UNIVERSIDAD
DE GRANADA

Utilización de árido reciclado en morteros de albañilería

Use of recycled aggregate in masonry mortars

TESIS DOCTORAL

Para la obtención del

TÍTULO DE DOCTORA CON MENCIÓN INTERNACIONAL

POR LA UNIVERSIDAD DE GRANADA

Gloria Mª Cuenca Moyano

Directores:
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G. M. Cuenca-Moyano, M. Martín-Morales, A. Bonoli, I. Valverde-Palacios, 2019. Environmental assessment of masonry mortars made with natural and recycled aggregates. The International Journal of Life Cycle Assessment 24, 191-210. https://doi.org/10.1007/s11367-018-1518-9 Impact factor 2017: 4.195 (Q1 Environmental, Science).

CONGRESOS INTERNACIONALES

G. M. Cuenca-Moyano, M. Martín-Morales, I. Valverde-Palacios, M. Zamorano, 2014. Study on the influence of moisture state in recycled fine aggregate on the properties of masonry mortars. 14th International Waste Management and Landfill symposium, (Sardinia, Italy).

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“Defiende tu derecho a pensar,
porque incluso pensar de manera errónea,
es mejor que no pensar”
Hipatia de Alejandría

“En la vida no existe nada que temer,
sólo cosas que comprender”
Marie Curie

“Para hacerme poderosa sólo necesito una cosa:
educación”
Malala Yousafzai

Dedicada a mis padres,
a Francis, Lucía y Javier.

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UTILIZACIÓN DE ÁRIDO RECICLADO EN MORTEROS DE ALBAÑILERÍA

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A	Acidification of soil and water
a/c ratio	aggregate/cement ratio
ACV	Análisis de Ciclo de Vida
ADe	Abiotic depletion of elements
ADf	Abiotic depletion of fossil fuels
AEPA	Air-entraining/plasticizer admixture
AFN	Árido fino natural
AFR	Árido fino reciclado
AIAP	Aditivo inclusor de aire/plastificante
AN	Árido natural
ANOVA	Analysis of variance
AR	Árido reciclado
C&DW	Construction and demolition waste
COD	Chemical oxygen demand
E	Eutrophication
EPD	Environmental Product Declaration
ET	Ecotoxicity
EU	European Union
GW	Global warming
HG	Homogeneous groups
HTc	Human toxicity for cancer effects
HTnc	Human toxicity for non-cancer effects
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LER	Lista Europea de Residuos
LoW	List of Waste
LU	Land use
NA	Natural aggregate
NFA	Natural fine aggregate
ODP	Ozone layer depletion

PM	Particulate matter
POF	Photochemical oxidation
RA	Recycled aggregates
RCD	Residuo de construcción y demolición
Relación a/c	Relación agua/cemento
Relación c/a	Relación cemento/árido
RFA	Recycled fine aggregate
t	Tonnes
UE	Unión Europea
w/c ratio	water/cement ratio
WD	Water depletion

RESUMEN

El sector de la construcción es una de las áreas económicas más importantes de la Unión Europea por su contribución a la generación de riqueza y empleo. Sin embargo, consume aproximadamente la mitad de los recursos naturales y genera casi un tercio de todos los residuos, por lo que causa un gran impacto sobre el medio ambiente. Por ello, este sector representa una excelente oportunidad en la transición de la Unión Europea hacia una economía circular en la que el valor de los recursos se mantenga por más tiempo y la generación de residuos se reduzca al mínimo, todo ello para lograr una economía sostenible, hipocarbónica, eficiente en el uso de los recursos y competitiva.

En este sentido, el uso de áridos reciclados procedentes del tratamiento de la fracción mineral de residuos de construcción y demolición como reemplazo de áridos naturales puede evitar el consumo de recursos naturales y reducir los impactos ambientales asociados, ya que reduce la eliminación en vertedero y mantiene el valor de los recursos por más tiempo en la economía. Sin embargo, su uso todavía es muy escaso debido la falta de confianza en su calidad, la ausencia de normas específicas o el bajo precio del árido natural. Además, la naturaleza y composición del árido reciclado (residuos de hormigón, cerámicos, de mortero, etc.) y su contenido en impurezas le confieren menor densidad y mayor capacidad de absorción de agua respecto a los áridos naturales. Esta última limitación se incrementa en la fracción fina de los áridos reciclados, que presenta un uso muy limitado para aplicaciones de alto requerimiento técnico. Por ello es necesario buscar aplicaciones que no presenten limitaciones al uso de árido fino reciclado, como es el caso de los morteros de albañilería.

Estudios preliminares han puesto de manifiesto que, debido a su mayor absorción de agua, el aumento de la cantidad de agua total necesaria para mejorar la consistencia del mortero es perjudicial para la resistencia a compresión, por lo que en general, no se han podido obtener resultados satisfactorios para incorporaciones superiores al 50% de árido fino reciclado. Además, no se han encontrado estudios que analicen, desde el punto de vista de su análisis del

ciclo de vida, la aplicación del árido fino reciclado en morteros. Por todo ello, el objetivo principal de esta investigación ha sido evaluar el uso de árido fino reciclado procedente del tratamiento de la fracción mineral de residuos de construcción y demolición en la fabricación de morteros de albañilería desde el punto de vista técnico y ambiental.

El ensayo de diferentes dosificaciones, teniendo en cuenta para ello la norma EN 998-2, y en las que ha variado el reemplazo de árido fino natural por árido fino reciclado (25%, 50%, 75% y 100%), la relación agua/cemento total del mortero, así como la cantidad de aditivo inclusor de aire/plastificante, ha puesto de manifiesto que los áridos finos reciclados estudiados son aptos para fabricar morteros de albañilería de uso corriente (G) de clase resistente M5 (>5 N/mm^2) y consistencia plástica (≥140 mm). Se pueden realizar reemplazos de hasta el 50% de árido fino natural por árido fino reciclado sin necesidad de aumentar la cantidad de agua del mortero, mientras que si el árido fino reciclado se utiliza premojado se puede realizar un reemplazo total.

Desde el punto de vista ambiental, el análisis de ciclo de vida realizado en base a las normas ISO 14040 e ISO 14044, ha puesto de manifiesto que el uso de árido fino reciclado disminuye los impactos ambientales asociados a los morteros de albañilería, debido a que se evita el transporte y la eliminación en vertedero de los residuos de construcción y demolición. Estas reducciones son de hasta el 94% en la categoría Land Use o del 3,3% en las emisiones de PM2.5 eq. Además, el reemplazo de árido fino natural por árido fino reciclado evita la extracción de recursos naturales y su consumo, permitiendo el uso eficiente de los recursos. Todo ello permite incrementar la tasa de reciclaje de los residuos de construcción y demolición manteniendo su valor, y contribuir así a cerrar el círculo en el marco de una economía circular.

ABSTRACT

The construction sector is one of the most important economic sectors in the European Union due to its contribution to the generation of wealth and employment. However, it consumes approximately half of all natural resources and generates almost one third of all waste, and this has a major impact on the environment. This sector, therefore, is a key factor in the EU's transition to a circular economy, in which resources maintain their value for longer and waste generation is minimised in order to achieve a sustainable, hypocarbonic, resource-efficient and competitive economy.

The use of recycled aggregates obtained from the treated mineral fraction of construction and demolition waste as a replacement for natural aggregates can reduce the consumption of natural resources and the corresponding environmental impact, since it reduces landfill disposal and maintains the value of resources for longer in the economy. However, recycled aggregate is seldom used due to lack of confidence in its quality, lack of specific standards, or the low price of natural aggregate. In addition, the nature and composition of recycled aggregate (waste of concrete, ceramic, mortar, etc.) together with its impurity content, give the aggregate higher density and water absorption capacity compared to natural aggregate. This latter limitation is increased in the fine fraction of recycled aggregate, which has very limited use in applications subject to high technical requirements. Therefore, applications that do not limit the use of fine recycled aggregate, such as masonry mortars, must be found.

Preliminary studies have shown that the greater amount of water needed to improve the consistency of mortar containing recycled fine aggregate, due its higher water absorption capacity, is detrimental to its compressive strength. This is why, the incorporation of 50% recycled fine aggregate does not usually give satisfactory results. Furthermore, we found no evidence of studies that analyse the use of recycled fine aggregate in mortar in terms of the life cycle assessment of the product. Therefore, the main aim of this study has been to evaluate the

use of recycled fine aggregate obtained from the treated mineral fraction of C&DW in the manufacture of masonry mortars from the technical and environmental perspective.

After testing different dosages, according to standard EN 998-2, in which natural fine aggregate was replaced with different percentages of recycled fine aggregate (25%, 50%, 75% and 100%), the total water/cement ratio of the mortar, and the amount of air-entraining plasticizer admixture, we found that the recycled fine aggregate studied is suitable for the manufacture of general purpose masonry mortar (G), class M5 (> 5 N/mm^2) with a plastic consistency of ≥140 mm. Up to 50% of natural fine aggregate can be replaced with recycled fine aggregate without the need to increase the water content of the mortar, and up to 100% if pre-soaked recycled fine aggregate is used.

From the environmental perspective, the life cycle assessment carried out in accordance with the ISO 14040 and ISO 14044 standards has shown that the use of recycled fine aggregate reduces the environmental impact associated with masonry mortars by eliminating the need to transport and dispose of the construction and demolition waste in landfills. Environmental impacts are reduced by up to 94% in the Land Use category and by 3.3% in PM2.5 eq emissions. In addition, replacing natural fine aggregate with recycled fine aggregate reduces the extraction and consumption of natural resources and maximises resource efficiency. This makes it possible to increase the recycling rate of construction and demolition waste while maintaining its value, which in turn helps close the loop in the framework of a circular economy.

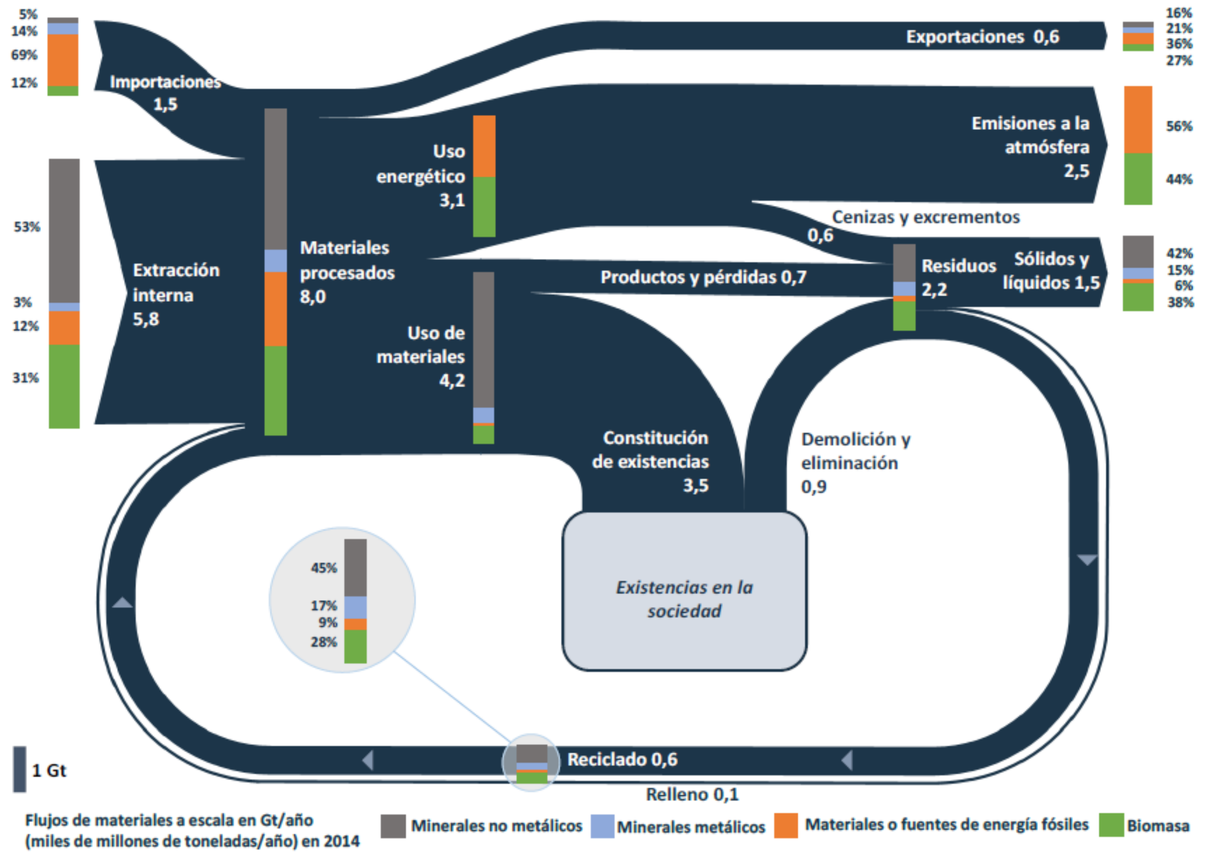
INTRODUCCIÓN, MOTIVACIÓN Y OBJETIVOS

1. Introducción

1.1. Los Residuos de Construcción y Demolición y su problemática ambiental

El crecimiento económico experimentado a lo largo del siglo XX, ha producido la mejora de la prosperidad y bienestar de la sociedad, pero a su vez, se ha fundamentado en el uso intensivo de los recursos. En consecuencia, el desarrollo sostenible se ha convertido en el objetivo clave de la sociedad moderna, con el fin de satisfacer las necesidades del presente sin comprometer la capacidad de las futuras generaciones para satisfacer sus propias necesidades (World Commission on Environment and Development, 1987). Para impulsar el uso racional de los recursos y el desarrollo sostenible del medio ambiente deben establecerse medidas clave orientadas a actuar sobre la economía, la sociedad y el medio ambiente (Giddings et al., 2002; Li et al., 2015). En la Unión Europea (UE), estas medidas constituyen las líneas de actuación de la Estrategia Europa 2020 (European Commission, 2010a), y también se han puesto en práctica dentro de los Objetivos de Desarrollo Sostenible y sus indicadores incluidos en la Agenda 2030 (UN, 2015).

En este punto, la transición a una economía más circular es una contribución esencial a los esfuerzos de la UE para desarrollar un economía sostenible, baja en carbono, eficiente en recursos y competitiva (European Commission, 2015). Las acciones apoyan la economía circular en cada paso de la cadena de valor, desde la producción hasta el consumo, la reparación y reutilización, la gestión de residuos y las materias primas secundarias que se reintroducen en la economía (European Commission, 2018a; Niero and Kalbar, 2019). La Figura 1 presenta una visión de conjunto de los flujos de materiales en la economía de la UE en 2014. En la parte izquierda, se muestra la entrada anual de 8000 millones de toneladas de materiales que se transforman en energía o productos, de los que tan sólo el 7,5% proceden del reciclaje. Con respecto a la salida de la economía, de los 2200 millones de toneladas de residuos que se generan, tan solo un tercio se reintroducen en el sistema como materiales reciclados. Respecto a los minerales no metálicos, de los 3500 millones de toneladas que se utilizan, el 89% se destina a edificios e infraestructura (constitución de existencias); además se introducen como materias primas 350 millones de toneladas (de operaciones de reciclaje y relleno) lo que supone el 39% de los residuos generados. El potencial de mejora radica, en particular, en aumentar la proporción de materiales reciclados como materias primas secundarias y disminuir los residuos generados (European Commission, 2018b).



Nota: Es posible que la suma de las cifras no coincida con el total debido al redondeo.

Figura 1. Flujos de material en la economía de la UE-28 en 2014 (European Commission, 2018b)

El sector de la construcción, uno de los mecanismos reactivadores de la economía, no es ajeno al uso racional de los recursos y a la aplicación de acciones destinadas al desarrollo sostenible. Por ejemplo en el caso de la UE, genera aproximadamente el 9% del producto interior bruto y proporciona 18 millones de empleos directos (European Commission, 2016a). Sin embargo, también produce un gran impacto sobre el medio ambiente contribuyendo a las presiones ambientales que se producen en las diferentes fases del ciclo de vida, desde el consumo de alrededor de la mitad de los recursos naturales, durante la fabricación de los materiales de construcción, en el propio proceso constructivo, así como en la demolición (Bovea and Powell, 2016; Carpio et al., 2016; Lizana et al., 2018). Entre los impactos más importantes que se generan se encuentra la producción de residuos, que representan en torno a un tercio de todos los generados en la UE y debido a su volumen, constituyen el mayor flujo de residuos en este territorio (European Commission, 2017a).

Teniendo en cuenta el marco legal en materia de residuos a nivel europeo y nacional (European Parliament and Council, 2018, 2008; Jefatura del Estado, 2011; Ministerio de la Presidencia, 2008) se define Residuo de Construcción y Demolición (RCD) como cualquier sustancia u objeto generado en una obra de construcción o demolición y del cual su poseedor tenga la intención o la obligación de desechar. El Real Decreto 105/2008 (Ministerio de la Presidencia, 2008) define obra de construcción o demolición como toda aquella actividad incluida dentro de la construcción, rehabilitación, reparación, reforma o demolición de un edificio, carretera, puerto, aeropuerto, ferrocarril, canal, presa, instalación deportiva o de ocio, así como cualquier otro análogo de ingeniería civil; también comprende la realización de trabajos que modifiquen la forma o sustancia del terreno o del subsuelo, tales como excavaciones, inyecciones, urbanizaciones u otros análogos, con exclusión de aquellas actividades a las que sea de aplicación la Directiva 2006/21/CE (European Parliament and Council, 2006) sobre gestión de los residuos de industrias extractivas. Finalmente, en esta definición se incluyen igualmente los residuos generados en las instalaciones que den servicio exclusivo a la obra siempre que el montaje y desmontaje de estas instalaciones tenga lugar durante la ejecución de la obra o al final de la misma, como los parques de ferralla, almacenes de materiales, etc. El citado Real Decreto excluye específicamente de esta consideración:

i) las tierras y piedras no contaminadas por sustancias peligrosas reutilizadas en la misma obra, en una obra distinta o en una actividad de restauración, acondicionamiento o relleno, siempre y cuando pueda acreditarse de forma fehaciente su destino a reutilización;

ii) los residuos regulados por otras legislaciones específicas, como los residuos de industrias extractivas regulados por la Directiva 2006/21/CE (European Parliament and Council, 2006);

iii) los residuos generados en la industria de los productos de construcción (cerámicos, prefabricados, materiales de construcción, etc.) que, aunque sus características son muy similares a los residuos generados en las obras, estos residuos se incluyen en la definición de residuos industriales no peligrosos.

En este punto, resulta necesario puntualizar que la exclusión de las tierras y piedras no contaminadas presenta una consideración diferente en la Directiva Marco de residuos 2008/98/CE (European Parliament and Council, 2008) y su trasposición española mediante la Ley 22/2011 de residuos y suelos contaminados (Jefatura del Estado, 2011). En este caso, se excluyen los suelos no contaminados excavados y otros materiales naturales excavados durante las actividades de construcción, cuando se tenga la certeza de que estos materiales se utilizarán con fines de construcción en su estado natural en el lugar u obra donde fueron extraídos.

Dada la problemática ambiental que generan los RCDs, su gestión se ha establecido como un área prioritaria en el Plan de Acción de la UE para la Economía Circular, donde el valor de los productos, materiales y recursos se mantiene en la economía por el mayor tiempo posible, y se minimiza la generación de residuos (European Commission, 2015). Es por ello que la transformación del sector hacia una construcción sostenible se presenta como una oportunidad, en la que el equilibrio entre respeto y compromiso con el medioambiente se mantenga durante todo el ciclo de vida, con el uso eficiente de los recursos y de materiales no perjudiciales para el medioambiente como puede ser utilizar productos de construcción fabricados con materiales reciclados y reciclar o reutilizar materiales y productos existentes, y dirigida hacia una reducción de los impactos ambientales ya que menos residuos se depositan en vertederos (European Commission, 2014a; Kibert, 1994; López Zaldívar et al., 2016). Además, el beneficio ambiental generado por la reducción de los impactos se puede cuantificar mediante la aplicación de herramientas como el Análisis de Ciclo de Vida (ACV).

1.2. Composición y clasificación de los RCDs

La composición de los RCDs varía ampliamente según su lugar de procedencia, tipología de la obra o características constructivas. Generalmente, están compuestos por residuos procedentes de hormigón, ladrillos o materiales cerámicos que configuran principalmente la fracción mineral, constituyendo el resto cantidades variables de residuos de metal, vidrio, plástico, madera o tierras de excavación (Figura 2).

La mayor parte de los RCDs aparecen codificados en el Capítulo 17 de la Lista Europea de Residuos (LER), publicada en el anexo de la Decisión 2014/955/CE (European Commission, 2014b) que modifica a la Decisión 2000/532/CE (Commission of the European Communities, 2000) como se muestra en la Tabla 1, y que tiene su equivalencia con la nomenclatura de la Clasificación Europea de Residuos para Estadísticas CER-Stat/Rev. 4 establecida en el Reglamento (UE) Nº 849/2010 (European Commission, 2010b) que modifica al Reglamento (CE) Nº 2150/2002 (European Parliament and Council, 2002) sobre estadísticas de residuos. La codificación de los RCDs de acuerdo al LER permite su clasificación como no peligrosos, y particularmente inertes (Blengini and Garbarino, 2010; Mercante et al., 2012), a excepción de una pequeña proporción clasificada como peligrosos.

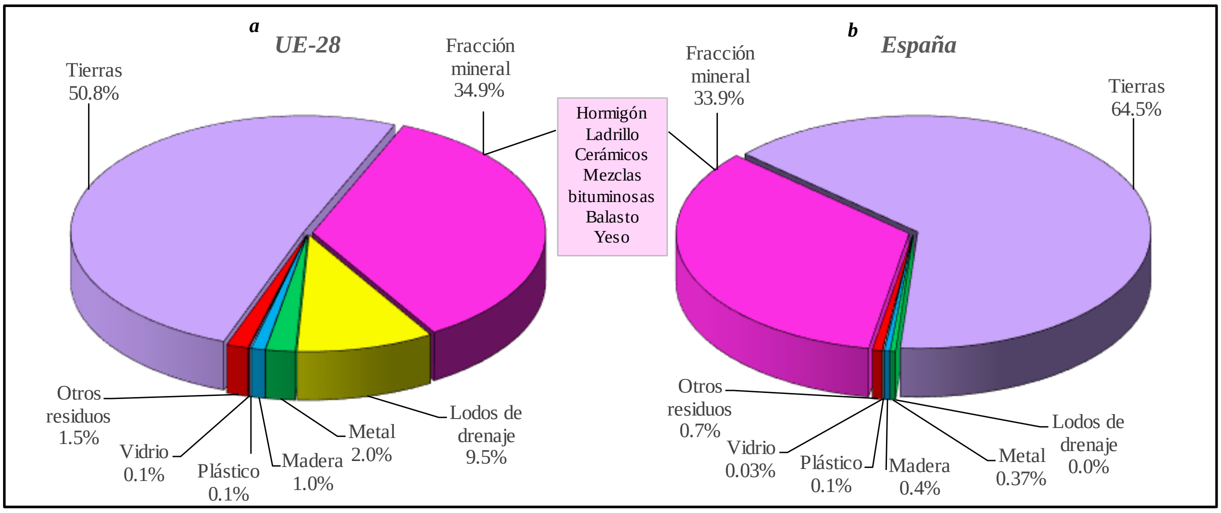


Figura 2. Composición de los RCDs en la UE-28 (a) y en España (b) en 2016 (Eurostat, 2019)

Los residuos inertes son aquellos no peligrosos que no experimentan transformaciones físicas, químicas o biológicas significativas, no son solubles ni combustibles, ni reaccionan física ni químicamente ni de ninguna otra manera, no son biodegradables, ni afectan negativamente a otras materias con las cuales entran en contacto de forma que puedan dar lugar a contaminación del medio ambiente o perjudicar a la salud humana; en este caso la lixiviabilidad total, el contenido de contaminantes del residuo y la ecotoxicidad del lixiviado deberán ser insignificantes, y en particular no deberán suponer un riesgo para la calidad de las aguas superficiales o subterráneas (Ministerio de la Presidencia, 2008).

Tabla 1. Capítulo 17 (LER) y equivalencia con CER-Stat/Rev.4 (residuos no peligrosos)

Capítulo 17 LER (European Commission, 2014b)	CER-Stat/Rev. 4 (European Commission, 2010b)	Residuos de construction y demolición. Descripción
17 01		Hormigón, ladrillos, tejas y materiales cerámicos
17 01 01	12.1 (12.11)/FM [a]	Hormigón
17 01 02	12.1 (12.11)/FM [a]	Ladrillos
17 01 03	12.1 (12.11)/FM [a]	Tejas y materiales cerámicos
17 01 07	12.1 (12.11)/FM [a]	Mezclas de hormigón, ladrillos, tejas y materiales cerámicos, distintas de las especificadas en el código 17 01 06
17 02		Madera, vidrio y plástico
17 02 01	7.5 (7.53)	Madera
17 02 02	7.1 (7.12)	Vidrio
17 02 03	7.4 (7.42)	Plástico
17 03		Mezclas bituminosas, alquitrán de hulla y otros productos alquitranados
17 03 02	12.1 (12.12)/FM [a]	Mezclas bituminosas distintas de las especificadas en el código 17 03 01
17 04		Metales (incluidas sus aleaciones)
17 04 01	6.2 (6.24)	Cobre, bronce, latón
17 04 02	6.2 (6.23)	Aluminio
17 04 03	6.2 (6.25)	Plomo
17 04 04	6.2 (6.25)	Zinc
17 04 05	6.1	Hierro y acero
17 04 06	6.2 (6.25)	Estaño
17 04 07	6.3 (6.32)	Metales mezclados
17 04 11	6.2 (6.25)	Cables distintos de los especificados en el código 17 04 10
17 05		Tierra (incluída la tierra excavada de zonas contaminadas), piedras y lodos de drenaje[b]
17 05 04	12.6	Tierra y piedras distintas de las especificadas en el código 17 05 03
17 05 06	12.7	Lodos de drenaje distintos de los especificados en el código 17 05 05
17 05 08	12.1 (12.11)/FM [a]	Balasto de vías férreas distinto del especificado en el código 17 05 07
17 06		Materiales de aislamiento y materiales de construcción que contienen amianto
17 06 04	12.1 (12.13)/FM [a]	Materiales de aislamiento distintos de los especificados en los códigos 17 06 01 y 17 06 03
17 08		Materiales de construcción a base de yeso
17 08 02	12.1 (12.11)/FM [a]	Materiales de construcción a base de yeso distintos de los los especificados en el código 17 08 01
17 09		Otros residuos de construcción y demolición
17 09 04	12.1 (12.13)/FM [a]	Residuos mezclados de construcción y demolición distintos de los especificados en los códigos 17 09 01, 17 09 02 y 17 09 03

FM[a]: Fracción mineral de RCD; [b] No contabilizan a efectos del objetivo de cumplimiento.

En aquel caso en el que los residuos contengan sustancias con alguna de las características peligrosas enumeradas en el Anexo III de la Directiva Marco de Residuos 2008/98/CE (European Parliament and Council, 2008), los residuos serán considerados peligrosos[1].

1.3. Generación de RCDs

En el año 2016, en la UE se generaron 923 millones de toneladas de RCDs (peligrosos y no peligrosos), de acuerdo a los datos facilitados por Eurostat (Eurostat, 2018a) y que se relacionan en la Tabla 2. Se puede observar que los países con mayor producción fueron Francia (24,3%), Alemania (23,9%) y Reino Unido (14,7%), mientras que España ocupó el séptimo puesto con el 3,9% (35 millones de toneladas). En cuanto a la composición, la fracción mineral de estos residuos (categoría 12.1 de CER-Stat/Rev. 4) representó el 34,9% como valor medio de la UE-28, pero osciló ampliamente entre los diferentes países. Así, en España constituyó el 33,9%, mientras que Malta y Letonia fue del 96,4% y en Bulgaria del 6,3%. La mayoría de estos residuos se clasificaron como no peligrosos, con porcentajes que oscilaron entre el 88,4% y el 100%.

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[1] Entre las sustancias con alguna de las características peligrosas enumeradas en el Anexo III de la Directiva Marco de Residuos 2008/98/CE (European Parliament and Council, 2008), se encuentran las recogidas en el Protocolo de Gestión de RCD en la UE (European Commission, 2016b): suelo contaminado y dragado, materiales y sustancias que pueden incluir componentes adhesivos, sellantes o másticos (inflamables, tóxicos o irritantes), alquitrán (tóxico, cancerígeno), materiales a base de amianto que contienen fibras que pueden pasar a las vías respiratorias (tóxico, cancerígeno), madera tratada con fungicidas, pesticidas, etc. (tóxico, ecotóxico, inflamable), revestimientos halogenados ignífugos (tóxico, ecotóxico, cancerígeno), equipamiento que consta de policlorobifenilos (ecotóxico, cancerígeno), sistemas de iluminación que contienen mercurio (tóxico, ecotóxico), sistemas con clorofluorocarbonos, material de aislamiento que contiene clorofluorocarbonos, contenedores para sustancias peligrosas (solventes, pinturas, adhesivos, etc.) y el embalaje de residuos que puedan haber sido contaminados.

Tabla 2. Cantidad de RCDs (peligrosos y no peligrosos) generados en la UE-28 en 2016 (Eurostat, 2018a)

País	*RCD total (t)*	*(%)*[a]	*Fracción mineral de RCDs*			
			Peligrosos y no peligrosos (t)	*(%)*[b]	*No peligrosos (t)*	*(%)*[c]
UE-28	923.910.000	100,0	322.570.000	34,9	313.110.000	97,1
Francia	224.355.946	24,3	60.245.692	26,9	59.101.518	98,1
Alemania	220.499.432	23,9	86.379.764	39,2	80.967.723	93,7
Reino Unido	136.196.492	14,7	63.525.298	46,6	63.046.541	99,2
Holanda	98.551.957	10,7	19.267.996	19,6	17.570.661	91,2
Italia	54.576.762	5,9	34.916.038	64,0	34.804.036	99,7
Austria*	40.265.570	4,4	8.947.894	22,2	8.933.873	99,8
España	35.827.923	3,9	12.156.104	33,9	12.116.802	99,7
Bélgica	19.573.150	2,1	15.818.121	80,8	15.769.321	99,7
Polonia	18.890.577	2,0	2.471.974	13,1	2.435.829	98,5
Finlandia	13.825.168	1,5	1.315.581	9,5	1.267.270	96,3
Dinamarca	12.224.799	1,3	3.460.195	28,3	3.357.696	97,0
Rep. Checa	10.141.985	1,10	2.803.748	27,6	2.741.527	97,8
Suecia	9.810.987	1,06	2.552.319	26,0	2.368.147	92,8
Luxemburgo	7.614.894	0,8	545.329	7,2	482.124	88,4
Hungría	3.591.612	0,4	1.959.136	54,5	1.957.445	99,9
Bulgaria	2.089.131	0,23	131.450	6,3	131.450	100,0
Irlanda*	1.884.390	0,20	133.312	7,1	130.677	98,0
Portugal	1.710.703	0,19	888.356	51,9	887.793	99,9
Malta	1.354.892	0,15	1.305.818	96,4	1.305.818	100,0
Croacia	1.291.506	0,14	561.037	43,4	554.247	98,8
Estonia	1.173.517	0,13	485.489	41,4	484.982	99,9
Eslovaquia	967.275	0,10	297.323	30,7	297.159	99,9
Chipre	876.525	0,09	325.399	37,1	325.399	100,0
Eslovenia	541.574	0,06	160.940	29,7	160.920	100,0
Lituania	505.758	0,05	445.837	88,2	445.720	100,0
Grecia*	479.999	0,05	355.171	74,0	355.171	100,0
Rumania	323.461	0,04	172.998	53,5	172.981	100,0
Letonia	111.133	0,01	107.095	96,4	107.095	100,0

[a] Porcentaje de RCD respecto al total de la UE; [b] Porcentaje de la fracción mineral respecto al total de RCD del país; [c] Porcentaje de la fracción mineral de RCD de residuos no peligrosos respecto al total de la fracción mineral; * Datos de 2014.

La Figura 3 recoge la composición de los RCDs no peligrosos generados en la UE-28 en 2016 (Eurostat, 2018a). Las diferencias de composición de los RCDs que pueden observarse entre los países se produce por la diversificación de los hábitos constructivos, la disponibilidad de las materias primas de los componentes, así como la época en la que se llevó a cabo la construcción (Bustillo Revuelta, 2010).

No obstante, la fracción de RCDs no peligrosos generados se constituye, en su mayoría, por tierras (51,5%), seguidos por la fracción mineral (35%), lodos de drenaje (11%) y el 3% restante la suma de metal, vidrio, plástico y madera (Figura 3a). La tierra es el componente mayoritario en dieciseis países, con porcentajes superiores al 50% en trece de ellos, destacando Luxemburgo con el 93%; para el resto de países, la fracción mineral (categoría 12.1) fue predominante en diez países, y los lodos de drenaje en Bulgaria y Holanda. En el caso de España, las tierras alcanzaron el 65%, seguidas por la fracción mineral (34%) y el 1% restante para los demás componentes.

Si se excluyen las tierras o suelos no contaminados (Figura 3b), la composición de los RCDs en la UE-28 se estructura principalmente en residuos minerales (71%), lodos de drenaje (23%), metal (4%), y finalmente, madera, vidrio, y plástico (2%). La fracción mineral compone el porcentaje mayoritario en todos los países excepto para Bulgaria y Holanda, donde predominan los lodos de drenaje. Así mismo, en España el porcentaje más elevado corresponde a la fracción mineral (97,4%), y en menor medida a los residuos de madera, vidrio y plástico (1,5%), y de metal (1,1%).

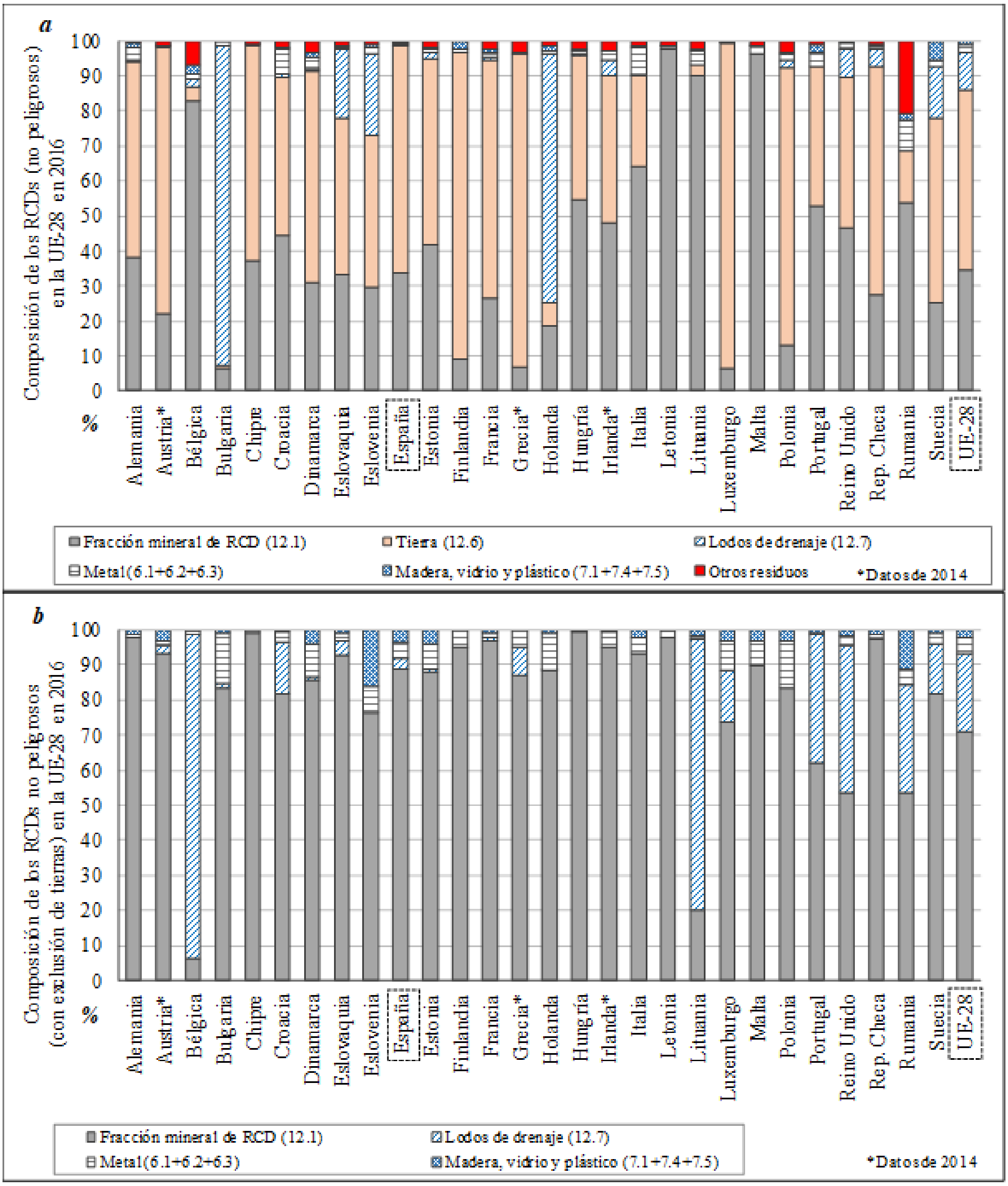


Figura 3. Composición de los RCDs no peligrosos en la UE-28 en 2016 (Categorías CER-Stat/Rev.4) (Eurostat, 2018a)

1.4. Gestión

Se define gestión de residuos como la recogida, el transporte, la valorización (incluida la clasificación), y la eliminación de los residuos, incluida la vigilancia de esas operaciones, así como el mantenimiento posterior al cierre de los vertederos, incluidas las actuaciones realizadas en calidad de negociante o agente (European Parliament and Council, 2018). La inadecuada gestión de los residuos provoca importantes problemas ambientales, por lo que es fundamental la planificación e implantación de medidas que favorezcan prácticas adecuadas en todas sus fases de gestión. En consecuencia, desde que la Comunidad Europea estableció en 1975 la primera Directiva sobre residuos 75/442/EEC (Council of the European Communities, 1975), el objetivo de las políticas de gestión de residuos de la UE ha sido reducir el impacto sobre el medio ambiente y la salud, y mejorar la eficiencia en el uso de los recursos (de la Hoz-Torres et al., 2018; European Commission, 2011). Actualmente, el marco normativo establecido en la UE con la Directiva sobre residuos 2008/98/CE (European Parliament and Council, 2008), su modificación con la Directiva (UE) 2018/851 (European Parliament and Council, 2018) y su trasposición al marco legal español a través de la Ley 22/2011 (Jefatura del Estado, 2011) incorporan el principio de jerarquía. Así, el orden de prioridad en la producción y gestión de residuos debe centrarse en la prevención (evitando la generación de residuos y su impacto), la preparación para la reutilización (volviendo a utilizar el residuo), el reciclado (introducir el residuo en el ciclo productivo), otro tipo de valorización (incluidas las operaciones de relleno y la valorización energética) y, por último, la eliminación.

El objetivo a largo plazo de estas políticas ha sido reducir la cantidad de residuos generados y, cuando la generación de residuos sea inevitable, promover los residuos como recurso y lograr niveles más elevados de reciclado y una eliminación de residuos segura. Así, las medidas propuestas relativas a la prevención y gestión de residuos contribuirán a alcanzar el objetivo de la Directiva sobre residuos 2008/98/CE (European Parliament and Council, 2008) de aumentar la preparación para la reutilización, el reciclado y otra valorización de materiales hasta un mínimo del 70% en peso de los RCDs no peligrosos (excluyendo el material en estado natural como se define en la categoría LER 17 05 04) en 2020, cerrando así el ciclo de vida de los productos mediante el aumento del reciclaje y la reutilización.

En consecuencia, la gestión de residuos desempeña un papel crucial en la economía circular, toda vez que determina la manera en que se pone en práctica la jerarquía de los residuos de la UE. Tras la adopción por la Comisión Europea del Plan de Acción para la Economía Circular (European Commission, 2015) se establece un programa concreto de acciones que describe medidas que cubren todo el ciclo de vida del producto: desde la producción y el consumo hasta la gestión de residuos y el mercado de materias primas secundarias. En este sentido, es posible realizar un seguimiento y evaluación de los progresos realizados para la consecución de los objetivos previstos en la gestión de RCDs a través de la tasa de recuperación. Este indicador de economía circular comprende la fracción mineral de los RCDs no peligrosos (categoría 12.1 de acuerdo a CER-Stat/Rev. 4) e indica la proporción de RCDs preparada para su reutilización, reciclada o sujeta a recuperación material, incluidas las operaciones de relleno.

En la Figura 4 se muestran los tratamientos de gestión aplicados a la fracción mineral de RCDs no peligrosos (Eurostat, 2018b) y la tasa de recuperación (Eurostat, 2018c) para los países de la UE-28 en el año 2016. Como se puede observar, el valor de la tasa de recuperación en la UE fue del 90%, valor que alcanzaron o superaron dieciocho Estados miembros. En seis países la tasa de recuperación estuvo comprendida entre el 70% y el 90%, donde se encontró España con un valor del 79%. Así mismo, el objetivo de valorización de RCDs del 70% establecido para 2020 no había sido alcanzado por cuatro países (Grecia, Chipre, Eslovaquia y Suecia).

En cuanto a los tratamientos aplicados (Figura 4), del total de residuos minerales de C&D tratados en la UE-28, el 84% se reciclaron, el 6% se utilizó como relleno, y en torno al 10% fue eliminado. En España se procesaron 9 millones de toneladas por gestores de residuos autorizados (plantas de tratamiento y/o vertederos), de los cuales el 71% se recicló, el 8% se utilizó como relleno, y el 21% restante fue depositado en vertederos. Así mismo, el tratamiento de gestión mayoritario realizado en los países de la UE fue el reciclado, con valores superiores al 50% en veintitrés Estados miembros, y siendo superior al 95% en Holanda, Eslovenia, Italia, Bélgica y Reino Unido. La eliminación fue la opción mayoritaria para Grecia (100%), y con porcentajes superiores al 40% en Eslovaquia (46%) y Chipre (43%). Y la recuperación energética se utilizó en menor medida, en Suecia (15%), Finlandia (10%) y Dinamarca (6%).

