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Mechanical and environmental performance comparisons of improved asphalt pavement wearing courses with high quality aggregates, steel slags, and polymeric compound

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ABSTRACT

The use of waste materials in the construction of hot mix asphalt (HMA) pavements is an important opportunity for environmental sustainability. When properly designed, the alternative mixtures may also guarantee excellent mechanical performance.

In this study, the results of an experimental analysis carried out on dense-graded HMAs are presented. In particular, the performance of a "traditional" surface mixture with limestone aggregate (designed with neat bitumen or a polymer-modified bitumen within the typical acceptance requirements for intended use in wearing courses) was compared with two alternative mixtures. The research investigated a surface mixture including coarse basaltic aggregates (a high-quality non-renewable resource) and one in which the coarse aggregate is substituted by a waste material, i.e. steel slags, in a high percentage. Both the improved mixtures included neat bitumen and a polymeric compound too, for advanced performance. Finally, for a more comprehensive comparison, a Life Cycle Assessment - LCA (cradle-to-gate approach) was carried out on the different mixtures, to compare the environmental impacts related to their production in asphalt plants, considering the features of the materials and fuels involved. The laboratory results showed comparable structural performance for the two mixtures with basalt aggregates and steel slag. In addition, other positive aspects concerned the higher crushing resistance of metal slag compared to basalt aggregates and the lower percentage of bitumen required by the proposed mixture with slags, with evident practical benefits. Furthermore, the LCA provided useful information about the environmental sustainability of the different mixtures, so that the feasibility of use of these recycled materials may be evaluated considering not only the technical and cost perspectives but the environmental ones too. The numerical results evidenced remarkable benefits for several impact categories for the mixtures with recovered waste materials, with promising advantages with their growing wide adoption.

1. Introduction

Road constructions involve large quantities of construction materials, primarily obtained from natural sources with consequent continuous demand for raw material extraction and consumption of precious resources. Their extraction, in turn, involves a significant environmental impact, with major problems linked to dust emissions and consumption of energy, also determining an economic burden that should not be underestimated [12].

The current EU policy for waste mainly aims at prevention, recycling and, only as a final solution, disposal [14]. The waste management strategy in the last few years has focused on waste recovery, by means of solutions that may ensure its reuse in substitutions of commonly used materials, which may be characterized by high costs or difficulties in supplying.

Accordingly, considering asphalt mixtures, a lot of attention has focused on the use of waste materials, to improve the mixture performance, or of secondary aggregates, which can be defined as by-products of industrial processes or other human activities, useful to replace primary raw aggregates. From this point of view, in the literature there are studies and applications aimed to evaluate the performance of asphalt mixtures containing, for example, reclaimed asphalt materials [13], tire rubber [7,46], glass waste and steel slag [45,20] or plastic materials [23,30,47] and other additives [9]. In this regard, previous studies have

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proved, for example, that polymers can improve rutting resistance, high-temperature stiffness, susceptibility to temperature variations and, sometimes, also fatigue cracking resistance [22,11,28,39,8].

Among the various alternatives, according to numerous studies, steel slag, thanks to its physical and mechanical properties, can be successfully used as a high-quality aggregate in road pavements [5,31,52]). Slag is a waste product from metallurgical processing of various ores and can be classified into ferrous and non-ferrous slag. In particular, steel slag is a by-product of steelmaking and steel refining processes, and it is classified based on the type of furnace used. Considering its benefits in pavement applications, some researchers [1,33,36–38,42] affirmed that including steel slag aggregates also the structural and durability performance of mixtures.

According to literature, steel slags have different applications in road construction such as asphalt mix aggregate [10,34,19,6,3,38,25], anti-skid layer [4,24], granular base and subbase material [10,40,2]. Other studies have investigated application of steel slag in hot mix asphalt [36,44], warm mix asphalt [18,27], chip seal [49]and stone mastic asphalt [33,50,51], with positive results. Some researchers (such as [15,42,53]) have shown though that steel slags could evidence volumetric instability with volume increase in the presence of water, probably because of the presence of unstable phases in their mineralogy.

A methodology study for the mechanical behaviour of bituminous mixtures with steel slag aggregates by performing loading tests was carried out by Freire et al. [17]. The results obtained, concerning a macadam layer, have shown that the studied mixture presents an adequate behaviour, namely regarding fatigue and permanent deformation.

Moreover, tests were undertaken on steel slag aggregates for evaluating their potential usage as a road construction material comparing electric arc furnace slag (EAFS) and ladle furnace slag (LFS) [26]. From an environmental perspective, EAFS and LFS were found to pose no environmental risks for use as aggregates in road constructions. The engineering properties of LFS aggregates (which have satisfactory geotechnical and, in particular, satisfactory bearing capacity in terms of CBR – California Bearing Ratio values), indicated that the material was ideal for usage as a construction material such as pavement bases/subbases and engineering fills. EAFS, with its comparatively lower CBR value, was found to be only suitable for use as a construction material for pavement subbases and engineering fills.

Generally speaking, using recycled material is also advantageous for asphalt producers, involving materials with a lower cost than those normally used, such as basalt, widely adopted in the Southern Italian context. Basalt, indeed, has a glassy porphyritic microcrystalline or fine-grained structure that guarantees high mechanical resistance, making it very useful in road applications for construction of the most stressed layers of the pavement. At the same time, however, this material offers low affinity with bitumen. Indeed, its composition, mainly based on silicon, causes adhesion problems between aggregates and binder [54]. To compensate the problems relating to the percentage of residual voids normally encountered using basalt [21], this is combined with limestone. However, extraction and crushing of these stone aggregates entail very high costs and environmental impacts, very critical for sustainability evaluation of asphalt mixtures [43,25].

Thus, to broaden the reasons why it is advantageous to use these recycled materials, not only the results obtained for mechanical performance but also those related to emissions into the environment should be integrated in the assessment of alternative solutions. For this purpose, the Life Cycle Assessment (LCA) approach may be a reliable solution for investigating the entire life cycle of both products and processes [55,56]. The assessment can assure an overview of the entire life cycle of the material by taking into consideration production of raw materials and mixtures, construction, effective exercise, and final disposal, considering all the resources involved and evaluating the environmental impact generated [43].

In a previous study, for example, Mladenovič et al. [29], through LCA, have shown that use of steel slag aggregates in asphalt mixtures contributes to reducing environmental impact, although this positive effect decreases when the delivery distance increases, due to the high particle density of slags.

In this context, this paper reports a comprehensive experimentation, considering mechanical and environmental performances, on asphalt mixtures for wearing courses including waste materials, for improving mechanical quality and durability and as an alternative to high quality aggregates. In particular, traditional mixtures (with neat or polymer modified bitumen), designed with limestone aggregates only, were compared with two improved mixtures: one represents an ordinary mixture typical of Southern Italian pavements, including high-quality aggregates (basalt), while the other includes a high percentage of steel slags instead of basalt aggregates. Mix design of both mixtures considered neat bitumen and the dry addition of a polymeric compound, for improving mechanical and durability performance. It should be clarified that the aim of the research is the evaluation of an alternative mixture to that generally adopted, with coarse basalt aggregates, that are necessary because of the unsatisfactory performance of the limestone aggregates available in Southern Italy, mainly in terms of resistance to polishing. Since basalt aggregates are very expensive and have a bad impact on the environment, providing a reliable alternative solution is urgent.

