eman ta zabal zazu

Universidad del País Vasco
Euskal Herriko Unibertsitatea

BILBOKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE BILBAO

SUSTAINABLE LIMESTONE AND EAF AGGREGATE CONCRETES THROUGH PARTICLE PACKING MODELS (PPMs) AND LIFE CYCLE ASSESSMENT (LCA)

VERONICA GARCIA CORTES

Supervisors:

Dr. José Tomás San-José Lombera

Dr. David García Estévez

April 2020, Bilbao

Universidad del País Vasco Euskal Herriko Unibertsitatea

BILBOKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE BILBAO

SUSTAINABLE LIMESTONE AND EAF AGGREGATE CONCRETES THROUGH PARTICLE PACKING MODELS (PPMs) AND LIFE CYCLE ASSESSMENT (LCA)

VERONICA GARCIA CORTES

Supervisors:

Dr. José Tomás San-José Lombera

Dr. David García Estévez

April 2020, Bilbao

Agradecimientos

Realizar una tesis doctoral requiere un gran trabajo y esfuerzo personal durante varios años, que sería muy difícil superar sin el apoyo y ayuda de muchas personas. Por ello, me gustaría agradecer a todas las personas que han estado cerca durante estos 4 años y han hecho posible este trabajo.

En primer lugar, agradecer a mis directores, Tomás y David. Gracias por darme la oportunidad de realizar la presente Tesis Doctoral, por confiar en mí y por vuestro apoyo tanto moral como técnico durante todo el proceso. Asimismo, agradecer también a Javier Jesús Gonzalez y Juan Antonio Polanco por sus consejos y todo el conocimiento prestado.

A todas las personas que forman parte de la división de Building Technologies de Tecnalia, por darme la oportunidad de formarme como investigadora en un entorno industrial, desde el primer día me recibisteis con los brazos abiertos y estaré siempre agradecida. Especial mención a las personas del área Cement-Based Products del que he formado parte, sin vuestro apoyo emocional y técnico esta tesis no hubiese sido posible. Y también a todas las personas que me han ayudado en el laboratorio haciendo las horas más agradables.

I want to thank Professor Will Hansen for accepting me as a member of his team during my time at the University of Michigan, being kind whenever I needed help and providing me with valuable knowledge. Of course, thanks also to all the people who made my stay in Ann Arbor so memorable. I wish also to acknowledge the European Commission and the members of the SUPERCONCRE EU project (Grant agreement ID: 645704) for its support in part of the development of this thesis.

Agradecer al Gobierno Vasco, en especial al departamento de educación, por la financiación aportada a través de la convocatoria de ayuda para el Programa Predoctoral de Formación de Personal de Investigador no Doctor 2016. Al ministerio español MCI, AEI, EU y CEDER (RTI2018-097079-494-B-C31) y la Universidad del País Vasco (PGA19/61) por los fondos adicionales. Y al grupo de investigación del Gobierno Vasco (IT1314-19).

Mi agradecimiento también a las empresas que han contribuido suministrando los materiales empleados en la tesis, Hormigones y Morteros Agote (Hormor), Cementos Rezola (FYM HeilderbergCement Group), Grupo Amantegui. Y también a aquellas que han aportado los datos necesarios para evaluar el impacto ambiental, Hormigones y Morteros Agote (Hormor), Grupo Amantegui y Prefabricados Alberdi.

Finalmente, agradezco a mi familia por estar siempre ahí y haberme apoyado para lograr mis objetivos tanto en lo personal como durante toda mi carrera universitaria, sin

vosotros esto no hubiese sido posible. También a mis amigos, los de siempre y los que han aparecido en el camino, mil gracias por aguantarme y darme tanto ánimo durante estos últimos años. Y por supuesto a mi compañero de viaje, has sido mi gran motor para conseguir esto, te quiero.

Abstract

In view of the current concern about environmental problems, the depletion of natural resources, the lack of space in landfills and climate change among others, initiatives such as the valorisation of waste and industrial by-products in cement-based products are currently a priority that will lead to sustainable development in the construction sector.

As a result of this approach, the use of slags from the Electric Arc Furnace (EAF) as aggregates in the concrete has been proved to be successful for multiple applications avoiding the use of natural aggregates. Hence, the range of aggregates available for designing concretes is continuously growing.

The morphology of granular materials strongly depends on their physical properties and the processing operations to which they have been exposed. In particular, the EAF slag possess a cavernous structure which difficult the concrete mix design according to the conventional methods. Thus, the growing need to manufacture a more sustainable concrete with the available materials taking advantage of all the natural resources and including waste or by-products from other industries, requires the optimization of the concrete mix design considering the properties of the components and reducing the environmental and economic impact.

The main objective of this thesis is to design economic and environmentally sustainable concrete mixes made with natural limestone (NL) aggregates and electric arc furnace (EAF) aggregate through a particle packing density perspective without compromising their compressive strength and workability.

In order to verify the potential of particle packing theories to design more economical and environmentally sustainable NL aggregate and EAF aggregate concrete mixes, two traditional optimal curves and two current discrete packing models were validated with experimental packing results to demonstrate its feasibility in the prediction of the most compacted structure. Several (17) NL and EAF aggregate concrete mixes were then designed by varying the aggregate proportion and the content of cement paste to analyse the effect of aggregate packing density on the fresh and hardened concrete properties. Finally, the economic and environmental impact of the different concrete mixes were assessed to evaluate the potential of the particle packing methods in the development of more sustainable concrete.

It was concluded that the concrete mixtures designed by maximizing the coarse aggregates content in the range of the maximum packing density present the highest compressive strength and workability and the low environmental and economic impact. In addition, due to the higher compressive strength and the low contribution of aggregate in the concrete environmental impact, the EAF aggregate concrete contributes to a greater reduction of the environmental and economic impact.

Table of Contents

TABLE OF CONTENTS

Acronyms

3-P	3-parameter Packing Model
A&A	Andreasen and Andersen model
AAC	Alkali-activated Cements
ABS	Air-cooled Blast furnace Slag
ADP-E	Abiotic depletion potential (Resource use, minerals and metals)
ADP-F	Abiotic depletion potential-fossil fuels (Resource use, energy carries)
AGM	Aim and Goff Model
AHP	Analytic Hierarchy Process
AP	Acidification potential
BOF	Basic Oxygen Furnace
C&DW	Construction & Demolition Waste
CA	Coarse Aggregate
CAS	Concurrent algorithm-based simulation
CCS	Carbon Capture Storage
CIPM	Compaction-Interaction Packing Model
CLAS	Concrete Life Cycle Assessment System
CPM	Compressible Packing Model
CSD	Commission on Sustainable Development
D-C	Compacted by means of a tamping rod packing
D-C26	Compaction by vibration (26 Hz) and compression (10kPa)
D-C33	Compaction by vibration (33 Hz) and compression (10kPa)
DEM	Discrete element method
D-L	Loose packing
EAF	Electric Arc Furnace
EAF	Electric Arc Furnace
EAFS	Electric Arc Furnace Slag
EI	Environmental Impact
ELCD	European Life Cycle Database
ELECTRE	Elimination and Choice Expressing Reality
EP	Eutrophication potential
EPD	Environmental Product Declaration
EPfw	Eutrophication, aquatic freshwater
EPmw	Eutrophication, aquatic marine
EPt	Eutrophication, terrestrial
ERs	Environmental Reports
ET	Ecotoxicity (freshwater)
FA	Fine Aggregate
FM	Fineness Modulus or Furnas Model
FU	Funtional Unit

GBFS	Granulated Blast Furnace Slag
GDP	Gross Domestic Product
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GWP	Global warming potential (climate change)
HTc	Human toxicity, cancer effects
HTn-c	Human toxicity, non-cancer effects
IR	Ionising radiation, human health
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFS	Ladle Furnace slag
LMPM	Linear-Mixture Packing Model
LPM	Linear Packing density Model
LU	Land use
MA	Medium size aggregate
MCDM	Multiple-Criteria Decision Methods
MFT	Mortar film thickness
MIVES	Integrated Value Model for Sustainable Assessment
MLPM	Modified Linear Packing Model
MPM	Mixture Packing Model
MRA	Mixed Recycled Aggregate
MTM	Modified Toufar Model
NL	Natural Limestone
ODP	Ozone depletion potential
OPC	Ordinary Portland Cement
PCR	Product Category Rules
PD	Packing Density
PEF	Product Environmental Footprint
Pe-NRe	Total non-renewable primary energy consumption
Pe-Re	Total renewable primary energy consumption
PFT	Paste film thickness
PM	Particle matter/Respiratory inorganics
POCP	Photochemical ozone creation potential
PPM	Particle Packing Model
PROMEHTEE	The Preference Ranking Organization Method for Enrichment of Evaluations
RA	Recycled Aggregate
RAC	Recycled Aggregate Concrete
RCA	Recycled Concrete Aggregate
R-GB	Glass Marbles

R-S	Rounded Siliceous aggregates
RSA	Random sequential addition
R-WTB	White Tumbled Boulder
SCC	Self-Compacting Concrete
SCM	Supplementary Cementitious Materials
SSA	Specific Surface Area
SSD	Saturated Surface Dry density
SSM	Solid Suspension Model
TOPSIS	Technique for Order of Preference by Similarity to Ideal solution
TPM	Theory of Particle Mixtures
W/C	Water-to-Cement ratio
W/S	Water to Solid ratio
WFT	Water Film Thickness
WS	Water scarcity

6

Environmental and economic impact of NL and EAF aggregate concretes

CONTENT

6 Environmental and economic impact of NL and EAF aggregate concretes

In Chapter 6, the environmental and economic impact of the natural limestone (NL) and electric arc furnace (EAF)aggregate concrete developed in chapter 5 will be assessed to determine the feasibility of the particle packing model (PPM) in sustainable concrete mix design. In addition, a detailed life cycle inventory (LCI)at local scale of the natural limestone (NL) aggregates and electric arc furnace (EAF) aggregates will be presented and the environmental impact of both aggregate and the recycled concrete aggregate (RCA) will be compared.

6.1 Introduction

Although concrete has a low environmental impact (200 kg CO_2 eq./t of concrete)compared to other construction materials (recycled steel 1100 kg CO_2 eq./t of steel), its huge consumption causes a substantial environmental impact (Favier et al. 2018).Cement is the main responsible of the CO_2 concrete emission. However, the impacts are not only because of CO_2emission, but also because of the mass consumption of raw material (mainly aggregates that represent 70-80% of the total concrete volume) and the waste that is generated after its life cycle(Rodríguez-Robles et al. 2019).This causes not only a depletion of natural resources but also a lack of available space due to the disposal of waste in landfills.

In addition, to avoid industrial by-products from other industries such as slag from electric arc furnaces, these are successfully used as aggregates in concretes. However, the use of recycled products as aggregates in concrete is not always beneficial from an environmental and economic point of view. The use of EAF aggregates in concrete may contribute to the environmental impact by reducing both waste or by-product landfilling and natural resources extraction, as happens with the RCA aggregates from C&DW. However, in some cases, the environmental burdens connected to the recycled aggregate concrete production process lead to a reduction in environmental benefits. One of the reasons is the long distance among the generation source, the treatment facility, the concrete production plant and the construction site or when the energy demand to achieve the desire granular size is higher than for the NL aggregates. Concerning the economic impact, although the price of EAF and RCA aggregates is usually cheaper in comparison with NL aggregates, the transport cost can increase the economic impact. For the social impact it is expected that potential impact on human health will be equivalent or even lower than for natural aggregates as the treatment process of EAF slag and C&DW compared to natural crushed aggregates is mainly mechanical (crushing and screening). Therefore, PM_{10} emissions related to the extraction process of the natural rock are avoided.

From among the available methods to assess the environmental impact of concrete, Life Cycle Assessment (LCA) is perhaps the most widely used (Pradhan et al. 2019; Schuurmans et al. 2005; Turk et al. 2015; Hossain et al. 2016a; Hossain et al. 2017; Simion et al. 2013; Chen et al. 2010; Smith & Durham 2016; Hossain et al. 2016b; Salas et al. 2016; García-Gusano et al. 2014; Penteado et al. 2015; Gursel et al. 2014; Ruan & Unluer 2016). Among the limits of this methodology are the flexibility of the LCA approach that complicated their comparison because of the use of different data base and life cycle impact categories (LCIA) methodologies, and the lack of reliable and detailed life cycle inventory (LCI) data with geographic and technological representativity.

To deal with the first limit, until now the environmental product declaration (EPD) based on (UNE-EN 15804 2013)have been widely in the construction sector, this methodology has been used the LCIA characterization factors developed by CML. However, a more recent methodology developed by the European Commission, the Product Environmental Footprint (PEF)(EC-JRC 2012) is intended to provide a "common way of measuring environmental performance of product", therefore the EPD norm has been recently updated in an attempt to converge with the PEF method.

The aim of this chapter is to assess the feasibility of the concrete mix design with NL and EAF aggregates through PPM and to support the local construction sector to make decisions in the selection of concrete components considering the environmental and economic burdens and to provide a useful LCI for upcoming LCA studies.

With these aim in mind, the following partial goals are proposed:

- To develop a detailed LCI for NL and EAF aggregate production in Basque Country, based on primary data from representative companies.
- To compare and assess the environmental impact of NL and EAF aggregates produced in the Basque Country. Two scenarios will be contemplated for the EAF aggregates:
    - Scenario A: Considering the EAF slag treatment process and transport from the facilities to the treatment plant.
    - Scenario B: Considering also the avoided environmental burden of delivering to landfill the EAF slags.

  In addition, a sensitive analysis will be performed to find the limit of the transport distance compared to the NL aggregate.

- To compare and assess the environmental impact of RCA with the NL and EAF aggregates. For this purpose, a tentative LCA analysis for two common sources of RCA will be performed attending to estimated LCI values from literature.

- To compare and assess the environmental burden and economic impact of different concrete mixes made with NL and EAF aggregates. For this purpose, the tool and the global index developed in the SUPERCONCRETE project (645704 - SUPERCONCRETE 2014)has been updated and applied to the assessment of these concrete. The influence of the functional unit (FU) selection were also analysed. In addition, the limits of the transport distance of EAF aggregates compared to NL aggregate attending to environmental impact has been stablished through. a sensitive analysed.

6.2 Life cycle Assessment (LCA) approach

The standardised LCA methodology(ISO 14040 - ISO 14044:2006)was used to assess and to compare the environmental impact of NL and EAF aggregates and the concrete mixes, presented in chapter 5, made with both aggregates types.

In addition, in order to analyse the environmental feasibility of other recycled aggregate options at local scale, the environmental impact of RCAs has also been assessed and compared to the NL and EAF impacts.

The four mandatory steps of the of the LCA framework, goal and scope definition, Inventory analysis (LCI), environmental impact assessment (LCIA), and interpretation were detailed below.

6.2.1 Goal and scope definition

The goal of this LCA includes:

- First, to develop a regional LCI for NL and EAF aggregate production in Basque Country, based on primary data.
- Second, to compare the environmental burden of different aggregates (NL, EAF and RCA) produced in the Basque Country through reliable data.
- Third, to compare and study the environmental impact of different concrete mixes made with NL and EAF aggregates.

The three objectives intend to support the local construction sector to make decisions in the selection of concrete components considering the environmental burdens and to provide a useful LCI for upcoming LCA studies.

Thus, the scope can be divided in two comparative LCA studies:

- Aggregates LCA
- Concrete mixes LCA

Both analyses were conducted from a cradle-to-gate approach since the studies were performed at material scale regardless the final application of the product.

For the comparative LCA of the aggregates, 1t of aggregate was selected as the functional unit (FU). The main reason is that energy consumption during production or recycling process is accounted by mass of the aggregate, regardless of the specific density of the material. Therefore, the unit of mass is considered to be more reliable and representative for comparing different types of aggregates. In addition, for the construction sector, 1t of concrete ingredient is usually used as the reference unit for the price.

However, it should be noted that the higher density of EAF compared to NL will have effect in the environmental impacts of the material transport and in concrete mix, as higher mass will be needed to fill a unit volume. Therefore, both aspects should be also considered in the environmental impact of concrete production.

The system boundaries of the NL aggregate involve the extraction of raw materials from the quarry, the transport of the raw materials to the processing facilities and the processing stages (crushing, grinding and screening) (see Fig. 6.1).

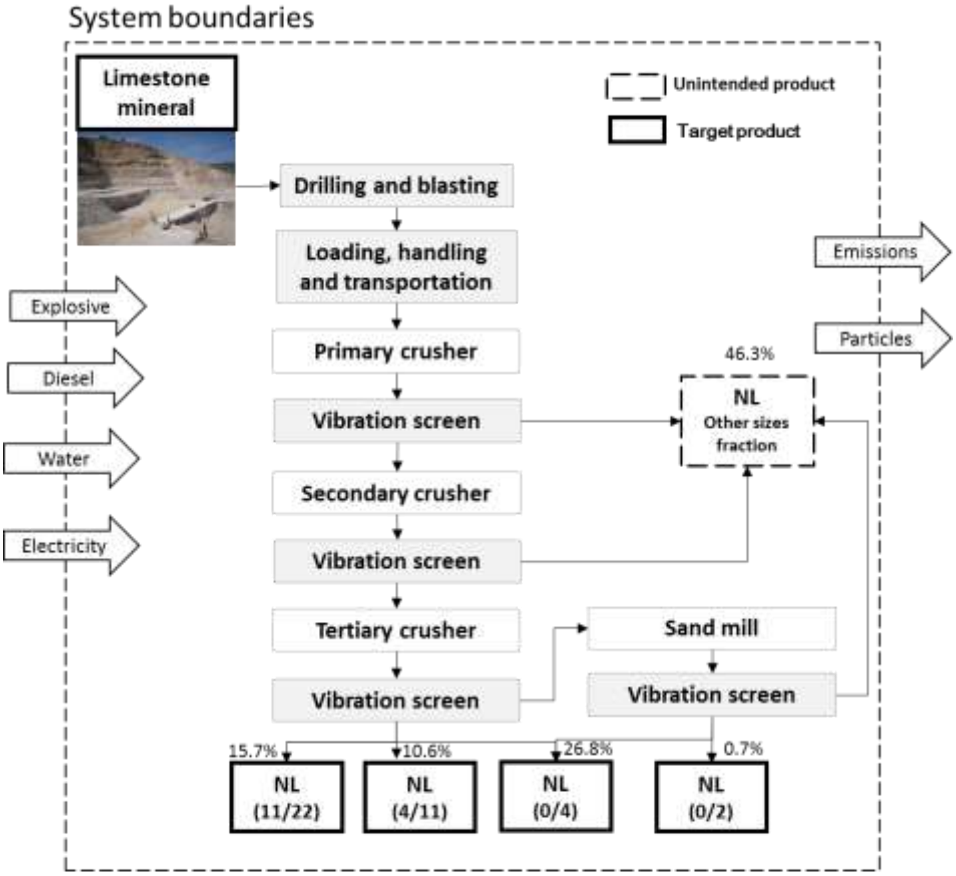


Fig. 6.1. System boundary of NL aggregate production.

The system boundaries of the EAF aggregates (see Fig. 6.2) include the transport of the EAF slag to the treatment plant, the process of watered and aerated until its volumetric stabilization for 90 day to limit expansion phenomena and there cycling process (crushing, magnetic separation of metallic fractions and screening). The cooling process of the EAF slag is out of the boundaries systems since it is necessary regardless the EAF slag will be valorised or landfilled (CEDEX 2011). Two scenarios were considered:

- Scenario A: Considering, the transport of the EAF slag and the EAF slag treatment process. The avoided burdens will be out of the system boundaries.
- Scenario B: An additional scenario that takes into account the avoided impacts of sending the EAF slag to landfill.

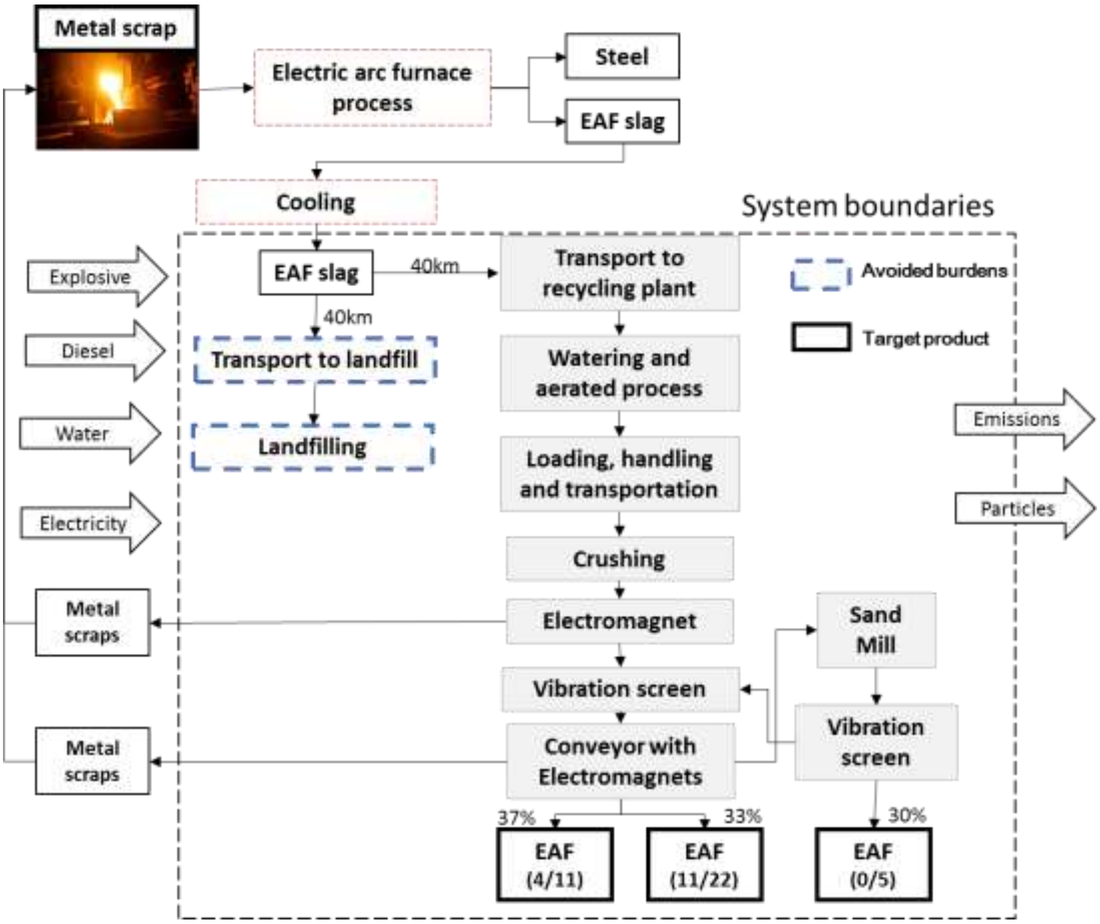


Fig. 6.2. System boundaries of EAF aggregate production.

For the RCA aggregates, two scenarios were assumed to consider RCA from C&DW of concrete structures and RCA from the waste stream of the precast companies.

- Scenario A: The RCA are recycled from C&DW in a stationary recycling plant.
- Scenario B: The RCA are recycled from the rejected concrete fractions of a precast concrete company in a mobile crusher.

The scenario A includes the transport of the C&DW from the demolition site to the stationary recycling plant and the recycling process (crushing, magnetic separation of metallic fractions and screening). The scenario B includes the transport of the mobile crusher to the precast company to treat the waste fraction generated during a year and the crushing process.

For the comparative *LCA of concrete mixes,* the selection of the FU plays a relevant role and only concrete with the same performance properties should be compared. As the assessed concrete mixes present differences on compressive strength values, 1m^3 of concrete per unit of compressive strength at 28 days (1 m^3·MPa) was selected as functional unit (FU).

The system boundaries of the concrete production analysis include the three stages of the product stage described in UNE-EN 15804:2012+A1 (see Fig. 6.3).

- 1. Raw material which includes, extraction, handling, transportation and processing of the raw materials to obtain each final concrete ingredient.
- 2. Transport of raw material to the concrete mix facilities.
- 3. Concrete manufacturing.

Due to the concrete mixes were only prepared at lab scale, in a first approach the delivery distances of the different materials and the energy consumption for concrete production were not considered as it was assumed to be the identical for all concrete mixes. The energy consumption of the mixing process energy was assumed also the same regardless of the concrete mix. Therefore, the goal of the comparative LCA is not affected by transport and manufacturing environmental impacts. In addition, the raw materials production accounts for approximately 94% (Filippo et al. 2018) of the concrete environmental impact during the production stage, thus it is global impact is almost negligible. In a second approach a transport sensitive analysis was carried out to study the influence of the distance of NL and EAF aggregates treatment plants to the concrete mix facilities(Turk et al. 2015).

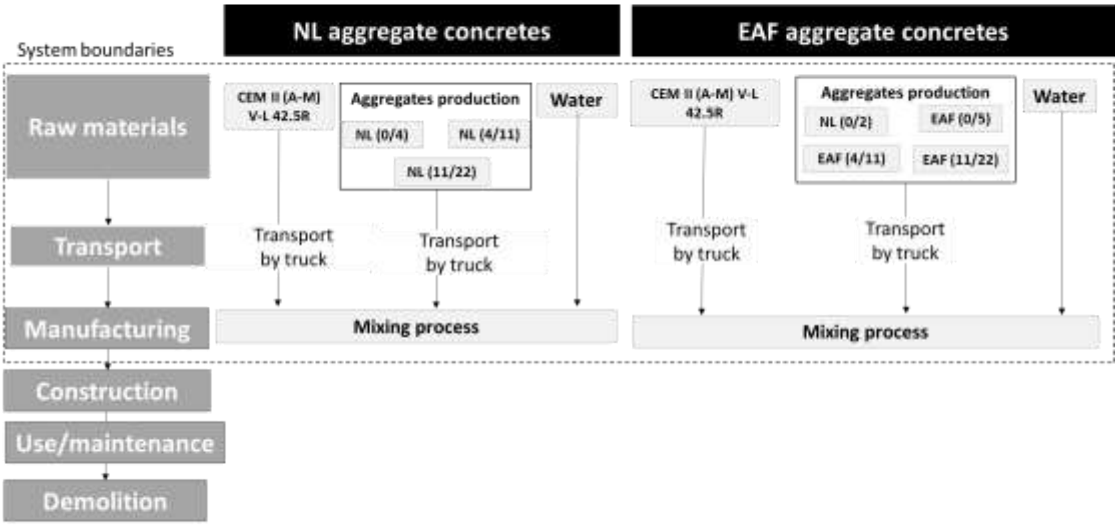


Fig. 6.3. System boundaries of NL aggregate concrete and EAF aggregate concrete.

6.2.2 Life Cycle Inventory (LCI)

This stage comprises the collection and quantification of the relevant input and out flows of a product. Different sources have been considered for the data collection in the following order of priority:

- Data provided by the companies involved.

- Environmental product declaration and databases.

- Articles, books and reports directly related to the materials and processes under study.

The materials and energy flows to produced NL and EAF aggregates were supplied by the companies (see sections 6.2.2.1 and 6.2.2.2). Due to the lack of primary data related to the RCA aggregates because of the scope of the thesis, the energy consumptions and materials flows for the RCA, were taken from related papers and reports (see section 6.2.2.3).

Regarding the LCI of the CEMII A-M (V-L) 42.5R used in the concrete mixes, due to the lack of primary data, environmental product declaration (EPD) and specific databases (there are EPD and CEMII databases with average data, but these do not take into account the amount and type of addition), the input/output data system of the production process was designed by collecting data from the PEF Database, the CPM database (Swedish Life Cycle Center 1996)and related sources.

The data of the secondary process electricity, fuel, water, landfill and transport was collected from the PEF Life Cycle Database.

The secondary LCI to perform the LCA are summarised in Table 6.1:

Table 6.1. LCI data set use for the LCA methodology and the EF LCIA.

Type of flow	Process	Database source
Diesel	Diesel mix at filling station, consumption mix, at filling station, from crude oil and bio components, 7.23 wt.% bio components - EU-27	PEF database
Electricity	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - ES	PEF database
CEMI	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I	PEF database
Water	Tap water, at user, technology mix, per kg water	PEF database
Transport	Total weight >32 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, more than 32t gross weight / 24,7t payload capacity - ROW w/o EU-28+3	PEF database
Landfill	Landfill of inert (construction materials), production mix (region specific sites), at landfill site, landfill including leachate treatment and with transport without collection and pre-treatment - ES	PEF database
Flows		
Water to Cooling - ES		PEF database
particles (PM10)		PEF database
from arable, irrigated, intensive (land transformation)		PEF database
Mineral extraction site -ES (land use)		PEF database
To mineral extraction site -ES (land transformation)		PEF database
industrial area(land use)		PEF database

Type of flow	Process	Database source
from unspecified (land transformation)		PEF database
to industrial area(land transformation)		PEF database

6.2.2.1 NL aggregate production

The process description and the energy consumption to produce NL aggregate were supplied by the Amantegui S.L company. Their quarry (Markomin-Goikoa) and facilities located in Mañaria produces limestone aggregates of different quality and particles size distribution according to the application (aggregate for concrete production, mortars, asphalts and public works in general). Their product portfolio can be found on-line[19].

The production capacity of the crushed limestone plant is designed to produce between 1,200,000 and 1,500,000 tons per year. However, given the instability of the sector, production is lower. Thus, the energy consumption was obtained on the basis of production over the last 5 years in ***Table 6.2*** (see annex for more details).

Limestone rock is extracted from the quarry by using explosive. Once the material has been extracted from the exploitation, it is transported by truck to the processing facilities where the limestone is crushed, grinding and screening obtaining different particles size fractions. For this propose, the treatment plant consists on the following facilities, primary crushing, intermediate stock, secondary crushing, tertiary crushing and sand plant. The common treatment process is as follow:

In the first step the limestone is fed into the primary crusher to reduces larger pieces and a vibrating screen to providing pieces between 75 and 300 mm and the all in one fraction(0/32mm). Then, the larger limestone pieces pass through a secondary crusher and a vibrating screen, which generates streams of different particle size, generally useful for drainage application (20/40; 40/80; 31.5/90).Afterward, the material passes through a tertiary crusher and through a vibrating screen to obtain aggregate fraction commonly use in concrete (10/20; 11/22; 4/11; 2/6). Finally, the material passes through a mill and vibrating screen in the sand plant to obtain sand fractions (0/4; 0/2). Along the process, there are several, vibration feeder, vibration screening and conveyor belts, and different system to minimize dust emissions. The production of different particle size materials is regulated according to the market demand.

The impact related to the transport of the raw material will be minimal, as the common practice is to locate the treatment plants close to the quarry to reduce the energy consumption and cost. Likewise, concrete mixing plants in Basque Country are usually located close to the aggregate facilities maximum at a distance of 30km radius.

---

[19] http://www.amantegi.com/

The sources of emissions are related to the fuel and electricity consumed by machinery in both extraction and processing and to the uncontrolled particle release to the air. The water consumption is assumed to be zero, since the water used to wet tracks and to reduce dust during the crushing process comes from rainwater stored in settling ponds.

The amount of fuel and electricity consumed per year was provided by the company and the particle release to the air were estimated according to recent guide published recently with this aim (Consejería de agricultura, ganadería 2019).

It is commonly assumed that the environmental impact of aggregates is the same regardless of the size of the fraction, as the production process is complex to isolate the impact of each fraction and it is assumed that all aggregate fraction has a similar function. However, it is well known that sand production requires more energy consumption and is therefore more costly than other fractions. Hence, in this thesis, in order to obtain the environmental impact of each aggregate size fraction (0/2; 0/4; 4/12 and 12/22) from a realistic point of view, the economic allocation was used.

The other possibilities considered and the reason for their exclusion are detailed below:

- The option of accounting for all energy consumption needed to produce 1 tonne of each fraction by considering the aggregate production flows in recent years, was discarded as the environmental impact of the finer aggregate size fraction will be disproportionately high due to the lower production of these materials. Moreover, for a same energy consumption and therefore for the same impact burdens, more products are produced (multifunctional process), so the environmental impact should not be related to only one aggregate fraction.
- Physical mass allocation was also excluded, since according to the material flow, more coarse aggregate is produced. Therefore, although it is known that the fine fraction consumes more energy to be produced, applying this method, the impact will be greater for the coarse aggregate fractions.

Table 6.3 shows the mass balance and the allocated flow through economic allocation.

Table 6.2. Global LCI data of the NL aggregate production.

	Quantity	**Source**
Total production of NL aggregate (t)	456377	Primary data (Average value base on the last 5 years) (see Annex)
Diesel consumption (l)	196850	Primary data (Average value base on the last 5 years) (see Annex)
Electricity (kWh)	957972	Primary data (Average value base on the last 5 years) (see Annex)
Particles emission PM_{10} (kg)	1244.25	Value calculated according to the recommendations of the following guide(Consejería de agricultura, ganadería 2019) (see Annex)

	Quantity	Source
Explosives (t)	108[20]	Estimated value according to the LCI published by (Kittipongvises 2017)
Land Occupation (m^2a)	311000	The calculations were performed according to the methodology recommended by Frischknecht et al. (Frischknecht et al. 2007), which suggests the period of 20 years for the mining activity. (see Annex)
Land transformation (m^2)	15550	

Table 6.3. Economic allocation of the NL aggregate fractions. Energy consumption and particles emissions.

Product	Mass balance (%)	Price[21](€/t)	Economic Allocation factor	Diesel (L/t)	Electricity (kWh/t)	PM_{10} (kg/t)
NL (11/22)	0.7	15.5	1.3	0.85	4.14	5.38E-03
NL (4/11)	26.8	10.7	37.5	0.59	2.86	3.71E-03
NL (0/4)	10.6	7.1	9.9	0.39	1.89	2.46E-03
NL (0/2)	15.7	7.3	14.9	0.40	1.94	2.53E-03
Other fractions	46.3	6.5 [22]	36.3	0.36	1.73	2.25E-03

6.2.2.2 EAF aggregate production

The process description and the energy consumption to valorize EAF slag were supplied by HORMOR company. Their facilities are in Zestoa (Gipuzkoa). After the cooling the EAF slags are transported about 40 km from the ArcelorMittal steel making company located in Olaberria to the treatment plant. The nearest inert landfill (Aizmendi, located in San Sebastian) is at the same distance (40 km).

The plant is designed to treat 80 t/h. Considering a journey of 1826 h/year and a 70% of efficiency rate due to the maintenance processes and stops for loading and unloading as recommend Evangelista et al. (Evangelista et al. 2018a), 102256 t of EAF aggregate are produced per year. The energy consumption was obtained on the basis of last year's production (see Table 6.4) (see annex for details). Diesel consumption was directly provided by Hormor company and the electricity consumption was calculated from the power of the machinery and the production capacity. Although it is known that other granular size fractions are obtained for other application, it was assumed that only the aggregate fraction for concrete were manufactured (EAF 0/5; EAF 4/11; EAF 11/22).

---

[20] The explosive is considered by the quarry company as an energy source, so its emissions have been related to energy consumption data. Particle emission due to the blasting process has not been considered.

[21] Details of the price source are in the section 6.2.

[22] It was assumed an average price of the all-in-one aggregate fractions and aggregates for breakwater application. http://baseprecioscontruccion.gobex.es/p/p01ag/p01ag.html

The EAF slags is previously cooled by a continuous spraying system while the material is deposited in a pit. After that the EAF slag is transported to the treatment plant where the slag is watering and aerated for 90 days for its volumetric stability. Then, the slag is transported to the feeding hopper of the crusher where there is a magnetic separator to remove the metal pieces. Then, the crushed slag is transported through a conveyor with several magnetic separators to the vibration screens to obtaining the coarse aggregate fractions (4/11; 11/22). After that, the rejected fraction is transported to a mill to obtain the sand and the remaining materials returns to the previous circuit where it is screened again. Finally, the material is transported from the storage hoppers to the stockpiles.

Concerning to the European Union directives (European Union 2008) the EAF slags are considered as by-products rather than waste and consequently, allocation should be applied to considered not only the environmental impact related to EAF slag treatment but also the impact related to the steel making production. However, the choice of the allocation type is very influential in the results of an LCA and is therefore one of the most controversial issues in LCA (Chen et al. 2010).In the EAF slag cases, there are several reasons for considering the EAF slag as waste or raw material and not consider its upstream impact:

- There is no consensus on the most optimal allocation (physical, economic or none) type for this type of product and conflicts of interest can arise between the metallurgical and construction sectors. Due to the high emissions of steel compared to natural aggregates, if allocation by mass is applied for example to eq. CO_2 emission it will result in higher emission values than natural aggregates. In case of economic allocation, the price of the EAF slag is usually unknown and it may fluctuate depending on availability
- In the Basque Country the valorization of EAF slag for construction application had to be enhanced through mandatory restrictions to avoid landfilled(DECRETO 64 2019).
- The lack of data on EAF slag primary production.

In literature, the LCA related with EAF aggregate only consider the treatment or recycling process (Faleschini et al. 2014; Evangelista et al. 2018b; Anastasiou et al. 2017).

Therefore, during the EAF aggregate production, the environmental impact is related to the fuel and electricity consumed by machinery, the water during the stabilization process and to the uncontrolled particle release to the air during the crushing stages.

In contrast to the NA aggregate production process, the EAF treatment process is simpler and produces a similar amount of each aggregate fraction. In addition, the product price is the same for all produced fractions (0/5; 4/11; 11/22) to be used as aggregate in concrete. Therefore, it was assumed that the environmental impact of the aggregates is the same regardless of the size of the fraction.

Table 6.4. Global LCI data of the EAF aggregate production.

	Quantity	Source
Total production capacity (t/h)	80	Primary data
Total aggregate production (t)	102256	Calculated by considering a journey of 1826 h/year and a 70% of efficiency rate due to the maintenance processes and stops for loading and unloading as recommend Evangelista et al. (Evangelista et al. 2018a)(see annex)
Diesel consumption (l)	16100	Primary data
Electricity consumption (kWh)	387314	Calculated from the machinery power (Primary data) and assuming a 70% of efficiency of the total plant capacity due to the maintenance processes and stops for loading and unloading as recommend Evangelista et al. (Evangelista et al. 2018a)(see annex)
Particles emission PM_{10} (kg)	109.15	Value calculated according to the recommendations of the following guide(Consejería de agricultura, ganadería 2019) (see Annex)
Land Occupation (m^2a)	15700	The calculations were performed according to the methodology recommended by Frischknecht et al. (Frischknecht et al. 2007), which suggests the period of 50 years for the industrial activity. (see Annex)
Land transformation (m^2)	314	

Due to the lack of data of water consumption the following assumptions were considered:

- Cooling process of the EAF slag: 0.1 l of water per kg of EAF slag.
  This value was established by considering a water consumption of 0.5 l/s during the dumping time of 180 t of EAF slag to the pit, which is approximately 10hours.
- Volumetric stabilization of the EAF slag: 1 l of water per kg of EAF slag.
  This value was established by considering that the EAF slag needed a 5% of water each three days (1l of water per 20 kg of EAF slag), and a third of the days are rainy. So, for the 90 day of the stabilisation process, 20l of water are needed for every 20 kg of EAF slags.

