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Mechanical and environmental performance of asphalt concrete with high amounts of recycled concrete aggregates (RCA) for use in surface courses of flexible pavements

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Abstract: Using aggregates from alternative sources has been considerably encouraged in recent decades. Reducing the consumption of natural aggregates from quarries (which have a substantial economic, visual and environmental impact) is increasingly a concern. These needs have led to the broader use of more sustainable aggregates, increasing the incorporation percentages and extending their use to more demanding pavement layers (e.g., surface). In order to prove the efficiency of recycled concrete aggregates (RCA) under such conditions, the "*CirMat*" project was developed. Among other works and tests, an asphalt concrete (AC) incorporating 52.3% RCA was characterized mechanically and environmentally. Empirical properties were evaluated (including the Marshall test and assessment of resistance to permanent deformation), as well as a life cycle assessment (LCA). The test samples were taken from mixtures produced in the laboratory and at a plant (after which they were applied on a construction site). Comparing the results with those obtained in a reference AC (with natural aggregates), it was possible to conclude that the performance of the AC with RCA was very similar. Therefore, using these aggregates at a high rate does not represent additional risks for bituminous mixtures and has lower environmental impacts in most categories.

Keywords: Asphalt concrete; environmental product declaration; life cycle assessment; Marshall test; permanent deformation resistance; recycled concrete aggregate; water sensitivity.

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1. Introduction

In recent years, various methodologies have been established to stimulate the circular economy and the implementation of green public procurement (GPP). The main objectives of these guidelines are to increase the reuse of materials and reduce the environmental impacts caused by state purchases, helping them to simultaneously achieve environmental and development policy objectives [1–3].

As the World Road Association (PIARC) [4] has also recently recommended (even without having analyzed the techniques that "minimize recovery time"), pavements should also be designed and built to be more resilient, taking into account not only traffic and climate changes but also using "innovative materials" and techniques.

Thus, for example, using recycled concrete aggregates (RCA) fits in perfectly with these policies. For these reasons, it is essential to continue developing the study and application of all materials that incorporate such aggregates, and their use must be better regulated/standardized.

In this regard, some standardisation systems already cover "nontraditional" aggregates and their complete characterization (as is the case with ASTM). For example, ASTM D6155 – 19 (“*Nontraditional Coarse Aggregates for Asphalt Paving Mixtures*”) specifies that the results obtained in the following test methods should be evaluated: grading (C136/C136M), unit weight (C29/C29M), soundness (C88/C88M), degradation (C131/C131M), expansion (D4792/D4792M), friable particles (C142/C142M), coating (D2489/D2489M), adherent coatings (D5711), fractured particles (D5821), leaching (EPA SW846 1311), and stripping (D4867/D4867M).

In pursuit of these crucial objectives, a project called "*CirMat*" [*https://cirmat.pt/en_GB*] was recently organized and developed for almost three years, leading to several relevant conclusions. This article describes the mechanical and environmental characterization of an “nontraditional” asphalt concrete (AC) with a high content of RCA (resulting from the processing of construction and demolition waste, CDW), suitable for use as a surface course and developed as part of the “*CirMat*” project.

The use of RCA has been reported in several works, especially in granular layers [5], but also in bituminous mixtures [6] and concrete, mortars, grouts, and so on [e.g., using recycled concrete fines (mainly non-reactive) as specified in EN 197-6:2023 standard]. In fact, these aggregates have already attracted interest for application in different layers and types of mixtures, mainly in bituminous base and binder courses [7], as well as in dense/semi-dense asphalt mixtures [8], in stone mastic asphalt (SMA) [9], and even in porous asphalt (PA) [10]. In the meantime, its use has been extended to a wide variety of production methods, namely cold asphalt mixes (CMA) [11], foamed asphalt mixtures (FAM) [12], warm mix asphalt (WMA) [13–15], in addition to “traditional” hot mix asphalt (HMA) [16–20]. However, it was also noted that its use in high percentages of incorporation in mixtures for surface layers has not been shared, with only two references describing laboratory studies [9,21].

With regard to the technical and environmental characterization of paving materials, several studies have recently been published on bituminous mixtures incorporating RCA [15,18,22,23], including some reviews that concisely systematize the knowledge at the time [6,7,24].

In the “*CirMat*” project, the environmental performance of these mixtures was measured through a life cycle assessment (LCA). This methodology evaluates the environmental impacts across all stages of a solution or product's life cycle, encompassing manufacturing, distribution, usage, recycling, and final disposal in a landfill, which parallels the processes involved in road pavement construction [25]. As already suggested in 2016 by the European Commission [2], one of the award criteria which should be used by contracting authorities derives precisely from the execution of an LCA (considered the most ambitious and complex criterion).

LCA is a valuable tool for estimating the resource depletion of asphalt mixtures containing recycled materials, aligning with the primary objective of utilizing recycled materials to minimize landfill waste and reduce material consumption [22,26]. Furthermore, when innovative materials and solutions are in development, using LCA tools enables the assessment of environmental impacts, measuring the benefits of reduced use of raw materials and non-renewable resources when incorporating recycled materials into adopted solutions [25].

In short, the hypothesis of increasing environmental sustainability and significantly reducing the consumption of aggregates in surface layers were the essential themes that motivated the research described throughout this article. To this end, the mechanical and environmental properties of the constituent materials used and the mixtures produced were determined and presented here. The test methods, equipment and respective procedures are also identified and described. The asphalt mixtures [with nominal maximum aggregate size (NMAS) of 14 mm (AC14)] were produced in the laboratory and at an asphalt plant (then applied to the surface layer of a road). The results achieved were also compared with those obtained in a reference or "traditional" AC14 for the surface.

2. Materials and Methods

2.1. Materials

2.1.1. Binder

The binder used to manufacture the asphalt mixtures studied was a traditional 35/50 paving bitumen. This bitumen had a needle penetration (at 25 °C) of 44 ×0.1mm (under the EN 1426:2015 standard) and a softening point of 52.9 °C (determined according to EN 1427:2015).

2.1.2. Natural aggregates (NA)

The asphalt mixtures, designed for surface courses, used three complementary fractions of natural aggregates (0/4, 6/10, and 10/14 mm). The main characteristics of these fractions (granitoids) are shown in Table 1.

Table 1. Natural aggregates (NA) – Geometrical and physical properties (0/4, 6/10, 10/14 fractions).

Property	Standard	NA 0/4	NA 6/10	NA 10/14
Methylene blue value, MB_F (g/kg)	EN 933-9	3.2	-	-
Particle density, ρ_a (Mg/m^3)	EN 1097-6	2.69	2.65	2.63
Water absorption, WA_{24} (%)	EN 1097-6	0.4	0.8	0.6
Flakiness index, FI (%)	EN 933-3	-	9	10
Shape index, SI (%)	EN 933-4	-	13	10
Los Angeles, LA (%)	EN 1097-2	-	-	29
Micro-Deval, M_{DE} (%)	EN 1097-1	-	-	14
Polished stone value, PSV (%)	EN 1097-8	-	-	58

2.1.3. Recycled concrete aggregates (RCA)

The recycled aggregates incorporated into the asphalt mix were processed from structural concrete. This processing included the obligatory pre-sorting and subsequent crushing and screening. Figure 1 shows some images of these aggregates after appropriate treatment before they are used in the asphalt plant.

(**a**) (**b**) (**c**)

Figure 1. Recycled concrete aggregates (RCA): (**a**) 0/6 fraction; (**b**) 6/14 fraction; (**c**) section observed under an optical microscope (Nicóis X).

After an exhaustive evaluation of the properties of these aggregates, it was found that the most critical parameters, shown in Table 2, are very similar to natural aggregates (except for water absorption).

Table 2. RCA – Geometrical, physical, and chemical properties for each fraction (0/6 and 6/14 mm).

Property	Standard	RCA 0/6	RCA 6/14	Specifications[1]
Sand equivalent, SE (%)	EN 933-8	71	-	-
Methylene blue value, MB_F (g/kg)	EN 933-9	0.2	-	$MB_{F\,10}$
Loose bulk density, ρ_b (Mg/m^3)	EN 1097-3	1.32	1.31	-
Particle density, ρ_a (Mg/m^3)	EN 1097-6	2.35	2.44	DV [2]
Water absorption, WA_{24} (%)	EN 1097-6	4.4	2.8	≤ 1 (surf)
Flakiness index, FI (%)	EN 933-3	-	5	FI_{20} (surf)
Shape index, SI (%)	EN 933-4	-	5	-
Los Angeles, LA (%)	EN 1097-2	-	29	LA_{30} [3] (surf)
Micro-Deval, M_{DE} (%)	EN 1097-1	-	12	$M_{DE\,15}$ (surf)
Polished stone value, PSV (%)	EN 1097-8	-	60	PSV_{50}
Affinity aggregate/bitumen after 24 h (%)	EN12697-11	-	40	DV [2]
Volumetric stability, S (%)	EN 1367-4	0.035		-
Acid-soluble chloride content, CL^- (%)	EN 1744-1 +A1	-	<0.001	-
Water-soluble sulphate content, SO_3 (%)	EN 1744-1 +A1	-	0.05	-
Total Sulphur content, S (%)	EN 1744-1 +A1	-	0.1	-
Light organic contaminants (%)	EN 1744-1 +A1	-	2.1	-

[1] In Portugal [27]; [2] DV = Declared Value; [3] Categories for granitoid rocks (*LA_{20}* for the others).