The mixtures were studied through an extended experimental laboratory campaign including physical and mechanical tests. Furthermore, a specific LCA was carried out, to compare the expected environmental impacts due to their production at industrial scale, in asphalt plants. The goal was to validate a mixture for the wearing course of flexible pavements as an alternative to the ones commonly used, through the adoption of an industrial by-product, in a high percentage. This solution makes this alternative sustainable, in environmental terms, and economically advantageous in comparison with the traditional mixtures including virgin materials and high quality non-renewable natural resources, such as basalt aggregate.

In the following sections, first materials and methods are presented; then the results of the laboratory tests and the LCA outcomes are presented; finally, the experimental results are discussed, evidencing advantages and potentialities of the improved materials in practical applications.

2. Materials and methods

The aim of the experimentation was to carry out a comparative analysis amongst four different mixtures of dense-graded HMA for wearing courses fulfilling the typical requirements of the Italian technical specifications. In particular, two traditional control mixtures with aggregate skeleton in limestone aggregates only, specifically designed in laboratory with both neat bitumen and polymer-modified bitumen and no further additives – as a precise design choice -, were compared with two “improved” mixtures. The improved mixtures both include neat bitumen only: one with coarse basaltic aggregates in substitution of the limestone coarse fraction and a second one with the coarse aggregate replaced with steel slags. Considering the neat bitumen used, for ensuring high mechanical performances, both the improved mixtures included a polymeric compound, in dry addition to the mixture, as detailed below.

The experimentation first focused on the characterization of the different selected aggregates and binders; then, a laboratory mix-design (trough both Marshall and volumetric methods) was performed. Furthermore, specific tests for evaluating the mechanical performance of the mixtures were carried out (tensile strength, sensitivity to water, dynamic stiffness modulus, and rutting resistance). Finally, an LCA was defined and performed, according to the cradle-to-gate approach, considering emissions and impacts related to the production phase of the studied mixtures.

2.1. *Aggregates*

As a first characterization of the aggregates, a gradation analysis was performed (EN 933-2). In Table 1 and Table 2 the passing of the different aggregates (both virgin and secondary ones) and the specific gravity of the different types are reported, respectively.

Then both the shape (EN 933-4) and the flakiness (EN 933-3) indices were calculated according to reference standards for natural and secondary aggregates. The abrasion and degradation resistance were evaluated through the "Los Angeles" test, according to the EN 1097-2 standard. The results of these tests on the different aggregate fractions are reported in Table 3, evidencing that the materials comply with the requirements defined in the technical specifications.

As previously stated in the Introduction, the PSV (Polished Stone Value) of the limestone coarse aggregates being below the threshold for wearing courses, for acceptance purposes the coarse limestone aggregate only may not be used in the mixture, but a coarse fraction with improved resistance to polishing must be included (so far, only basaltic aggregate), in any case. Thus, finding a recycled material that can substitute this fraction is of great importance.

Finally, the affinity of the aggregates with bitumen was evaluated according to the EN 12697-11 standard, annex C (boiling water test – considering 10 min of immersion), as there are significant percentages of silicon in the composition of both basalt and slags (equal to 15% for the latter). In Fig. 1 the related results for the virgin neat bitumen are shown. It can be noticed that both the basalt aggregates and steel slags exhibited extremely low affinity with bitumen (<15% even for limestone aggregate, characterized by higher porosity). Therefore, it was decided to proceed with the addition of an anti-stripping agent (AS): 0.3% of the bitumen weight was added to the materials studied and the affinity test was repeated. The results obtained with the AS are also shown in Fig. 1 and they evidenced the positive effect of the adopted additive, with a very significant increase of affinity. It should be clarified that this test was limited to virgin neat bitumen only, as it is the only binder used in this paper for producing mixtures with basalt or steel slags as a substitute for the coarse limestone fraction, while the Polymer Modified Binder (PMB) is intended for mechanical comparison purposes only.

2.2. *Bitumen*

In Table 4, the characteristics of the binders used for producing the mixtures to be compared are reported. The adopted PMB is a proprietary product, therefore the percentage of SBS was not known or specifically investigated in this study; nevertheless, the product is certified in compliance with the harmonized standards for bitumen modification with polymers adopted in Italy (EN 14023).

2.3. *Polymeric compound and additive*

As anticipated, for further improvements of the mixture performance, the mixtures studied in this research were modified using a polymeric compound (PC) of selected polymers, designed for commercial purposes. This compound is a mix of low-density polyethylene (LDPE) and ethylene–vinyl acetate (EVA) and other polymers with low molecular weight and medium melting point, which are found in semi-soft and flexible granules. According to literature and product indications, the PC was added to the mixture as 0.3% of the weight of the aggregates as it guarantees better performance of the asphalt mixes in the dry method modification, especially in terms of stiffness modulus, durability and both permanent deformation and fatigue resistance [8]. In particular, this dry addition was defined for improving the mechanical performance of the neat bitumen, which thanks to the PC was expected to exhibit similar performance to the PMB.

In addition, for the purpose of guaranteeing the perfect adhesion of bitumen to the aggregates, as resulting from the preliminary affinity tests shown in Fig. 1, an anti-stripping agent (AS) was added to the mixtures having as a coarse fraction basalt or steel slags (0.3% of the bitumen weight). This technique modifies the chemical structure of the bitumen extending the service life of the pavement and making it possible to obtain better workability, compaction, and high mechanical resistance. In this regard, specific tests were performed on the aggregates for evaluating improvements (EN 12697-11).

2.4. *Mix-design and performance tests*

The tests for mix design described below were performed on mixtures including different types of aggregates (limestone and mixtures of limestone and basalt or slags) and various percentages of bitumen. The optimal percentage of bitumen was derived from the Marshall test (EN 12697-34) and by means of the volumetric method based on a Superpave Gyratory Compactor (EN 12697-31), by varying this percentage between 4.5% and 6.3% of the aggregate weight. The mixtures containing basalt and slags also included 0.3% of the aggregate weight of PC and 0.3% of the bitumen weight of the AS.

Volumetric characterization of the mixtures, carried out to evaluate the void percentage (EN 12697-8) to be compared with those prescribed in the national technical specifications, was performed considering the theoretical maximum density (TMD) of the material (EN 12697-5) and the bulk density calculated through the hydrostatic weight method (EN 12697-6).

Further, during the compaction process by means of the Gyratory Compactor, the results obtained at N revolutions representing three field conditions: N1 initial compaction at the construction phase, N2, design compaction on site, in service, and N3, end-of-life compaction, were analysed and compared with thresholds set according to the type of mixture, road, and traffic. According to the Italian standards for this type of surface mixtures, the values of N1, N2, and N3 were fixed at 10, 140, and 230 gyrations, respectively.

Subsequently, the indirect tensile test, in accordance with to EN 12697-23, was carried out both after dry and wet conditioning. The ratio between the values obtained in these scenarios (ITSR) was calculated, providing useful information on the water sensitivity of the mixtures (EN 12697-12). The stiffness modulus of the mixtures, ITSM (Indirect Tensile Strength Modulus), was calculated by applying a cyclic stress into the specimen according to EN 12697-26C. Finally, a rutting test was carried out in accordance with EN 12697-22, at a temperature of 60° C, on prismatic specimens (300x400x40 mm) obtained by means of a Slab Compactor.