In the first scenario in which the environmental impact to avoid landfill is not considered the transport by truck of the EAF slag were assumed. The truck is supposed to returns load with the metal scrap recovered during the recycling process. As the 1.075 ton of EAF slag were considered to obtain 1 ton of EAF aggregates only one trip was considered(Evangelista et al. 2018a).The transport were modelled as follows according to the PEF recommendation (Zampori & Pant 2019): *The truck is fully loaded for delivery but 93.25% empty at its return, the utilisation ratio is (24.7t real load / 24.7t payload x 50%km + 1.7t real load / 24.7t payload x 50%km) = 53% which was assumed 50%.*

In the second scenario, the environmental impact to avoid EAF slag landfill is considered. In this case, the real distance from the steelmaking company to the nearest landfill was assumed (40km). According to the PEF guide (Zampori & Pant 2019), bulk shall be modelled with a default utilisation ratio of 50%. Therefore, the truck is fully loaded for delivery but empty at its return, the utilisation ratio is (24.7t real load / 24.7t payload x 50%km + $1 \cdot 10^{-3}$treal load / 24.7t payload x 50%km) = 50%.

The mass balance and the LCI flows were detailed in ***Table 6.5***.

Table 6.5. Energy consumption, water demand and particles emissions of EAF aggregates.

Product	**Mass balance (%)**	**Price (€/t)**	**Diesel (L/t)**	**Electricity (kWh/t)**	**Water (l/t)**	**PM_{10} (kg/t)**
EAF (0/5)	30	4.5	0.157	4.15	0.001	2.12E-04
EAF (4/11)	37	4.5	0.157	4.15	0.001	2.12E-04
EAF (11/22)	33	4.5	0.157	4.15	0.001	2.12E-04

6.2.2.3 RCA aggregates

Due to the lack of primary data, the RCA LCI was conducted by considering data related to recent papers involving treatment processes and technologies like those of local recycling plants. Two scenarios were considered, with the aim to assess two of the common streams of the RCA:

- Scenario A: The RCA are recycled from C&DW in a stationary recycling plant.
- Scenario B: The RCA are recycled from the rejected concrete fractions of a precast concrete company in a mobile crusher.

The stationary C&DW plants in the Basque Country consist commonly of a previous selection of the received material by removing the materials and large impurities manually or by means of a mobile machine equipped with a clamp. This is called the triage stage. Then, the clean flow of C&DW pass directly through the crusher (primary and secondary) and the vibration screening, while the flow with impurities goes through different separation technologies to remove the impurities. These technologies consist of vibrating screens to separate the fine fraction (<40mm), blowers to remove light waste, manual triage and electromagnets to separate the metal elements. Finally, the stone stream passes through the primary and secondary crusher and the vibrating screen to classify the material by its granular distribution.

The mobile plant is basically a crusher. These plants allow to reduce the transport cost of huge volumes of C&DW to the treatment plants but only cleaned C&DW can be recycled.

For the stationary plant, the energy consumption were collected from the data published by Pradhan et al. (Pradhan et al. 2019) since the treatment process and the equipment are comparable to the local process.

Considering the distance between the different locations of the authorized recycling plants in the Basque Country. A maximum radius of 50 km from the demolition site to the recycling plant was assumed. The truck is supposed to returns empty. The transport were modelled according to the PEF recommendation (Zampori & Pant 2019): bulk shall be modelled with a default utilisation ratio of 50%. Therefore, the truck is fully loaded for delivery but empty at its return, the utilisation ratio is (24.7t real load / 24.7t payloadx50%km + $1{\cdot}10^{-3}$treal load / 24.7t payload x 50%km) = 50%.

In the case of scenario B, precast concrete waste is taken into account to obtain a high and controlled quality RCA of the rejected fractions of its products and close the life cycle. For this scenario, data on production capacity and waste generated were provided by a representative precast concrete company in the Basque Country (Prefabricados Alberdi). Its annual production varies between 40,000 to 50,000 t of concrete per year and the waste stream represent 1% of the total production. In addition, the 50% of the waste stream are clean aggregates obtained from the equipment cleaning processes. Therefore, only the remaining fraction must be crushed to obtain recycled concrete aggregate and close the life cycle. To obtain the recycled aggregate there are two options: renting a mobile crusher or sent the waste to a RCD stationary plant. In this study, the first option was chosen. The energy consumption of the mobile crusher (Metso LT1213) were assumed to be 3.15 l/t according to the Zhao study (Zhao et al. 2020).

A distance of 50km was considered to transport the mobile crusher. The transport is assumed to be full for delivery and return. The impact of the machinery transport was allocated by mass of waste to be treated (45,000*0.01*0.5=225t).

Table 6.6 and Table 6.7 includes the LCI assumed for the RCA aggregates and the transport distances considered for each scenario.

Table 6.6.Energy consumption, water demand and particles emissions of RCA aggregates *(Pradhan et al. 2019).*

Scenario	Product	Diesel (l/t)	Electricity (kWh/t)	Water (kg/t)	PM_{10} (kg/t)
A	RCA	0.1	2.15	5	1.51E-3
B	RCA	3.15	-	-	8.52E-4

Table 6.7. Transportation distances.

Scenario	Product	From	To	Distance (km)
A	C&DW waste	Demolition site	Recycling plant	50
B	Concrete waste	Precast company	Crusher equipment	-
B	Crusher equipment (42 t)	Renting company	Precast company	50

6.2.2.4 Cement production

The nominal composition of CEMII/A-M (V-L) 42.5R provided by FYM Heilderberg Cement group is as follow[23]:

Clinker	Fly ash	Limestone	Minor constituents
80%	9%	9%	2%

As the revised EPD and database only provide average values for all the CEMII production in a region regardless of its compositions, the unitary process has been designed to consider the fly ash and limestone content (see Table 6.8 and Table 6.9).

With this aim, the following assumption were done:

- The "Portland cement (CEM I); CEMBUREAU technology mix, EN 197-1; CEMBUREAU production mix, at plant" process from the ELCD database, was used to calculate the impact of the sum of clinker and minor constituents.
- The fly ash is a by-product from the combustion of pulverized coal in thermal power plants that does not require further processing before it is incorporated into cement therefore the upstream impact related to the electricity production were not considered. This assumption is common applied in other LCA studies related to cementing products (Athena Sustainable Materials Institute 2016).
- The consumption energy and the dust emission of the limestone powder were considered according to the production process "Production of powdered limestone" of the CML dataset(Swedish Life Cycle Center 1996) and the typical consumption of a commercial mill used for that proposed[24]. The considered values are show in Table 6.8.

The transport of the materials was considered negligible.

Table 6.8. LCI unitary process to produce 1t of powered limestone.

Flow type	Process	Amount	Source of data	Source of process
Electricity consumption	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - ES	25 kWh	CPM dataset and typical consumption of a commercial mill	PEF database
Dust emission		72 g	CPM dataset	ELCD v3.2

---

[23] https://www.fym.es/es/ipro-tecno-425-r

[24] https://www.hcmilling.com/solutions/mineral-processing/limestone-processing-solution.html

Table 6.9. LCI unitary process to produce 1 t of CEMII/A-M (V-L) 42.5R

Flow type	**Process**	**Amount**	**Source of process**
CEMI	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I	0.82 t	PEF database
Powdered limestone	Powdered limestone	0.09 t	Table 6.9
Fly ash	-	0.09 t	-

6.2.2.5 Concrete mixes

The concrete mixes studied and characterized in chapter 5 were analyzed here. These mixes include concrete made with NL aggregates and concrete made with EAF aggregates.

The aggregates combination in both types of concretes were designed through conventional methods (optimal grading curves), particle packing models and experimental packing density results. In addition, the cement content of the concrete mix was also modified according to the packing degree of the aggregates. Therefore, concrete mixes with different aggregate combination, cement contents and compressive strength were assessed.

The concrete mix design is included in Table 6.10.

After obtaining the environmental impact of each raw material, the environmental impact of concrete was modeled by multiplying the mass of each concrete component for its environmental impact. After that, each impact was divided by its compressive strength at 28 days.

Table 6.10. Concrete mixes.

Materials (kg/m^3)	**NL-$_{(47:53):41}$**	**NL-$_{(60:40):50}$**	**NL-$_{(50:50):50}$**	**NL-$_{(40:60):60}$**	**NL-q$_{0.29}$**	**NL-q$_{0.31}$**	**NL-q$_{0.33}$**	**EAF-q$_{0.33}$**	**EAF-q$_{0.35}$**	**E-NL-V$_1$**	**E-NL-V$_2$**	**3-P-NL-V$_1$**	**3-P-NL-V$_2$**	**E-EAF-V$_1$**	**E-EAF-V$_2$**	**CPM-EAF-V$_1$**	**CPM-EAF-V$_2$**
NL (0/4)	776	1030	947	1143	978	996	965	-	-	905	844	804	751	-	-	-	-
NL (4/12)	587	412	474	458	542	579	615	-	-	436	407	594	555	-	-	-	-
NL (12/22)	530	618	474	305	373	403	440	-	-	664	619	603	563	-	-	-	-
NL (0/2)	-	-	-	-	-	-	-	376	335	-	-	-	-	402	375	905	844
EAF (0/5)	-	-	-	-	-	-	-	828	919	-	-	-	-	1065	994	586	547
EAF (4/12)	-	-	-	-	-	-	-	518	574	-	-	-	-	630	588	433	404
EAF (12/22)	-	-	-	-	-	-	-	594	681	-	-	-	-	416	389	430	401
CEM II 42.5R	290	290	290	290	306	270	252	326	267	260	317	260	317	260	317	260	317
W$_{free}$	180	180	180	180	168	149	139	179	147	143	174	143	174	143	174	143	174
W$_{abs}$	10.6	11.1	10.7	11.3	11.1	11.6	11.8	31.2	37.2	10.6	9.9	11	10.3	34.3	32	33.6	31.4
Properties																	
Bulk density (kg/m^3)	2378	2349	2355	2370	2397	2385	2445	2864	2935	2426	2401	2441	2422	2952	2870	2791	2719
Hardened density (kg/m^3)	-	-	-	-	2487	2484	2412	2974	3049	2509	2492	2526	2501	2907	2850	2727	2702
Slump (mm)	120	90	80	25	40	10	10	160	15	15	80	15	150	0	150	15	40
Compr. strength (MPa)*	42.2	40.2	39.4	37.8	42.8	38.5	40.7	45.4	44.2	48.7	45.5	42.3	39.8	51.9	53.1	47.0	41.6

*** *100mm* cubis specimen at *28d***

6.2.2.6 Limitations

- Aggregates are considered as an intermediate product; therefore, the use stage and the end of life were excluded. In case of the concrete LCA, the use stage and end of life were not considered due to the final application of concrete is unknown. In addition, the transportation of concrete components and the concrete manufacturing was not considered as it was supposed the same for all the concrete mixes. Hence, the characterized impact results should be carefully considered.
- The LCI data for NL and EAF aggregate is collected from plants stablished in the Basque Country
- Emissions of particle matter and the land occupation were calculated due to the lack of primary data.
- The lubrication oil of the vehicles used during the treatment of the aggregates were not considered.
- During the EAF treatment the recovery metal fraction were not accounted due to the lack of primary data.
- The primary LCI data were collected attending to geographic, temporal and technological representativity. However, when a secondary LCI process were not available for the specific geography, national and European averages conditions were selected.
- The transport scenarios, vehicle type and transport distances, were designed according to the local conditions. These distances can vary drastically depending on the geographical area and the availability of materials.Fig. 6.4 shows the differences between transport systems according to the type of aggregate. Therefore, this study is more relevant in a Basque Country context.

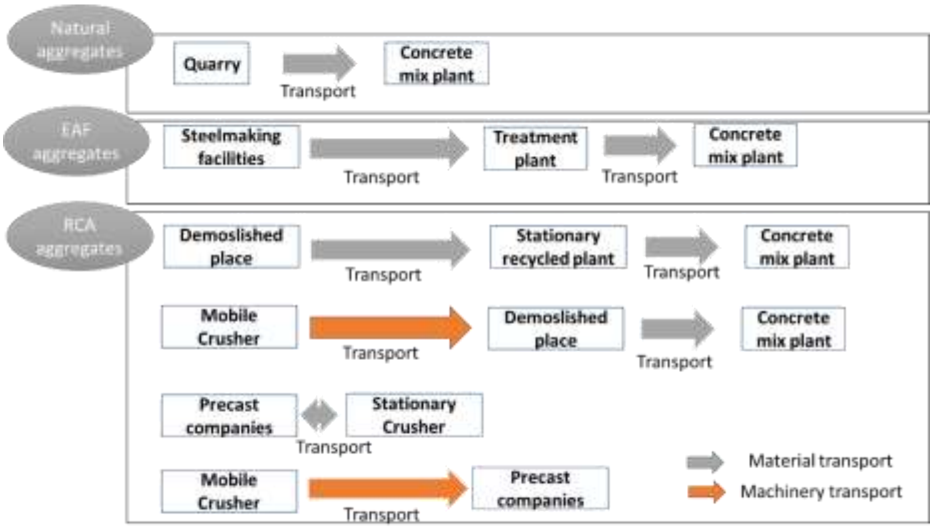


Fig. 6.4. Delivery of natural, EAF and RCA aggregates

6.2.3 Environmental impact assessment (LCIA)

The LCIA has been carried out following the impact methodology recommended by the product environmental footprint method (PEF) by the European Commission (Zampori & Pant 2019).

It was selected since it is the method recommended by the European Commission to assess the environmental impact of products in a harmonized way and will be the reference method in a recent future. In addition, until now the available EPDs are developed according to the EN-15804:2012+A1:2013 framework and the CML LCIA methodology has been used. However, the EPDs has a limited valid date and an update of the EN-15804 (EN 15804:2012+A1:2013+A2:2019) has recently published with the aim to converge with the PEF method. One of the changes is the use of the European Commission's EF Environmental Footprint impact methodologies with slight exceptions. More information can be obtained in (Durão et al. 2020). Therefore, the trend is to assess the environmental impact according to the PEF LCIA methodology.

The list with the names, acronyms and the units are included in ***Table 6.11***. It should be noted that the LCA were not globally performed according to PEF since there not yet a Product Environmental Footprint Category Rules (PEFCRs) for construction products.

Table 6.11. Recommended impact categories according to EF method *(Fazio et al. 2018)*.

Impact Category		**Abbreviations**	**Units**
1	Global warming potential (climate change)	GWP100	kg CO_2 eq.
2	Ozone depletion potential	ODP	kg CFC-11 eq.
3	Human toxicity, cancer effects	HTc	CTUh
4	Human toxicity, non-cancer effects	HTn-c	CTUh
5	Particle matter/Respiratory inorganics	PM	Disease incidences
6	Ionising radiation, human health	IR	kBq U^{235}
7	Photochemical ozone formation	POCP	Kg NMVOC ew.
8	Acidification	AP	Mol H+ eq
9	Eutrophication, terrestrial	EPt	Mol H+ eq
10	Eutrophication, aquatic freshwater	EPfw	kg P eq.
11	Eutrophication, aquatic marine	EPmw	kg N eq.
12	Ecotoxicity (freshwater)	ET	CTUe
13	Land use	LU	aggregated index[25]
14	Water scarcity	WS	kg world eq. deprived
15	Abiotic depletion potential (Resource use, minerals and metals)	ADP-E	kg Sb eq.
16	Abiotic depletion potential-fossil fuels (Resource use, energy carries)	ADP-F	MJ

---

[25] Dimensionless, aggregated index of: kg biotic production/ (m2·a)7 kg soil/ (m2·a) m3 water/ (m2·a) m3g.water/ (m2·a)

The open source software OpenLCA 1.10.2 were used to calculate the environmental impact. The PEF LCA data sets and the EF LCIA method recently available for OpenLCA was used for modelling the LCA system.

6.2.3.1 Normalization and weighting

The normalization and weighting steps are optional in the LCA studies according to (ISO 14040 - ISO 14044:2006). However, in the PEF studies both are mandatory steps.

The aim of the normalization is to compare the magnitude of the impact categories to a reference unit. With this aim the normalization factor defined in the PEF method were applied to the LCIA results. These factors are expressed per capita based on a global value (Zampori & Pant 2019).

In addition, the weighting step was also considered as it is stablished in the PEF studies. The weighted results of different impact categories help to compare and assess their relative importance. In addition, these values can be aggregate to obtain a single score across life cycle impact categories.

6.3 Economic assessment

The economic impact of the concrete mix was calculated attending to the material unit price. It was calculated in the same way of the environmental impact (multiplying the mass of each material for its price), using the material prices detailed in the Table 6.12.

Table 6.12. Material prices.

Material	Price €/t	Ref. Year	Source	Assumptions
CEM II/ A-M (V-L) 42.5R	93.57	2019	(Colegio oficial de aparejadores 2019)	CEM II/ A-M 42.5R
NL (0/4)	10.72	2019	(Colegio oficial de aparejadores 2019)	Crushed limestone sand (0/5)
NL (4/12)	7.71	2019	(Colegio oficial de aparejadores 2019)	Crushed aggregate 6/12 D.A.<30
NL (12/22)	7.30	2019	(Colegio oficial de aparejadores 2019)	Crushed aggregate 12/18 D.A.<30
NL (0/2)	15.53	2019	(Colegio oficial de aparejadores 2019)	Crushed limestone sand 0.5/1.5
EAF (0/5)	4.5	2019	Direct data from a local EAF slag treatment plant in the Basque country	-
EAF (4/12)	4.5	2019	Direct data from a local EAF slag treatment plant in the Basque country	-
EAF (12/22)	4.5	2019	Direct data from a local EAF slag treatment plant in the Basque country	-
Water	1.73	2018	https://www.iagua.es/data/servicios/bilbao	-

The unit price was obtained from different sources of data representative at local and country scale. Prices do not include profit margins nor transportation costs.

6.4 Global environmental and economic index

With the aim of comparing the concrete mix attending to environmental, performance and economic criteria, a global index were calculated according to the method proposed in the SUPERCONCRETE project(645704 - SUPERCONCRETE 2014).

The performance criteria were including in the environmental impact assessment as the FU selected in the LCA was 1 m3of concrete MPa of compressive strength at 28 days.

To combine economic and environmental parameters in a global index, a unique value of impact for each criteria was calculated. On the one hand, the environmental impact was quantifying through LCA methodology and EF impact assessment including normalization and weighing steps to obtain a global value. On the other hand, the economic impact was calculated according to the market price of each concrete ingredient. Therefore, a unique value has been considered, avoiding the weighting step.

The main aim of the global index is to help in the selection of the optimal alternative. In this thesis the alternatives include 17 concrete mixes. The options involve two types of concretes, NL aggregate concrete and EAF aggregate concrete which has been designed attending to experimental aggregate packing results and different particle packing model (PPM), models with different cement contents as was explained in chapter 5.

To combine economic and environmental parameters in a global index, environmental and economic criteria were considered of equal weight. This assumption may change depending on the interests of the stakeholders. For this end, the impact of each criteria environmental an economic, were normalised by dividing each impact by the maximum environmental or economic impact. Thus, values from 0 to 1 are assigned to each concrete mix.

Finally, equal weighting was considered to obtain the global index for both criteria, environmental and economic. Therefore, each environmental and economic impact was multiplied by 0.5 and the result was summed for each concrete mix to obtain the global index of each one.

The concrete mix with higher global index (close to 1) has the higher environmental and economic impact. By contrast, the concrete mixes with lower global index will be the most suitable from the environmental and economic point of view.

6.5 Comparative LCA of aggregates

This section presents the results of a comparative LCA between the NL, EAF and RCA aggregates. First, the environmental impact of each type of aggregate is analyzed individually to identify the most relevant impact categories and processes. Then, the weighted environmental impact is analyzed to compare the impact of different aggregate alternatives on a local scale.

6.5.1 Natural aggregates

The environmental impact of the NL aggregates involves all the production process including the transport from the extraction site to the treatment facilities, the handling activities and the treatment process since the primary data supplied by the company include the total energy consumption during a year. Table 6.13 shows the environmental impact resulting from the production of each fraction of NL aggregate and Fig. 6.5 includes the relative impact of each impact categories comparing the four size fractions. From these results, the following observation can be done:

- As was expect, the production of the NL (0/2) aggregate fraction presents the highest environmental impact, following by the NL (0/4) and the NL (11/22) and NL (4/12) which have similar impact.

Table 6.13. LCIA impact per ton of product.

Impact category	Unit	NL (0/2)	NL (0/4)	NL (4/11)	NL (4/11)
AP	Mol H+ eq	8.06E-03	5.58E-03	3.69E-03	3.79E-03
GWP100	kg CO_2 eq.	2.13E+00	1.48E+00	9.77E-01	1.00E+00
ET	CTUe	5.23E-01	3.62E-01	2.39E-01	2.80E-03
EPmw	kg N eq.	1.87E-03	1.29E-03	8.57E-04	9.93E-01
EPfw	kg P eq.	1.75E-05	1.21E-05	8.02E-06	8.83E-03
EPt	Mol H+ eq	1.92E-02	1.33E-02	8.80E-03	2.46E-01
HTc	CTUh	1.93E-08	1.34E-08	8.85E-09	8.81E-04
HTn-c	CTUh	2.65E-07	1.83E-07	1.21E-07	8.24E-06
IR	kBq U^{235}	3.33E-01	2.31E-01	1.53E-01	9.05E-03
LU	Item(s)	2.45E+02	1.69E+02	1.12E+02	9.10E-09
ODP	kg CFC-11 eq.	3.68E-10	2.55E-10	1.69E-10	1.25E-07
PM	Disease incidences	3.66E-07	2.53E-07	1.67E-07	1.57E-01
POCP	kg NMVOC ew.	5.20E-03	3.60E-03	2.38E-03	1.15E+02
ADP-F	MJ	6.31E+01	4.36E+01	2.89E+01	1.74E-10
ADP-E	kg Sb eq.	8.13E-07	5.63E-07	3.72E-07	1.72E-07
Water use	m^3	1.37E+00	9.47E-01	6.27E-01	2.45E-03

- The contribution in all categories is the same as to define the impact of each size fraction, economic allocated were used. In terms of relative impact, Fig. 6.5

shows that the all the categories impacts of are reduced by 31% for the production of the NL(0/4)fraction compared to the NL (0/2) and the impact of coarse aggregate fractions NL (4/11) and NL (11/22) are reduced by up to 53%. Hence, the common practice of assuming the average impact regardless of the size fraction, may benefit the impact of the fine fraction sizes and impair the impact of the coarse fraction. This fact has not shown a relevant effect in the global impact of conventional concrete made with natural since cement is the main contribution. However, when aggregates are used in other application or concrete made with alternative binders, the difference between the effect of the two fine fractions NL (0/2) and NL (0/4) and the coarse fractions NL(4/11) and NL (11/22) can acquire a greater relevance in the final impact values of the product.

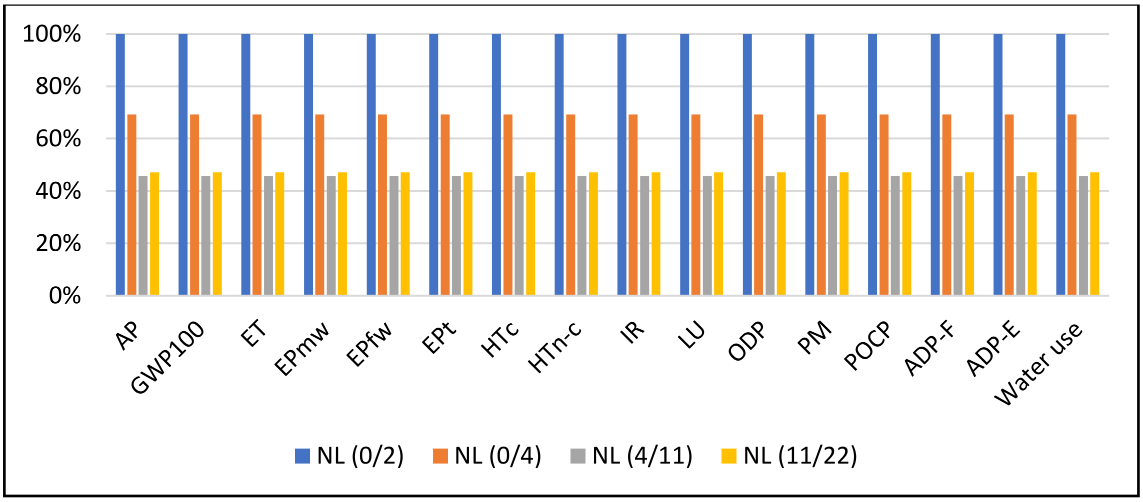


Fig. 6.5. Relative impact comparing the difference aggregates fractions

To compare the impact of different categories the values were normalized and weighted as was detailed in section 6.2.3.1. The results are shown in Fig. 6.6 and Fig. 6.7 respectively.

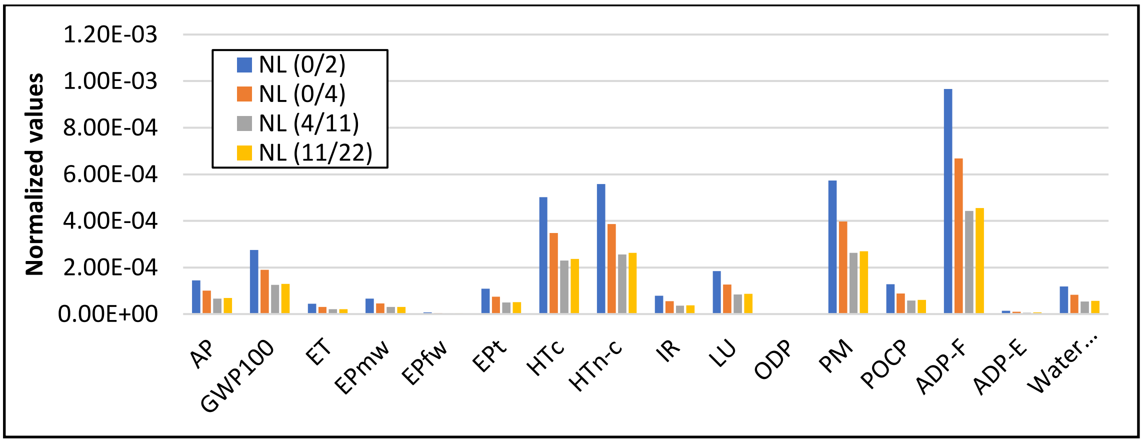


Fig. 6.6. Normalized values.

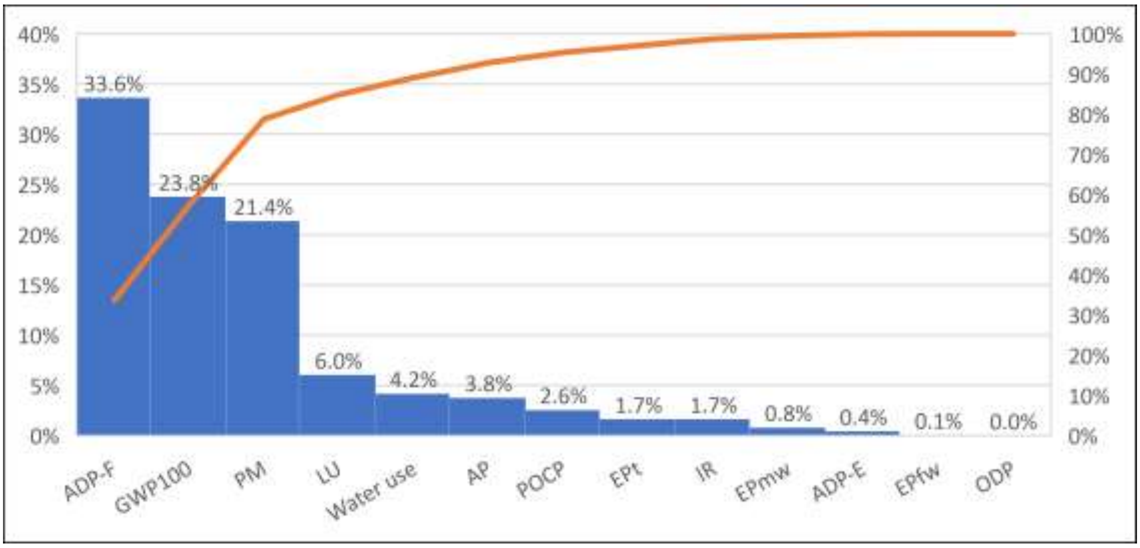


Fig. 6.7. Contribution of different impact categories based on normalised and weighted results

Based on the normalised and weighted results, the most relevant impact categories are: Resource use fossils (ADP-F), climate change (GWP), particulate matter (PM) and land use (LU) for a cumulative contribution of 84.8% of the total impact.

Fig. 6.8 shows the contribution of the different flows to each impact category, land use in the quarry facilities, particles matter emission during the treatment process and electricity and diesel use during the aggregate production. As can be seen, the electricity use is relevant in 9 impact categories AP, GWP, EPmw, EPt, IR, ODP, POCP, ADP-E and water use and the diesel use is main responsible of 5 categories, ET, EPfw, HTc, HTnc and ADP-F. The PM and Land use impact are mainly due to the direct particles' emission during the treatment process and the land occupation and transformation impact.

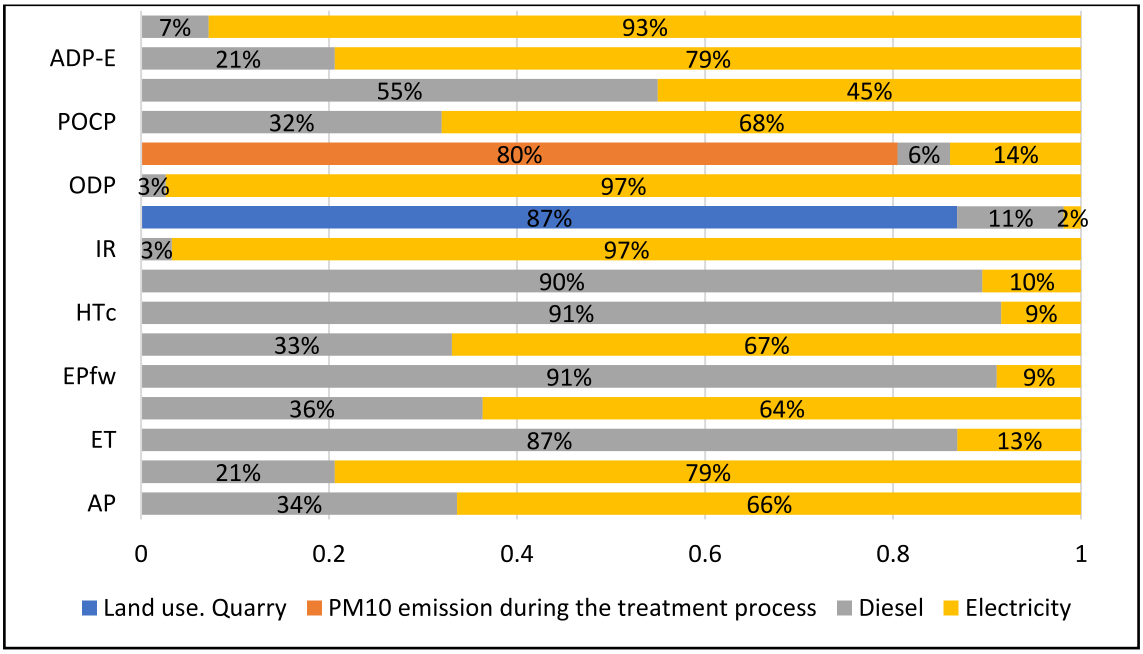


Fig. 6.8. Contribution of flows to the impact categories based on characterized results.

From all of them, the main responsible flows of aggregate impact are the flows with the highest contribution in the most relevant impact categories. For ADP-F, both the use of diesel (55%) and the electricity (45%) have a similar relevance in the abiotic depletion of fossil fuels. In GWP impact the electricity consumption acquired the highest relevance (79%). Diesel consumption is mainly related to the vehicle needed to transport and handling the material while the electricity is linked to the treatment process machinery.

For the categories PM and LU, the emission values were estimated as mentioned in Section 6.2.2, so the actual emission could vary. Concerning the water use impact, although water is used to irrigate the track to avoid the emission of particles and to feed the dust control systems, as previously stated, the rainwater that is collected is used for this function reducing the environmental impact.

The options for reducing the impact are limited, as it is a simple process and its impact is very low compared to other building materials. With the technology upgrading, the use of electricity from renewable sources and the use of electricity or even biofuel for the vehicle could lead to greater protection of the environment. Improving the energy and production efficiency of material processing equipment, mainly crushers, as they are the most energy-intensive and require the most maintenance, could be another way to reduce impacts.

6.5.2 EAF aggregates

Two different scenarios have been considered to assess the environmental impact of the EAF aggregates. The first one (scenario A) involves the transport from the steelmaking company to the treatment plant and the energy consumption during the treatment process while the second one (scenario B) includes also the avoided burden of sending the EAF slag to landfill. Table 6.14 includes the processes involved in each scenario.

The characterized impact results for each scenario are shown in Table 6.15. Fig. 6.9 and ***Fig. 6.10*** include the contribution of each process in the environmental impact for the scenario A and scenario B respectively. From these results, the following observation can be done:

- For the scenario A, as can be seen in Fig. 6.9, transport process is the main responsible for all the impact categories excepting IR, LU, ODP, ADP-E and water use. IR, ODP and ADP-E are mainly related to the consumption of electricity while land use and water used are directly related with the land occupation and transformation of the recycling facilities and to the water use during the watering and aerated process of the EAF slag.
- Concerning the results of the scenario B, the negative values indicate environmental benefits as the disposal of inert waste produces a greater

environmental impact than the process of treating the EAF slag. As can be seen in ***Fig. 6.10*** all the impact categories are highly affected by the landfill process excepting ODP and IR.

- The results show that the valorization of EAF slag is by far more environmentally sustainable than the disposal of EAF slag in landfill. It should be noted that, the landfill process was selected from the PEF database. Therefore, these results should be taken with caution since the actual emission of this type of waste could have a minor impact on the environment.
- Regarding the present conditions of the landfills in the Basque Country and the commitment to enhance the economic circularity force to valorize the EAF slags without option to deliver them to landfill. Therefore, at present there is no option to send these EAF slag to landfill.

Table 6.14. Processes of the scenarios assessed.

Scenario A		**Avoided burden of the scenario B**	
A1-Transport to EAF recycling plant	A2-EAF processing	B1-Transport to landfill	B2-Avoided landfill

Table 6.15. LCIA impact per ton of EAF aggregate.

Impact category	**Scenario A**			**Scenario B**		
	A1	**A2**	**A1 +A2**	**B1**	**B2**	**A1+A2+B1+B2**
AP	2.47E-02	5.87E-03	3.06E-02	-2.30E-02	-1.60E-01	-1.52E-01
GWP100	2.43E+00	1.78E+00	4.22E+00	-2.26E+00	-2.74E+01	-2.54E+01
ET	5.68E-01	1.53E-01	7.21E-01	-5.28E-01	-4.71E+00	-4.51E+00
EPmw	1.19E-02	1.32E-03	1.33E-02	-1.11E-02	-4.77E-02	-4.56E-02
EPfw	1.04E-05	4.53E-06	1.50E-05	-9.72E-06	-4.02E-04	-3.97E-04
EPt	1.31E-01	1.41E-02	1.45E-01	-1.22E-01	-5.31E-01	-5.07E-01
HTc	3.04E-08	4.93E-09	3.53E-08	-2.82E-08	-2.99E-07	-2.92E-07
HTn-c	8.65E-08	7.20E-08	1.58E-07	-8.05E-08	-1.21E-05	-1.20E-05
IR	2.49E-03	3.26E-01	3.28E-01	-2.32E-03	-3.09E-01	1.73E-02
LU	8.08E+00	3.37E+01	4.18E+01	-7.51E+00	-1.22E+02	-8.74E+01
ODP	3.94E-12	3.62E-10	3.66E-10	-3.67E-12	-4.54E-11	3.17E-10
PM	1.63E-07	1.13E-07	2.76E-07	-1.52E-07	-1.75E-06	-1.63E-06
POCP	2.21E-02	3.86E-03	2.60E-02	-2.06E-02	-1.30E-01	-1.24E-01
ADP-F	3.26E+01	3.50E+01	6.75E+01	-3.03E+01	-3.58E+02	-3.21E+02
ADP-E	2.01E-07	6.79E-07	8.80E-07	-1.87E-07	-2.53E-06	-1.84E-06
Water use	1.43E-01	1.29E+00	1.44E+00	-1.33E-01	-2.10E+00	-7.99E-01

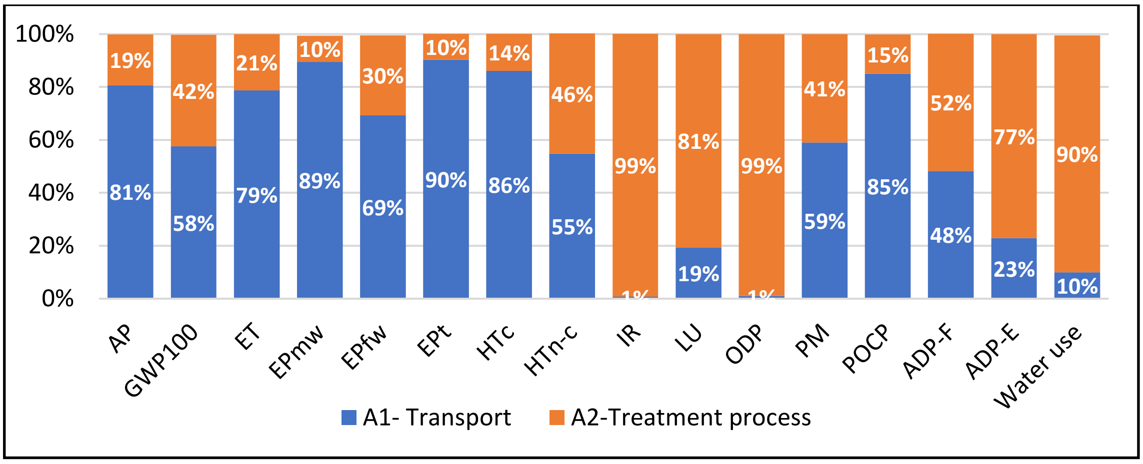


Fig. 6.9. Contribution of different process of the environmental impact. Based on characterised results. Scenario A: EAF aggregates.

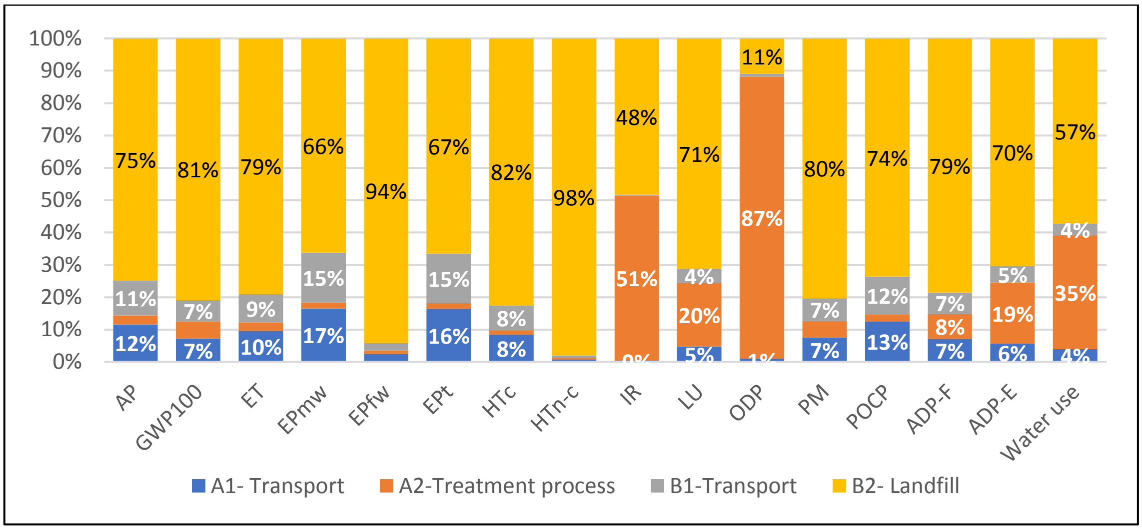


Fig. 6.10. Contribution of different process of the environmental impact. Based on characterised results. Scenario B: EAF aggregates.