2.1.4. Filler

In the case of asphalt concrete with RCA, only the filler recovered at the asphalt plant (RF) was added to the final mix. However, in "traditional" asphalt concrete, which only incorporates natural aggregates (AC14-NA), it was necessary to add some "commercial" filler, NF (calcium carbonate). The properties of these fillers are shown in Table 3.

Table 3. New and recovered filler – Some geometrical and physical properties.

Property		Standard	NF [1]	RF [2]	Specifications [3]
Grading (cumulative % passing)	Sieves (mm) 2.000	EN 933-11	100	100	100
	0.125		99	93	85 – 100
	0.063		86	79	70 – 100
Average filler density, ρ_f (Mg/m^3)		EN 1097-7	2.59±0.05	2.68	DV [4]
Voids of dry compacted filler, Rigden, v (%)		EN 1097-4	30.0±1	39.8	$v_{28/38}$

[1] NF = New filler; [2] RF = Recovered filler. [3] In Portugal [27]; [4] DV = Declared Value.

2.2. Methods for characterization of asphalt concrete empirical properties

The asphalt mixtures studied were subjected to different tests to assess their performance in several parameters. The main test methods used during the work carried out to find the best mixes with these processed RCA are described below.

A particle size distribution, expressed as the mass percentages passing a specified set of sieves (base series + series 2, as defined in standard EN 13043:2002/AC:2004), was obtained following EN 933-1:2012 for each aggregate fraction and also for the aggregate mix.

Following the Marshall methodology, five percentages of bitumen were studied following the EN 12697-34:2020 standard. Four cylindrical specimens were molded for each percentage and compacted according to EN 12697-30:2018, applying 75 blows per side. These specimens were then immersed in a water bath, keeping the temperature at (60±1) ºC for 40 to 60 min, and then tested at the same temperature on a Marshall testing machine (Controls, Cernusco, Italy). In order to obtain the optimum binder content and other properties, in this Marshall test, the stability (S) and deformation (F) of the compacted samples were obtained for all the asphalt mixtures produced.

The water sensitivity of the asphalt concrete studied was determined by the indirect tensile strength ratio (ITSR), according to section D.3 of European standard EN 13108-20:2016 and respecting EN 12697-12:2018. The specimens were prepared following section

6.5 of EN 13108-20:2016, and their compaction was selected from Table C.1 of the same standard. Six cylindrical specimens were molded with the same number of blows used in Marshall specimens (2×75). After appropriate conditioning, both groups of specimens (dry and wet) were tested on the same compression testing machine identified above (according to EN 12697-23:2017). The index of retained stability (IRS) was also evaluated according to the CRD-C 652-95 procedure (formerly MIL-STD-620A, Method 104) [28].

The resistance of the specimens to permanent deformation was determined using the wheel-tracking test (WTT) in accordance with EN 12697-22:2020. The test conditions were selected from Table D.1 of EN 13108-20 - reference D.1.3: small size device - procedure A (in air, at 60 °C) with a test duration of 10,000 cycles. The slabs (with a volume of $\approx 30 \times 30 \times 4$ cm^3) were prepared following section 6.5 of EN 13108-20, and their compaction conditions (used in a roller compactor, Matest, Treviolo, Italy) were selected from Table C.1 of the same standard. The porosity of the specimens was also specified following section D.2. With these conditions, the parameters obtained on a small-size device were the mean rut depth in the air (RD_{AIR}), the mean proportional rut depth in the air (PRD_{AIR}), and, finally, the wheel-tracking slope also in the air (WTS_{AIR}).

2.3. Life Cycle Assessment (LCA)– methodology and scope of the study

The Life Cycle Assessment (LCA) methodology adopted for the asphalt mixtures studied in this work was based on the guidelines from standards EN ISO 14040:2006 and EN ISO 14044:2006/A2:2020. A comparative LCA study was conducted aiming at assessing the environmental impacts of two asphalt mixtures throughout their life cycles: a conventional asphalt mixture AC14 surf 35/50 with natural aggregates (AC14-NA) and an asphalt mixture AC14 surf 35/50 incorporating recycled concrete aggregates (AC14-RCA).

This study encompasses several vital phases, namely goal definition and scoping, inventory analysis, and impact assessment (calculated using the "*EN 15804 + A2 Method V1.02/EF 3.0 normalization and weighting set*" method on *SimaPro* software version 9.3.0.3.), evaluation and interpretation. In this context, the environmental assessment for the asphalt mixtures used the "cradle to gate" approach, i.e., it includes only stage A, with modules A1-A3, according to EN 15804:2012+A2:2019/AC:2021.

In this environmental assessment, great importance was given to selecting and characterizing data quality, representativeness, and reliability. In the various phases under study, specific and primary data provided by the dst, S.A. company (producer of the mixtures) were preferably used. When this was impossible, generic data from the *Ecoinvent 3.8* database, the Ecoinvent European Life Cycle Database (ELCD), certified environmental product declarations (EPD), legal limit values, and other sources were used.

Additional information regarding the methodologies, model development, and calculations carried out in this research study is presented in the subsequent sections.

2.3.1. Goal definition

The paving industry has a long way to go to become more sustainable. So, the main goal of this LCA was to investigate and compare, from a life cycle environmental perspective, the main impacts of producing a conventional against an eco-asphalt mixture with recycled concrete aggregates. This assessment raised awareness of the significance of expanding the environmental and economic boundaries of a life cycle assessment system.

2.3.2. Functional and declared unit

The functional unit is the foundation for the system under investigation. It provides a point of reference for adjusting input and output data throughout all the product or service life cycle phases [25], used to compare different systems with the same utility for the same function.

However, in this research, a declared unit was employed instead of a functional unit because the scope of the LCA study does not encompass all stages of the product life cycle. Thus, the declared unit of all asphalt mixtures studied in this work refers to manufacturing one metric ton (1 metric ton) of this material.

2.3.3. Technical description of the product and normative references

Besides considering the standards relating to the technical specifications for producing and evaluating the asphalt mixtures, different standards were considered in this paper for the development of the LCA study, namely EN 15804:2012+A2:2019/AC:2021, EN ISO 14040:2006 and EN ISO 14044:2006/A2:2020. Standard ISO 14025:2009 was also used to develop the recycled mixture's EPD.

The system description and boundaries were expressed according to the recommendations given in different product category rules (PCR) related documents, namely:

1. Draft European technical specification number CEN/TC 227/WG 1 N2357;
2. "*Guidance document for preparing PCR and EPD for Asphalt Mixtures*"–EAPA (2017);
3. Product category rules. NPCR 025. Part B for Asphalt – EPD-Norge (2022).

2.3.4. System description and boundaries

The LCA models the life cycle system of a product with one or more defined functions. The systems of the products are divided by unit processes linked with the environment by elementary fluxes [26].

The system boundaries refer to the borders between the environment and the technological system [26]. Their definition is crucial to identifying the system's mass and energy flows that enter and exit. In the "cradle to gate" (A1-A3) approach used in this study of asphalt mixtures, the gate is defined as the point from which the asphalt mix is transferred to the truck for transportation to the consumer. The calculation of environmental impacts included all the primary inputs and outputs for the identified unit processes.

According to the standard EN 15804:2012+A2:2019/AC:2021, this LCA study covers the product stage (A) of the asphalt mixture's life cycle, as well as the extraction and processing of raw materials and waste/by-products (A1), the transport to the production plant (A2), and the production (A3) of the asphalt mixture.

Figure 2 presents the product life cycle phases and processes within the system boundaries of the asphalt mixtures studied in this work. However, the system boundaries of AC14-NA do not include the RCA processes.