Table 1
Passing of the various aggregates.

Sieve opening [mm]	Filler	Sand 0/6.3	Limestone 4/12	Limestone 8/12	Slag 4/6	Slag 8/12	Basalt 4/8	Basalt 8/12
16	100	100	100	100	100	100	100	100
12.5	100	100	100	83	100	91	100	95
8	100	100	67	19	100	37	99	10
4	100	82	9	5	30	1	2	1
2	97	57	4	3	2	0	0	1
0.5	93	22	2	2	0	0	0	1
0.25	87	13	1	2	0	0	0	1
0.063	71	5	1	2	0	0	0	1

Table 2
Specific gravity of the various aggregates.

	Filler	Sand 0/6.3	Limestone 4/12	Limestone 8/12	Slag 4/6	Slag 8/12	Basalt 4/8	Basalt 8/12
Specific gravity [mg/m^3]	2.701	2.671	2.645	2.844	3.558	3.561	2.941	2.900

Table 3
Geometrical and mechanical characterization of the coarse aggregate fractions.

Characteristic	Limestone 8/12	Slag 4/6	Slag 8/12	Basalt 4/8	Basalt 8/12	Requirement	Units	Standard
Flakiness index (FI)	5	10	10	9	9	< 20	%	EN 933–3
Shape index (SI)	3	1	5	5	7		%	EN 933–4
Los Angeles abrasion (L.A.)	17	13	13	17	17	< 20	%	EN 1097–2
Polished Stone Value (PSV)	40		73		48	> 44		EN 1097–8
Percent Fragmented Face	100	100	100	100	100	>98	%	EN 933–5

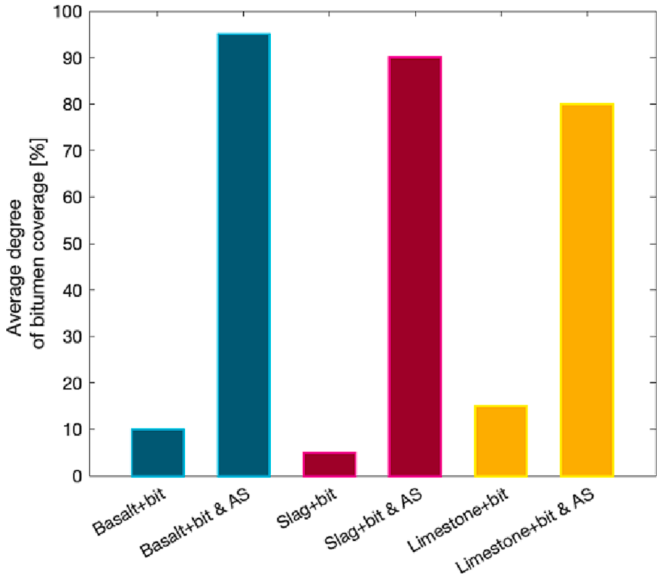


Fig. 1. Results of the aggregate and bitumen affinity test.

Table 4
Characteristics of the adopted bitumen.

Characteristic	Units	Neat bitumen 50/70	SBS modified pmb bitumen	Relevant standard
Specific weight	g/cm^3		1.04	EN 3808
Penetration @25 °C	dmm	68.9	50.8	EN 1426
Softening point	°C	49.9	88.5	EN 1427
Penetration index	–	−0.4	5.4	UNI 4163
Ductility	cm	> 100		EN 13398
Elastic recovery	%	n.a.	96	EN 13398
Viscosity at 160 °C	Pa • s	0.13	0.99	EN 13302
		After aging at RTFOT (EN 12607–1)		
Penetration @25 °C	dmm	64.7		EN 1427
Softening point	°C	53.8		UNI 4163
Viscosity at 160 °C	Pa • s		1.07	EN 13302

2.5. Life cycle assessment

For a comprehensive comparison of the different mixtures studied, an LCA was carried out to evaluate the environmental impacts related to their production in asphalt plants, considering the different sources of the materials involved and the various contributions of fuel consumptions. As in a previous study [43], a “cradle-to-gate” (i.e. stopped when the product is ready to leave the factory gate) approach in accordance with ISO 14040 [55] and ISO 14044 [56] standards was applied to estimate the environmental burdens related to the production stage of the asphalt mixtures, due to the contribution of this stage to the overall impacts.

For this specific analysis, the production is supposed to be carried out in a typical batch-mix asphalt plant: as a functional unit (reference or declared unit, DU) 1 metric ton of asphalt mixture for surface layer was considered, according to the different recipes as defined in the mix design phase. The Ecoinvent database was used for calculating the unitary impacts of virgin raw material extraction processing and manufacturing (background processes) [48].

As concerns energy consumption of the plant for production of the DU, based on a direct interview carried out in an asphalt plant in the geographical area of the study (eastern Sicily, in Italy), an average hourly production of 70 tons was considered, with production temperatures depending on the type of bitumen used, but in any case in the range 155–170 °C with no significant changes in energy consumption. Based on the data collected, the unitary consumptions are on average equal to 12 kg/DU, for the Low Sulphur Fuel (LSF) oil needed for heating the aggregate. Other relevant consumptions related to DU production are those needed for bitumen heating as well as those for moving and loading the aggregate in the hopper: these were set equal to those defined in previous studies [16,43], i.e. a Liquid Petroleum Gas (LPG) for bitumen heating 0.63 kg/DU and a diesel consumption for the loader equal to 0.19 kg/DU, obtained from primary data, too.

To take into account the impacts related to the transport of the raw materials to the plant, the transport distances were set as in Table 5, based on actual supplier locations and hauling distances to the plant. For extraction of LPG only, processing and manufacturing was considered, based on the Ecoinvent database, but no surface transport distance was considered, since it is supplied through pipelines directly to the plant.

Impact calculations were based on the impact categories and characterization factors of the EPD 2018 method. The following five emission substances were calculated according to the above method to describe the performance of the considered DU: 1) CO: carbon monoxide (g); 2) Pb: lead (mg); 3) Hg: mercury (µg); 4) NOx: nitrogen oxides (g); 5) PM10: particulates (g).

Furthermore, to extend the analysis and evaluate some reference values directly related to the effects of the DU on the environment, the following eight impact categories (as defined in EN15804) were evaluated:

1) AC: Acidification (kg SO_2-eq);
2) EU: Eutrophication (kg PO_4-eq);
3) GW: Global warming (100 years) (kg CO_2-eq);
4) PO: Photochemical oxidation (kg NMVOC-eq);
5) AD: Abiotic depletion (kg Sb-eq);

Table 5

Transport distances for the raw materials needed for DU production.

	Steel slags	Basalt aggregate	Limestone aggregate	Neat bitumen and diesel	PMB	PC	AS	LSF oil
km	46.0	42.0	0.3	11.7	44.4	1423.0	1423.0	30.0

6) AD*: Abiotic depletion, fossil fuels (MJ);
7) WS: Water scarcity (m^3 eq);
8) OD: Ozone layer depletion (kg CFC-11 eq).

3. Experimental results

In the following sections, to improve readability, the four mixtures are codified according to the following list:

- Control mixture with neat bitumen (CN)
- Control mixture with PMB (CPMB)
- Mixture with basalt (BM)
- Mixture with slags (SM)

3.1. Mix-design

The aggregate gradation of the mixtures was evaluated in terms of weight (Fig. 2). For all the four mixtures, the design curves fulfil the limits prescribed in the technical specifications defined by the national managing body for wearing courses. The composition of the different aggregate mixtures is given in Table 6. It is clear that CN and CPMB have the same aggregate skeleton.