Finalmente, en el caso de opción de la utilización del material como relleno, fue superior al 50% en Malta, Portugal e Irlanda, y con valores comprendidos entre el 20% y el 40% en siete Estados miembros. De acuerdo a lo recogido en la última modificación de la Directiva sobre residuos 2008/98/CE (European Parliament and Council, 2008) mediante la Directiva (EU)

2018/851 (European Parliament and Council, 2018), esta práctica no conlleva el mantenimiento del valor de los materiales en la economía por lo que no contribuye a una economía circular. En consecuencia, será necesario establecer nuevas normas para el cálculo de la consecución de los objetivos de reciclado de manera que, desde la entrada en vigor de esta última Directiva, los materiales utilizados como material de relleno no podrán ser contabilizados a estos efectos.

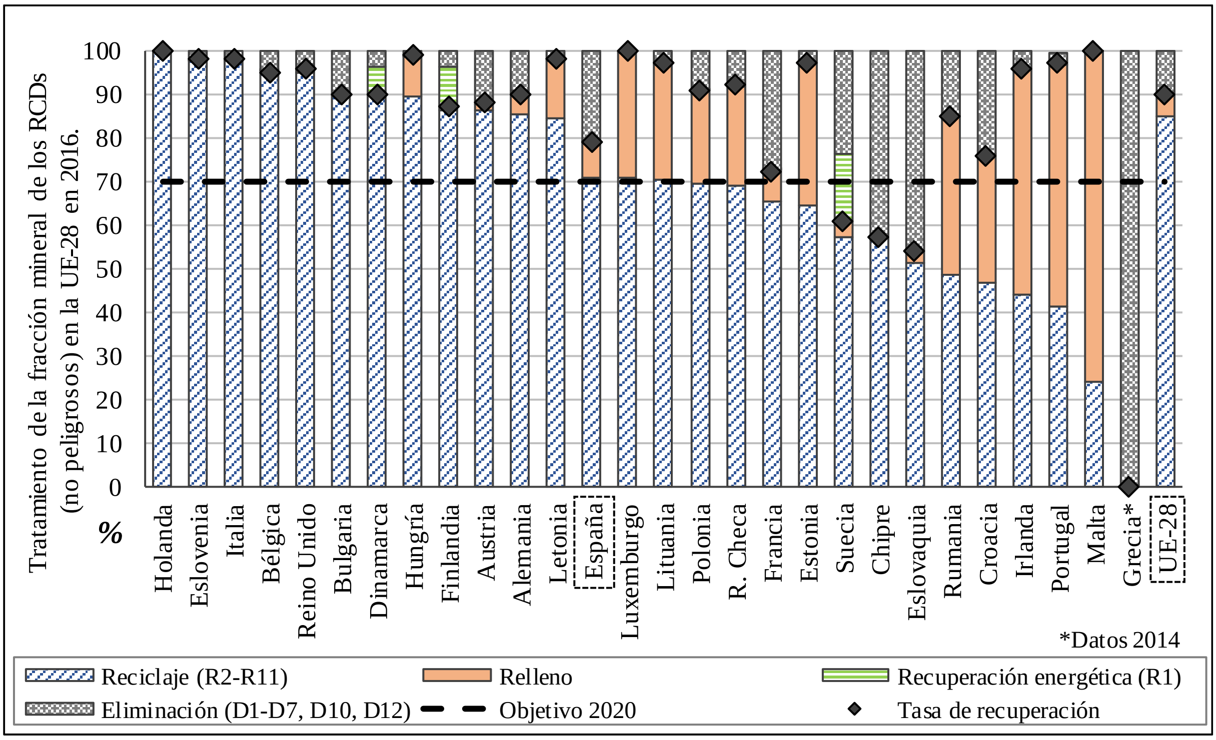


Figura 4. Tasa de recuperación y tratamiento de la fracción mineral de RCDs en la UE-28 en 2016 (Eurostat, 2018c, 2018b)

1.5. Usos y limitaciones de los áridos reciclados

Los áridos constituyen la principal materia prima suministrada para la construcción de infraestructuras o para la edificación y se emplean en la fabricación de hormigones, prefabricados, morteros, aglomerados asfálticos, bases y subbsases de carreteras, balasto para ferrocarril , etc, que pueden constituir hasta el 95% de la composición de estos materiales (ANEFA, 2018). La elevada demanda de esta materia prima ha causado que haya sido incluída para su evaluación en la tercera lista de Materias Primas Críticas (European Commission, 2017b). Los resultados indican que estos materiales deben seguir siendo evaluados en el futuro para determinar su criticidad de acuerdo con su importancia económica y el riesgo de suministro.

En este sentido, el uso de materias primas secundarias es una parte clave de la economía circular, ya que los materiales reciclados sustituyen la extracción de recursos naturales. Pero la contribución de materiales reciclados a la demanda global de materias primas todavía es relativamente pequeña. En 2016, la demanda de áridos ascendió a 2,7 billones de toneladas en Europa (UEPG, 2017). Sin embargo, según el marco de seguimiento para la economía circular y los indicadores clave para materias primas secundarias (European Commission, 2018c, 2018b) la contribución de árido reciclado (AR) a la demanda de árido natural (AN) fue del 8%, determinada mediante ‘end-of-life recycling input rate’ (EOL-RIR) (Eurostat, 2018d; UEPG, 2017). En concreto, en España, la demanda de áridos para trabajos de construcción fue de 96,6 millones de toneladas, de las cuales tan sólo el 1% lo componían AR (ANEFA, 2017).

Para cerrar el círculo de la economía circular, los materiales y productos que pueden ser reciclados necesitan ser reinvertidos en última instancia en la economía. Sin embargo, el uso de AR en construcción todavía es muy escaso, ya que presenta una serie de obstáculos. La desconfianza en cuanto a la calidad de los materiales reciclados, la ausencia de normas y prescripciones técnicas específicas para AR, y los bajos precios de la materia prima natural por su abundancia implican que las materias primas secundarias procedentes del reciclado de RCDs no tengan suficiente demanda (Calvo et al., 2014; Rodríguez et al., 2015). Una gestión adecuada de los RCDs y de los materiales reciclados, que incluya la separación de flujos de residuos y una manipulación correcta de residuos peligrosos, así como el fomento desde las administraciones públicas, puede suponer grandes beneficios en cuanto a la sostenibilidad y la calidad de vida, así como al sector de la construcción y demolición en la UE. En este sentido, la Comisión Europea ha publicado recientemente diversos documentos que pueden potenciar la demanda de AR procedentes de RCDs, como son el “Protocolo de Gestión de residuos de la construcción y demolición en la UE” (European Commission, 2016b), las “Directrices para las auditorías de residuos antes de los trabajos de demolición y renovación de edificios” (European Commission, 2018d) y los “Criterios de contratación Pública Ecológica en el sector de la construcción relativos a edificios de oficinas y carreteras” (European Commission, 2018e). Estos documentos se enmarcan dentro de la Estrategia Construcción 2020 (European Commission, 2012), de la Comunicación sobre Oportunidades de Eficiencia de Recursos en el Sector de la Edificación (European Commission, 2014a) y también forma parte del paquete sobre economía circular presentado por la Comisión Europea en 2015 (European Commission, 2015).

El AR presenta mayor capacidad de absorción de agua que el AN, como consecuencia del mortero que queda adherido en los AR de hormigón y de la mayor porosidad del material cerámico en el caso de AR cerámicos (Debieb and Kenai, 2008; Evangelista and de Brito, 2007; Rodríguez Robles, 2016). Además, la capacidad de absorción de agua de la fracción fina (0/4 mm) del AR es todavía mayor (Barbudo et al., 2012; Corinaldesi and Moriconi, 2009). Esta circunstancia tiene una importante influencia sobre las propiedades en estado fresco y endurecido de hormigones y morteros, pues se reduce el agua de amasado disponible para hidratar la mezcla de árido y cemento, causando la reducción de la trabajabilidad y del valor de la consistencia, así como de la resistencia mecánica (Bektas et al., 2009; Pereira et al., 2012a).

Para solucionar este problema, se han realizado numerosas investigaciones con diferentes métodos de compensación de agua y se ha evaluado su efecto en el desarrollo de las propiedades en estado fresco y endurecido de hormigones o morteros. Una forma de reducir la capacidad de absorción de agua del AR consiste en incrementar la cantidad de agua de amasado (Corinaldesi and Moriconi, 2009; Jiménez et al., 2013; Leite et al., 2013). Leite et al., (2013) tomaron como referencia la capacidad de absorción de agua (WA_{24h}) del AR y llegaron a la conclusión de que en el caso de hormigón reciclado, un valor comprendido entre el 80% y 90% sería satisfactorio tanto para la trabajabilidad como para la resistencia a compresión. Otros autores mojaron el AR antes del amasado (premojado) y mantuvieron constante el agua de amasado (Barra de Oliveira and Vazquez, 1996; Etxeberria et al., 2007; Miranda et al., 2014; Poon et al., 2004). Estos autores concluyeron que, para un índice de compensación total (100%) de WA_{24h}, la resistencia a compresión disminuyó debido a que la unión mecánica entre la pasta de cemento y el AR se debilita. Sin embargo, mediante el uso de AR premojado con el 80% de WA_{24h} se obtiene una eficiente zona de transición que mejora el rendimiento mecánico. Finalmente, el empleo de aditivos plastificantes en hormigones fabricados con reemplazos parciales de árido fino natural (AFN) por árido fino reciclado (AFR) sin aumentar el agua de amasado, proporcionó niveles óptimos de trabajabilidad, rendimiento mecánico y durabilidad, cumpliendo los requisitos establecidos para hormigón estructural (Pereira et al., 2012a; Zega and Di Maio, 2011).

Como consecuencia de las limitaciones observadas, se han desarrollado numerosas investigaciones con la finalidad de evaluar el uso de AR procedentes del tratamiento de RCDs como reemplazo de AN. Entre ellas destacan la incorporación de AR en la fabricación de hormigón estructural (Eckert and Oliveira, 2017; Etxeberria et al., 2007; Frondistou-Yannas, 1977; Hansen and Narud, 1983; Tošić et al., 2015), hormigón no estructural (Hossain et al., 2016a; Martín-Morales et al., 2017; Sánchez-Roldán et al., 2016; Soutsos et al., 2011), construcción de carreteras (Jiménez et al., 2012; Martín-Morales et al., 2013a; Mroueh et al., 2001; Poon and Chan, 2006; Vegas et al., 2011), fabricación de morteros de albañilería (Bektas et al., 2009; Corinaldesi and Moriconi, 2009b; Fernández-Ledesma et al., 2016; Jiménez et al., 2013) o como material de sustrato en cubiertas verdes (López-Uceda et al., 2018; Mickovski et al., 2013; Molineux et al., 2015). Además, en los últimos años se ha evaluado la incorporación de AFR en diferentes aplicaciones con resultados satisfactorios, como la fabricación de hormigón (Bravo et al., 2017; Pereira et al., 2012b; Zega and Di Maio, 2011), ladrillos (Ismail and Yaacob, 2010), bloques de hormigón prefabricado (Martín-Morales et al., 2017), mezclas de asfalto (Chen et al., 2011) y morteros de albañilería (Corinaldesi et al., 2002; de Oliveira Andrade et al., 2018; Martínez et al., 2013; Vegas et al., 2009).

Aunque dichos estudios han demostrado la posibilidad de ampliar el campo de aplicación del AR aumentando las oportunidades de evaluación y reciclaje de RCDs, la incorporación de AR está condicionada por las especificaciones técnicas vigentes en el país de aplicación (Martín-Morales et al., 2013c). En el caso de España, la Instrucción de Hormigón Estructural EHE-08 (Ministerio de Fomento, 2008) permite el 20% de reemplazo de AN por AR grueso procedente de residuos de hormigón para la fabricación de hormigón estructural, y hasta el 100% en el caso de hormigón no estructural; el uso de AFR está prohibido. De esta manera, la fracción fina de AR está infrautilizada, y en la mayoría de los casos, es depositada en vertederos o almacenada en las plantas de reciclaje (Torres-Gómez et al., 2016). En el caso de la construcción de capas de firmes de carreteras, el Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Ministerio de Fomento, 2015) posibilita el uso de AR como zahorras para bases granulares de firmes, suelos reciclados, material drenante, suelo-cemento y gravacemento para firmes de carreteras, y árido grueso para hormigón estructural, no estructural y compactado con rodillo.

Sin embargo, existen otro tipo de aplicaciones que requieren menos exigencias técnicas en las que su uso está contemplado. Éste es el caso de la norma EN 13.139: “Aridos para morteros” (CEN, 2002a), que permite la incorporación de AR sin restricciones, por lo que la fabricación de morteros de albañilería constituye un uso potencial para estos áridos.

1.6. El ACVcomo herramienta para determinar la viabilidad ambiental de los AR

El ACV es un proceso objetivo que nos permite evaluar las cargas ambientales asociadas a un producto, proceso o actividad, identificando y cuantificando tanto el uso de materia y energía como las emisiones al entorno, para determinar el impacto del uso de esos recursos y de las emisiones, para evaluar y llevar a la práctica estrategias de mejora ambiental (Righi et al., 2018). Incluye el ciclo completo del producto, proceso o actividad, teniendo en cuenta las etapas de extracción y procesado de materias primeras, producción, transporte y distribución, uso, reutilización y mantenimiento, reciclado y disposición final.

Los inicios del ACV se remontan a la década de los 70 del siglo pasado, donde Hunt et al. (1974) presentaron los resultados de su estudio como perfiles de recursos y emisiones, aunque no se realizó el análisis cuantitativo de los impactos asociados sobre los recursos y el ambiente. Los primeros métodos para evaluar los impactos ambientales en el ACV se publicaron a principios de 1990 con ejemplos destacados como la metodología Swiss Ecoscarcity (o Ecopoints) (Ahbe et al., 1990) y la metodología CML 1992 (Heijungs et al., 1992). Así mismo, en 1993 se inició el proceso de estandarización para el ACV bajo la Organización Internacional de Normalización, ISO, y culminó en 2006 con las normas ISO 14040 (ISO, 2006a) y ISO 14044 (ISO, 2006b) que constituyen el marco normativo actual. Al mismo tiempo, se iniciaron proyectos específicos en varios países para desarrollar metodologías de evaluación del impacto del ciclo de vida: i) métodos midpoint como EDIP (Wenzel et al., 1997) y CML 2002 (Guinée et al., 2002); ii) métodos endpoint como Ecoindicator 99 (Goedkoop and Spriensma, 2000) y EPS (Steen, 1999); o iii) métodos que combinan los enfoques de midpoint y endpoint, como IMPACT 2002+ (Jolliet et al., 2003), LIME (Itsubo et al., 2004) y ReCiPe (Goedkoop et al., 2009).

En la actualidad, la metodología del ACV basada en la normas ISO 14040 (ISO, 2006a) y ISO 14044 (ISO, 2006b), junto a la norma ISO 15804 (CEN, 2013a) establecen el marco normativo para evaluar y cuantificar los impactos ambientales de materiales y productos de construcción. La información basada en el ACV puede cubrir sólo la etapa de producto (suministro de materias primas, el transporte y la fabricación), es decir, “de la cuna a la puerta” (Colangelo et al., 2018; Densley Tingley et al., 2015), o el ciclo de vida completo de un producto de acuerdo a los límites del sistema (etapa de producto, construcción, uso y fin de vida) y que se denomina “de la cuna a la tumba” (Bueno et al., 2016; Pini et al., 2014).

El uso de AR puede incrementar la eficiencia en el uso de los recursos, así como impulsar el mercado de materias primas secundarias al introducir residuos como recursos. De este modo, se reduce el consumo de recursos naturales y la disposición de residuos en vertederos, lo que se traduce en beneficios ambientales. En este contexto, una evaluación real de los beneficios ambientales requiere el uso de herramientas que cuantifiquen con precisión tales beneficios, por ejemplo el ACV, que está siendo utilizada en el sector de la construcción para determinar las estrategias de gestión de RCDs que proporcionen el mejor resultado ambiental, así como para el diseño de materiales de construcción más sostenibles (Ding, 2014; Fernández-García et al., 2016).

El ACV se ha utilizado en diversos estudios para desarrollar y analizar un inventario de ciclo de vida de los sistemas de gestión de RCDs, que engloba todas las etapas de los residuos de la construcción de edificios (que incluye el transporte, la clasificación, el relleno o disposición en vertederos, la recuperación y reutilización, y la transformación y valorización en productos secundarios) en diferentes escenarios como España (Mercante et al., 2012; Ortiz et al., 2010), Brasil (Penteado and Rosado, 2016) o Hong Kong (Hossain et al., 2017), entre otros. Los resultados obtenidos mostraron que los escenarios de prevención generaron los impactos ambientales más bajos; así, la reducción en un 60% de la cantidad de RCDs generados, también habría disminuido al menos el 60% de todos los impactos de las categorías analizadas en Bizcocho and Llatas (2018). Además se observó, que en términos de Potencial de Calentamiento Global, el tratamiento más respetuoso con el medio ambiente fue el reciclaje, seguido por la incineración y, finalmente, la disposición en vertedero, aunque los beneficios medioambientales dependen principalmente de la composición de los residuos, su clasificación y si ésta se realiza in situ o en otro lugar. Respecto a la influencia de la ubicación de las plantas de tratamiento, el reciclaje de los RCDs y la incineración fueron mejores que la disposición en vertedero. Estos resultados coinciden con el principio de jerarquía de gestión de residuos (prevención, la preparación para la reutilización, el reciclado y la recuperación de energía hasta la eliminación (depósito en vertederos)) establecido en la Directiva Marco de Residuos 2008/98/CE (European Parliament and Council, 2008). Desde el punto de vista del transporte, Blengini and Garbarino (2010) aplicaron la metodología del ACV para identificar y cuantificar la energía y las cargas ambientales bajo diferentes supuestos relacionados con las distancias de transporte, calidad de los AR, disponibilidad local de AN y la cobertura geográfica de la demanda del mercado. Se estimó que la distancia de transporte de los AR debería aumentar dos o tres veces antes de que los impactos inducidos superen a los impactos evitados. Asimismo, Penteado and Rosado (2016) determinaron la distancia óptima entre el lugar de generación y la unidad de reciclaje en un radio de 30 km.

Además, los impactos ambientales generados durante la producción de AR procedentes de RCDs también se han evaluado y comparado con los impactos causados por la producción de AN. Simion et al. (2013) mostraron que el proceso de reciclaje generó menor impacto comparado con el resultante del procesamiento de AN, y destacaron la necesidad de una clasificación in situ para garantizar la eficiencia del proceso. De la misma manera, Hossain et al. (2016b) concluyeron que es posible reducir aún más los impactos ambientales a través del diseño efectivo del sistema de recogida y transporte de los residuos para la producción de AR. Y Faleschini et al. (2016) observaron que los impactos ambientales de AR en una perspectiva de ciclo de vida deberían tener en cuenta los indicadores específicos del lugar, que puedan captar los impactos del procesamientoy suministro de actividades a escala local, como evitar el uso de la tierra y el consumo de recursos naturales, mediante el tiempo de agotamiento de la cantera.

Finalmente, también se analizaron los impactos asociados al uso de AFR como reemplazo de AFN en diferentes aplicaciones constructivas, como la producción de hormigón (Knoeri et al., 2013; Turk et al., 2015; Yazdanbakhsh et al., 2017), construcción de carreteras (Butera et al., 2015; Mroueh et al., 2001) y la fabricación de bloques de hormigón (Hossain et al., 2016a). Los resultados generales mostraron que, en todos los casos, el material reciclado genera un menor impacto ambiental que su material primario equivalente. En este sentido, Yazdanbakhsh et al. (2017) concluyeron que los beneficios son mayores cuando el residuo de hormigón se recicla en instalaciones móviles en el lugar de demolición y se utiliza para construcción en el mismo lugar. Knoeri et al. (2013), Turk et al. (2015), Butera et al. (2015) y Mroueh et al. (2001), destacan que la distancia de transporte y el tipo de transporte son parámetros clave para mantener los beneficios ambientales. Hossain et al. (2016a) destacan que es necesario fortalecer la política y el mercado de productos reciclados para fomentar un tratamiento ingeniosos de los residuos, así como las construcciones sostenibles.

2. Motivación

2.1. Morteros de albañilería. Definición y clasificación

El mortero se define como la mezcla de uno o varios conglomerantes inorgánicos (cemento, cal o yeso), áridos, agua y a veces, adiciones y/o aditivos (European Mortar Industry Organisation, 2013). Es tan antiguo como la civilización humana, ya que la primera aplicación de mortero en la historia se data unos 10.000 años a. C. en la cultura neolítica, que emplearon morteros de cal para la ejecución de pavimentos (Álvarez Galindo et al., 1995). Posteriormente, los egipcios fueron los primeros en utilizar el yeso en la unión de los bloques durante la construcción de la pirámide de Keops (Furlan and Bisseger, 1975). Por su parte, los griegos innovaron los morteros de cal mediante la adición de materiales puzolánicos para aumentar la resistencia y estabilidad, y los romanos mejoraron los procesos de fabricación de la cal, así como la puesta en obra del mortero (Álvarez Galindo et al., 1995). Durante la Edad Media no hubo ningún progreso técnico notable en la evolución de los morteros, pero el descubrimiento del cemento en el siglo XIX y su uso como conglomerante marca el gran avance de los morteros modernos, al conseguir elevadas resistencias, un endurecimiento más lento y mayor hidraulicidad (Alejandre Sánchez, 2002). Actualmente, la industria de los morteros en Europa produce más de cien clases de morteros, que se presentan en diferentes formas y ofrecen propiedades y características físicas, químicas y mecánicas especialmente adaptadas a edificación y obras de ingeniería civil de diversa índole (European Mortar Industry Organisation, 2013).

La amplia variedad de aplicaciones de los morteros permite que se puedan estructurar varios grupos (AFAM, 2018): i) morteros para albañilería y revestimiento; ii) morteros técnicos, como los morteros de solados, morteros de reparación y morteros de impermeabilizantes; y iii) otros morteros, como los adhesivos cementosos para baldosas cerámicas, morteros para recrecido y acabado de suelos, y los materiales de rejuntado para baldosas cerámicas.

Según los datos publicados en el Análisis Sectorial de Morteros (AFAM, 2012), la producción de mortero en España en el año 2011 fue de aproximadamente 18 millones de toneladas, de las cuales 11 millones de toneladas (60%) correspondieron a mortero fabricado en obra y 7 millones de toneladas (40%) a morteros industriales. La producción de mortero para albañilería (para revoco y enlucido, y de albañilería) fue de 6 millones de toneladas, abarcando el 85% de la producción de mortero industrial que fue suministrado en forma de mortero húmedo (50%) y como mortero seco (35%). El 15% restante, 1 millón de toneladas, correspondió a la producción de morteros técnicos o especiales. En cuanto al destino de la producción de mortero, principalmente fue dirigida a obras de reforma, rehabilitación y restauración (58%), a vivienda (16%), a obra civil (15%) y a edificación no residencial (11%). Estas cifras ponen de manifiesto como el mortero de albañilería es uno de los productos de construcción más empleados en el sector de la construcción.

Las especificaciones de los morteros para albañilería se establecen en la Norma EN 998-1: “Especificaciones de los morteros para albañilería. Parte 1: Morteros para revoco y enlucido” (CEN, 2010) y en la Norma EN 998-2: “Especificaciones de los morteros para albañilería. Parte 2: Morteros para albañilería” (CEN, 2012a). Como el término mortero para albañilería también incluye a los morteros para revoco y enlucido, para evitar confusiones se utilizará en este documento el término “mortero de albañilería” en referencia a los morteros incluidos en la Norma EN 998-2: “Especificaciones de los morteros para albañilería. Parte 2: Morteros para albañilería”(CEN, 2012a). La principal diferencia entre ambos grupos se centra en las aplicaciones. Los morteros para revoco y enlucido se emplean para realizar revocos exteriores o enlucidos interiores, respectivamente (CEN, 2010). Su aplicación se realiza sobre la superficie externa de otro elemento o sistema constructivo, con el fin de cubrirlo por razones funcionales (la protección de la fachada de los agentes externos) o simplemente estéticas (acabado de acuerdo a su textura, color, despiece, etc.) (AFAM, 2018). Los morteros de albañilería se utilizan para colocar, unir y rejuntar piezas de albañilería para la ejecución de fábricas (de ladrillo, hormigón, piedra, etc), que pueden tener carácter estructural (muro de carga, cimentación, etc) o función de cerramiento/separación (fachada, medianería, tabique, etc.) (AFAM, 2018; CEN, 2012a).

De acuerdo a la Norma EN 998-2 (CEN, 2012a), los morteros para albañilería se pueden clasificar según el concepto (diseñado o prescrito), por el sistema de fabricación (hecho en fábrica, en el lugar de utilización, etc.) y por sus propiedades y/o utilización (para uso corriente-G, ligero-L, o para juntas y capas finas-T).

2.1.1. Componentes

La norma EN 998-2 (CEN, 2010) relaciona los componentes del mortero de albañilería, que son los siguientes:

- Árido. Constituye el 90% de la dosificación del mortero de albañilería, siendo el componente más importante en peso. Los requisitos exigidos a los áridos para la fabricación de morteros se establecen en la norma EN 13139: “Áridos para morteros” (CEN, 2002a). Esta Norma define árido como el material granular utilizado en construcción, y lo clasifica según su procedencia en: i) AN (granular o de machaqueo) de origen mineral obtenido únicamente por procedimientos mecánicos; ii) árido artificial, de origen mineral resultante de un proceso industrial que comprende una modificación térmica o de otro tipo; y iii) AR, resultante del tratamiento de material inorgánico previamente empleado en la construcción. El AN puede ser de naturaleza caliza, silícea o dolomía como el utilizado en este estudio. Concretamente, en España el 63% de la producción de dolomía se suministró como áridos para construcción y obras públicas, principalmente para la fabricación de hormigones, morteros y prefabricados (78.3%), para su uso en carreteras (20.3%) y en la formación de escolleras (1.4%). En Andalucía, la producción de dolomía alcanzó el 82.7% de la producción nacional, y en la provincia de Granada el 32% (Ministerio de Energía Turismo y Agenda Digital, 2018).

- Conglomerante. Junto a los áridos, es el componente más importante de los morteros ya que permite unir partículas sólidas de tal manera que formen una masa coherente. Se puede utilizar cualquier conglomerante inorgánico (cemento, cal y yeso) siempre que cumplan los requisitos establecidos, aunque el más utilizado es el cemento ya que presenta mayor rapidez de endurecimiento y resistencias más altas (Bustillo Revuelta, 2008; Rodríguez-Mora, 2003). Se regulan por las normas RC-16: “Instrucción para la recepción de cementos” (Ministerio de la Presidencia, 2016), EN 413-1: “Cementos de albañilería. Parte 1: Composición, especificaciones y criterios de conformidad” (CEN, 2011) y EN 413-2: “Cementos de albañilería. Parte 2: Métodos de ensayo” (CEN, 2016).

- Aditivo. Se trata de un material añadido en pequeñas cantidades para modificar determinadas propiedades del mortero. Deben cumplir las exigencias de las normas EN

934-1: "Aditivos para hormigones, morteros y pastas. Parte 1: Requisitos comunes" (CEN, 2009a) y EN 934-3: "Aditivos para hormigones, morteros y pastas. Parte 3: Aditivos para morteros para albañilería" (CEN, 2012b). Los más utilizados son:

  - Aditivo inclusor de aire/plastificante (AIAP). Incrementa la trabajabilidad o permite una reducción del contenido en agua al incorporar durante el amasado una cantidad controlada de pequeñas burbujas de aire, uniformemente distribuidas, que permanecen retenidas después del endurecimiento. Estos aditivos causan en los morteros los siguientes efectos (Rodríguez-Mora, 2003): i) aumentan la plasticidad del mortero al facilitar la dispersión temporal de las partículas de cemento; ii) disminuyen la densidad aparente del mortero en estado fresco; e iii) interrumpen la red capilar de la masa de mortero, impidiendo la penetración de agua y productos de la hidratación del cemento, protegiendo la masa del efecto de las heladas. Estas mejoras se tienen en cuenta cuando se utilizan AR, ya que el AIAP compensa la necesidad de añadir el agua que sería absorbida por ellos para obtener la misma trabajabilidad (Barra Bizinotto et al., 2017; Bravo et al., 2017; Lotfy and Al-Fayez, 2015; Vegas et al., 2009).
  - Aditivo retardador de fraguado. Retrasan el tiempo de fraguado del cemento para prolongar el tiempo de trabajabilidad del mortero.

- Agua. Se utiliza para el amasado de los morteros, debe ser de naturaleza inocua, y no debe contener en exceso sustancias que puedan alterar las propiedades del mortero o provocar la corrosión del acero, como es el caso de sulfatos o cloruros. No existe una norma específica sobre los requisitos que debe reunir el agua de amasado, pero en general, se suele utilizar agua sancionada como aceptable por la práctica.

2.1.2. Propiedades de los morteros de albañilería

Las propiedades de los morteros de albañilería varían en función del tipo o de la clase de mortero, aunque existen un grupo de características comunes a la gran mayoría de ellos. Estas propiedades se pueden agrupar en dos categorías: i) en estado fresco, que afectan directamente a la puesta en obra del mortero, como la consistencia, la densidad y el contenido en aire; y ii) en estado endurecido, que definirán el comportamiento del mortero, como la densidad, la resistencia y la absorción de agua por capilaridad. No obstante, estas propiedades no son independientes, pues las propiedades en el estado fresco tienen gran influencia en las prestaciones finales del mortero.

El mortero de albañilería para uso corriente (G) de clase M5 es el de uso más generalizado y se utiliza en elementos constructivos no sometidos a requisitos estructurales. De acuerdo al Código Técnico de la Edificación (Ministerio de Fomento, 2009), la fábrica podrá estar expuesta a las clases I, IIa y IIb sin disminuir sus propiedades, lo que permite su utilización en interiores de edificios protegidos de la intemperie, exteriores protegidos de la lluvia y exteriores no protegidos de la lluvia o sótanos no ventilados. Los componentes principales de este mortero son cemento (10%) y árido (90%) en proporciones relativas a la masa seca total, y agua (14%), de acuerdo a la dosificación facilitada por el fabricante. Desde el punto de vista técnico, las propiedades que se requieren para esta clase de mortero son un valor mínimo de resistencia a compresión a 28 días de 5 N/mm^2, así como un valor de consistencia plástica (≥ 140 mm) que permita una adecuada puesta en obra.

2.1.3. Uso del AR en morteros de albañilería

La aplicación de AFR en morteros de albañilería ha sido el objeto de estudio de algunas investigaciones desde finales del siglo XX hasta la actualidad (Álvarez-Cabrera et al., 1997; Corinaldesi and Moriconi, 2009; de Oliveira Andrade et al., 2018). En la Tabla 3 se realiza un estudio comparativo de la bibliografía consultada y se especifican algunos de los aspectos comunes más importantes, entre ellos: dosificación empleada, relación cemento/árido (c/a), relación agua/cemento (a/c), reemplazo de AFN por AFR, tamaño y densidad del árido, naturaleza del AFR o la resistencia a compresión a 28 días edad. A continuación, se hace un análisis de los resultados obtenidos.

- Dosificación empleada, relación c/a, y relación a/c. El Código Técnico de la Edificación (Ministerio de Fomento, 2009) determina que los morteros ordinarios para fábricas pueden especificarse por el valor de su resistencia a compresión o por la proporción en volumen de sus componentes fundamentales. La Norma EN 998-2 (CEN, 2012a) establece que la proporción de todos los componentes de los morteros prescritos debe ser declarada por el fabricante en volumen o en peso; además, se debe indicar la resistencia a compresión basada en las proporciones de la mezcla. Por tanto, el fabricante puede establecer la dosificación que considere oportuna para obtener un producto adecuado. Actualmente, las dosificaciones se realizan por proporciones referidas a partes en volumen, en masa o por porcentaje de masa seca total.

En la revisión bibliográfica realizada, se ha observado que la proporción de los componentes se hizo mayoritariamente en masa (64%), y en volumen el 36% restante. También se observó una gran variedad de dosificaciones de los morteros; la relación c/a de 1:3 fue la más estudiada (33%), mientras que tan sólo en el 4% se utilizó por porcentaje de cemento sobre la masa seca total (Miranda and Selmo, 2006; Vegas et al., 2009).

La relación a/c varió desde 0,5 hasta 2,5, en función de la relación c/a, de manera que al aumentar la proporción de AFR, se necesitó más agua para hidratar la mezcla y, por tanto, la relación a/c se incrementó. No obstante, Bektas et al. (2009) y Mesbah and Buyle-Bodin (1999) mantuvieron una relación a/c constante de 0,5 y 0,75, respectivamente.

Generalmente, los AFR se utilizaron en estado seco, aunque algunos autores los mojaron previamente. Cabrera-Covarrubias et al. (2017, 2015) mezclaron los AFR con agua durante un minuto antes de incorporar el cemento dentro de la amasadora. Martínez et al. (2018) utilizaron AFR mojado durante 30 minutos. Miranda et al. (2014) y Miranda and Selmo (2004) premojaron el AFR durante 30 segundos y 10 minutos después incorporaron el cemento y el agua restante.

- Reemplazo de AFN por AFR. En referencia a la cantidad de AFR incorporado en la fabricación del mortero, el 29% de los estudios evaluaron reemplazos parciales, el 31% efectuaron el reemplazo total, y en el 40% se realizaron reemplazos parciales y totales. Además, el reemplazo de AFN por AFR se realizó por volumen en el 48,5% de los estudios analizados y por masa en el 51,5%. Algunos autores justificaron el reemplazo por volumen como consecuencia de la variación en los valores de densidad de los áridos (de Oliveira Andrade et al., 2018; Jiménez et al., 2013). Así mismo, Evangelista et al. (2018) justificó el reemplazo realizado por masa ya que ambos áridos presentaron valores próximos de densidad. En general, los valores de densidad de los AFN fueron más altos que los de AFR, y oscilaron entre 1,14 kg/dm^3 (Silva et al., 2010) y 2,83 kg/dm^3 (López Gayarre et al., 2017), mientras que para AFR los valores estuvieron comprendidos entre 1,03 kg/dm^3 (Silva et al., 2010) y 2,68 kg/dm^3 (Miranda and Selmo, 2006). Las mayores variaciones entre valores de densidad de AFN y AFR fueron del 39% (Vegas et al., 2009), 29% (López Gayarre et al., 2017) o el 25% (Martínez et al., 2018; Neno et al., 2014); por el contrario, las diferencias más bajas correspondieron al 2% (Lima and Leite, 2012), 7% (Muñoz-Ruiperez et al., 2016) o el 8% (Corinaldesi and Moriconi, 2009; Miranda et al., 2013; Poon and Kou, 2010; Stefanidou et al., 2014). Por el contrario, el valor de densidad de AFR fue un 4% más alto que el de AFN en Miranda and Selmo (2006) y un 2% en Raeis Samiei et al. (2015). Sin embargo, no se puede establecer que la diferencia entre los valores de densidad de los áridos condicionase a los autores a realizar el reemplazo de AFN por AFR por volumen o por masa. De hecho, en los estudios en los que el reemplazo se realizó por masa las diferencias entre los valores de densidad de los áridos oscilaron entre el 1% y el 39%, mientras que cuando el reemplazo se efectuó por volumen, las diferencias oscilaron entre el 9% y el 29%.

- Naturaleza del AFR. De acuerdo a la naturaleza del AFR, predominaron los AR mixtos que se evaluaron en el 38% de los estudios, seguidos por los áridos procedentes de residuos de hormigón (33%) y de material cerámico (29%). En cuanto al tamaño de árido los estudios evaluaron, preferentemente, morteros fabricados con árido fino, de tamaño 0/4 mm (54%) y de tamaño 0/2 mm el 14% de los estudios (Dapena et al., 2011; López Gayarre et al., 2017; Miranda et al., 2014, 2013; Vegas et al., 2009); para el resto, el tamaño del árido fue superior a la fracción 0/4 mm.

- Resistencia a compresión a 28 días. El valor de resistencia a compresión de referencia también presentó una gran amplitud de valores, y varió desde 5 N/mm^2 (Stefanidou et al., 2014) hasta 60 N/mm^2 (Bektas et al., 2009). Sin embargo, aunque la Norma EN 998-2 (CEN, 2012a) admite valores de resistencia a compresión por encima de 25 N/mm^2, no son usuales en los morteros de albañilería. Los valores de resistencia más altos se encontraron en las dosificaciones con mayor cantidad de cemento y menor cantidad de agua, es decir, para la relación c/a de 1:3 y la relación a/c de 0,5. Para los morteros reciclados, en términos generales, el aumento de la incorporación de AFR hizo que los valores de resistencia disminuyeran respecto al mortero de referencia, de forma general. Así, para reemplazos del 20% de AFN por AFR, los valores de resistencia se redujeron en torno al 4% (Bektas et al., 2009; Martínez et al., 2016), el 23% para incorporaciones del 50% de AFR (Dapena et al., 2011), el 53% para incorporaciones del 75% de AFR (Muñoz-Ruiperez et al., 2016) y hasta el 85% cuando se realizó un reemplazo total de AFN por AFR (Vegas et al., 2009). No obstante, en algunos estudios se observó el aumento de la resistencia a compresión de los morteros reciclados respecto al mortero de referencia. Así, Lima and Leite (2012) apreciaron un incremento del 15% del valor de la resistencia para reemplazos del 50% de

AFN, justificado por el mayor tamaño del AFR (4,8 mm) respecto al AFN (2,4 mm) y a que ambos áridos presentaron valores de densidad similares (2,55 kg/dm^3). Neno et al. (2014) mostraron que las resistencias aumentaron hasta el 88% cuando se incorporó el 100% de AFR; esto es debido a que este mortero tiene el menor contenido de agua en su composición y menor volumen de huecos, creando una mayor cohesión y mayor resistencia en el mortero, además de que el porcentaje del material que pasa por el tamiz 0,063 mm fue completamente distinto en el AFN (0,64%) y el AFR (10,49%). En el estudio desarrollado por López Gayarre et al., (2017), la resistencia se incrementó un 20% para el reemplazo total de AFN por AFR realizado por volumen en una relación c/a de 1:6 por masa, justificado por la reducción del agua efectiva a medida que aumenta la incorporación de AFR.

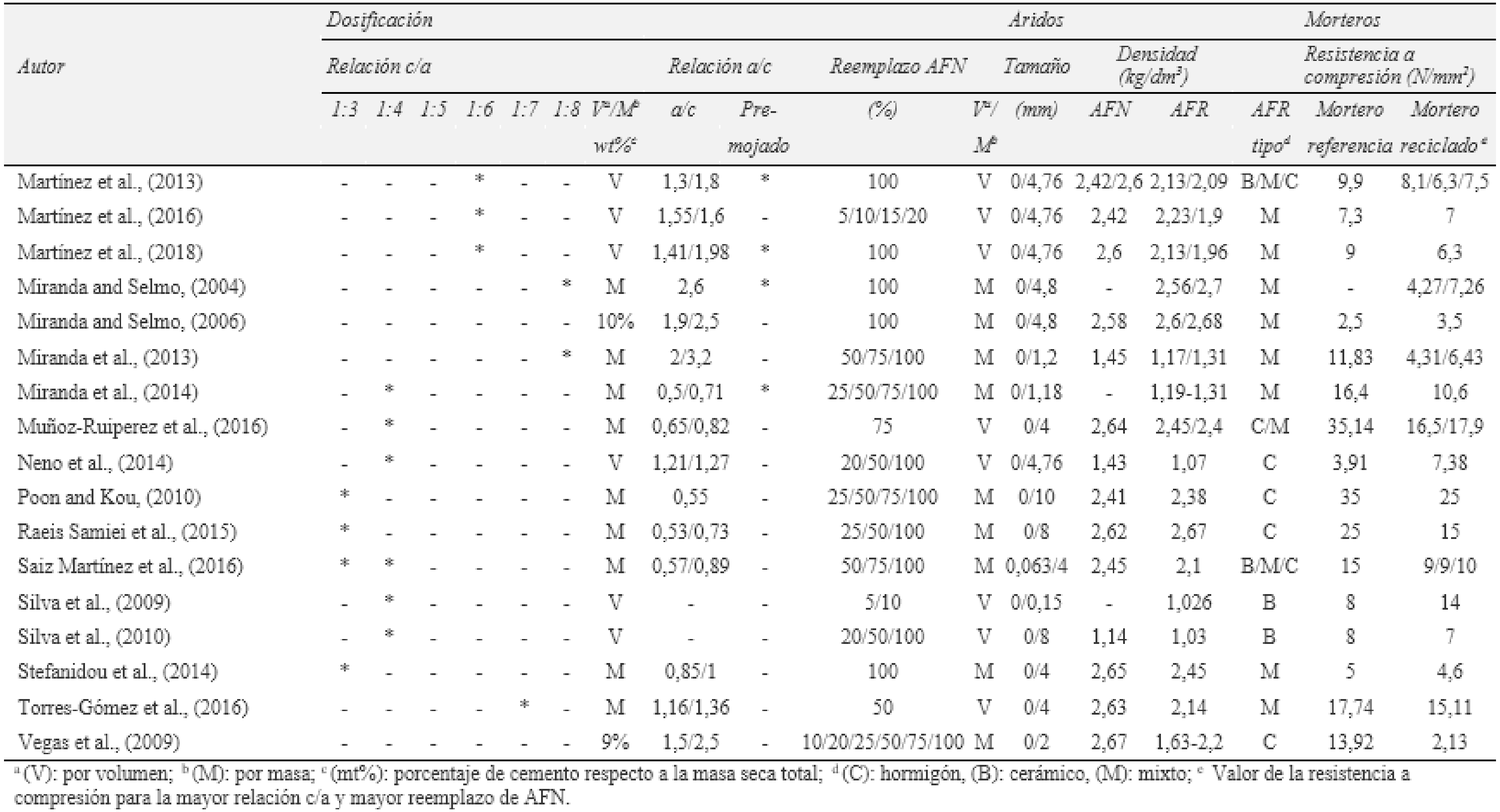
- A pesar de que la norma EN 998-2 (CEN, 2012a) establece la clasificación de los morteros en base a sus resistencia a compresión, la clase resistente del mortero sólo fue especificada en el 14% de los estudios evaluados, siendo M5 y M10 las clases analizadas. Jiménez et al. (2013) and Ledesma et al. (2014) emplearon una relación c/a de 1:7 por volumen, con árido de tamaño 0/4 mm para un mortero de clase M5, y efectuaron un reemplazo máximo del 40% de AFN por AFR. Ledesma et al. (2015) y Fernández-Ledesma et al. (2016) utilizaron una relación c/a de 1:5 por volumen y árido de tamaño 0/4 mm para un mortero de clase M10, y realizaron el reemplazo total de AFN por AFR. Finalmente, Vegas et al. (2009) evaluaron morteros fabricados con árido de tamaño 0/2 mm, con una dosificación del 9% de cemento sobre la masa seca total y realizaron el reemplazo total de AFN por AFR. En estos estudios, los morteros reciclados han podido alcanzar las resistencias del mortero de referencia para incorporaciones de hasta el 50% de AFR (Fernández-Ledesma et al., 2016; Ledesma et al., 2015), del 40% de AFR (Jiménez et al., 2013; Ledesma et al., 2014) y del 25% de AFR (Vegas et al., 2009).