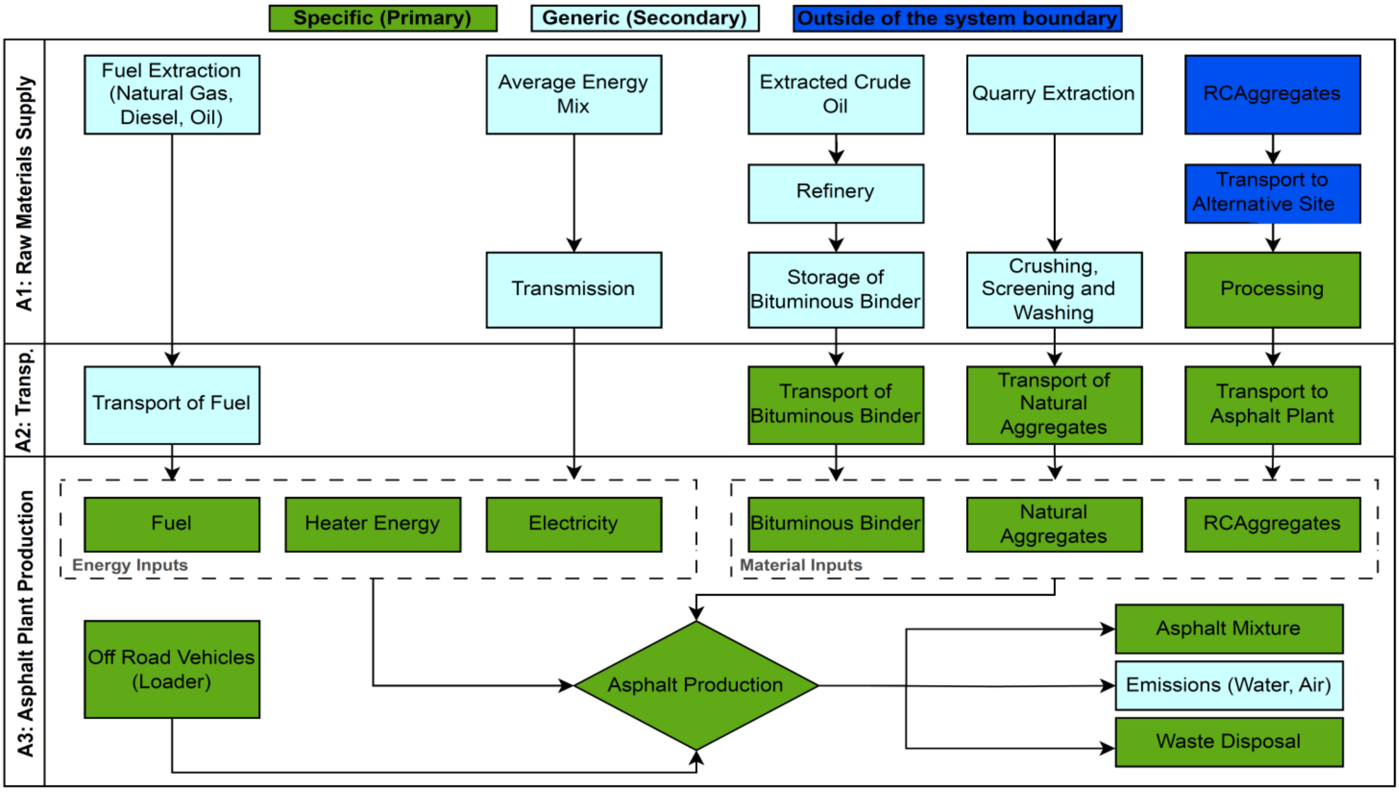
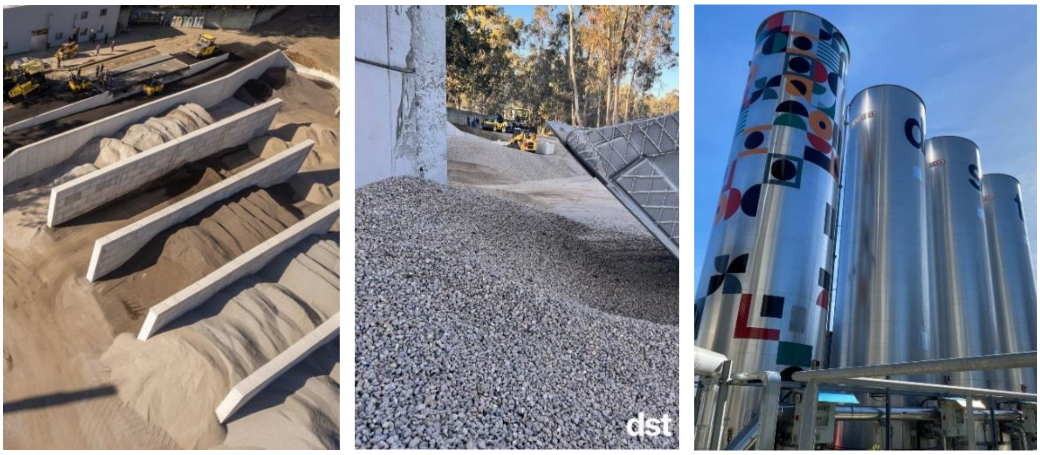


Figure 2. Flowchart of the system boundaries, processes, and data types for asphalt mixtures.

The composition of an asphalt mixture refers to the specific arrangement and proportion of constituent materials within the mixture, including natural, artificial, or recycled aggregates and the asphalt binder. The composition of the AC14-NA and AC14-RCA can be observed later in Section 2.4.3 (Table 4). Figure 3 presents the natural and recycled concrete aggregates and bitumen storage (using vertical tanks - the most appropriate).

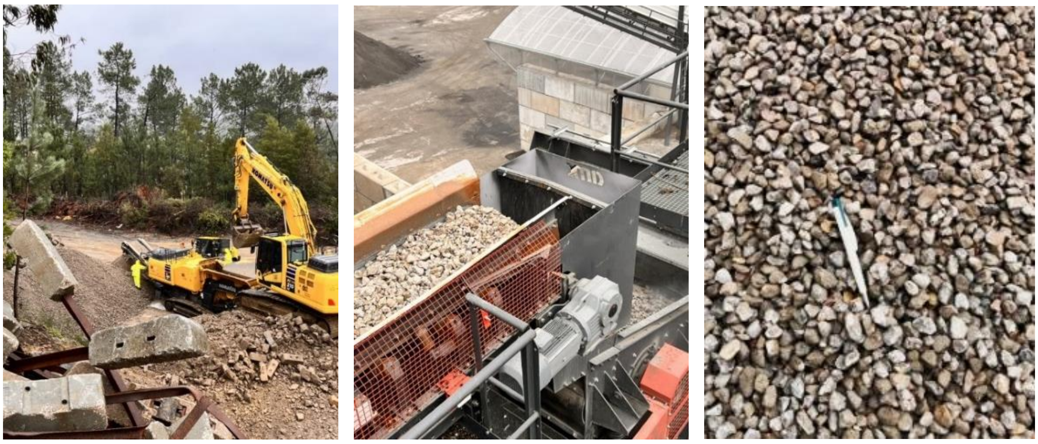


(**a**) (**b**) (**c**)

Figure 3. Raw materials: (**a**) natural aggregates storage; (**b**) RCA storage; (**c**) bitumen storage tanks.

Regarding module A1 of the product stage (raw material supply), it is essential to note that the AC14-NA only incorporated natural aggregates (NA). In contrast, the AC14-RCA incorporated 55.1% RCA and only used 44.9% NA (percentages without bitumen).

All the environmental impacts regarding the upstream processes of natural aggregates (extraction, crushing, and screening) were accounted for in module A1 of this LCA study. However, some specific allocation rules were considered for RCA, which must be explained in detail. The upstream impacts of RCA's previous life cycles, including product/manufacturing, transport, and use, are excluded from the system boundary. So, only the impacts associated with the RCA preparation processes for use in the asphalt mixture are considered within the system boundary. Thus, the processing of the RCA (reception, crushing, screening, and stocking) to become ready-to-use as aggregate (Figure 4) was included in module A1 of the system boundary.



(**a**) (**b**) (**c**)

Figure 4. RCA processing: (**a**) crushing; (**b**) screening; (**c**) stocking.

Module A2 includes transporting the raw materials to the asphalt plant. Also, the transportation between the RCA processing site and the asphalt plant must be included.

However, the company has a waste treatment and processing facility within its premises, so RCA's transport-associated environmental impact was considered null.

Module A3 represents the asphalt mixture manufacturing process in a batch asphalt plant (Figure 5). This module includes the production of asphalt and all waste processes up to its end-of-state or disposal during the product stage.

(**a**) (**b**) (**d**) (**e**)

Figure 5. Asphalt mix production and laying processes: (**a**) conveyor belt system; (**b**) asphalt plant; (**c**) asphalt mix with RCA; (**d**) spreading the mixture on a surface course; (**e**) infrared (IR) image of the same layer for temperature control; (**f**) appearance of the surface layer after exposure to heavy traffic for eight months.

2.3.5. Collected data

This LCA study includes all available data directly associated with the production processes of the asphalt mixtures. However, according to the EN 15804 standard, this study did not consider the processes meeting the cut-off criteria of 1% energy and mass use of the unit process. Upstream impacts of extraction, production, and manufacturing of materials not consumed in the asphalt mixture production (e.g., headquarters operations and water consumption in the administrative areas) were considered part of the plant infrastructure and, therefore, excluded from the system boundary.

The inventory data needed for an LCA study is categorized as primary or secondary. Primary data is information acquired expressly for a particular research endeavor through direct measurement, estimation, or computation from the primary source (i.e., specific data provided by the asphalt producer). In opposition, secondary data comprises general or typical data gathered from existing literature [29], fulfilling prescribed data quality characteristics for precision, completeness, and representativeness. More precisely, the primary data include: (1) the mix-design of the asphalt mixtures, (2) the annual natural gas consumption, (3) the annual electricity consumption, (4) the production and life period of the batch asphalt plant, (5) transportation distances; and (6) vehicles fleet composition.

Regarding the upstream processes (raw materials, fuels, auxiliary materials, and off-site transports) outside the manufacturer's purview, secondary data from databases (*Ecoinvent 3.8* and *ELCD*) and EPDs of the materials were used. Furthermore, preliminary information was added to existing processes in the *Ecoinvent 3.8* database throughout the LCA study to define specific cases to approach the Portuguese circumstances.