The characterised results were weighted after its normalization to identify the most relevant impact categories. The results are shown in Fig. 6.11 for the scenario A and in ***Fig. 6.12***.for the scenario B.

Based on the normalised and weighted results, the most relevant impact categories for the scenario A are: Resource use (minerals and metals and fossils) ADP-F abiotic depletion, climate change (GWP), particulate matter (PM), acidification (AP) and photochemical ozone formation(POCP), for a cumulative contribution of 83% of the total impact. The most relevant impact categories correspond to those of scenario B for a cumulative contribution of 82.4 % of the total impact except for POCP.

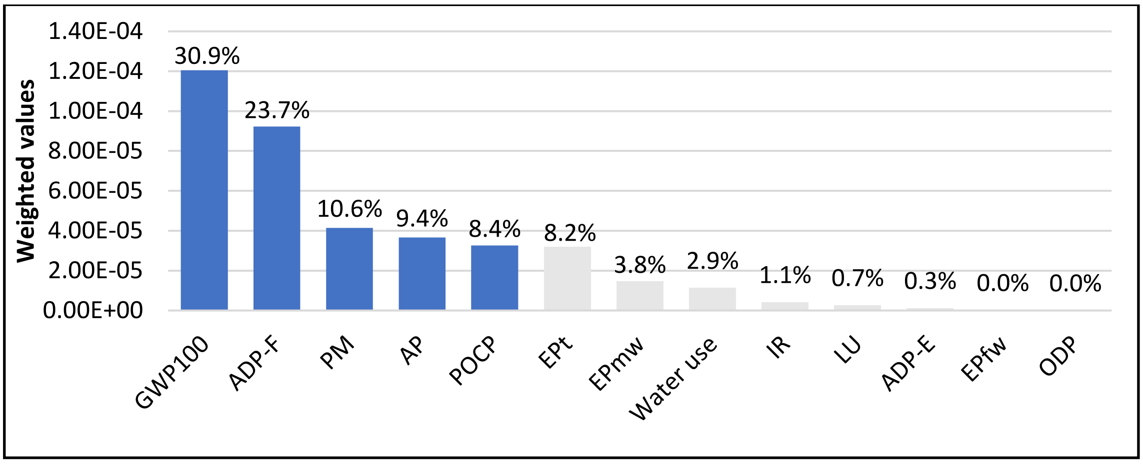


Fig. 6.11. Contribution of different impact categories based on normalised and weighted values. Scenario A: EAF aggregates.

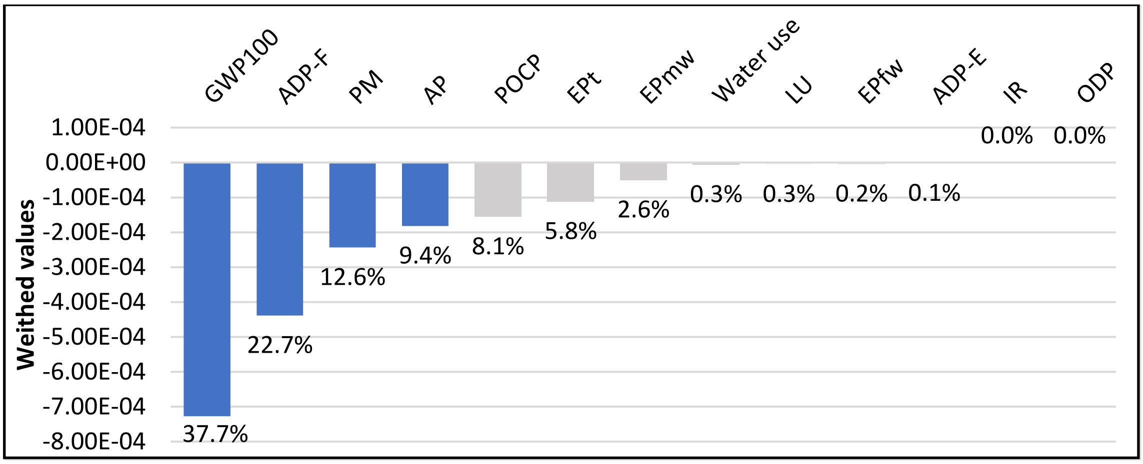


Fig. 6.12. Contribution of different impact categories based on normalised and weighted values. Scenario B: EAF aggregates.

Fig. 6.13 shows the contribution flows to each environmental impact for scenario A. Considering the most relevant categories, transport is responsible of between 48-58% of the emission of GWP, ADP-F and PM while for AP and POCP represent more than 80%. Hence, to reduce the environmental impact of EAF aggregates, the distance between the steelmaking facilities and the treatment plant must be reduced. It is only possible, by locating the treatment plant of EAF slag close as possible of the steelmaking or by using mobile recycling plant. However, for concrete application the distance from the treatment plant to the concrete mix plant should be also consider finding a balance. In the following section a sensitive analysis of the transport compared to the natural aggregates has been carried out.

In addition, with the technology upgrading, the use of electricity from renewable sources and the use of electricity or even biofuel for the vehicle could lead to greater protection of the environment.

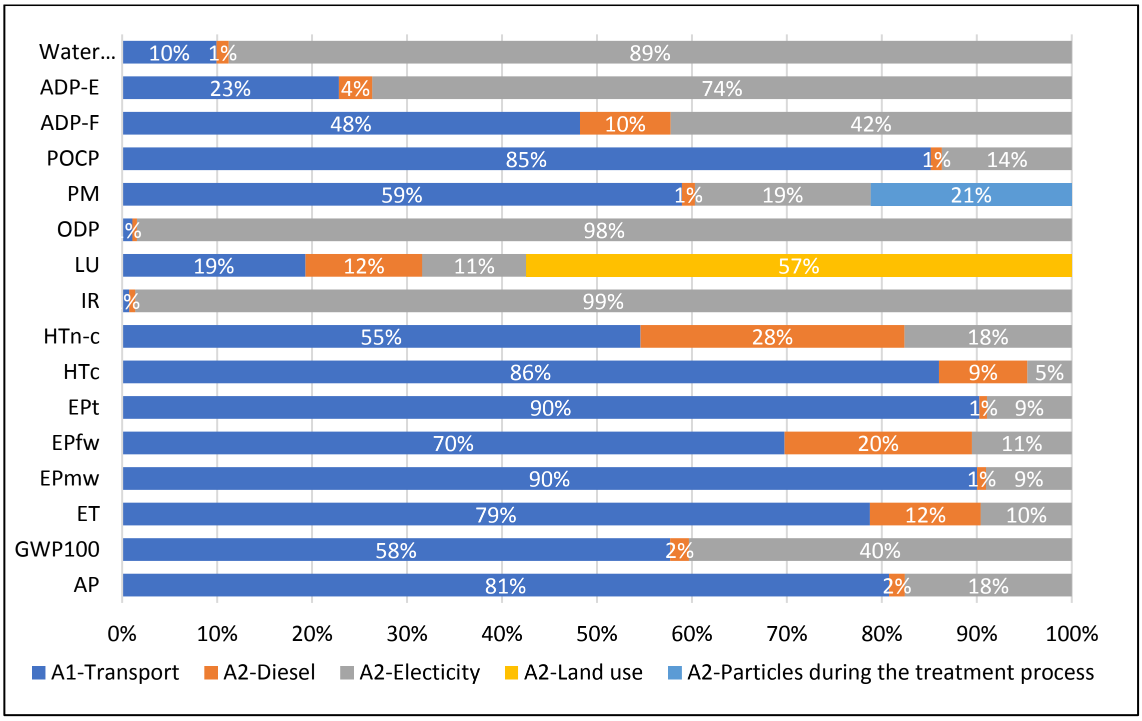


Fig. 6.13. Contribution of flows to the impact categories (Scenario A), based on characterized values.

6.5.2.1 Sensitive analysis of transport.

The sensitive analysis of transport from the steelmaking facilities to the treatment plant were considered for both scenarios A and B. The results were compared to the NL aggregates as reference to establish the limit transport distance of EAF slag. The analysis was carried out for the most relevant impact categories GWP, ADP-F, PM and AP (see Fig. 6.14). Finally, it was also assessed for the weighed impact results (see Fig. 6.15).

It should be noted that the transport from steelmaking company to landfill were kept constant (40km) in scenario B.

For the scenario A the production of EAF aggregates for the base case (40 tkm) is advantageous for fossil fuel resource use (ADP-F) and particle mater (PM) but its results disadvantageous for climate change (GWP) and acidification (AP) compared to natural aggregates. Considering the sum of the weighted impact values (see Fig. 6.15), for distance higher than 33 tkm the production of EAF aggregates results disadvantageous compared to the NL aggregates.

The scenario B includes the benefits of recycling avoiding the end on life of the EAF slag. For this scenario, the production of EAF aggregates is beneficial for all the assessed categories for more than 450 tkm excepting for the AP where the distances are limited at 300 tkm. Considering the sum of the weighted impact values (see ***Fig. 6.15***), for distance lower than 400 tkm the production of EAF aggregates results advantageous compared to the NL aggregates.

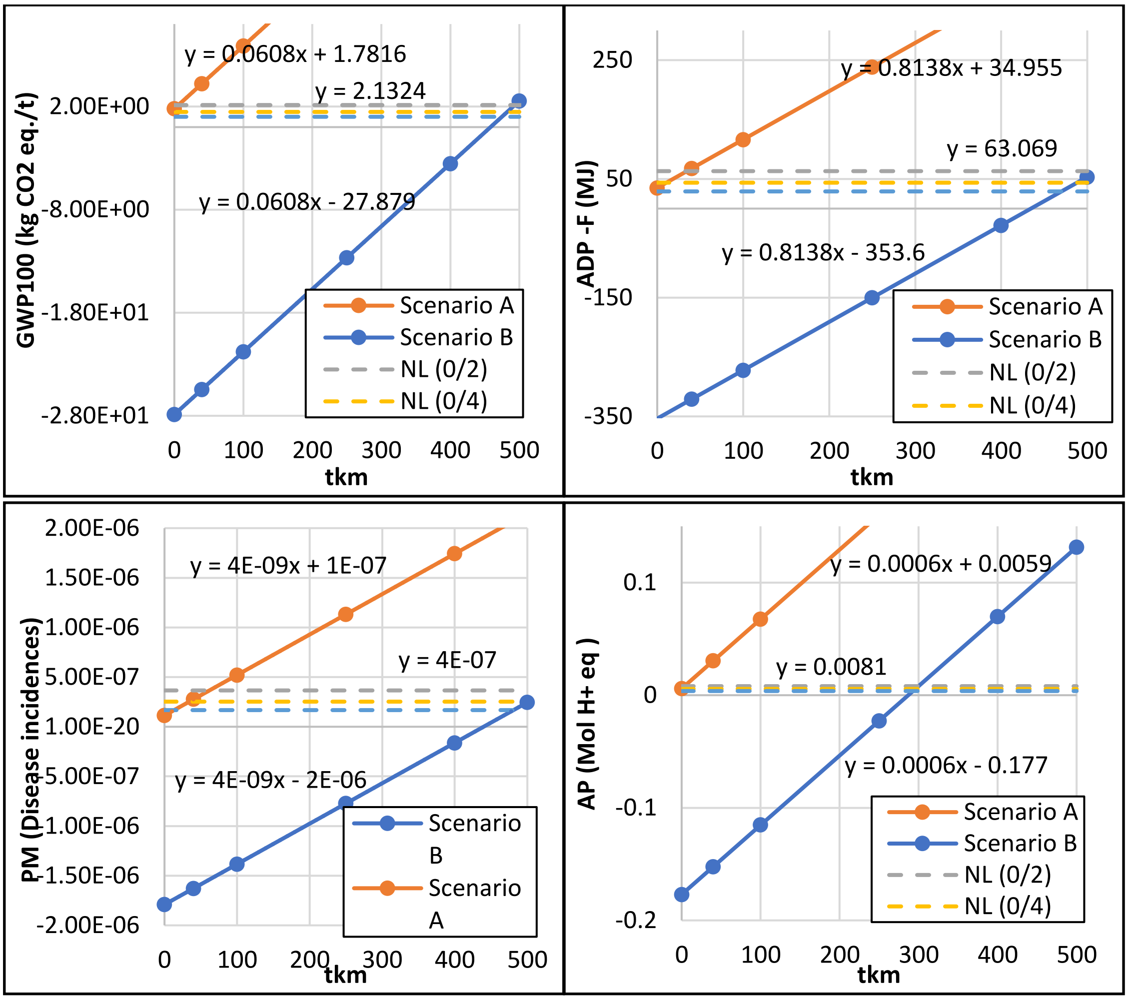


Fig. 6.14. Influence of the transport distance of EAF slag in the most relevant categories.

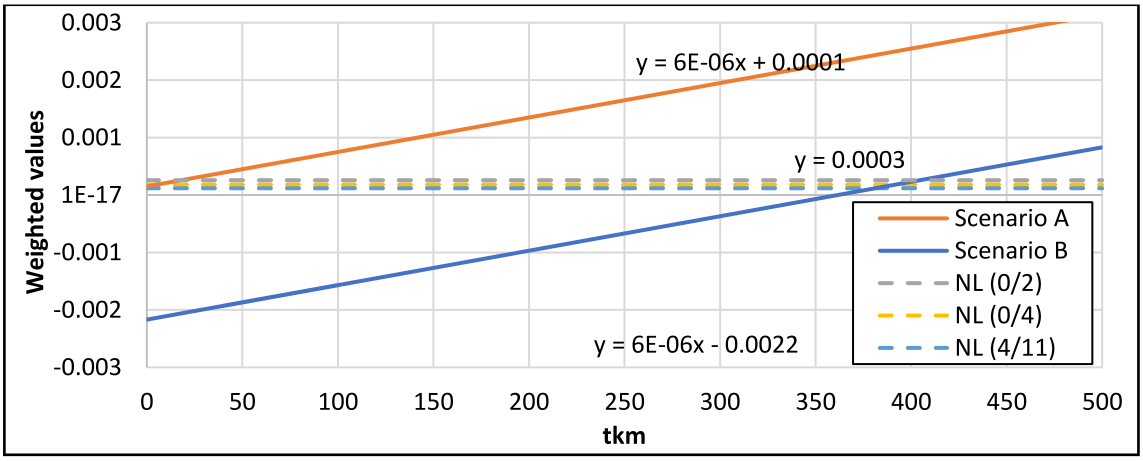


Fig. 6.15. Influence of transport distant of EAF slag in the global weighted results.

6.5.3 Recycled aggregates

For the RCA aggregates, two different scenarios have been considered to assess the environmental impact. In the first one (scenario A), the RCA is recycled from C&DW in a stationary recycling plant while in the second one (scenario B) the RCA is recycled from the rejected concrete fractions of a precast concrete company in a mobile crusher.

In both scenarios, only the recycling and transport process was considered, leaving the avoided boundaries related to the disposal of waste in the landfill outside of the system boundaries.

Table 6.16 show the environmental impact resulting from the production of the RCA aggregate and Fig. 6.16 include the relative impact of each impact categories comparing the both scenarios. Fig. 6.17 and Fig. 6.18 show the environmental impact contribution of each process. From these results, the following observation can be done:

- According to the characterized results, it is not possible to predict which scenario present the highest environmental benefit as differences between the impact categories can be found. Hence, to compare both scenarios the values were weighted after the normalization step to obtain the weighted value (see Table 6.17). The results show that the scenario A is slightly (4%) more environment-friendly than the scenario B. Considering that aggregates will be used to make concrete, the small difference may be supplied by the fact that the recycled aggregates are in the same recycling plant and therefore the impact of the RCA transport to the concrete manufacturing site is avoided.
- In the scenario A, transport is responsible of the most impact categories while for the scenario B, the treatment process is more influential. The differences are probably due to the type of energy used to feed the crusher. In the scenario A (stationary recycling plant) the crushers run with electricity while in the scenario B diesel is needed to feed the mobile crusher. The contribution impact of each flow can be seen in Fig. 6.19 and Fig. 6.20.

Table 6.16. LCIA impact per ton of RCA aggregate.

Impact category	Scenario A			Scenario B		
	A1	A2	A1+A2	B1	B2	B1+B2
AP	2.87E-02	3.10E-03	3.18E-02	1.07E-02	1.01E-02	2.08E-02
GWP100	2.83E+00	9.33E-01	3.76E+00	3.62E-04	1.63E+00	2.69E+00
ET	6.60E-01	8.93E-02	7.49E-01	2.46E-01	1.67E-02	1.93E+00
EPmw	1.39E-02	7.00E-04	1.46E-02	5.19E-03	1.55E+00	7.71E-03
EPfw	1.21E-05	2.69E-06	1.48E-05	4.54E-06	6.75E-02	6.37E-05
EPt	1.52E-01	7.44E-03	1.59E-01	5.68E-02	1.69E+00	8.04E-02
HTc	3.53E-08	2.94E-09	3.82E-08	1.32E-08	2.52E-03	7.88E-08
HTn-c	1.01E-07	4.24E-08	1.43E-07	3.76E-08	5.92E-05	9.18E-07
IR	2.89E-03	1.69E-01	1.72E-01	1.08E-03	2.36E-02	4.16E-02
LU	9.39E+00	5.63E+00	1.50E+01	3.51E+00	6.57E-08	1.06E+02

Impact category	Scenario A			Scenario B		
	A1	**A2**	**A1+A2**	**B1**	**B2**	**B1+B2**
ODP	4.58E-12	1.88E-10	1.93E-10	1.71E-12	8.81E-07	3.75E-11
PM	1.89E-07	1.12E-07	3.01E-07	7.07E-08	4.05E-02	1.93E-07
POCP	2.58E-02	2.04E-03	2.78E-02	9.61E-03	1.03E+02	1.58E-02
ADP-F	3.79E+01	1.89E+01	5.67E+01	1.41E+01	3.58E-11	1.43E+02
ADP-E	2.34E-07	3.56E-07	5.89E-07	8.72E-08	1.23E-07	7.09E-07
Water use	1.66E-01	1.06E+00	1.23E+00	6.21E-02	6.18E-03	4.27E-01

Table 6.17. Sum of all the weighed results for scenarios A and scenario B.

	Scenario A	Scenario B	Impact difference
Total weighted value	3.68E-04	3.84E-04	4.2%

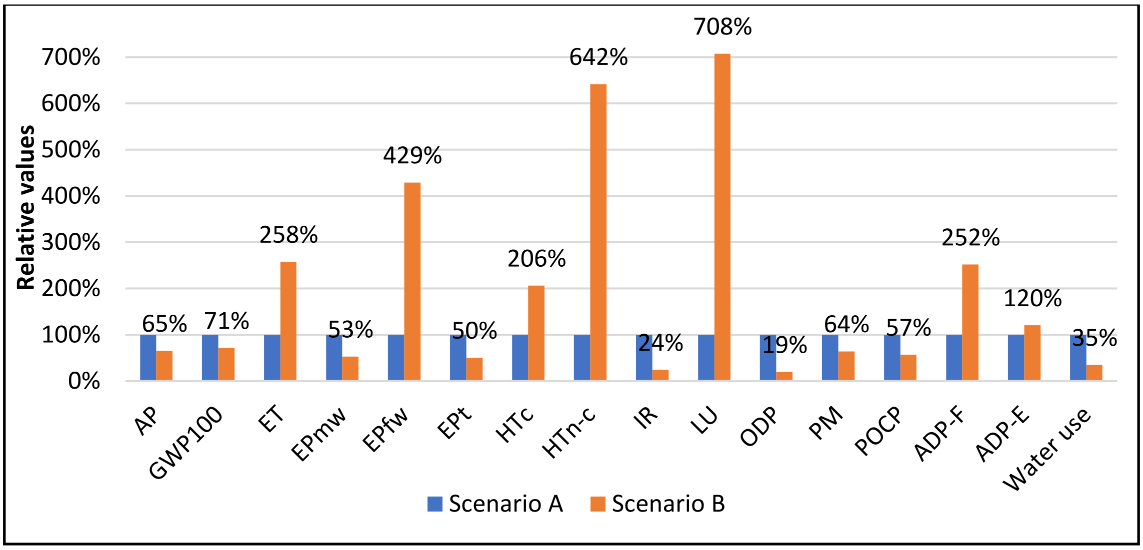


Fig. 6.16. Relative impact comparing both scenarios. RCA aggregates.

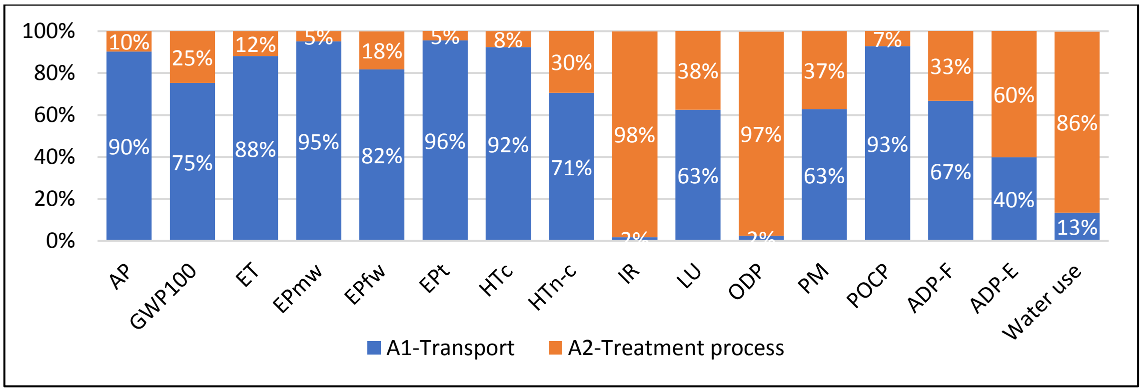


Fig. 6.17.Contribution of different process of the environmental impact. Based on characterised values. Scenario A: RCA aggregates.

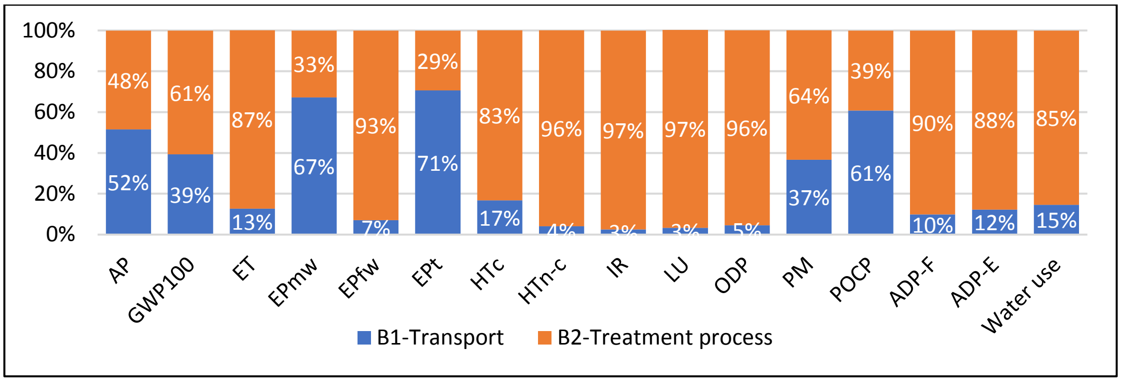


Fig. 6.18. Contribution of different process of the environmental impact. Based on characterised values. Scenario B: RCA aggregates.

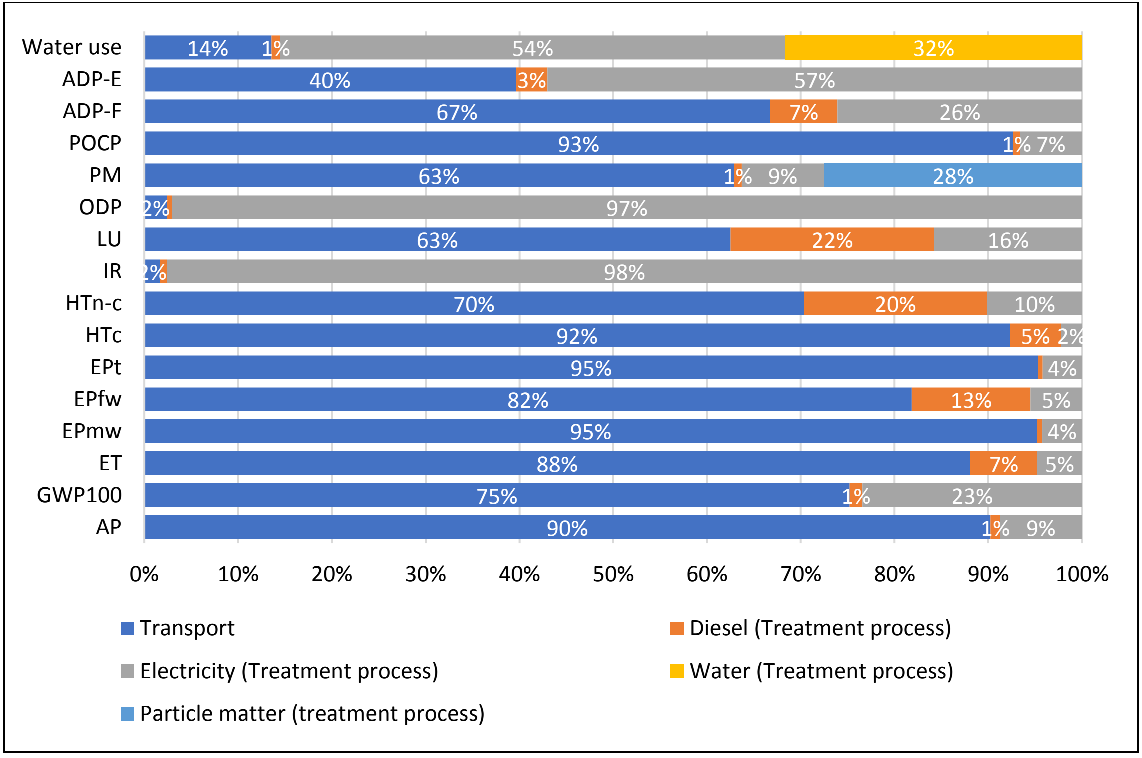


Fig. 6.19. Contribution of flows to the impact categories based on characterized values. Scenario A: RCA aggregates.

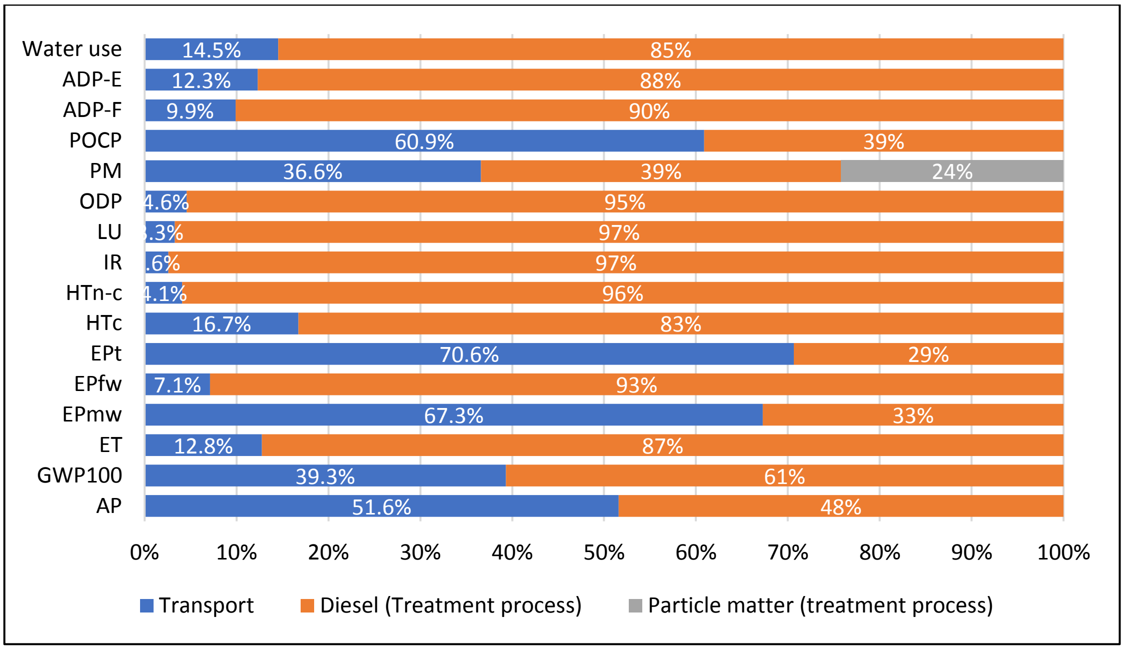


Fig. 6.20. Contribution of flows to the impact categories based on characterized results. RCA: Scenario B: RCA aggregates

Based on the normalised and weighted results, the most relevant impact categories for the scenario A are: climate change (GWP), Resource use (minerals and metals and fossils) (ADP-F), particle matter (PM) and Eutrophication, terrestrial (EPt).for a cumulative contribution of 82.4% of the total impact. In the case of scenario B, the most relevant impact categories correspond to those of scenario A. However, as expected due to the different energy systems during the treatment process, the ADP-F is the most relevant impact for scenario B, as diesel fuel consumption is higher.

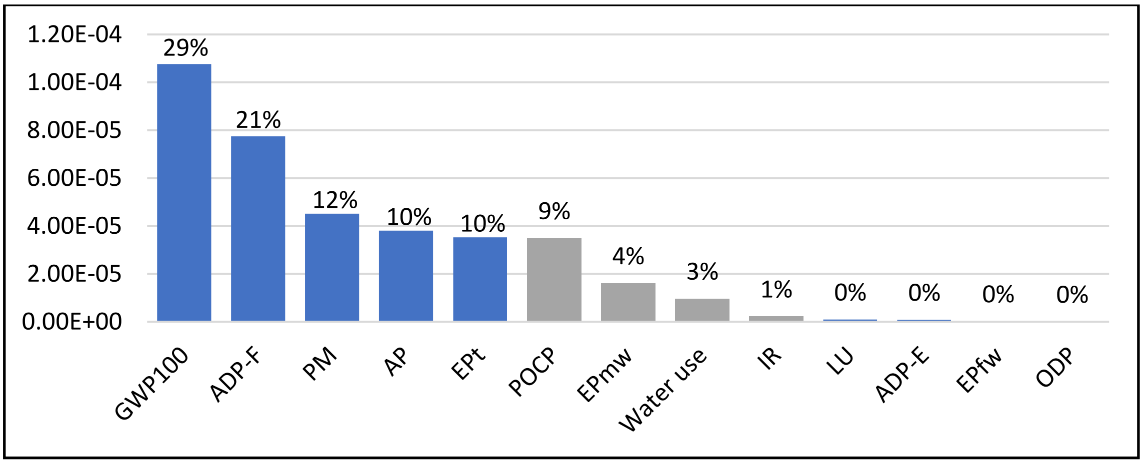


Fig. 6.21.Contribution of different impact categories based on normalised and weighted values. Scenario A: RCA aggregates.

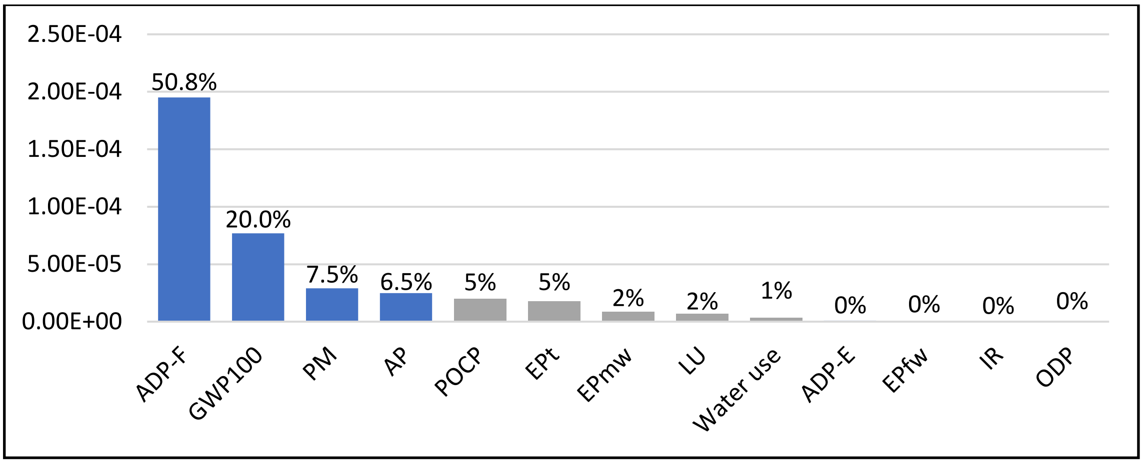


Fig. 6.22. Contribution of different impact categories based on normalised and weighted results. Scenario B: RCA aggregates.

Fig. 6.23 shows the transport influence in the environmental impact of both scenarios. As can be seen, for short distances the transport of the C&DW (scenario A) can results beneficial for the environmental impact. However, there is a limit (54 km in this study case) from which the displacement of the material has a greater impact than the transport of the equipment (scenario B).

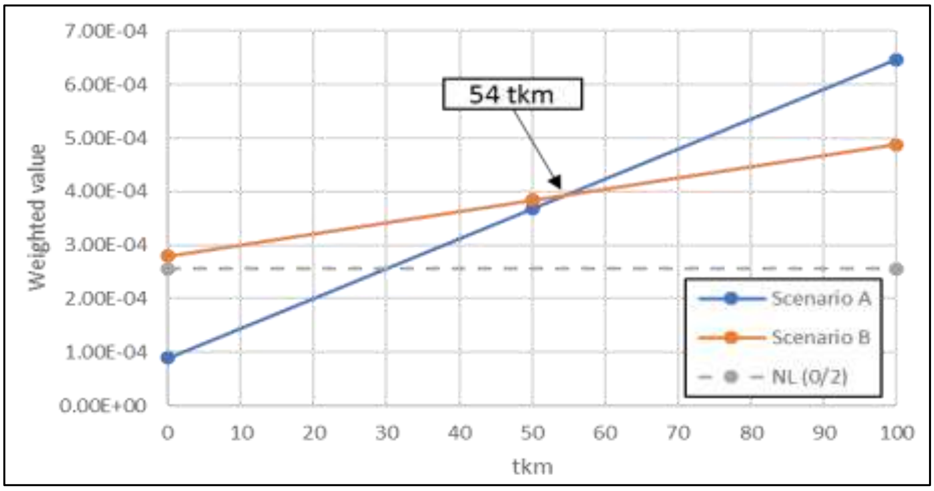


Fig. 6.23. Influence of transport distance in both RCA scenarios

6.5.4 Comparison

This section includes the comparison of all the production process of NL, EAF and RCA aggregates. With the aim of comparing all aggregate in the same conditions, only the emission related to the transport and treatment process has been considered. Hence, the scenario B of the EAF aggregate were not considered as it is also included the avoided impact. From an environmental point of view this would be the worst scenario, as the recycling benefits of the raw material scarcity and end-of-life impacts are not considered for the EAF and RCA aggregate.

The environmental impact of the aggregates was compared by means of the weighted results (see Table 6.18). Both the contribution of the different flows and the contribution of each environmental impact were represented in Fig. 6.25 and Fig. 6.24.

As can be seen the natural aggregates presents the lowest impact values as the facilities are strategically located to avoid the transport impact. For the EAF and RCA aggregates transport is the highest contributor excepting for the scenario B of the RCA for which the diesel consumption of the mobile crusher is the main responsible of the environmental impact. For the recycled aggregates (EAF and RCA) slight differences can be found in the total environmental impact. However, it can be observed that the treatment process of the scenario A of the RCA presents the lowest environmental impact even lower than for the natural aggregates. Therefore, a reduction of the transport distance could rank them as the best option from an environmental point of view. The environmental impact related to the treatment process of EAF aggregates is also lower than that of NL aggregates.

Concerning to the impact categories, climate change (GWP), abiotic depletion of fossil fuels (ADP-F) and particles matter (PM) can be established as the most affected during the aggregate production process. The acidification (AP), photochemical ozone formation, human health (POCP) and eutrophication, terrestrial (EPt) are also relevant for the EAF and RCA aggregate as its value increase with the use of transport.

Table 6.18. Total weighted values for each aggregate type.

Type of aggregate	Weighted value
NL (0/2)	2.56E-04
NL (0/4)	1.77E-04
NL (4/11)	1.17E-04
NL (11/22)	1.21E-04
EAF (Scenario A)	3.89E-04
RCA (Scenario A)	3.68E-04
RCA (Scenario B)	3.84E-04

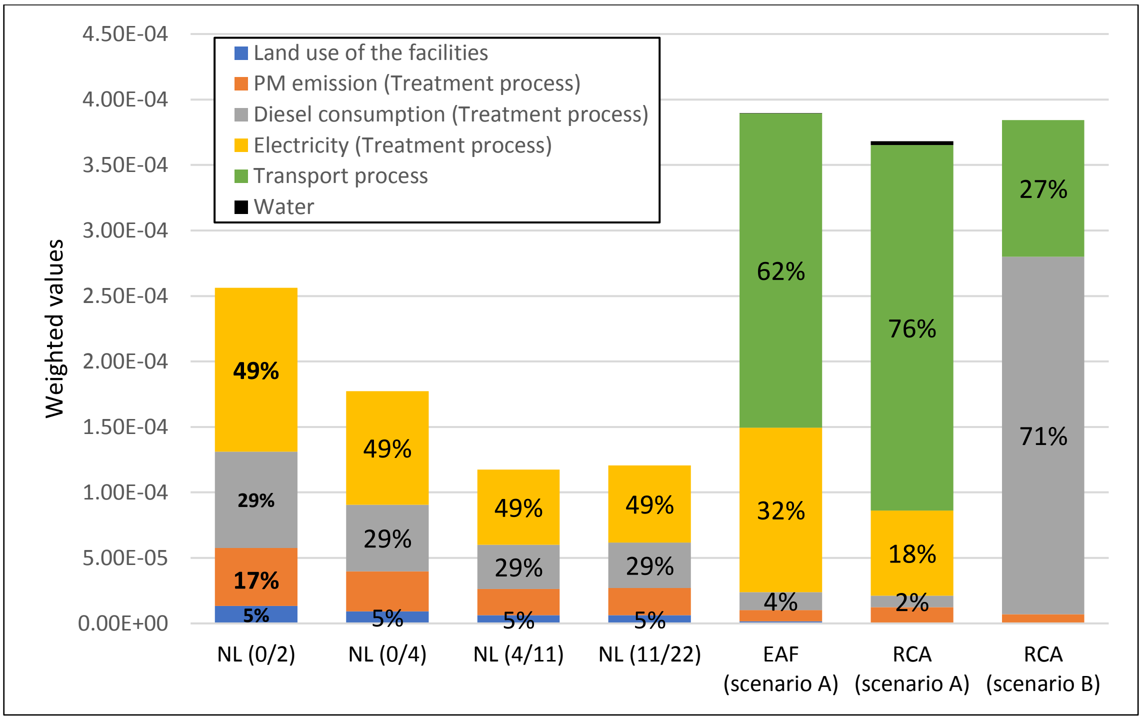


Fig. 6.24. Contribution of the flows on the aggregates impact. Based on weighted values.