Tabla 3. Comparación de estudios sobre morteros de albañilería fabricados con AFR de RCDs

Autor	*Dosificación*									*Aridos*					*Morteros*		
	Relación c/a							*Relación a/c*		*Reemplazo AFN*		*Tamaño*	*Densidad (kg/dm³)*		*Resistencia a compresión (N/mm²)*		
	1:3	*1:4*	*1:5*	*1:6*	*1:7*	*1:8*	*V[a]/M[b] mt%[c]*	*a/c*	*Pre-mojado*	*(%)*	*V[a]/ M[b]*	*(mm)*	*AFN*	*AFR*	*AFR tipo[d]*	*Mortero referencia*	*Mortero reciclado[e]*
Alvarez-Cabrera et al., (1997)	-	*	*	*	-	*	V	-	-	100	V	0/4,76	-	-	C	-	4,29
Bektas et al., (2009)	*	-	-	-	-	-	M	0,5	-	10/20	M	0/4,75	-	-	B	60	58
Braga et al., (2012)	-	*	-	-	-	-	V	1,41/1,12	-	5/10/15	V	0/0,15	-	-	C	3,91	8,64
Cabrera-Covarrubias et al., (2015)	-	*	-	-	-	-	M	0,84/1,48	*	10/20/30/50/100	M	0/5	2,62	2,15	B	25	≈25
Cabrera-Covarrubias et al., (2017)	*	*	*	-	-	-	M	0,68/1,74	*	100	M	0/5	2,62	2,15	B	-	-
Corinaldesi et al., (2002)	*	-	-	-	-	-	M	0,67/0,78	-	100	M	0/6	2,62	2,15	M	35	38
Corinaldesi, (2009)	*	-	-	-	-	-	M	0,52/0,71	-	100	M	0/6	2,62	2,15	C	30	15
Corinaldesi, (2012)	*	-	-	-	-	-	M	0,5/0,51	-	100	M	0/4	2,59	2,06	B	30	17
Corinaldesi and Moriconi, (2009a)	*	-	-	-	-	-	M	0,6/0,91	-	100	M	0/5	2,59	2,06/2,38	C/B/M	27	21/16/17
Dapena et al., (2011)	*	-	-	-	-	-	M	0,5	-	5/10/15/20/50	M	0/2	2,66	2,3	C	62	48
De Oliveira Andrade et al., (2018)	-	-	*	-	-	-	M	0,99-1,2	-	25/50/75/100	V	0/4,76	2,65	2,39-2,4	C/M	7,04	6,31/5,2
Evangelista et al., (2018)	*	-	-	-	-	-	M	0,55	-	20/30/50/100	M	-	-	2,38	B	36,4	28
Fernández-Ledesma et al., (2016)	-	-	*	-	-	-	V	0,78/0,97	-	25/50/75/100	V	0/4	2,63	2,2	C	11,5	9,1
Jiménez et al., (2013)	-	-	-	-	*	-	V	0,94/1,13	-	5/10/20/40	V	0/4	2,63	2,14	B	7,1	7,5
Ledesma et al., (2014)	-	-	-	-	*	-	V	0,94/1,07	-	5/10/20/40	V	0/4	2,63	2,2	C	7,1	7,2
Ledesma et al., (2015)	-	-	*	-	-	-	V	0,78/1,05	-	25/50/75/100	V	0/4	2,63	2,14	M	11,5	7,5
Lima and Leite, (2012)	-	*	-	-	-	*	M	0,7/1,72	-	50	V	0/4,8	2,6/2,55	2,55	M	12,3	14,2
López Gayarre et al., (2017)	-	-	-	*	-	-	M	1,3/1,5	-	20/35/50/70/100	V	0/2	2,83	2,02	B	6,5	7,8

[a] (V): por volumen; [b] (M): por masa; [c] (mt%): porcentaje de cemento respecto a la masa seca total; [d] (C): hormigón, (B): cerámico, (M): mixto; [e] Valor de la resistencia a compresión para la mayor relación c/a y mayor reemplazo de AFN.

Tabla 3. Comparación de estudios sobre morteros de albañilería fabricados con AFR de RCDs (continuación)



Autor	Dosificación									Aridos					Morteros		
	Relación c/a							Relación a/c		Reemplazo AFN		Tamaño	Densidad (kg/dm³)			Resistencia a compresión (N/mm²)	
	1:3	1:4	1:5	1:6	1:7	1:8	V[a]/M[b] wt%[c]	a/c	Pre-mojado	(%)	V[a]/M[b]	(mm)	AFN	AFR	AFR tipo[d]	Mortero referencia	Mortero reciclado[e]
Martínez et al., (2013)	-	-	-	*	-	-	V	1,3/1,8	*	100	V	0/4,76	2,42/2,6	2,13/2,09	B/M/C	9,9	8,1/6,3/7,5
Martínez et al., (2016)	-	-	-	*	-	-	V	1,55/1,6	-	5/10/15/20	V	0/4,76	2,42	2,23/1,9	M	7,3	7
Martínez et al., (2018)	-	-	-	*	-	-	V	1,41/1,98	*	100	V	0/4,76	2,6	2,13/1,96	M	9	6,3
Miranda and Selmo, (2004)	-	-	-	-	-	*	M	2,6	*	100	M	0/4,8	-	2,56/2,7	M	-	4,27/7,26
Miranda and Selmo, (2006)	-	-	-	-	-	-	10%	1,9/2,5	-	100	M	0/4,8	2,58	2,6/2,68	M	2,5	3,5
Miranda et al., (2013)	-	-	-	-	-	*	M	2/3,2	-	50/75/100	M	0/1,2	1,45	1,17/1,31	M	11,83	4,31/6,43
Miranda et al., (2014)	-	*	-	-	-	-	M	0,5/0,71	*	25/50/75/100	M	0/1,18	-	1,19-1,31	M	16,4	10,6
Muñoz-Ruiperez et al., (2016)	-	*	-	-	-	-	M	0,65/0,82	-	75	V	0/4	2,64	2,45/2,4	C/M	35,14	16,5/17,9
Neno et al., (2014)	-	*	-	-	-	-	V	1,21/1,27	-	20/50/100	V	0/4,76	1,43	1,07	C	3,91	7,38
Poon and Kou, (2010)	*	-	-	-	-	-	M	0,55	-	25/50/75/100	M	0/10	2,41	2,38	C	35	25
Raeis Samiei et al., (2015)	*	-	-	-	-	-	M	0,53/0,73	-	25/50/100	M	0/8	2,62	2,67	C	25	15
Saiz Martínez et al., (2016)	*	*	-	-	-	-	M	0,57/0,89	-	50/75/100	M	0,063/4	2,45	2,1	B/M/C	15	9/9/10
Silva et al., (2009)	-	*	-	-	-	-	V	-	-	5/10	V	0/0,15	-	1,026	B	8	14
Silva et al., (2010)	-	*	-	-	-	-	V	-	-	20/50/100	V	0/8	1,14	1,03	B	8	7
Stefanidou et al., (2014)	*	-	-	-	-	-	M	0,85/1	-	100	M	0/4	2,65	2,45	M	5	4,6
Torres-Gómez et al., (2016)	-	-	-	-	*	-	M	1,16/1,36	-	50	V	0/4	2,63	2,14	M	17,74	15,11
Vegas et al., (2009)	-	-	-	-	-	-	9%	1,5/2,5	-	10/20/25/50/75/100	M	0/2	2,67	1,63-2,2	C	13,92	2,13

[a] (V): por volumen; [b] (M): por masa; [c] (mt%): porcentaje de cemento respecto a la masa seca total; [d] (C): hormigón, (B): cerámico, (M): mixto; [e] Valor de la resistencia a compresión para la mayor relación c/a y mayor reemplazo de AFN.

Se puede por tanto concluir, que los estudios evaluados han permitido alcanzar valores de resistencia similares al del mortero de referencia con incorporaciones de hasta el 50% de AFR y una proporción mínima de cemento que corresponde a la relación c/a de 1:7. Dicha cantidad de cemento es superior al 10% de cemento sobre la masa seca total de los componentes que determina la dosificación del fabricante del mortero de clase M5 que se va a estudiar en este documento; de manera que utilizar más cemento del requerido resulta innecesario y ambientalmente más desfavorable. Además, y a pesar de que la viabilidad ambiental del uso de AR ha sido constatada en varias aplicaciones constructivas, no se han encontrado referencias bibliográficas que apliquen el ACV a morteros de albañilería fabricados con AFR procedente de RCDs. Por ello, se requiere llevar a cabo un estudio que permita, por un lado, determinar la dosificación más efectiva, que permita la viabilidad técnica de morteros de albañilería de clase M5 fabricados con la mayor incorporación de AFR y la proporción de cemento determinada por el fabricante (10% sobre la masa seca total), además de analizar los impactos ambientales derivados de su aplicación. Para ello, es necesaria la evaluación de diferentes dosificaciones que permitan conocer cómo influye la variabilidad de la relación a/c, la cantidad de AFR y de AIAP en las propiedades de los morteros de albañilería, en estado fresco y en estado endurecido.

3. Objetivos

Por todo lo anterior, se justifica la necesidad de evaluar el uso de AFR en aplicaciones que no presenten limitaciones de uso como los morteros de albañilería y cuantificar los impactos ambientales asociados. Por tanto, resulta primordial la evaluación de diferentes dosificaciones que permitan obtener morteros técnicamente y ambientalmente viables con el máximo aprovechamiento de estos materiales reciclados. Se busca así reducir el consumo de AN, incrementar el reciclaje de estos residuos manteniendo su valor, y contribuir así a cerrar el círculo en el marco de una economía circular.

En consecuencia, el **objetivo principal** que se plantea en este trabajo es el estudio de la viabilidad técnica y ambiental de la utilización de AFR procedentes de RCDs para su aplicación en morteros de albañilería.

Para alcanzar este objetivo principal, es necesario desarrollar los siguientes **objetivos secundarios**:

1. Estudio de la viabilidad técnica:
    - 1.1. Evaluación de diferentes métodos de compensación de agua para determinar su efectividad sobre las propiedades de los morteros de albañilería.
    - 1.2. Estudio de los efectos que pueden causar la variabilidad de la relación a/c, el AFR y el aditivo inclusor de aire/plastificante en las propiedades de los morteros de albañilería, así como la determinación de las dosificaciones que satisfagan los requerimientos técnicos.
2. Estudio de la viabilidad ambiental:
    - 2.1. Desarrollo del inventario para la aplicación del ACV de los morteros de albañilería.
    - 2.2. Cuantificación de los impactos ambientales asociados a los morteros de albañilería fabricados con AFR de acuerdo al inventario desarrollado para determinar la dosificación más idónea en el cumplimiento de los requisitos ambientales.

La presente tesis queda enmarcada dentro de los objetivos establecidos en el marco legislativo comunitario mediante la Directiva de Residuos 2008/98/CE (European Parliament and Council, 2008), el paquete sobre Economía Circular presentado por la Comisión Europea en 2015 en la COM (2015) 614 (European Commission, 2015), además de la normativa nacional y autonómica constituída por la Ley 22/2011 de residuos y suelos contaminados (Jefatura del Estado, 2011) y el Plan Director Territorial de Gestión de Residuos No Peligrosos de Andalucía 2010-2019 (Consejería de Medio Ambiente, 2010), y específicamente en el Real Decreto 105/2008 por el que se regula la producción y gestión de los residuos de construcción y demolición (Ministerio de la Presidencia, 2008).

INTRODUCTION, MOTIVATION AND OBJETIVES

1. Introduction

1.1. The environmental issues of Construction and Demolition Waste

The economic growth experienced throughout the twentieth century has led to an improvement of prosperity and welfare of society, but has in turn, been driven by the intensive use of resources. Consequently, sustainable development has become the key objective of modern society, in order to meet the needs of the present without jeopardizing the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). To promote the rational use of resources and environmentally sustainable development, key measures must be established to act on the economy, society and the environment (Giddings et al., 2002; Li et al., 2015). In the European Union (EU), these measures represent the guidelines of the Europe 2020 Strategy and have also been implemented within the Sustainable Development Goals and their indicators included in the 2030 Agenda (UN, 2015).

On this, the transition to a more circular economy is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy (European Commission, 2015). The actions support the circular economy in each step of the value chain, from production to consumption, repair and remanufacturing, waste management, and secondary raw materials that are fed back into the economy (European Commission, 2018a; Niero and Kalbar, 2019). Figure 1 presents an overview of material flows in the EU economy in 2014. On the left, it shows the annual input of 8000 million tonnes (t) of materials that are transformed into energy or products, of which only 7.5% come from recycling. With regard to the output of the economy, of the 2200 million t of waste generated, only a third are reintroduced into the system as recycled materials. Regarding non-metallic minerals, of the 3500 million t that are used, 89% goes to buildings and infrastructure (stock building); in addition, 350 million t (from recycling and backfilling) are introduced as raw materials, representing 39% of the waste generated. The potential for improvement particularly lies in increasing the proportion of recycled materials as secondary raw materials and decreasing the waste generated (European Commission, 2018b).

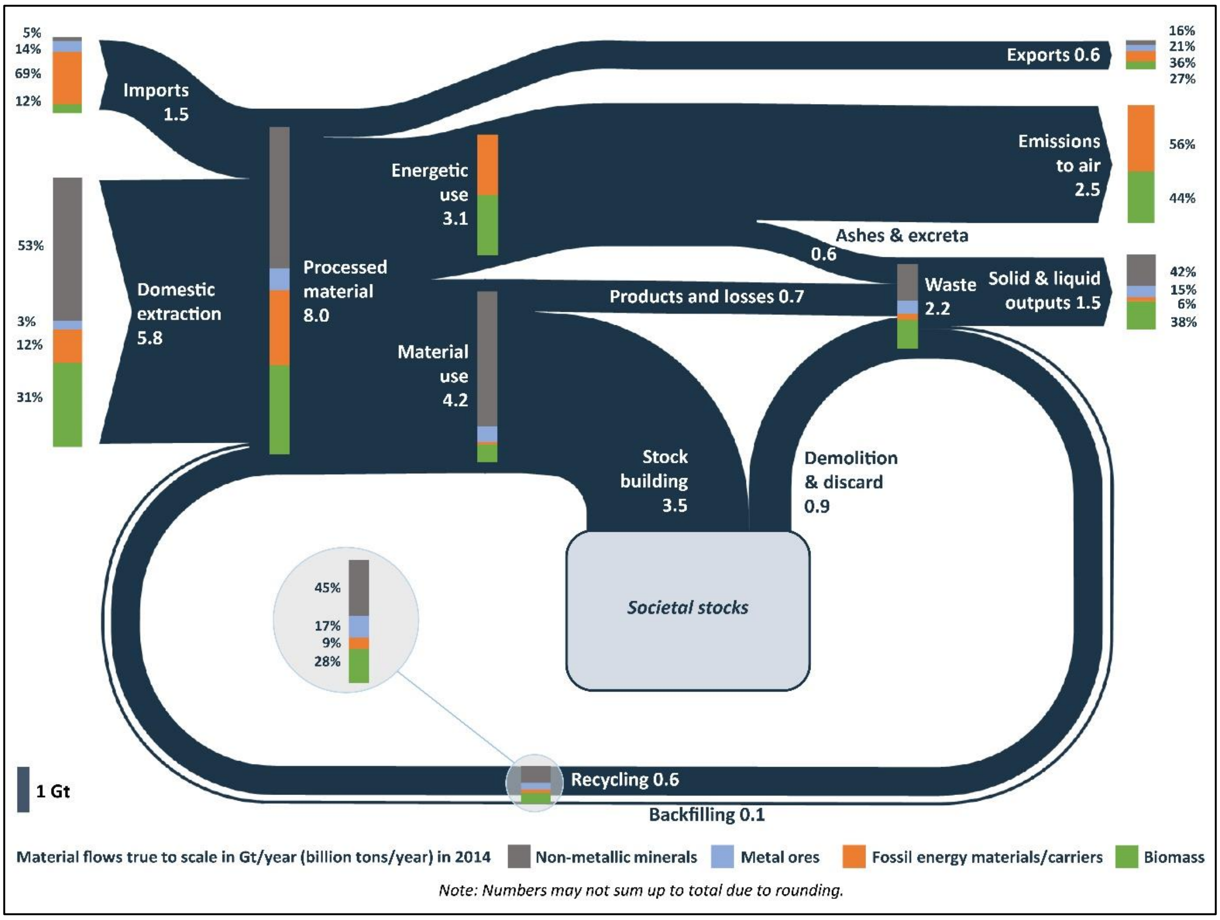


Figure 1. Material flows in the EU-28 economy in 2014 (European Commission, 2018b)

The construction sector is no stranger to the rational use of resources and to the application of actions aimed at sustainable development since it is one of the reactivating mechanisms of the economy. Moreover it is one of the most important economic areas of the EU since it generates approximately 9% of Gross Domestic Product and provides 18 million direct jobs (European Commission, 2016a). It nonetheless has a huge impact on the environment, contributing to pressures that occur at different phases of the life cycle: from the consumption of about half of natural resources during the manufacture of construction materials, the construction process itself, to the demolition and waste management generated as a result (Bovea and Powell, 2016; Carpio et al., 2016; Lizana et al., 2018). Among the most important impacts that are generated is the production of C&DW, accounting for approximately one third of all the waste generated in the EU and due to its volume, constitutes the largest waste stream in this area (European Commission, 2017a).

Taking into account the legal framework on waste at European and national level (European Parliament and Council, 2018, 2008; Jefatura del Estado, 2011; Ministerio de la Presidencia, 2008) Construction and Demolition Waste (C&DW) is defined as any substance or object generated in a construction or demolition work and of which its possessor has the intention or the obligation to dispose of. The "Real Decreto 105/2008" (Ministerio de la Presidencia, 2008) defines construction or demolition work as any activity included in the construction, rehabilitation, repair, reform or demolition of a building, road, port, airport, railway, canal , dam, sports or leisure facility, as well as any other similar civil engineering; it also includes the performance of works that modify the shape or substance of the land or subsoil, such as excavations, injections, urbanizations or other analogous ones, excluding those activities to which Directive 2006/21/EC on the management of waste from extractive industries (European Parliament and Council, 2006) is applicable. Finally, this definition also includes the waste generated in the facilities that give exclusive service to the work provided that the assembly and disassembly of these facilities takes place during the execution of the work or at the end of it, such as the ironworks, warehouses of materials, etc. The following are excluded from this consideration:

i) soils and stones not contaminated by hazardous substances reused in the same construction work, in different construction work or in restoration, conditioning or filling activities, as long as their destination for reuse can be reliably certified;
ii) waste regulated by other specific legislation, such as waste from extractive industries regulated by Directive 2006/21/EC (European Parliament and Council, 2006);
iii) waste generated in the construction products industry (ceramics, precasts, construction materials, etc.), although their characteristics are very similar to the waste generated in construction works, this waste is included in the definition of non-hazardous industrial waste.

On this point, it is necessary to note that the exclusion of uncontaminated soils and stone presents a different consideration in Directive 2008/98/EC (European Parliament and Council, 2008) and its Spanish transposition defined under the “Ley 22/2011 de residuos y suelos contaminados” (Jefatura del Estado, 2011). In this case, excavated uncontaminated soil and other natural materials excavated during construction activities are excluded, when it is certain that these materials will be used for construction purposes in their natural state in the place or construction site where they were extracted.

Given the environmental problems generated by C&DW, their management has been established as a priority area in the EU Action Plan for the Circular Economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized (European Commission, 2015). That is why the transformation of the sector towards sustainable construction is presented as an opportunity, by which the balance between respect and commitment to the environment is maintained throughout the life cycle with the efficient use of resources and materials that are not harmful to the environment, such as using construction products made of recycled materials and recycling or reusing existing materials and products, that are aimed at reducing environmental impacts since less waste is deposited in landfills (European Commission, 2014a; Kibert, 1994; López Zaldívar et al., 2016). In addition, the environmental benefit generated by the reduction of impacts can be quantified through the application of tools such as Life Cycle Assessment (LCA).

1.2. Composition and classification of C&DW

The composition of C&DW varies widely according to its place of origin, type of work or construction characteristics. Generally, it is composed of waste from concrete, bricks or ceramic materials that mainly make up the mineral fraction; the remainder being variable amounts of metal, glass, plastic, wood or excavated soil waste (Figure 2).

Most C&DW is codified in Chapter 17 of the European List of Waste (LoW), published in the annex to Decisión 2014/955/EC (European Commission, 2014b) which amends Decision 2000/532/EC (Commission of the European Communities, 2000) as shown in Table 1. This has its equivalence with the European Waste Classification for Statistics nomenclature EWC-Stat/Rev. 4 established in Regulation (UE) Nº 849/2010 (European Commission, 2010b) which amends Regulation (CE) Nº 2150/2002 (European Parliament and Council, 2002) on waste statistics. The coding of C&DW, in accordance with the LoW, allows their classification as non-hazardous and particularly inert (Blengini and Garbarino, 2010; Mercante et al., 2012), a except for a small proportion classified as hazardous.

Inert waste is a non-hazardous waste that does not undergo significant physical, chemical or biological changes, is not soluble or combustible, does not react physically or chemically or in any other way, is not biodegradable and does not adversely affect other materials with which it enters contact in a way that could lead to environmental contamination or harm to human health. In this case, the total leachability, the pollutant content of the waste and the ecotoxicity of the leachate should be insignificant; in particular, it should not pose a risk to the quality of surface or groundwater (Ministerio de la Presidencia, 2008). In that case where the waste contains substances with any of the hazardous characteristics listed in Annex III of the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008), it will be considered hazardous [2].

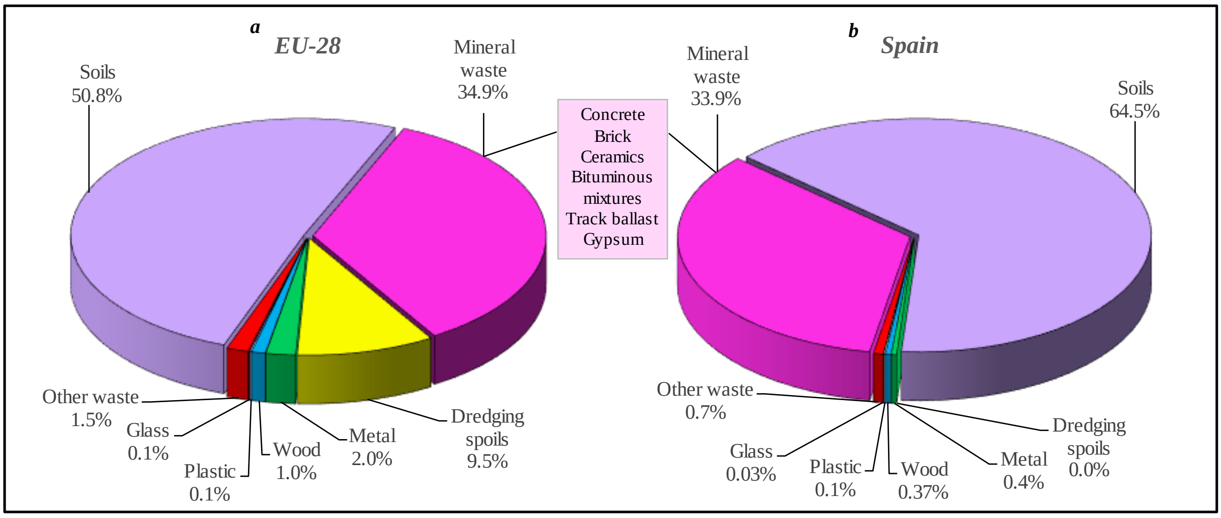


Figure 2. Composition of C&DW in the EU-28 (a) and in Spain (b) in 2016 (Eurostat, 2019)

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[2] Among substances with any of the hazardous characteristics listed in Annex III of the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008) are those included in the EU Construction & Demolition Waste Management Protocol (European Commission, 2016b): contaminated soil and dredging spoil, materials and substances that may include adhesives, sealants and mastic (flammable, toxic or irritant), tar (toxic, carcinogenic), asbestos-based materials in the form of respirable fibre (toxic, carcinogenic), wood treated with fungicides, pesticides, etc. (toxic, ecotoxic, flammable), coatings of halogenated flame retardants (ecotoxic, toxic, carcinogenic), equipment with PCBs (ecotoxic, carcinogenic), mercury lighting (toxic, ecotoxic), systems with CFCs, insulation containing CFCs, containers for hazardous substances (solvents, paints, adhesives, etc.) and the packaging of likely contaminated waste.

Table 1. Chapter 17 of European LoW and equivalence with EWC-Stat/Revision 4 (non-hazardous waste)

Chapter 17 European LoW (European Commission, 2014b)	EWC-Stat/ Version 4 (European Commission, 2010b)	Construction and demolition wastes. Definition
17 01		Concrete, bricks, tiles and ceramics
17 01 01	12.1 (12.11)/MW [a]	Concrete
17 01 02	12.1 (12.11)/MW [a]	Bricks
17 01 03	12.1 (12.11)/MW [a]	Tiles and ceramics
17 01 07	12.1 (12.11)/MW [a]	Mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02		Wood, glass and plastic
17 02 01	7.5 (7.53)	Wood
17 02 02	7.1 (7.12)	Glass
17 02 03	7.4 (7.42)	Plastic
17 03		Bituminous mixtures, coal tar and tarred products
17 03 02	12.1 (12.12)/MW [a]	Bituminous mixtures other than those mentioned in 17 03 01
17 04		Metals (including their alloys)
17 04 01	6.2 (6.24)	Copper, bronze, brass
17 04 02	6.2 (6.23)	Aluminium
17 04 03	6.2 (6.25)	Lead
17 04 04	6.2 (6.25)	Zinc
17 04 05	6.1	Iron and Steel
17 04 06	6.2 (6.25)	Tin
17 04 07	6.3 (6.32)	Mixed metals
17 04 11	6.2 (6.25)	Cables other than those mentioned in 17 04 10
17 05		Soil (including excavated soil from contaminated sites), stones and dredging spoil[b]
17 05 04	12.6	Soil and stones other than those mentioned in 17 05 03
17 05 06	12.7	Dredging spoil other than those mentioned in 17 05 05
17 05 08	12.1 (12.11)/MW [a]	Track ballast other than those mentioned in 17 05 07
17 06		Insulation materials and asbestos-containing construction materials
17 06 04	12.1 (12.13)/MW [a]	Insulation materials other than those mentioned in 17 06 01 y 17 06 03
17 08		Gypsum-based construction material
17 08 02	12.1 (12.11)/MW [a]	Gypsum-based construction materials other than those mentioned in 17 08 01
17 09		Other construction and demolition wastes
17 09 04	12.1 (12.13)/MW [a]	Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

MW[a]: Mineral waste from construction and demolition; [b] Not taken into account for targets of compliance

1.3. Generation of C&DW

In 2016, 923 million t of C&DW (hazardous and non-hazardous) were generated in the EU, according to the data provided by Eurostat (Eurostat, 2018a) and listed in Table 2. It can be seen that the countries with the highest production were France (24.3%), Germany (23.9%) and the United Kingdom (14.7%), while Spain ranked seventh with 3.9% (35 million t). Regarding the composition, the mineral fraction of these waste (category 12.1 of EWC-Stat/Rev. 4) represented 34.9% as the average value of the EU-28, but it varied widely among the different countries. Thus, in Spain it constituted 33.9%, while for Malta and Latvia it was 96.4% and 6.3%. in Bulgaria. The majority of this waste was classified as non-hazardous, with percentages ranging between 88.4% and 100%.

Figure 3 shows the composition of the non-hazardous C&DW generated in the EU-28 in 2016 (Eurostat, 2018a). The composition differences of C&DW that can be observed between the countries is produced by the diversification of the constructive habits, the availability of the components' raw materials, as well as the time in which the construction was carried out (Bustillo Revuelta, 2010). However, the fraction of non-hazardous C&DW generated is mostly made up of soils (51.5%), followed by mineral fraction (35%), dredging spoil (11%) and the remaining 3% being the sum of metal, glass, plastic and wood (Figure 3a). Soils are the main component in sixteen countries with percentages higher than 50% in thirteen of them; Luxembourg stands out with 93%. As for the rest of the countries, the mineral fraction (category 12.1) was predominant in ten countries along with dredging spoil in Bulgaria and the Netherlands. In the case of Spain, soils reached 65% followed by the mineral fraction (34%) and the remaining 1% was for the other components.

If the uncontaminated soils are excluded (Figure 3b), the composition of C&DW in the EU-28 is mainly structured in mineral waste (71%), dredging spoil (23%), metal (4%), and finally, wood, glass, and plastic (2%). The mineral fraction makes up the main percentage in all countries except for Bulgaria and the Netherlands, where dredging spoil is predominant. Likewise, in Spain the highest percentage corresponds to the mineral fraction (97.4%), and to a lesser extent to wood, glass and plastic waste (1.5%), and metal (1.1%).

Table 2. Quantity of C&DW (hazardous and non-hazardous) generated in the EU-28 in 2016) (Eurostat, 2018a)

Country	*Total C&DW (t)*	*(%)*[a]	*Mineral waste from C&D*			
			Hazardous and non-hazardous (t)	*(%)*[b]	*Non-hazardous (t)*	*(%)*[c]
EU-28	923,910,000	100.0	322,570,000	34.9	313,110,000	97.1
France	224,355,946	24.3	60,245,692	26.9	59,101,518	98.1
Germany	220,499,432	23.9	86,379,764	39.2	80,967,723	93.7
U. Kingdom	136,196,492	14.7	63,525,298	46.6	63,046,541	99.2
Netherlands	98,551,957	10.7	19,267,996	19.6	17,570,661	91.2
Italy	54,576,762	5.9	34,916,038	64.0	34,804,036	99.7
Austria*	40,265,570	4.4	8,947,894	22.2	8,933,873	99.8
Spain	35,827,923	3.9	12,156,104	33.9	12,116,802	99.7
Belgium	19,573,150	2.1	15,818,121	80.8	15,769,321	99.7
Poland	18,890,577	2.0	2,471,974	13.1	2,435,829	98.5
Finland	13,825,168	1.5	1,315,581	9.5	1,267,270	96.3
Denmark	12,224,799	1.3	3,460,195	28.3	3,357,696	97.0
Czechia	10,141,985	1.10	2,803,748	27.6	2,741,527	97.8
Sweden	9,810,987	1.06	2,552,319	26.0	2,368,147	92.8
Luxembourg	7,614,894	0.8	545,329	7.2	482,124	88.4
Hungary	3,591,612	0.4	1,959,136	54.5	1,957,445	99.9
Bulgaria	2,089,131	0.23	131,450	6.3	131,450	100.0
Ireland*	1,884,390	0.20	133,312	7.1	130,677	98.0
Portugal	1,710,703	0.19	888,356	51.9	887,793	99.9
Malta	1,354,892	0.15	1,305,818	96.4	1,305,818	100.0
Croatia	1,291,506	0.14	561,037	43.4	554,247	98.8
Estonia	1,173,517	0.13	485,489	41.4	484,982	99.9
Slovakia	967,275	0.10	297,323	30.7	297,159	99.9
Cyprus	876,525	0.09	325,399	37.1	325,399	100.0
Slovenia	541,574	0.06	160,940	29.7	160,920	100.0
Lithuania	505,758	0.05	445,837	88.2	445,720	100.0
Greece*	479,999	0.05	355,171	74.0	355,171	100.0
Romania	323,461	0.04	172,998	53.5	172,981	100.0
Latvia	111,133	0.01	107,095	96.4	107,095	100.0

[a] Percentage of C&DW in relation to the EU total; [b] Percentage of the mineral fraction in relation to total C&DW of the country; [c] Percentage of the mineral fraction in non-harzardous C&DW in relation to the total mineral fraction; * 2014 Data.

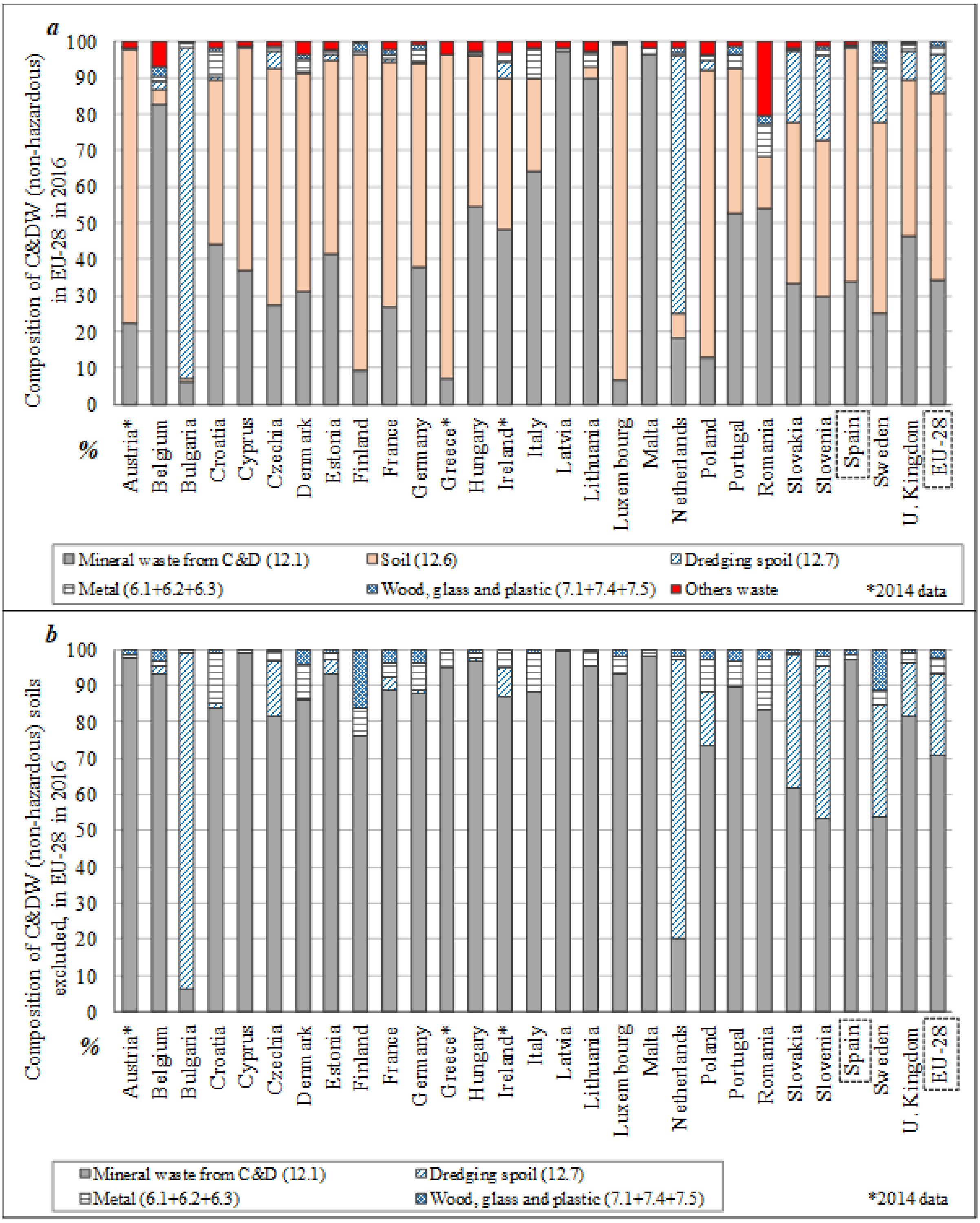

Figure 3. Composition of non-hazardous C&DW in the EU-28 in 2016 (Categories EWC-Stat/Rev. 4)
(Eurostat, 2018a)

1.4. Management

Waste management means the collection, transport, recovery (including sorting), and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker (European Parliament and Council, 2018). The inadequate management of waste causes major environmental problems, so it is essential to plan and implement measures that favor appropriate practices in all phases of management. Consequently, since the European Community established in 1975 the first Directive on waste 75/442/EEC (Council of the European Communities, 1975), the objective of EU waste management policies has been to reduce the impact on the environment and health, thus improving the efficiency in the use of resources (de la Hoz-Torres et al., 2018; European Commission, 2011). Currently, the principle of hierarchy is incorporated by the regulatory framework established in the EU with the Directive on waste 2008/98/EC (European Parliament and Council, 2008), its amendment with Directive (EU) 2018/851 (European Parliament and Council, 2018) and its transposition to the Spanish legal framework through “Ley 22/2011 de residuos y suelos contaminados” (Jefatura del Estado, 2011). Thus, the order of priority in the production and management of waste should go as follows: firstly focus on prevention (avoiding the generation of waste and its impact), preparing for reuse (reuse the waste), recycling (introduce the waste into the productive cycle), other types of recovery (including backfilling or energy recovery operations) and, lastly, disposal.

The long-term objective of these policies has been to reduce the amount of waste generated and, when the generation of waste is unavoidable, to promote waste as a resource and achieve higher levels of its recycling and safe disposal. Thus, the proposed measures related to the prevention and management of waste will contribute to achieving the target of the Directive on waste 2008/98/CE (European Parliament and Council, 2008) to increase the preparation for the reuse, recycling and other recovery of waste materials to a minimum of 70% by weight of non-hazardous C&DW by 2020, thus closing the life cycle of the products by increasing recycling and reuse; this does not include material in its natural state as defined in LoW category 17 05 04.

Consequently, waste management plays a crucial role in the circular economy, since it determines the way in which EU waste hierarchy is put into practice. Following the adoption by the European Commission of the Action Plan for the Circular Economy (European

Commission, 2015) a specific strategy has been established that outlines measures that cover the entire life cycle of the product: from production and consumption to management of waste and the market of secondary raw materials. In this sense, it is possible to monitor and evaluate the progress made to achieve the objectives set in C&DW management via the recovery rate. This circular economy indicator is comprised of the mineral fraction of non-hazardous C&DW (category 12.1 according to EWC-Stat / Revision 4) and indicates the proportion of C&DW prepared for re-use, recycled or subject to material recovery, including backfilling operations.

Figure 4 shows the management treatments applied to the non-hazardous C&DW mineral fraction (Eurostat, 2018b) and the recovery rate (Eurostat, 2018c) for the EU-28 countries in 2016. As can be seen, the value of the recovery rate in the EU was 90%, a value that was reached or exceeded by eighteen Member States. In six countries the recovery rate was between 70% and 90%, where Spain had a value of 78%. Similarly, the C&DW recovery target of 70% established for 2020 was not achieved by four countries (Greece, Cyprus, Slovakia and Sweden).

Regarding the treatments applied (Figure 4), of the total mineral C&DW treated in EU-28, 84% was recycled, 6% was used as backfilling, and around 10% was eliminated. In Spain, 9 million t were processed by authorized waste managers (treatment plants and / or landfills), of which 71% was recycled, 8% was used for backfilling, and the remaining 21% was landfilled. Likewise, the main management treatment carried out in the EU countries was recycling, with values higher than 50% in twenty-three Member States; over 95% in Holland, Slovenia, Italy, Belgium and the United Kingdom. Disposal of waste was the main option for Greece (100%), and with percentages higher than 40% in Slovakia (46%) and Cyprus (43%). And, energy recovery was used to a lesser extent, in Sweden (15%), Finland (10%) and Denmark (6%).

Finally, in the case of the use of C&DW for backfilling, it was higher than 50% in Malta, Portugal and Ireland, with values between 20% and 40% in seven Member States. According to the latest amendment to the Directive on Waste 2008/98/EC (European Parliament and Council, 2008) by Directive (EU) 2018/851 (European Parliament and Council, 2018), this practice does not entail maintaining the value of materials in the economy so it does not contribute to a circular economy. Consequently, it will be necessary to establish new regulations so as to calculate the attainment of the recycling targets; therefore, the moment that the latter

Directive comes into effect, the materials used for backfilling shall not be counted for these purposes.