Once the aggregate mixtures were defined, the optimal percentage of bitumen for the various mixtures was investigated, by means of the Marshall and volumetric methods. For this aim, according to the Italian standards, the optimal bitumen content was selected to maximize the performance of the mixtures in terms of the following criteria, for the surface layer:

- Stability [daN]: >1000
- Marshall ratio [daN/mm]: >300
- Voids @N1 [%]: 11÷15
- Voids @N2 [%]: 3÷6
- Voids @N3 [%]: >2
- ITS [N/mm^2]: 0.95÷1.90
- CTI [N/mm^2]: $\geq$ 75

The optimal bitumen content, with the percentages of the eventual additives (PC and AS), are reported Table 7.

In detail, for further investigating the volumetric properties of the mixtures, in Table 8 the results of the compactions performed using the Gyratory compactor, at the optimum binder content, are provided. Furthermore, Fig. 3 provides the measurement of voids and density during compaction of the specimens at optimum binder content. In detail, the density is provided in terms of the percentage ratio between the bulk specific gravity (Gmb) and the theoretical maximum density (TMD) values.

3.2. Indirect tensile strength

The results of the indirect tensile tests were obtained by testing specimens compacted by means of the Gyratory compactor up to N3 cycles. The statistical analysis on ITS (Indirect Tensile Strength) and CTI (Indirect Tensile Coefficient) – required by the national technical specifications and equal to CTI$= \frac{\pi}{2} \bullet \frac{ITS}{\epsilon_f}$, ($\varepsilon_f$ being the strain at failure) – was carried out by analysing three different specimens for each of the studied mixtures. Beyond the dry conditioning, for analysing the susceptibility of the mixtures to wet environmental conditions, other analogous specimens, for the various mixtures, were tested after conditioning in a thermostatic bath at 40 °C. In this case, the comparisons are performed in terms of ITSR (Indirect Tensile Strength Ratio), by evaluating the ratio between the ITS obtained on the specimens after dry and wet conditioning. The results of these tests are presented in Table 9.

3.3. Stiffness modulus

The stiffness modulus in terms of ITSM, in accordance with EN 12697-26C, was calculated at 5°, 20°, and 40 °C. The maximum deformation level for each pulse was equal to 4 μm at 5 °C, 7 μm at 20 °C, and 9 μm at 40 °C. After 10 preconditioning pulses, a peak time equal to 124 ms and 5 pulses was fixed. Three replicates were carried out for each of the two mixtures. For each specimen, compacted by means of the gyratory compactor at N3 cycles, 2 values of the stiffness modulus were obtained as a function of the position on which the measurement was

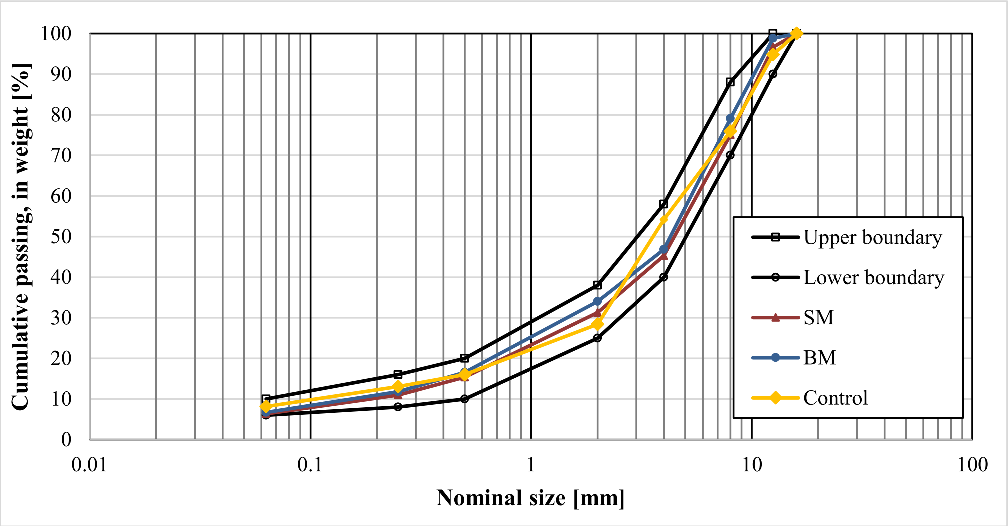


Fig. 2. Design gradation curves of the mixtures studied and comparison with the gradation upper and lower limits.

Table 6
Percentage of the different fractions used for the composition of the mixtures studied:

	Filler	Sand 0/6.3	Limestone 4/12	Limestone 8/12	Slag 4/6	Slag 8/12	Basalt 4/8	Basalt 8/12
% for CN and CPMB	7	17	37	39	0	0	0	0
% for BM	6	49	0	0	0	0	22	23
% for SM	6	44	5	0	8	37	0	0

Table 7
Optimum bitumen content and percentages of PC and AS for each mixture.

	Bitumen [% on agg. weight]	PC [% on agg. weight]	AS [% on bit. weight]
CN	5.5	–	–
CPMB	5.5	–	–
BM	5.2	0.3	0.3
SM	4.8	0.3	0.3

carried out. Fig. 4 reports the stiffness modulus in MPa of the various mixtures at different temperatures. In Table 10 the numerical values of the regression curves derived for the various mixtures, in the form $y = a \bullet e^{bx}$, are reported. In a logarithmic plot, these curves are seen as a straight line, with the intercept equal to *a* and slope equal to *b*.

3.4. Rutting resistance

In order to verify resistance to accumulation of permanent deformation, the mixtures were also tested, according to the Superpave approach, by means of a wheel tracker, in accordance with EN 12697–22. In this case, for comparison purposes, for the specimen

Table 8
Volumetric features for specimens obtained using Giratory compactor, at the optimum binder content.

	Gmb@N1 [g/cm^3]	Gmb@N2 [g/cm^3]	Gmb@N3 [g/cm^3]	v@N1 [%]	v@N2 [%]	v@N3 [%]	TMD [g/cm^3]
CN	2.270	2.538	2.579	14.5	4.4	2.8	2.538
CPMB	2.276	2.553	2.589	14.4	3.9	2.6	2.657
BM	2.079	2.381	2.422	18.4	6.6	5.0	2.549
SM	2.341	2.632	2.674	14.8	4.2	2.7	2.748
Thresholds				11%÷15%	3%÷6%	>2%	
	VMA@N1 [%]	VMA@N2 [%]	VMA@N3 [%]	VFB@N1 [%]	VFB@N2 [%]	VFB@N3 [%]	
CN	20.6	11.2	9.7	29.4	60.6	71.2	
CPMB	20.3	10.6	9.4	29.2	63.4	72.3	
BM	29.1	18.8	17.4	36.7	65.0	71.5	
SM	26.0	16.8	15.5	43.0	74.9	82.7	