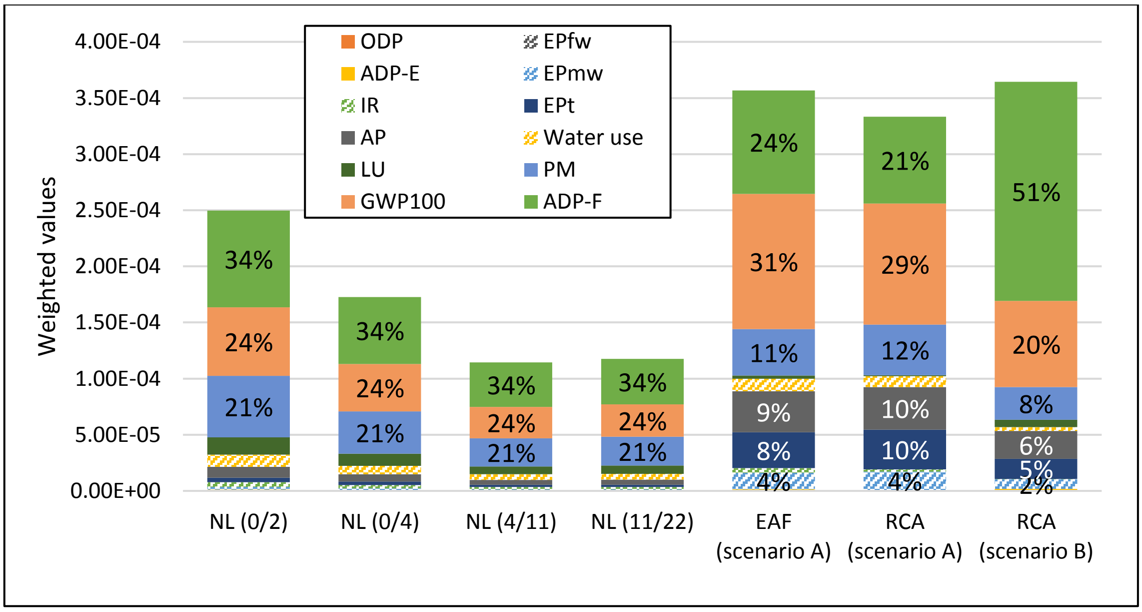


Fig. 6.25. Contribution of the impact categories on the aggregates impact. Based on weighted values.

6.6 Concrete assessment

17 concretes mixes for the 16 impact categories were analyzed to assess and to compare its economic and the environmental impact with the aim of understanding the

differences in the use of EAF aggregates instead of natural aggregates and to check the feasibility of use PPM to design concrete from a sustainable perspective.

In this regard, in a first approach the characterized impact results for each mix were calculated through an update version of the tool developed in the SUPERCONCRETE project(645704 - SUPERCONCRETE 2014). Then, the results were normalized and weighted, as explained in the methodology, to define the most relevant impact categories and the most relevant contribution material for each impact category; in other words, to identify the hotspots.

In a second approach, a single score of each of environmental impact were obtained from the weighted impacts and it was combined with the economic impact to obtain a comparative global index, as was explained in 6.4. Thus, all concrete mixes can be compared attending to environment, performance and economic requirement.

The environmental impact of the scenario A of the EAF aggregates has been selected to assess the environmental impact of concrete, since the govern of the Basque Country has recently established especial conditions for the dumping of some recoverable industrial waste in view of the deficit in the capacity of the landfills[26]. This announcement totally limits the delivery of EAF slag to landfill. Hence, the avoided impact burdens to landfilling were not considered.

6.6.1 SUPERCONCRETE tool

The tool developed in the SUPERCONCRETE project were designed to calculate the environmental and economic impact of concrete mix at raw material level attending to the impact categories registered in the EPD LCIA methodology (CML). However, with the development of PEF, the rules to perform the EPD are changing and the norm has been recently adapted to looking for the unification of the LCA studies. Therefore, the tool was used as reference by modifying and updating the impact categories and normalization and weighting factors according to PEF.

The characterized results of each concrete mix per m3·MPa and per m3are show in the annex (see Table A8 and Table A9). The maximum and minimum impact for each category has been highlighted in red and in green color respectively. It is possible to appreciate the differences in the results depending on the chosen functional unit.

Fig. 6.26 and ***Table 6.19*** shows the global environmental impact of each concrete mix. From these results the following observations can be done:

---

[26] https://www.euskadi.eus/gobierno-vasco/-/noticia/2020/medio-ambiente-establece-condiciones-para-el-vertido-de-algunos-residuos-industriales-valorizables-ante-el-deficit-de-capacidad-de-los-vertederos/

- Climate change (GWP100), resource use, fossils (ADP-F) and acidification (AP) are the most relevant impact categoriesfor a cumulative contribution of about 83% in all concrete mix. Photochemical ozone formation, human health (POCP) and particle matter (PM) have been also considered as the impact contribution is close to acidification impact. Therefore, in the effort to obtain more sustainable concretes, reducing the impact on these categories is key to reducing the environmental impact.
- Attending to the global impact results, the E-EAF-V1 presents the low impact following by the E-NL-V1, both mixes has been designed according to the range of maximum packing of aggregatesand the maximization of coarse aggregate fraction proportion and a low cement content260 kg/m^3.

  The 3-P-NL-V2 and the CPM-EAF-V2 presents the highest environmental impact. This concrete mix where designed attending to the maximum packing predicted by the 3-paramenters packing model and the compressible packing model (CPM) without considering the range of maximum packing. In addition, both mixes have a high cement content 317 kg/m^3.
- Seven (7) concrete mixes present a lower environmental impact than the average, four of them are made with EAF aggregates and only two of the EAF aggregate concrete mixes overcome the average value, EAF-q0.33 and CPM-EAF-V2. Both mixes were designed with a high cement content 326 and 317 kg/m^3 respectively. All the mixes with a lower environmental impact than the average value have conservative cement contents (lower than 270 kg/m^3) excepting the E-EAF-V2 which was designed to a cement content of 317 kg/m^3. Hence, the use of the EAF aggregates dosages through particles packing theories seem to be a promising alternative to reduce the environmental impact of concrete.
- Comparing the environmental impact of the NL-(47:53):41, NL-(60:40):50, NL-(50:50):50 and NL-(40:60):60 which were designed with the same cement content 300 kg/m^3 but different aggregates proportions, differences up to a maximum of 11% are observed in the global environmental impact. It should be noted that the mix with the low environmental impact (NL-(47:53):41) were designed through Fuller curve.
- The same happens when the E-NL-V1 and 3-P-NL-V1 (260 kg cement/m^3), E-NL-V2 and 3-P-NL-V2(317 kg cement/m^3), E-EAF-V1 and CPM-EAF-V1 (260 kg cement/m^3), E-EAF-V2 and CPM-EAF-V2(317 kg cement/m^3) are compared, finding environmental benefits of about 11-14% depending of the aggregate proportion and even environmental benefits of 22% by comparing E-EAF-V2 and CPM-EAF-V2.
- Despite the higher environmental impact of EAF due to the transport distance (see section 6.5.2) and the higher mass of EAF required to obtain the same volume of concrete due to its higher density, the environmental impact of EAF

concrete is similar or even lower than that of NL concrete when the compressive strength is considered.

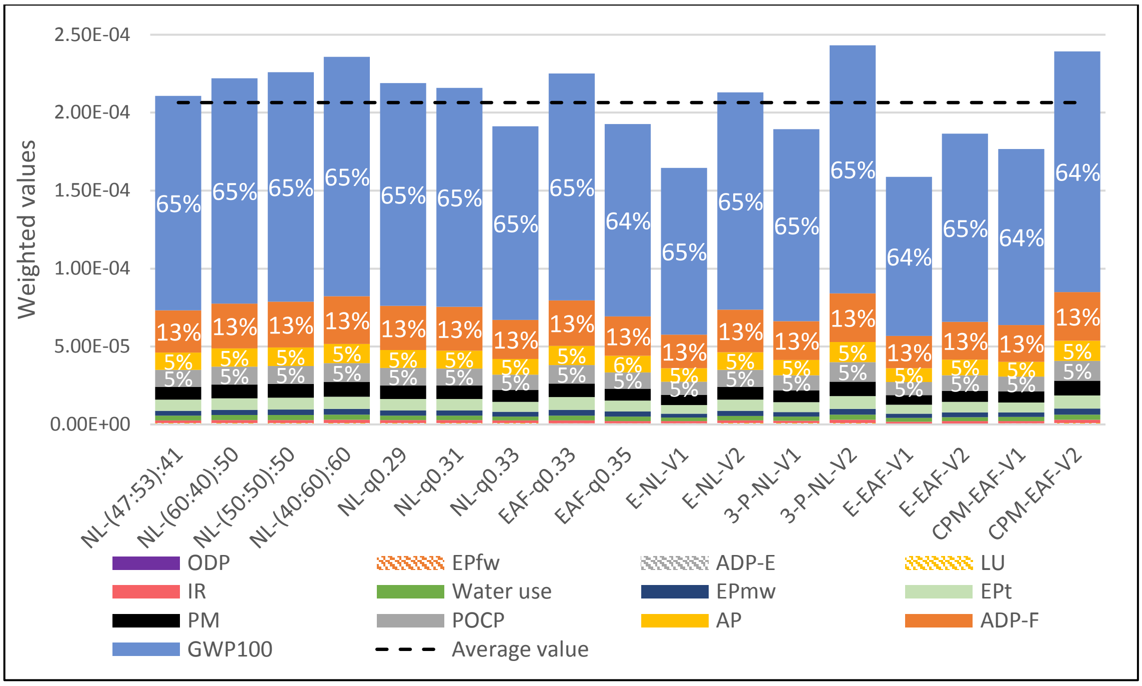


Fig. 6.26. Weighted environmental impact results of the concrete mix. Contribution of each impact category. Results per functional unit m³·MPa of concrete.

Table 6.19 includes the global environmental impact of concrete attending to two different functional units, m^3·MPa and m^3. The concrete mixes with the highest impact have been highlighted in rose and the mixes with the lowest impact in green. As can be seen, the concrete mixtures that have the greatest and least environmental impact do not match for the two selected functional units. This proves the importance of selecting an appropriate functional unit according to the function of the product.

The contribution results of the most relevant impact categories are depicted in Fig. 6.27. As can be seen, cement is responsible of more than the 80% of the impact in all categories and for the most relevant impact category (GWP100) represents almost the 100%.

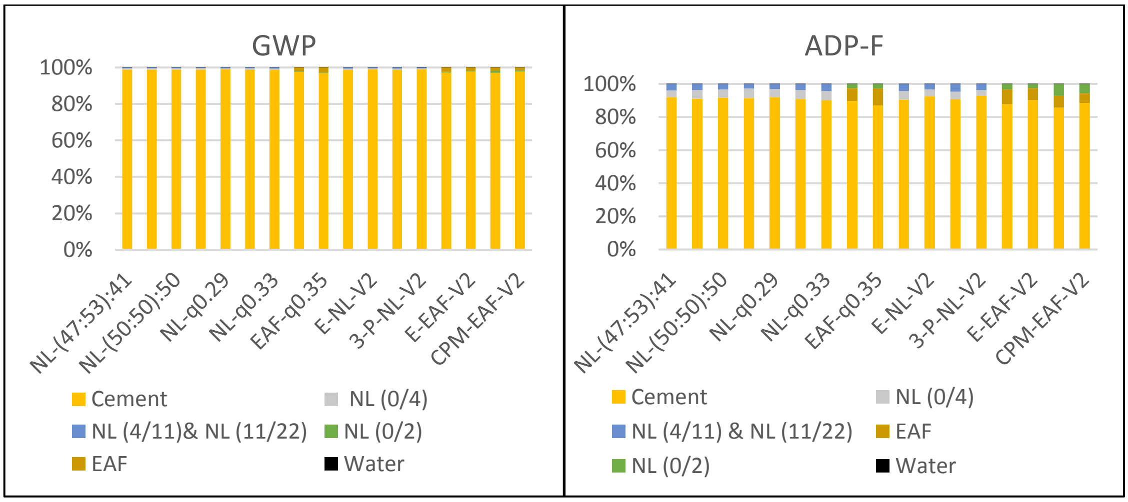
The aggregates production contributes about a 10% in the fossil a mineral resource use category (ADP-F). The impacts of this category are only related to the energy consumption during the treatment process of NL and EAF aggregates and the transport of the EAF aggregates. The limestone rock and the rest of the mineral have not any impact in this category since there are considered unlimited resources. However, at local scale the minerals sources are limited, and the impact related with its use should be considered in a near future.

Table 6.19. Global environmental impact for each concrete mix.

Concrete mix	Global EI (FU:m^3·MPa)	Global EI (FU:m^3)
NL-(47:53):41	2.11E-04	8.89E-03
NL-(60:40):50	2.22E-04	8.93E-03
NL-(50:50):50	2.26E-04	8.90E-03
NL-(40:60):60	2.36E-04	8.92E-03
NL-q0.29	2.19E-04	9.37E-03
NL-q0.31	2.16E-04	8.32E-03
NL-q0.33	1.91E-04	7.78E-03
EAF-q0.33	2.25E-04	1.02E-02
EAF-q0.35	1.93E-04	8.52E-03
E-NL-V1	1.65E-04	8.02E-03
E-NL-V2	2.13E-04	9.69E-03
3-P-NL-V1	1.89E-04	8.01E-03
3-P-NL-V2	2.43E-04	9.68E-03
E-EAF-V1	1.59E-04	8.24E-03
E-EAF-V2	1.86E-04	9.90E-03
CPM-EAF-V1	1.77E-04	8.30E-03
CPM-EAF-V2	2.39E-04	9.95E-03

The aggregates production contributes also to the particle matter (PM) (about 20% of the concrete impacts), since during the treatment process (crushing, grinding, sieving and handling) process different particles sizes are release to the air. Finally, the EAF aggregates contributes about 6-10% in the acidification and the photochemical ozone formation impacts (AP and POCP) due to the transport impact from the steelmaking company to the recycling plant.

The contribution of each concrete component in all the assessed impact categories can be seen in the annex section.



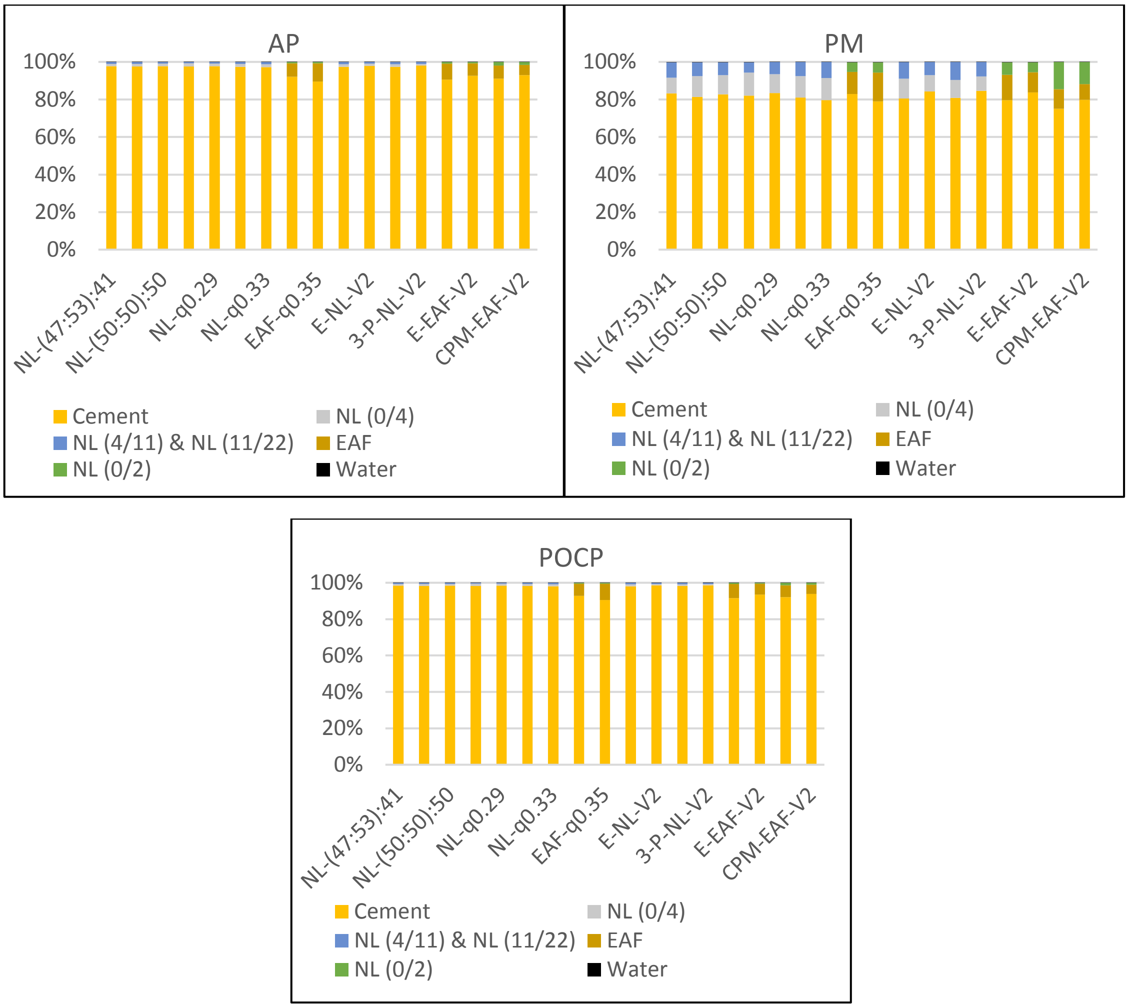
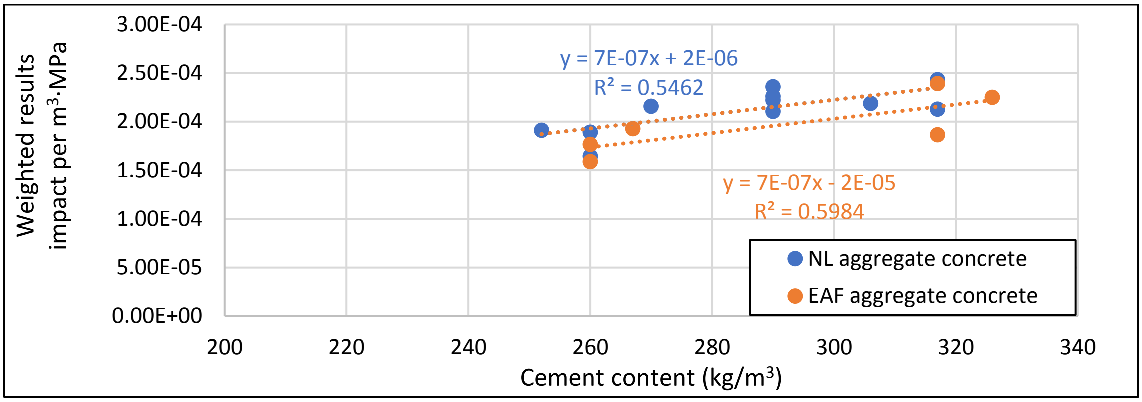


Fig. 6.27. Contribution of the concrete components to the concrete impact in the most relevant impact categories.

As cement production is the main process contributor in concrete manufacture it was expected that the concrete mix with lower cement content lead to a benefit in the environmental impact of the concrete mix. When the m^3 of concrete is considered as a functional unit (FU), the relationship of cement content and environmental impact fits perfectly into a linear regression (see Fig. 6.26). However, as shown in Fig. 6.26, when the compressive strength is also considered in the FU, this relationship is not clear, since the data does not fit well into a linear correlation and different environmental impacts can be observed for the same cement content. Therefore, the aggregates proportion influence in concrete environmental burdens. In addition, concretes with EAF aggregate tend to have a lower environmental impact than those made with natural aggregate, due to their higher mechanical strength to compression.



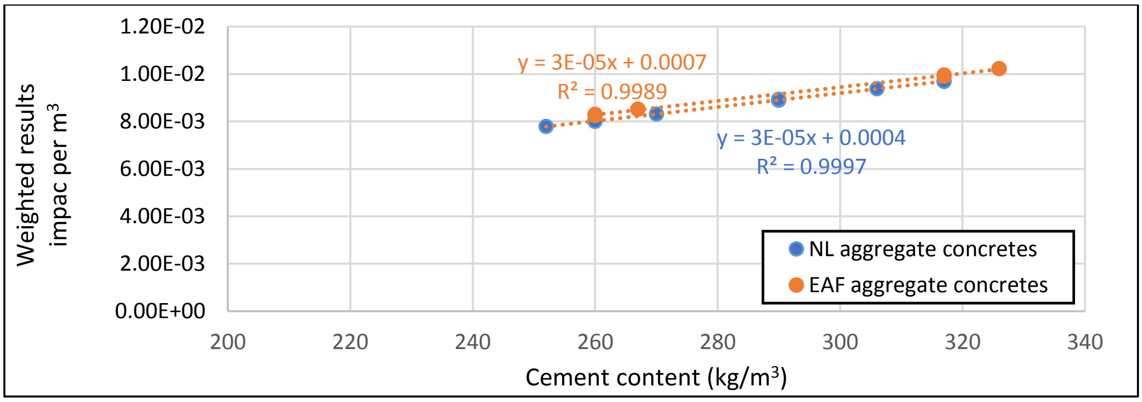


Fig. 6.28. Relationship between environmental impact and cement content. Top, Functional unit m^3·MPa; Above, Functional unit m^3

6.6.2 Sensitive analysis of EAF aggregates transport distance

Transport distance is one of the key aspects in the construction industry since significantly affects the environmental and economic impact. Therefore, the facilities of natural aggregates and cement are generally close to the concrete mix plant. However, when recycled products want to be valorized in construction application the facilities are not strategically located for minimize transport distance. Hence, distance should be carefully considered to prove the feasibility of the product.

Commonly, the distance of the EAF aggregate to the concrete plant is higher than the distance of the NL aggregate to the same location. To find the limit of the transport impact of EAF aggregates a sensitive analysis were carried out.

The NL aggregate concrete mixtures with the highest and lowest environmental impact were chosen as a reference. The transport analysis of three EAF concrete aggregates are depicted in ***Fig. 6.29***. The increment in the weighted impact results increase between 4.5% and8% per 100 km of distance. The limit for the most environmental concrete mix is of 50 km. It should be account that a distance of 40 km was also involved in the transport of the EAF aggregates according to the scenario A. Therefore, the limit of the total transport distance (from steelmaking company to treatment plant + from treatment plant to concrete mix plant) can be established at 90km. As can be seen, there are higher ranges (up to 500 and 700 km) when the mixtures are compares with the less environmental concrete mixtures.

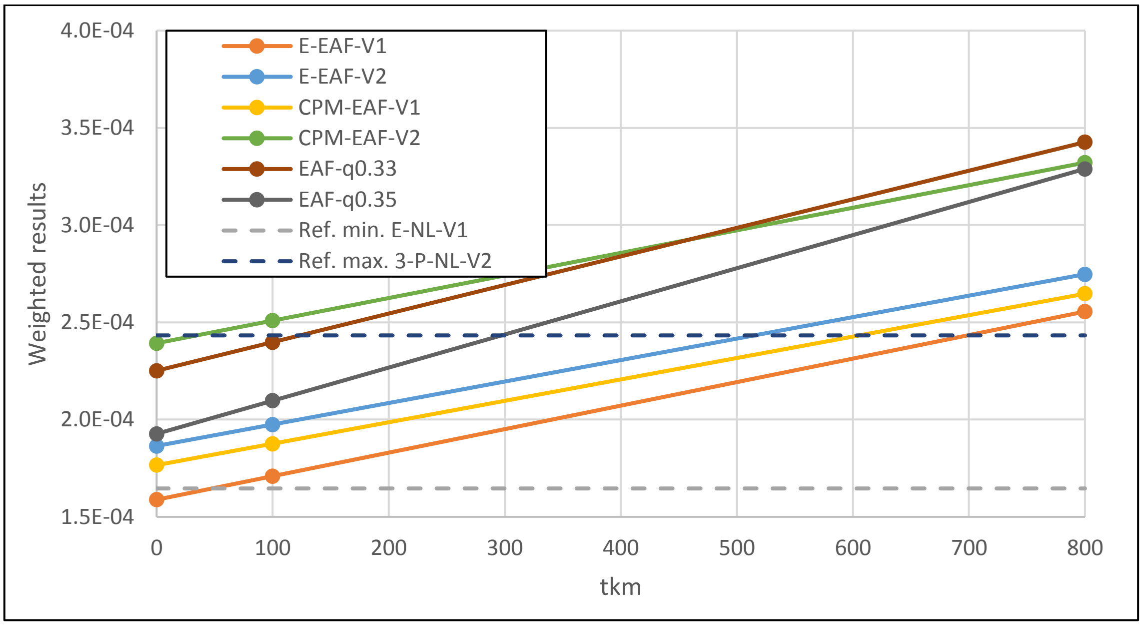


Fig. 6.29. Influence of different EAF concrete aggregates on transport distance

6.6.3 Economic and environmental impact. Global index

The economic impact of the concrete mixes was included in Fig. 6.30. Due to the differences in the compressive strength of the concrete mixes, the economic impact is also influence by the functional unit.

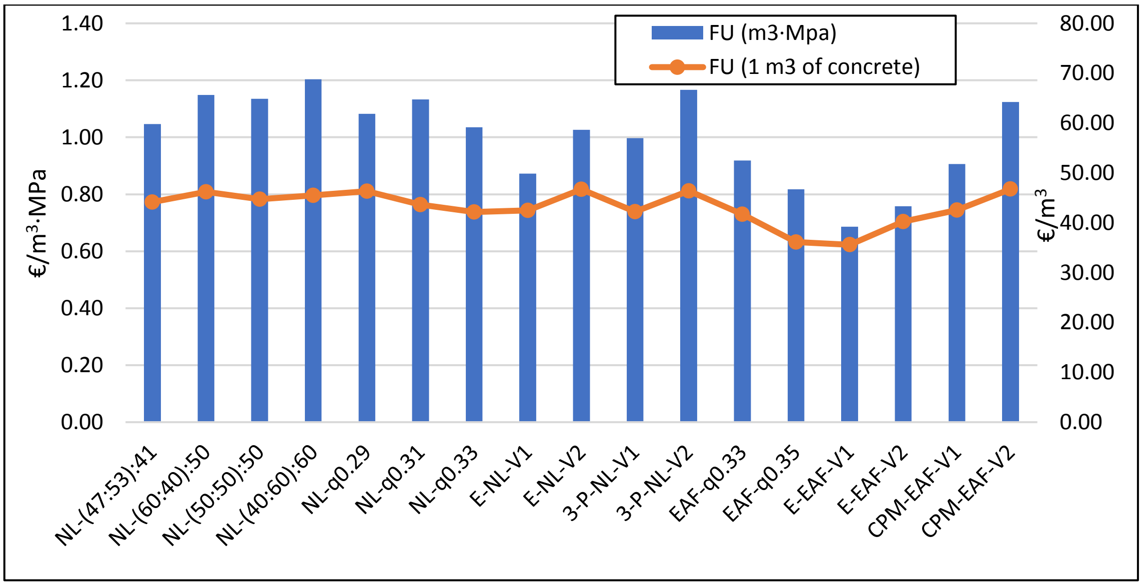


Fig. 6.30. Economic impact of concrete mixes

The contribution of each concrete component in the total cost were represented in Fig. 6.31. Its term of cost the cement is also the main contributor. However, the contribution is lower than for the environmental impacts, representing the between 56 to 74 % of the total impact depends on the type of concrete. As it can be observed cement cost is more relevant in EAF aggregate concrete mixes since the EAF aggregates are cheaper than the NL aggregates. In addition, the influence of the fine aggregates (NL (0/4) and NL (0/2)) is slightly higher compared to the coarse fraction and to the EAF aggregates.

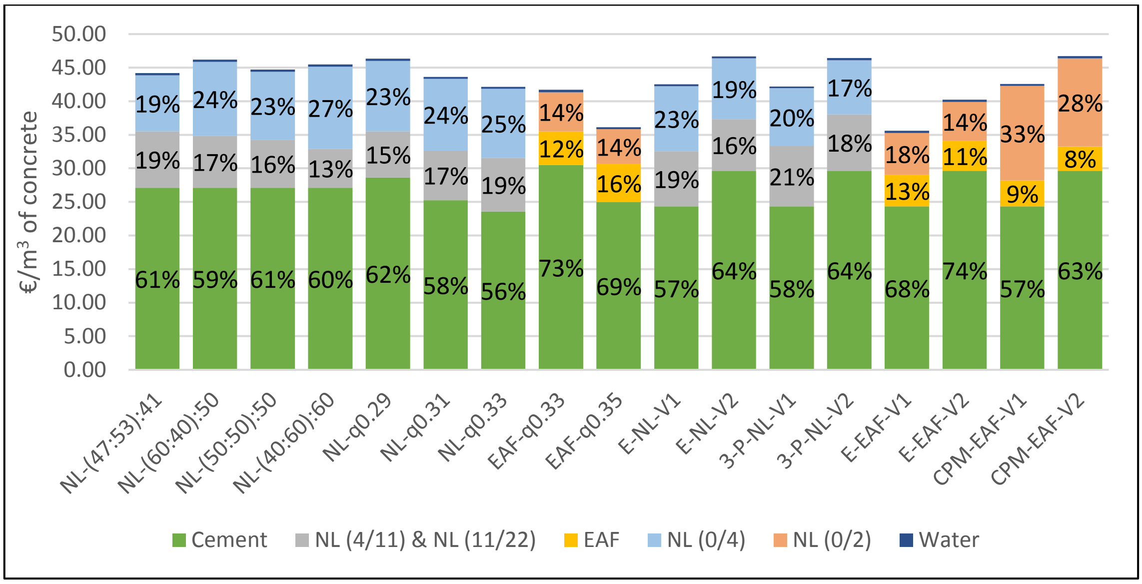


Fig. 6.31. Relative contribution of each concrete component in the global concrete cost.

Due to this fact, although the economic impact seems to increase as the cement content increases there is not a clear linear relationship between the price and the cement content as it shows in ***Fig. 6.32***, excepting for the NL aggregates concrete considering the m^3 as functional unit that a linear relationship can be observed. In the impact assessment considering the compressive strength of concrete, this happens because a higher cement content not always lead to a higher compressive strength as was concluded in chapter 5. In addition, in case of the EAF aggregates concretes the NL (0/2) and the cement content, both are the most influential factors in the economic impact of this concrete due to its high price compared to EAF aggregate. Therefore, the price of the material should be considered in the concrete mix design as the decision cannot be as simple as minimize the cement content.

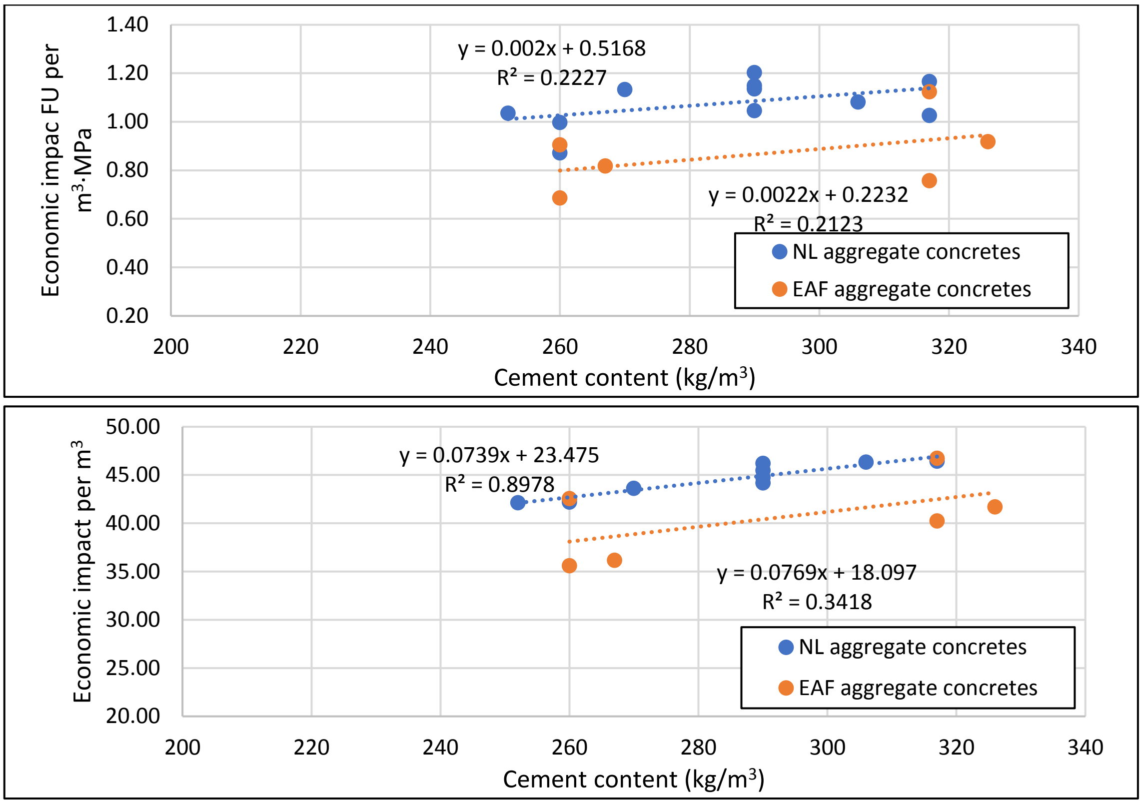


Fig. 6.32. Relationship between economic impact and cement content. Top, Functional unit m³·MPa; Above, Functional unit m³

Finally, with the aim of considering both criteria economic and environmental, a global index was calculated according to the method propose in section 6.4. The same weighting factor was established for both parameters and the results are shown in Fig. 6.33 and Table 6.20.

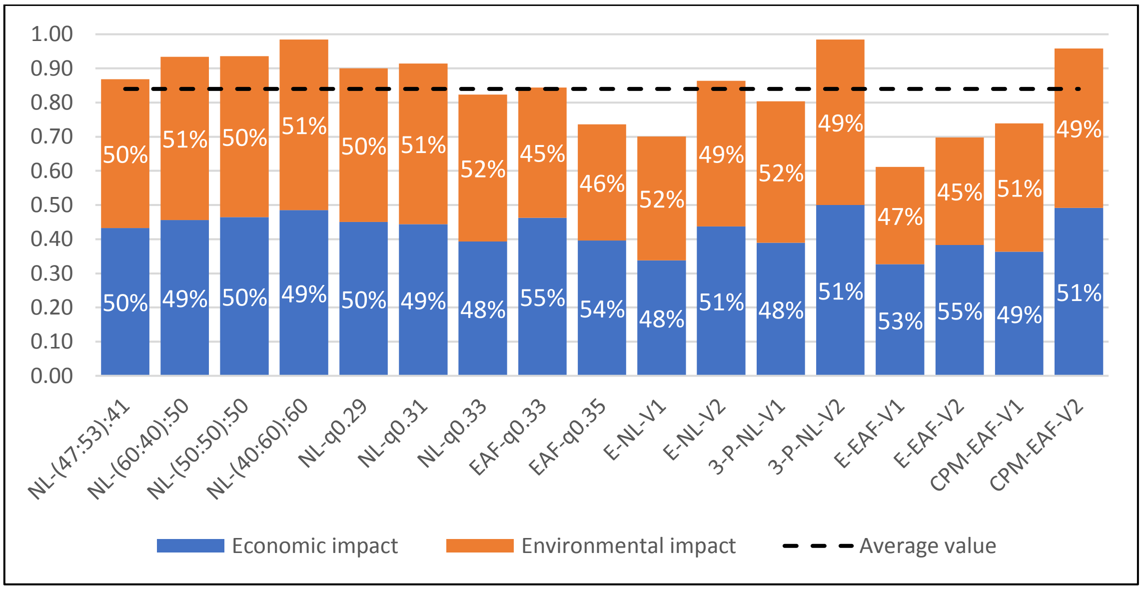


Fig. 6.33. Global index attending to economic and environmental criteria

E-EAF-V1, E-EAF-V2 and E-NL-V1 are the more sustainable concrete mixes according to the environmental and economic criteria (global index) (see Table 6.20). All three mixes were designed by maximizing the coarse aggregate content within the range of the maximum experimental packing density of aggregates. Hence, the combination of PPM and LCA assessment seem to be a promising alternative in the design of sustainable concrete mixes. In addition, the E-EAF-V1 and E-NL-V1 were designed with a low content of cement 260 kg/m^3 and consequently low workability (slump 0mm and 15mm), being only useful for application where high energy of compaction is applied, as rolled compacted concrete or precast concrete. By contrast, the E-EAF-V2 were designed with a cement content of 317 kg/m^3 and its slump results is 150mmresulting in a fluid consistency according to the EHE-08. It should be noted, that admixtures where no added, therefore the workability properties could be improved by using them.

Considering the 5 concrete mixes with the lowest global index impact, it can be found, that four of them are EAF aggregate concretes. Hence, the use of EAF aggregates seem to be competitive alternative of the NL aggregate. In addition, its valorization goes through a circular economic avoiding the sending to landfill of waste and the use of natural resources.

Table 6.20. Concrete mixes ranked according to the global index.

Concrete ID	Environmental impact	Economic impact	Global Index
NL-(40:60):60	0.97	1.00	0.98
3-P-NL-V2	1.00	0.97	0.98
CPM-EAF-V2	0.98	0.93	0.96
NL-(50:50):50	0.93	0.94	0.94
NL-(60:40):50	0.91	0.96	0.93
NL-q0.31	0.89	0.94	0.91
NL-q0.29	0.90	0.90	0.90
NL-(47:53):41	0.87	0.87	0.87
E-NL-V2	0.88	0.85	0.86
EAF-q0.33	0.93	0.76	0.84
NL-q0.33	0.79	0.86	0.82
3-P-NL-V1	0.78	0.83	0.80
CPM-EAF-V1	0.73	0.75	0.74
EAF-q0.35	0.79	0.68	0.74
E-NL-V1	0.68	0.73	0.70
E-EAF-V2	0.77	0.63	0.70
E-EAF-V1	0.65	0.57	0.61

As can been seen in Fig. 6.34, the global index decreases as the compressive strength increases for both types of concrete. However, although there is a tendency for the overall index to increase as the cement content increases, the relationship is not totally lineal as there are concrete mixtures with the same cement content that have large differences in the global index.

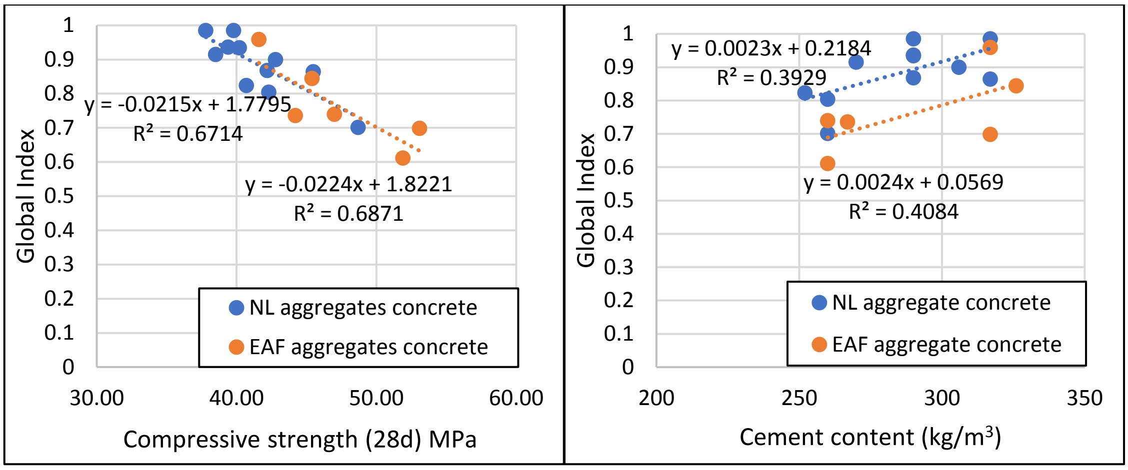


Fig. 6.34. Effect of compressive strength and cement content in the global index

6.7 Conclusions

A regional LCI of the NL and EAF aggregates for the production process in the Basque Country has been developed to further LCA studies. In addition, the environmental impact related to both materials has been assessed according to the recent PEF life cycle impact, which can be useful for the development of future an updated EPD.