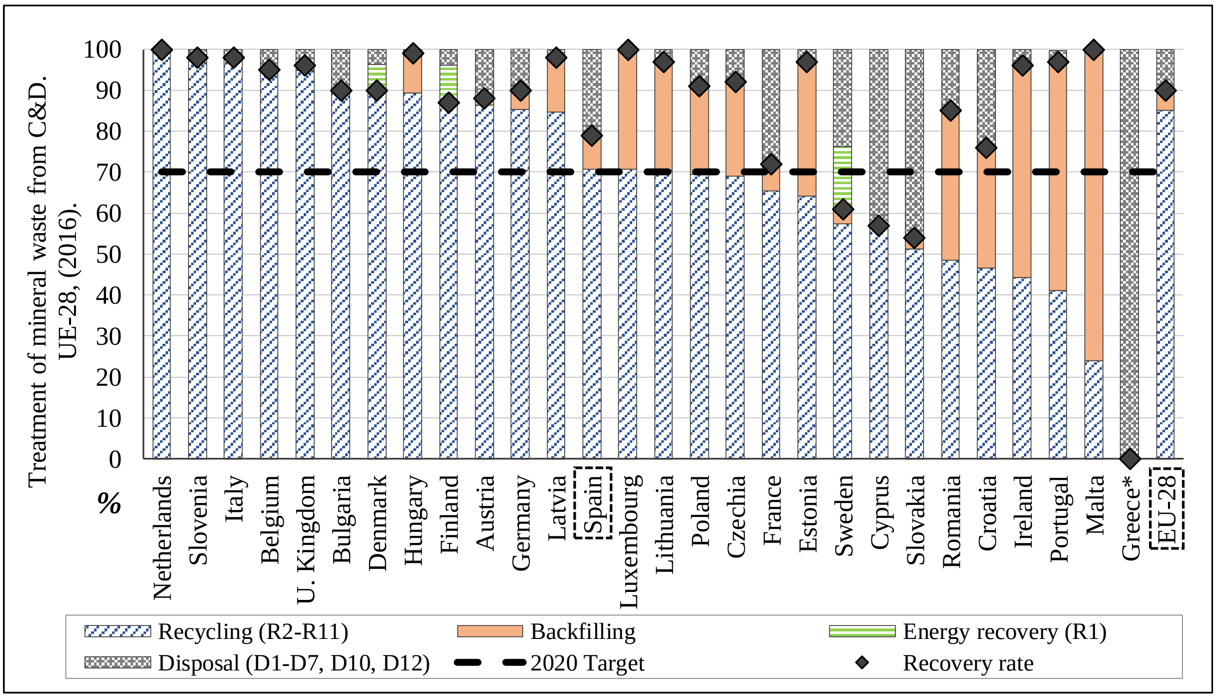

Figure 4. Recovery rate and treatment of C&DW mineral fraction the EU-28 in 2016 (Eurostat, 2018c, 2018b)

1.5. Uses and limitations of RA

Aggregates are the main raw material supplied for the construction of infrastructures or buildings. They are used in the manufacture of concrete, precast, mortar, asphalt agglomerates, bases and sub-bases of roads, railway ballast, etc., which can constitute up to 95% of the composition of these materials (ANEFA, 2018). The high demand for this raw material has caused it to be included for evaluation in the third list of Critical Raw Materials (European Commission, 2017b). The results indicate that these materials should continue to be evaluated in the future to determine their criticality according to their economic importance and supply risk.

In this sense, the use of secondary raw materials is a key part of the circular economy, as recycled materials replace extraction of natural resources. Nonetheless, the contribution of recycled materials to the global demand for raw materials is still relatively small. In 2016, demand for aggregates amounted to 2.7 billion t in Europe (UEPG, 2017). However, according to the monitoring framework for the circular economy and the key indicators for secondary raw materials (European Commission, 2018c, 2018b) the contribution of recycled aggregate (RA) to natural aggregate (NA) demand was from 8%, determined by the 'end-of-life recycling input rate' (EOL-RIR) (Eurostat, 2018d; UEPG, 2017). Specifically, in Spain, the demand for aggregates for construction activities was 96.6 million t, of which only 1% consisted of RA (ANEFA, 2017).

To close loops of the circular economy, materials and products need to ultimately be reinjected in the economy. However, the use of RA in construction is still very scarce, since it presents a series of obstacles. Mistrust regarding the quality of recycled materials, the absence of standards and technical prescriptions specific to RA, and the low prices of natural raw materials due to their abundance mean that secondary raw materials from C&DW recycling do not have sufficient demand (Calvo et al., 2014; Rodríguez et al., 2015). Proper management of C&DW and recycled materials, that can be achieved by separating waste streams and appropriately handling hazardous waste, along with promotion from public administrations can bring great benefits, not just in terms of sustainability and quality of life, but also to the EU construction and demolition sector as a whole.

In this regard, the European Commission has recently published several documents that can boost the demand for RA from C&DW, such as the "EU Construction and Demolition Waste Management Protocol" (European Commission, 2016b), the "Guidelines for the waste audits before demolition and renovation works of buildings" (European Commission, 2018d) and the "Green Public Procurement Criteria in the construction sector relating to office buildings and road" (European Commission, 2018e). These documents are part of the Construction Strategy 2020 (European Commission, 2012), the Communication on Resource Efficiency Opportunities in the Building Sector (European Commission, 2014a) and is also part of the Action Plan for the Circular Economy presented by the European Commission in 2015 (European Commission, 2015).

The RA has a greater water absorption capacity than the NA, as a consequence of the mortar that remains adhered to the concrete RA and the greater porosity of the ceramic material in the case of ceramic RA (Debieb and Kenai, 2008; Evangelista and de Brito, 2007; Rodríguez Robles, 2016). In addition, the water absorption capacity of the fine fraction (0/4 mm) of the RA is even greater (Barbudo et al., 2012; Corinaldesi and Moriconi, 2009). This situation has an important influence on the properties in fresh and hardened states of concretes and mortars, since the available mixing water is reduced to hydrate the mixture of aggregate and cement, causing the reduction in the workability and the value of the consistency, as well as mechanical strength (Bektas et al., 2009; Pereira et al., 2012a). To solve this problem, numerous investigations have been carried out with different methods of water compensation, their effect on the development of properties in fresh and hardened states of concrete or mortar has also been evaluated. One way to reduce the water absorption capacity of the RA is to increase the amount of mixing water (Corinaldesi and Moriconi, 2009; Jiménez et al., 2013; Leite et al., 2013). Leite et al., (2013) took as reference RA water absorption capacity (WA_{24h}) and they concluded that in the case of recycled concrete an index of between 80% and 90% would be satisfactory for both workability and compressive strength. Other authors pre-soaked RA before kneading and keeping mixing water (Barra de Oliveira and Vazquez, 1996; Etxeberria et al., 2007; Miranda et al., 2014; Poon et al., 2004). They concluded that at total compensation index (100%) of RA WA_{24h}, the compressive strength decreased because the mechanical bonding between the cement paste and the RA is weakened. However, the use of pre-soaked RA with 80% of WA_{24h} obtains an efficient interfacial transition zone thus improving performance. Finally, without increasing the mixing water, optimum levels of workability were achieved with the use of plasticizing admixture in manufactures concrete with partial replacements of natural fine aggregate (NFA) with RFA: these meet the requirements established for structural concrete (Pereira et al., 2012a; Zega and Di Maio, 2011).

As a consequence of the observed limitations, numerous investigations have been carried out in order to evaluate the use of RA arising from the treatment of C&DW as a replacement for NA. These include the incorporation of RA in the manufacture of structural concrete (Eckert and Oliveira, 2017; Etxeberria et al., 2007; Frondistou-Yannas, 1977; Hansen and Narud, 1983; Tošić et al., 2015), non structural concrete (Hossain et al., 2016a; Sánchez-Roldán et al., 2016; Soutsos et al., 2011), road construction (Jiménez et al., 2012; Martín-Morales et al., 2013a; Mroueh et al., 2001; Poon and Chan, 2006; Vegas et al., 2011), masonry mortar production (Bektas et al., 2009; Corinaldesi and Moriconi, 2009b; Fernández-Ledesma et al., 2016; Jiménez et al., 2013) or as extensive green roof substrate material (López-Uceda et al., 2018; Mickovski et al., 2013; Molineux et al., 2015). In addition, in recent years the incorporation of RFA has been evaluated in different applications with satisfactory results, such as concrete manufacturing (Bravo et al., 2017; Pereira et al., 2012b; Zega and Di Maio, 2011), brick manufacturing (Ismail and Yaacob, 2010), precast concrete hollow blocks (Martín-Morales et al., 2017), asphalt mixture (Chen et al., 2011) and masonry mortars (Corinaldesi et al., 2002; de Oliveira Andrade et al., 2018; Martínez et al., 2013; Vegas et al., 2009).

Although such studies have shown the possibility to widen the application range of RA and increase possibilities for assessment and recycling of C&DW, the incorporation of RA is conditioned by the technical specifications in force in the country of application (Martín-Morales et al., 2013c). In the case of Spain, the “Instrucción de Hormigón Estructural EHE-08” (Ministerio de Fomento, 2008) allows for a 20% replacement of NA by coarse RA from concrete waste; this being for the manufacture of structural concrete. Moreover, even 100% is allowed in the case of non-structural concrete however the use of RFA is prohibited. In this way, the fine fraction of RA is underutilized, and in most cases, it is deposited in landfill or stored in recycling plants (Torres-Gómez et al., 2016). In the case of road pavement layers construction, the “Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3)” (Ministerio de Fomento, 2015) allows the following as use for RA: gravel for granular pavement foundations, recycled soils, drainage material, soil-cement, graveling for road surfaces and coarse aggregate for roller compacted structural/non-structural concrete. Nonetheless, there are other types of applications that require less technical demands in which their use is contemplated. This is the case of the Standard EN 13.139: “Aggregates for mortar” (CEN, 2002a), which allows the incorporation of RA without restrictions, for which the manufacture of masonry mortars constitutes a potential use for these aggregates.

1.6. LCA as a tool to determine the environmental feasibility of RA

LCA is an impartial process that allows us to evaluate the environmental burdens associated with a product, process and activity. It lets us identify and quantify the use of matter, energy and environmental emissions in order to determine the impact of using such resources and their emissions: this is done to evaluate and implement environmental improvement strategies (Righi et al., 2018). It includes the complete cycle of the product, process or activity, taking into account the stages of extraction and processing of raw materials, production, transport and distribution, use, reuse, maintenance, recycling and final disposal.

The beginnings of the LCA can be traced back to the 1970's, where Hunt et al. (1974) presented their study findings as resource and emission profiles. Despite this, they did not carry out the quantitative analysis of the associated impacts on the resources and environment. The first methods for assessment of environmental impacts in LCA were published in the early 1990s with prominent examples as the Swiss Ecoscarcity (or Ecopoints) methodology (Ahbe et al., 1990) and the CML 1992 methodology (Heijungs et al., 1992). Likewise, in 1993 the standardization process for LCA under the International Organization for Standardization was initiated and peaked in 2006 with the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards that constitute the current regulatory framework. Specific projects were simultaneously initiated in several countries to develop methodologies for the life cycle impact assessment: i) midpoint methods such as EDIP (Wenzel et al., 1997) and CML 2002 (Guinée et al., 2002); ii) endpoint methods such as Ecoindicator 99 (Goedkoop and Spriensma, 2000) and EPS (Steen, 1999); or iii) methods that combine midpoint and endpoint approaches, such as IMPACT 2002+ (Jolliet et al., 2003), LIME (Itsubo et al., 2004) and ReCiPe (Goedkoop et al., 2009).

Currently, the LCA methodology based on ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), together with ISO 15804 (CEN, 2013a) establish the regulatory framework to evaluate and quantify environmental impacts of materials and construction products. The information based on LCA can only cover the product stage (supply of raw materials, transport and manufacturing), i.e. "cradle to gate" (Colangelo et al., 2018; Densley Tingley et al., 2015). Whereas the complete life cycle of a product according to the limits of the system (stage of product, construction, use and end of life) is called "cradle to grave" (Bueno et al., 2016; Pini et al., 2014).

The use of RA can increase the efficiency in the use of resources, as well as boost the market of secondary raw materials by introducing waste as resources. In this way, the consumption of natural resources and the disposal of waste in landfills is reduced, which translates into environmental benefits. In this context, a real evaluation of the environmental benefits requires the use of tools that accurately quantify such benefits; for example, the LCA that is not only being used in the construction sector to determine management strategies of C&DW that provide the best environmental outcome, but also for the design of more sustainable building materials (Ding, 2014; Fernández-García et al., 2016).

LCA has been employed in various studies to develop and analyse a life cycle inventory of C&DW management systems including all stages of building construction waste (including transportation, sorting, public fill or landfill disposal, recovery and reuse, and transformation and valorization into secondary products) in different settings such as Spain (Mercante et al., 2012; Ortiz et al., 2010), Brazil (Penteado and Rosado, 2016) or Hong Kong (Hossain et al., 2017), among others.The results obtained showed that prevention measures generated the lowest environmental impacts; thus the reduction of 60% in the amount of C&DW generated would have also meant a reduction of at least 60% in all of the categories analyzed in Bizcocho and Llatas (2018). Furthermore, it was observed that in terms of the Global Warming Potential, the most environmentally friendly treatment was recycling, followed by incineration and lastly landfilling, although the environmental benefits mainly depend on the waste compositions, their sortability as well as the use of off-site or on-site sorting. According to the influence of treatment plants location, incineration and recycling of construction waste were better than landfilling. These results are aligned with the principle of the waste management hierarchy (prevention, preparation for re-use, recycling and recovery of energy until disposal (landfill) as established in the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008). From the point of view of transport distances, Blengini and Garbarino (2010) applied LCA methodology to identify and quantify energy and environmental loads, under different assumptions relevant to delivery distances, quality of RA, local availability of NA and geographical coverage of market demand. It was estimated that the transportation distance of RA should increase 2–3 times before the induced impacts outweigh the avoided impacts. Furthermore, Penteado and Rosado (2016) estimated the optimal distance between the generation source and the recycling unit in within 30 km.

In addition, environmental burdens generated during RA production coming from C&DW were assessed and compared to those impacts caused by NA production. Simion et al. (2013) showed that the recycling process generated lower environmental impact compared to that resulted from the NA processing, and highlighted the need for on-site sorting to ensure the efficiency of the process. In the same way, Hossain et al. (2016b) concluded that it is possible to further reduce environmental impacts through the effective design of waste collection and transport system for RA production. And Faleschini et al. (2016) remarked that the environmental impacts of RA in a life cycle perspective should take into account site-specific indicators, which can capture the impacts of processing and supplying activities at local scale, such as land use and natural resources consumption avoidance, through the quarry exhaustion time.

Eventually, the impacts associated with the use of RFA as a replacement for NFA were analysed for different applications in construction such as concrete production (Knoeri et al., 2013; Turk et al., 2015; Yazdanbakhsh et al., 2017), road construction (Butera et al., 2015; Mroueh et al., 2001) and concrete blocks production (Hossain et al., 2016a). Overall results showed that in all cases recycled material generates lower environmental impact that its equivalent primary material. In this sense, Yazdanbakhsh et al. (2017) concluded that the benefits are the highest when old concrete is recycled in the demolition site by mobile facilities, and use for construction at the same site. Knoeri et al. (2013), Turk et al. (2015), Butera et al. (2015) and Mroueh et al. (2001), highlight that the transportation distance and the type of transport are key parameters to maintain environmental benefits. Hossain et al. (2016a) remark that it is necessary to strengthen the policy and the market for recycled products to encourage a resourceful treatment of waste, as well as sustainable constructions.

2. Motivation

2.1. Masonry mortar. Definition and classification

Mortar is defined as the mixture of one or several inorganic binders (cement, lime or gypsum), aggregates, water and sometimes additions and/or admixtures (European Mortar Industry Organisation, 2013). It is as old as human civilization, given that the first application of mortar in history dates back about 10000 BC years to Neolithic culture, in which lime mortars were used for the construction of pavements (Álvarez Galindo et al., 1995). Later on, gypsum was first used by the Egyptians to join the blocks during the construction of the Great Pyramid of Giza For their part, the Greeks innovated lime mortars by adding pozzolanic materials to increase strength and stability, and the Romans improved the lime manufacturing processes as well as mortar application (Álvarez Galindo et al., 1995). During the Middle Ages there was no notable technical progress in the evolution of mortars, but the discovery of cement in the nineteenth century and its use as a binder marks the breakthrough of modern mortars; thus achieving high resistance, a slower hardening and greater hydraulics (Alejandre Sánchez, 2002). Currently, the industry of mortars in Europe produces more than one hundred types of mortars, which come in different forms that offer properties and consist of physical, chemical and mechanical characteristics specially adapted to various kinds of building and civil engineering works (European Mortar Industry Organisation, 2013).

The wide variety of applications of mortars allows for several groups to be structured (AFAM, 2018): i) mortars for masonry and rendering/plastering; ii) technical mortars (floor mortars), repair mortars and waterproofing mortars; and iii) other mortars such as cementitious adhesives for ceramic tiles, mortars for screeds and floor finishes, and grouting materials for ceramic tiles.

According to the data published in Spain in “Análisis Sectorial de Morteros” (AFAM, 2012), in 2011 approximately 18 million t of mortar were produced: 11 million t (60%) corresponded to site-made mortars and 7 million t (40%) for factory-made mortars. The production of mortar for masonry (rendering/plastering and masonry) amounted to 6 million t, covering 85% of the production of factory-made mortar that was supplied in the form of wet mortar (50%) and as dry mortar (35%). The remaining 15% (1 million t) corresponded to the production of technical or special mortars. As for the destination of the mortar production, it was mainly directed at; reform, rehabilitation and restoration works (58%), housing (16%), civil works (15%) and non-residential buildings (11%). These figures show how masonry mortar is one of the most used construction products in the construction sector.

The requirements for mortars for masonry are established in the Standard EN 998-1: “Specifications for mortar for masonry. Part 1: Rendering and plastering mortar” (CEN, 2010) and in the Standard EN 998-2: “Specifications for mortar for masonry. Part 2: Masonry mortar” (CEN, 2012a). As the term '"mortar for masonry" also includes mortars for rendering and plastering, to avoid confusion, the term "masonry mortar" will be used in this document in reference to the mortars included in Standard EN 998-2: “Specifications for mortar for masonry. Part 2: Masonry mortar” (CEN, 2012a). The main difference between both groups lies in their applications. Mortars for rendering and plastering are used in outdoors and indoors respectively (CEN, 2010). Their application is done on external surfaces of another element or construction system (walls, ceilings, etc) in order to cover it, be it for functional reasons (the protection of the facade of external agents) or simply aesthetic (finishing according to its texture, color, cutting, etc.) (AFAM, 2018). Masonry mortars are used to place, join and grout pieces of brick, concrete blocks or stone for the execution of masonry, which may be structural in character (loading wall, foundation, etc.) or have an enclosure/separation function (facade, partition, etc.) (AFAM, 2018; CEN, 2012a).

According to Standard EN 998-2 (CEN, 2012a), mortars for masonry can be classified by the concept (designed or prescribed), according to location of finished manufacture (factory-made, semi-finished, site-made, etc.) and for its properties and use (for general purpose-G, light-L, or for joints and thin layers-T).

2.1.1. Components

The Standard EN 998-2 (CEN, 2010) relates with masonry mortar components, which are the following:

- Aggregate. It constitutes 90% of the masonry mortar dosage, being the most important component in weight. The requirements outlined on aggregates for the manufacture of mortars are established in the Standard EN 13139: “Aggregates for mortars” (CEN, 2002a). This regulation defines aggregate as the granular material used in construction and classifies it according to its origin in: i) NA (granular or crushed) of mineral origin obtained only by mechanical procedures; ii) artificial aggregate of mineral origin resulting from an industrial process that includes thermal or other modification; iii) RA resulting from the treatment of inorganic material previously used in construction. The NA can be limestone, siliceous or dolomite like the one used in this study. Specifically, in Spain 63% of dolomite production was supplied as aggregates for construction and public works, mainly for the manufacture of concrete, mortar and precast (78.3%), for use on roads (20.3%) and in the formation of seawalls (1.4%). In Andalusia, dolomite production reached 82.7% of national production, and 32% in the province of Granada (Ministerio de Energía Turismo y Agenda Digital, 2018).

- Binder. Together with aggregates, is the most important component of mortars since it allows solid particles to be joined in such a way that they form a coherent mass. Any inorganic binder (cement, lime and gypsum) can be used as long as they meet the established requirements, although cement is the most commonly used since it has a higher resistances and hardening speed (Bustillo Revuelta, 2008; Rodríguez-Mora, 2003). The cement is regulated by the Standards RC-16: “Instrucción para la recepción de cementos” (Ministerio de la Presidencia, 2016), EN 413-1: “Masonry cement. Part 1: Composition, specification and conformity criteria” (CEN, 2011) and EN 413-2: “Masonry cement. Part 2: Test methods” (CEN, 2016).

- Admixture. It is a material added in small quantities to modify certain properties of the mortar. They must meet the requirements of the Standards: EN 934-1: “Admixtures for concrete, mortar and grout. Part 1: Common requirements” (CEN, 2009a) and EN 934-3: “Admixtures for concrete, mortar and grout. Part 3: Admixtures for masonry mortar” (CEN, 2012b). The most used are the following:
    - Air entraining/plasticizer admixture (AEPA): increases the workability or allows a reduction of the water content by incorporating a controlled amount of uniformly distributed small air bubbles during the mixing which remain retained after hardening. These admixtures cause the following effects in mortars (Rodríguez-Mora, 2003): i) they increase the plasticity of the mortar by facilitating the temporary dispersion of the cement particles; ii) decrease the apparent density of the mortar in the fresh state; iii) they interrupt the capillary network of the mortar mass preventing the penetration of water and cement hydration products, thus protecting the mass from the effect of frost. These improvements are taken into account when RA is used, since the AEPA compensates for the need to add the water that would be absorbed by them to obtain the same workability (Barra Bizinotto et al., 2017; Bravo et al., 2017; Lotfy and Al-Fayez, 2015; Vegas et al., 2009).
    - Retarder admixture. It delays the setting time of the cement to prolong the workability time of the mortar.

- Water: It is used for mortar mixing. It must be harmless in nature and not contain excess substances that could alter the properties of the mortar or cause corrosion of the steel, as is the case of sulfates or chlorides. There is no specific rule outlining the requirements that mixing water must meet, but in general, sanctioned water is usually acceptable use by practice.

2.1.2. Properties of masonry mortars

The properties of masonry mortars vary depending on the type or class although there is a group of characteristics common to the vast majority of them. These properties can be grouped into two categories: i) in a fresh state where they directly affect the implementation of the mortar i.e. consistency, bulk density and air content; and ii) in a hardened state where dry bulk density, mechanical strength and water absorption by capillary action will be defined by mortar behavior. Nonetheless, these properties are not independent, because the properties in the fresh state have a great influence on the final performance of the mortar.

The masonry mortar for general purpose (G) of class M5 is the most widely used in construction elements not subject to structural requirements. According to the Spanish “Código Técnico de la Edificación” (Ministerio de Fomento, 2009), the masonry may be exposed to classes I, IIa and IIb without diminishing its properties, which allows its use in the interior of buildings protected from the weather, in the exterior protected from rain and in the exterior not protected from rain, or in unventilated basements. In accordance with the dosage provided by the manufacturer, the main components of this mortar are cement (10%) and aggregate (90%) in proportions relative to the total dry mass, and water (14%). From a technical point of view, the properties required for this kind of mortar are a minimum value of compressive strength at 28 days of 5 N/mm^2, as well as a value of plastic consistency ($\geq$ 140 mm) that allows an adequate on-site application.

2.1.3. Use of RA in masony mortars

The application of RFA in masonry mortars has been the focus of study in some investigations from the end of the 20th century to present day (Álvarez-Cabrera et al., 1997; Corinaldesi and Moriconi, 2009; de Oliveira Andrade et al., 2018). Table 3 shows a comparative study of the consulted bibliography and specifies some of the most important common aspects, among them: dosage used, c/a ratio, w/c ratio, replacement of NFA by RFA, size and density of the aggregate, nature of RFA or compressive strength after 28 days. Following this, an analysis of the results obtained is made.

- Dosage used, c/a ratio, and w/c ratio. The Spanish “Código Técnico de la Edificación” (Ministerio de Fomento, 2009) determines that ordinary mortars for masonry can be specified by the value of their compressive strength or by the proportion in volume of their fundamental components. Standard 998-2 (CEN, 2012a) states that the proportion of all components of prescribed mortars must be declared by the manufacturer in volume or weight; in addition, compressive strength based on the proportions of the mixture should be indicated. Therefore, the manufacturer can establish the dosage that is considered opportune to obtain an adequate product. Currently, dosages are made by proportions referred to parts by volume, mass or percentage of total dry mass.

In the literature review, it was observed that the proportion of the components was mostly in mass (64%), and the remaining 36% in volumen. A wide variety of mortar dosages were also observed; the c/a ratio of 1:3 was the most studied (33%), while in only 4% was it used as a percentage of cement on total dry mass (Miranda and Selmo, 2006; Vegas et al., 2009).

The w/c ratio varied from 0.5 to 2.5, depending on the c/a ratio; so that as the proportion of RFA increased, more water was needed to hydrate the mixture and, consequently, the w/c ratio also increased. However, Bektas et al. (2009) and Mesbah and Buyle-Bodin (1999) maintained a constant w/c ratio of 0.5 and 0.75, respectively.

Generally, aggregates were used in a dry state, although some authors soaked them previously. Cabrera-Covarrubias et al. (2017, 2015) mixed the aggregates with water for one minute before incorporating the cement into the mixer. Martínez et al. (2018) used RFA soaked for 30 minutes. Miranda et al. (2014) and Miranda and Selmo (2004) presoaked RFA for 30 seconds and rest for 10 minutes before add the cement and the remaining water.

- Replacement of NFA by RFA. In reference to the amount of RFA incorporated in the manufacture of the mortar, 29% of the studies evaluated partial replacements, 31% made the total replacement, and in 40% partial and total replacements were made. In addition, the replacement of NFA by RFA was performed by volume in 48.5% of the studies analyzed as well as by mass in 51.5%. Some authors justified the replacement by volume as a consequence of the variation in the aggregates 'density values (de Oliveira Andrade et al., 2018; Jiménez et al., 2013). Likewise, Evangelista et al. (2018) justified the replacement carried out by mass since both aggregates presented close density values. In general, the density values of the NFA were higher than those of RFA, and ranged between 1.14 kg/dm^3 (Silva et al., 2010) and 2.83 kg/dm^3 (López Gayarre et al., 2017), while for RFA the values were between 1.03 kg/dm^3 (Silva et al., 2010) and 2.68 kg/dm^3 (Miranda and Selmo, 2006). The greatest variations between density values of NFA and RFA were 39% (Vegas et al., 2009), 29% (López Gayarre et al., 2017) or 25% (Martínez et al., 2018; Neno et al., 2014); on the contrary, the lowest differences corresponded to 2% (Lima and Leite, 2012), 7% (Muñoz-Ruiperez et al., 2016) or 8% (Corinaldesi and Moriconi, 2009; Miranda et al., 2013; Poon and Kou, 2010; Stefanidou et al., 2014). In contrast, the RFA density value was 4% higher than that of NFA in Miranda and Selmo (2006) and 2% in Raeis Samiei et al. (2015).

However, one cannot establish that the difference between the density values of the aggregates conditioned the authors to perform the replacement of NFA by RFA by volume or mass. In fact, in the studies in which the replacement was made by mass, the differences between the density values of the aggregates ranged between 1% and 39%, whereas when the replacement was made by volume, the differences varied between the 9% and 29%.

- Nature of the RFA. According to the nature of the RFA, mixed RA predominated accounting for 38% of the studies which were evaluated, followed by aggregates from concrete waste (33%) and ceramic material (29%). Regarding the aggregate size, mortars manufactured with fine aggregate were evaluated preferably, of 0/4 mm size (54%) and size 0/2 mm which represents 14% of the studies (Dapena et al., 2011; López Gayarre et al., 2017; Miranda et al., 2014, 2013; Vegas et al., 2009); for the rest, the aggregate size was greater than the 0/4 mm fraction.

- Compressive strength at 28 days. The reference compressive strength value also had a large amplitude of values, and ranged from 5 N/mm^2 (Stefanidou et al., 2014) to 60 N/mm^2 (Bektas et al., 2009). However, although the Standard EN 998-2 (CEN, 2012a) accepts compressive strength values above 25 N/mm^2, they are not usual in masonry mortars. The highest strength values were found in the dosages with the highest amount of cement and the least amount of water, that is, for c/a ratio of 1:3 and w/c ratio of 0.5. Generally, for recycled mortars, the increase in the incorporation of RFA made the resistance values decrease with respect to the reference mortar. Thus, for replacements of 20% of NFA by RFA, strength values were reduced by around 4% (Bektas et al., 2009; Martínez et al., 2016), 23% for incorporations of 50% of RFA (Dapena et al., 2011), 53% for incorporations of 75% of RFA (Muñoz-Ruiperez et al., 2016) and up to 85% when a total replacement of NFA by RFA was made (Vegas et al., 2009). However, in some studies the increase in the compressive strength of recycled mortars was observed with respect to the reference mortar. Therefore, Lima and Leite (2012) observed an increase of 15% in the strength value for replacements of 50% NFA; this was justified by the larger size of the RFA (4.8 mm) compared to the NFA (2.4 mm) since both aggregates presented similar density values (2.55 kg/dm^3). Neno et al. (2014) showed that the strength values increased to 88% when 100% of RFA was incorporated; this is because this mortar has the lowest water content in its composition of recycled mortars and lower voids volume, thus creating greater cohesion and higher strength in the mortar. In addition to the percentage of material, passing the 0.063 mm sieve was completely different in the NFA (0.64%) and the RCA (10.49%). In the study developed by López Gayarre et al. (2017), the compressive strength was increased by 20% for the total replacement of NFA by RFA performed by volume in a dosage c/a ratio of 1:6 by weight, justified by reduction of the effective water as the percentage of replacement of RA increased.

- Although the Standard EN 998-2 (CEN, 2012a) establishes the classification of mortars based on their compressive strength, the strength class of mortar was only specified in 14% of the evaluated studies, M5 and M10 being the classes analyzed. Jiménez et al. (2013) and Ledesma et al. (2014) used a c/a ratio of 1:7 per volume with aggregate of size 0/4 mm for a mortar of class M5, and made a maximum replacement of 40% of NFA by RFA. Ledesma et al. (2015) and Fernández-Ledesma et al. (2016) used a c/a ratio of 1:5 per volume and aggregate of size 0/4 mm for a mortar of class M10, and made the total replacement of NFA by RFA. Finally, Vegas et al. (2009) evaluated mortars made with aggregate of size 0/2 mm, with a dosage of 9% cement on total dry mass and made the total replacement of NFA by RFA. In these studies, recycled mortars have been able to achieve the strength of the reference mortars for incorporations of up to 50% of RFA (Fernández-Ledesma et al., 2016; Ledesma et al., 2015), of 40% of RFA (Jiménez et al., 2013; Ledesma et al., 2014) and 25% of RFA (Vegas et al., 2009).

Table 3. *Comparative relation of studies on masonry mortars manufactured with RA from C&DW*

Author	*Dosage*										*Aggregates*					*Compressive*	
	c/a ratio							*w/c ratio*		*NFA Replacement*		*Size*	*Density (kg/dm³)*			*Strength (N/mm²)*	
	1:3	*1:4*	*1:5*	*1:6*	*1:7*	*1:8*	*V[a]/M[b] wt%[c]*	*w/c*	*Pre-soaked*	*(%)*	*V[a]/ M[b]*	*(mm)*	*NFA*	*RFA*	*RFA type[d]*	*Reference mortar*	*Recycled mortar[e]*
Alvarez-Cabrera et al., (1997)	-	*	*	*	-	*	V	-	-	100	V	0/4.76	-	-	C	-	4.29
Bektas et al., (2009)	*	-	-	-	-	-	M	0.5	-	10/20	M	0/4.75	-	-	B	60	58
Braga et al., (2012)	-	*	-	-	-	-	V	1.41/1.12	-	5/10/15	V	0/0.15	-	-	C	3.91	8.64
Cabrera-Covarrubias et al., (2015)	-	*	-	-	-	-	M	0.84/1.48	*	10/20/30/50/100	M	0/5	2.62	2.15	B	25	≈25
Cabrera-Covarrubias et al., (2017)	*	*	*	-	-	-	M	0.68/1.74	*	100	M	0/5	2.62	2.15	B	-	-
Corinaldesi et al., (2002)	*	-	-	-	-	-	M	0.67/0.78	-	100	M	0/6	2.62	2.15	M	35	38
Corinaldesi, (2009)	*	-	-	-	-	-	M	0.52/0.71	-	100	M	0/6	2.62	2.15	C	30	15
Corinaldesi, (2012)	*	-	-	-	-	-	M	0.5/0.51	-	100	M	0/4	2.59	2.06	B	30	17
Corinaldesi and Moriconi, (2009a)	*	-	-	-	-	-	M	0.6/0.91	-	100	M	0/5	2.59	2.06/2.38	C/B/M	27	21/16/17
Dapena et al., (2011)	*	-	-	-	-	-	M	0.5	-	5/10/15/20/50	M	0/2	2.66	2.3	C	62	48
De Oliveira Andrade et al., (2018)	-	-	*	-	-	-	M	0.99-1.2	-	25/50/75/100	V	0/4.76	2.65	2.39-2.4	C/M	7.04	6.31/5.2
Evangelista et al., (2018)	*	-	-	-	-	-	M	0.55	-	20/30/50/100	M	-	-	2.38	B	36.4	28
Fernández-Ledesma et al., (2016)	-	-	*	-	-	-	V	0.78/0.97	-	25/50/75/100	V	0/4	2.63	2.2	C	11.5	9.1
Jiménez et al., (2013)	-	-	-	-	*	-	V	0.94/1.13	-	5/10/20/40	V	0/4	2.63	2.14	B	7.1	7.5
Ledesma et al., (2014)	-	-	-	-	*	-	V	0.94/1.07	-	5/10/20/40	V	0/4	2.63	2.2	C	7.1	7.2
Ledesma et al., (2015)	-	-	*	-	-	-	V	0.78/1.05	-	25/50/75/100	V	0/4	2.63	2.14	M	11.5	7.5
Lima and Leite, (2012)	-	*	-	-	-	*	M	0.7/1.72	-	50	V	0/4.8	2.6/2.55	2.55	M	12.3	14.2
López Gayarre et al., (2017)	-	-	-	*	-	-	M	1.3/1.5	-	20/35/50/70/100	V	0/2	2.83	2.02	B	6.5	7.8

[a] (V): by volumen; [b] (M): by mass; [c] (wt%): cement by percentage of total dry mass; [d] (C): concrete, (B): Ceramic, (M): mixed; [e] Compressive strength value for higher c/a ratio and higher NFA replacement.

Table 3. Comparative relation of studies on masonry mortars manufactured with RA from C&DW (continued)

Author	Dosage									Aggregates						Compressive	
	c/a ratio							w/c ratio		NFA Replacement		Size	Density (kg/dm³)			Strength (N/mm²)	
	1:3	1:4	1:5	1:6	1:7	1:8	V[a]/M[b] wt%[c]	w/c	Pre-soaked	(%)	V[a]/M[b]	(mm)	NFA	RFA	RFA type[d]	Reference mortar	Recycled mortar[e]
Martínez et al., (2013)	-	-	-	*	-	-	V	1.3/1.8	*	100	V	0/4.76	2.42/2.6	2.13/2.09	B/M/C	9.9	8.1/6.3/7.5
Martínez et al., (2016)	-	-	-	*	-	-	V	1.55/1.6	-	5/10/15/20	V	0/4.76	2.42	2.23/1.9	M	7.3	7
Martínez et al., (2018)	-	-	-	*	-	-	V	1.41/1.98	*	100	V	0/4.76	2.6	2.13/1.96	M	9	6.3
Miranda and Selmo, (2004)	-	-	-	-	-	*	M	2.6	*	100	M	0/4.8	-	2.56/2.7	M	-	4.27/7.26
Miranda and Selmo, (2006)	-	-	-	-	-	-	10%	1.9/2.5	-	100	M	0/4.8	2.58	2.6/2.68	M	2.5	3.5
Miranda et al., (2013)	-	-	-	-	-	*	M	2/3.2	-	50/75/100	M	0/1.2	1.45	1.17/1.31	M	11.83	4.31/6.43
Miranda et al., (2014)	-	*	-	-	-	-	M	0.5/0.71	*	25/50/75/100	M	0/1.18	-	1.19-1.31	M	16.4	10.6
Muñoz-Ruiperez et al., (2016)	-	*	-	-	-	-	M	0.65/0.82	-	75	V	0/4	2.64	2.45/2.4	C/M	35.14	16.5/17.9
Neno et al., (2014)	-	*	-	-	-	-	V	1.21/1.27	-	20/50/100	V	0/4.76	1.43	1.07	C	3.91	7.38
Poon and Kou, (2010)	*	-	-	-	-	-	M	0.55	-	25/50/75/100	M	0/10	2.41	2.38	C	35	25
Raeis Samiei et al., (2015)	*	-	-	-	-	-	M	0.53/0.73	-	25/50/100	M	0/8	2.62	2.67	C	25	15
Saiz Martínez et al., (2016)	*	*	-	-	-	-	M	0.57/0.89	-	50/75/100	M	0.063/4	2.45	2.1	B/M/C	15	9/9/10
Silva et al., (2009)	-	*	-	-	-	-	V	-	-	5/10	V	0/0.15	-	1.026	B	8	14
Silva et al., (2010)	-	*	-	-	-	-	V	-	-	20/50/100	V	0/8	1.14	1.03	B	8	7
Stefanidou et al., (2014)	*	-	-	-	-	-	M	0.85/1	-	100	M	0/4	2.65	2.45	M	5	4.6
Torres-Gómez et al., (2016)	-	-	-	-	*	-	M	1.16/1.36	-	50	V	0/4	2.63	2.14	M	17.74	15.11
Vegas et al., (2009)	-	-	-	-	-	-	9%	1.5/2.5	-	10/20/25/50/75/100	M	0/2	2.67	1.63-2.2	C	13.92	2.13

[a] (V): by volumen; [b] (M): by mass; [c] (wt%): cement by percentage of total dry mass; [d] (C): concrete, (B): Ceramic, (M): mixed; [e] Compressive strength value for higher c/a ratio and higher NFA replacement.

It can therefore be concluded that the studies evaluated have helped to achieve values of compressive strength similar to those of reference mortars with incorporations of up to 50% of RFA and a minimum proportion of cement corresponding to the c/a ratio of 1:7. This amount of cement is greater than 10% of cement on total dry mass of the components determined by the manufacturer's dosage of the M5 class mortar that will be studied in this document; this is so that using more cement than required is unnecessary and environmentally more unfavorable. In addition, and despite the fact that the environmental feasibility of the use of RA has been verified in several constructive applications, no bibliographic references have been found that apply LCA to masonry mortars made with RFA from C&DW. Therefore, it is necessary to carry out a study that can, on the one hand, determine the most effective dosage which; allows the technical feasibility of class M5 masonry mortars manufactured with the highest incorporation of RFA and the proportion of cement determined by the manufacturer (10% on the total dry mass), as well as analyzing the environmental impacts derived from its application. For this, one needs to evaluate different dosages in order to know how the variability of the w/c ratio, the amount of RFA and the AEPA in the properties of masonry mortars in fresh state and in hardened state are influenced.

3. Objetives

Given all the aforementioned, the need to evaluate is justified concerning the use of RFA in applications that do not present limitations of use, such as masonry mortars, and quantify the associated environmental impacts. Therefore, it is essential to evaluate different dosages to obtain technically and environmentally viable mortars with the maximum exploitation of these recycled materials. The aim is to reduce the consumption of NA, increase the recycling of this waste while maintaining its value, and thus contribute to closing the loops within the framework of a circular economy.

Consequently, the **main objective** that arises in this document is the study of the technical and environmental feasibility of the use of RFA from C&DW for its application in masonry mortars.

To achieve this main objective, it is imperative to develop the following **secondary objectives**:

1. Study of technical feasibility:
   - 1.1. Evaluation of different water compensation methods to determine their effectiveness on masonry mortar properties.
   - 1.2. Study of the effects that can cause variability of the water/cement ratio, the RFA and the air entraining/plasticizer admixture in the properties of the masonry mortars, as well as the determination of dosages that satisfy technical requirements.
2. Study of environmental feasibility:
   - 2.1. Development of the inventory for the application of the LCA of masonry mortars.
   - 2.2. Quantification of the environmental impacts associated with masonry mortars manufactured with RFA according to the inventory developed to determine the most suitable dosage in compliance with environmental requirements.

This thesis is framed within the objectives established in the Community legislative framework on the Waste Directive 2008/98/EC (European Parliament and Council, 2008), the Circular Economy Package presented by the European Commission in 2015 in the COM (2015) 614 (European Commission, 2015),), in addition to the national and regional regulations established by “Ley 22/2011 de residuos y suelos contaminados” (Jefatura del Estado, 2011) and the “Plan Director Territorial de Gestión de Residuos No Peligrosos de Andalucía 2010-2019” (Consejería de Medio Ambiente, 2010), and specifically in “Real Decreto 105/2008 por el que se regula la producción y gestión de los residuos de construcción y demolición” (Ministerio de la Presidencia, 2008).

PART 1: TECHNICAL FEASIBILITY

CHAPTER 1. Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar[3]

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[3] *The results shown in this Chapter were presented in: Cuenca-Moyano G. M., Martín-Morales M., Valverde-Palacios I., Valverde-Espinosa I., Zamorano M. Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar. Construction and Building Materials, 2014, 70: 71-79. https://doi.org/10.1016/j.conbuildmat.2014.07.098*

4. Introduction

The construction industry can help improve the environment by reusing and recycling C&DW, which would in turn reduce both landfill volumes and consumption of raw materials (Coelho and De Brito, 2012; de Guzmán Báez et al., 2012; Solís-Guzmán et al., 2009). In this regard, the use of RA from C&DW in different building (Agrela et al., 2011; Martín-Morales et al., 2013b, 2011; Mas et al., 2012) and civil engineering (Barbudo et al., 2012; Martín-Morales et al., 2013b; Vegas et al., 2011) projects would make a major contribution to the sustainable development of the construction industry, even though the coarse fraction of the RA is usually used in these applications. RFA is composed of NA bonded with cement mortar, which reduces the density and increases the water absorption capacity with respect to NA (Martín-Morales et al., 2011; Sánchez de Juan, 2005; Vegas et al., 2009). These properties are detrimental to concrete and mortar quality because they directly affect the w/c ratio, giving poor fresh state consistency and workability, and also affecting the mechanical performance in the hardened state (Rodríguez-Mora, 2003). As a result, most international regulations forbid the use of RFA in concrete (Martín-Morales et al., 2013c); however, there are no prohibitions on its use in mortar.