2.4. Life Cycle Inventory (LCI) Analysis

The life cycle inventory (LCI) phase involves gathering actual data and modeling the system. Apart from the data sources, it depends on the choice of several models for representing the processes examined within the various subsystems. Thus, the production data of AC14-NA and AC14-RCA, including material flows, processes, and emissions, were collected for all plant-specific factors. Additionally, secondary information on off-site processes was gathered, with detailed documentation of all data sources. The primary data collection was conducted in 2023 regarding the reference year 2022.

2.4.1. Geographic, time, and technological representation

The most appropriate databases were chosen considering this study's technology and geographical coverage. The primary data from the production company (dst, S.A.) geographically represent the situation of continental Portugal. For the generic or secondary information, the databases used to model the system in *SimaPro* software were, whenever possible, based on average European data (RER) without Switzerland. When these are unavailable, the rest-of-the-World (RoW) or Global data (GLO) databases were chosen.

In version 3.8 of *Ecoinvent*, the databases have been updated during the last decade and currently utilize data based on an average year. Manufacturer-specific data have been disclosed for the average production of 2022. The databases utilized to simulate the production processes, electricity generation, other energy sources, and other related processes are based on the actual physical reality and technology utilized.

2.4.2. Reliability, significance, and representativeness of sources

The data acquisition for developing this study was carried out according to EN ISO 14044:2006/A2:2020. The data sets were completed according to the system boundaries but within limits set by the criteria for excluding inputs and outputs (EN 15804). Furthermore, the data chosen were representative and up-to-date (i.e., at most five years).

The study ensured the reliability of database sources, such as the *Ecoinvent* and ELCD databases, widely recognized as transparent and reliable sources of LCI data.

2.4.3. Module A1 flows balance

Module A1 of LCI involves extracting and processing raw and secondary materials (EN 15804), including producing raw materials used in asphalt mixtures and ingredients used in the raw materials, starting with extracting material and energy resources from nature. This module also includes all transports of materials and energy upstream of the asphalt raw material production processes. Table 4 presents the input flows for each asphalt mixture (AC14-NA and AC14-RCA) in module A1 of the system boundary.

Table 4. Input flows of the studied asphalt mixtures associated with module A1.

Material/Activity		**Inventory description**	**Unit**	**Quantity**		**Source**
				AC14-NA	**AC14-RCA**	
Bitumen		Bitumen production final LCI - Eurobitume 2021 System, without infrastructure	kg	51	51	*Eurobitume 2021 - V3.1*
RCA		Modeled in this study	kg	-	523	-
NA		Gravel, crushed {RoW}∣ production ∣ Cut-off, S	kg	894	388	*Ecoinvent v3.8*
Limestone filler		Limestone, unprocessed {Row} ∣ limestone quarry operation∣ Cut-off, S Limestone, crushed, for mill {RoW}∣ production ∣ Cut-off, S	kg	19	-	*Ecoinvent v3.8*
Recovered filler		-	kg	36	38	-
Processing RCA	Reception and storing	Diesel, burned in building machine {GLO}∣ market for ∣ Cut-off, S	MJ	-	19.6	*Ecoinvent v3.8*
	Crushing	Diesel, burned in building machine {GLO}∣ market for ∣ Cut-off, S	MJ	-	42.0	*Ecoinvent v3.8*
	Screening	Diesel, burned in building machine {GLO}∣ market for ∣ Cut-off, S	MJ	-	11.7	*Ecoinvent v3.8*

The input flows comprised the quantities (masses) of each material (in kg) needed for producing one metric ton of asphalt mixture and the diesel consumption during the

RCA processing activities, transformed in energy (in MJ) of each specific equipment used for reception and storage, crushing, and screening one metric ton of RCA.

2.4.4. Module A2 flows balance

Module A2 included transporting the raw materials to the asphalt plant (the transportation of RCA between the alternative site and the asphalt production plant has zero allocation because the company has a waste treatment and processing facility within its premises). For all the materials transportation, a diesel construction truck (EURO 5) with a load capacity exceeding 32 tons was considered ("*Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S*").

Modeling the transportation of materials to the asphalt plant considers information about the type of lorry, maximum load, and distance from the supplier. The manufacturer provided that information, which was used to model the transportation of one tonne of each component, represented in t.km (transport of one tonne over the distance of one kilometer). Tables 5 and 6 present the parameters used to model the transportation of the materials to produce the AC14-NA and AC14-RCA mixtures.

Table 5. Transport distance for each material with module A2.

Material	Transport from	Transport to	Distance (km)
Bitumen	Supplier	Asphalt plant	64.3
NA	Supplier	Asphalt plant	20
RCA	Supplier	Processing site	0 *
	Processing site	Asphalt plant	0

* Outside of the system boundary.

Table 6. Input flow associated with module A2.

Material	Inventory description	Unit	Quantity		Source
			AC14-NA	AC14-RCA	
Bitumen	Transport, freight, lorry >32 metric ton, EURO5	t.km	3.30	3.30	*Ecoinvent v3.8*
NA	{RER}| transport, freight, lorry >32 metric ton,	t.km	17.86	4.70	*Ecoinvent v3.8*
Limestone filler	EURO5	Cut-off, S	t.km	0.38	-	*Ecoinvent v3.8*

2.4.5. Module A3 flows balance

Module A3 represents the asphalt plant's manufacturing processes of AC14-NA and AC14-RCA mixtures. Besides asphalt production, this module includes all processes up to the end-of-waste state or disposal of any residues generated during the product stage.

AC14-NA and AC14-RCA are hot-mix asphalt manufactured in a purpose-built plant where controlled amounts of aggregates of various sizes, previously blended and graded to meet a required specification, are dried and heated in a drum. The heated material continues to an elevator and is transported to the batch tower. The next step comprises screening using a hot screen where the heated aggregates are separated according to grain size and put into a weigh hopper. The material is mixed with bitumen and other components (if necessary) in the mixing chamber. When a homogeneous asphalt mixture is obtained, it is transferred with a skip hoist to an insulated storage silo before being loaded onto a truck.

This manufacturing process requires energy inputs in the form of electricity and fuels. Electricity provides the energy required to operate the asphalt plant and heat the tank storing the bitumen. In the company's asphalt plant, natural gas is used to heat and dry the aggregates. Diesel and oils are also required for on-site mobile equipment, such as front-end loaders, which feed the aggregates into the asphalt plant.

The thermal energy consumption of the asphalt plant is an essential parameter to calculate the environmental impacts of the asphalt mixtures in the study. Two methods were used to calculate this parameter.

Method A was chosen to determine the energy consumption of natural gas for heating the aggregates and the bitumen. Much energy is required to turn water into steam or dry the aggregate [30]. The thermal energy (TE) used to produce the various asphalt mixtures is determined through an energy balance represented by Equation 1. It represents the energy consumed by drying aggregate moisture, heating aggregate, heating stack gases, and casing losses. Thus, this equation considers variations in mixture composition, mixing temperature, aggregates' moisture content, raw materials' initial temperature, aggregates thermal properties, and ambient temperature. Table 7 shows the values of the parameters used to calculate the thermal energy.

$$TE = \begin{bmatrix} \sum_{i=1}^{M} m_{agg\,i} \times \ C_{agg\,i} \times (t_{mix} - t_0) + \sum_{i=1}^{M} m_{agg\,i} \times \ W_{agg\,i} \times C_w \times (100 - t_0) + \\ + L_v \sum_{i=1}^{M} m_{agg\,i} \times \ W_{agg\,i} + \sum_{i=1}^{M} m_{agg\,i} \times \ W_{agg\,i} \times C_{vap} \times (t_{mix} - 100) \end{bmatrix} \times (1 + CL) \quad (1)$$

Where,

TE - thermal energy (MJ/ton mixture) used to produce 1 ton of asphalt mixture;
M - total number of aggregate fractions;
$m_{agg\,i}$ - mass of aggregates of fraction i;
$C_{agg\,i}$ - specific heat capacity coefficient of aggregate fraction i;
t_{mix} - mixing temperature of the asphalt mixture;
t_0 - ambient temperature;
$W_{agg\,i}$ - water content of aggregates fraction i;
C_w - specific heat capacity coefficient of water;
L_v - latent heat required to evaporate water;
C_{vap} - specific heat capacity coefficient of water vapor;
CL - casing losses factor.

Table 7. Parameter values considered in Equation 1.

Parameter	**Definition**	**Unit**	**Quantity**	
			AC14-NA	**AC14-RCA**
t_0	Ambient temperature	°C	14	14
t_{mix}	Mixture temperature	°C	175	175
C_{agg}	Specific heat of NA	kJ/kg/°C	0.74	0.74
C_{RCA}	Specific heat of RCA	kJ/kg/°C	-	1.12
W_{agg}	Water content of NA	%/m_{agg}	3	3
W_{RCA}	Water content of RCA	%/m_{agg}	-	3
C_W	Specific heat of water at 15 °C	kJ/kg/°C	4.1855	4.1855
L_v	Latent heat of vaporization of water	kJ/kg	2,256	2,256
C_{vap}	Specific heat of water vapor	kJ/kg/°C	1.83	1.83
CL	General casing losses factor	%	27	27

Method B was considered to estimate the electricity consumption per ton of asphalt mixture. The electricity consumption was calculated by dividing the energy consumption (in kWh) by the production of asphalt mixtures (in tons) during 2022.