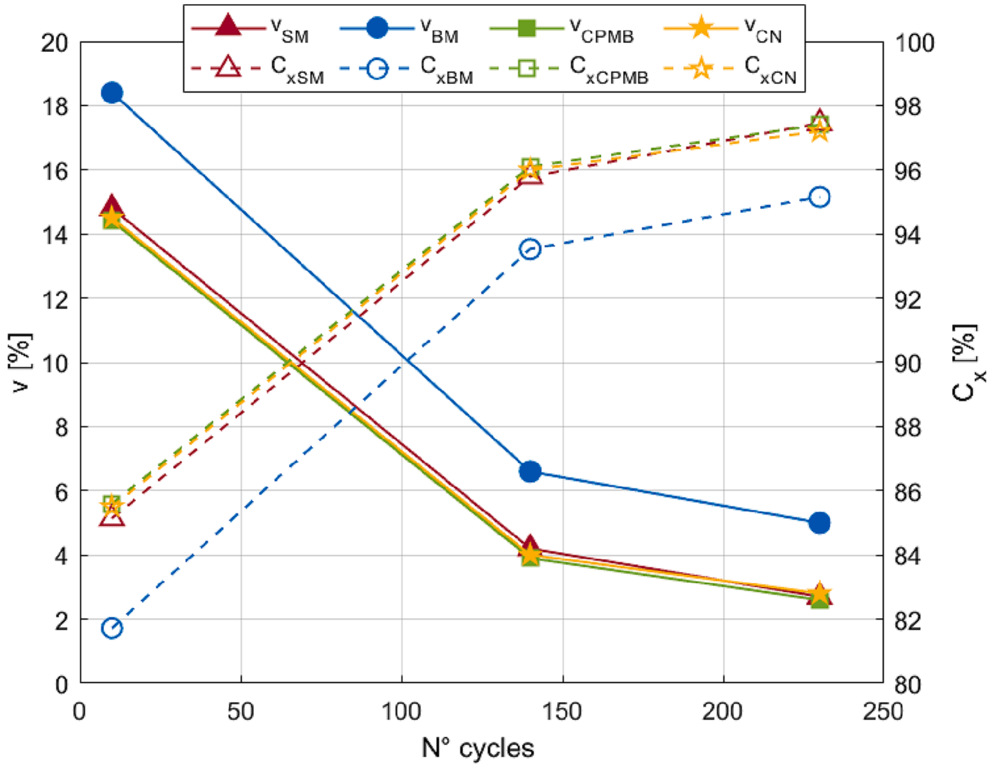


Fig. 3. Voids and density values during compaction using Gyratory compactor, at the optimum binder content for the four mixtures.

Table 9
Indirect Tensile Strenght Ratio of the mixtures.

	ITS [N/mm^2]	CTI [N/mm^2]	Delta ITS Vs CPMB [%]	ITS [N/mm^2]	CTI [N/mm^2]	ITSR [%]	Delta ITSR Vs CPMB [%]
		Dry				***Wet***	
CN	1.45	75	−9.9	1.01	51	70	−14.6
CPMB	1.61	80	0.0	1.33	83	82	0.0
BM	1.566	173	−2.7	1.523	177	97	+18.3
SM	1.640	188	+0.6	1.599	179	98	+19.5
Standard values	**0.95÷1.90**	**≥75**		**0.95÷1.90**	**≥75**		

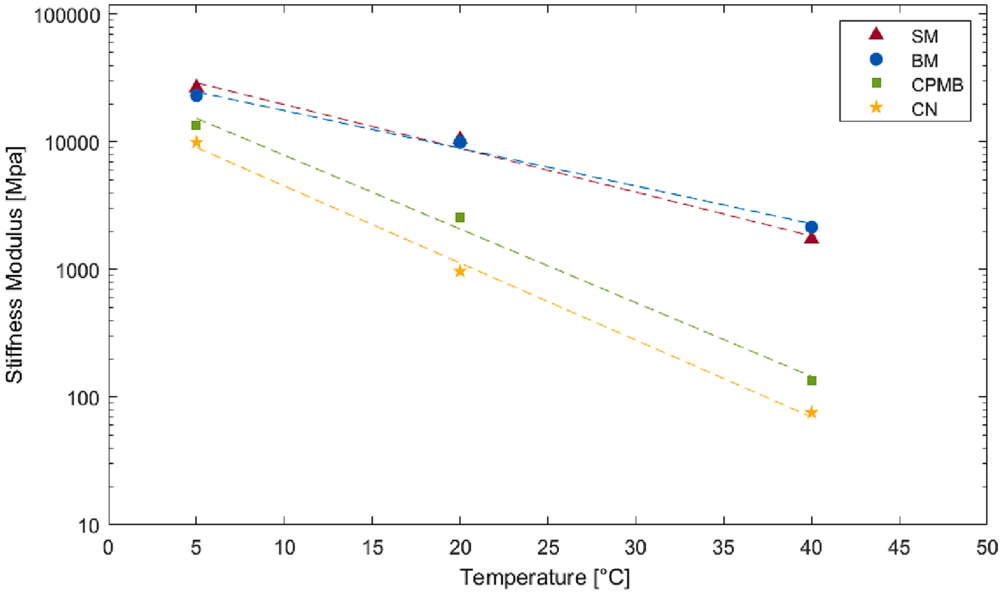


Fig. 4. Stiffness modulus of the various mixtures at different temperatures.

Table 10
Numerical values of the regression curves derived for the various mixtures.

	R^2	*a*	*b*
CN	0.9993	18159	−0.139
CPMB	0.9974	29753	−0.133
BM	0.9928	34775	−0.068
SM	0.9900	43280	−0.079

production using the roller compactor, the target density was derived by fixing the void ratio at a value of 5%, derived from the mix design results, in compliance with the specific performance of the various mixtures. In Fig. 5, the results of the total vertical deformation for the various mixtures are reported.

4. LCA results

In Figs. 6 and 7, the results of the LCA are provided. As anticipated in section 2.5, the assessment was performed with a cradle-to gate approach. In detail, Fig. 6 lists the emissions of the five reference substances (CO, Pb, Hg, Nox, PM10) for the four mixtures. Fig. 7 provides the impacts (AC, EU, GW, PO, AD, AD*, WS, OD) of the four mixtures studied. To increase the readability of the results, both the charts are presented in relative terms, with respect to BM, since this is the mixture with virgin components only that can be considered as a benchmark for both mechanical and environmental performances.

An analysis of the environmental effects of the various phases of the cradle-to-gate approach was also considered for the different mixtures. In particular, the process was split into three phases: raw material production, raw material transport, and mixture production. In the latter, the contributions due to the water consumption and the fuel transport are also included. Considering impacts and emissions of the single phases, relevant differences emerge only for raw material production and transport. In this regard, in Fig. 8, the values for the different variables are shown for the four mixtures for these two phases.

Furthermore, for a deeper analysis, the contribution of each mixture component on the various phases for the two improved mixtures (BM and SM) was investigated in terms of GW, AC, and AD impacts and PM10 emission, in the graphs provided in Fig. 9.

5. Discussions

The various experimental results performed in this research and presented in the previous sections evidenced the adequate performance of the mixture including slags, representing, for sure, an improvement with respect to CN and ensuring similar results to CPMB and to BM. In addition, this solution may preserve precious non-renewable resources (such as basalt aggregates) and reduce costs for the industries, as better described below.