The workability of mortar is determined by its consistency, and must be suitable for each specific on-site application. A suitable workability is achieved when a plastic consistency is obtained with the addition of the required amount of water, thus enabling the binder paste to cover the surface of the aggregate (Rodríguez-Mora, 2003). When the RFA absorbs part of the mixing water consistency is impaired, and this in turn affects workability. Bektas et al., (2009) used RFA as a replacement for NA in mortar at a constant w/c ratio, and this had a negative effect on the flow of the mortar. However, incorporating 30% RFA to their study mixture provided enough workability and good consolidation, depending on the proportions used in the mixture.

One way to reduce the absorption capacity of the RA is to increase the amount of mixing water (Cachim, 2009; Corinaldesi and Moriconi, 2009; Jiménez et al., 2013; Leite et al., 2013; Silva et al., 2010; Vegas et al., 2009). Corinaldesi and Moriconi (2009) and Jiménez et al. (2013), for example, increased the volume of mixing water to achieve the required mortar consistency. Leite et al. (2013) evaluated the compensation index of RA water absorption rates (60, 70, 80 and 90%) and concluded that in the case of recycled concrete an index of between

80 and 90% would be satisfactory for both workability and compressive strength. Several authors pre-soaked RA before use, keeping mixing water constant (Barra de Oliveira and Vazquez, 1996; Etxeberria et al., 2007; Poon et al., 2004; Sagoe-Crentsil et al., 2001). De Oliveira and Vazquez (1996) and Poon et al. (2004b) note the impaired strength of concretes made with saturated RA, concluding that at higher saturation levels the mechanical bonding between the cement paste and the RA is weakened, and that semi-saturated RA improved performance. Finally, Etxeberria et al. (2007) used pre-soaked RA with 80% of total absorption capacity, obtaining an efficient interfacial transition zone between RA and new cement paste.

The presence of larger amounts of adhered cement mortar in RFA increases absorption with respect to coarse RA; pre-soaking, therefore, could improve the manufacture of mortars. Some authors reported using RFA in the manufacture of masonry mortars by increasing mixing water (Corinaldesi and Moriconi, 2009; Jiménez et al., 2013; Silva et al., 2010; Vegas et al., 2009), however the use of pre-soaked RFA has not been studied in depth. Consequently, the main objective of this study was to analyse the influence of pre-soaked RFA on the behaviour of masonry mortars in the fresh and hardened state in order to manufacture strong mortars with sufficient plasticity to be used in construction.

5. Materials and methods

5.1. Materials

Mortar samples were manufactured according to the dosage recommendations for commercial masonry mortar provided by ARGOS D.C. The components used are shown in Figure 5 and they are described below:

- Cement. The cement used in this study was CEM II/A-L 42.5 R.
- Admixture. A commercial air-entraining plasticizing admixture (RHEOMIX 932) was used to improve workability.
- Filler. A BETOCARB P1-DA limestone filler was added to the aggregate to adjust the fineness modulus.
- Tap water.
- Aggregate. Two types of aggregate were used in this study: a dolomitic NFA produced in a local quarry in Padul (Granada, Spain), and a RFA produced in a C&DW treatment

and recovery plant located in Alhendín (Granada, Spain). RFA was obtained from RA from civil engineering concrete waste, the components of which, determined according to EN 933-11 (CEN, 2009b), included: 87% concrete (Rc), 7.5% NA (Ru), 2.5% brick (Rb), 1.6% asphalt (Ra) and 0.2% others impurities (X) (Figure 6). Table 4 summarizes the physical, mechanical and chemical properties and standards used to determine the properties of the aggregate according to EN 13139 (CEN, 2002a) specifications for mortar aggregates. Figure 7 shows the particle size distribution of the aggregates, analysed in accordance with Standard EN 933-1 (CEN, 2012c). The Spanish National Association of Mortar Manufacturers (Asociación Nacional de Fabricantes de Morteros -AFAM-) recommends a larger amount of fines (Rodríguez-Mora, 2003) (see ideal aggregate (IA) curve in Figure 7), so it was necessary to add limestone filler to correct the fineness modulus of NFA and RFA to nearer 2.23, resulting in the corrected curves in Figure 7 used for this study.

Figure 5. Components of masonry mortars

Figure 6. RA composition

Table 4. Properties of NFA and RFA

Property	*Standard*	*Limit value*	*NFA*	*RFA*
Aggregate size	EN 933-1 (CEN, 2012c)	No limit	0/2	0/2
Fines content (%)	EN 933-1 (CEN, 2012c)	≤ 30	8.71	3.36
Fineness modulus	EN 13.139 (CEN, 2002a)		2.43	2.49
Sand equivalent (%)	EN 933-8 (CEN, 1999a)	No limit	71	99
Dry sample density (g/cm^3)	EN 1097-6(CEN, 2013b)	No limit	2.82	2.63
Water absorption (WA_{24h})(%)	EN 1097-6 (CEN, 2013b)	No limit	1.3	6.3
(WA_{10min})(%)				5.8
Water-soluble chlorides (%)	EN 1744-1 (CEN, 2009c)	≤ 0.06	0.003	0.014
Acid soluble chlorides (%)	EN 1744-5(CEN, 2007)	No limit		0.009
Acid soluble sulphates (%)	EN 1744-1 (CEN, 2009c)	≤ 0.8	0.3	0.58
Total sulphur (%)	EN 1744-1 (CEN, 2009c)	≤ 1	≤ 1	0.66
Humus content (%)	EN 1744-1 (CEN, 2009c)	No limit	Exempt	Exempt
Light organic impurities (%)	EN 1744-1 (CEN, 2009c)	No limit	Exempt	Exempt

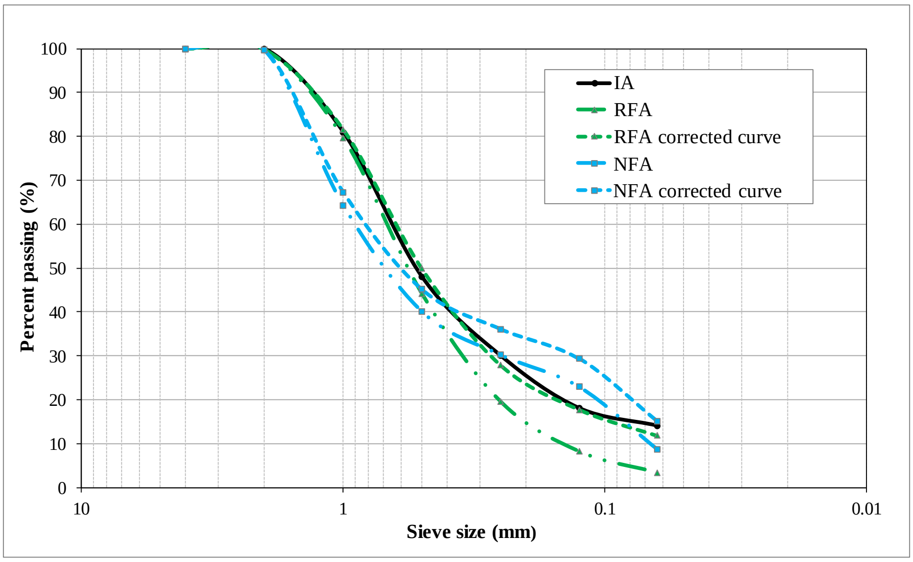

Figure 7. Particle size distribution of aggregates

5.2. Methods

5.2.1. RFA pre-soaking method

A pre-soaking method was used for RFA, and consisted in mixing it with water before adding it to the other dry components of the mortar (NFA, cement and admixture). The pre-soaking water and the RFA were mixed in the mixer at a slow speed for 5 minutes. Subsequently, the pre-soaked RFA was left to rest for 10 minutes. Four pre-soaking methods were used, one based on the literature consulted and the other three proposed specifically for this study, varying the amount of pre-soaking water used with the RFA. The methods used are described below (Table 5):

- PS-100 Method. The RFA was pre-soaked in a volume of water equivalent to its full absorption capacity (WA_{24h}).
- PS-80 Method. Proposed by Etxeberria et al., (2007), the RFA was pre-soaked in 80% of its WA_{24h}.
- PS-92 Method. The RFA was pre-soaked in 92% of its WA24h; this was the water absorbed during a 10-min period (WA10min) (Table 4), which according to other authors (Agrela et al., 2011; Cachim, 2009) is the volume of water absorbed by the RFA during mixing.

- PS-67 Method. Pre-soaking water was 2/3 of the total absorption capacity of RFA, corresponding to 67% of WA_{24h}.

Table 5. Characteristics of the pre-soaking methods used

Pre-soaking method	*Pre-soaking water*		*Reference*
	% of WA_{24h}	*Value ^{a}(%)*	
PS-100	100	6.30	*
PS-80	80	5.04	Etxeberria et al. (2007)
PS-92	92	5.80	*
PS-67	67	4.22	*

[a] By dry mass (g) of RFA added.

* Proposed by this study.

5.2.2. Mortar samples

Six masonry mortar series with various substitution ratios (25%, 50%, 75% and 100%) of NA by RFA by mass and a control mortar to be used as a reference were manufactured for this study (Table 6). Mortar samples were assigned the name of the series and the RFA content ratio. Mortar components were dosed by weight according to the manufacturer's directions to obtain a dry mass of 3 kg for a type M5 compressive strength mortar according to EN 998-2 (CEN, 2012a) (Table 7). The same mixing procedure, according to EN 1015-2 (CEN, 1998a), was used to manufacture all the mortar series. This included the following steps: (i) solid components (including pre-soaked RFA according to the process described in section 5.2.1 above) were mixed to obtain a dry homogeneous mixture; (ii) mixing water was poured into the mixer container; (iii) solid components were added to the water; (iv) all components were mixed for 90 seconds at low speed.

Three groups of series were manufactured according to the literature (A0, B0, C0), differing in the amount of mixing water, total water and RFA moisture (non-pre-soaked or pre-soaked RFA). Some of the foregoing methods were modified to identify new test conditions, resulting in series A1, C1 and C2. For all mortar series, the total water was pre-soaking water plus mixing water, while the effective w/c ratio was determined by subtracting the water absorbed by NFA and RFA according to its WA_{24h} (Table 4) from the total amount of water. The mortar series are summarised in Table 6 and described below:

- The control mortar was made with 14% of the mixing water used as a reference for manufacturing the remaining series.

- Series A0 and A1 were manufactured with the same total water content as the control mortar (14%) irrespective of the amount of RFA added, according to Bektas et al. (2009). As a result, the total w/c ratio of these mortars was the same as the control mortar, while the effective w/c ratio decreased as the amount of RFA increased. As a new condition, in the A1 series pre-soaked RFA according to the PS-100 method was used; the pre-soaking water volume was subtracted from the total water.
- In series B0, the amount of mixing water was increased as RFA content increased, as some authors have reported (Corinaldesi and Moriconi, 2009; Jiménez et al., 2013; Silva et al., 2010; Vegas et al., 2009). As the RFA in this series was not pre-soaked, the total water amount is equal to the mixing water. The total w/c ratio was greater than the control mortar, while the effective w/c ratio remained the same.
- Following the guidelines of Etxeberria et al. (2007), series C0 was made according to the PS-80 method. The new conditions modified the amount of pre-soaking water; in series C1 and C2 the PS-92 and PS-67 pre-soaking methods were used, respectively. In these series, the amount of mixing water was that of the control mortar (14%), the total w/c ratio increased as RFA was added, while the effective w/c ratio varied slightly.

Table 6. Masonry mortar manufacturing process

Mortar Series	*RFA content (%)*	*Pre-soaking method*	*Mixing water (%)*	*Total water (%)*	*Reference*
Control	0	-	14	14	Manufacturer's Masonry Mortar
A0	25/50[a]	-	14	14	Bektas et al. (2009)
A1	25/50[a]	PS-100	14 - PSW[b]	14	*
B0	25/50/75/100	-	14 + X[c]	14 + X	Corinaldesi and Moriconi (2009a) Jiménez et al. (2013) Vegas et al. (2009)
C0	25/50/75/100	PS-80	14	14 + PSW	Etxeberria et al. (2007)
C1	25/50/75/100	PS-92	14	14 + PSW	*
C2	25/50/75/100	PS-67	14	14 + PSW	*

[a] Mortar samples with 75 and 100% replaced NA were not workable

[b] RFA pre-soaking water determined according to the pre-soaking method used

[c] Water required (according to the amount of RFA) to reach the same consistency (± 10 mm) as the control mortar

* New conditions tested

Since the main objective of this study was to obtain mortars with good consistency, the manufacturing process was conducted as follows: First, the control mortar consistency was determined according to EN 1015-3 (CEN, 1999b), giving reference value 153 ± 10 mm. Series A0 and A1 were manufactured using the same total water as the control mortar (14%); higher RFA content, therefore, caused significant consistency impairment (105 mm), and no more than 50% of NFA could be replaced. To achieve good consistency it was necessary to increase the w/c ratio of the mortar as RFA content increased by increasing the amount of mixing water (series B0) or using pre-soaked RFA and constant mixing water (series C0, C1 and C2); series C1 and C2 were manufactured using the highest and lowest total w/c ratio, respectively, while it was similar for series B0 and C0 (Table 7).

Table 7. Dosage table of mortars studied

Mortar	*NA (g)*	*RFA (g)*	*Filler (g)*	*Cement (g)*	*Additive (g)*	*Pre-soaking water (g)*	*Mixing water (g)*	*Total water (g)*	*Total w/c*	*Effective w/c*
	Mix proportions-Dry weight (3 kg)									
Control	2430	0	270	300	3	0	420	420	1.400	1.295
A0-25	1836	594	270	300	3	0	420	420	1.400	1.196
A0-50	1215	1215	270	300	3	0	420	420	1.400	1.092
A1-25	1836	594	270	300	3	37	383	420	1.400	1.196
A1-50	1215	1215	270	300	3	77	343	420	1.400	1.092
B0-25	1836	594	270	300	3	0	450	450	1.500	1.296
B0-50	1215	1215	270	300	3	0	480	480	1.600	1.292
B0-75	594	1809	297	300	3	0	510	510	1.700	1.294
B0-100	0	2403	297	300	3	0	540	540	1.800	1.295
C0-25	1836	594	270	300	3	30	420	450	1.500	1.295
C0-50	1215	1215	270	300	3	61	420	481	1.604	1.296
C0-75	594	1809	297	300	3	91	420	511	1.704	1.298
C0-100	0	2403	297	300	3	121	420	541	1.804	1.299
C1-25	1836	594	270	300	3	34	420	454	1.515	1.310
C1-50	1215	1215	270	300	3	70	420	490	1.635	1.327
C1-75	594	1809	297	300	3	105	420	525	1.749	1.344
C1-100	0	2403	297	300	3	139	420	559	1.864	1.360
C2-25	1836	594	270	300	3	25	420	445	1.484	1.279
C2-50	1215	1215	270	300	3	51	420	471	1.571	1.263
C2-75	594	1809	297	300	3	76	420	496	1.655	1.249
C2-100	0	2403	297	300	3	101	420	521	1.738	1.233

5.2.3. Testing methods

The masonry mortars were evaluated in the fresh and hardened state. The properties studied, the standards applied and limits established are summarized in Table 8. To obtain the average value according to test standards for each mixture and property, two samples were tested for fresh mortar and three 40x40x160 mm prisms were tested for hardened mortar after a curing period of 28 days. A further three specimens were tested for compressive and flexural strength after each mixture had been cured for 7 days.

Table 8. Properties of masonry mortars studied, standards applied and limits established

Properties	*Test Standard*	*Limit value*	*Reference*
Fresh state			
Consistency	EN 1015-3 (CEN, 1999b)	Dry (< 140 mm)	EN 1015-6 (CEN, 1998b)
		Plastic (140-200 mm)	
		Fluid (> 200 mm)	
Bulk density	EN 1015-6 (CEN, 1998b)	-	-
Air content	EN 1015-7 (CEN, 1998c)	-	-
Hardened state			
Dry bulk density	EN 1015-10 (CEN, 1999c)	-	-
Compressive and flexural strength	EN 1015-11 (CEN, 1999d)	fc 28-day ≥ 5 N/mm^2 (MPa) (M5 Mortar)	EN 998-2 (CEN, 2012a)
Water absorption coefficient due to capillary action	EN 1015-18 (CEN, 2002b)	-	-

6. Results and discussion

The results of the tests are summarized in Table 9 and Figure 8 to Figure 19, and are analysed and discussed below.

Table 9. Tests results of mortars

Mortar Series	Fresh state			Hardened state					
	Consistency	Bulk density	Air content	Dry bulk density	Compressive and Flexural Strength (N/mm^2)				Water absorption coefficient
	(mm)	(kg/m^3)	(%)	(kg/m^3)	f_f 7d	f_c 7d	f_f 28d	f_c 28d	($kg/(m^2.min^{0.5})$)
Control	153	1960	14.0	1800	1.9	4	2.6	7	0.700
A0-25	143	1920	14.5	1800	2.2	4.9	3.5	8.7	0.605
A0-50	120	1970	13.5	1830	2.7	6.2	3.8	11.3	0.543
A1-25	142	1940	14.0	1790	2.0	4.1	2.8	8.1	0.654
A1-50	105	2020	13.0	1880	2.7	8.0	3.9	12.8	0.461
B0-25	154	1850	16.5	1660	1.5	3.0	2.1	4.6	0.683
B0-50	153	1700	19.0	1550	1.0	2.1	1.6	3.7	0.652
B0-75	151	1630	20.0	1440	1.0	1.5	1.3	2.6	0.717
B0-100	148	1530	22.5	1340	0.8	1.5	1.2	3.0	0.680
C0-25	154	1850	16.5	1680	1.4	3.0	2.1	5.5	0.736
C0-50	149	1710	19.0	1600	1.1	2.0	1.6	4.1	0.671
C0-75	148	1640	20.0	1460	1.1	1.9	1.5	3.0	0.697
C0-100	143	1670	19.5	1470	1.2	2.3	1.6	4.5	0.732
C1-25	156	1840	17.0	1670	1.4	2.9	2.2	5.6	0.776
C1-50	154	1680	20.0	1560	1.1	2.0	1.6	3.9	0.731
C1-75	151	1610	20.5	1450	0.9	1.6	1.4	3.1	0.788
C1-100	144	1560	21.5	1410	0.7	1.3	1.4	3.3	0.684
C2-25	153	1860	16.0	1710	1.4	3.1	2.2	6.3	0.693
C2-50	146	1730	18.5	1620	1.3	2.5	2.1	4.9	0.616
C2-75	143	1650	20.0	1580	1.3	2.3	1.9	4.8	0.585
C2-100	140	1680	19.5	1520	1.3	2.5	1.9	5.2	0.611

6.1. Fresh mortar

6.1.1. Consistency

Figure 8 shows the consistency, total w/c ratio and effective w/c ratio of the series tested and the limit of plastic consistency. We observed that consistency was impaired when RFA content increased. All mortar series achieved plastic consistency (140-200 mm) except mortar samples with the same total w/c ratio as the control mortar and 50% of RFA (series A0 and A1). The high water absorption capacity of RFA significantly reduced the effective w/c ratio, which affected mortar consistency. According to Bektas et al. (2009) increased RFA content caused the excessive reduction of consistency observed in these series, up to 31% less in the

A1 series (PS-100) with respect to the control mortar.

We also noted a decline in the consistency of mortars manufactured with a greater total w/c ratio than the control mortar as the substitution of NA by RFA increased (Series B0, C0, C1 and C2). The same trend has been noted by other authors (Corinaldesi and Moriconi, 2009; Leite et al., 2013; Silva et al., 2010; Vegas et al., 2009) reported, and according to Wong et al., (2001) mixtures produced with angular and rough-textured particles, such as RA, tend to interlock and reduce inter-particle movement. Additionally, more uniform particle size distribution could have been detrimental to consistency due to particle packing (Leite, 2001). The greater the RFA content, therefore, the worse the consistency. Also mortars manufactured using pre-soaked RFA had slightly lower consistency values than those made using non-pre-soaked RFA. This, according to Poon et al., (2004) could be the result of adding a greater volume of water to the mix to obtain a consistency similar to that of the control mortar when RFA was not pre-soaked. The pre-soaking method reduced the amount of free water in the mix, indicating that the consistency of mortar was strongly dependent on the initial free water content. If we compare the mortar series with the same total w/c ratio (B0 and C0), consistency values were up to 3% lower when pre-soaked RFA was used (series C0). In pre-soaked RFA series, increasing the volume of pre-soaking water improved consistency (series C1, PS-92).

We can conclude, therefore, that consistency of fresh mortar is impaired when both RFA and pre-soaked RFA is added, and improves as the total w/c ratio is increased.

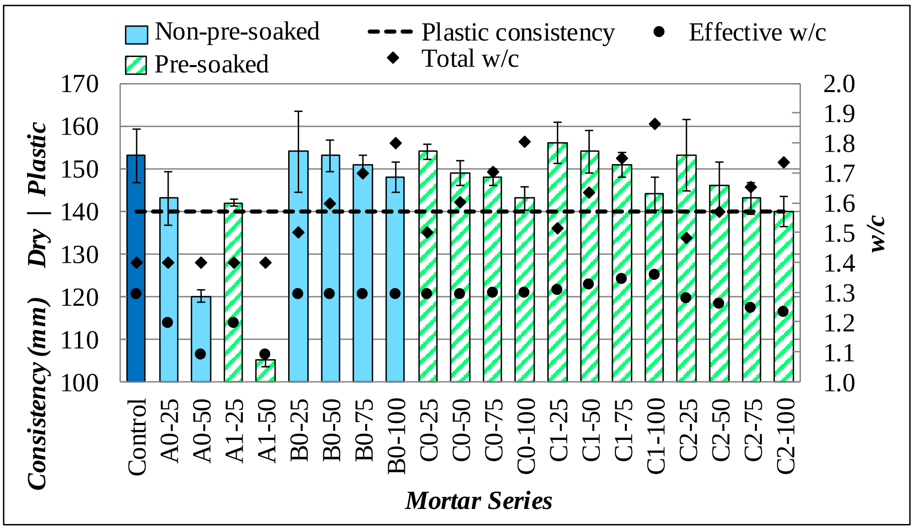

Figure 8. Consistency values, total w/c ratio and effective w/c ratio

6.1.2. Bulk density of fresh mortar

The bulk density values, total w/c ratio and effective w/c ratio of mortar series are shown in Figure 9. We observed that mortars manufactured using the same total w/c ratio as that used in the control mortar achieved similar bulk density values as the control mortar. Bulk density was even slightly higher (between 0.5 - 3%) when 50% NA was replaced by RFA (A0-50 and A1-50). This could be due to the fact that the RFA contains a far greater number of particles for the same volume of mortar due to its lower dry sample density with respect to NA, resulting in a more compact mortar. The reduction in the effective w/c ratio caused by increasing the RFA content was also a contributing factor. In terms of the amount of RFA added, bulk density values were considerably higher (between 1-2.5%) when pre-soaked RFA was used (series A1, PS-100).

We also observed that bulk density values fell as total w/c ratio and RFA content increased. In this case, increasing total water volume in mortars to achieve the required consistency as a result of adding RFA caused bulk density values to fall with respect to the control mortar. These results were consistent with other studies (Jiménez et al., 2013; Silva et al., 2010; Vegas et al., 2009) that showed that the bulk density of fresh mortar decreased when NA was replaced by RFA due to the increase in water content; a higher proportion of water in the mortar makes it lighter. These mortar samples (B0, C0, C1 and C2) achieved similar bulk density values for the same RFA content except for the case of total NA replacement, where the worst value was obtained in mortar manufactured using non-pre-soaked RFA (B0-100), 9.1% lower than the series using pre-soaked RFA (C0-100, PS-80). This could be due to the combined effect of pre-soaking and RFA particle size: i) pre-soaking the RFA minimised the volume of free water in the mixture; ii) the more uniform particle size of RFA allowed for better binding when NA was wholly replaced, compared to those cases of partial replacement. The higher bulk density values of the series manufactured using pre-soaked RFA correlated to the least amount of pre-soaking water, and therefore to the lower total w/c ratio (series C2, PS-67).

The relationship between bulk density and total w/c ratio was confirmed by the good regression correlation index (Figure 10).

Based on the results obtained, therefore, we can conclude that fresh mortar bulk density values increase with the pre-soaking method when NA is totally replaced, and fall as the total w/c ratio is increased with the incorporation of RFA.

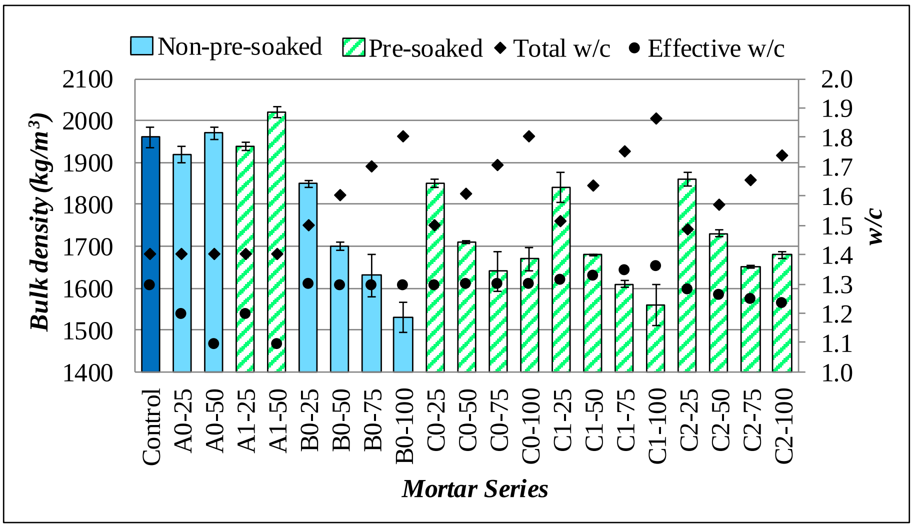

Figure 9. Bulk density of fresh mortar, total w/c ratio and effective w/c ratio

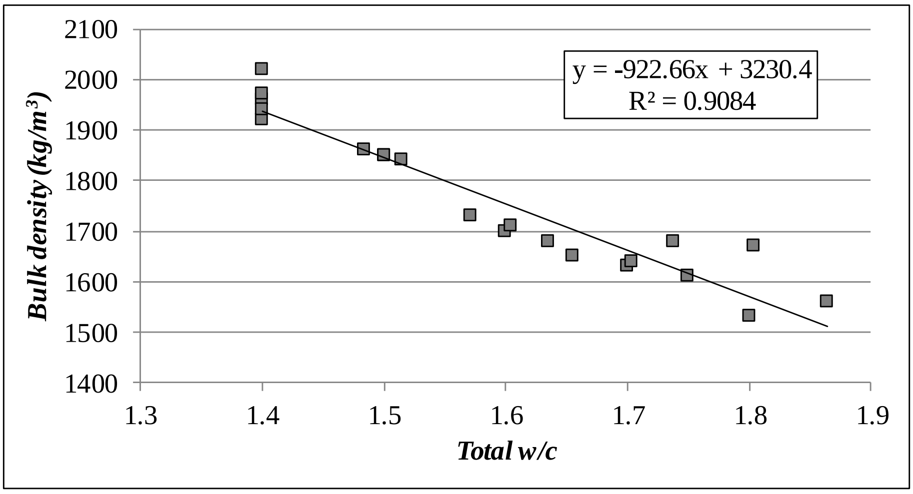

Figure 10. Relationship between bulk density of fresh mortar and total w/c ratio

6.1.3. Air content of fresh mortar

The air content of the mortar is important to achieve good durability and mechanical strength. Adequate air content enables the mortar to withstand freeze-thaw cycles without disrupting the matrix. However, excessive air gradually impairs mechanical strength. Air content, therefore, should remain within appropriate values. Although European Standard EN 998-2 (CEN, 2012a) does not set specific limits for air content values, some references include recommendations in this regard, and the values put forward by Bustillo Revuelta, (2008) (between 5 and 20%) have been taken as a reference for this study.

The air content values, total w/c ratio and effective w/c ratio for mortar series are show in Figure 11. The recommended values were attained by all mortars with up to 50% added RFA. The mortar series with the same total w/c ratio as the control mortar (series A0 and A1) achieved similar air content as the control mortar, and values fell (between 3.5% and 7.1%) when 50% NA was replaced with RFA. These results can be explained by the reduction in the effective w/c ratio. The use of pre-soaked RFA (series A1, PS-100) reduced air content slightly (3.7%). These results confirm the bulk density compactness of the fresh mortar.

The rise in the total w/c ratio resulting from the incorporation of RFA led to an increase in air content values. Based on the results obtained by others authors (Leite et al., 2013; Sánchez de Juan, 2005), we observed a clear influence of w/c ratio on the air content of the mortar, resulting in mortar with a high total w/c ratio and high air content. In these mortar series (B0, C0, C1 and C2) we also observed that mortars with the same RFA ratio reached similar air content values, except for total replacement of NA: the poorest value was achieved with the non- pre-soaked RFA mortar (B0-100), where air content rose by 13% with respect to C0-100 (PS-80). The lowest air content values in pre-soaked series corresponded to the least amount of pre-soaking water (series C2, PS-67).

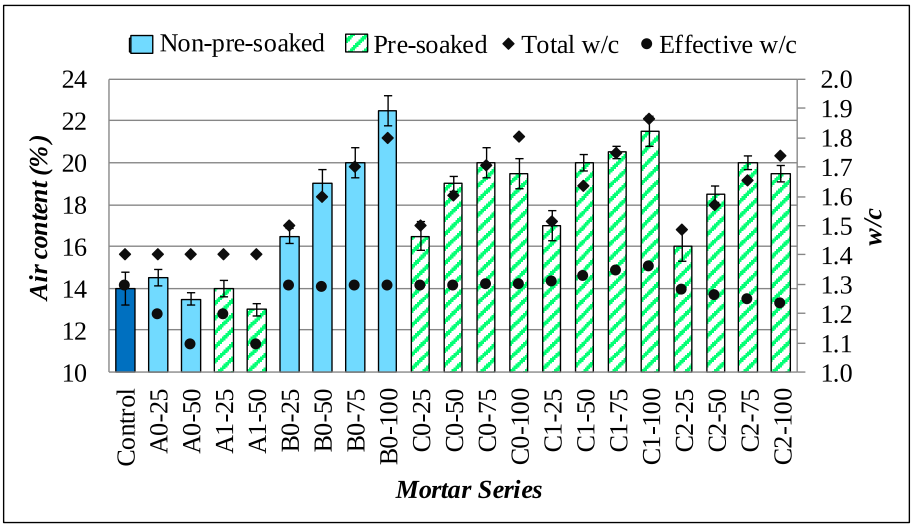

Figure 11. Air content of fresh mortar, total w/c ratio and effective w/c ratio

The relationship between air content and total w/c ratio was confirmed by the good correlation index (Figure 12).

Based on the bulk density results obtained for fresh mortar, it is reasonable to conclude that the air content of fresh mortar decreases with the pre-soaking method when NA is totally replaced, and increases as total w/c ratio and RFA content increase.

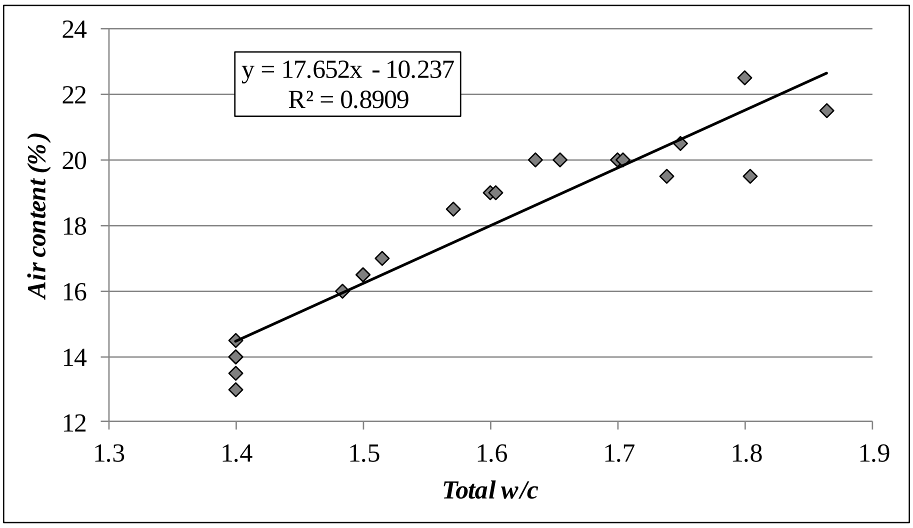

Figure 12. Relationship between air content and total w/c ratio

6.2. Hardened mortar

6.2.1. Dry bulk density

The dry bulk density values, total w/c ratio and effective w/c ratio for all the mortar series studied are shown in Figure 13. Hardened mortar showed the same tendency as bulk density and air content of dry mortar: dry bulk density values increased slightly (between 1.7 - 4.4%) after 50% RFA incorporation in mortars with the same total w/c ratio as the control mortar (Series A0 and A1). The highest value was obtained when using the pre-soaked RFA (series A1-50, PS-100).

The increase in total w/c ratio when RFA is added, reduced dry bulk density values in mortar series (B0, C0, C1 and C2), according to the literature consulted (Jiménez et al., 2013; Silva et al., 2010; Vegas et al., 2009). Mortars with the same amount of RFA had similar values except when NA was totally replaced by pre-soaked RFA; in C0-100 (PS-80) dry bulk density increased by 9.7% with respect to B0-100, which confirmed the bulk density and air content trend in fresh mortar. Increasing the amount of pre-soaking water decreased the dry bulk density in series manufactured using pre-soaked RFA (series C1, PS-92).

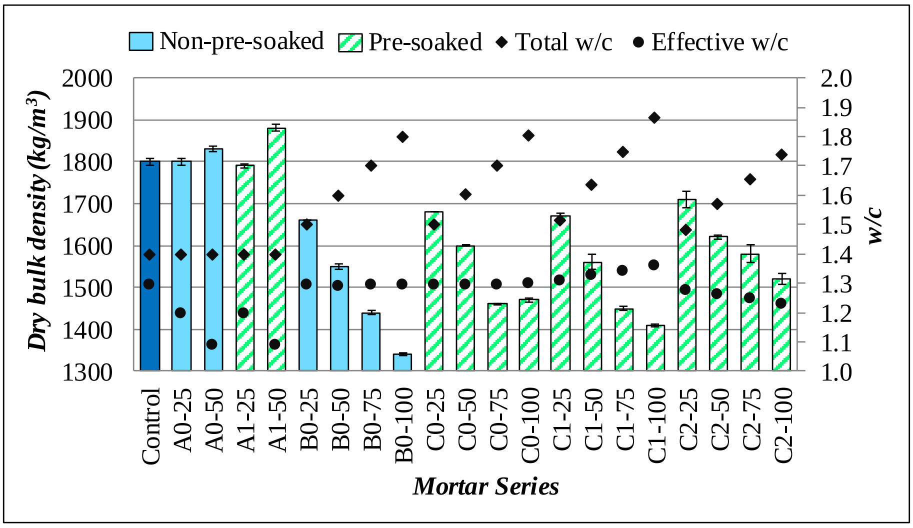

Figure 13. Dry bulk density, total w/c ratio and effective w/c ratio

The relationship between dry bulk density and total w/c ratio is shown in Figure 14 by the good correlation index.

Figure 15 shows the relationship between bulk density and dry bulk density for all mortar series. We observed a linear relationship with a very good correlation index. The results show that dry bulk density is around 92% of the value of bulk density. Furthermore, we observed an inverse linear relationship between bulk density, air content and dry bulk density, with good correlation indexes (Figure 16). The air content, therefore, increased as bulk density and dry bulk density decreased.

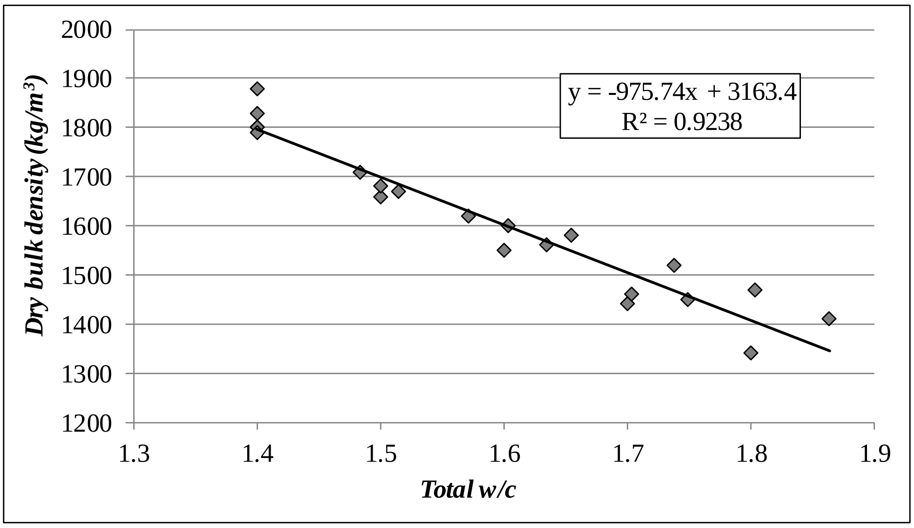

Figure 14. Relationship between the dry bulk density and total w/c ratio

Based on the results obtained for bulk density and air content of fresh mortar, it can be said that the dry bulk density of hardened mortar increased with pre-soaking when NA was totally replaced and decreased as the amount of total w/c ratio increased when RFA was added.

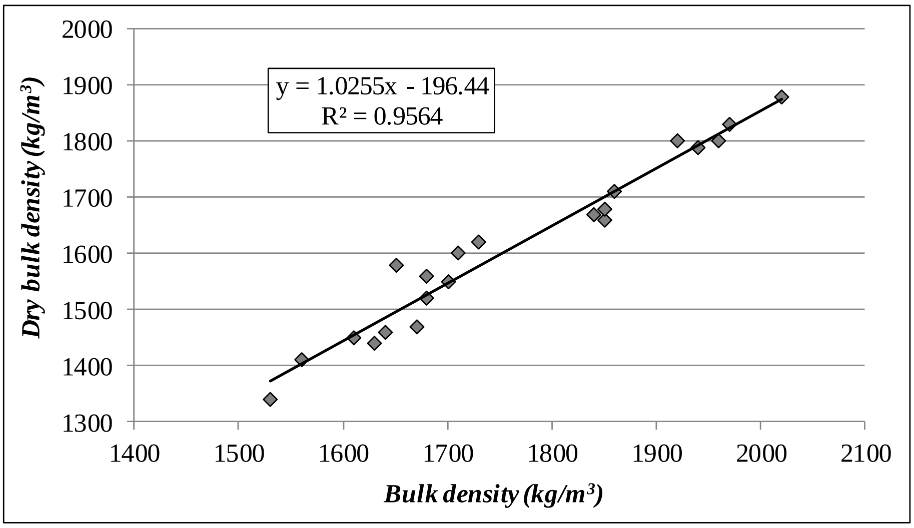

Figure 15. Relationship between bulk density and dry bulk density

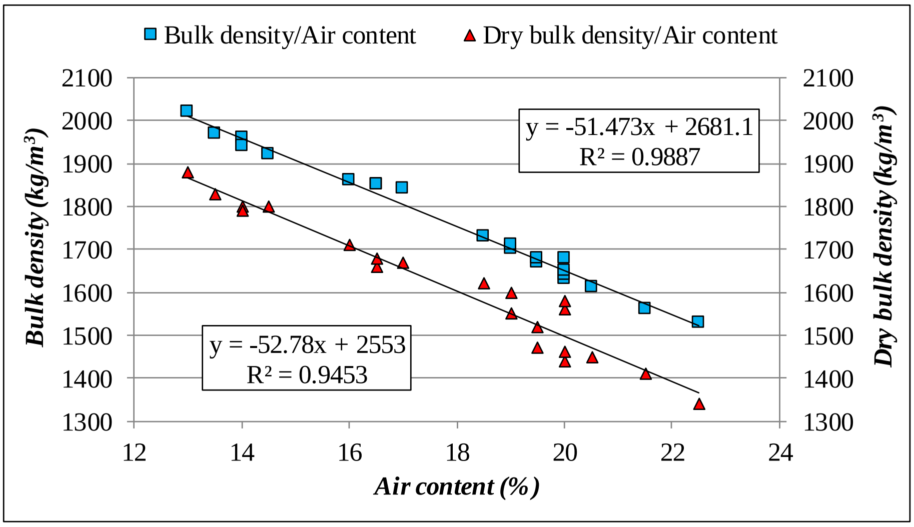

Figure 16. Relationship between bulk density/air content and dry bulk density/air content

6.2.2. Compressive and flexural strength of hardened mortar

Compressive strength is the most important property of masonry mortars in their hardened state, since to a large extent it determines their durability; indeed, masonry mortars are classified according to their compressive strength (CEN, 2012a). The compressive and flexural strength values of mortar series aged 7 and 28 days are shown in Table 9. Figure 17 shows the compressive strength at 28 days, total w/c ratio and effective w/c ratio of all mortar series together with the lower limit of compressive strength of a M5 mortar. We observed that the compressive strength of mortars manufactured using the same total w/c ratio as the control mortar increased with the addition of RFA. The increase was significant (between 61.4-82.5%) when 50% of NA was replaced with RFA (series A0 and series A1) due to the reduction of the effective w/c ratio. In this case, when pre-soaked RFA was used (A1, PS-100) compressive strength was up to 13.2% higher than when non-pre-soaked RFA was used (A0). This can be explained because RFA absorbed a certain amount of free water during mixing, and this reduced the initial w/c in the interfacial transition zone and improved the interfacial bond between RFA and the new cement paste (Etxeberria et al., 2007). These compressive strength results were associated with dry consistency values, high bulk density and dry bulk density and low air content, therefore, the compactness of the mortars was further confirmed by their compressive strength.

The results obtained confirm that the addition of RFA does not have a negative effect on compressive strength, as reported by Bektas et al. (2009) who observed that replacing 30% of NA with brick aggregate did not impair strength.