The diesel/oils consumption of the front-end loaders' movements was calculated as a function of these machines' time operation (seconds) to feed one ton of each aggregate to the asphalt plant.

The input flow associated with the energy consumption in module A3 of mixture AC14-NA and mixture AC14-RCA is presented in Table 8.

Table 8. Input flow associated with module A3.

Designation	Inventory description	Unit	Quantity		Source
			AC14-NA	**AC14-RCA**	
Loader movements of NA	Machine operation, diesel, ≥74.57 kW, high load factor {GLO}| | Cut-off, S	s	11	3	*Ecoinvent v3.8*
Loader movements of RCA	Machine operation, diesel, ≥74.57 kW, high load factor {GLO}| | Cut-off, S	s	0	8	*Ecoinvent v3.8*
Heating of the materials	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100 kW | Cut-off, S	MJ	250	296	*Ecoinvent v3.8*
Electrical equipment	Electricity, medium voltage {PT}| market for | Cut-off, U Adjusted 2021	kWh	1.1	1.1	*Ecoinvent v3.8*

2.5. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase aims to translate the input and output data from the life cycle inventory into quantifiable indicators representative of impact categories. These indicators serve as comprehensible metrics for specific environmental concerns that can influence ecological systems, human health, and the sustainability of natural resources. This study calculated the LCI results using the "*EN 15804 + A2/AC Method V1.02/EF 3.0 normalization and weighting set*" on *SimaPro* software version 9.3.0.3. Table 9 presents the core environmental indicators and the impact categories assessed.

Table 9. List of impact categories and indicators for the LCIA according to EN 15804:2012+A2:2019/AC:2021.

Impact category	Indicator	Unit
Climate change – total	Global Warming Potential, total (GWP-total)	kg CO_2 eq.
Climate change – fossil	Global Warming Potential, fossil fuels (GWP-fossil)	kg CO_2 eq.
Climate change – biogenic	Global Warming Potential, biogenic (GWP-biogenic)	kg CO_2 eq.
Climate change – land and land use change	Global Warming Potential, land use and land use change (GWP-luluc)	kg CO_2 eq.
Ozone depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H^+ eq.
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater or EPf)	kg P eq.
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-marine)	kg N eq.
Eutrophication terrestrial	Eutrophication potential, accumulated exceedance (EP-terrestrial)	mol N eq.
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC eq.
Depletion of abiotic resources – mineral and metals	Abiotic depletion potential for non-fossil resources (ADP-minerals & metals)	kg Sb eq.
Depletion of abiotic resources – fossil fuels	Abiotic depletion for fossil resources potential (ADP-fossil)	MJ, net calorific value
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived

3. Results and Discussion

3.1. Characterization of asphalt concrete mixtures empirical properties

3.1.1. Geometrical properties and compositions

The final compositions of the two AC14 surf mixtures studied in this work (conventional AC14-NA only with natural aggregates and new AC14-RCA with significant incorporation of recycled concrete aggregates) were obtained after several iterations and are described in Table 10. The resulting grading curves of the aggregates obtained for both

AC14-NA and AC14-RCA mixtures are presented in Figure 6, including the grading envelopes specified by the Portuguese public road concessionaire [27].

Table 10. Composition of the AC14 surface course mixtures with NA or RCA studied in this work.

Constituent materials		**Content (%)**	
		AC14-NA	**AC14-RCA**
Natural aggregates (NA)	10/14 fraction	24.6	14.2
	6/10 fraction	35.1	10.4
	0/4 fraction	29.6	14.2
Recycled concrete aggregates (RCA)	6/14 fraction	-	28.6
	0/6 fraction	-	23.7
Filler (commercial and/or recovered)	0/2 fraction	5.5	3.8
Bitumen	35/50 type	5.1	5.1

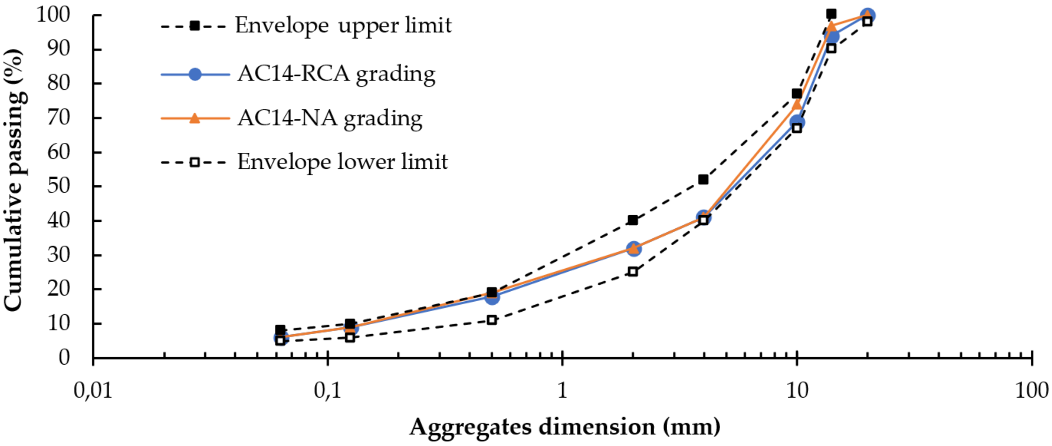


Figure 6. Aggregates grading curves of the two surface course mixtures studied in this work.

As can be seen, the proportions of RCA fractions (and filler) are different from those used in the case of the mixture with NA. However, the aggregate mix's final grading curve and the optimum bitumen content are practically the same.

3.1.2. Marshall test and void characteristics

The results obtained in the Marshall test for the final job mix formulas are shown in Table 11, which also includes the respective volumetric characteristics.

Table 11. AC 14 surf 35/50 with NA/RCA – Marshall test results and void characteristics.

Property		**Standard**	**AC14-NA**	**AC14-RCA**	**Specifications** [1]
Marshall test	Stability, S (kN)	EN 12697-30 EN 12697-34	20.9	20.2	$S_{min\,7.5} - S_{max\,21}$ [2]
	Flow, F (mm)		3.1	2.9	$F_{min\,2} - F_{max\,4}$
	Marshall quotient, Q (kN/mm)		6.7	7.0	$Q_{min\,3}$
Maximum density, ρ_{mh} (Mg/m^3)		EN 12697-5	2.461	2.394	DV[3]
Bulk density, ρ_b (Mg/m^3)		EN 12697-6	2.386	2.310	DV[3]
Air voids content, V_a (%)		EN 12697-8	3.1	3.3	$V_{min\,3} - V_{max\,5}$
Void in the mineral aggregate, VMA (%)		EN 12697-8	15.1	14.7	$VMA_{min\,14}$
Voids filled with binder, VFB (%)		EN 12697-8	76.3	77.5	-

[1] In Portugal [27]; [2] Categories for granitoid rocks ($S_{max\,15}$ for the others); [3] DV = Declared Value.

Apart from the fact that the densities (ρ_{mh} and ρ_b) are lower in the case of the mixture with RCA, the differences in the other parameters are not significant (in fact, they are similar in both mixtures).

3.1.3. Water sensitivity and index of retained stability (ITSR and IRS)

The water sensitivity of the specimens was evaluated through the ITSR. The result for the AC14-NA was equal to 87%, similar to the result of 86% for AC14 - RCA. These values are not high but align with results obtained in identical asphalt concrete mixtures made with other granitoid aggregates. However, the index of retained stability (IRS) was 93% for AC14-NA, while for AC14-RCA, it was 99% (which can be considered an excellent result).

The result observed in ITS_{wet} (group of wet specimens), 2,452 kPa, although affected by the presence of mortar in some of the RCA particles (which led to more significant water absorption), was not low. However, in the case of NA, the test result for the same group of wet specimens was only 1,513 kPa, which is much lower. This value could be related to the low affinity between the aggregate and the bitumen - a known limitation of the granitoid used.

Regarding the determination of the tensile strength (TS), it should be noted that the results obtained according to the European standards (EN) cannot be directly compared, for example, with US standards (ASTM). Among other essential differences, the EN 12697-12:2018 stipulates that the specimens must be compacted to obtain samples with porosities greater than or equal to the upper limit required in the field or using one of the following energy levels (in impact compaction, respecting EN 12697-30): 2×25; 2×35; or 2×50 blows (in addition, some Technical Specifications [27] also define a number of blows equal to 2×75, which was the same number used in the "*CirMat*" project). However, the ASTM D4867/D4867M–22 requires specimens to be compacted to (7±1)% air voids or with a level of voids equal to that expected in the field. As for the test temperature, EN 12697-12:2018 defines (15±1) °C (for asphalt mixtures which include binders with penetration ≤70 ×0.1mm, at 25 °C), while ASTM D4867/D4867M–22 specifies a higher temperature, equal to (25±1.0) °C.

3.1.4. Permanent deformation resistance

The results obtained in the WTT method to assess the susceptibility of the AC14-NA and AC14-RCA mixtures to permanent deformation at high temperatures (under a given rolling load) are described in Figure 7 and Table 12 (average values for both mixtures).