The environmental impact assessment of the NL aggregates through economic allocation has permitted to define the environmental impact for each aggregate size fraction. Thus, differences up to 53% were found for finer fraction (NL (0/2)) compared to the coarse fractions.

Concerning to the environmental impact of EAF aggregate, transport process is responsible for more than 50% of the impact in the most relevant categories (GWP, ADP-F, PM, AP and POCP). When the avoided burden to EAF slag disposal in landfill is considered (scenario B that considers also the avoided environmental burden of delivering to landfill the EAF slags), the environmental impact results beneficial for all impact categories as the disposal of inert wastes produces greater environmental impact than the transportation and processing of the EAF slags.

The sensitive analysis of EAF aggregate transport distance revealed that the EAF aggregate production is environmental feasible compared to the NL aggregate for distance of less than 33 km. For the scenario B, distance up to 400 km was found beneficial from an environmental perspective.

The two analyzed scenarios of the RCA aggregates shown slightly differences in the environmental impact (4%).However the transport process is the main impact contributor (76%) for the scenario A (RCA recycled from C&DW in a stationary recycling plant) while the diesel consumption of the mobile crusher is responsible of the 71% of the total weighted impact valuefor the scenario B (RCA recycled from the rejected concrete fractions of a precast concrete company in a mobile crusher).

In the Basque Country, the environmental impact of the treatment process of EAF and RCA aggregates in a stationary plant is similar or even lower than for the NL aggregate production. However, the material transport conducts to a higher impact of the EAF and RCA. Hence, NL aggregates present the lowest environmental impact as the treatment facilities are strategy located next to the quarries to avoid the transport impact. It should be also noted that if the avoided environmental burden from waste disposal in landfill is considered, the benefit of recycling is included and therefore, at least for the EAF aggregate, the environmental impact result negative, which is possitive.

Cement is responsible for more than the 80% of the environmental impact in the most relevant impact categories of concrete, being close to the 100% for the climate change impact category (GWP). This fact is due to the simplicity and relative low energy consumption of the aggregate production against the CO_2 released during the calcination process of the limestone that account for more than the 50% of cement Portland production process. The highest contribution of the aggregate can be found in the use of resource fossil fuel (ADP-F) and the emission of particle matter (PM), accounting about 10% and 20% of the total impact contribution respectively. The EAF aggregates also contributes between 6 to 10% on the AP and POCP mainly due to the transport process.

Contrary as it can be expected, a higher cement content does not necessary lead to a high environmental impact when the concrete compressive strength is considered in the FU. Therefore, although aggregate has low influence in the environmental impact, environmental benefits between 11-14% has been found in both types of concrete, due to the aggregate skeleton design within the range of maximum packing density of aggregates and the maximization of the coarse aggregate proportion.

In addition, although the EAF aggregates present a environmental impact higher than the NL aggregates in the proposed local scenario (due to the transport stage), it was found that the concrete made with EAF aggregates contributes, in general, to a reduction of the environmental impact and cost.

The sensitive analysis of EAF aggregate transport distance revealed that the use of EAF aggregate as replacement of NL aggregate is environmental feasible for distance of 50 km and up to 90 km if the transport from steelmaking company to the treatment plant is also considered. Longer distance up to 700 km were found feasible comparing all the EAF aggregate concrete mix with the natural aggregate mix with the highest environmental impact. To determine the economic and environmental feasibility the transport cost should be further analyzed.

Although cement is the most expensive material in concrete mix, the higher concrete cost does not match with the higher cement content. The cement cost contributes between 56 to 74% of the total material concrete cost, being most relevant in EAF aggregate concrete due to the low price of the EAF aggregates. The use of the NL (0/2) to improve the granular size distribution in EAF aggregate concrete accounts for half or even more of the total price of the aggregates due to its high price compared to EAF aggregates. Consequently, the amount of NL (0/2) in the EAF aggregates must be optimised as much as possible to obtain the required functional properties without significantly impairing the economical and environmental, respectively impacts.

In line with the findings of other authors (Braga et al. 2017), the higher environmental impacts are not always related to greater cost. Therefore, the use of the global index that includes environmental and economic criteria could support decision making in comparing different dosages of concrete.

As the cost of the EAF aggregates is lower than the NL aggregate, the global index results again beneficial for the concrete mix made with EAF aggregates. The most sustainable concrete mix attending to economic and environmental criteria match again with the aggregate mix design proposed in chapter 5.

6.8 References

645704 - SUPERCONCRETE (2014) *SUstainability-driven international/intersectoral Partnership for Education and Research on modelling next generation CONCRETE*. Available at: http://www.superconcrete-h2020.unisa.it/.

Anastasiou, E. K., Liapis, A. and Papachristoforou, M. (2017) 'Life Cycle Assessment of Concrete Products for Special Applications Containing EAF Slag', *Procedia Environmental Sciences*. The Author(s), 38, pp. 469–476. doi: 10.1016/j.proenv.2017.03.138.

Athena Sustainable Materials Institute (2016) *A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members - Version 2.0*. Available at: https://www.nrmca.org/sustainability/EPDProgram/Downloads/NRMCA_LCA_ProjectReportV2_20161006.pdf.

Braga, A. M., Silvestre, D. and Brito, J. De (2017) 'Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates', 162(2017). doi: 10.1016/j.jclepro.2017.06.057.

CEDEX (2011) 'Ficha técnica escorias de horno de arco eléctrico', *Cedex*, 2.3, pp. 1–19. Available at: http://www.cedex.es/NR/rdonlyres/22980D5E-377B-4697-AEFE-CE897A68963D/119858/ESCORIASDEACERIADEHORNODEARCOELECTRICO.pdf.

Chen, C., Habert, G., Bouzidi, Y., Jullien, A. and Ventura, A. (2010) 'Resources , Conservation and Recycling LCA allocation procedure used as an incitative method for waste recycling : An application to mineral additions in concrete', *'Resources, Conservation & Recycling'*. Elsevier B.V., 54(12), pp. 1231–1240. doi:

10.1016/j.resconrec.2010.04.001.

Colegio oficial de aparejadores, arquitectos técnicos e ingenieros de edificación de G. (2019) 'Precio de la construcción centro'.

Consejería de agricultura, ganadería, pesca y desarrollo sostenible (2019) *Guía de apoyo para la notificación de las emisiones en explotaciones a cielo abierto y canteras*.

DECRETO 64 (2019) *DECRETO 64/2019, de 9 de abril, del régimen jurídico aplicable a las actividades de valorización de escorias negras procedentes de la fabricación de acero en hornos de arco eléctrico.* Available at: https://www.euskadi.eus/gobierno-vasco/-/eli/es-pv/d/2019/04/09/64/dof/spa/html/.

Durão, V., Silvestre, J. D., Mateus, R. and de Brito, J. (2020) 'Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes', *Resources, Conservation and Recycling*. Elsevier, 156(January), p. 104703. doi: 10.1016/j.resconrec.2020.104703.

EC-JRC (2012) 'Product Environmental Footprint (PEF) Guide', *Eropean Commision Joint Research Centre*, p. 154. doi: Ares(2012)873782 - 17/07/2012.

European Union (2008) 'Directive 2008/98/EC of the European parliament and of the council on waste and repealing certain directives.', p. L312: 3–30.

Evangelista, B. L., Rosado, L. P. and Penteado, C. S. G. (2018a) 'Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute', *Journal of Cleaner Production*. Elsevier Ltd, 178(February), pp. 176–185. doi: 10.1016/j.jclepro.2018.01.007.

Evangelista, B. L., Rosado, L. P. and Penteado, C. S. G. (2018b) 'Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute', *Journal of Cleaner Production*, 178, pp. 176–185. doi: 10.1016/j.jclepro.2018.01.007.

Faleschini, F., De Marzi, P. and Pellegrino, C. (2014) 'Recycled concrete containing EAF slag: Environmental assessment through LCA', *European Journal of Environmental and Civil Engineering*, 18(9), pp. 1009–1024. doi: 10.1080/19648189.2014.922505.

Favier, A., de Wolf, C., Scrivener, K. and Habert, G. (2018) *A sustainable future for the european cement and concrete industry. Technology assessment for full decarbonisation of the industry by 2050*. Switzerland.

Fazio, S., Castellani, V., Sala, S., Schau, E., Secchi, M., Campori, L. and Diaconu, E. (2018) *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method*. doi: 10.2760/671368.

Filippo, J. Di, Karpman, J. and Deshazo, J. R. (2018) 'The impacts of policies to reduce CO 2 emissions within the concrete supply chain', *Cement and Concrete Composites*. Elsevier, (August), pp. 1–16. doi: 10.1016/j.cemconcomp.2018.08.003.

Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. and Spielmann, M. (2007) *Overview and Methodology. Ecoinvent report No. 1*. Available at:

https://www.ecoinvent.org/files/200712_frischknecht_jungbluth_overview_methodology_ecoinvent2.pdf.

García-Gusano, D., Herrera, I., Garraín, D., Lechón, Y. and Cabal, H. (2014) ‘Life cycle assessment of the Spanish cement industry: implementation of environmental-friendly solutions’, *Clean Technologies and Environmental Policy*, pp. 59–73. doi: 10.1007/s10098-014-0757-0.

Gursel, P., Masanet, E., Horvath, A. and Stadel, A. (2014) ‘Life-cycle inventory analysis of concrete production: A critical review’, *Cement and Concrete Composites*. Elsevier Ltd, 51, pp. 38–48. doi: 10.1016/j.cemconcomp.2014.03.005.

Hossain, M. U., Poon, C. S., Lo, I. M. C. and Cheng, J. C. P. (2016a) ‘Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA’, *Resources, Conservation and Recycling*. Elsevier B.V., 109, pp. 67–77. doi: 10.1016/j.resconrec.2016.02.009.

Hossain, M. U., Poon, C. S., Lo, I. M. C. and Cheng, J. C. P. (2016b) ‘Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach’, *International Journal of Life Cycle Assessment*, 21(1), pp. 70–84. doi: 10.1007/s11367-015-0988-2.

Hossain, M. U., Poon, C. S., Lo, I. M. C. and Cheng, J. C. P. (2017) ‘Comparative LCA on using waste materials in the cement industry: A Hong Kong case study’, *Resources, Conservation & Recycling*, 120, pp. 199–208. doi: 10.1016/j.resconrec.2016.12.012.

ISO 14040 (2006) ‘Environmental management - Life cycle assessment - Principles and framework’.

Kittipongvises, S. (2017) ‘Assessment of environmental impacts of limestone quarrying operations in Thailand’, *Environmental and Climate Technologies*, 20(1), pp. 67–83. doi: 10.1515/rtuect-2017-0011.

Penteado, C. S. ., Rosado, L. . and Lopes, A. . (2015) ‘Life cycle assessment of construction and demolition waste from small generators’, in *Fifteenth International Waste Management and Landfill Symposium*. Sardania, pp. 196–205. Available at: https://www.researchgate.net/publication/284727258_Life_Cycle_Assessment_of_Construction_and_Demolition_Wastes_from_Small_Generators.

Pradhan, S., Tiwari, B. R., Kumar, S. and Barai, S. V (2019) ‘Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix’, *Journal of Cleaner Production*. Elsevier Ltd, 228, pp. 679–691. doi: 10.1016/j.jclepro.2019.04.328.

Rodríguez-Robles, D., van den Heede, P. V and de Belie, N. (2019) ‘9-Life cycle assessment applied to recycled aggregate concrete’, in de Brito, J. and Agrela, F. (eds) *New Trends in Eco-efficient and Recycled Concrete*. Woodhead Publishing (Woodhead Publishing Series in Civil and Structural Engineering), pp. 207–256. doi: 10.1016/B978-0-08-102480-5.00009-9.

Ruan, S. and Unluer, C. (2016) ‘Comparative life cycle assessment of reactive MgO and Portland cement production’, *Journal of Cleaner Production*, 137, pp. 258–273. doi: 10.1016/j.jclepro.2016.07.071.

Salas, D. A., Ramirez, A. D., Rodriguez, C. R., Petroche, D. M., Boero, A. J. and Duque-Rivera, J. (2016) 'Environmental impacts, life cycle assessment and potential improvement measures for cement production: A literature review', *Journal of Cleaner Production*, 113, pp. 114–122. doi: 10.1016/j.jclepro.2015.11.078.

Schuurmans, A., Rouwette, R., Vonk, N., Broers, J., Rijnsburger, H. and Pietersen, H. (2005) 'LCA of Finer Sand in Concrete (5 pp)', *The International Journal of Life Cycle Assessment*, 10(2), pp. 131–135. doi: 10.1065/lca2004.04.154.

Simion, I. M., Bonoli, A. and Gavrilescu, M. (2013) 'Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA', *Journal of Environmental Engineering and Landscape Management*, 21 (4)(September 2014), pp. 273–287. doi: 10.3846/16486897.2013.852558.

Smith, S. H. and Durham, S. A. (2016) 'A cradle to gate LCA framework for emissions and energy reduction in concrete pavement mixture design', *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 5(1), pp. 23–33. doi: 10.1016/j.ijsbe.2016.01.001.

Swedish Life Cycle Center (1996) *CPM LCA Database*. Available at: http://cpmdatabase.cpm.chalmers.se/Start.asp (Accessed: 20 February 2020).

Turk, J., Cotič, Z., Mladenovič, A. and Šajna, A. (2015) 'Environmental evaluation of green concretes versus conventional concrete by means of LCA.', *Waste management (New York, N.Y.)*, 45(305), pp. 194–205. doi: 10.1016/j.wasman.2015.06.035.

UNE-EN 15804 (2013) 'UNE-EN 15804:2013+A1. Sostenibilidad en la construcción; Declaraciones ambientales de producto; Reglas de categoría de producto básicas para productos de construcción', *AENOR*.

Zampori, L. and Pant, R. (2019) *Suggestions for updating the Product Environmental Footprint (PEF) method*. doi: 10.2760/424613.

Zhao, Z., Courard, L., Groslambert, S., Jehin, T., Léonard, A. and Xiao, J. (2020) 'Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study', *Resources, Conservation and Recycling*. Elsevier, 157(October 2019), p. 104786. doi: 10.1016/j.resconrec.2020.104786.

7

Conclusions and Future Research

CONTENT

7 Conclusions and Future Perspectives

In Chapter 7, a summary of the contributions will be presented, as well as the lessons that have been learned in relation to the most innovative aspects of this thesis. Drawing from the experimental work, some lines of investigation that might be explored in the future will also be discussed in the last section.

7.1 Conclusions

The central conclusion of this study is that the particle packing approach to the design of aggregate mixes both with NL aggregate concretes and with EAF aggregate concretes is a valid approach for the production of high compressive strength concrete and for the reduction of their environmental and economic impacts.

At the end of each previous chapter, a series of partial conclusions may be found on the contents of each chapter. In consequence, only the fundamental conclusions of the research and the lessons that have been learned in relation to its most innovative results are summarized here.

- From the comparison of the experimental results on the maximum packing density of aggregate and the application of the ideal distribution curves to aggregate mix design to find the highest packing density, it has been concluded that the predictions from the ideal curves matched the packing densities of the NL aggregate mixtures far more closely than the packing densities of the EAF aggregate mixtures. Therefore, other methods, in which aggregate shape is considered for the design of the EAF aggregate mixture, may be preferred.
- Two discrete Particle Packing Methods (PPM) were compared to validate their suitability, accuracy and practicality at an industrial scale for the prediction of the aggregate packing density of NL aggregate concrete and EAF aggregate concretes. From those results, the 3-parameter packing model (3-PPM) showed high accuracy for the ternary and the quaternary mixtures of the aggregates under study.
- Experimental packing density measurements revealed that a range of combinations, rather than a single aggregate combination within the maximum packing density can be obtained, due to the nature of the aggregate fraction (granular size distribution and shape variability).
- Maximizing the amount of the larger-size aggregate fraction within the range of aggregates that reached maximum packing densities was beneficial for the concrete mix design with NL and EAF aggregates, providing higher compressive strength, greater workability, and requiring a lower content of fines. In addition,

the environmental impact (carbon footprint) of these concretes was, in general, much lower than conventional concretes.

- The prediction of the optimal cement paste content of the concrete to obtain a specific workability, based only the packing density of aggregate, was not feasible, as the amount of concrete paste for the mix onset of flow will also depend on the total specific surface area of the aggregate. The aggregate packing density, measured by the compaction method using a tamping rod, appears to be a suitable starting point for calculating lower levels of paste content without excessive experimental testing, for the production of concrete mixes with a minimum cement content.
- The reduction of the cement in the design of both the NL and the EAF aggregate concretes without additives was limited by the workability of the mixtures. The low workability of concretes made with a reduced quantity of cement in this thesis limited their applicability to precast concrete or roller-compacted concrete. In terms of the hardened properties a reduction of cement of approximately 18% (from 317 kg/m^3 to 260 kg/m^3) was not detrimental to the compressive strength of the concrete at 28 days.
- There is no regional data base on NL and EAF aggregate production in the Basque Country, so the primary data were gathered from two representative aggregate facilities.
- Considering its weighted values, EAF aggregate production has an environmental impact of approximately 50-70% higher than NL aggregate production, due to the high contribution of the transport impact (62%). However, the concrete made with EAF aggregates, due to its higher compressive strength and the low contribution of those aggregates of its environmental impact, generally contributed to a reduction of the environmental impact when compressive strength was considered in the functional unit (FU). The transport distance from the treatment plant to the concrete plant may therefore be lengthier than the natural aggregate up to a minimum of 50 km according to the sensitivity analysis.
- Environmental benefits of between 11 and 14% were found for NL and EAF aggregates concretes designed with the same content of cement. So, despite the low contribution of EAF aggregates to the impact of concrete, aggregate mix design can increase the performance and consequently lower the environmental and economic impacts of EAF concretes significantly.
- Higher environmental impact is not always related to higher costs. The suitability of the global environmental and economic index as an easily used indicator was demonstrated for supporting decision-making when comparing the impact of different concrete mixes.

7.2 Afterthoughts: Future Perspectives

The research in this thesis has contributed to the existing literature on particle packing models for the design of sustainable concrete mixes and their validation through environmental and economic impact assessments. Specifically, the applicability and actual limitations of particle packing methods to the design of sustainable concrete mixtures made with conventional aggregates (NL aggregates) and recovered materials (EAF aggregates) have been analysed. From the observations during the experimental campaign, some promising lines of research have emerged for future in-depth investigations:

- Aggregate mix design purely based on maximum packing density will not necessarily lead to concrete mixes of higher compressive strength, as the paste (and water) demand will also depend on the specific surface area of the fine aggregate fraction and the nature of the material. Therefore, the optimum aggregate mix should be determined from both the maximum packing density and the paste that the mixture requires to arrive at onset of flow. From this perspective, aggregate concrete mix design through maximization of the amount of larger aggregate within the range of maximum packing density appears to be a valid means of approximating the optimal aggregate mix of both NL aggregate concrete and EAF aggregate concretes. However, further exploration of the relationship between aggregate specific surface and the demand for water and cement paste to arrive at the onset of flow of the mix appears to be a promising line for the development of a more accurate and rational method. The main limitation of this research line is the method that could be used to determine the specific surface area of crushed and cavernous aggregate in a reliable way for its eventual standardization within a recognized framework of reference.
- To extend the study to an exploration of the effect of adding admixtures to the concrete mixture designed through the particle packing method. Two aims arise here:
  - To analyse the potential for increasing the workability of concrete to extend the range of application of concretes with reduced cement content.
  - To analyse the effect on the environmental and economic sustainability of concrete mixtures.
- To explore aggregate packing under wet conditions more deeply. The results of aggregate mix packing densities with particle sizes lower than 4 mm under wet conditions differ from those in the dry state. As concrete is a wet material, the study of packing density under such conditions could improve the accuracy of concrete mix design with particle packing methods. In addition, the effect of the

admixtures, specially superplasticisers, could also be considered when measuring packing density under wet conditions.

- The experimental campaign testing concrete performance has been focused on the air content of the concrete, and concrete density, packing density workability, and compressive strength. Additional tests that could include mechanical tests (tensile splitting strength, modulus of elasticity, long-term compressive strength, shrinkage and creep) and durability tests (carbonation, chloride ingress, sulphate resistance, freeze-thaw resistance, permeability, alkali-silica reaction, alkali-silica), should also be performed, to assay all aspects of concrete performance and to assess the influence of aggregate mix design and cement content, in relation to the particular exposure class that may be required.
- As most of the data-base information represents averaged compilations from a country or a continent, the need for life cycle inventories (LCI) of construction materials at local levels that might be focused on geographical, and temporal technological representativeness is a key point to consider. Such a database could facilitate reliable comparisons of environmental impacts between various materials with similar functionalities, assisting decision-making in relation to product design.

ANNEX

Annex 1. Additional information of Chapter 4.

A- Calibration process of vibration-table acceleration

The vibration table was calibrated to achieve an acceleration of 4g (as suggested by F. de Larrard (de Larrard 1999)). The values were measured with an accelerometer sensor and an Arduino system at different frequencies (22, 24, 26, 28, 30, 32, 33 and 35 hz) and locations (on the vibration table (see Fig. A1.1), on both the lower zone (see Fig. A1.2) and the upper zone of the mould (see Fig. A1.3)).

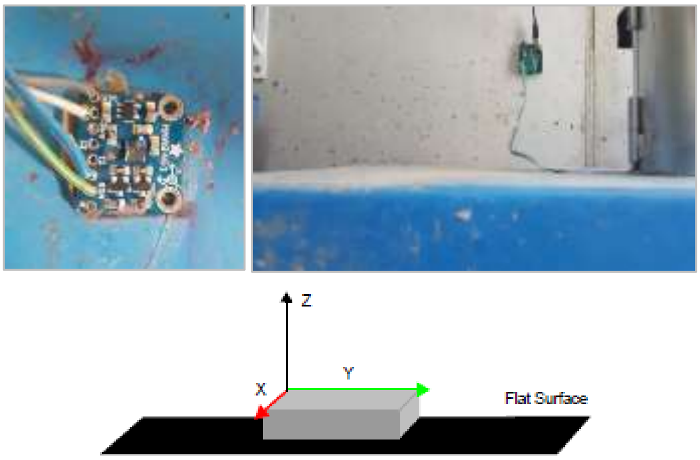


Fig.A1.1. Accelerometer sensor position on the vibration table.

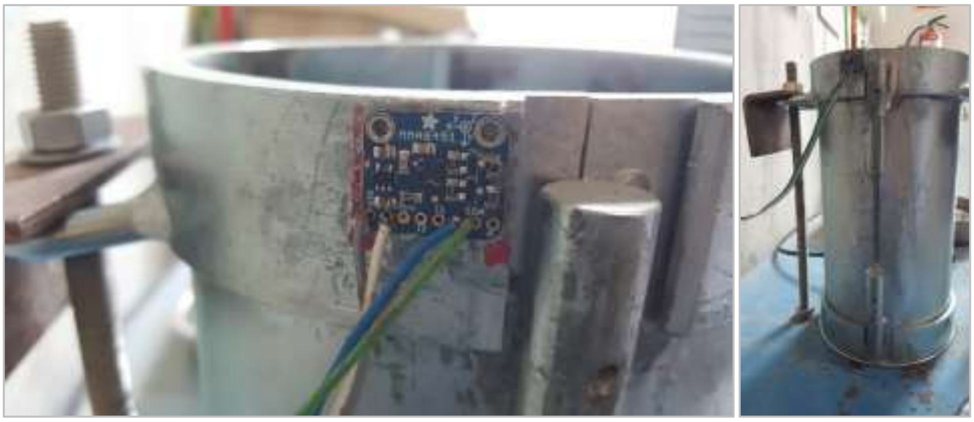


Fig.A1.0.1. Accelerometer sensor position on the upper zone of the mould.

Fig. A1.0.2. Accelerometer sensor positioned on the lower zone of the mould.

The sensor had a reading speed of 0.02 s and the acceleration values were registered during a period of approximately 40 s, as shown in Fig. A1.4.

Three tests were performed at each frequency for each sensor location and the average value was calculated for the minimum and maximum recorded values.

Sensor calibration requires a stationary sensor on a horizontal surface that measures 0g on both the X-axis and the Y-axis, while the Z-axis should measure 1g. Several tests were analysed at this position without vibration, to check for any deviations. Slight deviations can be observed in Fig. A1.5. These deviations were corrected for each test and possible changes were checked with a measurement before each test in the static state.

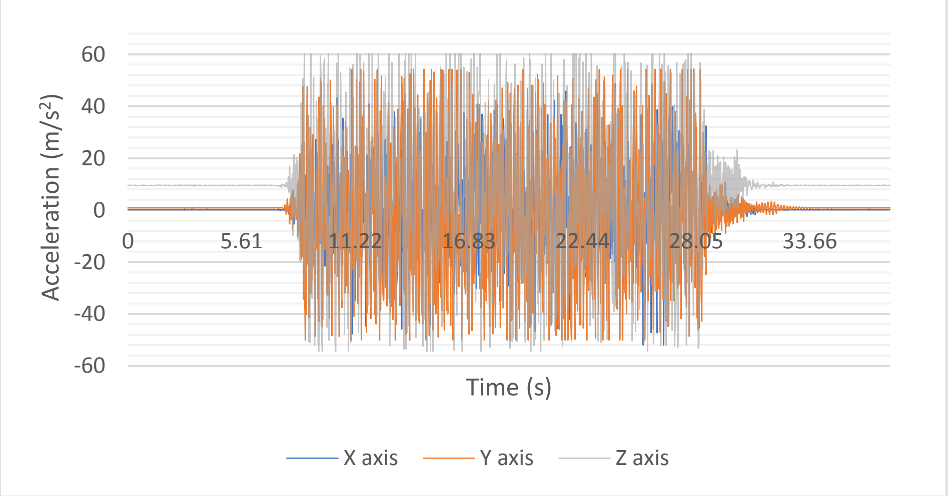


Fig. A1.0.3. Acceleration results at 50 Hz. Table secured to the ground with silent block supports.

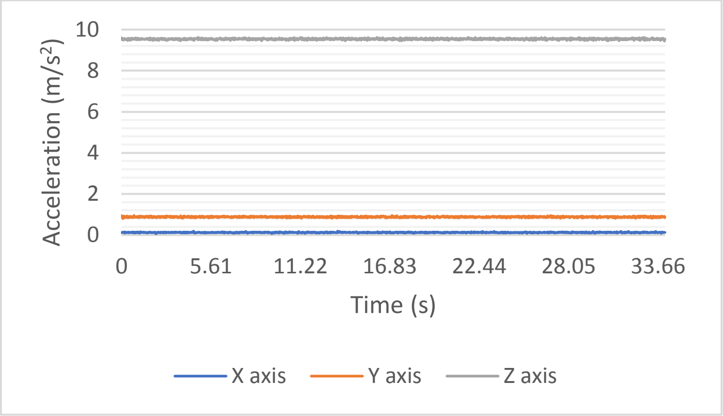


Fig. A1.0.4. Accelerometer static test

Fig. A1.6 shows the differences between the acceleration values for the table on the three axes at eight different frequencies. The largest difference is on both axes where the frequency increase appears to increase the acceleration. However, at 28 Hz the acceleration on the y-axis slightly decreased compared to the same acceleration at 26 Hz. The acceleration on the z-axis remained practically constant from a range of frequencies from 24 to 35Hz on the maximum values and from a range of 30 to 35Hz on the minimum values. The desired acceleration of 4g on all the three axes, both for the maximum and minimum acceleration, was reached at a frequency of 32Hz.

The low standard deviations (ranging from 0.04 to 0.61 g) between the three tests for the three sensor positions indicated that accurate values were obtained.

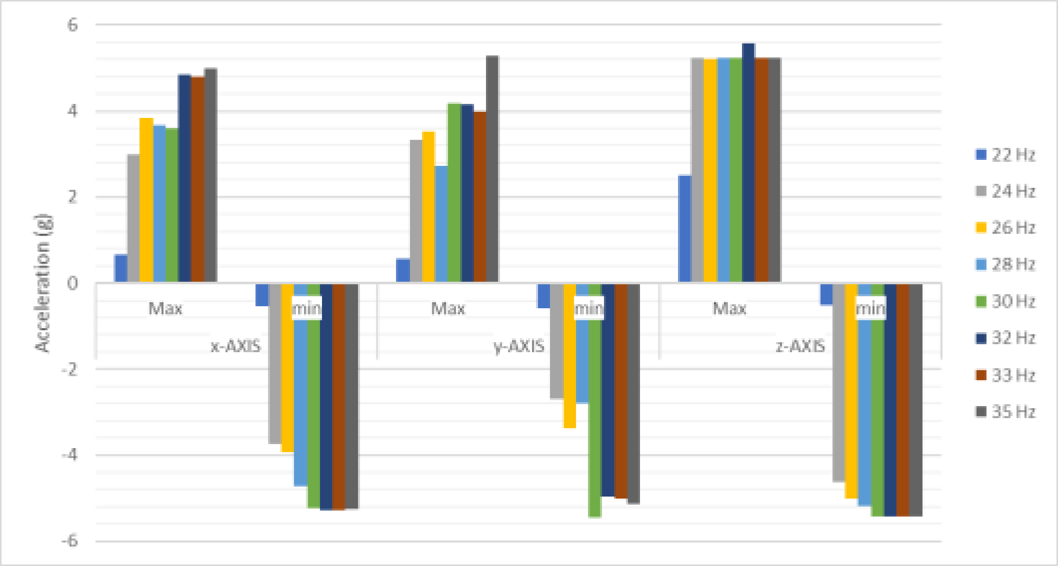


Fig. A1.0.5. Results of the maximum and minimum acceleration of each axis on the vibration table at different frequencies.

In Fig. A1.7, the results of the acceleration values for the upper zone of the mould on the three axes are shown at six different frequencies. In ***Fig. A1.0.2***, the acceleration values for the lower zone of the mould are shown at eight different frequencies.

In both the upper and the lower zone of the mould, the acceleration appeared to be practically independent of the selected frequency in the range of 26 to 35 Hz (see Fig. A1.7, Fig. A1.8). However, the acceleration was significantly lower at 22hz.

It can also be highlighted that the mould acceleration results showed an acceleration higher than 4g on all three axes, at frequencies higher than 22Hz, reaching and even exceeding 5g.

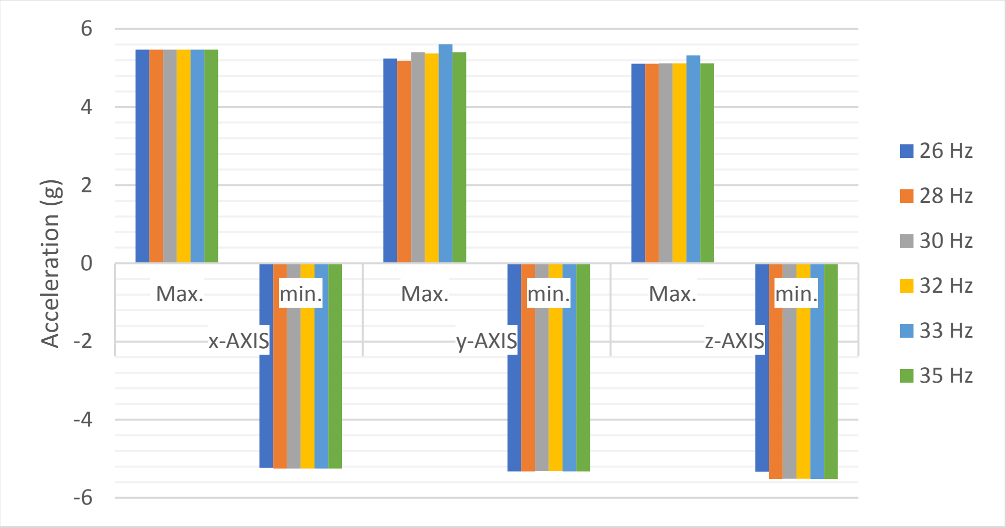


Fig. A1.0.6. Results of the maximum and minimum acceleration of each axis on the upper zone of the mould at different frequencies.

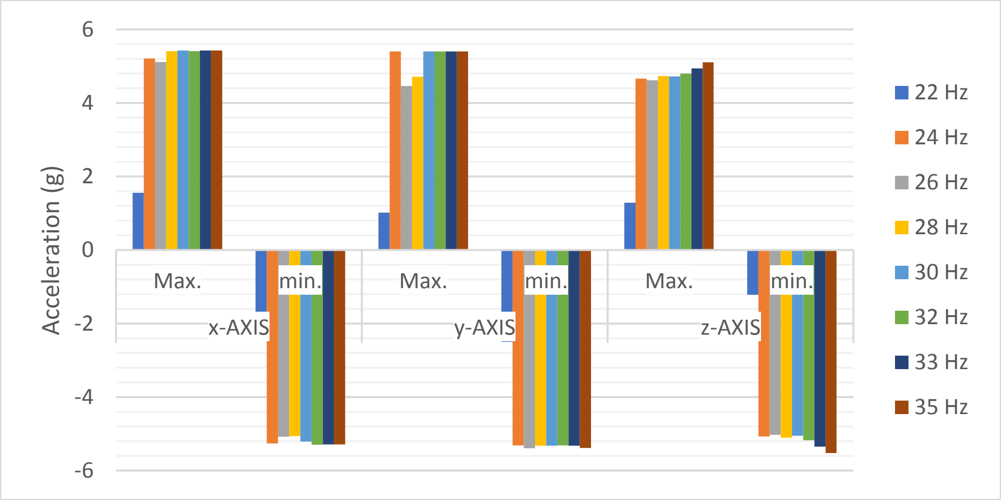


Fig. A1.0.7. Results of the maximum and minimum acceleration of each axis on the lower zone of the mould at different frequencies.

Fig. A1.9 shows slight differences between the acceleration values for the upper and lower zones of the mould. The largest difference, on the z-axis, corresponds to the y-axis on the table (the longitudinal direction, parallel to the table). In that case, the acceleration was higher in the upper zone, probably due to the fixations securing the mould to the table.

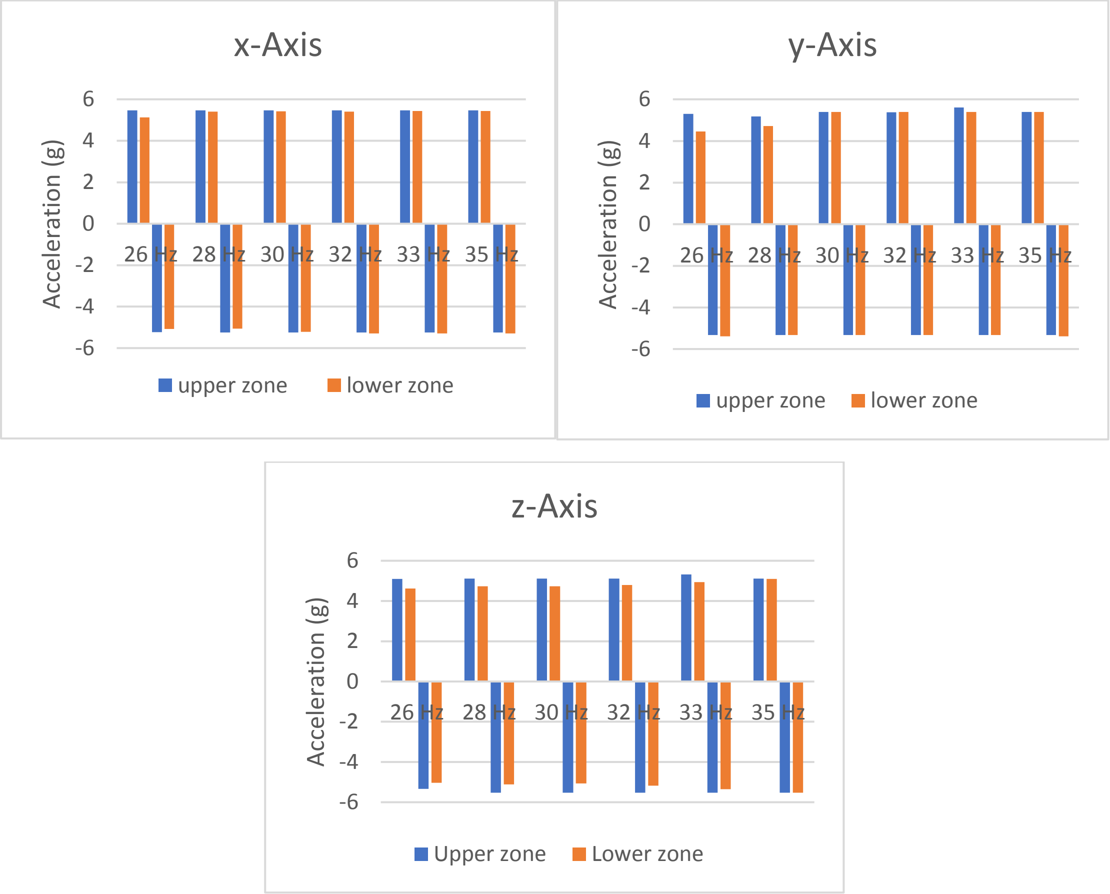


Fig.A1.0.8. Comparison of the maximum and minimum acceleration on the three axes in both the upper and the lower zones of the mould.

In view of the results and the vibration table in use, the frequency clearly cannot be adjusted to obtain an acceleration of 4g on all axes and parts of the mould, so two different test frequencies were selected.

On the one hand, 33 Hz was selected as the 4 g acceleration was reached or even exceeded in the three test zones. On the other hand, 26 Hz was chosen to compare the measurement of PD with two different accelerations, as the vibration table acceleration at 26 Hz was lower than at 33 Hz.

Calibration of the optimum vibration time (Test duration).

The optimal duration of the compaction process was measured, by conducting the compression and vibration packing tests until a constant PD was reached (i.e. until a constant height of aggregate was reached in the mould).

The coarse and medium fractions of crushed limestone aggregates (NL) were used to calibrate the test duration. Both fractions were tested at two different frequencies (26 and 33Hz). The same sample was vibrated four times for one minute, to ensure a constant PD value had been reached, verifying the piston movement at one-minute intervals. Having reached a constant measurement, another 3-minute test of continuous vibrations was performed to verify whether the measurement was the same.

The results are shown in Table A1.1.

Table A1.1. Aggregate heights within the cylindrical mould after the PD test.

	Frequency (Hz)	Aggregate Height (mm)				
		1 min	+1 min	+1 min	+1 min	3 min
NL (11/22)	33	20.2	20	19.9	19.9	19.9
NL (11/22)	26	21	20.8	20.6	20.6	20.5
NL (4/11)	33	19	18.9	18.6	18.6	18.6
NL (4/11)	26	20	19.7	19.5	19.5	19.4

On the basis of the results, the test duration was set at 3 min, within which time the PD appeared to have stabilized at a constant level.