We also noticed, however, that the increased total w/c ratio following addition of RFA reduced the compressive strength of mortar series (B0, C0, C1 and C2). According to Haach et al. (2011), the increase of the total w/c ratio to maintain good mortar plasticity resulted in higher porosity, and in consequence, decreased compressive and flexural strength because the presence of water between the solid particles resulted in a higher percentage of empty space in hardened mortar. Corinaldesi and Moriconi (2009) obtained similar results due to the lower density and higher water absorption of RFA compared with NA. Mortar series containing pre-soaked RFA were also observed to attain higher compressive strength values when compared to mortar series manufactured with non-pre-soaked RFA for all NA replacement ratios. In fact, if we compare series B0 and C0 (PS-80), we can see that compressive strength was as much as 50% higher when NA was totally replaced with pre-soaked RFA (C0-100) because, as indicated above, the use of pre-soaked RFA improved the interfacial bond between the RFA and the new cement paste (Etxeberria et al., 2007). The highest compressive strength values in series manufactured using pre-soaked RFA were obtained with the least volume of pre-soaking water (series C2, PS-92).

The compressive strength value of the control mortar (>5 MPa) was matched by all mortars manufactured with the same total w/c ratio as the control mortar. In mortars manufactured with a higher total w/c ratio, this value was only obtained in mortars using 25% pre-soaked RFA, and even with the incorporation of 100% RFA in the C2 series. This means that, like the control mortar, they can also be given the M5 classification under EN 998-2 (CEN, 2012a).

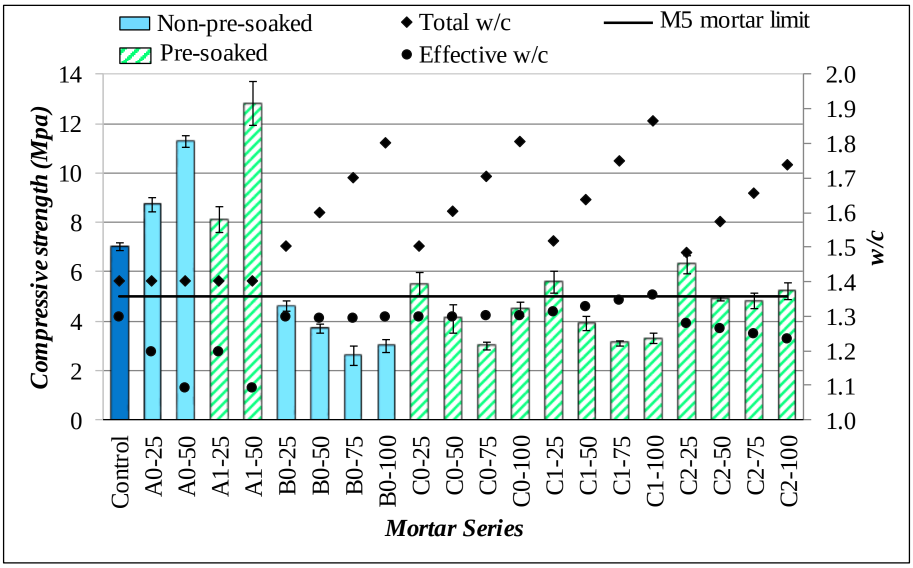

Figure 17. Compressive strength at 28 days, total w/c ratio and effective w/c ratio

Flexural strength values also improved in line with compressive strength values, as shown in Figure 18. A linear relationship between parameters can be seen, with a very good correlation coefficient. According to the results, flexural strength is around 40% of compressive strength.

After analysing the results obtained from the study mortars we can say that compressive strength increases as RFA content increases and also benefits from the pre-soaking method, but decreases as the total w/c ratio rises due to the addition of RFA.

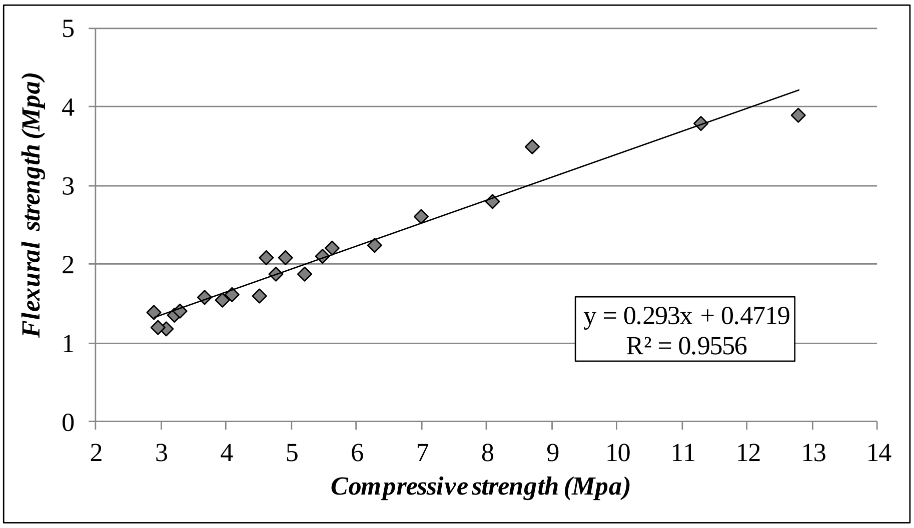

Figure 18. Relationship between flexural and compressive strength after 28 days

6.2.3. Water absorption coefficient due to capillary action of hardened mortar

Water absorption due to capillary action should be as low as possible in order to prevent infiltrations resulting from ascension of capillary water that can seriously degrade the material. This depends on the capillary structure of the mortar; the more compact the mortar, the smaller the capillary network and the lower the absorption (Rodríguez-Mora, 2003).

Figure 19 shows the water absorption coefficient due to capillary action values, total w/c ratio and effective w/c ratio. We observed that in mortars manufactured using the same total w/c ratio as the control mortar (series A0 and A1), the water absorption coefficient values fell as more RFA content was added, particularly when 50% of NA was replaced with pre-soaked RFA, as much as 34% less (series A1, PS-100). This could be explained by the greater number of particles in the RFA and the low effective w/c ratio of the mixture, which caused the cement paste to fill the pores, making the mortar more compact. Based on previous observations, this series also achieved high compressive strength and density values (in both the fresh and hardened state), and lower consistency and air content values, giving the mortars a smaller capillary network.

We also observed that the increase in total w/c ratio resulted in a slightly higher water absorption coefficient, irrespective of the amount of RFA added and the humidity of the aggregate. Mortars manufactured with the highest total w/c ratio (series C1, PS-92) had the highest water absorption coefficient values due to their increased porosity (Fernandes et al., 2005). The fact that this was not affected by the amount of RFA content could be due to the nailing effect of the cement paste to the RFA (due to its porosity and rougher texture), since the pores that would otherwise contain water were occupied by cement paste (Silva et al., 2010). The use of pre-soaked RFA did not affect the water absorption coefficient due to capillary action.

An analysis of the results showed that the water absorption coefficient due to capillary action increased as the total w/c ratio increased, irrespective of the percentage of replacement NA and the degree of humidity of the RFA.

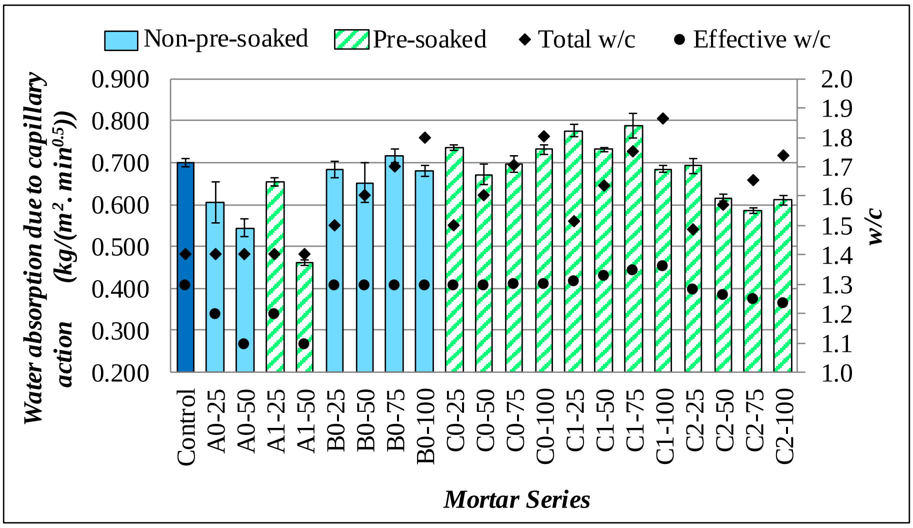

Figure 19. Water absorption coefficient values, total w/c ratio and effective w/c ratio

7. Conclusions

The use of RFA affects the properties of mortar in the fresh and hardened state compared to NA, due to the lower density and higher water absorption values of RFA. First, this study has evaluated the influence of adding RFA to masonry mortars without increasing the total w/c ratio over that of the control mortar made with NA, concluding it created an effective interfacial transition zone between the RFA and the cement paste, which in turn improved mechanical strength and reduced the water absorption coefficient due to capillary action values with respect to the control mortar; bulk density, air content and dry bulk density had similar values to those obtained from NA mortars. However the addition of RFA reduced the effective w/c ratio, which had a negative effect on consistency since the RFA absorbed part of the mixing water, thus giving a mortar with a dry consistency that made it impossible to use when more than 25% of NA was replaced with RFA.

Increasing the total w/c ratio of recycled mortars in order to improve consistency negatively affected other properties, for example, bulk density (in both the fresh and hardened state), air content of fresh mortar, compressive and flexural strength and water absorption coefficient. Therefore, this study has analyzed the effect of the use of pre-soaked RFA in masonry mortars as well as the quantity of water used for pre-soaking, with the objective of achieving good plasticity without affecting the other properties, mainly strength. We can conclude that the use of pre-soaked RFA compared to non-pre-soaked RFA reduced only slightly the consistency and air content of fresh mortar, and the capillary water absorption coefficient values were similar when compared to mortars manufactured with NA; however bulk density (in the fresh and hardened state) and compressive and flexural strengths increased. On the other hand, the ideal amount of pre-soaking water in partial replacement of NA was 67% of WA_{24h} RFA (PS-67), while in the case of total replacement this increased to 80% of WA_{24h} RFA (PS-80); these values gave mortars plastic consistency and yielded good results for the properties studied. The following justifies the foregoing results:

- The pre-soaked RFA caused a slight reduction in mortar consistency because there was less free water in the mix, and the consistency of mortar is largely dependent on initial free water content.
- The air content of fresh mortar made with pre-soaked RFA was lower and bulk density (in the fresh and hardened state) increased. These improvements were more noticeable in the case of 100% replacement with pre-soaked RFA. This can be explained because the uniform aggregate size of the RFA facilitated particle binding, which was more effective in the case of total NA replacement.
- Compressive and flexural strength improved irrespective of the amount of NA replaced. This is explained by improvement in the interfacial transition zone between RFA and the new cement paste as a result of using the pre-soaking method. In the case of mortars manufactured using 25% pre-soaked RFA, compressive strength was greater than 5 MPa, allowing the mortar to receive an M5 classification under EN 998-2; however, the same results were not achieved with non-pre-soaked RFA.

- The water absorption coefficient due to capillary action did not vary significantly as a result of using pre-soaked RFA.

In consequence increasing the total water content of mortars due to the high water absorption capacity of RFAs can be more effective if the pre-soaking method is used. It can improve the performance of mortar manufactured with RFA, thereby increasing the recycling rate of C&DW. In practice, the pre-soaking method would be feasible if the mixing method were changed to allow pre-soaking of RFA before incorporating the remaining mortar components. This would increase manufacturing time by 15 minutes (5 minutes for pre-soaking and 10 minutes to rest).

CHAPTER 2. Effects of water to cement ratio, recycled fine aggregate and air entraining/plasticizer admixture on masonry mortar properties.[4]

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[4] *The results shown in this Chapter were presented in: Cuenca-Moyano G. M., Martín-Pascual J., Martín-Morales M., Valverde-Palacios I., Zamorano M. Effects of water to cement ratio, recycled fine aggregate and air entraining/plasticizer admixture on masonry mortar properties. Submitted to Journal of Cleaner Production.*

8. Introduction

C&DW is the largest waste stream in the EU (European Commission, 2017a), with 923 million tons generated in 2016 (Eurostat, 2018a). In order to move towards a European recycling society with a high level of resource efficiency, the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008) established a C&DW recovery target of 70% by 2020. In 2016, this target had been achieved, with C&DW mineral fraction recovery rates of 90% in Europe and 79% in Spain (Eurostat, 2018c).

Despite this, the potential for reuse and recycling of this waste stream has not yet been fully exploited, as shown by the indicators of the circular economy monitoring framework (European Commission, 2018b). For example, in 2016 the contribution of RA to NA demand was 8% in Europe and 1% in Spain (Eurostat, 2018d; UEPG, 2017). This, on the one hand, is due to the fact that until the recent approval of Directive (EU) 2018/851 (European Parliament and Council, 2018) amending Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008), the recovery target included backfilling, a practice that does not keep the value of the materials in the economy and is therefore not conducive to a circular economy (European Commission, 2018b). The Directive (EU) 2018/851 (European Parliament and Council, 2018) established new rules for calculating targets, which meant that materials used for backfilling shall not be counted towards the attainment of the recycling targets. Moreover, lack of confidence in the quality of these materials, the absence of specific regulations, or the low price of NA, have had a negative effect on effective C&DW management (Menegaki and Damigos, 2018). Therefore, in compliance with the measures laid out in the Action Plan for the Circular Economy (European Commission, 2015), the European Commission recently published the "EU Construction and Demolition Waste Management Protocol" (European Commission, 2016b) and "Guidelines for the waste audits before demolition and renovation works of buildings" (European Commission, 2018d). The aim of these documents is to provide a methodology to help national authorities achieve the EU 2020 target for CDW recycling, by institutionalising the practice of selective demolition, thereby facilitating the task of segregating the different components and handling each one separately (Silva et al., 2018). This enables C&DW to be used as a secondary raw material in a circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimised (European Commission, 2014c).

The use of RA as a replacement for NA in different construction applications has been evaluated in numerous studies, which have shown the possibility of broadening the application range of RA and C&DW recycling. These include the use of RA in the manufacture of structural concrete (Etxeberria et al., 2007; Muduli and Mukharjee, 2019; Tošić et al., 2015), non-structural concrete (Guo et al., 2018; Sánchez-Roldán et al., 2016), road construction (Chan et al., 2019; López-Alonso et al., 2019; Martín-Morales et al., 2013a; Vegas et al., 2011), masonry mortar production (Fernández-Ledesma et al., 2016; Jiménez et al., 2013), or as extensive green roof substrate (López-Uceda et al., 2018; Mickovski et al., 2013; Molineux et al., 2015). All these studies have shown that RA has greater water absorption capacity than NA, mainly due to the presence of mortar and ceramic material (Sánchez de Juan, 2005). In addition, the water absorption capacity of RFA is even greater than RA (Barbudo et al., 2012; Corinaldesi and Moriconi, 2009). This characteristic has an important effect on the properties of concretes and mortars in the fresh and hardened state, particularly in terms of reducing workability and mechanical strength (Bektas et al., 2009; Pereira et al., 2012a). This is why RFA cannot be used in the manufacture of structural concrete (Martín-Morales et al., 2013c), although recent studies evaluating its use in the manufacture of structural and non-structural concrete (Bravo et al., 2017; Long et al., 2018; Pereira et al., 2012b; Zega and Di Maio, 2011), bricks (Ismail and Yaacob, 2010), precast concrete hollow blocks (Martín-Morales et al., 2017), asphalt mixture (Chen et al., 2011), and masonry mortars (Corinaldesi et al., 2002; de Oliveira Andrade et al., 2018; Martínez et al., 2013; Vegas et al., 2009) have reported good results. Nevertheless, RFA currently has little use, and is usually sent to landfill or stored in recycling plants (Torres-Gómez et al., 2016).

Despite regulatory restrictions, RFA does have some applications. For example, in standard EN 13.139: Aggregates for mortar (CEN, 2002a), its use is permitted in the manufacture of masonry mortars. Given the limitations of RFA, some studies have attempted to determine the effect that increasing the total w/c ratio (Jiménez et al., 2013; Martínez et al., 2018) or incorporating admixtures (Vegas et al., 2009) would have on the properties of fresh and hardened mortar. The aim has been to establish the dosages needed to compensate for the effect of water absorption capacity of this aggregate and reduced consistency and mechanical strength. However, no studies have yet determined the combined influence of the variables responsible for these properties.

In light of the foregoing, the main aim of this study has been to determine the influence of total w/c ratio, RFA, and plasticizer admixture on the fresh and hardened properties of masonry mortars made with NFA and RFA from C&DW, in order to obtain mortars made with RFA that meet regulatory requirements. This will allow C&DW to be used as a resource in the circular economy, and will help conserve natural resources and reduce waste generation.

9. Materials and methods

9.1. Materials

The masonry mortars were made with the following materials:

- Fine aggregate:
    - A dolomitic NFA of 0/2 mm size with a bulk density of 2.818 t/m^3.
    - A RFA of 0/2 mm size produced in a C&DW treatment and recovery plant. The RFA was obtained from civil engineering concrete waste which, according to EN 933-11 (CEN, 2009b), consists of: 87% concrete (Rc), 7.5% NA (Ru), 2.5% brick (Rb), 1.6% asphalt (Ra) and 0.2% other impurities (X). The bulk density of this RFA is 2.630 t/m^3.
- Filler. A limestone BETOCARB P1-DA filler with a bulk density of 0.890 t/m^3 was added to the aggregate to adjust the fineness modulus to comply with EN 13139 (CEN, 2002a).
- Cement. Portland cement EN 197-1- CEM II/AL 42.5 R according to RC-16 (Ministerio de la Presidencia, 2016), with a bulk density of 1.100 t/m^3 was used.
- Admixture. A commercial air entraining/plasticizer admixture (AEPA) supplied in powder form (RHEOMIX 932), with a bulk density of 0.900 t/m^3 was used. According to EN 934-3 (CEN, 2012b), the main function of this admixture is to increase workability by incorporating during mixing a controlled quantity of small, uniformly distributed air bubbles which remain after hardening.

9.2. Methods

9.2.1. Mortar samples

For the purposes of this study, two mortar series in which NFA was replaced with varying percentages of RFA (25%, 50%, 75% and 100%) and four different dosages of AEPA with respect to cement mass (1%, 3%, 6% and 9%) were manufactured. A traditional mortar made with NFA was used as the control sample, and denominated and classified as mortar for masonry for general purpose (G), class M5, according to EN 998-2 Standard (CEN, 2012a); this mortar is the most widely used in construction elements not subject to structural requirements, according to the Spanish "Código Técnico de la Edificación" (Ministerio de Fomento, 2009). All these mortars were grouped into two series (D and P) depending on the moisture state of the RFA. The characteristics of these series are summarised in Table 10, and defined as:

- In the D series, the RFA was used in the dry state. The total w/c ratio of 1.4 remained constant, so the effective w/c ratio decreased with each dosage of RFA, ranging from 1.196 to 0.895.
- In the P series, RFA pre-soaked to 67% of its WA24h was used for mortars with partial RFA content (25%, 50% and 75%) and to 80% of its WA24h for mortars with total NFA replacement (100%), according to the results obtained in the Chapter 1 of this document. These pre-soaking water values gave the mortars plasticity and yielded good results for the properties studied. The total w/c ratio increased with the increase in RFA content, and ranged from 1.484 to 1.804.

Table 10. Characteristics of the mortar series

Mortar	*RFA*	*AEPA*	*Pre-soaking*	*Pre-soaking water*		*Mixing water*	*Total water*	*Reference*
Series	*(%)*	*(%)*	*method*	*% WA_{24h}*[a]	*Value*[b] *(%)*	*(%)*	*(%)*	
Reference	0	1	-	-	-	14	14	Manufacturer
D	25/50/75[c]/100[c]	1/3/6/9	-	-	-	14	14	[d]
P	25/50/75	1/3/6/9	PS-67	67	4.22	14	14 + PSW[e]	[d]
P	100	1/3/6/9	PS-80	80	5.04	14	14 + PSW	[d]

[a] *WA_{24h}* value of RFA = 6.3% (Water absorption capacity of RFA according to EN 1097-6 (CEN, 2013b)).
[b] By dry mass (g) of RFA added.
[c] Mortar samples with 75% and 100% replaced NFA were not workable to test in hardened state.
[d] New conditions tested.; [e] RFA pre-soaking water determined according to the pre-soaking method used.

The dosage of mortars is related in Table 11. Mortars were dosed by weight following the procedure used by other authors (Cabrera-Covarrubias et al., 2015; Evangelista et al., 2018; Poon and Kou, 2010; Vegas et al., 2009) and according to the manufacturer's instructions for an M5 class masonry mortar for general purposes (G) as determined in EN 998-2 (CEN, 2012a). The AEPA dosage, expressed as a % of cement mass, was within the manufacturer’s dosage range (1%-9%), taking as reference the dosage established for M5 class mortar, which is 1%. The different mortar samples were assigned the letter of the series (D or P) and a number, corresponding to the percentage of RFA and AEPA incorporated. Mixing followed the procedure set forth in standard EN 1015-2 (CEN, 1998a). The RFA pre-soaking process consisted of mixing the aggregate with pre-soaking water in the mixer at a low speed for 5 minutes and leaving it to rest for 10 minutes. Following this, the pre-soaked RFA was mixed with the rest of the dry mortar components (NFA, cement, and AEPA) and the mixing water was added.

9.2.1. Testing methods

The properties of the masonry mortars, the test methods applied, and the limits established according to the category and strength class are shown in Table 12. For the purposes of this study, the following values have also been taken into account: i) plastic consistency (140-200 mm) that facilitates the use of the fresh mortar during construction works; and ii) 5% to 20% air content of fresh mortar, as recommended by to Bustillo Revuelta (2008).

Table 11. Dosage table of mortars studied

Masonry Mortars	*NFA (g)*	*RFA (g)*	*Filler (g)*	*Cement (g)*	*AEPA (g)*	*Pre-soaking water (g)*	*Mixing water (g)*	*Total water (g)*	*Total w/c*	*Effective w/c*
	Mix proportions–Dry mass (3 kg)									
Reference	2430	0	270	300	3	0	420	420	1.400	1.295
D-25-1	1836	594	270	300	3	0	420	420	1.400	1.196
D-50-1	1215	1215	270	300	3	0	420	420	1.400	1.092
D-75-1	594	1809	297	300	3	0	420	420	1.400	0.994
D-100-1	0	2403	297	300	3	0	420	420	1.400	0.895
D-25-3	1836	594	270	300	9	0	420	420	1.400	1.196
D-50-3	1215	1215	270	300	9	0	420	420	1.400	1.092
D-75-3	594	1809	297	300	9	0	420	420	1.400	0.994
D-100-3	0	2403	297	300	9	0	420	420	1.400	0.895
D-25-6	1836	594	270	300	18	0	420	420	1.400	1.196
D-50-6	1215	1215	270	300	18	0	420	420	1.400	1.092
D-75-6	594	1809	297	300	18	0	420	420	1.400	0.994
D-100-6	0	2403	297	300	18	0	420	420	1.400	0.895
D-25-9	1836	594	270	300	27	0	420	420	1.400	1.196
D-50-9	1215	1215	270	300	27	0	420	420	1.400	1.092
D-75-9	594	1809	297	300	27	0	420	420	1.400	0.994
D-100-9	0	2403	297	300	27	0	420	420	1.400	0.895
P-25-1	1836	594	270	300	3	25	420	445	1.484	1.279
P-50-1	1215	1215	270	300	3	51	420	471	1.571	1.263
P-75-1	594	1809	297	300	3	76	420	496	1.655	1.249
P-100-1	0	2403	297	300	3	121	420	541	1.804	1.299
P-25-3	1836	594	270	300	9	25	420	445	1.484	1.279
P-50-3	1215	1215	270	300	9	51	420	471	1.571	1.263
P-75-3	594	1809	297	300	9	76	420	496	1.655	1.249
P-100-3	0	2403	297	300	9	121	420	541	1.804	1.299
P-25-6	1836	594	270	300	18	25	420	445	1.484	1.279
P-50-6	1215	1215	270	300	18	51	420	471	1.571	1.263
P-75-6	594	1809	297	300	18	76	420	496	1.655	1.249
P-100-6	0	2403	297	300	18	121	420	541	1.804	1.299
P-25-9	1836	594	270	300	27	25	420	445	1.484	1.279
P-50-9	1215	1215	270	300	27	51	420	471	1.571	1.263
P-75-9	594	1809	297	300	27	76	420	496	1.655	1.249
P-100-9	0	2403	297	300	27	121	420	541	1.804	1.299

Table 12. Properties of masonry mortars, test standards, and established limits

Properties	*Test Standard*	*Limits*	*Category / Mortar class*	*Reference*
Fresh state				
Consistency	EN 1015-3(CEN, 2004)	Dry (< 140 mm) Plastic (140-200 mm) Fluid (> 200 mm)	-	EN 1015-6 (CEN, 1998b)
Bulk density	EN 1015-6 (CEN, 1998b)	Not specified	-	Manufacturer
Air content	EN 1015-7 (CEN, 1998c)	5-20%	-	(Bustillo Revuelta, 2008)
Hardened state				
Dry bulk density	EN 1015-10 (CEN, 1999c)	Not specified	-	-
Water absorption due to capillary action	EN 1015-18 (CEN, 2002b)	Not specified	G	-
Compressive and flexural strength	EN 1015-11 (CEN, 1999d)	fc 28-day ≥ 5 N/mm^2	G / M5	EN 998-2 (CEN, 2012a)

9.2.2. Statistical Analysis

The data were analysed using analysis of variance (ANOVA) tests on IBM SPSS statistics (v.24) software (IBM Corp., 2016). The following factors and levels were analysed: i) two levels of total w/c ratio (1.4 and >1.4); ii) four levels of RFA dosage (25%, 50%, 75% and 100%); and iii) four levels of AEPA dosage (1%, 3%, 6% and 9%). The combinations of these was studied in a total of 32 samples.

Three-way ANOVA was used to simultaneously study the effect of the factors, which were called main effects, pared interactions (first-order interactions), and three-way interactions (second order interaction), on each property of the recycled masonry mortar mixtures analysed. A factor or interaction between factors was considered to have a significant effect on a property if a P value associated with an F statistic was found to be less than 0.05 (95% confidence level); the larger the F value, the higher the effect of the factor (Cheng et al., 2016). To facilitate the interpretation of the results, the main effects of the factors were plotted on graphs. The percentage contribution of each factor or interaction was also used to determine the degree of effect on the dependent variable. This was calculated by dividing the factor sequential sum of squares by the total sequential sum of squares. Tukey post hoc multiple comparison, with a significance level of 0.05, was used on factors with more than two levels (RFA and AEPA), and to determine the difference between means.

Finally, one-way ANOVA with a confidence interval of 95% ($p < 0.05$) was used to compare the means of the mortars manufactured, and regression analysis was used to determine the existence of factor/property dependency. The type of correlation was determined according to the R^2 effect size proposed in Moore et al. (2013): i) Very weak, if $R^2 < 0.3$; ii) Weak or low if $0.3 < R^2 < 0.5$; iii) Moderate if $0.5 < R^2 < 0.7$; and iv) Strong if $R^2 > 0.7$.

10. Results and discussion

The properties of the fresh and hardened mortars are shown in Table 13 and Table 14, respectively. In these tables, data are expressed as mean and standard deviation, and the superscript letter shows the Tukey HSD homogeneous groups (HG) to which each mortar belongs, determined by one-way ANOVA. As can be seen in, it was not possible to evaluate the properties of D series hardened mortar with 75% and 100% RFA. This was because the lack of plasticity of the mortar (with consistency values between 100 and 110 mm) made it impossible to create test specimens. Figure 20 and Figure 21 show a 3D representation of the results obtained in each series, according to RFA and AEPA percentage dosage, based on the regulatory limit values for consistency and compressive strength. For the remaining properties, the worse value of all the mortars in the same homogeneous group as the reference mortar was used; these are highlighted in bold in Table 13 and Table 14. Table 15 and Table 16 show the results of the three-way ANOVA performed to determine the properties of fresh and hardened mortars, respectively. The sum of squares, degrees of freedom, mean of squares, F-ratio, P-value, significance, and percentage contribution are given for each property evaluated and for each factor and interaction. Table A1 (in Annex) lists compliance with the technical requirements of mortars. The results obtained are analysed and discussed below.

Table 13. Results of tests to determine the properties of fresh mortars

Mortar	Factors			Properties					
	T w/c	RFA (%)	AEPA (%)	Consistency (mm)	HG[a]	Bulk density (kg/m^3)	HG[a]	Air content (%)	HG[a]
Reference	1.4	0	1	153 ± 2.0	f,g,h,i,j,k	1958 ± 24	g,h,i	14.3 ± 0.58	b,c,d,e
D-25-1	1.4	25	1	143 ± 4.5	c,d,e,f	1922 ± 23	e,f,g,h,i	14.7 ± 0.58	b,c,d,e
D-25-3	1.4	25	3	142 ± 2.0	c,d,e,f	1974 ± 14	h,i	12.5 ± 0.50	a,b
D-25-6	1.4	25	6	155 ± 1.5	g,h,i,j,k	1803 ± 68	a,b,c,d,e,f,g,h	17.8 ± 0.29	d,e,f,g
D-25-9	1.4	25	9	155 ± 0.0	g,h,i,j,k	1823 ± 107	a,b,c,d,e,f,g,h	16.2 ± 2.04	b,c,d,e,f
D-50-1	1.4	50	1	120 ± 1.0	b	1968 ± 18	h,i	13.7 ± 0.29	a,b,c,d
D-50-3	1.4	50	3	121 ± 1.0	b	2028 ± 28	i	9.0 ± 0.45	a
D-50-6	1.4	50	6	136 ± 1.0	c	1868 ± 43	c,d,e,f,g,h,i	16.0 ± 0.50	b,c,d,e,f
D-50-9	1.4	50	9	144 ± 0.6	c,d,e,f	1900 ± 61	d,e,f,g,h,i	14.9 ± 1.65	b,c,d,e
D-75-1	1.4	75	1	100 ± 0.6	a	1850 ± 11	b,c,d,e,f,g,h,i	16.0 ± 0.50	b,c,d,e,f
D-75-3	1.4	75	3	105 ± 0.6	a	1849 ± 50	b,c,d,e,f,g,h,i	16.0 ± 0.45	b,c,d,e,f
D-75-6	1.4	75	6	100 ± 0.6	a	1856 ± 25	c,d,e,f,g,h,i	16.0 ± 0.50	b,c,d,e,f
D-75-9	1.4	75	9	110 ± 1.0	a,b	1940 ± 16	f,g,h,i	13.0 ± 1.00	a,b,c
D-100-1	1.4	100	1	100 ± 0.6	a	**1785** ± 17	a,b,c,d,e,f,g	17.5 ± 0.50	c,d,e,f,g
D-100-3	1.4	100	3	100 ± 0.6	a	1747 ± 121	a,b,c,d,e	**18.3** ± 2.52	d,e,f,g
D-100-6	1.4	100	6	100 ± 0.6	a	1773 ± 21	a,b,c,d,e,f	**12.0** ± 0.50	a,b
D-100-9	1.4	100	9	100 ± 0.6	a	1727 ± 25	a,b,c,d	22.0 ± 1.00	g
P-25-1	>1.4	25	1	159 ± 8.4	i,j,k,l	1860 ± 11	c,d,e,f,g,h,i	16.5 ± 0.50	b,c,d,e,f
P-25-3	>1.4	25	3	157 ± 3.5	h,i,j,k,l	1882 ± 48	c,d,e,f,g,h,i	15.8 ± 1.26	b,c,d,e,f
P-25-6	>1.4	25	6	172 ± 3.8	n	1792 ± 95	a,b,c,d,e,f,g,h	19.0 ± 2.65	e,f,g
P-25-9	>1.4	25	9	170 ± 3.0	m,n	1906 ± 44	d,e,f,g,h,i	15.7 ± 1.53	b,c,d,e,f
P-50-1	>1.4	50	1	146 ± 4.0	c,d,e,f,g,h	1710 ± 12	a,b,c	19.0 ± 1.00	e,f,g
P-50-3	>1.4	50	3	148 ± 2.5	d,e,f,g,h,i	1891 ± 33	c,d,e,f,g,h,i	15.5 ± 0.50	b,c,d,e,f
P-50-6	>1.4	50	6	163 ± 1.0	k,l,m,n	1842 ± 104	b,c,d,e,f,g,h	16.0 ± 3.61	b,c,d,e,f
P-50-9	>1.4	50	9	168 ± 2.1	l,m,n	1846 ± 21	b,c,d,e,f,g,h,i	16.0 ± 1.00	b,c,d,e,f
P-75-1	>1.4	75	1	142 ± 3.8	c,d,e,f	1650 ± 2	a	19.8 ± 0.29	f,g
P-75-3	>1.4	75	3	140 ± 1.5	c,d,e	1833 ± 50	b,c,d,e,f,g,h	15.5 ± 1.50	b,c,d,e,f
P-75-6	>1.4	75	6	145 ± 4.5	c,d,e,f,g	1816 ± 46	a,b,c,d,e,f,g,h	15.0 ± 1.50	b,c,d,e
P-75-9	>1.4	75	9	160 ± 5.5	j,k,l,m	1752 ± 17	a,b,c,d,e	17.3 ± 0.75	c,d,e,f,g
P-100-1	>1.4	100	1	140 ± 3.6	c,d,e	1670 ± 22	a,b	17.5 ± 0.50	c,d,e,f,g
P-100-3	>1.4	100	3	142 ± 8.0	c,d,e,f	1725 ± 102	a,b,c,d	16.3 ± 2.84	b,c,d,e,f
P-100-6	>1.4	100	6	140 ± 4.5	c,d	1772 ± 17	a,b,c,d,e,f	15.3 ± 0.29	b,c,d,e,f
P-100-9	>1.4	100	9	151 ± 6.9	e,f,g,h,i	1710 ± 141	a,b,c	17.7 ± 3.62	c,d,e,f,g

HG[a]: Homogeneous groups

Table 14. Results of tests to determine the properties of hardened mortars

Mortars	*Factors*			*Properties*											
	t w/c	*RFA*	*AEPA*	*Dry bulk density*		*Capillary water absorption coefficient*		*Compressive strength (7-d)*		*Compressive strength (28-d)*		*Flexural strength (7-d)*		*Flexural strength (28-d)*	
		(%)	*(%)*	*(kg/m^3)*	*HG^a*	*(kg/(m^2*min$^{0.5}$))*	*HG^a*	*(N/mm^2)*	*HG^a*	*(N/mm^2)*	*HG^a*	*(N/mm^2)*	*HG^a*	*(N/mm^2)*	*HG^a*
Reference	1.4	0	1	1795 ± 8	g,h,i,j	0.690 ± 0.010	i,j	4.0 ± 0.25	f,g	7.0 ± 0.09	d,e,f	1.9 ± 0.05	c,d,e,f,g	2.6 ± 0.21	d,e,f,g
D-25-1	1.4	25	1	1800 ± 17	h,i,j	0.605 ± 0.177	h,i,j	4.9 ± 0.07	h,i	8.7 ± 0.10	g,h,i	2.2 ± 0.19	g,h,i,j,k	3.5 ± 0.16	i,j
D-25-3	1.4	25	3	1802 ± 25	h,i,j	0.404 ± 0.008	c,d,e,f	6.0 ± 0.17	j,k	8.2 ± 0.33	f,g,h	2.1 ± 0.04	f,g,h,i,j	2.9 ± 0.04	g,h,i
D-25-6	1.4	25	6	1722 ± 86	c,d,e,f,g,h,i	0.274 ± 0.012	a,b,c	5.1 ± 0.23	i	9.1 ± 0.12	h,i,j	2.2 ± 0.07	h,i,j,k	3.3 ± 0.07	h,i,j
D-25-9	1.4	25	9	1762 ± 103	e,f,g,h,i,j	0.224 ± 0.008	a,b	6.0 ± 0.10	j,k	9.7 ± 0.43	i,j	2.4 ± 0.12	j,k,l	3.6 ± 0.04	j
D-50-1	1.4	50	1	1830 ± 17	i,j	0.543 ± 0.015	g,h	6.2 ± 0.23	k,l	11.3 ± 0.07	k	2.7 ± 0.00	l	3.8 ± 0.06	j
D-50-3	1.4	50	3	1896 ± 6	j	0.335 ± 0.007	b,c,d,e,f	6.8 ± 0.07	l	10.2 ± 0.26	j,k	2.7 ± 0.25	l	3.5 ± 0.24	i,j
D-50-6	1.4	50	6	1807 ± 20	h,i,j	0.312 ± 0.102	a,b,c,d,e	6.0 ± 0.08	j,k	10.2 ± 0.19	j,k	2.5 ± 0.03	k,l	3.8 ± 0.25	j
D-50-9	1.4	50	9	1778 ± 73	f,g,h,i,j	0.195 ± 0.015	a	5.4 ± 0.49	i,j	9.9 ± 0.21	i,j	2.3 ± 0.07	i,j,k	3.7 ± 0.06	j
P-25-1	>1.4	25	1	1710 ± 15	b,c,d,e,f,g,h,i	0.693 ± 0.001	i,j	3.1 ± 0.06	b,c,d,e	6.3 ± 0.24	b,c,d,e	1.4 ± 0.03	a,b	2.2 ± 0.17	b,c,d,e,f
P-25-3	>1.4	25	3	1828 ± 34	i,j	0.445 ± 0.004	f,g	4.0 ± 0.10	f,g	6.7 ± 0.38	d,e	2.0 ± 0.10	e,f,g,h,i	2.7 ± 0.02	e,f,g,h
P-25-6	>1.4	25	6	1712 ± 70	b,c,d,e,f,g,h,i	0.281 ± 0.005	a,b,c	3.1 ± 0.10	c,d,e	5.3 ± 1.06	a,b,c	1.5 ± 0.10	a,b,c	2.3 ± 0.43	b,c,d,e,f,g
P-25-9	>1.4	25	9	1807 ± 18	h,i,j	0.309 ± 0.003	a,b,c,d,e	4.4 ± 0.72	g,h	7.0 ± 0.10	d,e,f	2.2 ± 0.30	f,g,h,i,j,k	2.7 ± 0.06	d,e,f,g
P-50-1	>1.4	50	1	1620 ± 4	a,b,c,d,e	0.616 ± 0.006	h,i,j	2.4 ± 0.07	a,b	4.9 ± 0.00	a,b	1.3 ± 0.04	a,b	**2.1** ± 0.07	a,b,c,d
P-50-3	>1.4	50	3	1802 ± 23	h,i,j	0.433 ± 0.005	e,f,g	4.8 ± 0.10	h,i	6.7 ± 0.56	d,e	2.0 ± 0.10	e,f,g,h,i	2.6 ± 0.00	d,e,f,g
P-50-6	>1.4	50	6	1693 ± 17	b,c,d,e,f,g,h,i	0.321 ± 0.001	a,b,c,d,e,f	3.5 ± 0.10	d,e,f	5.7 ± 0.14	a,b,c,d	1.6 ± 0.10	a,b,c,d	2.4 ± 0.07	b,c,d,e,f,g
P-50-9	>1.4	50	9	1677 ± 123	b,c,d,e,f,g,h	0.280 ± 0.009	a,b,c	4.0 ± 0.10	f,g	5.7 ± 1.06	a,b,c,d	2.1 ± 0.10	f,g,h,i,j	2.4 ± 0.28	d,e,f,g
P-75-1	>1.4	75	1	1580 ± 15	a,b,c,d	0.585 ± 0.004	h,i	2.3 ± 0.20	a	4.8 ± 0.22	a	1.3 ± 0.03	a	1.9 ± 0.04	a,b,c
P-75-3	>1.4	75	3	1730 ± 30	d,e,f,g,h,i	0.418 ± 0.007	d,e,f,g	4.3 ± 0.10	g,h	6.8 ± 0.77	d,e	2.0 ± 0.10	e,f,g,h,i	2.5 ± 0.12	c,d,e,f,g
P-75-6	>1.4	75	6	1732 ± 25	e,f,g,h,i	0.330 ± 0.004	b,c,d,e,f	4.1 ± 0.10	f,g	7.4 ± 0.45	e,f,g	1.9 ± 0.10	d,e,f,g,h	2.8 ± 0.19	f,g,h
P-75-9	>1.4	75	9	1634 ± 79	b,c,d,e,f	0.293 ± 0.006	a,b,c,d	4.4 ± 0.10	g,h	6.5 ± 0.43	c,d,e	2.2 ± 0.10	f,g,h,i,j	2.4 ± 0.74	f,g,h
P-100-1	>1.4	100	1	1470 ± 20	a	**0.732** ± 0.008	j	2.7 ± 0.07	a,b,c	4.7 ± 0.27	a	1.4 ± 0.05	a,b	1.6 ± 0.08	a
P-100-3	>1.4	100	3	1563 ± 9	a,b	0.416 ± 0.004	d,e,f,g	2.8 ± 0.10	a,b,c,d	4.6 ± 0.18	a	1.3 ± 0.10	a,b	1.8 ± 0.10	a,b
P-100-6	>1.4	100	6	**1648** ± 23	b,c,d,e,f,g	0.366 ± 0.009	c,d,e,f	3.9 ± 0.10	f,g	6.3 ± 0.55	c,d,e	1.8 ± 0.10	c,d,e,f	2.4 ± 0.41	c,d,e,f,g
P-100-9	>1.4	100	9	1574 ± 24	a,b,c	0.378 ± 0.001	c,d,e,f	3.7 ± 0.10	e,f,g	5.9 ± 0.19	a,b,c,d	1.7 ± 0.10	b,c,d,e	2.2 ± 0.24	a,b,c,d,e