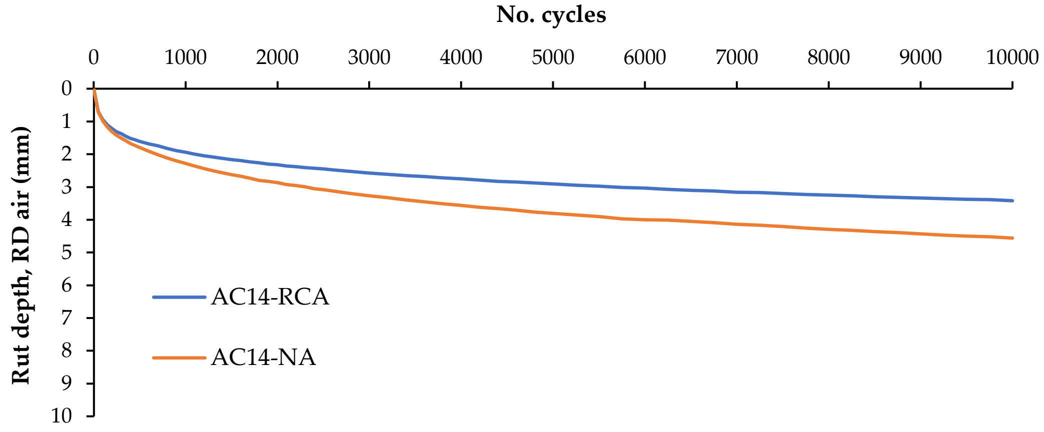


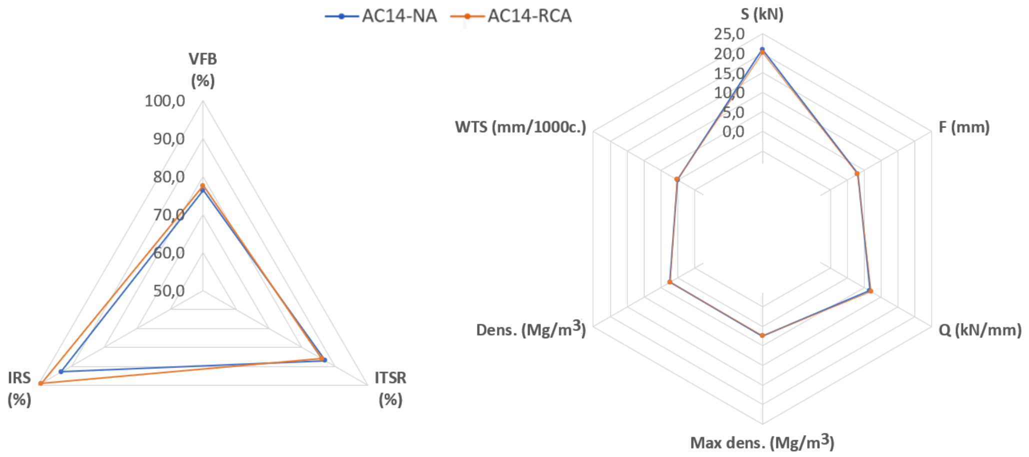
Figure 7. AC 14 surf 35/50 with NA/RCA – WTT – Rut depth.

Table 12. AC 14 surf 35/50 with NA/RCA – WTT results

Mixture	Bulk density (Mg/m³)	RD_{AIR} (mm)	PRD_{AIR} (%)	WTS_{AIR} (mm/10^3 cycles)
AC14-RCA	2.281	3.40	8.40	0.10
AC14-NA	2.290	4.60	11.20	0.15

In these WT tests, the results of the AC14-RCA were better than those achieved with the reference mixture. In fact, the WTS_{AIR} (0.10 mm/10^3cycles) is even substantially better than that observed in the AC14-NA (0.15 mm/10^3cycles).

Comparing all the most relevant results of the tests carried out, it can be concluded that AC14-RCA has very similar empirical properties to those exhibited by AC14-NA, as shown in the summary graphs in Figure 8. Although these values cannot be directly compared with the results found in the available literature on this subject (because the RCA used, the percentages of its incorporation, the types of bitumen and the job mix formulas are different), they are in line with the general trends pointed out there (for mixtures with some similarities).



(**a**) (**b**)

Figure 8. AC14 with NA/RCA - empirical properties: (**a**) VFB, IRS and ITSR; (**b**) other results.

3.2. Life Cycle Assessment (LCA) of both asphalt mixtures

3.2.1. LCA results of processing RCA for use in asphalt mixtures

The contribution of RCA to the impact categories comes 100% from stage A3, namely from the consumption and burning of fuel for the recycling process. These impacts need to be calculated and considered in the asphalt mixture impacts. The results of the life-cycle assessment of RCA are presented in Table 13, according to the core environmental impact assessment method EN 15804:2012+A2:2019/AC:2021.

Table 13. Core environmental impacts of the RCA.

Impact category	Unit	RCA
GWP - total	kg CO_2 eq.	6.71E+00
GWP - fossil	kg CO_2 eq.	6.71E+00
GWP - biogenic	kg CO_2 eq.	1.87E-03
GWP - luluc	kg CO_2 eq.	6.72E+04
ODP	kg CFC 11 eq.	1.45E-06
AP	mol H^+ eq.	7.02E-02
EP - freshwater	kg P eq.	2.44E-05
EP - marine	kg N eq.	3.10E-02
EP - terrestrial	mol N eq.	3.40E-01
POCP	kg NMVOC eq.	9.34E-02
ADP - minerals & metals	kg Sb eq.	1.03E-05
ADP - fossil fuels	MJ, net calorific value	9.23E+01
WDP	m^3 world eq. deprived	1.24E-01

Table 13 presents the environmental impacts of diesel consumption during the RCA processing. Notably, the most pronounced impact is observed in the GWP category, with total and fossil GWP values of approximately 6.71 kg of equivalent CO_2, indicating a substantial carbon footprint from greenhouse gas emissions. The impacts in other categories, such as ODP, EPf, and ADP minerals and metals, are relatively low. However, there are significant environmental concerns regarding ADP for fossil fuels, where RCA processing contributes substantially to resource depletion.

The results emphasize the need for more environmentally friendly and resource-efficient methods in RCA recycling. Given the high GWP and ADP values, minimizing diesel consumption and developing sustainable recycling practices are essential to reducing the global environmental footprint and increasing the ecological compatibility of incorporating RCA in asphalt mixtures.

3.2.2. LCA global results for asphalt mixtures

The purpose of the Life Cycle Impact Analysis is to use the results obtained in the inventory to assess the significance of potential environmental impacts, also providing information for the interpretation phase [31].

The modeling in the *SimaPro* software of all data collected in the LCI allowed us to obtain the set of impacts generated by producing 1 ton of asphalt mixture in Stage A. The results of the LCA were translated into impact categories according to the core environmental impact assessment method EN 15804:2012+A2:2019/AC:2021 and are presented in Table 14 for the mixtures with NA and RCA.

Table 14. Core environmental impacts of the AC14-NA and AC14-RCA mixtures.

Impact category	Unit	AC14-NA			AC14-RCA		
		A1	A2	A3	A1	A2	A3
GWP - total	kg CO_2 eq.	1.97E+01	1.96E+00	1.88E+01	1.48E+01	7.27E-01	2.22E+01
GWP - fossil	kg CO_2 eq.	1.95E+01	1.95E+00	1.88E+01	1.48E+01	7.26E-01	2.22E+01
GWP - biogenic	kg CO_2 eq.	1.31E-01	1.99E-03	8.13E-03	4.46E-02	7.05E-04	9.57E-03
GWP - luluc	kg CO_2 eq.	1.56E-02	7.02E-04	1.08E-02	4.17E-03	2.61E-04	5.79E-03
ODP	kg CFC 11 eq.	1.71E-06	4.66E-07	2.73E-06	1.87E-06	1.73E-07	3.30E-06
AP	mol H^+ eq.	1.50E-01	8.15E-03	2.23E-02	1.34E-01	3.03E-03	2.41E-02
EP - freshwater	kg P eq.	5.50E-03	1.22E-04	5.32E-04	1.50E-03	4.52E-05	4.30E-04
EP - marine	kg N eq.	3.78E-02	2.49E-03	5.26E-03	4.19E-02	9.24E-04	6.27E-03
EP - terrestrial	mol N eq.	4.31E-01	2.72E-02	5.69E-02	4.63E-01	1.01E-02	6.80E-02
POCP	kg NMVOC eq.	1.10E-01	8.75E-03	1.90E-02	1.21E-01	3.25E-03	2.62E-02
ADP - minerals&metals	kg Sb eq.	1.03E-04	4.48E-06	4.97E-06	2.30E-05	1.66E-06	4.52E-06
ADP - fossil fuels	MJ, net calorific value	2.46E+03	3.04E+01	3.16E+02	2.40E+03	1.13E+01	3.75E+02
WDP	m^3 world eq. deprived	6.79E+01	1.05E-01	5.05E-01	4.47E+00	3.89E-02	3.02E-01

Table 14 provides a comprehensive overview of the core environmental impacts of AC14-NA and AC14-RCA in Stage A. While the results for the mixture with NA offer valuable insights for understanding the environmental advantages of RCA incorporation in asphalt mixtures and will be used in the following subsection, this subsection predominantly concentrates on discussing the environmental impacts of the AC14-RCA mixture.

