB*)AA to HMA (MB): the impact indicators are on average greater by 1.9 %		• Comparing CMA/AA vs CMA: a non-negligible positive effect on OFH, OFT, PM, A, FE, ME. CT and FR indicators, and a non-negligible effect on the remaining indicators (variation ≤10 %). • Comparing CMA/AA vs HMA(NB): all the impact indicators decrease on average by 62 %	• Comparing CMA/AS vs CMA: a non-negligible positive effect on OFH, OFT, PM, A, FE and FR indicators, and a non-negligible effect on the remaining indicators (variation ≤10 %). • Comparing CMA/AS vs HMA(NB): all the impact indicators decrease on average by 59 %

necessarily consequential except for the characterization of the raw waste that is preliminary for the mix design.

4. Conclusions

In conclusion, the present study intended to formalize and apply a comprehensive evaluation path for the valorisation of the solid residue from municipal waste incineration. In detail, the study explored the reuse of artificial aggregates and sand according to 4 alternative technologies, 2 HMAs, using neat and modified bitumen, and 2 in-place cold-produced asphalt mixtures for the binder layer of a road pavement.

The solid waste underwent the characterization of its main physical and mechanical properties to assess the compliance with local tender specifications; subsequently, the asphalt mixtures were designed and characterized mechanically (i.e., ITS, ITSR, ITSM and RD testing) and in terms of environmental compatibility (i.e., Asbestos content, concentration of contaminants in the eluate of the leaching test and ecotoxicity towards living organisms); lastly, the alternative asphalt mixtures were placed into a broader context, considering a 6 cm-thick binder layer of a typical southern Italian rural road with an expected service life equal to 30 y, and underwent the LCA procedure to quantify 18 indicators of specific environmental issues that are more or less affected by the valorisation of such waste into asphalt mixtures. A final ready-to-use checklist was drawn up taking into account the results of the investigations, from which the following broader considerations can be made:

- Using the artificial aggregates from MSWI in substitution of limestone aggregates into traditional hot asphalt mixtures with neat bitumen 50/70 does not significantly affect the mechanical performance of the mixture in terms of stiffness modulus and rutting accumulation nor its leaching ability and ecotoxicity, but entails higher bitumen content compared to a conventional HMA, which negatively affects the overall environmental performance across the life cycle;
- Using a commercial polymer modified bitumen in combination with the artificial aggregates from MSWI strengthens and stiffens the mixture and significatively improves the durability against fatigue and rutting distresses, according to the predictive damage equations, with 0.2 greater optimum bitumen content compared to the conventional asphalt mixture with polymer modified bitumen, and complying with the mandatory leaching and ecotoxicity thresholds. Similarly to what is observed for asphalt mixtures with neat bitumen, the environmental impact indicators are slightly higher when using the artificial aggregates for the same maintenance frequency;
- Cold recycling of the artificial aggregates allows to maximize the uptake of waste into cold asphalt mixtures and improve the mechanical performance compared to a conventional cold recycled mixture, returning the lowest frequency of ordinary maintenance activities and remarkably achieving 9 and 64 % reduction of all the impact category indicators compared to traditional HMA and CMA, respectively. Notably, the proximity of the result in terms of acute toxicity on Daphnia (102 mg/L) to the limit imposed by the EU Regulation 1272/2008 is to be attributed to the whole mix composition, including cement and additives, rather than to the recycled artificial aggregates themselves;
- Cold recycling of the artificial sand entails smaller cement binder content compared to the coarse artificial aggregates, as well as achieving the greatest total recycling rate (78 %) and still complying with all the preliminary environmental assessments; slight drawbacks compared to the cold recycling of coarser artificial aggregates result from lower intake of solid residue of MSWI (−5 %) and more frequent ordinary maintenance treatments applied to prevent structural damage within 30 y from construction. The impact category indicators of the whole life cycle are not significatively different from those obtained using the artificial aggregates into cold mixes.

Further research is needed to expand the use of the solid waste residue from incineration of municipal waste to the whole asphalt pavement structure (i.e., wearing course and base layer) counting, on the one hand, on more and more efficient recycling practices of the solid residue of municipal waste incineration, and, on the other hand, on the evolution of asphalt pavement technologies to increase the intake of secondary materials without affecting negatively the durability of materials in terms of mechanical performance and/or friction-related characteristics, when wearing courses are concerned. Nevertheless, the main limitation of the present research lies in the uncertainty associated with the service life prediction (equal durability in the case of hot asphalt mixtures; greater durability of the cold asphalt mixtures with artificial aggregates compared to conventional in-place recycled mixtures). In particular, the reliability of the durability estimates requires further investigation through fatigue tests, which will allow to lower the uncertainty of the service life prediction; such experimental characterization will be paramount especially for predicting the durability of cold recycled mixtures. Additionally, future research should be focused on increasing the data availability and site-specificity to apply life cycle assessment methodology systematically to newly designed asphalt-based materials with artificial aggregates from solid waste incineration.

CRediT authorship contribution statement

Cristina Oreto: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Francesca Russo:** Writing – review & editing, Validation, Supervision, Conceptualization. **Gianluca Dell'Acqua:** Supervision, Validation. **Rosa Veropalumbo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171716.

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