B- Deviations of the theoretical models from the experimental packing density

Natural limestone aggregates

Binary mixtures

Loose packing (D-L)												
Vol. fraction (%)		Packing density & error (%)										
NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	1	0.502	0.5	-0.07%	0.48	-5.30%	0.5	-0.60%	0.502	0.00%	0.502	0.00%
0.1	0.9	0.512	0.52	1.63%	0.49	-4.10%	0.52	1.10%	0.514	0.30%	0.511	-0.12%
0.2	0.8	0.516	0.54	4.16%	0.51	-2.10%	0.54	3.60%	0.524	1.60%	0.520	0.81%
0.3	0.7	0.529	0.55	4.38%	0.52	-2.80%	0.55	3.70%	0.534	0.96%	0.528	-0.17%
0.4	0.6	0.535	0.56	4.84%	**0.52**	-3.30%	0.56	4.10%	0.542	1.35%	0.535	-0.05%
0.5	0.5	0.539	0.56	4.38%	0.51	-4.80%	0.56	3.50%	0.548	1.71%	0.540	0.14%
0.6	0.4	0.539	0.56	3.57%	0.51	-6.50%	0.55	2.60%	0.544	0.99%	0.539	-0.04%
0.7	0.3	0.542	0.55	1.53%	0.5	-9.30%	0.54	0.40%	0.539	-0.62%	0.534	-1.44%
0.8	0.2	0.54	0.54	-0.02%	0.48	-11.50%	0.53	-1.30%	0.532	-1.49%	0.529	-2.06%
0.9	0.1	0.536	0.53	-1.41%	0.47	-13.40%	0.52	-2.80%	0.525	-2.14%	0.523	-2.43%
1	0	0.517	0.52	-0.02%	0.46	-12.20%	0.51	-1.40%	0.517	0.00%	0.517	0.00%
Maximum error			4.8%		13.4%		4.1%		2.1%		2.4%	
Mean error			2.1%		-6.8%		1.2%		0.2%		-0.5%	
Standard Deviation			2.2%		3.9%		2.3%		1.2%		1.0%	

Compacted packing (D-C)												
Vol. fraction (%)		Packing density & error (%)										
NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	1	0.534	0.534	0.1%	0.507	-5.33%	0.530	-0.72%	0.534	0.00%	0.534	0.00%
0.1	0.9	0.544	0.555	2.0%	0.524	-3.82%	0.550	1.18%	0.547	0.57%	0.545	0.16%
0.2	0.8	0.557	0.575	3.1%	0.540	-3.15%	0.570	2.25%	0.560	0.47%	0.555	-0.32%
0.3	0.7	0.559	0.592	5.5%	0.551	-1.45%	0.586	4.60%	0.571	2.11%	0.565	1.01%
0.4	0.6	0.566	0.602	6.0%	**0.555**	-1.98%	0.596	4.99%	0.581	2.57%	0.573	1.20%
0.5	0.5	0.565	0.605	6.6%	0.552	-2.36%	0.597	5.43%	0.587	3.78%	0.579	2.49%
0.6	0.4	0.568	0.601	5.4%	0.545	-4.22%	0.593	4.17%	0.584	2.72%	0.578	1.77%
0.7	0.3	0.577	0.593	2.7%	0.535	-7.85%	0.584	1.24%	0.579	0.41%	0.575	-0.35%
0.8	0.2	0.577	0.583	1.0%	0.524	-10.11%	0.574	-0.53%	0.574	-0.53%	0.571	-1.06%
0.9	0.1	0.566	0.572	1.1%	0.512	-10.55%	0.563	-0.56%	0.568	0.31%	0.566	0.04%
1	0	0.561	0.561	0.0%	0.501	-11.98%	0.551	-1.73%	0.561	0.00%	0.561	0.00%
Maximum error			6.6%		12.0%		5.4%		3.8%		2.5%	
Mean error			3.0%		-5.7%		1.8%		1.1%		0.4%	
Standard Deviation			2.3%		3.6%		2.5%		1.3%		1.0%	

Compacted packing (D-C26)												
Vol. fraction (%)		Packing density & error (%)										
NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	1	0.566	0.566	0.0%	0.536	-5.60%	0.561	-1.07%	0.566	0.00%	0.566	0.00%
0.1	0.9	0.596	0.590	-1.0%	0.556	-7.19%	0.584	-0.81%	0.581	-2.52%	0.579	-2.93%
0.2	0.8	0.613	0.614	0.2%	0.576	-6.42%	0.608	0.25%	0.596	-2.82%	0.592	-3.61%
0.3	0.7	0.62	0.635	2.3%	0.592	-4.73%	0.628	2.48%	0.610	-1.62%	0.603	-2.74%
0.4	0.6	0.629	0.646	2.6%	**0.599**	-5.01%	0.638	2.15%	0.623	-1.03%	0.614	-2.42%
0.5	0.5	0.63	0.647	2.6%	0.595	-5.88%	0.638	1.08%	0.630	-0.06%	0.623	-1.15%
0.6	0.4	0.631	0.642	1.8%	0.587	-7.50%	0.633	0.65%	0.629	-0.38%	0.623	-1.31%
0.7	0.3	0.63	0.636	0.9%	0.577	-9.19%	0.627	1.36%	0.626	-0.59%	0.622	-1.32%
0.8	0.2	0.634	0.629	-0.8%	0.566	-12.01%	0.619	-2.07%	0.623	-1.76%	0.620	-2.28%
0.9	0.1	0.612	0.621	1.5%	0.556	-10.07%	0.611	-1.07%	0.619	1.11%	0.617	0.85%
1	0	0.614	0.614	0.0%	0.545	-12.66%	0.603	-1.96%	0.614	0.00%	0.614	0.00%
Maximum error			2.6%		12.7%		2.5%		2.8%		3.6%	
Mean error			0.9%		-7.8%		0.1%		-0.9%		-1.5%	
Standard Deviation			1.3%		2.6%		1.5%		1.1%		1.3%	

Compacted packing (D-C33)												
Vol. fraction (%)		**Packing density & error (%)**										
NL (4/11)	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (B: β)**		**CPM (C: Υ)**		**3-P (unc.)**		**3-P (comp.)**	
0	1	0.594	0.594	0.0%	0.56	-5.51%	0.588	-0.95%	0.594	0.00%	0.594	0.00%
0.1	0.9	0.617	0.619	0.3%	0.58	-5.65%	0.612	-2.03%	0.609	-1.24%	0.607	-1.65%
0.2	0.8	0.635	0.644	1.4%	0.6	-5.13%	0.637	-0.90%	0.624	-1.72%	0.619	-2.52%
0.3	0.7	0.642	0.666	3.7%	0.62	-3.72%	0.658	1.20%	0.638	-0.63%	0.631	-1.75%
0.4	0.6	0.656	0.679	3.4%	**0.62**	-5.13%	0.670	1.42%	0.650	-0.91%	0.641	-2.31%
0.5	0.5	0.663	0.680	2.5%	0.62	-7.28%	0.670	1.30%	0.653	-1.54%	0.646	-2.57%
0.6	0.4	0.659	0.674	2.2%	0.61	-8.21%	0.663	0.38%	0.651	-1.18%	0.646	-2.05%
0.7	0.3	0.645	0.665	3.0%	0.6	-7.86%	0.654	-0.55%	0.649	0.55%	0.644	-0.12%
0.8	0.2	0.657	0.655	-0.3%	0.59	-11.93%	0.644	-2.44%	0.645	-1.89%	0.642	-2.37%
0.9	0.1	0.64	0.645	0.8%	0.58	-11.11%	0.633	-0.17%	0.640	0.04%	0.639	-0.20%
1	0	0.635	0.635	0.1%	0.57	-12.39%	0.623	-1.82%	0.635	0.00%	0.635	0.00%
Maximum error			3.7%		12.4%		2.4%		1.9%		2.6%	
Mean error			1.6%		-7.6%		-0.4%		-0.8%		-1.4%	
Standard Deviation			1.4%		2.9%		1.3%		0.8%		1.0%	

Loose packing (D-L)											
Vol. fraction (%)			**Packing density & error (%)**								
NL (0/4)	**NL (4/11)**	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: Υ)**		**3-P (unc.)**		**3-P (comp.)**	
0	0.6	0.4	0.54	0.559	3.57%	0.553	2.57%	0.544	0.99%	0.540	0.14%
0.1	0.54	0.36		0.595		0.590		0.581		0.572	
0.2	0.48	0.32		0.632		0.627		0.617		0.602	
0.3	0.42	0.28	0.62	0.663	7.22%	0.660	6.81%	0.653	5.84%	0.630	2.37%
0.4	0.36	0.24	0.66	0.679	3.35%	0.679	3.34%	0.685	4.29%	0.655	-0.13%
0.5	0.3	0.2	0.67	0.677	0.43%	0.679	0.79%	0.685	1.54%	0.673	-0.12%
0.6	0.24	0.16	0.68	0.665	-2.25%	0.669	-1.63%	0.673	-1.09%	0.663	-2.51%
0.7	0.18	0.12	0.67	0.649	-3.85%	0.654	-3.02%	0.657	-2.59%	0.650	-3.70%
0.8	0.12	0.08		0.632		0.638		0.639		0.634	
0.9	0.06	0.04		0.614		0.621		0.618		0.616	
1	0	0	0.6	0.597	0.05%	0.605	1.25%	0.597	0.00%	0.597	0.00%
Maximum error				7.2%		6.8%		5.8%		3.7%	
Mean error				1.2%		1.4%		1.3%		-0.6%	
Standard Deviation				3.5%		3.0%		2.7%		1.8%	

Loose packing (D-C)												
Vol. fraction (%)			Packing density & error (%)									
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)		
0	0.6	0.4	0.57	0.601	5.43%	0.593	4.17%	0.584	2.72%	0.578	1.77%	
0.1	0.54	0.36		0.642		0.634		0.625		0.613		
0.2	0.48	0.32		0.685		0.678		0.668		0.648		
0.3	0.42	0.28	0.68	0.725	6.77%	0.718	5.91%	0.712	5.01%	0.684	1.10%	
0.4	0.36	0.24	0.72	0.750	4.45%	0.746	3.87%	0.753	4.79%	0.717	0.05%	
0.5	0.3	0.2	0.74	0.757	2.31%	0.755	1.95%	0.764	3.08%	0.747	0.96%	
0.6	0.24	0.16	0.76	0.753	-0.21%	0.752	-0.43%	0.760	0.70%	0.747	-1.13%	
0.7	0.18	0.12	0.75	0.744	-0.61%	0.743	-0.75%	0.752	0.45%	0.742	-0.98%	
0.8	0.12	0.08		0.733		0.733		0.741		0.733		
0.9	0.06	0.04		0.722		0.721		0.726		0.722		
1	0	0	0.71	0.709	0.05%	0.709	0.05%	0.709	0.00%	0.709	0.00%	
Maximum error				6.8%		5.9%		5.0%		1.8%		
Mean error				2.6%		2.1%		2.4%		0.3%		
Standard Deviation				2.8%		2.4%		1.9%		1.0%		

Compacted packing (D-C26)														
Vol. fraction (%)			Packing density & error (%)											
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)		
0	0.6	0.4	0.63	0.642	1.76%	0.587	-7.57%	0.642	1.69%	0.629	-0.38%	0.623	-1.31%	
0.1	0.54	0.36		0.689		0.625		0.688		0.673		0.660		
0.2	0.48	0.32		0.741		0.666		0.739		0.720		0.698		
0.3	0.42	0.28	0.75	0.793	5.50%	0.704	-6.45%	0.790	5.15%	0.767	2.31%	0.737	-1.65%	
0.4	0.36	0.24	0.79	0.821	3.57%	0.711	-11.43%	0.816	2.89%	0.804	1.47%	0.774	-2.37%	
0.5	0.3	0.2	0.8	0.821	2.11%	0.692	-16.26%	0.814	1.26%	0.809	0.56%	0.793	-1.36%	
0.6	0.24	0.16	0.82	0.813	-0.90%	0.667	-22.86%	0.805	-1.88%	0.808	-1.49%	0.795	-3.14%	
0.7	0.18	0.12	0.8	0.802	0.74%	0.643	-23.71%	0.793	-0.32%	0.803	0.87%	0.793	-0.40%	
0.8	0.12	0.08		0.791		0.621		0.782		0.794		0.787		
0.9	0.06	0.04		0.779		0.599		0.770		0.782		0.779		
1	0	0	0.77	0.768	-0.04%	0.579	-32.71%	0.758	-1.35%	0.768	0.00%	0.768	0.00%	
Maximum error				5.5%		32.7%		5.1%		2.3%		3.1%		
Mean error				1.8%		-17.3%		1.1%		0.5%		-1.5%		
Standard Deviation				2.0%		8.9%		2.3%		1.2%		1.0%		

Compacted packing (D-C33)													
Vol. fraction (%)			Packing density & error (%)										
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.6	0.4	0.66	0.674	2.17%	0.617	-6.87%	0.663	0.65%	0.651	-1.18%	0.646	-2.05%
0.1	0.54	0.36		0.721		0.655		0.710		0.697		0.683	
0.2	0.48	0.32		0.773		0.696		0.762		0.744		0.722	
0.3	0.42	0.28	0.75	0.819	8.30%	0.728	-3.20%	0.809	7.15%	0.791	5.07%	0.760	1.22%
0.4	0.36	0.24	0.83	0.835	1.01%	0.724	-14.25%	0.827	0.04%	0.814	-1.55%	0.796	-3.84%
0.5	0.3	0.2	0.84	0.831	-0.73%	0.701	-19.32%	0.823	-1.69%	0.818	-2.37%	0.803	-4.18%
0.6	0.24	0.16	0.85	0.821	-3.65%	0.677	-25.79%	0.813	-4.69%	0.816	-4.29%	0.804	-5.85%
0.7	0.18	0.12	0.85	0.810	-4.48%	0.652	-29.73%	0.801	-5.60%	0.810	-4.41%	0.801	-5.63%
0.8	0.12	0.08		0.798		0.629		0.789		0.801		0.795	
0.9	0.06	0.04		0.786		0.607		0.777		0.789		0.786	
1	0	0	0.78	0.775	-0.01%	0.587	-32.07%	0.765	-1.31%	0.775	0.00%	0.775	0.00%
Maximum error				8.3%		32.1%		7.1%		5.1%		5.8%	
Mean error				0.4%		-18.7%		-0.8%		-1.2%		-2.9%	
Standard Deviation				3.9%		10.4%		3.9%		3.0%		2.5%	

Loose packing (D-L)											
Vol. fraction (%)			Packing density & error (%)								
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.4	0.6	0.535	0.562	4.84%	0.558	4.08%	0.542	1.35%	0.535	-0.05%
0.1	0.36	0.54		0.600		0.596		0.590		0.575	
0.2	0.32	0.48		0.638		0.635		0.628		0.605	
0.3	0.28	0.42	0.611	0.670	8.81%	0.668	8.55%	0.665	8.12%	0.634	3.62%
0.4	0.24	0.36	0.65	0.685	5.07%	0.685	5.17%	0.698	6.83%	0.659	1.42%
0.5	0.2	0.3	0.662	0.681	2.83%	0.684	3.25%	0.693	4.46%	0.677	2.25%
0.6	0.16	0.24	0.665	0.668	0.46%	0.673	1.12%	0.679	2.13%	0.667	0.25%
0.7	0.12	0.18	0.654	0.651	-0.44%	0.657	0.39%	0.662	1.22%	0.652	-0.23%
0.8	0.08	0.12		0.633		0.639		0.642		0.636	
0.9	0.04	0.06		0.615		0.622		0.620		0.617	
1	0	0	0.597	0.597	0.05%	0.605	1.25%	0.597	0.00%	0.597	0.00%
Maximum error				8.8%		8.6%		8.1%		3.6%	
Mean error				3.1%		3.4%		3.4%		1.0%	
Standard Deviation				3.1%		2.6%		2.9%		1.3%	

Loose packing (D-C)											
Vol. fraction (%)			Packing density & error (%)								
NL (0/4)	**NL (4/11)**	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	0.4	0.6	0.566	0.602	6.01%	0.596	4.99%	0.581	2.57%	0.573	1.20%
0.1	0.36	0.54		0.645		0.639		0.632		0.617	
0.2	0.32	0.48		0.690		0.684		0.677		0.654	
0.3	0.28	0.42	0.663	0.731	9.29%	0.726	8.62%	0.721	8.07%	0.690	3.90%
0.4	0.24	0.36	0.704	0.756	6.82%	0.752	6.37%	0.763	7.77%	0.724	2.79%
0.5	0.2	0.3	0.723	0.761	5.04%	0.759	4.77%	0.772	6.33%	0.754	4.13%
0.6	0.16	0.24	0.73	0.756	3.48%	0.755	3.31%	0.767	4.88%	0.753	3.10%
0.7	0.12	0.18	0.728	0.747	2.49%	0.746	2.38%	0.758	3.95%	0.747	2.55%
0.8	0.08	0.12		0.735		0.734		0.744		0.737	
0.9	0.04	0.06		0.722		0.722		0.728		0.724	
1	0	0	0.709	0.709	0.05%	0.709	0.05%	0.709	0.00%	0.709	0.00%
Maximum error				9.3%		8.6%		8.1%		4.1%	
Mean error				4.7%		4.4%		4.8%		2.5%	
Standard Deviation				2.8%		2.6%		2.7%		1.4%	

Compacted packing (D-C26)													
Vol. fraction (%)			Packing density & error (%)										
NL (0/4)	**NL (4/11)**	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (B: β)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	0.4	0.6	0.629	0.654	3.77%	0.607	-3.65%	0.646	2.64%	0.623	-1.03%	0.614	-2.42%
0.1	0.36	0.54		0.703		0.648		0.695		0.675		0.660	
0.2	0.32	0.48		0.757		0.691		0.749		0.723		0.699	
0.3	0.28	0.42	0.726	0.807	10.07%	0.724	-0.34%	0.799	9.14%	0.771	5.89%	0.739	1.74%
0.4	0.24	0.36	0.778	0.829	6.10%	**0.719**	-8.13%	0.821	5.28%	0.811	4.06%	0.776	-0.20%
0.5	0.2	0.3	0.786	0.825	4.78%	0.696	-12.86%	0.818	3.93%	0.815	3.60%	0.799	1.68%
0.6	0.16	0.24	0.792	0.816	2.89%	0.671	-18.08%	0.808	1.95%	0.814	2.72%	0.801	1.07%
0.7	0.12	0.18	0.778	0.804	3.23%	0.646	-20.50%	0.796	2.21%	0.808	3.70%	0.797	2.43%
0.8	0.08	0.12		0.792		0.622		0.783		0.798		0.790	
0.9	0.04	0.06		0.780		0.600		0.770		0.784		0.780	
1	0	0	0.768	0.768	-0.04%	0.579	-32.71%	0.758	-1.35%	0.768	0.00%	0.768	0.00%
Maximum error				10.1%		32.7%		9.1%		5.9%		2.4%	
Mean error				4.4%		-13.8%		3.4%		2.7%		0.6%	
Standard Deviation				2.9%		10.3%		3.0%		2.2%		1.5%	

Compacted packing (D-C33)													
Vol. fraction (%)			Packing density & error (%)										
NL (0/4)	**NL (4/11)**	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (B: β)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	0.4	0.6	0.656	0.679	3.43%	0.632	-3.83%	0.670	2.15%	0.650	-0.91%	0.641	-2.31%
0.1	0.36	0.54		0.729		0.673		0.720		0.700		0.685	
0.2	0.32	0.48		0.783		0.715		0.773		0.748		0.724	
0.3	0.28	0.42	0.78	0.828	5.75%	0.742	-5.17%	0.819	4.75%	0.797	2.12%	0.763	-2.18%
0.4	0.24	0.36	0.825	0.840	1.83%	**0.731**	-12.90%	0.833	0.96%	0.821	-0.45%	0.800	-3.11%
0.5	0.2	0.3	0.839	0.834	-0.56%	0.706	-18.85%	0.827	-1.46%	0.824	-1.80%	0.809	-3.65%
0.6	0.16	0.24	0.825	0.824	-0.17%	0.680	-21.39%	0.816	-1.14%	0.822	-0.39%	0.809	-1.93%
0.7	0.12	0.18	0.809	0.812	0.32%	0.654	-23.66%	0.803	-0.73%	0.815	0.73%	0.805	-0.46%
0.8	0.08	0.12		0.799		0.630		0.790		0.804		0.798	
0.9	0.04	0.06		0.787		0.608		0.778		0.791		0.787	
1	0	0	0.775	0.775	-0.01%	0.587	-32.07%	0.765	-1.31%	0.775	0.00%	0.775	0.00%
Maximum error				5.8%		32.1%		4.8%		2.1%		3.6%	
Mean error				1.5%		-16.8%		0.5%		-0.1%		-1.9%	
Standard Deviation				2.2%		9.4%		2.1%		1.2%		1.2%	

Loose packing (D-L)											
Vol. fraction (%)			Packing density & error (%)								
NL (0/4)	**NL (4/11)**	**NL (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	0.5	0.5	0.539	0.564	4.38%	0.559	3.50%	0.548	1.71%	0.540	0.14%
0.1	0.45	0.45		0.600		0.596		0.586		0.572	
0.2	0.4	0.4		0.637		0.633		0.623		0.602	
0.3	0.35	0.35		0.668		0.666		0.659		0.630	
0.4	0.3	0.3	0.652	0.683	4.48%	0.683	4.54%	0.692	5.75%	0.655	0.48%
0.5	0.25	0.25	0.667	0.679	1.83%	0.682	2.22%	0.689	3.15%	0.673	0.92%
0.6	0.2	0.2	0.667	0.667	-0.05%	0.671	0.59%	0.676	1.34%	0.663	-0.55%
0.7	0.15	0.15		0.650		0.655		0.660		0.650	
0.8	0.1	0.1		0.632		0.639		0.640		0.634	
0.9	0.05	0.05		0.615		0.621		0.619		0.616	
1	0	0	0.597	0.597	0.05%	0.605	1.25%	0.597	0.00%	0.597	0.00%
Maximum error				4.5%		4.5%		5.7%		0.9%	
Mean error				2.1%		2.4%		2.4%		0.2%	
Standard Deviation				2.0%		1.4%		2.0%		0.5%	

Compacted packing (D-C26)													
Vol. fraction (%)			Packing density & error (%)										
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.5	0.5	0.63	0.656	3.97%	0.604	-4.24%	0.648	2.75%	0.630	-0.06%	0.623	-1.15%
0.1	0.45	0.45		0.704		0.644		0.695		0.675		0.660	
0.2	0.4	0.4		0.756		0.685		0.747		0.722		0.699	
0.3	0.35	0.35		0.805		0.718		0.796		0.770		0.738	
0.4	0.3	0.3	0.79	0.827	4.44%	**0.716**	-10.28%	0.819	3.57%	0.807	2.15%	0.775	-1.90%
0.5	0.25	0.25	0.814	0.824	1.20%	0.694	-17.24%	0.816	0.29%	0.812	-0.26%	0.796	-2.22%
0.6	0.2	0.2	0.795	0.814	2.37%	0.669	-18.80%	0.806	1.41%	0.811	1.98%	0.798	0.35%
0.7	0.15	0.15		0.803		0.645		0.795		0.805		0.795	
0.8	0.1	0.1		0.791		0.621		0.782		0.796		0.789	
0.9	0.05	0.05		0.779		0.599		0.770		0.783		0.780	
1	0	0	0.768	0.768	-0.04%	0.579	-32.71%	0.758	-1.35%	0.768	0.00%	0.768	0.00%
Maximum error				4.4%		32.7%		3.6%		2.2%		2.2%	
Mean error				2.4%		-16.7%		1.3%		0.8%		-1.0%	
Standard Deviation				1.7%		9.6%		1.7%		1.1%		1.0%	

Compacted packing (D-C33)													
Vol. fraction (%)			Packing density & error (%)										
NL (0/4)	NL (4/11)	NL (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.5	0.5	0.663	0.680	2.47%	0.627	-5.69%	0.670	1.08%	0.653	-1.54%	0.646	-2.57%
0.1	0.45	0.45		0.728		0.667		0.718		0.699		0.684	
0.2	0.4	0.4		0.780		0.708		0.770		0.747		0.723	
0.3	0.35	0.35		0.825		0.736		0.816		0.794		0.762	
0.4	0.3	0.3	0.833	0.838	0.65%	**0.728**	-14.48%	0.831	-0.27%	0.818	-1.85%	0.798	-4.33%
0.5	0.25	0.25	0.848	0.833	-1.83%	0.704	-20.49%	0.825	-2.77%	0.821	-3.31%	0.806	-5.15%
0.6	0.2	0.2	0.835	0.822	-1.53%	0.678	-23.14%	0.814	-2.54%	0.819	-1.97%	0.807	-3.51%
0.7	0.15	0.15		0.811		0.653		0.802		0.813		0.803	
0.8	0.1	0.1		0.799		0.630		0.790		0.803		0.796	
0.9	0.05	0.05		0.787		0.608		0.777		0.790		0.787	
1	0	0	0.775	0.775	-0.01%	0.587	-32.07%	0.765	-1.31%	0.775	0.00%	0.775	0.00%
Maximum error				2.5%		32.1%		2.8%		3.3%		5.2%	
Mean error				-0.1%		-19.2%		-1.2%		-1.7%		-3.1%	
Standard Deviation				1.6%		8.8%		1.4%		1.1%		1.8%	

Electric Arc Furnace (EAF) aggregates

Binary mixtures

Loose packing (D-L)												
Vol. fraction (%)		**Packing density & error (%)**										
EAF (4/11)	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (B: β)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	1	0.482	0.482	0.07%	0.449	-7.35%	0.477	-1.11%	0.482	0.00%	0.482	0.00%
0.1	0.9	0.497	0.502	0.97%	0.466	-6.65%	0.496	-0.19%	0.495	-0.36%	0.493	-0.71%
0.2	0.8	0.505	0.521	3.03%	0.483	-4.55%	0.515	1.93%	0.508	0.62%	0.505	-0.05%
0.3	0.7	0.531	0.537	1.20%	0.496	-7.06%	0.532	0.10%	0.520	-2.03%	0.515	-3.01%
0.4	0.6	0.513	0.550	6.65%	**0.505**	-1.58%	0.544	5.64%	0.532	3.51%	0.525	2.36%
0.5	0.5	0.527	0.556	5.15%	0.508	-3.74%	0.550	4.15%	0.541	2.64%	0.534	1.32%
0.6	0.4	0.529	0.556	4.90%	0.506	-4.55%	0.551	3.91%	0.547	3.28%	0.541	2.21%
0.7	0.3	0.525	0.553	5.11%	0.500	-5.00%	0.548	4.12%	0.545	3.73%	0.541	2.89%
0.8	0.2	0.54	0.548	1.47%	0.493	-9.53%	0.542	0.44%	0.543	0.50%	0.539	-0.10%
0.9	0.1	0.54	0.542	0.31%	0.485	-11.34%	0.536	-0.74%	0.539	-0.14%	0.538	-0.46%
1	0	0.535	0.535	-0.07%	0.476	-12.39%	0.529	-1.14%	0.535	0.00%	0.535	0.00%
Maximum error			6.7%		12.4%		5.6%		3.7%		3.0%	
Mean error			2.6%		-6.7%		1.6%		1.1%		0.4%	
Standard Deviation			2.3%		3.2%		2.4%		1.8%		1.6%	

Compacted packing (D-C)												
Vol. fraction (%)		**Packing density & error (%)**										
EAF (4/11)	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (B: β)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0	1	0.54	0.547	0.04%	0.505	-6.93%	0.539	-1.47%	0.540	0.00%	0.540	0.00%
0.1	0.9	0.552	0.572	0.14%	0.524	-5.34%	0.564	-1.31%	0.555	0.46%	0.553	0.12%
0.2	0.8	0.569	0.597	2.19%	0.541	-5.18%	0.589	0.90%	0.569	-0.04%	0.565	-0.71%
0.3	0.7	0.583	0.620	-0.08%	0.556	-4.86%	0.614	-1.08%	0.582	-0.13%	0.577	-1.09%
0.4	0.6	0.568	0.637	6.24%	**0.564**	-0.71%	0.634	5.83%	0.595	4.46%	0.587	3.31%
0.5	0.5	0.584	0.643	4.51%	0.567	-3.00%	0.642	4.38%	0.605	3.46%	0.597	2.15%
0.6	0.4	0.585	0.643	2.51%	0.564	-3.72%	0.641	2.24%	0.606	3.48%	0.600	2.54%
0.7	0.3	0.582	0.641	3.06%	0.557	-4.49%	0.637	2.46%	0.605	3.79%	0.600	3.06%
0.8	0.2	0.601	0.637	0.77%	0.550	-9.27%	0.630	-0.25%	0.603	0.30%	0.600	-0.23%
0.9	0.1	0.602	0.633	-0.84%	0.541	-11.28%	0.624	-2.31%	0.600	-0.37%	0.598	-0.65%
1	0	0.596	0.628	0.03%	0.532	-12.03%	0.617	-1.87%	0.596	0.00%	0.596	0.00%
Maximum error			6.2%		12.0%		5.8%		4.5%		3.3%	
Mean error			1.7%		-6.1%		0.7%		1.4%		0.8%	
Standard Deviation			2.1%		3.3%		2.6%		1.8%		1.6%	

Compacted packing (D-C26)												
Vol. fraction (%)		Packing density & error (%)										
EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	1	0.547	0.547	0.04%	0.508	-7.68%	0.539	-1.47%	0.547	0.00%	0.547	0.00%
0.1	0.9	0.571	0.572	0.14%	0.529	-7.94%	0.564	-1.31%	0.563	-1.35%	0.562	-1.69%
0.2	0.8	0.584	0.597	2.19%	0.551	-5.99%	0.589	0.90%	0.580	-0.75%	0.576	-1.40%
0.3	0.7	0.621	0.620	-0.08%	0.571	-8.76%	0.614	-1.08%	0.595	-4.29%	0.590	-5.27%
0.4	0.6	0.597	0.637	6.24%	**0.583**	-2.40%	0.634	5.83%	0.610	2.17%	0.603	1.02%
0.5	0.5	0.614	0.643	4.51%	0.586	-4.78%	0.642	4.38%	0.623	1.51%	0.615	0.20%
0.6	0.4	0.627	0.643	2.51%	0.582	-7.73%	0.641	2.24%	0.628	0.19%	0.622	-0.79%
0.7	0.3	0.621	0.641	3.06%	0.577	-7.63%	0.637	2.46%	0.630	1.37%	0.625	0.61%
0.8	0.2	0.632	0.637	0.77%	0.570	-10.88%	0.630	-0.25%	0.630	-0.32%	0.627	-0.86%
0.9	0.1	0.638	0.633	-0.84%	0.563	-13.32%	0.624	-2.31%	0.629	-1.36%	0.628	-1.65%
1	0	0.628	0.628	0.03%	0.555	-13.15%	0.617	-1.87%	0.628	0.00%	0.628	0.00%
Maximum error			6.2%		13.3%		5.8%		4.3%		5.3%	
Mean error			1.7%		-8.2%		0.7%		-0.3%		-0.9%	
Standard Deviation			2.1%		3.2%		2.6%		1.7%		1.6%	

Compacted packing (D-C33)												
Vol. fraction (%)		Packing density & error (%)										
EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	1	0.583	0.582	-0.12%	0.542	-7.56%	0.573	-1.69%	0.583	0.00%	0.583	0.00%
0.1	0.9	0.606	0.608	0.31%	0.564	-7.45%	0.598	-1.26%	0.599	-1.09%	0.597	-1.44%
0.2	0.8	0.62	0.634	2.26%	0.586	-5.80%	0.624	0.71%	0.616	-0.71%	0.612	-1.38%
0.3	0.7	0.651	0.659	1.23%	0.604	-7.78%	0.649	-0.31%	0.631	-3.15%	0.625	-4.13%
0.4	0.6	0.635	0.676	6.12%	**0.615**	-3.25%	0.666	4.69%	0.645	1.61%	0.638	0.44%
0.5	0.5	0.651	0.682	4.56%	0.615	-5.85%	0.672	3.10%	0.655	0.67%	0.649	-0.36%
0.6	0.4	0.662	0.680	2.66%	0.610	-8.52%	0.670	1.14%	0.657	-0.73%	0.651	-1.63%
0.7	0.3	0.652	0.675	3.40%	0.603	-8.13%	0.664	1.83%	0.658	0.88%	0.653	0.19%
0.8	0.2	0.67	0.669	-0.22%	0.596	-12.42%	0.657	-1.91%	0.657	-1.92%	0.654	-2.42%
0.9	0.1	0.663	0.662	-0.22%	0.588	-12.76%	0.650	-1.98%	0.656	-1.06%	0.654	-1.31%
1	0	0.654	0.654	0.05%	0.580	-12.76%	0.643	-1.77%	0.654	0.00%	0.654	0.00%
Maximum error			6.1%		12.8%		4.7%		3.2%		4.1%	
Mean error			1.8%		-8.4%		0.2%		-0.5%		-1.1%	
Standard Deviation			2.1%		3.0%		2.2%		1.3%		1.3%	

Ternary mixtures

Loose packing (D-L)											
Vol. fraction (%)			Packing density & error (%)								
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.6	0.4	0.529	0.562	5.87%	0.556	4.91%	0.547	3.28%	0.541	2.21%
0.1	0.54	0.36		0.590		0.584		0.569		0.559	
0.2	0.48	0.32		0.617		0.612		0.591		0.577	
0.3	0.42	0.28	0.594	0.639	7.06%	0.635	6.39%	0.612	2.93%	0.593	-0.10%
0.4	0.36	0.24	0.603	0.651	7.39%	0.648	6.87%	0.622	3.00%	0.608	0.86%
0.5	0.3	0.2	0.616	0.652	5.47%	0.649	5.08%	0.624	1.23%	0.615	-0.24%
0.6	0.24	0.16	0.625	0.645	3.03%	0.642	2.72%	0.622	-0.41%	0.615	-1.70%
0.7	0.18	0.12	0.618	0.634	2.45%	0.632	2.20%	0.618	0.07%	0.612	-0.95%
0.8	0.12	0.08		0.621		0.620		0.612		0.608	
0.9	0.06	0.04		0.608		0.606		0.604		0.602	
1	0	0	0.594	0.594	0.02%	0.593	-0.12%	0.594	0.00%	0.594	0.00%
Maximum error				7.4%		6.9%		3.3%		2.2%	
Mean error				4.5%		4.0%		1.4%		0.0%	
Standard Deviation				2.5%		2.3%		1.5%		1.2%	

Compacted packing (D-C)											
Vol. fraction (%)			Packing density & error (%)								
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.6	0.4	0.585	0.623	6.11%	0.617	5.12%	0.598	2.17%	0.592	1.14%
0.1	0.54	0.36		0.652		0.646		0.622		0.611	
0.2	0.48	0.32		0.679		0.673		0.645		0.629	
0.3	0.42	0.28	0.65	0.698	6.90%	0.693	6.16%	0.663	2.02%	0.646	-0.62%
0.4	0.36	0.24	0.657	0.705	6.80%	0.700	6.17%	0.668	1.65%	0.658	0.21%
0.5	0.3	0.2	0.679	0.701	3.13%	0.697	2.56%	0.669	-1.47%	0.660	-2.83%
0.6	0.24	0.16	0.682	0.691	1.32%	0.687	0.77%	0.667	-2.22%	0.660	-3.40%
0.7	0.18	0.12	0.67	0.679	1.26%	0.675	0.74%	0.663	-1.13%	0.657	-2.05%
0.8	0.12	0.08		0.665		0.662		0.656		0.652	
0.9	0.06	0.04		0.651		0.648		0.647		0.645	
1	0	0	0.637	0.637	0.06%	0.634	-0.46%	0.637	0.00%	0.637	0.00%
Maximum error				6.9%		6.2%		2.2%		3.4%	
Mean error				3.7%		3.0%		0.1%		-1.1%	
Standard Deviation				2.7%		2.6%		1.7%		1.6%	

Compacted packing (D-C26)													
Vol. fraction (%)			Packing density & error (%)										
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.6	0.4	0.627	0.643	2.51%	0.582	-7.66%	0.633	0.92%	0.628	0.19%	0.622	-0.79%
0.1	0.54	0.36		0.679		0.609		0.668		0.656		0.645	
0.2	0.48	0.32		0.716		0.635		0.704		0.683		0.668	
0.3	0.42	0.28	0.698	0.750	6.90%	0.656	-6.44%	0.738	5.46%	0.707	1.26%	0.690	-1.21%
0.4	0.36	0.24	0.713	0.767	7.03%	**0.656**	-8.62%	0.756	5.70%	0.717	0.54%	0.707	-0.85%
0.5	0.3	0.2	0.713	0.766	6.90%	0.640	-11.39%	0.755	5.55%	0.723	1.44%	0.714	0.18%
0.6	0.24	0.16	0.726	0.758	4.22%	0.620	-17.19%	0.747	2.76%	0.727	0.12%	0.719	-0.98%
0.7	0.18	0.12	0.724	0.748	3.22%	0.599	-20.92%	0.736	1.65%	0.728	0.48%	0.721	-0.40%
0.8	0.12	0.08		0.738		0.579		0.725		0.726		0.721	
0.9	0.06	0.04		0.727		0.560		0.714		0.722		0.719	
1	0	0	0.716	0.716	0.06%	0.542	-32.15%	0.703	-1.86%	0.716	0.00%	0.716	0.00%
Maximum error				7.0%		32.2%		5.7%		1.4%		1.2%	
Mean error				4.4%		-14.9%		2.9%		0.6%		-0.6%	
Standard Deviation				2.5%		8.6%		2.7%		0.5%		0.5%	

Compacted packing (D-C33)													
Vol. fraction (%)			Packing density & error (%)										
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.6	0.4	0.662	0.672	1.52%	0.610	-8.49%	0.670	1.14%	0.657	-0.79%	0.651	-1.68%
0.1	0.54	0.36		0.724		0.650		0.705		0.685		0.675	
0.2	0.48	0.32		0.764		0.670		0.742		0.714		0.698	
0.3	0.42	0.28	0.73	0.791	7.69%	0.667	-9.50%	0.772	5.40%	0.732	0.28%	0.720	-1.39%
0.4	0.36	0.24	0.751	0.794	5.37%	**0.653**	-15.01%	0.782	4.01%	0.742	-1.26%	0.732	-2.54%
0.5	0.3	0.2	0.758	0.787	3.72%	0.638	-18.88%	0.779	2.63%	0.748	-1.34%	0.739	-2.51%
0.6	0.24	0.16	0.774	0.779	0.60%	0.622	-24.38%	0.770	-0.53%	0.751	-3.00%	0.744	-4.04%
0.7	0.18	0.12	0.766	0.769	0.45%	0.607	-26.12%	0.760	-0.82%	0.752	-1.83%	0.746	-2.65%
0.8	0.12	0.08		0.760		0.593		0.749		0.751		0.747	
0.9	0.06	0.04		0.751		0.579		0.739		0.747		0.745	
1	0	0	0.742	0.742	-0.05%	0.566	-31.07%	0.728	-1.91%	0.742	0.00%	0.742	0.00%
Maximum error				7.7%		31.1%		5.4%		3.0%		4.0%	
Mean error				2.8%		-19.1%		1.4%		-1.1%		-2.1%	
Standard Deviation				2.7%		7.9%		2.5%		1.0%		1.2%	