Figures 8 and 9 visually represent how each raw material and process contributes to impact categories within Stages A. These visual aids clearly understand the specific environmental contributions and highlight the elements that significantly influence each impact category.

A general analysis of Stage A's impacts (Figure 9) reveals that the most substantial contributions come from modules A1 and A3. It is primarily attributed to the production of bitumen, natural aggregates (NA) extraction, RCA processing, and heating of the aggregate and bitumen, as seen in Figure 10.

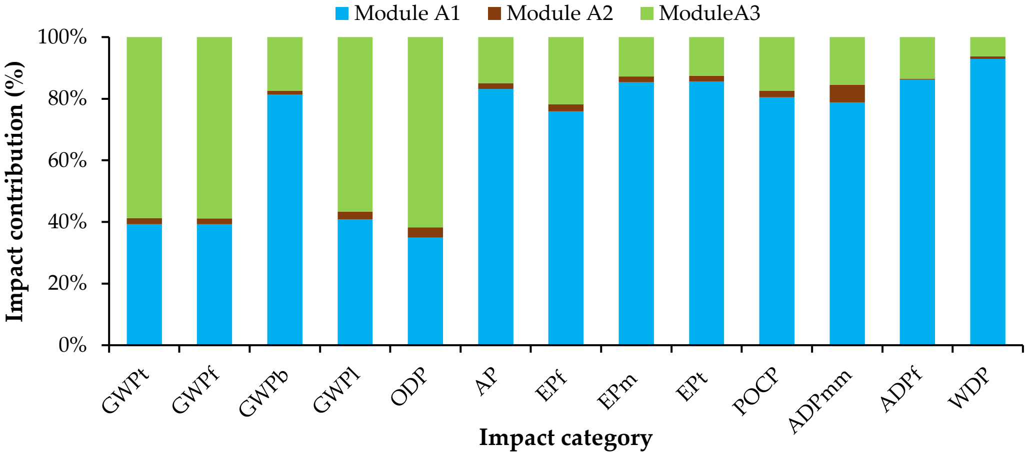


Figure 9. Core environmental impacts of the AC14-RCA in Stage A per module (A1, A2 and A3).

Bitumen's environmental impact is significant, particularly regarding its carbon footprint, as evidenced by the GWP, AP, and POCP categories. These findings highlight substantial greenhouse gas emissions, potential acidification, and ozone formation associated with bitumen production. Furthermore, bitumen notably influences Eutrophication Potential in marine (EPm) and terrestrial (EPt) environments, suggesting that its production can contribute to nutrient runoff in marine and land ecosystems.

The extraction of NA, a crucial component of asphalt production, reveals complex environmental impacts, contributing to various categories, including GWPb and GWPl, pointing to emissions and land-use changes related to global warming. Moreover, natural aggregate extraction influences EPf, implying potential issues related to nutrient runoff. ADP for minerals and metals underscores the resource-intensive nature of this extraction, emphasizing the depletion of non-renewable resources. Water Depletion Potential (WDP) also indicates its impact on water resources, highlighting the importance of sustainable water management practices.

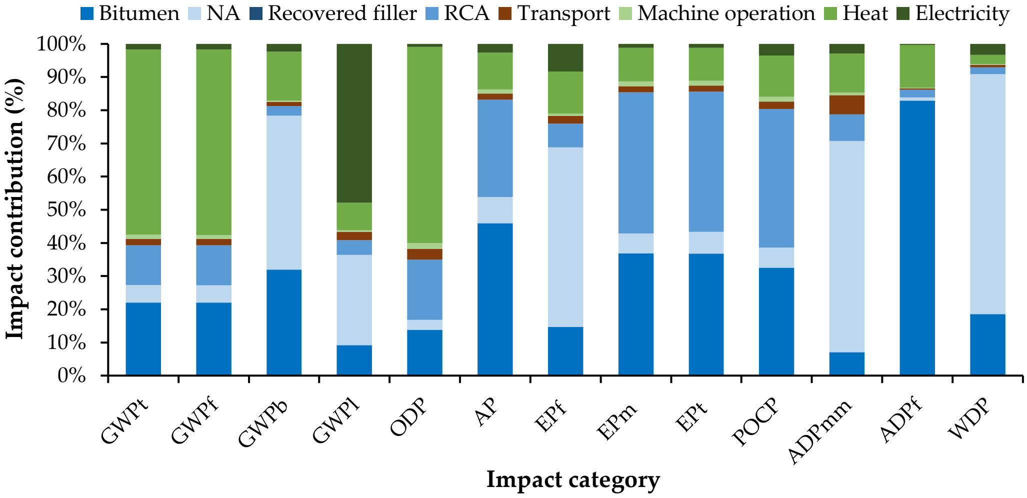


Figure 10. Contribution of each input flow to the core environmental impacts of the AC14-RCA in Module A.

While RCA's environmental impacts are linked to its recycling process, primarily the diesel consumption involved, it helps to reduce the environmental footprint of asphalt mixtures by replacing conventional aggregates with recycled materials. Thus, developing more efficient and sustainable RCA recycling methods is imperative to maximize these benefits.

The analysis of the heating process indicates a significant contribution to the overall carbon footprint, with substantial GWP primarily driven by emissions of greenhouse gases, particularly carbon dioxide (CO_2). Thus, measures to reduce the impact of this process on global warming and climate change shall be studied. Additionally, the heating process contributes to the ODP, highlighting the potential release of ozone-depleting substances, although in relatively small amounts. It highlights the importance of addressing ODP concerns and reducing GWP emissions to ensure a more sustainable and environmentally responsible approach to asphalt mixture production.

Examining the results presented for each impact category at this stage, the environmental benefits of replacing NA with RCA in the asphalt mixture production process become evident. Nevertheless, making direct result comparisons can be challenging due to the inherent unit variations within each impact category. Therefore, a normalization process was employed to standardize the data and facilitate result interpretation. Normalization quantifies the degree to which an impact category indicator deviates from a chosen reference point, whether relatively high or low. This approach furnishes valuable insights into the specific impact category outcomes concerning a selected benchmark. Each impact per emission unit was divided by the total impact of all substances within the same category per person and year (for Europe) to normalize the results. This standardization process mitigates unit incompatibility and enhances the clarity of conclusions, enabling a more coherent evaluation of the results, as shown in Figure 11.

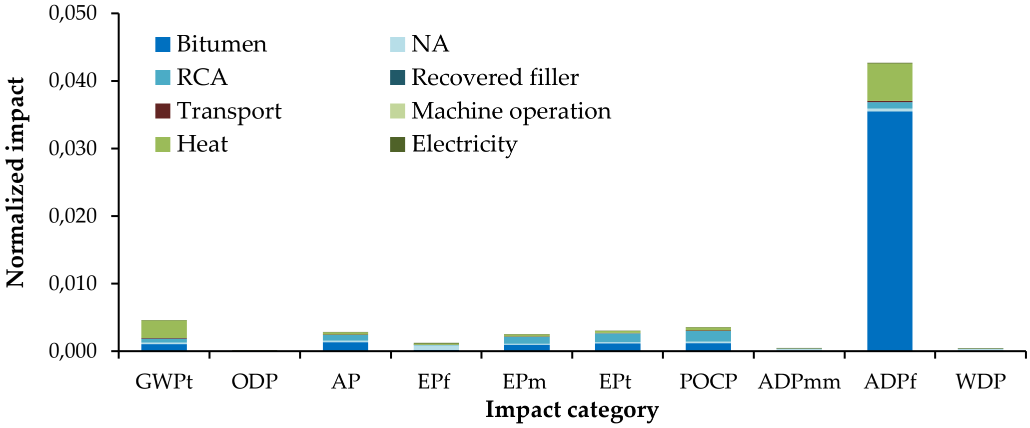


Figure 11. Normalization of the LCA results of the AC14-RCA.

It can be noticed that the most significant impact category is ADP-fossil fuels (ADPf), with bitumen emerging as the primary contributor. The data reveals that ADPf has an exceptionally pronounced impact compared to all other factors. This prominence in the normalized value directly results from assessing the average annual consumption per inhabitant across various products. Consequently, the graph illustrates that ADPf stands out as the most significant impact category related to using bitumen in producing asphalt mixtures.

3.2.3. Comparison between LCA impacts of AC14-RCA and AC14-NA mixtures

A comparative analysis was conducted to understand better the environmental advantages achieved by replacing NA with RCA in the asphalt mixture. This comparison assessed impact values for each category between a control mixture made exclusively with natural aggregates and the alternative mixture incorporating RCA. The analysis was limited to the mixture production phase since the direct influence of RCA incorporation is confined to this phase.

As previously mentioned, the normalization process simplifies the results and enhances their analytical clarity. Thus, the same normalization process was applied to the control mixtures to facilitate a meaningful comparison between mixtures. This approach ensures that the results from both control and RCA mixtures are presented consistently and standardized.

Table 15 and Figure 12 comprehensively compare the environmental impacts of the two asphalt mixtures. The impacts are assessed across various categories, highlighting the percentage reduction in environmental consequences when incorporating RCA.