Taking into account the various laboratory tests, the first considerations may derive from the experiments on aggregates. In this regard, shake and flakiness indices are not different between the two improved materials, i.e. basalt and slags (Table 3). These results may prove that the slags can ensure the same granular interlocking as basalt aggregates, i.e. good suitability for compaction, even with better crushing resistance, as shown by the Los Angeles tests, for which slags surpass basalt aggregates. Another advantage is related to the potential of the different aggregates for resisting polishing under the action of traffic: based on the PSV results (Table 3), steel slags can be seen as a good alternative to basalt aggregates for improving the resistance to polishing of mixtures with limestone aggregates.

Considering the affinity with bitumen, as anticipated, focused on the

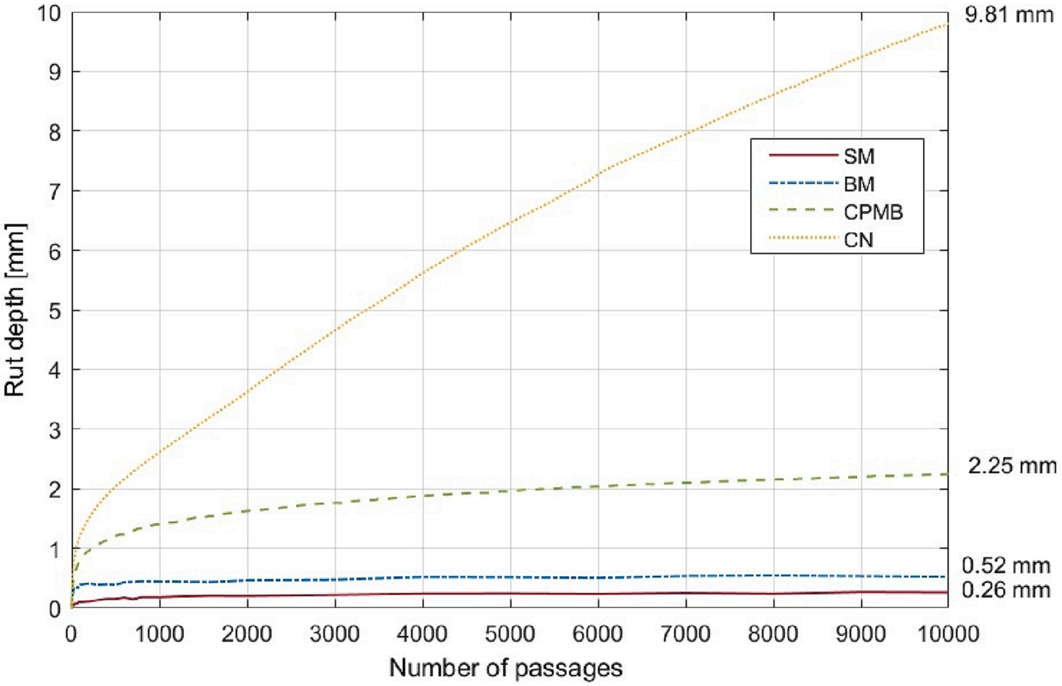


Fig. 5. Permanent deformation cumulated (rut depth versus the number of passes for the mixtures studied.

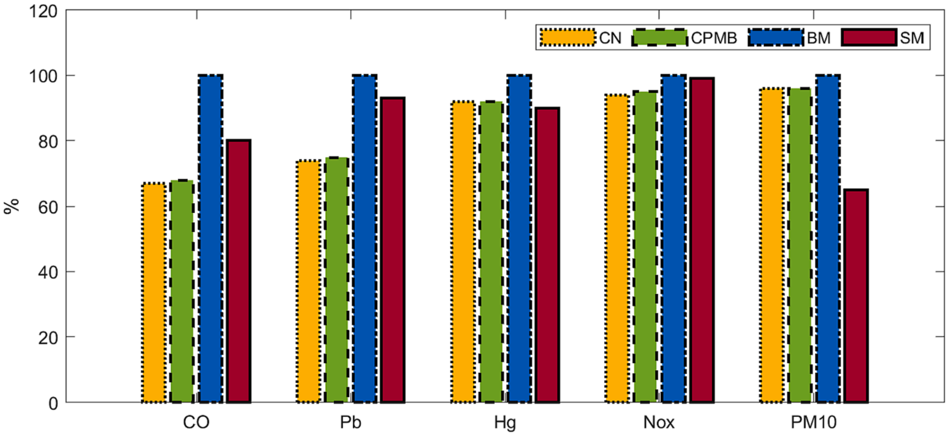


Fig. 6. Considered emissions for the four mixtures in relative terms, with respect to BM (BM = 100%).

binder used for the improved mixtures only (i.e. neat bitumen), the results of the water boiling test evidenced that both basalt and slag aggregates have low affinity values (up to 10%), lower than limestone (15%), due to remarkable percentages of silicon (Fig. 1). However, the addition of an anti-stripping agent resolved this issue, giving the mixtures more durability. The efficiency of this addition for both slags and basalt is more remarkable than for limestone, reaching affinity values with bitumen respectively of 95% and 90%, against 80 %.

The gradation curves of all the investigated aggregate mixtures were fully comparable in both weight and volume methods and in compliance with the existing standards (Fig. 2).

Considering the mix-design results, it is interesting to notice that the improved mixtures may determine a saving in bitumen (Table 7), too. While the control mixtures require 5.5% of bitumen, as the optimum binder content, BM and SM require respectively 5.2% and 4.8%. This reduction of the required bitumen content, more remarkable for the slags, may be only partially due to the slightly finer gradation for the control mixtures, and has to be related to the lower quantity of binder absorbed by slags and basalt when compared to that absorbed by limestone aggregates. Indeed, this determine major savings and greater environmental sustainability. Considering the aim of the paper, in the comparison between the two improved mixtures, the reduction of bitumen required by SM compared to BM – that exhibit almost identical gradation curves (Fig. 2) – is effective and useful for the practical applications.

By analysing the volumetric measurement during Gyratory compaction (Table 8), SM ensures a compaction level in compliance with the specification limits for the void ratio, at all the relevant cycles (N1, N2, N3) as also happens for the control mixtures. By contrast, the results for BM were not acceptable for the compaction levels corresponding to the initial in-situ compaction of the pavement (N1) and in-service compaction (N2). Moreover, SM again showed higher density values than BM and both CN and CPMB. The trends of voids and density for the various mixtures during gyratory compaction (Fig. 3) provide other interesting considerations. SM exhibits similar compaction curves to CN and CPMB, while BM evidences some difficulties in the compaction process, with higher void percentages and lower density values at all cycles. This result, probably due to the different shape characteristics

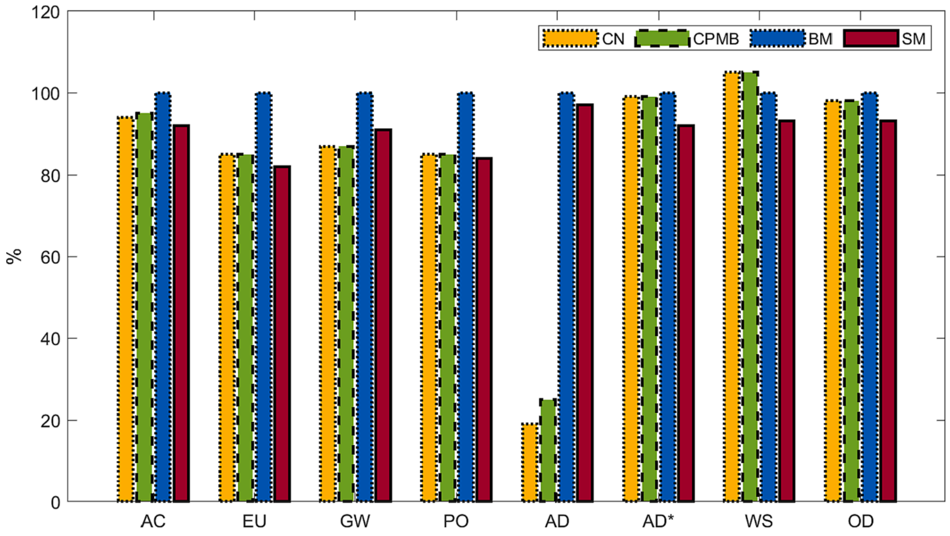


Fig. 7. Considered impact categories for the four mixtures in relative terms, with respect to BM (BM = 100%).