HG^a: Homogeneous groups

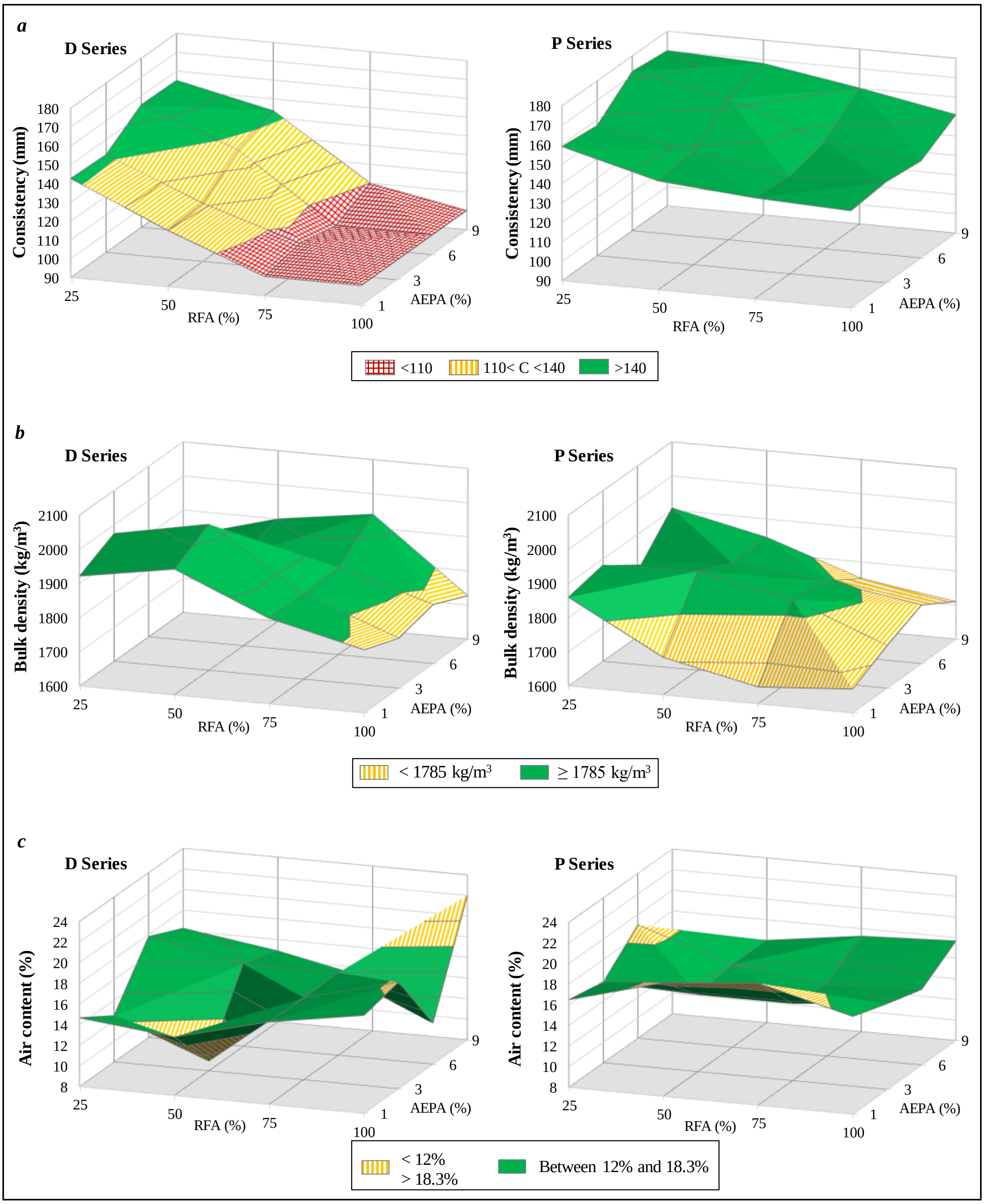

Figure 20. 3D representation of the properties of fresh mortars

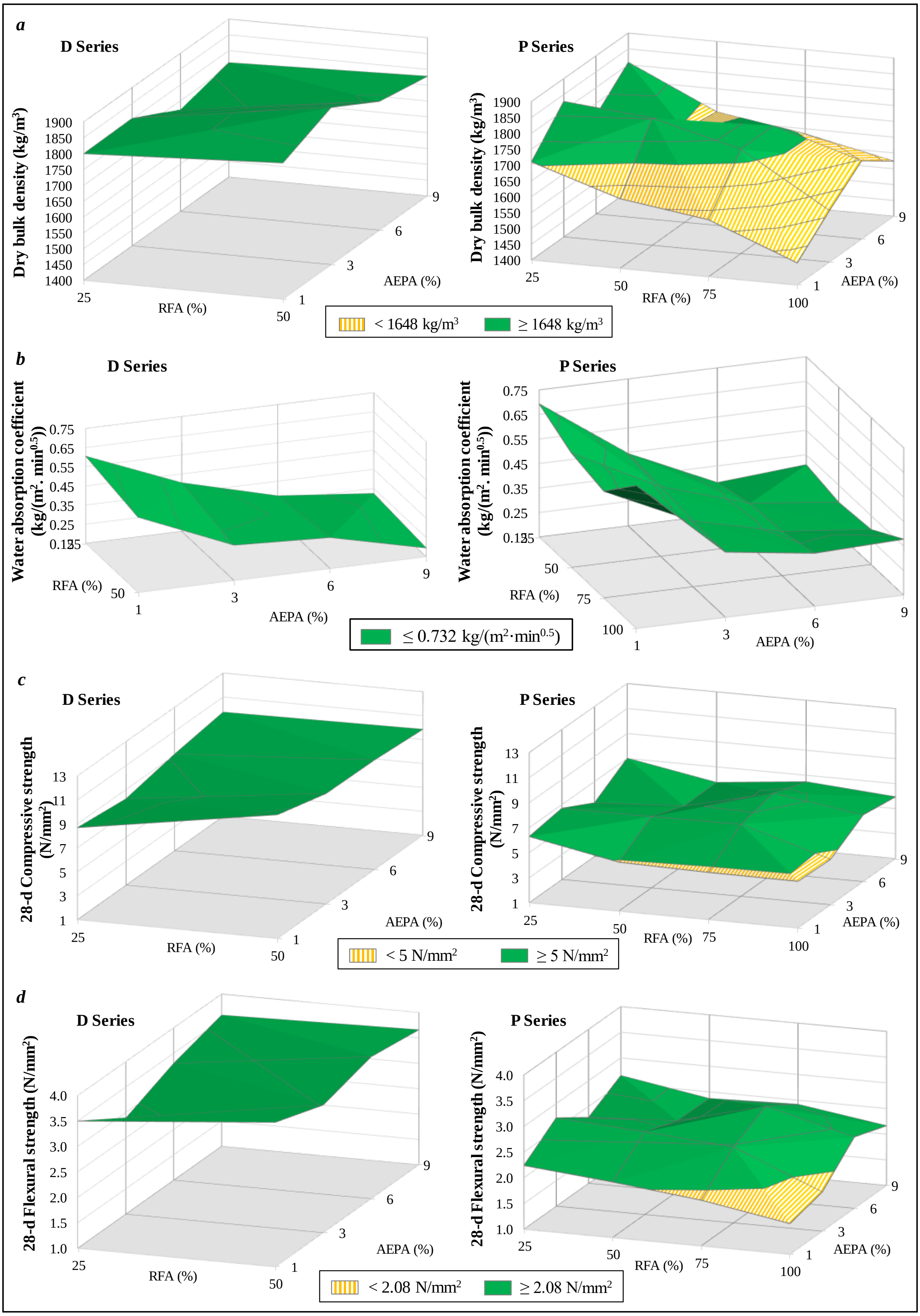

Figure 21. 3D representation of the properties of hardened mortars

Table 15. Results of three-way ANOVA to determine the properties of fresh mortars

Source of variation	*Sum of squares*	*Degrees of free*	*Mean of squares*	*F-ratio*	*P value*	*Significance*	*Contribution (%)*
Consistency							
total w/c	24288.844	1	24288.844	2045.376	<0.0001	Yes	46.9
RFA	18953.865	3	6317.955	532.038	<0.0001	Yes	36.6
AEPA	2926.865	3	975.622	82.158	<0.0001	Yes	5.7
total w/c*RFA	3247.198	3	1082.399	91.149	<0.0001	Yes	6.3
total w/c*AEPA	88.198	3	29.399	2.476	0.0694	Non	0.2
RFA*AEPA	1272.094	9	141.344	11.903	<0.0001	Yes	2.5
total w/c*RFA*AEPA	203.927	9	22.659	1.908	0.0665	Non	0.4
Error	760.000	64	11.875	-	-	-	1.5
Total	51740.990	95	-	-	-	-	100
Model	50980.99	31	1644.548	138.488	<0.0001	Yes	98.5
Bulk density							
total w/c	85741.260	1	85741.260	15.611	0.0002	Yes	13.0
RFA	306213.245	3	102071.082	31.270	<0.0001	Yes	31.6
AEPA	55394.411	3	18464.804	5.657	0.0017	Yes	5.7
total w/c*RFA	44836.661	3	14945.554	4.579	0.0057	Yes	4.6
total w/c*AEPA	66594.828	3	22198.276	6.801	0.0005	Yes	6.9
RFA*AEPA	98275.737	9	10919.526	3.345	0.0021	Yes	10.1
total w/c*RFA*AEPA	62798.820	9	6977.647	2.138	0.0387	Yes	6.5
Error	208909.253	64	3264.207	-	-	-	21.6
Total	968637.026	95	-	-	-	-	100
Model	759727.773	31	24507.348	7.508	<0.0001	Yes	78.4
Air content							
total w/c	46.760	1	46.760	21.165	<0.0001	Yes	6.7
RFA	51.690	3	17.230	7.799	0.0002	Yes	7.5
AEPA	55.787	3	18.596	8.417	0.0001	Yes	8.1
total w/c*RFA	48.711	3	16.237	7.349	0.0003	Yes	7.0
total w/c*AEPA	23.550	3	7.850	3.553	0.0191	Yes	3.4
RFA*AEPA	209.371	9	23.263	10.529	<0.0001	Yes	30.2
total w/c*RFA*AEPA	115.728	9	12.859	5.820	<0.0001	Yes	16.7
Error	141.400	64	2.209	-	-	-	20.4
Total	692.998	95	-	-	-	-	100
Model	551.598	31	17.793	8.054	<0.0001	Yes	79.6

Table 16. Results of three-way ANOVA to determine the properties of hardened mortars

Source of variation	*Sum of squares*	*Degrees of free*	*Mean of squares*	*F-ratio*	*P value*	*Significance*	*Contribution (%)*
Dry bulk density							
total w/c	253753.56	1	253753.568	106.525	<0.0001	Yes	29.5
RFA	224935.57	3	74978.526	31.476	<0.0001	Yes	26.2
AEPA	96705.437	3	32235.146	13.532	<0.0001	Yes	11.2
total w/c*RFA	45112.588	1	45112.588	18.938	0.0001	Yes	5.2
total w/c*AEPA	52219.647	3	17406.549	7.307	0.0004	Yes	6.1
RFA*AEPA	71994.844	9	7999.427	3.358	0.0029	Yes	8.4
total w/c*RFA*AEPA	723.724	3	241.241	0.101	0.9589	Non	0.1
Error	114340.74	48	2382.099	-	-	-	13.3
Total	859786.13	71	-	-	-	-	100
Model	745445.38	23	32410.669	13.606	<0.0001	Yes	86.7
Water absorption coefficient							
total w/c	0.078	1	0.078	43.418	<0.0001	Yes	4.9
RFA	0.038	3	0.013	6.996	0.0005	Yes	2.3
AEPA	1.334	3	0.445	248.709	<0.0001	Yes	83.5
total w/c*RFA	0.000	1	0.000	0.194	0.6616	Non	0.02
total w/c*AEPA	0.012	3	0.004	2.253	0.0942	Non	0.8
RFA*AEPA	0.047	9	0.005	2.936	0.0074	Yes	3.0
total w/c*RFA*AEPA	0.002	3	0.001	0.431	0.7319	Non	0.1
Error	0.086	48	0.002	-	-	-	5.4
Total	1.597	71	-	-	-	-	100
Model	1.511	23	0.066	36.748	<0.0001	Yes	94.6
Compressive strength 7-d							
total w/c	79.344	1	79.344	1768.118	<0.0001	Yes	68.7
RFA	2.635	3	0.878	19.574	<0.0001	Yes	2.3
AEPA	15.377	3	5.126	114.220	<0.0001	Yes	13.3
total w/c*RFA	1.003	1	1.003	22.347	<0.0001	Yes	0.9
total w/c*AEPA	4.123	3	1.374	30.628	<0.0001	Yes	3.6
RFA*AEPA	8.938	9	0.993	22.131	<0.0001	Yes	7.7
total w/c*RFA*AEPA	1.933	3	0.644	14.361	<0.0001	Yes	1.7
Error	2.154	48	0.045	-	-	-	1.9
Total	115.508	71	-	-	-	-	100
Model	113.354	23	4.928	109.826	<0.0001	Yes	98.1
Compressive strength 28-d							
total w/c	218.894	1	218.894	1114.437	<0.0001	Yes	77.1
RFA	8.058	3	2.686	13.675	<0.0001	Yes	2.8
AEPA	4.605	3	1.535	7.815	0.0002	Yes	1.6
total w/c*RFA	12.267	1	12.267	62.456	<0.0001	Yes	4.3
total w/c*AEPA	7.355	3	2.452	12.483	<0.0001	Yes	2.6
RFA*AEPA	18.610	9	2.068	10.528	<0.0001	Yes	6.6
total w/c*RFA*AEPA	4.663	3	1.554	7.914	0.0002	Yes	1.6
Error	9.428	48	0.196	-	-	-	3.3
Total	283.882	71	-	-	-	-	100
Model	274.454	23	11.933	60.752	<0.0001	Yes	96.7

Table 16. Results of three-way ANOVA to determine the properties of hardened mortars (continued)

Source of variation	*Sum of squares*	*Degrees of free*	*Mean of squares*	*F-ratio*	*P value*	*Significance*	*Contribution (%)*
Flexural strength 7-d							
total w/c	7.363	1	7.363	533.477	<0.0001	Yes	53.0
RFA	0.831	3	0.277	20.073	<0.0001	Yes	6.0
AEPA	1.703	3	0.568	41.129	<0.0001	Yes	12.3
total w/c*RFA	0.325	1	0.325	23.515	<0.0001	Yes	2.3
total w/c*AEPA	1.385	3	0.462	33.446	<0.0001	Yes	10.0
RFA*AEPA	1.448	9	0.161	11.661	<0.0001	Yes	10.4
total w/c*RFA*AEPA	0.178	3	0.059	4.299	0.0091	Yes	1.3
Error	0.662	48	0.014	-	-	-	4.8
Total	13.896	71	-	-	-	-	100
Model	13.233	23	0.575	41.686	<0.0001	Yes	95.2
Flexural strength 28-d							
total w/c	21.854	1	21.854	561.628	<0.0001	Yes	68.7
RFA	2.412	3	0.804	20.662	<0.0001	Yes	7.6
AEPA	1.568	3	0.523	13.435	<0.0001	Yes	4.9
total w/c*RFA	0.615	1	0.615	15.804	0.0002	Yes	1.9
total w/c*AEPA	1.799	3	0.600	15.410	<0.0001	Yes	5.7
RFA*AEPA	1.561	9	0.173	4.457	0.0003	Yes	4.9
total w/c*RFA*AEPA	0.119	3	0.040	1.020	0.3919	Non	0.4
Error	1.868	48	0.039	-	-	-	5.9
Total	31.796	71	-	-	-	-	100
Model	29.928	23	1.301	33.440	0.000	Yes	94.1

10.1. Properties of fresh mortars

10.1.1. Consistency

According to the experimental results (Table 13) and to facilitate analysis of the effect of total w/c ratio, RFA and AEPA on the consistency of the mortar specimens, Figure 20a shows the values obtained in the D and P series, based on the percentage content of RFA and AEPA. It can be seen that all mortars in the P series achieved plastic consistency, with values ranging from 140 mm to 172 mm, whereas the lowest values were observed in D series mortars, manufactured without pre-soaked aggregate, and therefore with a lower overall w/c ratio. In this case, consistency ranged from 100 mm to 155 mm - a reduction of up to 34.4% with respect to the reference mortar (153 mm). In fact, plastic consistency (> 140 mm) was only achieved in mortars manufactured with 25% RFA, regardless of the dosage of AEPA, and in mortar D-50-9. This decrease in consistency values has also been reported in other studies (Pereira et al., 2012a; Zega and Di Maio, 2011), and is due to the dry RFA absorbing part of the mixing water, which reduces the water available for the cement dispersion action of the AEPA. This undermined the effectiveness of the AEPA to such an extent that it was rendered wholly ineffective when 100% NFA was replaced with RFA, resulting in mortars with dry consistency values of less than 110 mm that could not be evaluated in the hardened state.

As the results show, increasing AEPA content and total w/c ratio improved the consistency values of the mortars. This is due, respectively, to improved dispersion of cement particles, making the mortar more fluid and workable (Mendes et al., 2017; Ouyang et al., 2008), and to pre-soaking the RFA, which prevented it from absorbing part of the mixing water, thus allowing the binder paste to coat the surface of the aggregate and giving the mixture greater plasticity (Rodríguez-Mora, 2003; Corinaldesi et al., 2002;Jiménez et al., 2013). In contrast, as reported in other studies (Alonso et al., 2018; Bektas et al., 2009; Vegas et al., 2009) increasing the RFA content reduced consistency due to the greater water absorption capacity of RFA with respect to NFA (Martín-Morales et al., 2013c), which significantly reduced the effective w/c ratio. Similarly, the rough and angular texture of the RFA tends to interlock and reduce inter-particle movement (Wong et al., 2001). Additionally, more uniform particle size distribution could have been detrimental to consistency due to particle packing (Leite, 2001).

The foregoing results were confirmed by three-way ANOVA (Table 15 and Figure 22) to analyse the effect of total w/c, RFA and AEPA on consistency. These three factors, together with the interactions included in the model, explained 98.5% of the variance. Specifically, total w/c ratio was the main factor affecting consistency and had the highest percentage of contribution (46.9%), followed by RFA (36.6%), and AEPA, which had the least effect (5.7%). Considering the mean consistency values for each factor obtained after multiple Tukey HSD comparisons, the highest values were observed in mortars with 25% of RFA and 9% of AEPA. Furthermore, no statistically significant differences were found between mean consistency values of mortars with 1% and 3% of AEPA (Figure 22). Interactions between total w/c*AEPA and total w/c*RFA*AEPA showed no statistically significant differences ($p < 0.05$). This proves the equality of means hypothesis, where the effect of one of the factors was the same at each level of other factor. This was confirmed by the correlation values of the D and P series mortars (Figure 23), that show a strong inverse linear relationship ($R^2 > 0.7$) between consistency and replacement of NFA by RFA for all AEPA dosages, except for 1% and 3% in the P series, where the inverse linear relationship was moderate ($R^2 \approx 0.6$).

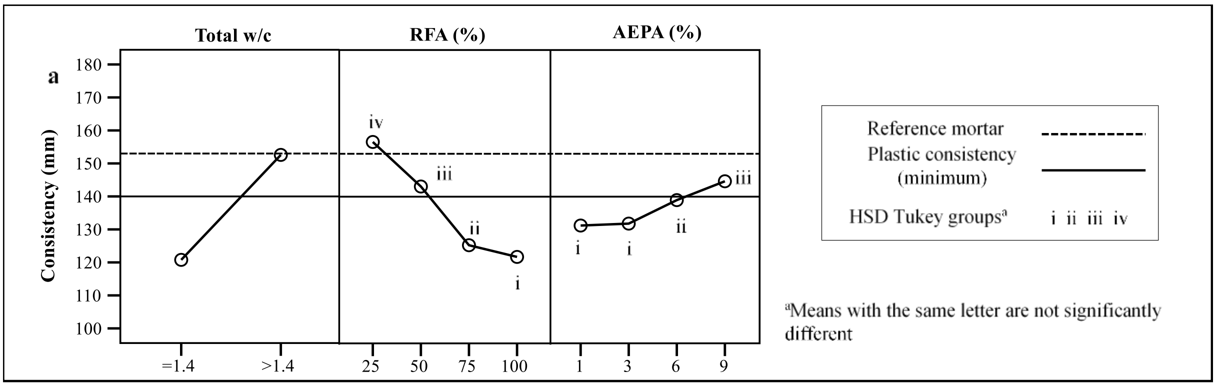

Figure 22. Main effect of factors on the mean values of consistency of masonry mortars

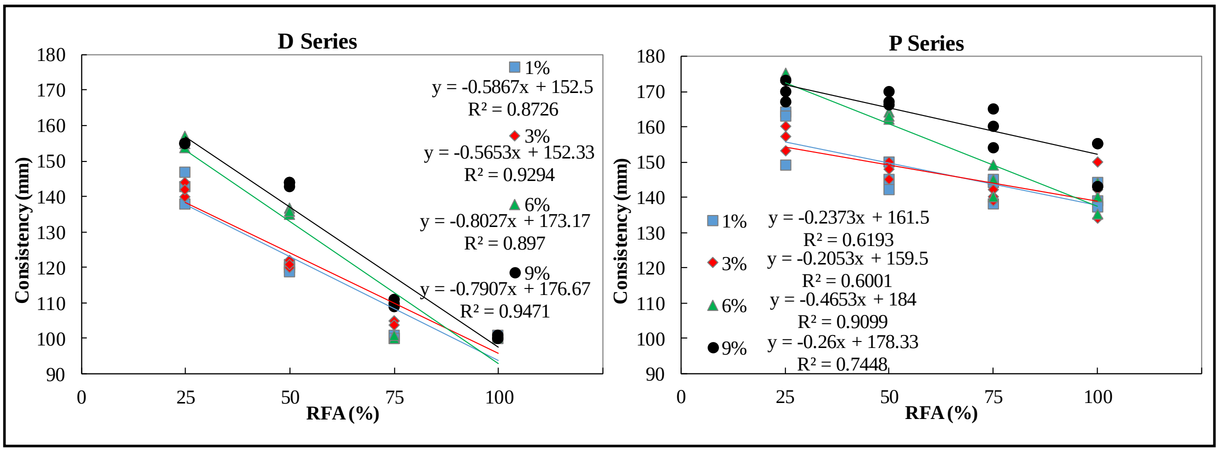

Figure 23. Linear relationships between consistency and RFA as a function of AEPA dosage, for D and P series mortars

10.1.2. Bulk density

The bulk density values of the mortar series are shown in Table 13 and Figure 20b. With respect to the control mortar (1958 kg/m^3), the bulk density of the D series mortars ranged from -11.8% to 3.6%, while those of the P series decreased by between 2.7% and 15.7%.

Generally speaking, decreased bulk density correlated with an increase in total w/c and RFA content, and increased bulk density with increased AEPA content. The best results, from a technical stand point, were obtained in mortars with bulk density values equal to or higher than mortar D-100-1 (1785 kg/m^3), according one-way ANOVA (Figure 20b). The reduction of bulk density in mortars with a higher total w/c ratio has been attributed to the higher water content of the fresh mortar (Silva et al., 2010; Vegas et al., 2009). In the case of mortars with increased RFA content, the decrease in bulk density was due to the relatively lower density of the RFA compared to NFA (Colangelo and Cioffi, 2017; Jiménez et al., 2013; Ledesma et al., 2014; Neno et al., 2014). In the D series in particular, bulk density was higher in mortars with 50% RFA with respect to 25%, due to the decrease in effective w/c ratio that increased the compactness of the mortar (Cartuxo et al., 2016; Kou and Poon, 2009). The increase in bulk density due to the increase in AEPA content is explained by the larger cement/water interface resulting from the action of the AEPA, which helps disperse the cement particles and thus facilitates bonding of solid particles that give rise to a more compact, or less porous, mortar.

Table 15 shows the significant critical values ($p < 0.05$) of the F statistics of the three factors and of all the interactions observed in the three-way ANOVA, confirming the foregoing results. It can be seen that 78.4% of the variation in bulk density was due to the main effects of the three factors (50.3%) and their interactions (28.1%), while the remaining 21.6% was due to chance (error). RFA, which contributed 31.6%, was the major determining factor, followed by total w/c (13%) and AEPA (5.7%). However, the significance of the interactions and their high contribution to variation (28.1%) confirmed the fact that the main effect of the AEPA ratio did not show a linear trend, as can be seen in Figure 24. Likewise, the data also show that the highest average bulk density values were observed in mortars with 50% and 25% RFA content, with no significant differences. In respect of AEPA, density values were higher in mortars manufactured with 3% and 9% of AEPA than those manufactured with 6% and 1%, according to the two groups determined by the HSD Tukey test. A strong inverse linear relationship between bulk density and RFA could be established for AEPA dosages of 1% in the P series, with a value of $R^2 = 0.722$.

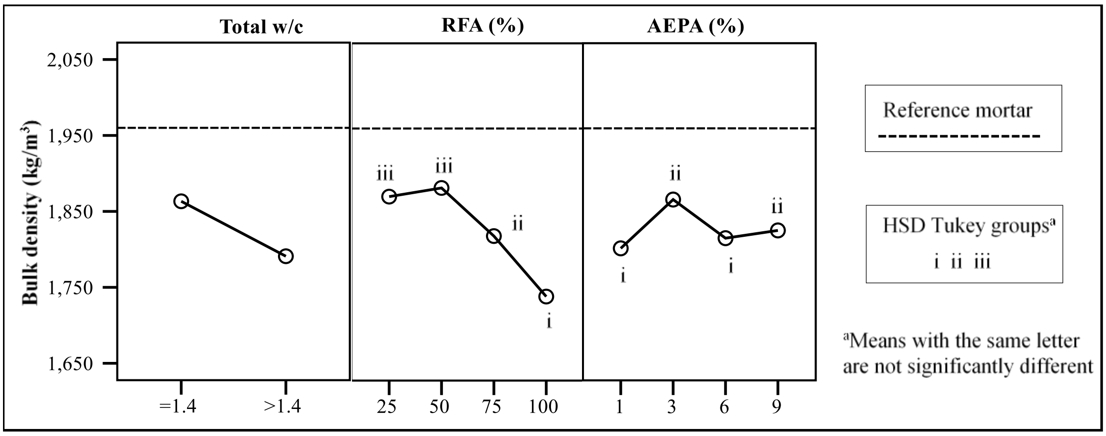

Figure 24. Main effect of factors on the mean bulk density values of masonry mortars

10.1.3. Air content

The durability of the mortar depends on adequate air content. Air content is particularly important to protect against freezing, since the bubbles act as an expansion chamber allowing the water to enter without destroying the mortar matrix (Bustillo Revuelta, 2008). However, excessive air content can undermine the mechanical strength of the mortar. Despite the effects of occluded air on durability, the EN 998-2 standard (CEN, 2012a) does not establish a limit value, although the recommended content is between 5% and 20%, (Bustillo Revuelta 2008). The results obtained (Table 13) show that all the mortars achieve the recommended air content, with the exception of sample D-100-9 (22%), which contained 53.5% more air than the reference mortar (14.3%); this mortar also had the lowest bulk density of the D series, suggesting that the higher air content and lower density of the mortar could be due to inadequate casting in the mould due to the low w/c ratio (Chandra and Björnström, 2002). Furthermore, one-way ANOVA tests (Table 15) found no statistically significant differences between the reference mortar and the mortars with air content ranging from 12% to 18.3%, and therefore they were grouped in the same homogeneous group, as shown in Figure 20c.

Overall, the analysis of the results shows that air content increases with the increase in total w/c and RFA, and decreases with the incorporation of AEPA. The influence of the w/c ratio in the increase in air content is due to the fact that increasing the water content produces a more fluid mixture that facilitates the incorporation of air during mixing (Dolch, 1996; Fernandes et al., 2005; Sánchez de Juan, 2005). Air content is also increased in parallel with increased RFA content, due to the presence of more porous aggregates and the influence of their grading and shape (Rodríguez Robles, 2016; Tahar et al., 2017), although in D series mortars with 50% RFA, a decrease in air content was observed, as in the case of bulk density. Finally, the decrease in air content as a result of an increase in AEPA coincided with an increase in bulk density, showing that the AEPA helped to bind solid particles and obtain a less porous mortar with lower air content.

The results of the three-way ANOVA (Table 15) allowed us to conclude that the three factors and their interactions showed a statistically significant effect ($p < 0.05$) on air content, generating a model that explained 79.6% of the variance, mainly due to the effects of the interactions (57.3%) and to a lesser extent due to the factors (22.3%). In fact, as in the case of bulk density, the high contribution of interactions to the variation meant that the main effects of the RFA and AEPA factors did not show a linear trend (Figure 20c**)**. Similarly, according to the groups determined by the HSD Tukey test, the mean air content values were significantly equal and lower in mortars in which 50%, 25% and 75% of NFA was replaced with RFA, and with 3% and 6% of AEPA. Therefore, a strong inverse linear relationship could only be established between the air content of the D series mortars and 6% AEPA dosages, with R^2 = 0.817, due to the high contribution to the variation of the significant interactions among the three factors (57.3%).

Finally, the strong inverse linear relationship between the air content and bulk density in mortars dosed with 1% and 9% of AEPA, and the moderate linear relationship those with 3% of AEPA confirmed the observation that air content increased as bulk density decreased (Figure 26).

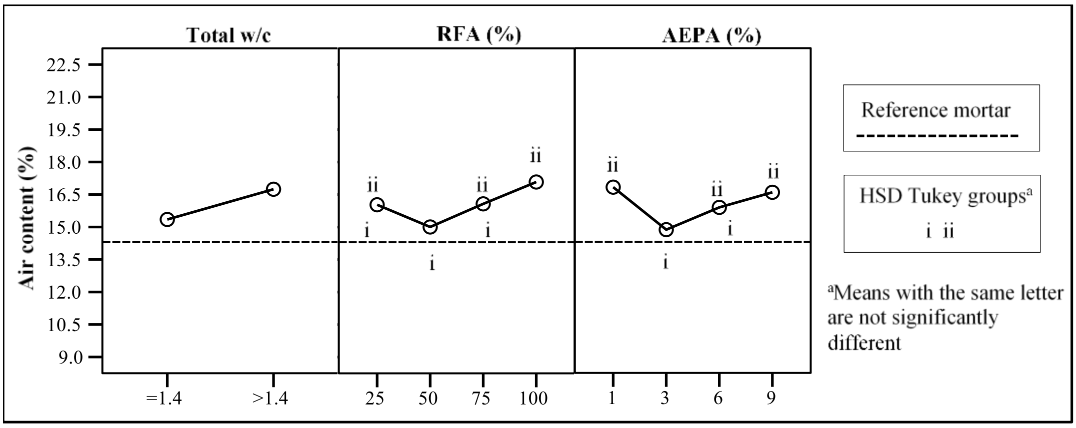

Figure 25. Main effect of factors on the mean air content values of masonry mortars

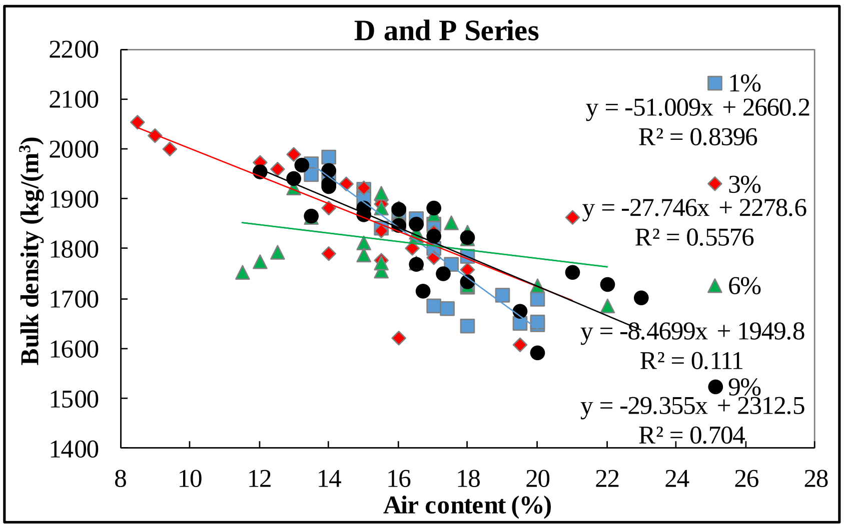

Figure 26. Linear relationships between air content and bulk density as a function of AEPA

10.2. Hardened mortar

10.2.1. Dry bulk density

The dry bulk density values of the mortar series are shown in Table 14 and Figure 21a. As in the case of fresh mortar density, the increase in total w/c and the incorporation of RFA reduced dry bulk density. In fact, a moderate direct linear relationship between both properties was observed, with a correlation of $R^2 = 0.6043$ *(*Figure 27*)*, representing a dry bulk density of approximately 94% of that obtained in fresh mortar. In contrast, the values of this property increased with increased dosages of AEPA.

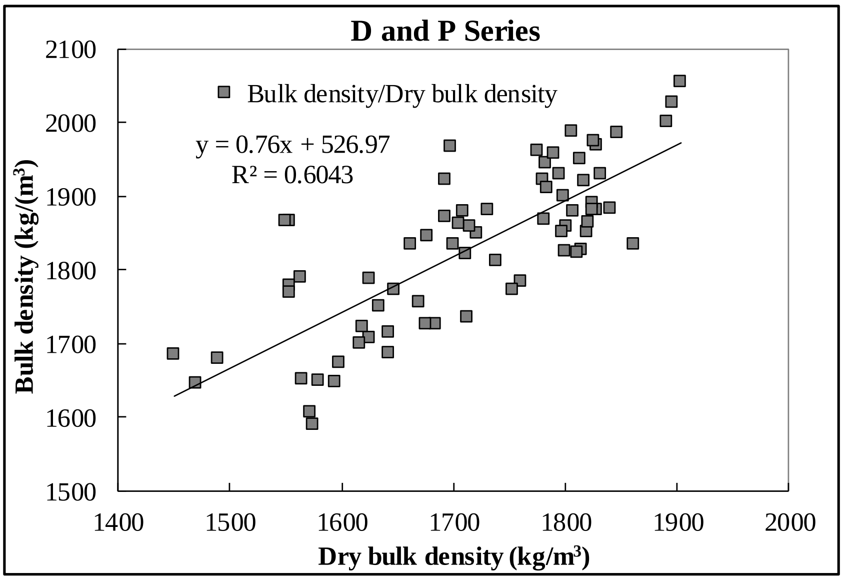

Figure 27. Linear relationship between bulk density and dry bulk density

The increase in total w/c ratio makes the mortar more porous and therefore less dense. With respect to the reference mortar (1795 kg/m^3), the P series showed the lowest values, ranging from -18.1% to 1.8%, while the values in the D series ranged from -4.1% to 5.6%. Likewise, the increase in RFA reduced the density of the mortars as a consequence of the lower density of RFA compared to NFA (de Oliveira Andrade et al., 2018; Ledesma et al., 2015; Vegas et al., 2009). An increase in density was observed in D series mortars manufactured with 50% RFA, as occurred in the fresh state, coinciding with the decrease in air content. In contrast, the increase in AEPA increased the values of this property, since the action of the AEPA facilitated bonding of the solid particles and increased the compactness of the mortar. In the P series, the highest values corresponded to 3% AEPA dosages. According to the results of the one-way ANOVA, mortars with a dry bulk density equal to or higher than mortar P-100-6 (1648 kg/m^3) were technically optimal (Figure 21a).

The three-way ANOVA shown in Table 16 and Figure 21a confirmed these results. It can be seen that the factor with the greatest effect on dry bulk density was total w/c (29.5%), followed by RFA (26.2%) and AEPA (11.2%). Thus, the model generated by the three factors and their interactions explained 86.7% of the variance. In addition, the mean dry bulk density values were significantly equal and higher in mortars in which 25% and 50% of NFA was replaced with RFA. With respect to AEPA, the highest values corresponded to 3% dosages, and no significant differences were observed between the 6% and 9% dosages, according to the groups determined by the HSD Tukey test (Figure 28).

Finally, in the D series, a strong direct linear relationship was confirmed between dry bulk density and RFA with dosages of 3% of AEPA, and a moderate relationship for dosages of 1% and 6%. However, in the P series it was possible to establish strong inverse linear relationships for the 1% and 3% dosages, and moderate relationships for the 9% dosages (Figure 29).

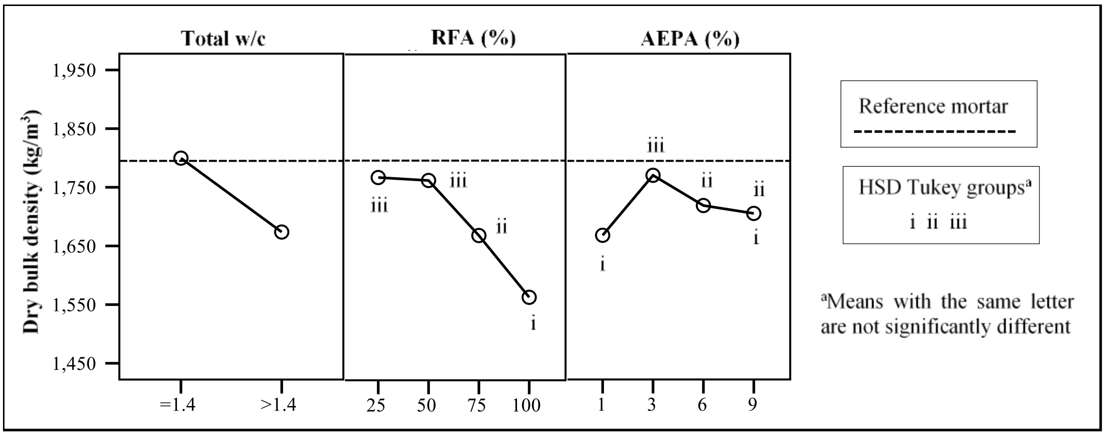

Figure 28. Main effect of factors on the mean dry bulk density values of masonry mortars

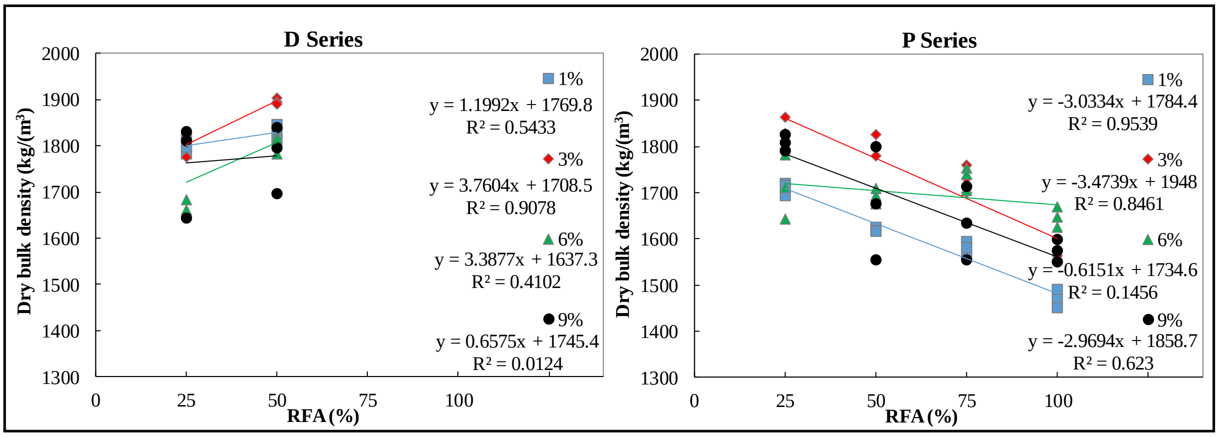

Figure 29. Linear relationships between dry bulk density and RFA as a function of AEPA dosage, for the D and P series

10.2.2. Water absorption coefficient due to capillary action of hardened mortar

Water absorption due to capillary action determines to a large extent the durability of the masonry mortar, since it can seriously affect exposure of the material to external agents. Absorption depends on the capillary structure of the material; therefore, the smaller the capillary network, the lower the absorption of the mortar (Rodríguez-Mora, 2003).

The results of water absorption coefficient tests are shown in Table 14 and Figure 21b. As can be seen, in all test mortars the water absorption coefficient was lower than the reference mortar (0.69 kg/(m^2*$min^{0.5}$)), except for samples P-25-1 and P-100-1 (0.732 kg/(m^2*$min^{0.5}$)), which had higher values and therefore least durability. Nevertheless, one-way ANOVA classified these mortars in the same homogeneous group as the reference mortar, so no statistically significant differences were found between them, and they were considered technically valid (Figure 21b). In the D series, values varied from -12.3% to -71.7%, while in the P series they ranged from 6.1% to -59.4%.

This showed that the capillary water absorption coefficient decreased in mortars with the lowest total w/c ratio, because it reduced both the space between cement grains and aggregate and the capillary network (Łaźniewska-Piekarczyk, 2013; Lenart, 2013). In addition, the water absorption coefficient increased with the increase in RFA, particularly when 100% NFA was replaced with RFA, due to its high water absorption capacity (Fernández-Ledesma et al. 2016). In contrast, increased AEPA dosage significantly reduced the water absorption coefficient, which was up to 55.5% lower in mortars manufactured with 9% vs. 1% AEPA.

According to Lenart (2013), admixtures of this type cause air bubbles to appear and prevent the formation of interconnected pores, thus interrupting the system of capillaries, resulting in reduced capillary water absorption.

This is shown in the results of the three-way ANOVA shown in Table 16 and Figure 30, since the AEPA factor showed the highest F statistics value (248.709), causing 83.5% of the variance, followed by total w/c (4.9%) and RFA (2.3%). Thus, the model explained 94.6% of the variance, and the three factors and the first-order RFA*AEPA interaction showed significant critical F statistic values ($p < 0.05$). In addition, the lowest mean values (Figure 30) were found in mortars with less than 75% of replaced RFA, among which no significant differences were observed; similar results were reported by Fernández-Ledesma et al. (2016). Similarly, the lowest values, and therefore the greatest durability, occurred in the samples with the highest AEPA dosages, namely 9% and 6%.