Table 15. Comparison between the core environmental impacts of the AC 14 mixture produced with NA and RCA.

Impact category	Unit	AC14-NA	AC14-RCA	% decrease
GWP - total	kg CO_2 eq.	4.04E+01	3.77E+01	7%
GWP - fossil	kg CO_2 eq.	4.02E+01	3.77E+01	6%
GWP - biogenic	kg CO_2 eq.	1.41E-01	5.49E-02	61%
GWP - luluc	kg CO_2 eq.	2.71E-02	1.02E-02	62%
ODP	kg CFC 11 eq.	4.90E-06	5.34E-06	-9%
AP	mol H^+ eq.	1.81E-01	1.61E-01	11%
EP - freshwater	kg P eq.	6.15E-03	1.98E-03	68%
EP - marine	kg N eq.	4.55E-02	4.91E-02	-8%
EP - terrestrial	mol N eq.	5.15E-01	5.41E-01	-5%
POC	kg NMVOC eq.	1.38E-01	1.50E-01	-9%
ADP - mineral&metals	kg Sb eq.	1.12E-04	2.92E-05	74%
ADP - fossil fuels	MJ, net calorific value	2.81E+03	2.78E+03	1%
WDP	m^3 world eq. deprived	6.85E+01	4.81E+00	93%

The RCA mixture exhibits lower environmental impacts in most categories, highlighting its potential for enhanced sustainability. Compared to the NA mixture, the total GWP and its fossil fuel component are reduced by 7% and 6%, respectively. This reduction emphasizes the capacity of RCA to lower greenhouse gas emissions in asphalt production. Furthermore, the RCA mixture demonstrates a remarkable 61% decrease in biogenic GWP and a substantial 62% decrease in land use and land-use change (GWP - luluc).

The results also reveal a 93% decrease in the RCA mixture's Water Depletion Potential (WDP). This significant reduction in WDP highlights a crucial environmental advantage of using RCA in asphalt production. The high water demand associated with the extraction of natural aggregates significantly contributes to WDP, and by using RCA as an alternative, this resource-intensive phase becomes notably more sustainable.

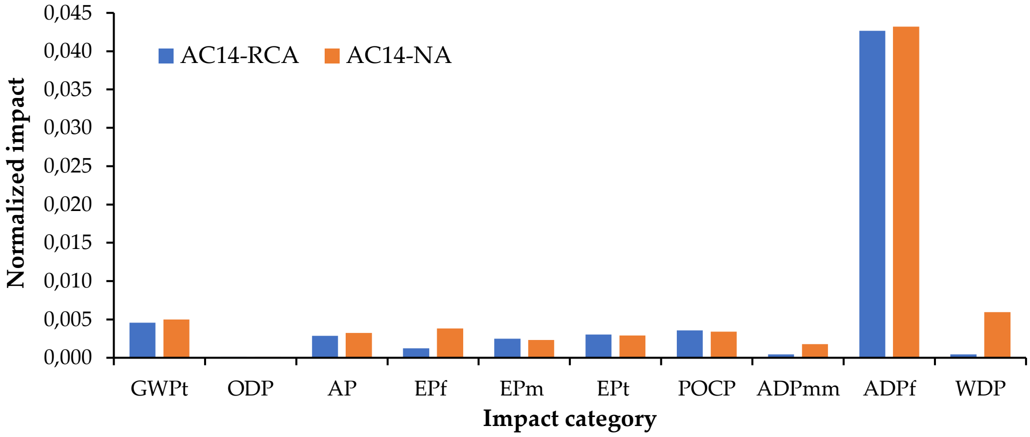


Figure 12. Comparison between the normalized results of the RCA and NA mixture.

However, it is crucial to recognize that for specific impact categories, i.e., Ozone Depletion Potential (ODP), Eutrophication Potential (EP) in marine and terrestrial environments, and Photochemical Ozone Creation Potential (POCP), the mixture with RCA exhibits higher environmental impact values. These results can be attributed to the RCA recycling process, which involves diesel consumption, significantly contributing to these specific environmental categories.

Therefore, finding sustainable and efficient methods for processing RCA is crucial to increasing its potential benefits in asphalt mixture production while reducing environmental concerns.

In fact, developing these sustainable recycling practices, especially on a large scale, can significantly alleviate the environmental impacts of asphalt mixtures. This analysis underlines the advantages of using RCA and highlights the need for more sustainable and resource-efficient recycling methods.

4. Conclusions and future work

This article describes the principal work on the mechanical and environmental characterization of bituminous concrete incorporating a high rate of recycled concrete aggregate, suitable for use in surface layers of road pavements. This application, whose industrial viability was confirmed during the CirMat project, increases environmental sustainability and significantly reduces the consumption of natural aggregates.

A comparison of the results obtained with those of a reference mix (produced only with natural aggregates) allows several conclusions to be drawn, the most important of which are the following:

- Except for water absorption, recycled aggregates can have properties very similar to those exhibited by natural aggregates;
- The composition of bituminous mixtures can also be similar;
- In the Marshall test and in the characteristics of the voids, only tiny variations were obtained: reductions of around 3% (in S, ρ_{mh}, ρ_b and VMA) and 6% (in F), while V_a increased slightly from 3.1% to 3.3%;
- When using natural aggregates of a granitoid nature, the water sensitivity assessed using the ITSR is similar, but when using the IRS, the result is better in the mixture with RCA (99% against 93%);
- The results in the assessment of resistance to permanent deformation were much better in the case of the mixture with RCA (35% lower in RD_{AIR}, 33% lower in PRD_{AIR} and 50% lower in WTS_{AIR});
- The data on environmental impacts suggests that incorporating RCA into AC can lead to overall reductions in several impact categories, including GWP, AP, EP, and WDP. On the one hand, nine indicators were improved (from 1% to 93%, with an average of ≈43%). On the other hand, only four indicators worsened slightly (the variation ranged from 5% to 9%, with an average of ≈8%).

Although some processes, such as aggregate extraction and bitumen production, contribute to strong environmental impacts, the benefits of using RCA outweigh these impacts, thus resulting in more sustainable and environmentally friendly production of asphalt mixtures. However, it is essential to consider each production facility's specific context and practices to assess the total environmental impact accurately.

In conclusion, the "*CirMat*" project has undoubtedly contributed to greater efficiency in the use of resources in the construction sector. As the bituminous mixture with RCA was produced and applied on a pavement, it was also possible to demonstrate the industrial viability of using this more sustainable material. These contributions will make it possible to achieve higher targets for the recovery of CDW and the promotion of secondary raw materials in more noble applications than those currently found in some construction projects.

Finally, disseminating knowledge from the activities carried out under this project will encourage more practical applications and boost future research. All this information could lead to a more in-depth assessment of the mechanical performance of bituminous mixtures with high rates of recycled aggregates, for example, by obtaining reliable correlations between the RCA properties, the stiffness/fatigue resistance of the mixtures and their permanent deformation resistance. Other relevant properties can also be determined in these mixtures, namely by assessing low-temperature cracking and friction after polishing, FAP (according to EN 12697-46:2020 and NP EN 12697-49:2022, respectively). Another critical assessment that could be included in future research is the validation of the mechanical performance of bituminous mixtures with RCA (for application in surface layers) after aging (essentially due to the incidence of ultraviolet solar radiation, UV [32]). For this purpose, a more comprehensive accelerated ageing simulator can be used, such as TEAGE [33], in which the samples are subjected to alternating periods of immersion in water/drying and exposure to UV radiation.

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Acronyms

The following acronyms are used in this manuscript:

AC	Asphalt concrete
AC14-NA	Asphalt concrete with NMAS of 14 mm and natural aggregates
AC14-RCA	Asphalt concrete with NMAS of 14 mm and recycled concrete aggregates
ADP	Abiotic depletion potential
AP	Acidification potential
CDW	Construction and demolition waste
EAPA	European Asphalt Pavement Association
ELCD	Ecoinvent European life cycle database
EP	Eutrophication potential
EPD	Environmental product declaration
EPf	Eutrophication potential, freshwater
EPm	Eutrophication Potential in marine environments
EPt	Eutrophication Potential in terrestrial environments
FAP	Friction after polishing
GLO	Global data
GPP	Green public procurement
GWP	Global warming potential

HMA	Hot mix asphalt
IR or UV	Infrared or ultraviolet radiation
IRS	Index of retained stability
ITS	Indirect tensile strength
ITSR	Wet/dry indirect tensile strength ratio
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NA	Natural aggregates
NF	New filler
NMAS	Nominal maximum aggregate size
ODP	Ozone depletion potential
PA	Porous asphalt
POCP	Photochemical ozone creation potential
PCR	Product category rules
PRD	Mean proportional rut depth
PSV	Polishing stone value
RCA	Recycled concrete aggregate
RD	Rut depth
RER	Regular Economic Report (EU)
RF	Recovered filler
RoW	the Rest-of-the-World
TE	Thermal energy
TS	Tensile strength
VFB	Voids filled with binder
VMA	Voids in mineral aggregate
WDP	Water (user) deprivation potential
WMA	Warm mix asphalt
WTS	Wheel-tracking slope
WTT	Wheel-tracking test

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