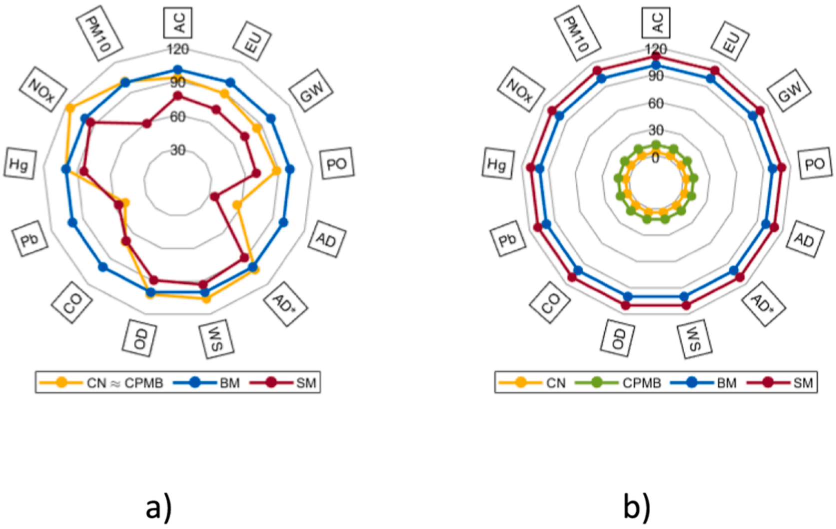


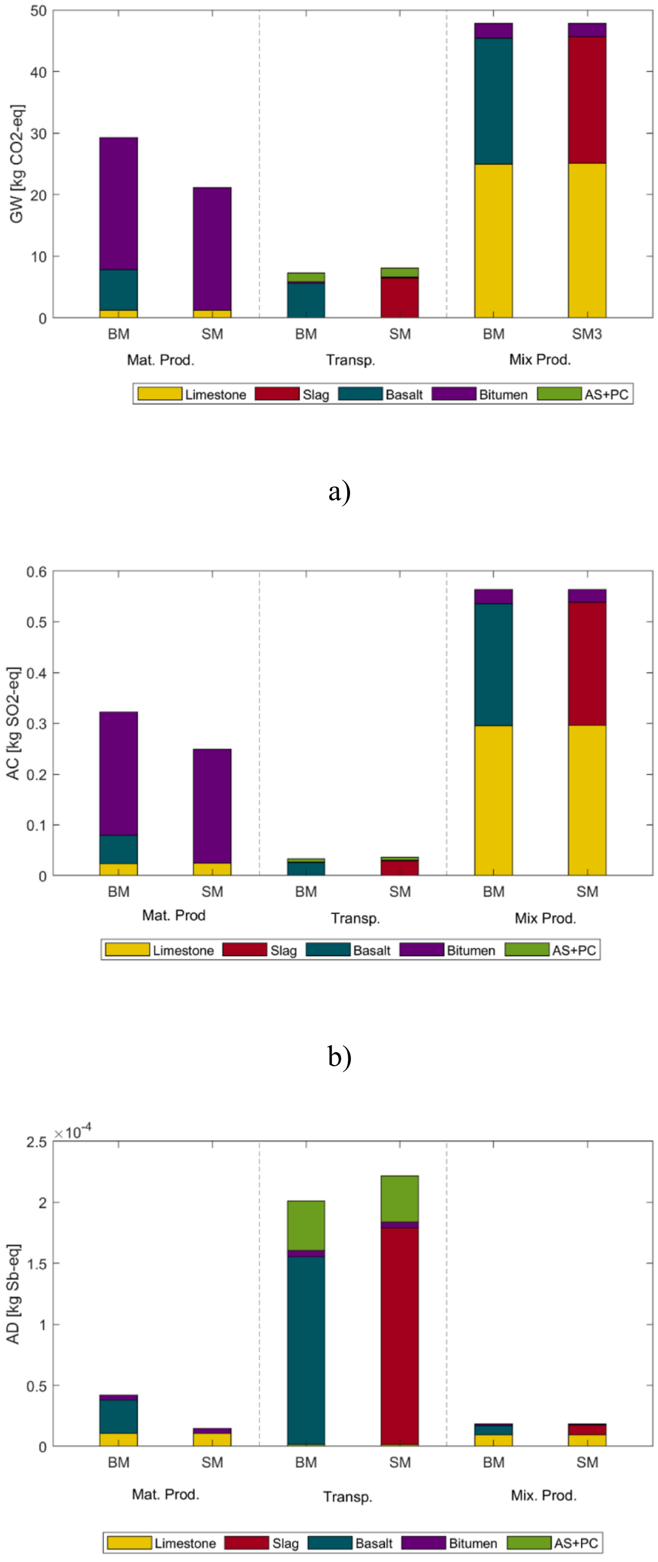
Fig. 8. Considered impact categories and emissions for the four mixtures in relative terms, with respect to BM (BM = 100%) for different phases: a) raw material production; b) raw material transport.

of the aggregates (Table 3), may represent another advantage of substituting basalt with slags, with positive benefits both in the construction and exercise phases.

In terms of ITS and ITSR, the advanced mixtures exhibited improved performance over the control mixture, and even over CPMB (Table 9). While for the dry conditioning tests SM and BM provided similar values to CPMB (almost identical for SM and 3% lower for BM), after wet conditioning the improved mixtures outperformed the CPMB, with values of ITSR up to almost 20% higher than CPMB (with absolute values of about 98%). Again, this evidences the remarkable performance of the improved mixture that, strategically, may ensure technical and economic sustainability advantages, especially when considering slags, as a reliable alternative to the traditionally adopted basalt aggregates. Indeed, there are no particular differences between the values of ITS, and therefore the use of slag in a high percentage does not invalidate the observed performance. For both the improved mixtures, no losses in performance capacity are found due to conditioning in a wet environment, with an ITSR value of 98% for SM and 97% for BM.

Analysis of the stiffness modulus results is very interesting. First, it is absolutely evident that both the improved mixtures provide much higher values at all temperatures (Fig. 4). Moreover, as is shown by an analysis of the b coefficients (slope of the straight lines) in Table 10 (almost halved for BM and SM compared to CN and CPMB), the straight lines of the improved mixtures are not parallel to those of the control ones, but both the improved materials have a lower slope, thus proving lower thermal susceptibility. SM and BM showed very similar behaviour at all the testing temperatures.