Loose packing (D-L)											
Vol. fraction (%)			Packing density & error (%)								
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.8	0.2	0.529	0.551	4.06%	0.546	3.07%	0.543	2.53%	0.539	1.94%
0.1	0.72	0.18		0.579		0.573		0.565		0.557	
0.2	0.64	0.16		0.605		0.600		0.586		0.575	
0.3	0.56	0.14	0.576	0.628	8.33%	0.624	7.64%	0.601	4.18%	0.591	2.52%
0.4	0.48	0.12	0.583	0.642	9.26%	0.639	8.73%	0.607	4.00%	0.600	2.83%
0.5	0.4	0.1	0.587	0.646	9.06%	0.643	8.66%	0.611	3.86%	0.604	2.77%
0.6	0.32	0.08	0.612	0.640	4.42%	0.638	4.10%	0.611	-0.13%	0.605	-1.12%
0.7	0.24	0.06	0.61	0.631	3.29%	0.629	3.03%	0.610	-0.07%	0.605	-0.86%
0.8	0.16	0.04	0.597	0.619	3.58%	0.618	3.37%	0.606	1.47%	0.603	0.92%
0.9	0.08	0.02		0.607		0.606		0.601		0.599	
1	0	0	0.594	0.594	0.02%	0.593	-0.12%	0.594	0.00%	0.594	0.00%
Maximum error				9.3%		8.7%		4.2%		2.8%	
Mean error				5.3%		4.8%		2.0%		1.1%	
Standard Deviation				3.1%		3.0%		1.8%		1.5%	

Loose packing (D-C)											
Vol. fraction (%)			Packing density & error (%)								
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0	0.8	0.2	0.589	0.606	2.74%	0.612	3.77%	0.599	1.65%	0.595	1.08%
0.1	0.72	0.18		0.634		0.641		0.622		0.614	
0.2	0.64	0.16		0.661		0.667		0.644		0.631	
0.3	0.56	0.14	0.638	0.682	6.51%	0.688	7.27%	0.652	2.15%	0.645	1.07%
0.4	0.48	0.12	0.641	0.693	7.45%	0.697	8.09%	0.657	2.39%	0.650	1.33%
0.5	0.4	0.1	0.631	0.692	8.76%	0.696	9.32%	0.659	4.18%	0.652	3.22%
0.6	0.32	0.08	0.656	0.684	4.06%	0.688	4.60%	0.658	0.29%	0.652	-0.58%
0.7	0.24	0.06	0.664	0.673	1.28%	0.676	1.82%	0.655	-1.36%	0.651	-2.06%
0.8	0.16	0.04	0.659	0.660	0.17%	0.664	0.70%	0.650	-1.31%	0.647	-1.80%
0.9	0.08	0.02		0.647		0.651		0.644		0.643	
1	0	0	0.637	0.634	-0.46%	0.637	0.06%	0.637	0.00%	0.637	0.00%
Maximum error				8.8%		9.3%		4.2%		3.2%	
Mean error				3.8%		4.5%		1.0%		0.3%	
Standard Deviation				3.2%		3.3%		1.8%		1.6%	

Compacted packing (D-C26)													
Vol. fraction (%)			Packing density & error (%)										
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: Υ)		3-P (unc.)		3-P (comp.)	
0	0.8	0.2	0.618	0.637	2.97%	0.570	-8.47%	0.626	1.26%	0.627	1.37%	0.630	1.91%
0.1	0.72	0.18		0.672		0.595		0.660		0.649		0.657	
0.2	0.64	0.16		0.708		0.622		0.696		0.671		0.683	
0.3	0.56	0.14	0.702	0.742	5.36%	0.643	-9.11%	0.730	3.80%	0.689	-1.91%	0.696	-0.86%
0.4	0.48	0.12	0.71	0.761	6.65%	**0.648**	-9.61%	0.749	5.23%	0.699	-1.64%	0.706	-0.60%
0.5	0.4	0.1	0.702	0.761	7.80%	0.634	-10.67%	0.750	6.42%	0.706	0.58%	0.713	1.52%
0.6	0.32	0.08	0.719	0.755	4.75%	0.616	-16.81%	0.743	3.25%	0.711	-1.06%	0.717	-0.22%
0.7	0.24	0.06	0.737	0.746	1.19%	0.596	-23.65%	0.734	-0.44%	0.715	-3.08%	0.720	-2.39%
0.8	0.16	0.04	0.72	0.736	2.20%	0.577	-24.77%	0.724	0.50%	0.717	-0.45%	0.720	0.02%
0.9	0.08	0.02		0.726		0.559		0.713		0.717		0.719	
1	0	0	0.716	0.716	0.06%	0.542	-32.15%	0.703	-1.86%	0.716	0.00%	0.716	0.00%
Maximum error				7.8%		32.2%		6.4%		3.1%		2.4%	
Mean error				3.9%		-16.9%		2.3%		-0.8%		-0.1%	
Standard Deviation				2.5%		8.4%		2.7%		1.4%		1.3%	

Compacted packing (D-C33)													
Vol. fraction (%)			Packing density & error (%)										
EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (B: β)		CPM (C: Υ)		3-P (unc.)		3-P (comp.)	
0	0.8	0.2	0.655	0.664	1.41%	0.596	-9.97%	0.653	-0.27%	0.657	0.34%	0.654	-0.15%
0.1	0.72	0.18		0.700		0.622		0.688		0.685	0.00%	0.677	0.00%
0.2	0.64	0.16		0.737		0.649		0.725		0.709	0.00%	0.700	0.00%
0.3	0.56	0.14	0.737	0.769	4.20%	0.670	-9.99%	0.757	2.70%	0.721	-2.22%	0.714	-3.19%
0.4	0.48	0.12	0.747	0.785	4.82%	**0.672**	-11.16%	0.774	3.45%	0.731	-2.26%	0.724	-3.21%
0.5	0.4	0.1	0.754	0.784	3.87%	0.658	-14.61%	0.773	2.49%	0.737	-2.24%	0.731	-3.13%
0.6	0.32	0.08	0.765	0.778	1.65%	0.639	-19.69%	0.766	0.17%	0.742	-3.08%	0.737	-3.86%
0.7	0.24	0.06	0.772	0.769	-0.34%	0.620	-24.54%	0.757	-1.93%	0.745	-3.67%	0.740	-4.30%
0.8	0.16	0.04	0.756	0.760	0.56%	0.601	-25.76%	0.748	-1.10%	0.745	-1.43%	0.742	-1.87%
0.9	0.08	0.02		0.751		0.583		0.738		0.744	0.00%	0.743	0.00%
1	0	0	0.742	0.742	-0.05%	0.566	-31.07%	0.728	-1.91%	0.742	0.00%	0.742	0.00%
Maximum error				4.8%		31.1%		3.5%		3.7%		4.3%	
Mean error				2.0%		-18.4%		0.4%		-1.3%		-1.8%	
Standard Deviation				1.9%		7.6%		2.0%		1.4%		1.7%	

Quaternary mixtures

Loose packing (D-L)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0.00	0.70	0.24	0.06	0.626	0.631	0.75%	0.629	0.49%	0.610	-2.70%	0.605	-3.51%
0.06	0.66	0.23	0.06	0.641	0.645	0.65%	0.644	0.41%	0.616	-4.00%	0.610	-5.04%
0.10	0.63	0.22	0.05		0.655		0.653		0.621		0.614	
0.13	0.61	0.21	0.05	0.647	0.662	2.31%	0.661	2.10%	0.624	-3.73%	0.616	-4.99%
0.19	0.57	0.19	0.05	0.657	0.677	2.94%	0.676	2.76%	**0.630**	-4.36%	0.621	-5.80%
0.20	0.56	0.19	0.05		0.679		0.678		0.630		0.622	
0.30	0.49	0.17	0.04	0.663	0.702	5.60%	0.701	5.49%	0.639	-3.80%	0.628	-5.51%
0.40	0.42	0.14	0.04		0.720		0.720		0.645		0.633	
0.47	0.37	0.13	0.03	0.665	0.725	8.32%	0.726	8.37%	0.648	-2.69%	0.636	-4.62%
0.50	0.35	0.12	0.03		0.725		0.726		0.646		0.636	
0.60	0.28	0.10	0.02		0.712		0.714		0.639		0.632	
0.70	0.21	0.07	0.02		0.687		0.688		0.630		0.625	
0.80	0.14	0.05	0.01		0.657		0.658		0.620		0.616	
0.90	0.07	0.02	0.01		0.626		0.627		0.609		0.607	
1.00	0.00	0.00	0.00	0.597	0.597	0.05%	0.598	0.19%	0.597	0.00%	0.597	0.00%
Maximum error					8.3%		8.4%		4.4%		5.8%	
Mean error					2.9%		2.8%		-3.0%		-4.2%	
Standard Deviation					2.8%		2.8%		1.4%		1.8%	

Compacted packing (D-C)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	EAF (0/5)	EAF (4/11)	EAF (11/22)	Φexp	CPM (A:βm)		CPM (C: ϒ)		3-P (unc.)		3-P (comp.)	
0.00	0.70	0.24	0.06		0.676		0.673		0.655		0.651	
0.06	0.66	0.23	0.06	0.689	0.694	0.73%	0.691	0.22%	0.665	-3.59%	0.659	-4.51%
0.10	0.63	0.22	0.05		0.706		0.703		0.672		0.665	
0.13	0.61	0.21	0.05	0.696	0.716	2.73%	0.712	2.27%	0.676	-2.89%	0.669	-4.01%
0.19	0.57	0.19	0.05	0.706	0.734	3.87%	0.731	3.46%	**0.686**	-2.93%	0.677	-4.23%
0.20	0.56	0.19	0.05		0.738		0.735		0.687		0.679	
0.30	0.49	0.17	0.04	0.723	0.769	6.03%	0.767	5.72%	0.702	-2.99%	0.691	-4.56%
0.40	0.42	0.14	0.04		0.798		0.797		0.715		0.703	
0.47	0.37	0.13	0.03	0.749	0.813	7.89%	0.812	7.81%	0.720	-3.99%	0.710	-5.55%
0.50	0.35	0.12	0.03		0.817		0.817		0.720		0.712	
0.60	0.28	0.10	0.02		0.815		0.816		0.720		0.712	
0.70	0.21	0.07	0.02		0.794		0.796		0.717		0.711	
0.80	0.14	0.05	0.01		0.764		0.766		0.713		0.709	
0.90	0.07	0.02	0.01		0.732		0.733		0.707		0.705	
1.00	0.00	0.00	0.00	0.7	0.700	0.05%	0.702	0.28%	0.700	0.00%	0.700	0.00%
Maximum error					7.9%		7.8%		4.0%		5.5%	
Mean error					3.5%		3.3%		-2.7%		-3.8%	
Standard Deviation					2.8%		2.8%		1.3%		1.8%	

Compacted packing (D-C26)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.70	0.24	0.06	0.754	0.746	-1.08%	0.734	-2.75%	0.720	-4.75%	0.715	-5.46%
0.06	0.66	0.23	0.06	0.763	0.763	0.06%	0.751	-1.60%	0.729	-4.60%	0.723	-5.52%
0.10	0.63	0.22	0.05		0.776		0.763		0.736		0.728	
0.13	0.61	0.21	0.05	0.773	0.785	1.50%	0.772	-0.15%	0.740	-4.43%	0.732	-5.56%
0.19	0.57	0.19	0.05	0.78	0.804	2.96%	0.790	1.32%	**0.749**	-4.13%	0.740	-5.44%
0.20	0.56	0.19	0.05		0.807		0.794		0.750		0.741	
0.30	0.49	0.17	0.04	0.791	0.840	5.84%	0.826	4.23%	0.764	-3.58%	0.752	-5.16%
0.40	0.42	0.14	0.04		0.873		0.858		0.769		0.761	
0.47	0.37	0.13	0.03	0.805	0.893	9.86%	0.878	8.30%	0.769	-4.71%	0.761	-5.80%
0.50	0.35	0.12	0.03		0.899		0.884		0.768		0.761	
0.60	0.28	0.10	0.02		0.893		0.878		0.766		0.759	
0.70	0.21	0.07	0.02		0.858		0.843		0.761		0.756	
0.80	0.14	0.05	0.01		0.816		0.802		0.755		0.752	
0.90	0.07	0.02	0.01		0.777		0.762		0.748		0.746	
1.00	0.00	0.00	0.00	0.74	0.740	-0.03%	0.725	-2.01%	0.740	0.00%	0.740	0.00%
Maximum error					9.9%		8.3%		4.8%		5.8%	
Mean error					2.7%		1.0%		-3.7%		-4.7%	
Standard Deviation					3.6%		3.7%		1.6%		1.9%	

Compacted packing (D-C33)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.70	0.24	0.06	0.739	0.769	3.96%	0.757	2.43%	0.745	0.76%	0.740	0.15%
0.06	0.66	0.23	0.06	0.768	0.787	2.35%	0.774	0.79%	0.753	-1.94%	0.747	-2.78%
0.10	0.63	0.22	0.05		0.798		0.786		0.759		0.752	
0.13	0.61	0.21	0.05	0.784	0.807	2.87%	0.794	1.30%	0.763	-2.76%	0.755	-3.83%
0.19	0.57	0.19	0.05	0.79	0.826	4.30%	0.812	2.73%	**0.771**	-2.52%	0.761	-3.77%
0.20	0.56	0.19	0.05		0.829		0.815		0.772		0.762	
0.30	0.49	0.17	0.04	0.81	0.860	5.82%	0.846	4.24%	0.782	-3.62%	0.771	-5.02%
0.40	0.42	0.14	0.04		0.890		0.875		0.781		0.773	
0.47	0.37	0.13	0.03	0.823	0.906	9.20%	0.891	7.60%	0.779	-5.71%	0.771	-6.69%
0.50	0.35	0.12	0.03		0.910		0.894		0.777		0.771	
0.60	0.28	0.10	0.02		0.895		0.878		0.772		0.767	
0.70	0.21	0.07	0.02		0.857		0.840		0.766		0.761	
0.80	0.14	0.05	0.01		0.815		0.800		0.758		0.755	
0.90	0.07	0.02	0.01		0.776		0.761		0.749		0.748	
1.00	0.00	0.00	0.00	0.74	0.740	-0.03%	0.725	-2.01%	0.740	0.00%	0.740	0.00%
Maximum error					9.2%		7.6%		5.7%		6.7%	
Mean error					4.1%		2.4%		-2.3%		-3.1%	
Standard Deviation					2.7%		2.8%		2.0%		2.3%	

Loose packing (D-L)												
Vol. fraction (%)				**Packing density & error (%)**								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.50	0.30	0.20	0.616	0.652	5.47%	0.649	5.08%	0.624	1.23%	0.615	-0.24%
0.06	0.47	0.28	0.19	0.636	0.668	4.73%	0.665	4.37%	0.631	-0.75%	0.621	-2.45%
0.10	0.45	0.27	0.18		0.678		0.676		0.636		0.625	
0.13	0.44	0.26	0.17	0.641	0.686	6.60%	0.684	6.28%	0.639	-0.26%	0.627	-2.16%
0.19	0.41	0.24	0.16	0.657	0.702	6.42%	0.700	6.14%	**0.646**	-1.78%	0.633	-3.87%
0.20	0.40	0.24	0.16		0.705		0.703		0.646		0.633	
0.30	0.35	0.21	0.14		0.729		0.727		0.655		0.640	
0.40	0.30	0.18	0.12		0.746		0.745		0.660		0.645	
0.47	0.27	0.16	0.11	0.67	0.749	10.55%	0.749	10.54%	0.662	-1.22%	0.646	-3.65%
0.50	0.25	0.15	0.10		0.747		0.748		0.660		0.647	
0.60	0.20	0.12	0.08	0.658	0.729	9.70%	0.730	9.83%	0.651	-1.05%	0.643	-2.40%
0.70	0.15	0.09	0.06		0.698		0.699		0.640		0.633	
0.80	0.10	0.06	0.04		0.663		0.664		0.627		0.622	
0.90	0.05	0.03	0.02		0.629		0.630		0.612		0.610	
1.00	0.00	0.00	0.00	0.597	0.597	0.05%	0.598	0.19%	0.597	0.00%	0.597	0.00%
Maximum error					10.5%		10.5%		1.8%		3.9%	
Mean error					6.2%		6.1%		-0.5%		-2.1%	
Standard Deviation					3.2%		3.2%		0.9%		1.4%	

Compacted packing (D-C)												
Vol. fraction (%)				**Packing density & error (%)**								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.50	0.30	0.20	0.679	0.701	3.13%	0.697	2.56%	0.669		0.660	
0.06	0.47	0.28	0.19	0.702	0.720	2.49%	0.716	1.95%	0.680	-3.23%	0.670	-4.81%
0.10	0.45	0.27	0.18		0.733		0.729		0.687		0.676	
0.13	0.44	0.26	0.17	0.715	0.743	3.73%	0.739	3.25%	0.692	-3.29%	0.680	-5.08%
0.19	0.41	0.24	0.16	0.727	0.763	4.67%	0.759	4.23%	**0.702**	-3.55%	0.689	-5.50%
0.20	0.40	0.24	0.16		0.766		0.762		0.704		0.691	
0.30	0.35	0.21	0.14		0.799		0.796		0.718		0.704	
0.40	0.30	0.18	0.12		0.827		0.825		0.731		0.715	
0.47	0.27	0.16	0.11	0.745	0.840	11.33%	0.839	11.23%	0.735	-1.33%	0.721	-3.32%
0.50	0.25	0.15	0.10		0.843		0.842		0.735		0.723	
0.60	0.20	0.12	0.08	0.727	0.834	12.78%	0.835	12.90%	0.733	0.77%	0.724	-0.45%
0.70	0.15	0.09	0.06		0.805		0.807		0.727		0.721	
0.80	0.10	0.06	0.04		0.770		0.772		0.720		0.715	
0.90	0.05	0.03	0.02		0.734		0.736		0.711		0.708	
1.00	0.00	0.00	0.00	0.7	0.700	0.05%	0.702	0.28%	0.700	0.00%	0.700	0.00%
Maximum error					12.8%		12.9%		3.5%		5.5%	
Mean error					5.5%		5.2%		-1.8%		-3.2%	
Standard Deviation					4.4%		4.5%		1.7%		2.2%	

Compacted packing (D-C26)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.50	0.30	0.20	0.713	0.766	6.98%	0.756	5.64%	0.723	1.44%	0.714	0.18%
0.06	0.47	0.28	0.19	0.745	0.785	5.07%	0.774	3.69%	0.734	-1.45%	0.724	-2.95%
0.10	0.45	0.27	0.18		0.797		0.786		0.741		0.730	
0.13	0.44	0.26	0.17	0.759	0.807	5.92%	0.795	4.54%	0.746	-1.69%	0.734	-3.39%
0.19	0.41	0.24	0.16	0.769	0.826	6.93%	0.814	5.54%	**0.756**		0.742	
0.20	0.40	0.24	0.16		0.830		0.817		0.758		0.744	
0.30	0.35	0.21	0.14		0.863		0.850		0.772		0.756	
0.40	0.30	0.18	0.12		0.896		0.882		0.779		0.766	
0.47	0.27	0.16	0.11	0.79	0.915	13.65%	0.901	12.33%	0.779	-1.45%	0.769	-2.79%
0.50	0.25	0.15	0.10		0.920		0.906		0.778		0.769	
0.60	0.20	0.12	0.08	0.782	0.907		0.894		0.775	-0.92%	0.767	-2.00%
0.70	0.15	0.09	0.06		0.865		0.852		0.769		0.763	
0.80	0.10	0.06	0.04		0.821		0.807		0.761		0.756	
0.90	0.05	0.03	0.02		0.778		0.764		0.751		0.749	
1.00	0.00	0.00	0.00	0.74	0.740	-0.03%	0.725	-2.01%	0.740	0.00%	0.740	0.00%
Maximum error					13.7%		12.3%		1.7%		3.4%	
Mean error					6.4%		5.0%		-0.7%		-1.8%	
Standard Deviation					4.0%		4.2%		1.1%		1.4%	

Compacted packing (D-C33)												
Vol. fraction (%)				Packing density & error (%)								
NL (0/2)	**EAF (0/5)**	**EAF (4/11)**	**EAF (11/22)**	**Φexp**	**CPM (A:βm)**		**CPM (C: ϒ)**		**3-P (unc.)**		**3-P (comp.)**	
0.00	0.50	0.30	0.20	0.758	0.789	3.96%	0.779	2.63%	0.748	-1.34%	0.739	-2.51%
0.06	0.47	0.28	0.19	0.772	0.807	4.34%	0.796	3.00%	0.758	-1.87%	0.748	-3.25%
0.10	0.45	0.27	0.18		0.819		0.808		0.764		0.753	
0.13	0.44	0.26	0.17	0.791	0.828	4.50%	0.817	3.14%	0.769	-2.91%	0.757	-4.54%
0.19	0.41	0.24	0.16	0.805	0.847	4.96%	0.835	3.58%	**0.777**	-3.59%	0.764	-5.40%
0.20	0.40	0.24	0.16		0.850		0.838		0.778		0.765	
0.30	0.35	0.21	0.14		0.882		0.869		0.789		0.775	
0.40	0.30	0.18	0.12		0.913		0.899		0.789		0.779	
0.47	0.27	0.16	0.11	0.824	0.928	11.25%	0.914	9.80%	0.787	-4.64%	0.778	-5.87%
0.50	0.25	0.15	0.10		0.931		0.916		0.786		0.778	
0.60	0.20	0.12	0.08	0.798	0.911		0.895		0.781		0.773	
0.70	0.15	0.09	0.06		0.866		0.851		0.773		0.767	
0.80	0.10	0.06	0.04		0.821		0.806		0.763		0.759	
0.90	0.05	0.03	0.02		0.779		0.764		0.752		0.750	
1.00	0.00	0.00	0.00	0.74	0.740	-0.03%	0.725	-2.01%	0.740	0.00%	0.740	0.00%
Maximum error					11.2%		9.8%		4.6%		5.9%	
Mean error					4.8%		3.4%		-2.4%		-3.6%	
Standard Deviation					3.3%		3.4%		1.5%		2.0%	

Annex 2. Additional information of Chapter 6

This appendix reports data and general information of the NL and EAF aggregate facilities and assumption. In addition, a section with extra data of the concrete environmental impact was included.

A- NL aggregate data:

The Natural limestone (NL) aggregates are extracted from quarry. These materials were supplied by AMANTEGUI company located in Mañaria Bizakaia and were obtained through crushing, screening and sorting processes.

The data supplied by the company are included in the tables reported below (Table A2.1 and Table A2.2).

Table A2.1. General data on the natural aggregate facility.

Production capacity		**1,200,000-1,500,000 t/year**			
Year	Total production (t)	Electric energy (kWh)		Diesel fuel	
		Total (kWh)	kWh/t	(l)	l/t
2015	719,030	1,403,164	3.26	242,712	0.56
2016	374,851	707,979	4.67	215,484	1.42
2017	353,524	688,546	4.41	183,000	1.17
2018	419,975	774,404	3.93	159,079	0.81
2019	424,506	1,215,766	4.20	183,973	0.63
Average values	456,377	957,972	4.09	196,850	0.92

The water consumption can be estimated as zero, since the water used to clean tracks and to control the dust pollution during the crushing process comes from rainwater stored in settling ponds.

Table A2.2. Mass balance of the NL aggregate production.

Aggregates	**2015(%)**	**2016(%)**	**2017(%)**	**2018(%)**	**2019(%)**
NL (0/2)	0.2	0.3	0.6	1.0	1.4
NL (0/4)	31.6	20.8	19.3	24.3	32.3
NL (4/12)	10.4	8.8	11.1	10.2	12.7
NL (12/22)	17.7	11.7	13.2	11.3	21.8
Others size fractions	40.1	58.4	55.8	53.1	31.7

In order to obtain the granular size distribution demanded by the market, the quarry has the following facilities with their corresponding capacity:

Primary installation (Primary crusher): 2000 t/hour

Secondary installation: 700 t/hour

Ternary installation: 650 t/hour

Quaternary installation 120 t/hour

Fig. A1 show a schematic process of the NL aggregate production used to estimate the particle matter emission during the treatment process.

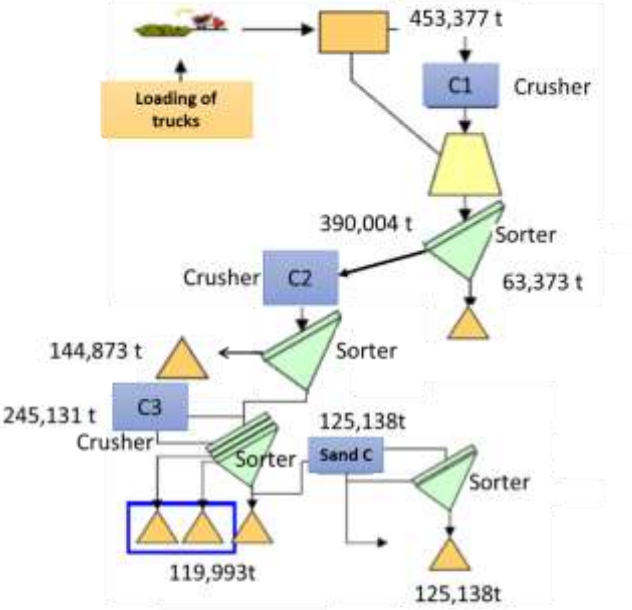


Fig. A2.1. Schematic process of the NL aggregate production. Adapted from(Consejería de agricultura, ganadería 2019)

The mass balance represented in Fig. A2.1 should be consider with caution as some of the mass flows has been assumed. To obtain a more accurate value of the PM10 emission the detailed mass balance of the quarry and all the processing machinery should be considered.

In Table A2.3, the particles emission were calculated according to the method and recommended emission factor proposed in a guide with this aim (Consejería de agricultura, ganadería 2019).

Table A2.3. Particles emission PM10 during the NL aggregate production.

	Material amount (t)	**Emission factors** (PM_{10} kg/t)	**Emissions**PM_{10}(kg)
Primary crusher	453377	2.7E-04	1.2E+02
Sorter	453377	3.7E-04	1.7E+02
Secondary crusher	390004	2.7E-04	1.1E+02
Sorter	390004	3.7E-04	1.4E+02
Tertiary crusher	245131	2.7E-04	6.6E+01

Sorter	245131	3.7E-04	9.1E+01
Sand crusher	125138	6.0E-04	7.5E+01
Sorter	125138	1.1E-03	1.4E+02
General particle material treatment	453377	7.2E-04[27]	3.2E+02
Conveyor	453377	2.3E-05	1.0E+01
Total emissions			1244.25

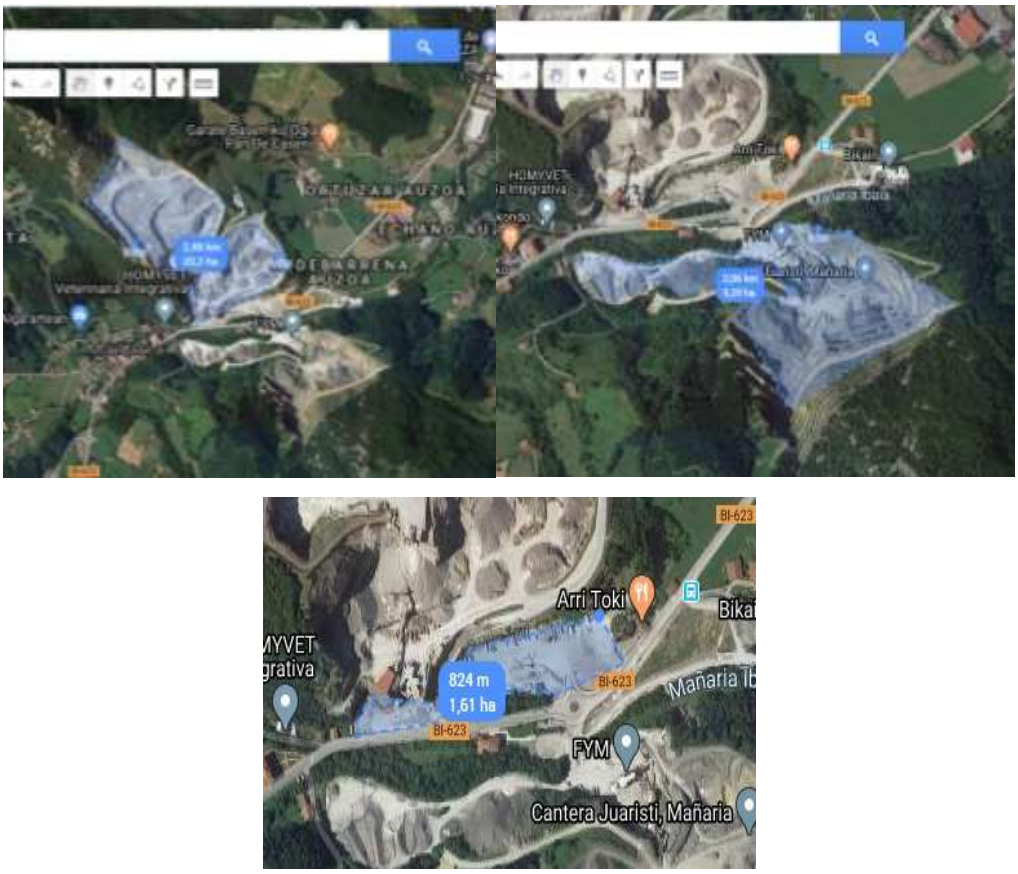


Fig. A2.2. Extension of the AMANTEGUI facilities. Screenshot of the satellite map of Google.

The land used were estimated according to the LCI published by (Kittipongvises 2017)

Total facilities area= 20.2+9.29+1.61 ha = 311,000 m^2

---

[27] Calculated by considered an average air speed of 2.8m/s and a material humidity of 2.1%.

Total facilities area= 20.2+9.29+1.61 ha = 311,000 m^2

FU: 1t of natural aggregate

Annual production: 456,377 t/year

Land Occupation= 311,000/(456,377)=0.67 m^2a

Occupation, mineral extraction site.

- Land Transformation= 311,000/(20·456,377)=0.034 m^2

  Transformation, from arable, irrigated, intensive.

  Transformation, to mineral extraction site

Total facilities area= 20.2+9.29+1.61 ha = 311,000 m^2

FU: 456377 t of natural aggregate

Annual production: 456,377 t/year

Land Occupation: 3110000m^2a

Land Transformation: 15550m^2

B- EAF aggregates data

Data supplied by HORMOR company.

Production capacity of the facilities:80 t/h

Table A2.4. Available machinery and consumption.

Type of equipment	**Quantity**	**CV**	**KW**
Conveyor	3	2	1.5
Conveyor	3	30	22.4
Electromagnet	3	1.5	1.1
Vibration Screen	1	15	11.2
Crusher	1	270	201.3
Crusher	1	250	186.4
Total		635.5	473.9

Fig. A2.3 show a schematic process of the EAF aggregate production used to estimate the particle matter emission during the treatment process.

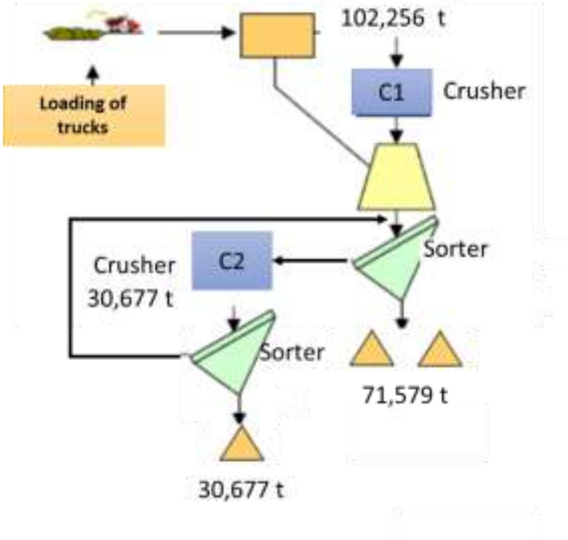


Fig. A2.3. Schematic process of the EAF aggregate production. Adapted from(Consejería de agricultura, ganadería 2019)

The mass balance represented in Fig. A2.3 should be considered with caution as some of the mass flows has been assumed. To obtain a more accurate value of the PM_{10} emission the detailed mass balance of the EAF treatment plant and all the processing machinery should be considered (see Fig. A2.4 Hormor facilities).

In Table A2.5, the particles emission were calculated according to the method and recommended emission factor proposed in a guide with this aim(Consejería de agricultura, ganadería 2019).

Table. A2.5. Particles emission PM_{10} during the EAF aggregate treatment.

	Material amount (t)	**Emission factors** (PM_{10} kg/t)	**Emissions** PM_{10}(kg)
Primary crusher	102256	2.70E-04	2.76E+01
Sorter	102256	3.70E-04	3.78E+01
Secondary crusher	30676.8	2.70E-04	8.28E+00
Sorter	30676.8	3.70E-04	1.14E+01
Conveyor	102256	2.30E-05	2.35E+00
General particle material treatment	102256	2.12E-04[28]	2.17E+01
Total emissions			109.15

---

[28] Calculated by considered an average air speed of 2.8m/s and a material humidity of 5%.

Fig. A2.4. Extension of the HORMOR facilities. Screenshot of the satellite map of Google

The land used were estimated according to the methodology published by (Kittipongvises 2017), which suggests the period of 50 years for the industrial activity.

Total area= 15700m^2

UF: 1t of natural aggregate

Annual production: 102,256 t/year

Land occupation= 15,700/(102,256)=0.15 m^2a

- Occupation, industrial area.

Land transformation= 15700/(50·102256)=3.07*10-3 m^2

- Transformation, from unknown.
- Transformation, to industrial area.

C- RCA aggregates

In Table A2.6 and Table A2.7, the particles emission were calculated according to the method and recommended emission factor proposed in a guide with this aim(Consejería de agricultura, ganadería 2019).

Table A2.6. Particles emission PM_{10} during the RCA aggregate treatment (scenario A).

	Material amount (t)	**Emission factors (PM_{10} kg/t)**	**Emissions** PM_{10}(kg)
Primary crusher	1	2.70E-04	2.70E-04
Sorter	1	3.70E-04	3.70E-04
Secondary crusher	1	2.70E-04	2.70E-04
Sorter	1	3.70E-04	3.70E-04
Conveyor	1	2.30E-05	2.30E-05
General particle material treatment	1	2.12E-04[10]	2.12E-04[10]
Total emissions			1.51E-03

Table A2.7. Particles emission PM_{10} during the RCA aggregate treatment (scenario B).

	Material amount (t)	**Emission factors**(PM_{10}kg/t)	**Emissions** PM_{10}(kg)
Primary crusher	1	2.70E-04	2.70E-04
Sorter	1	3.70E-04	3.70E-04
General particle material treatment	1	2.12E-04[10]	2.12E-04[10]
Total emissions			8.52E-04

D- Environmental impact of concrete mixes.

The characterized environmental impact of the concrete mixes per m^3·MPa of concrete are shown in Table A2.8.

Table A2.8. LCIA results per m^3·MPa of concrete.