Other major benefits emerge from an analysis of the rutting tests (Fig. 5), performed at 60 °C in accordance with the relevant standard, for extremizing the test conditions. In this case, indeed, the two improved mixtures almost did not show any susceptibility to accumulation of permanent deformation, reaching after 10,000 cycles a maximum deformation of 0.52 and 0.26 mm respectively for SM and BM. These results are remarkably more appreciable considering the results obtained for CN, which cumulated more than 9 mm after 10,000 cycles, and even for CPMB, which cumulated more than 2 mm deformation). It may be said that SM has a slightly lower performance compared to BM, which has lower accumulation of permanent deformations (Fig. 5), consistently with the results of the stiffness modulus at 40 °C (Fig. 4). However, the values obtained are significantly lower

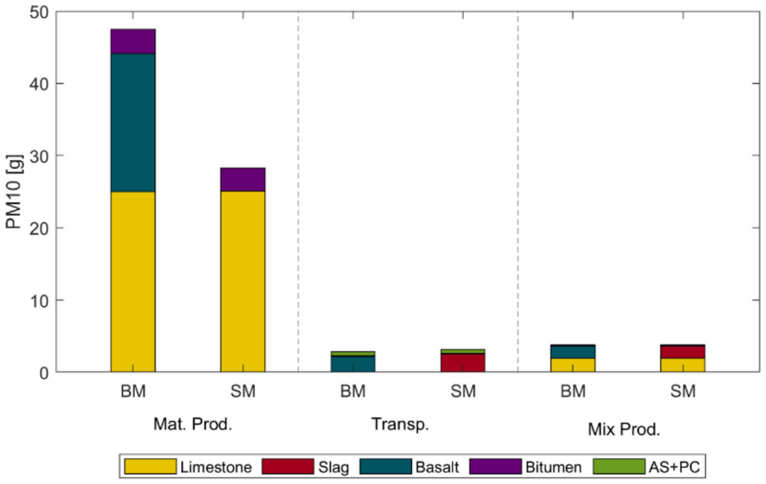


a)

b)

c)

Fig. 9. Contribution of each material to impacts and emissions for the various phases (raw material production, raw material transport, mixture production) - BM vs SM: a) GW; b) AC; c) AD; d) PM10.



d)

Fig. 9. (*continued*).

than those generally recorded for traditional mixtures and for the considered control mixtures (it should be considered that deformations for SM and BM were not visually detectable by the operators). Even at high operating temperatures, the results obtained by the two mixtures, with respect to the accumulation of permanent deformations, are perfectly comparable. The experimental results prove the feasibility of substituting a PMB with neat bitumen with a dry addition of polymers, thus confirming the beneficial effects of the polymeric compound on the mechanical performance, as highlighted in previous studies [8].

From the LCA, it is evident that SM performs better than BM for all the emissions and impact categories considered in the study. When compared with the control mixtures with limestone only (CN and CPMB), SM provides better results for Hg - mercury – and PM10 – particulate-, in terms of emissions as well as for almost for all the impact categories (exception made for abiotic depletion, elements, which refers to depletion of non-living natural resources). As previously said, for mechanical purposes (resistance to polishing) mixtures for wearing courses must include a coarse aggregate fraction able to resist to the polishing effect of tyre: so far, the basalt aggregates are the only solutions and the proposed substitution with steel slags provides environmental benefits.

Considering the environmental effects of each phase, beyond the equal values for mixture production, significant differences are evident for both material production and transport (Fig. 8). For the latter, due to the very long transport distances of the adopted additives and the very close location of the limestone quarry (respect to basalt and slag), CN and CPMB ensure reduced impacts and emissions. However, as clear by the previous comparisons, these reductions are overbalanced by the huger values for the raw material production phase, in which SM exhibits very large environmental benefits for all the considered categories. According to the aims of the research, the most relevant comparison regards BM versus SM. In this regard, in Fig. 9, impacts and emissions for each phase and each mixture component (limestone, bitumen, slag, basalt, additives) are plotted for these two mixtures and some selected categories (GW, AC, AD, PM10). In detail, in almost all the comparisons, when the values for the two mixtures are not similar, SM overperforms BM. The most evident benefits are related, as anticipated, to the raw material production phase for all the selected categories, while, in the considered scenario, the transport phase is just slightly more critical for SM, especially in terms of AD.

In general terms, the provided results, here regarding asphalt mixtures for surface layers, are still in line with literature [25,26,29], evidencing the environmental advantages of the introduction of slag in asphalt mixture, especially when compared with basalt aggregates [38]. However, it should be underlined that considering the LCA features, specific differences cannot be avoided, due to the geographical and technological representativeness of the various studies and the heterogeneity of contexts and mixtures [16]. Obviously, different hypotheses and selection criteria of the various studies can also contribute to eventual variations in result details. Despite these considerations, however, the benefits of the slag adoption are confirmed and evident for the considered scenario.

By analysing the performed tests, the mixture including slags (45 %) was proved to effectively represent a convenient solution in practical applications, for its remarkable advantages in technical, economic, and environmental terms. Based on these outcomes and strengthened by the LCA evidence, this research can significantly contribute to encourage a progressive substitution of basalt aggregates, currently strictly required in current practice in the South of Italy for improving the performance of 100% limestone mixtures, with the slags, especially if locally available. Indeed, transport distance of the various materials still plays a relevant role [43], requiring performing specific analyses on local-basis, since long supply travels can limit the environmental advantages of specific materials, such as slags [29,38]. Moreover, as evidenced, probably an important contribution to the positive performance of the improved mixtures derived from the addition of the polymeric compound. Although its influence on the LCA can be not negligible, its adoption remains remarkable, thanks to the important benefits to the mixture, for ensuring the reduction in the needs of both virgin aggregates and binder. Further, currently a similar product, fully relied on recycled polymers, has been studying. Then, in future studies, the ecological version of the adopted PC will be similarly tested to verify whether it is able to guarantee the same mechanical improvements, with a total cut of the related emissions and impacts.

6. Conclusions

This paper has presented the results of several mechanical and environmental comparisons among various mixtures for wearing courses, some of which include waste materials, i.e. steel slags. In detail, two mixtures including limestone aggregates only and alternatively neat bitumen or a PMB were used as control mixtures, to evaluate the performance of two improved mixtures including coarse basalt aggregates or steel slags. The experimental results evidenced that the two improved mixtures outperformed the control ones and that the two improved mixtures exhibit comparable performances. Then, the mixture with slags may represent a very effective solution in practical applications, because of its remarkable advantages in technical and financial terms and also regarding sustainability. In fact, these advantages may support the substitution of basalt aggregates, currently widely considered in current practice in the South of Italy for improving the performance of 100% limestone mixtures, with slags. The adoption of steel slags may guarantee financial savings, as they are by-products of industrial processes (they were initially considered as waste), and thus are cheaper than basalt aggregates. Furthermore, in a sustainability perspective, slags should be treated and/or disposed of by the steel industries, while the production of basalt aggregates has huge consequences for the environment and resources. All these issues may be positively reduced by extending adoption of asphalt mixtures including slags, favouring circular economy processes that may ensure preservation of resources and ecosystem quality.

Finally, for enriching the analysis, in a further study a comparative economic analysis of the production and supply costs will provide other useful information for supporting decision makers and technicians in the planning and design phases.

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

Some of the data used in this study may be available from the corresponding author upon reasonable request.

Acknowledgments

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