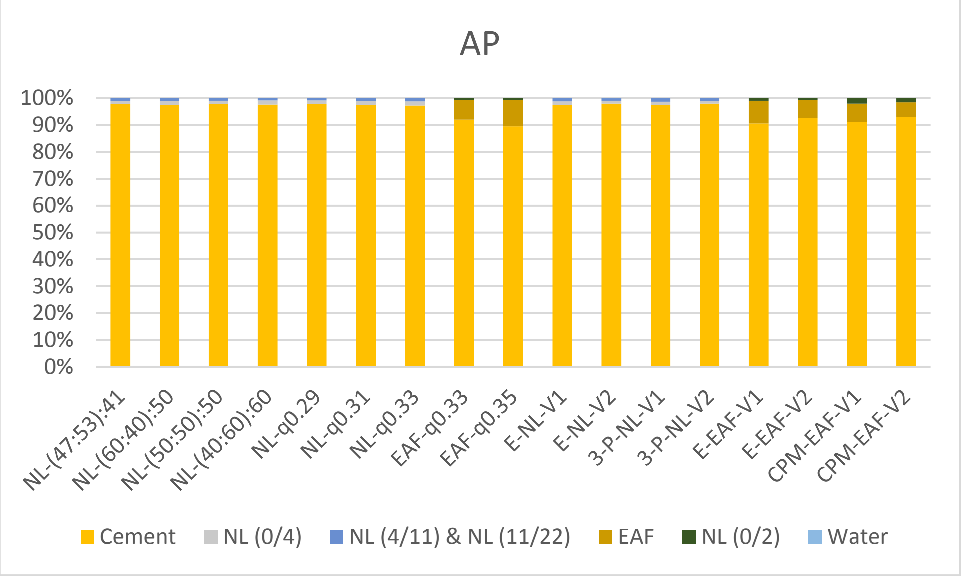
		AP	GWP100	ET	EPmw	EPfw	EPt	HTc	HTn-c	IR	LU	ODP	PM	POCP	ADP-F	ADP-E	Water use	COST
Nº	ID	Mol H+ eq	kg CO_2 eq.	CTUe	kg N eq.	kg P eq.	Mol H+ eq	CTUh	CTUh	kBq U235	Item(s)	g CFC-11 eq	ease inciden	g NMVOC e	MJ	kg Sb eq.	m^3	€
1	NL-(47:53):41	9.26E-03	4.81E+00	1.82E-01	2.94E-03	1.93E-06	3.21E-02	7.51E-09	3.39E-07	1.37E-01	9.64E+00	6.36E-11	5.49E-08	8.61E-03	1.99E+01	1.79E-07	3.78E-01	1.05E+00
2	NL-(60:40):50	9.75E-03	5.05E+00	1.93E-01	3.09E-03	2.08E-06	3.37E-02	7.95E-09	3.56E-07	1.45E-01	1.10E+01	6.81E-11	5.89E-08	9.06E-03	2.12E+01	1.91E-07	4.02E-01	1.15E+00
3	NL-(50:50):50	9.93E-03	5.15E+00	1.95E-01	3.15E-03	2.08E-06	3.44E-02	8.06E-09	3.63E-07	1.47E-01	1.06E+01	6.85E-11	5.92E-08	9.23E-03	2.14E+01	1.93E-07	4.06E-01	1.14E+00
4	NL-(40:60):60	1.04E-02	5.37E+00	2.04E-01	3.28E-03	2.19E-06	3.58E-02	8.43E-09	3.79E-07	1.53E-01	1.13E+01	7.20E-11	6.21E-08	9.63E-03	2.24E+01	2.02E-07	4.26E-01	1.20E+00
5	NL-q0.29	9.64E-03	5.00E+00	1.89E-01	3.05E-03	2.00E-06	3.34E-02	7.79E-09	3.52E-07	1.42E-01	9.95E+00	6.40E-11	5.70E-08	8.96E-03	2.07E+01	1.86E-07	3.70E-01	1.08E+00
6	NL-q0.31	9.49E-03	4.91E+00	1.87E-01	3.00E-03	2.04E-06	3.28E-02	7.73E-09	3.47E-07	1.41E-01	1.09E+01	6.47E-11	5.75E-08	8.81E-03	2.06E+01	1.86E-07	3.72E-01	1.13E+00
7	NL-q0.33	8.39E-03	4.34E+00	1.67E-01	2.66E-03	1.84E-06	2.90E-02	6.86E-09	3.07E-07	1.25E-01	1.01E+01	5.80E-11	5.16E-08	7.79E-03	1.83E+01	1.66E-07	3.33E-01	1.04E+00
8	EAF-q0.33	1.03E-02	5.09E+00	1.98E-01	3.36E-03	2.07E-06	3.67E-02	8.36E-09	3.53E-07	1.45E-01	6.73E+00	6.85E-11	5.76E-08	9.54E-03	2.14E+01	1.94E-07	4.02E-01	9.19E-01
9	EAF-q0.35	8.90E-03	4.31E+00	1.73E-01	2.93E-03	1.87E-06	3.20E-02	7.33E-09	2.98E-07	1.25E-01	6.13E+00	6.18E-11	5.08E-08	8.23E-03	1.85E+01	1.71E-07	3.62E-01	8.18E-01
10	E-NL-V1	7.23E-03	3.74E+00	1.43E-01	2.29E-03	1.56E-06	2.50E-02	5.90E-09	2.64E-07	1.08E-01	8.45E+00	4.94E-11	4.41E-08	6.71E-03	1.57E+01	1.42E-07	2.84E-01	8.73E-01
11	E-NL-V2	9.38E-03	4.87E+00	1.83E-01	2.97E-03	1.92E-06	3.25E-02	7.55E-09	3.43E-07	1.38E-01	9.28E+00	6.15E-11	5.49E-08	8.72E-03	2.01E+01	1.80E-07	3.57E-01	1.03E+00
12	3-P-NL-V1	8.32E-03	4.31E+00	1.64E-01	2.63E-03	1.79E-06	2.88E-02	6.78E-09	3.04E-07	1.24E-01	9.58E+00	5.67E-11	5.05E-08	7.72E-03	1.81E+01	1.63E-07	3.26E-01	9.98E-01
13	3-P-NL-V2	1.07E-02	5.57E+00	2.09E-01	3.40E-03	2.18E-06	3.71E-02	8.62E-09	3.92E-07	1.58E-01	1.05E+01	7.02E-11	6.25E-08	9.96E-03	2.29E+01	2.05E-07	4.08E-01	1.17E+00
14	E-EAF-V1	7.29E-03	3.57E+00	1.42E-01	2.39E-03	1.53E-06	2.61E-02	5.99E-09	2.47E-07	1.03E-01	5.30E+00	5.04E-11	4.17E-08	6.75E-03	1.52E+01	1.40E-07	2.95E-01	6.86E-01
15	E-EAF-V2	8.49E-03	4.22E+00	1.63E-01	2.77E-03	1.69E-06	3.02E-02	6.89E-09	2.93E-07	1.20E-01	5.55E+00	5.64E-11	4.74E-08	7.88E-03	1.76E+01	1.60E-07	3.33E-01	7.58E-01
16	CPM-EAF-V1	8.01E-03	3.95E+00	1.59E-01	2.61E-03	1.81E-06	2.85E-02	6.68E-09	2.75E-07	1.16E-01	8.31E+00	5.81E-11	4.89E-08	7.40E-03	1.72E+01	1.60E-07	3.35E-01	9.06E-01
17	CPM-EAF-V2	1.08E-02	5.40E+00	2.12E-01	3.50E-03	2.30E-06	3.82E-02	8.86E-09	3.77E-07	1.56E-01	9.67E+00	7.46E-11	6.35E-08	1.00E-02	2.30E+01	2.10E-07	4.33E-01	1.12E+00

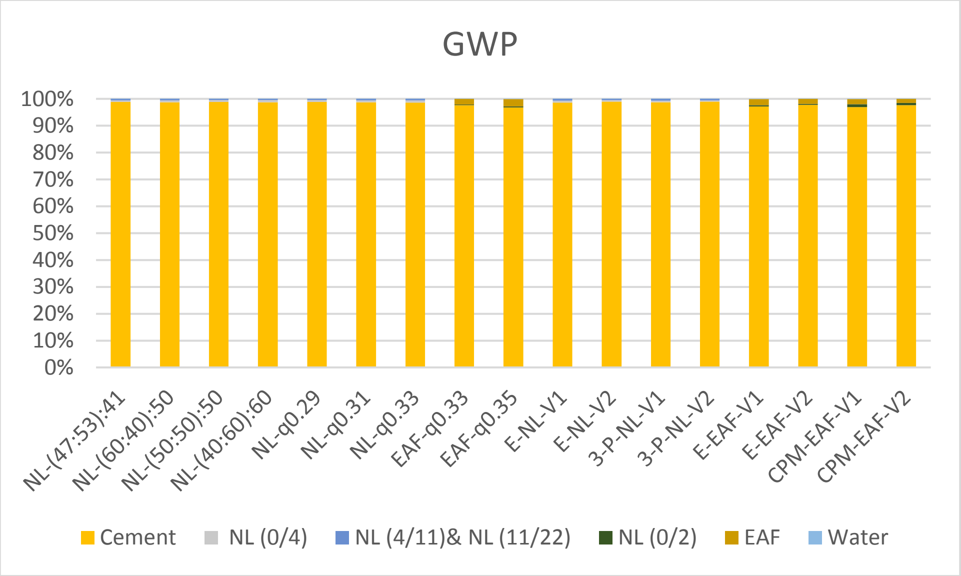
The characterized environmental impact of the concrete mixes per m^3 of concrete are shown in Table A2.9.

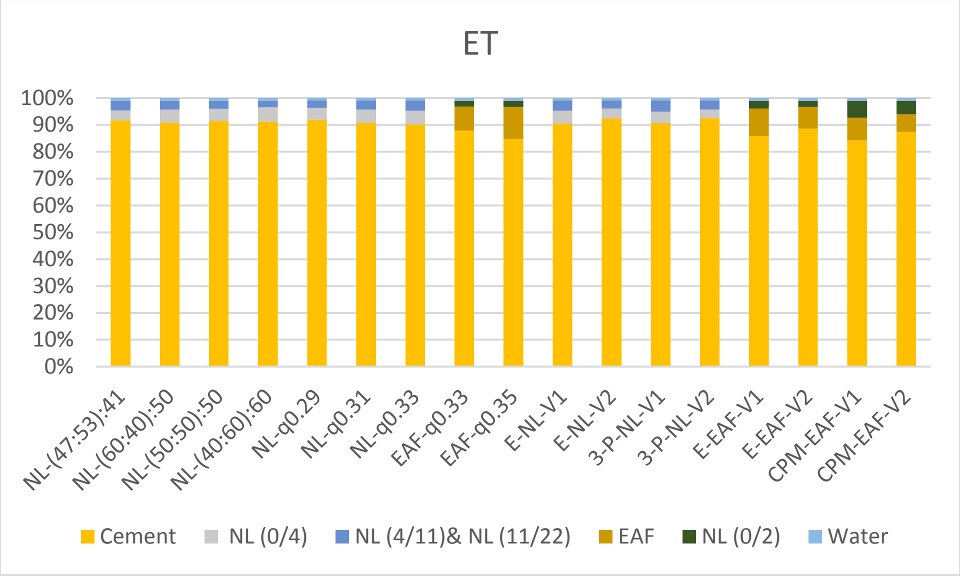
Table A2.9. LCIA results per m^3 of concrete.

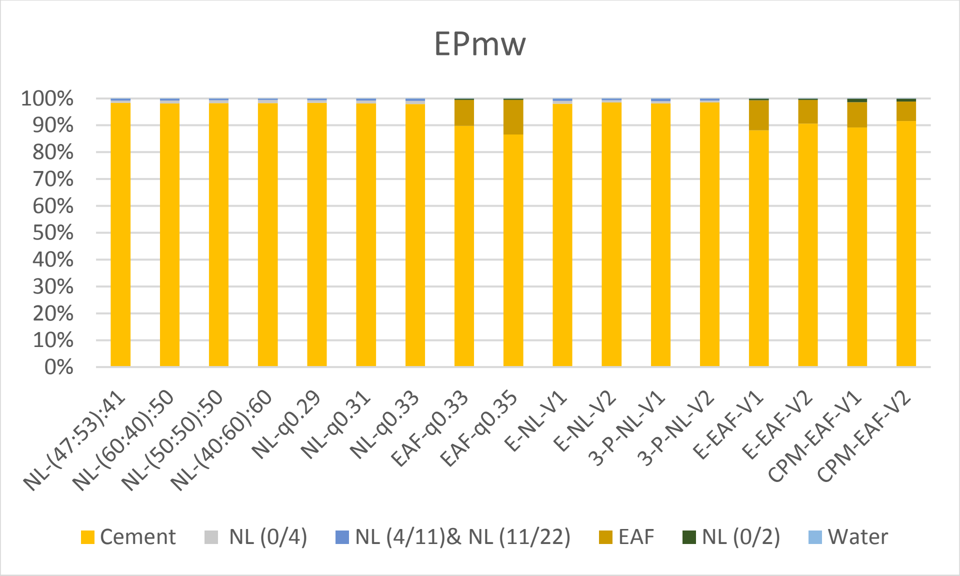
ID	AP	GWP100	ET	EPmw	EPfw	EPt	HTc	HTn-c	IR	LU	ODP	PM	POCP	ADP-F	ADP-E	Water use	COSt
	Mol H+ eq	kg CO$_2$ eq.	CTUe	kg N eq.	kg P eq.	Mol H+ eq	CTUh	CTUh	kBq U235	Item(s)	kg CFC-11 eq.	Disease	g NMVOCev	MJ	kg Sb eq.	m^3	€
NL-(47:53):41	3.91E-01	2.03E+02	7.67E+00	1.24E-01	8.14E-05	1.35E+00	3.17E-07	1.43E-05	5.77E+00	4.07E+02	2.68E-09	2.32E-06	3.63E-01	8.42E+02	7.57E-06	1.59E+01	4.42E+01
NL-(60:40):50	3.92E-01	2.03E+02	7.74E+00	1.24E-01	8.38E-05	1.36E+00	3.19E-07	1.43E-05	5.82E+00	4.40E+02	2.74E-09	2.37E-06	3.64E-01	8.50E+02	7.68E-06	1.62E+01	4.62E+01
NL-(50:50):50	3.91E-01	2.03E+02	7.69E+00	1.24E-01	8.21E-05	1.35E+00	3.18E-07	1.43E-05	5.79E+00	4.17E+02	2.70E-09	2.33E-06	3.64E-01	8.44E+02	7.60E-06	1.60E+01	4.47E+01
NL-(40:60):60	3.92E-01	2.03E+02	7.71E+00	1.24E-01	8.30E-05	1.35E+00	3.19E-07	1.43E-05	5.80E+00	4.28E+02	2.72E-09	2.35E-06	3.64E-01	8.47E+02	7.64E-06	1.61E+01	4.55E+01
NL-q0.29	4.12E-01	2.14E+02	8.07E+00	1.31E-01	8.55E-05	1.43E+00	3.33E-07	1.51E-05	6.08E+00	4.26E+02	2.74E-09	2.44E-06	3.83E-01	8.87E+02	7.95E-06	1.59E+01	4.63E+01
NL-q0.31	3.65E-01	1.89E+02	7.22E+00	1.16E-01	7.85E-05	1.26E+00	2.97E-07	1.33E-05	5.43E+00	4.18E+02	2.49E-09	2.22E-06	3.39E-01	7.94E+02	7.16E-06	1.43E+01	4.36E+01
NL-q0.33	3.42E-01	1.77E+02	6.78E+00	1.08E-01	7.48E-05	1.18E+00	2.79E-07	1.25E-05	5.09E+00	4.12E+02	2.36E-09	2.10E-06	3.17E-01	7.46E+02	6.75E-06	1.35E+01	4.21E+01
EAF-q0.33	4.67E-01	2.31E+02	9.00E+00	1.53E-01	9.39E-05	1.67E+00	3.80E-07	1.60E-05	6.58E+00	3.05E+02	3.11E-09	2.61E-06	4.33E-01	9.70E+02	8.82E-06	1.82E+01	4.17E+01
EAF-q0.35	3.93E-01	1.91E+02	7.64E+00	1.30E-01	8.27E-05	1.42E+00	3.24E-07	1.32E-05	5.52E+00	2.71E+02	2.73E-09	2.25E-06	3.64E-01	8.20E+02	7.56E-06	1.60E+01	3.62E+01
E-NL-V1	3.52E-01	1.82E+02	6.97E+00	1.11E-01	7.62E-05	1.22E+00	2.87E-07	1.29E-05	5.24E+00	4.12E+02	2.41E-09	2.15E-06	3.27E-01	7.67E+02	6.92E-06	1.38E+01	4.25E+01
E-NL-V2	4.27E-01	2.22E+02	8.32E+00	1.35E-01	8.71E-05	1.48E+00	3.44E-07	1.56E-05	6.28E+00	4.22E+02	2.80E-09	2.50E-06	3.97E-01	9.14E+02	8.17E-06	1.62E+01	4.67E+01
3-P-NL-V1	3.52E-01	1.82E+02	6.95E+00	1.11E-01	7.57E-05	1.22E+00	2.87E-07	1.29E-05	5.23E+00	4.05E+02	2.40E-09	2.14E-06	3.27E-01	7.65E+02	6.90E-06	1.38E+01	4.22E+01
3-P-NL-V2	4.26E-01	2.22E+02	8.31E+00	1.35E-01	8.67E-05	1.48E+00	3.43E-07	1.56E-05	6.27E+00	4.16E+02	2.79E-09	2.49E-06	3.97E-01	9.13E+02	8.15E-06	1.62E+01	4.64E+01
E-EAF-V1	3.78E-01	1.85E+02	7.35E+00	1.24E-01	7.92E-05	1.35E+00	3.11E-07	1.28E-05	5.34E+00	2.75E+02	2.62E-09	2.17E-06	3.50E-01	7.91E+02	7.27E-06	1.53E+01	3.56E+01
E-EAF-V2	4.51E-01	2.24E+02	8.68E+00	1.47E-01	9.00E-05	1.61E+00	3.66E-07	1.56E-05	6.37E+00	2.95E+02	3.00E-09	2.52E-06	4.19E-01	9.37E+02	8.50E-06	1.77E+01	4.02E+01
CPM-EAF-V1	3.77E-01	1.85E+02	7.48E+00	1.22E-01	8.52E-05	1.34E+00	3.14E-07	1.29E-05	5.45E+00	3.91E+02	2.73E-09	2.30E-06	3.48E-01	8.10E+02	7.52E-06	1.57E+01	4.26E+01
CPM-EAF-V2	4.49E-01	2.24E+02	8.80E+00	1.46E-01	9.56E-05	1.59E+00	3.69E-07	1.57E-05	6.47E+00	4.02E+02	3.10E-09	2.64E-06	4.17E-01	9.55E+02	8.73E-06	1.80E+01	4.67E+01

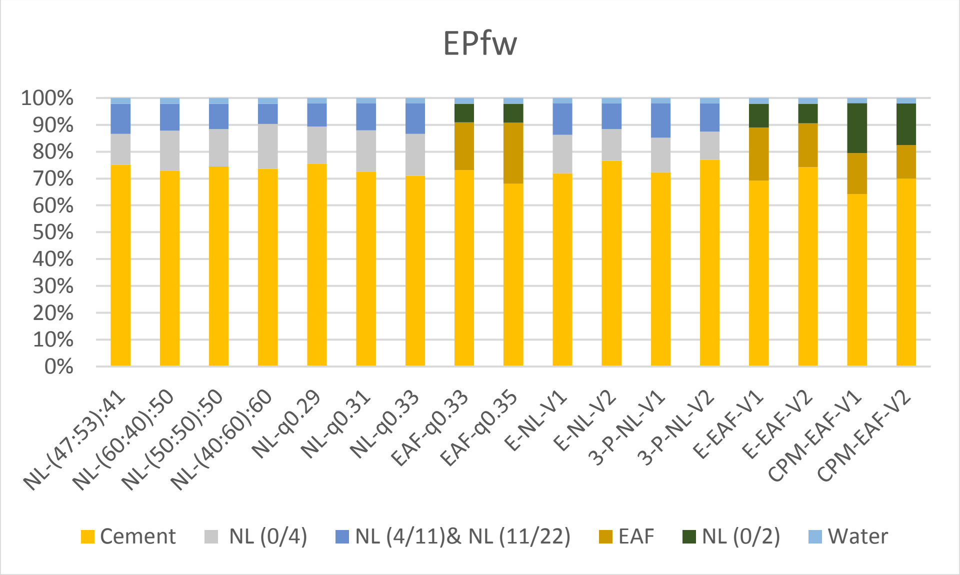
The impact contribution of each concrete component per impact categories is depicted in the following 17 figures.

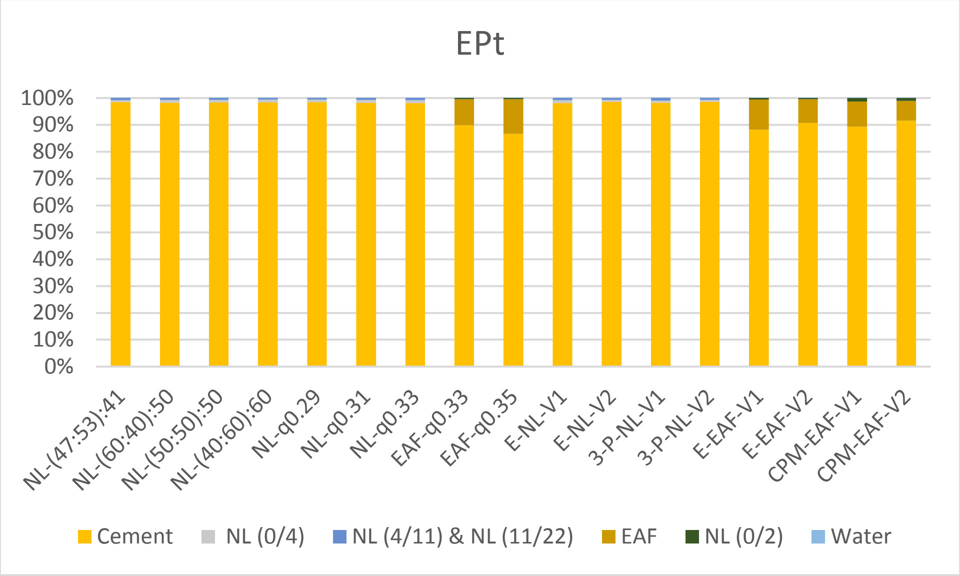


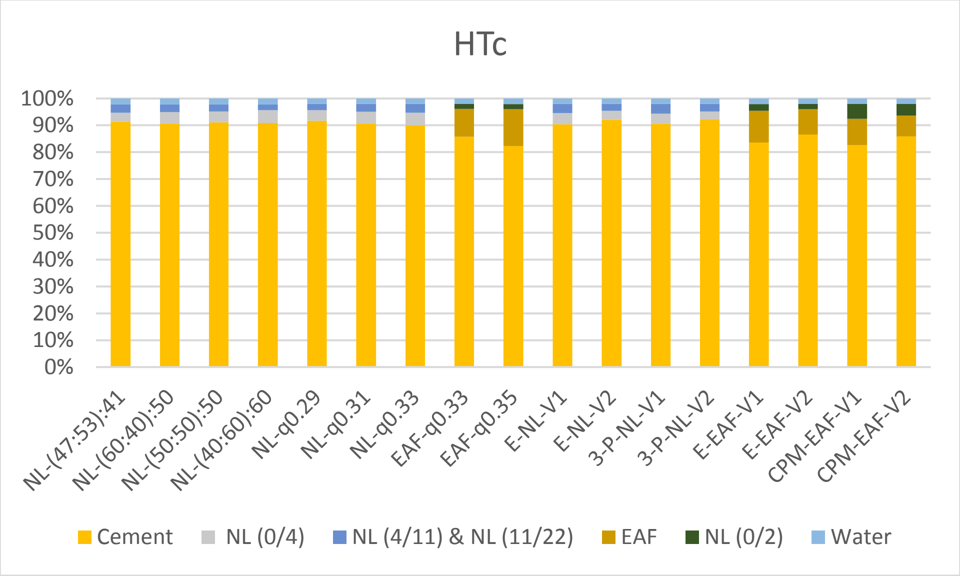


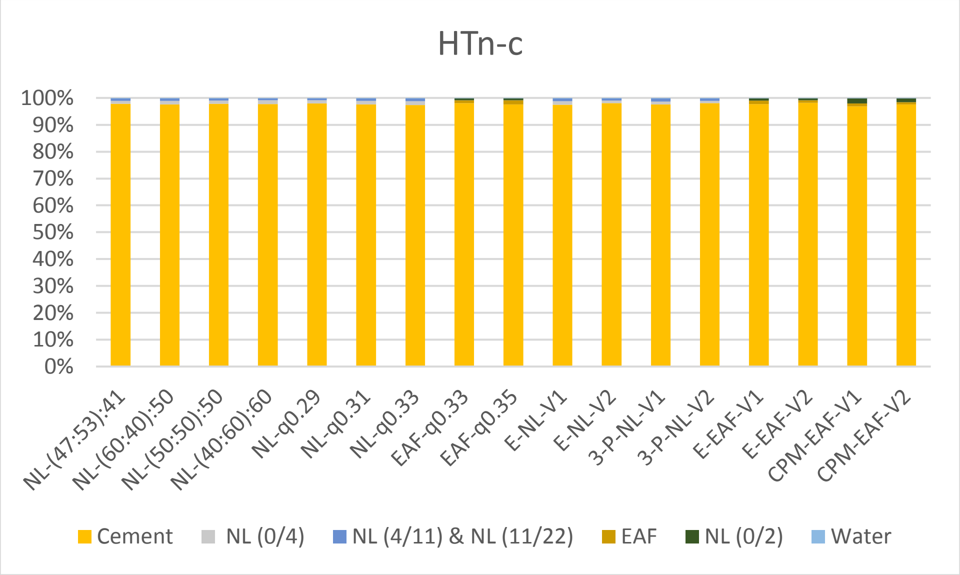

ET
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11)& NL (11/22)
EAF
NL (0/2)
Water

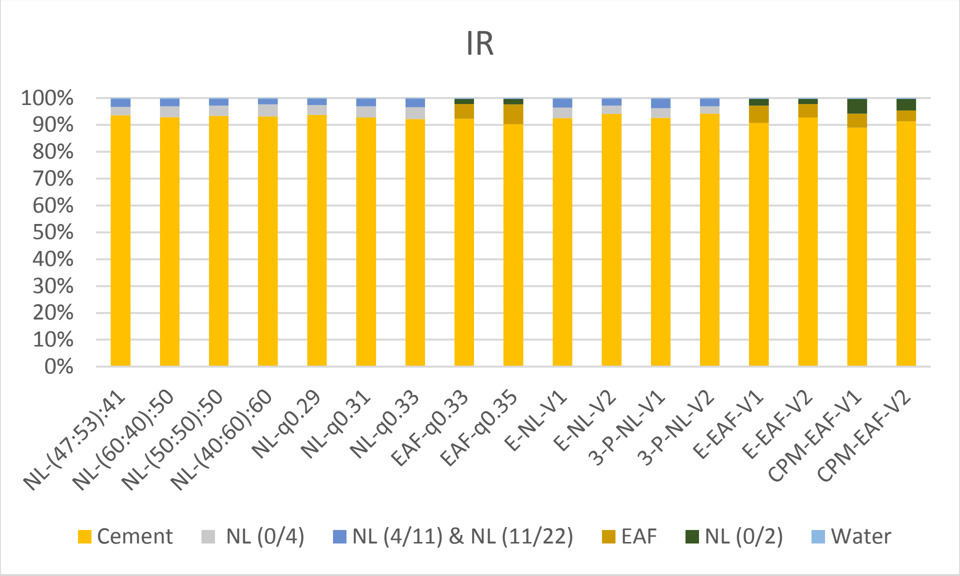

EPmw
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11)& NL (11/22)
EAF
NL (0/2)
Water

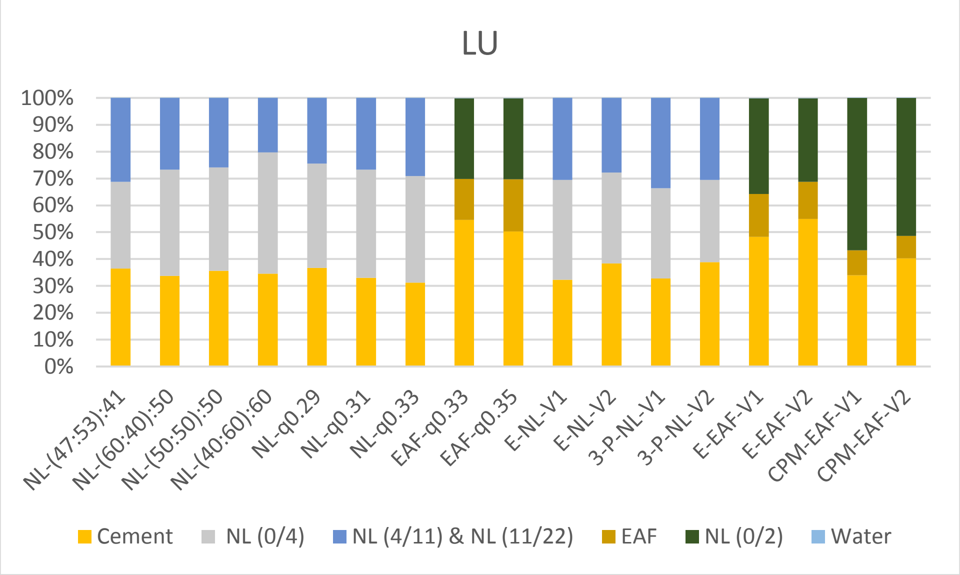

EPfw
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11)& NL (11/22)
EAF
NL (0/2)
Water

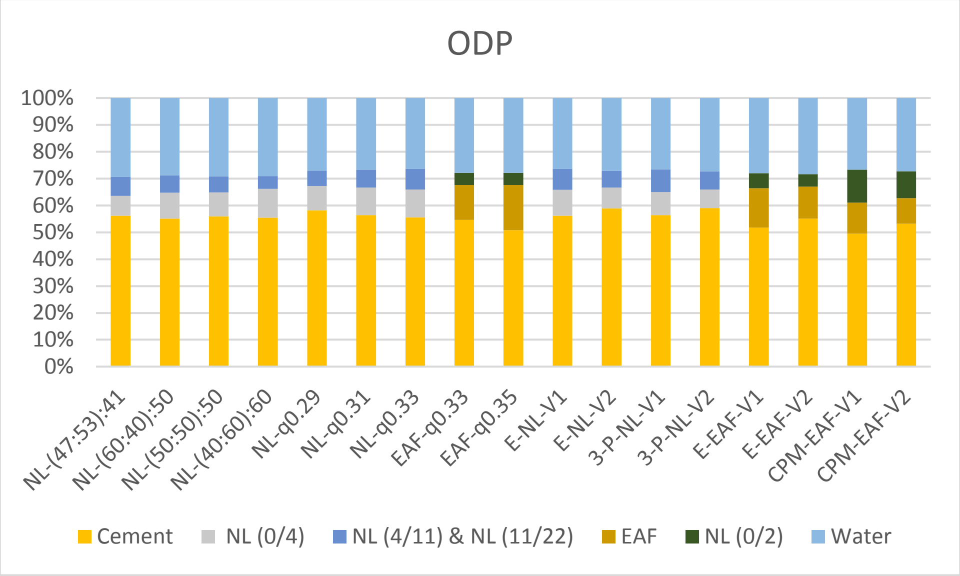

EPt
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

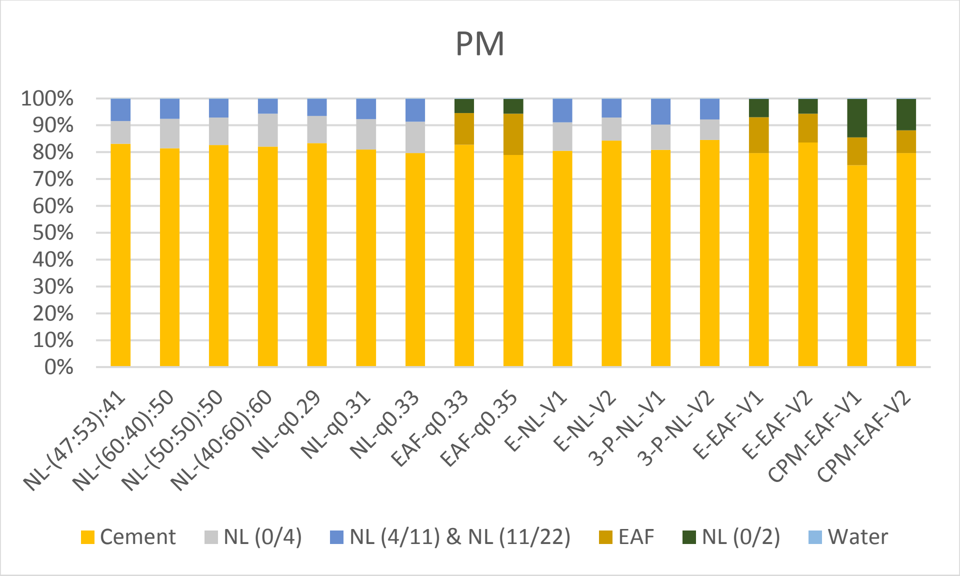

HTc
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

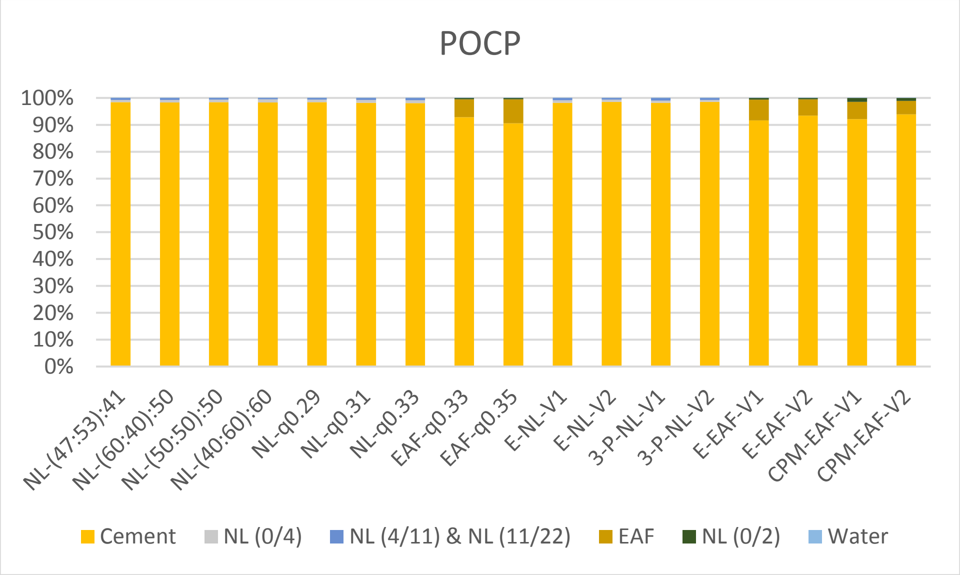

HTn-c
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

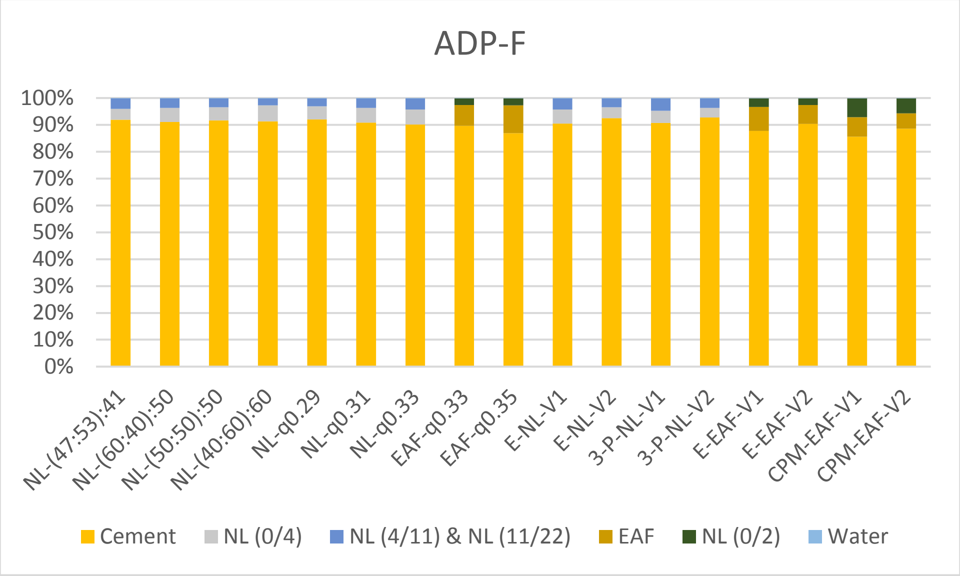

IR
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

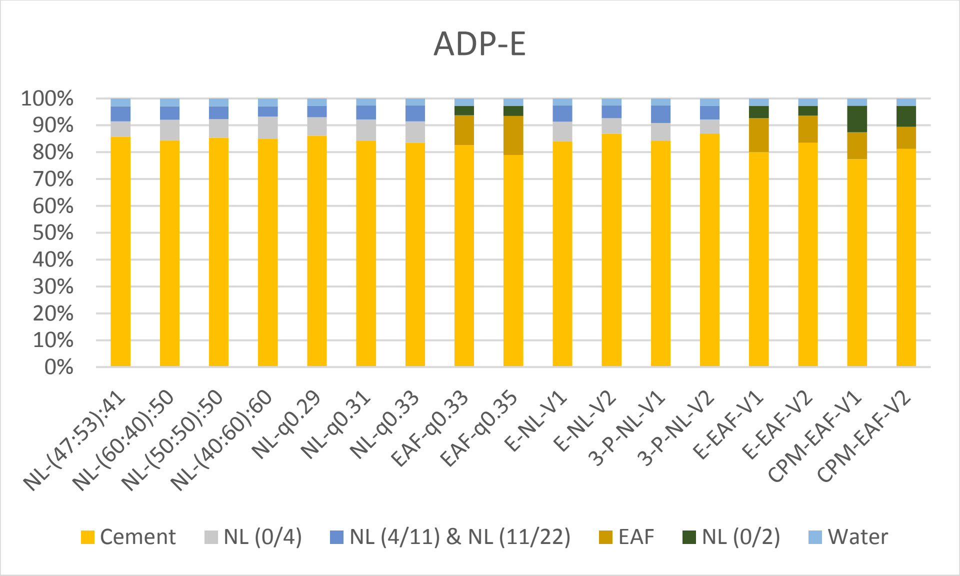

LU
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

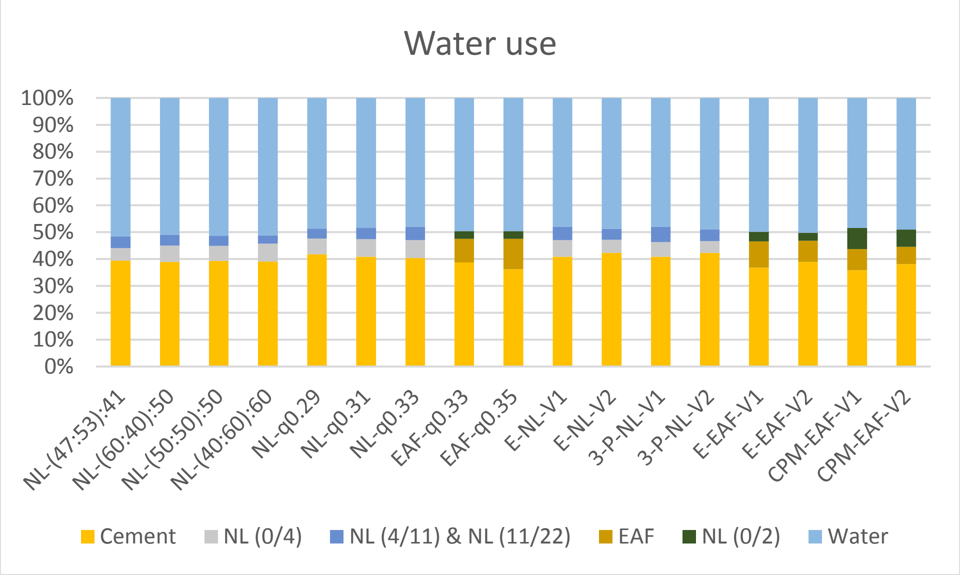

ODP
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water


PM
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water


POCP
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water


ADP-F
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water


ADP-E
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water


Water use
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NL-(47:53):41
NL-(60:40):50
NL-(50:50):50
NL-(40:60):60
NL-q0.29
NL-q0.31
NL-q0.33
EAF-q0.33
EAF-q0.35
E-NL-V1
E-NL-V2
3-P-NL-V1
3-P-NL-V2
E-EAF-V1
E-EAF-V2
CPM-EAF-V1
CPM-EAF-V2
Cement
NL (0/4)
NL (4/11) & NL (11/22)
EAF
NL (0/2)
Water

List of Figures

List of Tables

Curriculum Vitae

Name: Verónica García Cortés

Date of birth: February 7, 1992

2010-2014	Degree in Industrial Chemical Engineering. University of the Basque Country, Bilbao (Spain).
2014-2016	Master in Advanced Materials Engineering. University of the Basque Country, Bilbao (Spain). 2015-2016 Training period at Tecnalia Research and Innovation, Derio (Spain). Bussiness division: Sustainable Construction.
2016-2020	PhD Student, University of the Basque Country. Tecnalia Research and Innovation. Derio (Spain). PhD-study on ecological and economic concrete with alternative aggregates.

Publications and Congress:

Arribas, I.; Vegas, I.; **García, V**.; Vigil de la Villa, R.; Martínez-Ramírez, S.; and Frías, M. 'The Deterioration and Environmental Impact of Binary Cements Containing Thermally Activated Coal Mining Waste due to Calcium Leaching', Journal of Cleaner Production, 183 (2018), 887–97 http://dx.doi.org/10.1016/j.jclepro.2018.02.127

Moreno-Juez, J.; Vegas, I.J; Gebremariam, A.T; **García-Cortés, V**; Di Maio, F. 'Treatment of End-of-Life Concrete in an innovative Heating-air Classification System for Circular Cement-based Products', Journal of Cleaner Production, 263 (2020), p.121515. https://doi.org/10.1016/j.jclepro.2020.121515

D. García, A. Lisbona, J.S. Dolado, I. Vegas, J.T. San-José, **V. García** (2016) Sustainability assessment of concrete with recycled concrete aggregates (proceeding and presentation). ICCS16 - II International Conference on Concrete Sustainability (ISI-JCR). Madrid (Spain).

V.García; Environmental sustainability index for cement-based materials (oral presentation) (2016) 'Environmental Sustainability Index for cement based materials' BASKRETE. Donosti (Spain)

V. García, D. García, J.T. San-José and J.S. Dolado (2016) ‘Analyzing the practice of economic and environmental evaluation of structural concrete’ (paper). The New Boundaries of Structural Concrete 2016 –ACI chapter. Capri (Italy)

Santamaria, A; Ortega-Lopez, V; Skaff, M; **García, V**; Gaitero, J.J.; San-Jose, J.T. (2019) ‘Ladle Furnace Slag as cement replacement in mortar mixes’ SCMT5- 5th International Conference on Sustainable Construction Materials and Technologies. London (UK)

García, D; **García. V**; ‘Sustainability assessment of low carbon concrete’ (2019) Interdisciplinary Symposium in Civil, Environmental and Building Engineering, Salerno (Italy) Part of D5.1-D5.2 SUPERCONCRETE Project.

Santamaria, A; Fiol, F; **García, V**, Setién, J, González, J.J; Sustainable Masory Mortars Based on Ladle Furnace Slags from the Steel-Making Industry (2020) REHABEND 8th Euro-American Congress, Granada (Spain). (Posponed from 10th March to 28th September).