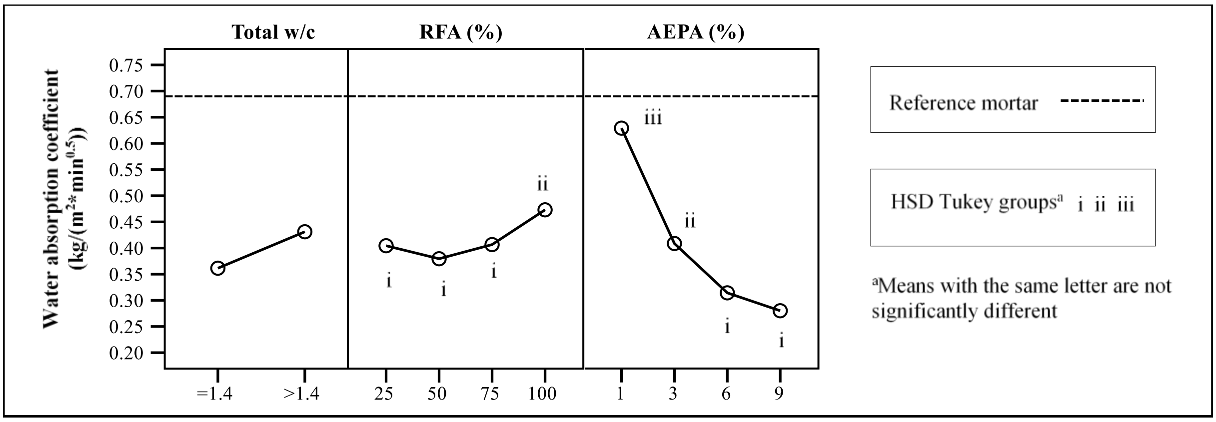

Figure 30. Main effect of factors on the mean values of capillary water absorption coefficient of masonry mortars

Figure 31 shows the dependency between water absorption coefficient and RFA as a function of AEPA dosage in D and P series mortars. As can be seen, in the D series, a strong inverse linear relationship was observed for the 3% AEPA dosage ($R^2 = 0.9714$), and a moderate relationship for the 9% dosage ($R^2 = 0.693$). In the P series, a strong inverse linear relationship ($R^2 = 0.8325$) was observed for the 3% AEPA dosage, while a strong direct linear relationship was observed for the 6% AEPA dosage ($R^2 = 0.935$).

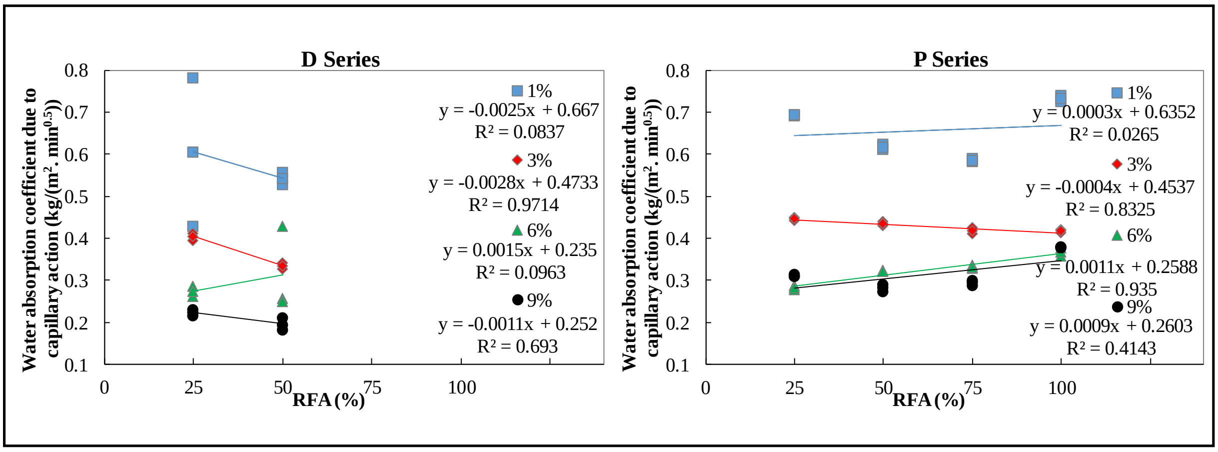

Figure 31. Linear relationships between capillary water absorption coefficient and RFA as a function of AEPA dosage, for the D and P series mortars

10.2.3. Compressive and flexural strength of hardened mortar

10.2.2.1. Compressive strength

The results of 28-day compressive strength test are shown in Table 14 and Figure 21c. As can be observed, all the mortars exceeded the minimum resistance value of 5 N/mm^2 established by EN 998-2 (CEN, 2012a) for the M5 resistant class, except samples P-50-1, P-75-1, P-100-1 and P-100-3. With respect to the reference mortar (7 N/mm^2), values in the P series ranged from -33.7% to 5.6%, while all D series mortars showed an increase of between 17.4% and 61.9%.

Lower total w/c ratios together with higher AEPA dosages improved compressive strength, while higher RFA content reduced it. This is because the presence of less water in the composition of mortar reduces the space between cement grains and aggregate; as a result, this space is filled with the products of hydration that improve the interface between cement matrix and aggregates (Łaźniewska-Piekarczyk, 2013). The loss of strength due to the presence of RFA (Silva et al., 2016) was expected, considering that the compressive strength of mortar is progressively dependent on the mechanical performance of the aggregate rather than the strength of the cement matrix; these aggregates, being rougher in texture and more porous, give poorer mechanical performance than NFA. However, as observed in the other properties discussed above, 50% of RFA in the D series increased the strength of the mortar by reducing the effective w/c ratio, thus increasing compactness. The RFA absorbed a certain amount of free water during mixing, reducing the initial w/c ratio in the interfacial transition zone and improving the bond between the RFA and the new cement paste (Etxeberria et al., 2007; Zega and Di Maio, 2011). These results coincide with those obtained by Miranda et al. (2014), who attributed this increase in dry-consistency mortars to the compaction effort during moulding of specimens, primarily because the mortar specimens are dry in consistency. The increase in strength due to the increase in AEPA dosage was attributed to a better distribution of the cement grains in the mortar matrix due to the action of the AEPA; nevertheless, the observed increase was not significant for AEPA dosages higher than 3%.

These results were confirmed with three-way ANOVA (Table 16 and Figure 32), which showed the high contribution of total w/c (77.1%), and to a lesser extent of RFA (2.8%) and AEPA (1.6%), to the variance in compressive strength. These three factors together with their interactions showed a statistically significant effect and explained 96.7% of the variance. Likewise, mean compressive strength values differed significantly between the four percentages of RFA content, and was highest in mortars in which 50% of NFA was replaced with RFA. With respect to AEPA, mortars manufactured with dosages equal to or greater than 3% were the strongest, and post hoc HSD Tukey tests confirmed that they were statistically equal (Figure 32).

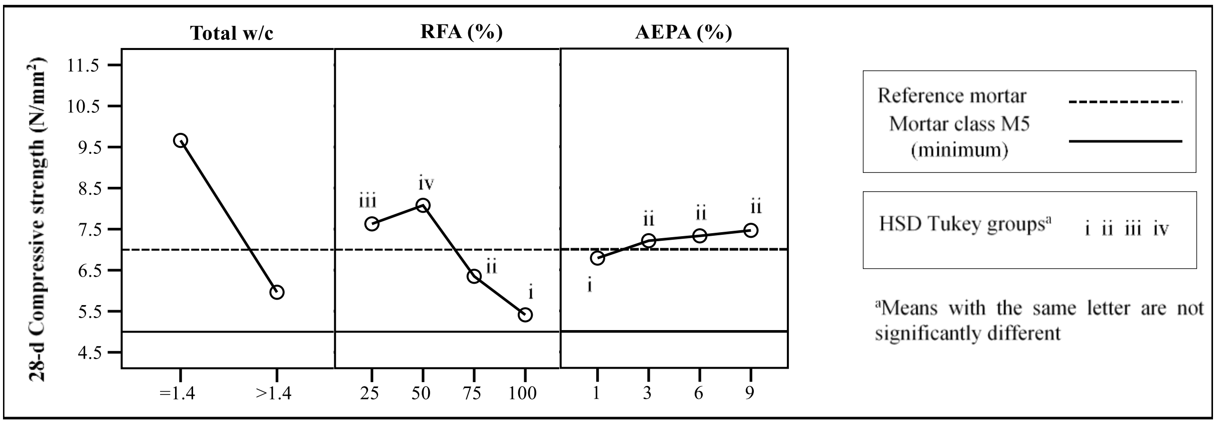

Figure 32. Main effect of factors on the mean compressive strength values of masonry mortars

Finally, based on the correlation values shown in Figure 33, in D series mortars, a strong direct linear relationship ($R^2 > 0.94$) could be established between 28-day compressive strength and RFA in mortars manufactured with dosages of up to 6% of AEPA. However, in P series samples, the results only allowed us to establish a moderate inverse linear relationship for the 1% AEPA dosage (Figure 33).

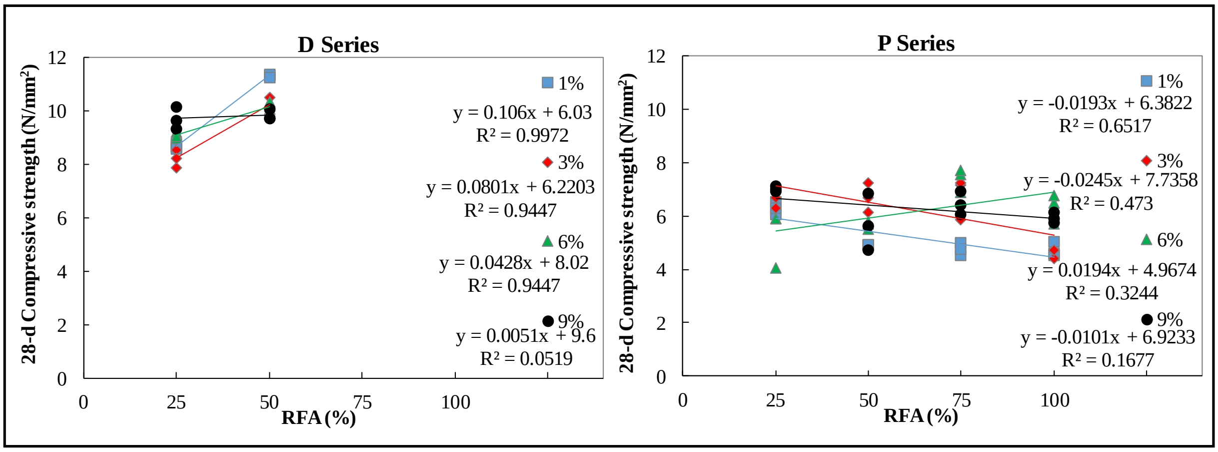

Figure 33. Linear relationships between compressive strength and RFA as a function of AEPA dosage, for the D and P series mortars

With respect to 7-day compressive strength (Table 14), the tests showed significant increases in strength in D series mortars compared to the reference mortar. Similarly, the three-way ANOVA results in Table 16 showed statistically significant effects ($p < 0.05$) for the three factors and the four interactions. In addition, total w/c made the greatest contribution to variance, followed by AEPA and RFA.

The results of ANOVA for 7-day and 28-day mortars (Table 16) showed that at both ages the factor with the most significant effect on variance was total w/c, confirming the correlation between water content and strength. In 7-day mortars, the second most significant factor was AEPA, and RFA in 28-day samples. Generally, the use of RA to replace NA in the manufacture of mortars and concrete is associated with a decrease in mechanical strength. However, the results obtained have shown that the mechanical strength of the mortar was mainly reduced by the increase in water content (between 53% and 77.1% contribution), and to a lesser extent by RFA content (between 2.3% and 7.6% contribution). In addition, these results coincide with the effects caused by increased water content in concretes and mortars manufactured with NA, showing that the loss of strength cannot be attributed solely to the use of RFA.

With respect to the relationship between 28-day compressive strength and the remaining properties (Figure 34), the strong inverse linear relationship for AEPA dosages of up to 6% ($R^2 > 0.92$) shows that greater strength is associated with a decrease in consistency in D series mortars; however, in the P series, strength increases with an increase in consistency values for AEPA dosages of 1%, establishing a moderate direct linear relationship ($R^2 = 0.6782$) (Figure 34a). Likewise, compressive strength is higher in mortars with lower air content, mainly for AEPA dosages of 1% and 3%, where a strong inverse linear relationship is observed, with correlation values of $R^2 = 0.8109$ and $R^2 = 0.7305$; in the D series, this also occurs for 6% AEPA dosages (Figure 34b). The increase in dry bulk density produces greater compressive strength, establishing a moderate direct linear relationship ($R^2 = 0.53$) between both properties (Figure 34c). In addition, a strong linear relationship between flexural and compressive strength values is observed, as shown by the correlation value $R^2 = 0.8838$ (Figure 34d); based on these results, flexural strength is approximately 38% of compressive strength. Finally, the increase in compressive strength is also associated with a decrease in capillary water absorption coefficient, as shown by the moderate inverse linear relationship for 3% and 9% AEPA dosages; with respect to D series mortars, a strong inverse linear relationship is observed for the 3% AEPA dosage (Figure 34e). Greater strength in mortar generally corresponds to greater compactness, and therefore lower absorption coefficient.

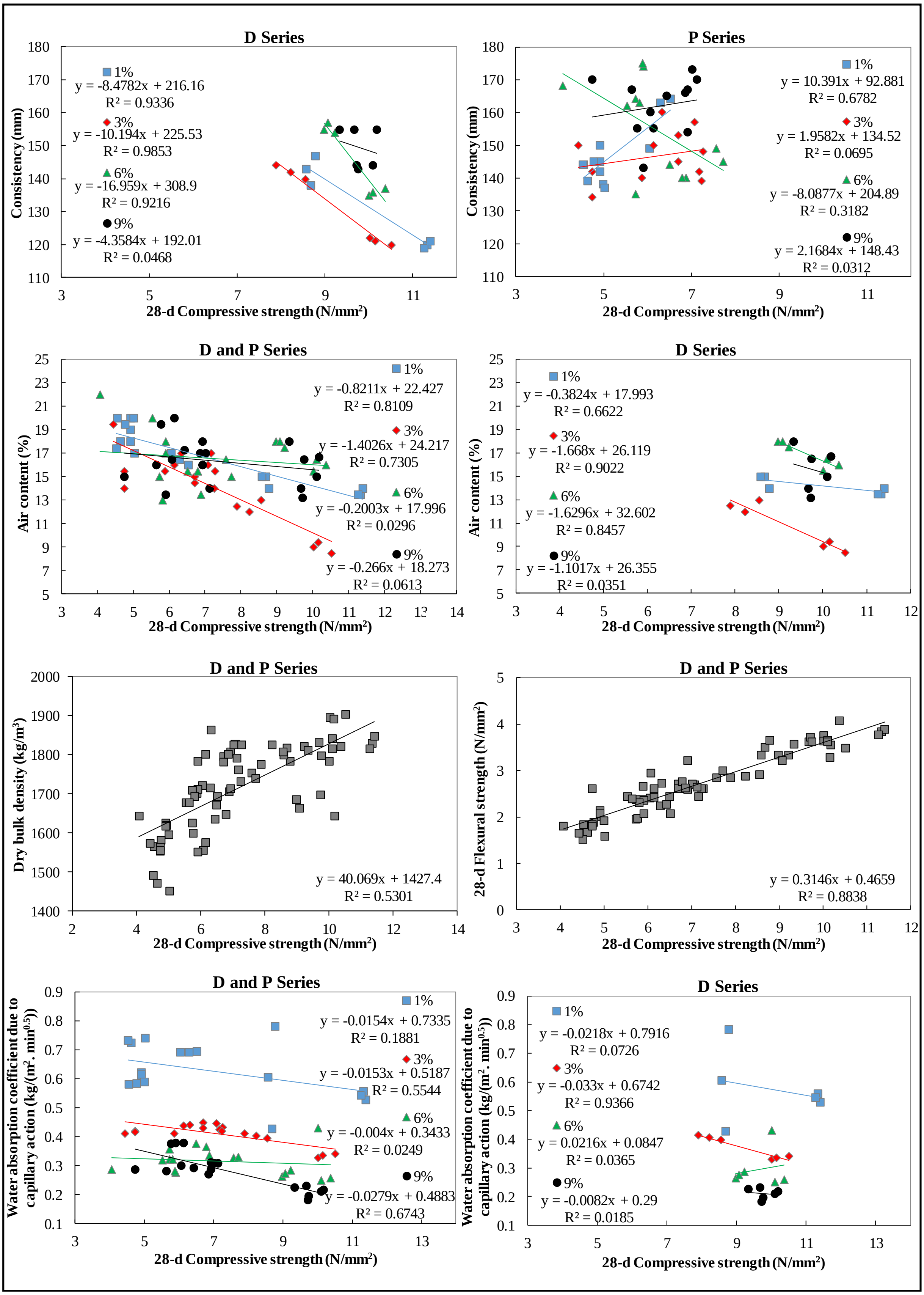

Figure 34. Dependency between 28-day compressive strength and consistency (a), air content (b), dry bulk density (c), flexural strength (d) and capillary water absorption coefficient (e)

10.2.2.2. Flexural strength

Flexural strength at 28 days (Table 14 and Figure 21d) follows the same trend as 28-day compressive strength. Flexural strength at 28 days decreased as total w/c and RFA content increased, and increased with increased AEPA content. The flexural strength of the reference mortar (2.61 N/mm^2) was achieved by all D series mortars, with values increasing between 10.6% and 47.1%. In the P series, the values ranged from -38.8% to 8.2%, and samples P-25-3, P-25-9, P-50-3, P-75-6 and P-75-9 exceeded the reference sample values. In addition, mortars with flexural strength values equal to or greater than that of mortar P-50-1 (2.08 N/mm^2) were considered technically optimal, according to the results of one-way ANOVA (Figure 21d).

These results were confirmed with three-way ANOVA (Table 16 and Figure 35), which showed that, like compressive strength, the greatest determining factor was total w/c (68.7%), followed by RFA (7.6%) and AEPA (4.9%). The factors and the three first-order interactions were significant ($p < 0.05$). Thus, the model defined by these factors and their interactions explained 94.1% of the variance observed. In addition, the highest and significantly equal mean values (Figure 35) corresponded to replacements of 50% and 25% of RFA, and to 9% and 6% AEPA dosages.

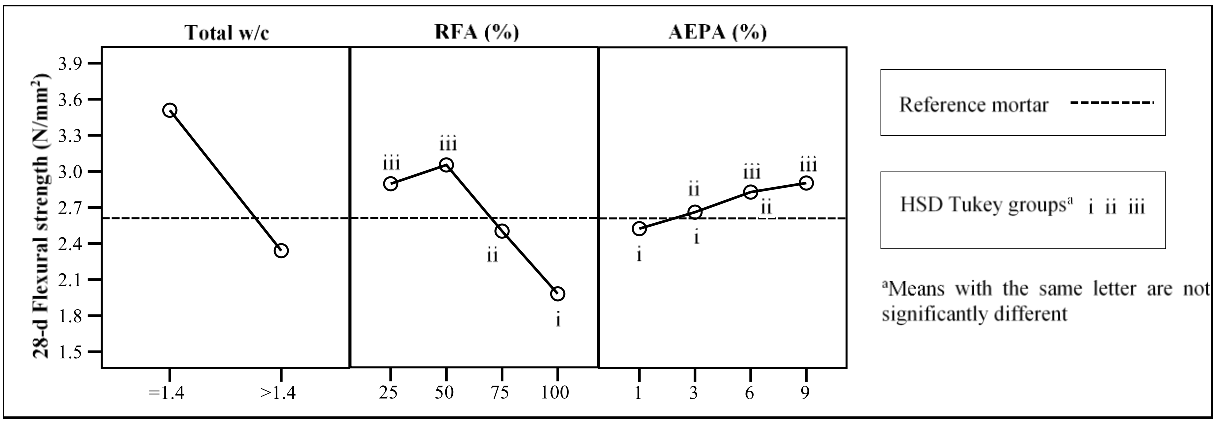

Figure 35. Main effect of factors on the mean flexural strength values of masonry mortars

With respect to 7-day flexural strength (Table 14), the tests also showed significant increases in strength in D series mortars compared to the reference mortar. Similarly, the three-way ANOVA results (Table 16) showed statistically significant effects ($p < 0.05$) for the three factors and the four interactions. In addition, total w/c made the greatest contribution to variance, followed by AEPA and RFA.

11. Conclusions

In this study, we have evaluated the effects and significance of the total w/c ratio, the replacement of NFA by RFA, and the dosage of AEPA on the fresh and hardened properties of general purpose masonry mortars (G) class M5, according to the EN 998-2 Standard.

In general terms, we can conclude that the manufacture of masonry mortars with up to 100% RFA is feasible. However, considering the effect of each study variable on the properties analysed, the best results, without detriment to the properties of the mortar, are obtained by replacing 25% of NFA with RFA. If a higher percentage of replacement RFA is used, the option of increasing the total w/c ratio by pre-soaking the RFA prior to use, and increasing the amount of AEPA dosage over 3% should be considered. Although such doses are technically effective, they may not be economically or environmentally optimal.

Using three-way ANOVA statistical analysis, we found total w/c ratio and RFA content to have the greatest effect on the study mortars. Total w/c ratio had the greatest effect on consistency, dry bulk density, and compressive and flexural strength; while RFA content only determined bulk density. AEPA had the least repercussion on the mortars, even though it determined air content and capillary water absorption coefficient.

In view of this, encouraging companies involved in the manufacture of plasticizing admixtures to study new formulations that will provide workability at lower dosages, wich would greatly facilitate the use of recycled aggregates.

These masonry mortars can be used in constructive elements that are not subject to structural requirements and are placed in the interior of buildings protected from the weather, in the exterior protected from rain and in the exterior not protected from rain, or in unventilated basements, according to exposure classes I, IIa and IIb of the Spanish “Código Técnico de la Edificación”.

PART 2: ENVIRONMENTAL FEASIBILITY

CHAPTER 3. Development of the life cycle inventory of masonry mortar made of natural and recycled aggregates[5]

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[5] *The results shown in this Chapter were presented in: G. M. Cuenca-Moyano, S. Zanni, A. Bonoli, I. Valverde-Palacios. Development of life cycle inventory of masonry mortar made of natural and recycled aggregates. Journal of Cleaner Production, 2017, 140: 1272-1286.* https://doi.org/10.1016/j.jclepro.2016.10.029

12. Introduction

The European standard EN 13139 on “Aggregates for mortars” (CEN, 2002a) allows the use of RA for the production of masonry mortars, and makes possible the recycling of the fine fraction of aggregates from C&DW. In fact, the use of RA for producing masonry mortars has been studied in several researches which have shown the technical feasibility for partially replacing the NFA with RFA without having any effects on the mortar properties (Bektas et al., 2009; Corinaldesi and Moriconi, 2009; Jiménez et al., 2013).

Replacing the NA with RA shall allow to decrease the amount of C&DW disposed to landfill, as well as to preserve the natural resources, which means a series of environmental benefits (Blengini and Garbarino, 2010; Knoeri et al., 2013; Simion et al., 2013). However, a real assessment of environmental benefits requires the use of tools in order to quantify accurately such benefits. According to Ding (2014), the LCA is an ideal tool for analysing the environmental impact of building materials. It measures and compares the environmental impacts of human activities, being able to provide an overview of the environmental profile of different strategies, additionally giving a comparison of the environmental impacts of all the options (Leme et al., 2014); all mass and energy flows, use of resources and potential impacts are accounted in relation with a functional unit that is the quantitative measure of the service offered by the system (Guinée et al., 1993).

Several studies gather the results of applying the LCA to the environmental impact assessment of C&DW, either in the RA production (Simion et al., 2013), applied to concrete production (Knoeri et al., 2013; Marinković et al., 2010) or for road base and subbase (Mroueh et al., 2001). Those studies concluded that the production of RA to be used in the production of concrete can reduce the environmental impact up to 70% (Knoeri et al., 2013), with seven times higher reductions of greenhouse emissions (Simion et al., 2013). Similar results were obtained in Mroueh et al. (2001) as using crushed concrete decreased the environmental loads caused by road construction. According to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), the LCA application is based on four stages: definition of the goal and scope, inventory analysis, impact assessment and interpretation of results. The first phase establishes the goal and previous use of the study, the scope according to boundaries of the system, the quality criteria of the inventory data and the functional unit to whom the results obtained shall make reference. The inventory consists of a detailed collection of the inputs (raw materials and energy) and outputs (products, coproducts, waste, and emissions to air, soil and water) for all the processes of the system at each stage of the life cycle. The impact assessment is the phase where the input and output inventory moves to indicators of potential environmental impacts. Finally, the last stage deals with the interpretation of results from both the life cycle inventory analysis and life cycle inventory assessment.

When applying the LCA, the data of the process is a major issue of data quality as it varies greatly from one region to another and from one production plant to another, so a critical first step in any LCA is the compilation of a credible life cycle inventory, upon which subsequent life cycle impact assessment can be based (Esin, 2007; Saghafi and Hosseini Teshnizi, 2011). Consequently, LCA relies heavily on the availability and completeness of life cycle inventory (LCI) data (Dong et al., 2015; Finnveden et al., 2009), in which data on inputs and outputs of mass and energy across the various life cycle processes are compiled (Gursel et al., 2014). So, LCI phase requires the highest efforts and resources on data collection, acquisition, and modelling (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010); it is also necessary to highlight the importance of the development of the inventory as it needs to be detailed in order to be reproduced by an independent practitioner (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010; ISO, 2006b; Rebitzer et al., 2004).

In this regard, there are many studies on the LCI regarding construction sector. Ingrao et al. (2014) discusses the LCI analysis of a precast reinforced cement shed, providing a fundamental building block for compiling a full LCA study. Gursel et al. (2014) reviewed the current literature on LCI of cement production to provide a roadmap for improving the utility of cement production LCI. Zendoia et al. (2014) described a LCI method for machine tools providing a new procedure, which improves the transparency and consistency of LCA data. However, at least in the bibliography reviewed, no references about LCI application to masonry mortars made of RA have been found.

Given the importance of the exhaustiveness in the inventory phase regarding a subsequent application of LCA (Mongelli et al., 2005), the aim of this study has been the development of the LCI for the production of masonry mortars, either made of NFA or different amounts of RFA. This study shall allow to the future application of the LCA with the purpose of quantifying and comparing the environmental impacts caused in the different mortars which have been thoroughly assessed.

13. Materials and methods

13.1. Materials

To determine the inventory, ISO 14040 (ISO, 2006a), ISO 14044 (ISO, 2006b), SimaPro 7.3.3 software format (PRé Consultants, 2011) and the mortar production system (Figure 36) were taken into account The system boundaries include both the production of the components (from cradle to gate level) and the production of the masonry mortar at the production plant (from gate to gate level). However, the procedures included in the commercialization, construction, use and mortar demolition phases have not been taken into account; therefore, future LCA shall be limited to cradle to gate level.

The inventory of the LCA was developed for the purpose of producing a masonry mortar with a minimum compressive strength of 5 N/mm^2, in accordance with the requirements established by the European standards EN 998-1 (CEN, 2010) and EN 998-2 (CEN, 2012a). The functional unit was defined as 1 tonne dry masonry mortar. It was manufactured according to the dosage recommendations for commercial masonry mortar provided by the specialized manufacturer and commercialized as a premixed dry mortar (ready to be mixed with water and applied). The mortar components are:

- Fine aggregate. Determining the environmental benefits of using RFA instead of NFA in the mortar production requires determining the LCA and comparing the results to the mortar produced with NFA. For this reason the following has been studied:
    - A dolomitic NFA of 0/2 mm size, bulk density 2.818 t/m^3 and produced in a local quarry at Padul (Granada, Spain).
    - A RFA of 0/2 mm size produced in a C&DW treatment and recovery plant located at Alhendín (Granada, Spain). It was obtained from civil engineering concrete waste with the following components, determined according to EN 933-11 (CEN, 2009b): 87% concrete, 7.5% NA, 2.5% brick, 1.6% asphalt and 0.2% others impurities. Its bulk density value is 2.630 t/m^3.
- Filler. A limestone filler of 0.890 t/m^3 bulk density was added to the aggregate to adjust

the fineness modulus according to EN 13139 (CEN, 2002a).

- Cement. A Portland cement of 1.100 t/m^3 bulk density was used, EN 197-1- CEM II/A-L 42.5 R according to RC-16 (Ministerio de la Presidencia, 2016).
- Additive. A commercial air-entraining plasticizer admixture (AEPA) (RHEOMIX 932) was used to improve workability. Its bulk density value is 0.900 t/m^3.

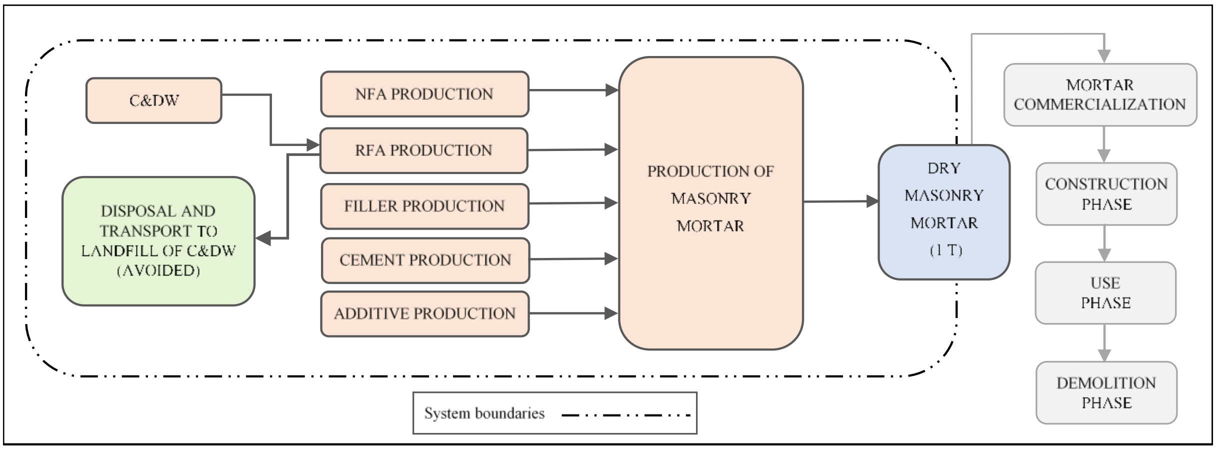

Figure 36. LCA of masonry mortar and system boundaries

RFA is composed of NA bonded with cement mortar, which reduces the density and increases the water absorption capacity with respect to NA (Martín-Morales et al., 2013c). These properties are detrimental to mortar quality because they directly affect the water/cement ratio, giving poor fresh-state consistency and workability, and also affecting the mechanical performance in the hardened state. For the same total amount of water, as the RA's water absorption and replacement level increase, the consistency of mortar tends to decrease (Silva et al., 2016). However, the partial replacement of NFA by RFA provided enough workability, improved mechanical strength and reduced the water absorption coefficient due to capillary action values (Bektas et al., 2009; López Gayarre et al., 2017). To compare the environmental impact of mortars either made of NFA or different amounts of RFA, it is necessary that these mortars fulfil similar functional requirements. This means that they have approximately the same properties. Therefore, recycled mortar dosages will be tested in order to obtain adequate plasticity for application on site (plastic consistency ≥140 mm) and a minimum compressive strength of 5 N/mm^2.

The mortar production system (Figure 36) can be divided into the following subsystems: i)

NFA production; ii) RFA production; iii) filler production; iv) cement production; v) additive production; and vi) mortar production. Recycling C&DW means an environmental benefit as the impacts caused by waste disposal to landfil and consumption of raw materials are avoided (Blengini and Garbarino, 2010; Ferreira et al., 2016; Knoeri et al., 2013; Turk et al., 2015; Zanni et al., 2014). In order to quantify the benefit it is necessary to include as part of the system those processes which are not performed due to the use of RA, that is, the processes which are avoided, also called avoided product. In this research, the avoided processes were the C&DW disposal and transport to landfill, which have been included in the inventory of RFA production subsystem. In mortar production the material resulting from the recycling process (RFA) displaces virgin material (NFA) on a 1:1 ratio. So as the amount of RFA increases, the quantity of NFA decreases and that is the avoided consumption of raw materials in the system.

13.2. Methods

13.2.1. Data collection

In the development of the life cycle assessment inventory the main input and output of each process included into the product system have been taken into account for the functional unit of 1 t dry masonry mortar. Inputs included those coming from nature (the resources that are directly taken from the natural resources), as well as raw materials and energy, which come from industrial processes and not from nature. Outputs included air, water and soil emissions, waste and emissions for treatment, the avoided product and final products (products and coproducts obtained in the same unit process or product system). For a better understanding of the system product, flow diagrams of the production processes were designed for the purpose of identifying the processes and their relation with data and the functional unit (Figure 37 to Figure 39).

For the purpose of carrying out an inventory as close to reality as possible, specific data on the mortar production processes and its components were used. The consideration of real data is very important in LCA studies to ensure the quality and representativeness of the environmental results. Foreground data were site specific data collected by means of surveys, interviews and technical visits to the producers concerning average production data in years 2012-2014. Foreground data collection included: raw materials (nature resources or processed materials), equipment used in the production processes and its characteristics (capacity, power, efficiency, energy consumption, service life), the description of production processes, the description of the production facilities (quarry, C&DW treatment plant, mortar plant, etc.), means of transport and distances (types of vehicles, load, fuel), the products resulting from the production process (products and coproducts, quantity) and waste (type and treatment). Background data were used for generic materials, energy, transport and waste management, management, and have been taken from the Ecoinvent v.2.2 database (Ecoinvent, 2010) and the Environmental Product Declaration (EPD) (EFCA, 2006). The Ecoinvent v.2.2 database (Ecoinvent, 2010) provides a unified set of high quality generic LCI data. The data are mainly from Switzerland and Western Europe, so the geographical and technological scope are European. The inventories are based on data from 2003 to 2010. In this study, where possible, data for Spain (ES) have been used for unit processes if available in the Ecoinvent v2.2 database (Ecoinvent, 2010); when unavailable, either regional European (RER) or Swiss (CH) data were used as a reasonable alternative. Some unit processes from the Ecoinvent v.2.2 database (Ecoinvent, 2010) were adapted to the system requirements by replacing or eliminating some subprocesses. The inclusion of subprocesses increased the inventory transparency. The EPD (EFCA, 2006) is a standard Eco-profile for plasticisers. It was created by collecting manufacturing data for the synthesis and blending of normal plasticisers, supplied by European Federation of Concrete Admixtures Associations. Its geographical and technological scope is Europe. The emissions (air, water and soil) taken into account for this research are those included in the unit processes of the Ecoinvent v.2.2 database (Ecoinvent, 2010) and EPD (EFCA, 2006).

The technology applied for the production of masonry mortar and its components corresponds to the current modal technologies implemented in Spain. The manufacturing process is representative of dry mortar factories and follows the standardized protocol to obtain masonry mortar according to European standards EN 998-1 (CEN, 2010) and EN 998-2 (CEN, 2012a). Dry industrial mortars are weighted mixtures of their primary components (aggregates, binder and additive) that have been dosed and mixed in a factory. Currently, dry industrial mortars are technologically advanced and are capable of meeting the demands of the planner and constructor both during installation and in building requirements. The technology used in the manufacturing plant ensures both, the quality and the exact composition of the product. The dry mortar factory is located in Padul (Granada, southern Spain) and basically consists of a system of silos for the collection of raw materials (aggregates, cement, additives, etc.) which are dosed and carried to a mixer, where the exact composition of the required mortar is achieved. After mixing all materials, dry mortar is available for bagging, temporary silo storage or can be loaded directly into a tanker truck to be transported. This study considers dry masonry mortar that is in temporary silo storage. The annual average production is 100,000 t of dry masonry mortar.

The raw material for NFA is extracted from a quarry located in Padul (Granada, southern Spain). The dolomite on the site is already fractured (Valverde-Espinosa, 1992), so this peculiar form of mining is carried out without explosives. Bulldozers just rip and push the dolomite rock downhill. The material is gathered above ground and treated using several crushing and screening processes, depending on the grade of aggregate required, since the quarry produces aggregates of differing sizes. Little machinery is required to process the raw material. On average, the quarry produces 380,000 t annually of manufactured NA.

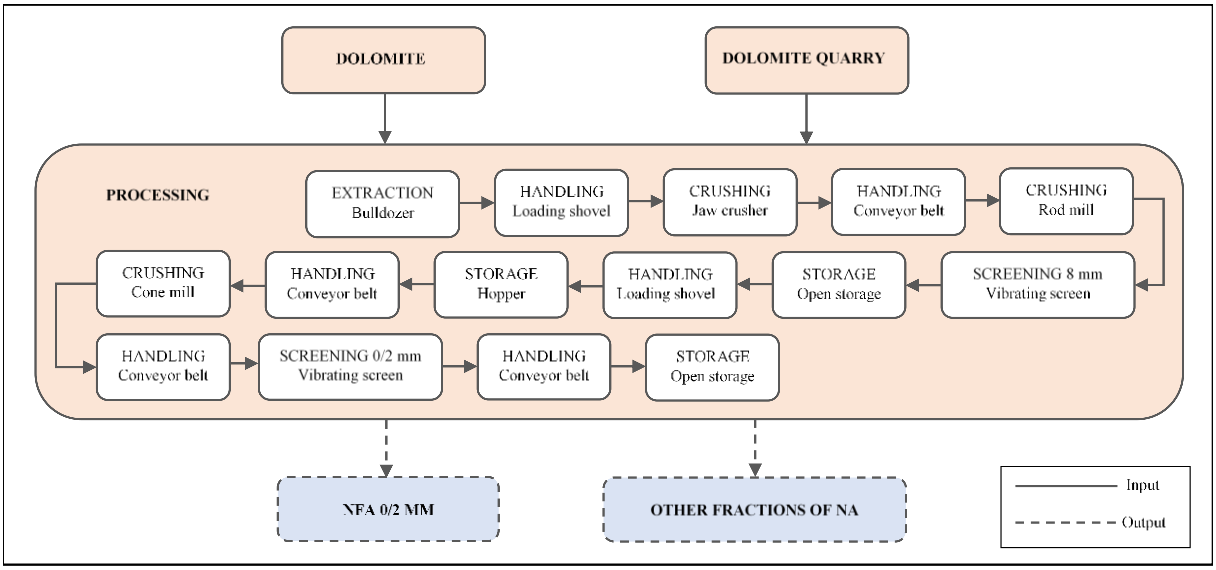

Figure 37. Diagram showing the NFA 0/2 mm production processes

RFA production is carried out at a C&DW treatment plant located in Alhendín (Granada, southern Spain). This is a permanent plant located in enclosed premises, with government authorization to recycle C&DW. The machinery is stationary and does not operate outside of the site where it is located. The facility has three treatment lines: one for C&DW from concrete and two for mixed C&DW. The recycling machinery is similar to that used in the production of NA, since this involves the same structural elements (crushing, grading, conveyor belts, etc.). It also has a section where employees manually sort through the material that passes along the conveyor belts and an overband magnet for the removal of ferric materials. Different RA fractions are obtained from the processing of C&DW. The non-recyclable material is transported to landfill located 15 km away for its final disposal. The area of influence of the treatment plant is 40 km. The annual average production of RA is 200,000 t.

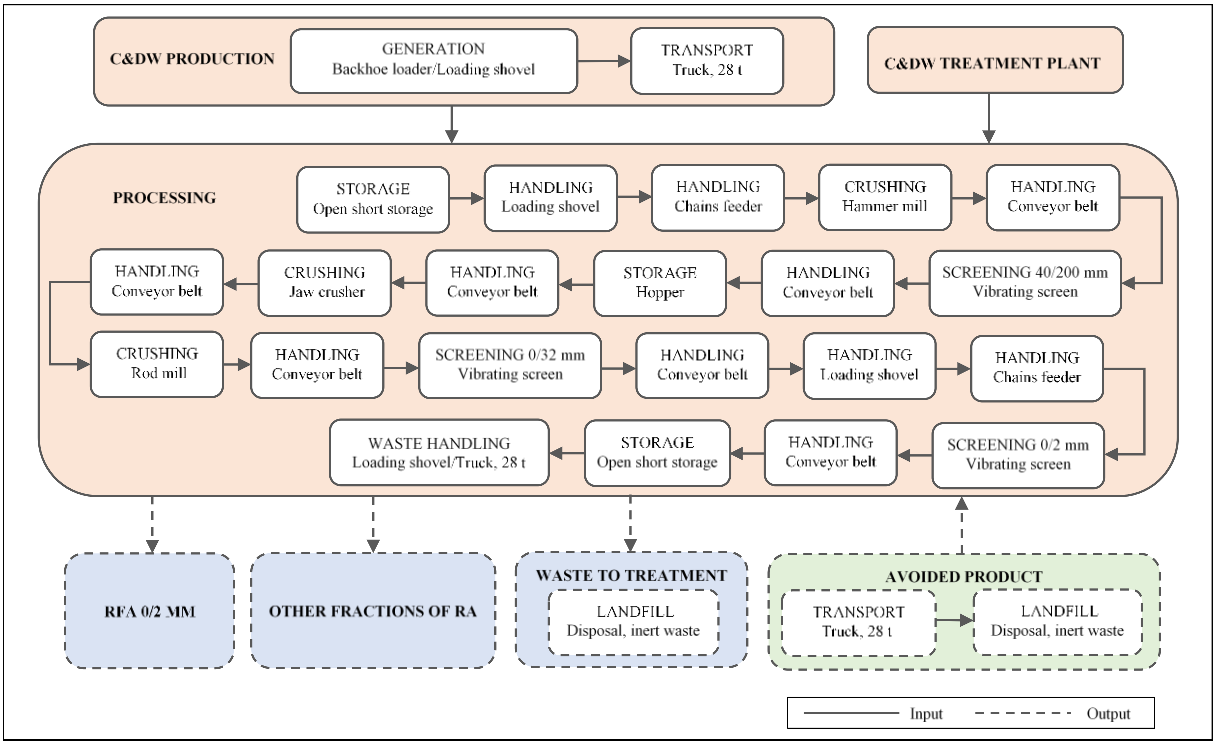

Figure 38. Diagram showing the RFA 0/2 mm production processes

Cement production takes place in a factory located in Cordoba (Spain). Cement manufacturing starts with the extraction of the raw material, mainly limestone which is subjected to different processes of trituration, dehydration, carbonation and sintering to obtain clinker. The cement is obtained after milling the clinker, gypsum and added mineral component. The cement is stored in silos awaiting bagging or transported in bulk. The annual average production of cement is 1,000,000 t.

Filler is obtained from limestone of great chemical purity that is processed using high-technology equipment. The product obtained is milled calcium carbonate. The factory is located in Darro (Granada, southern Spain) and the annual average production of filler is 6,000 t.

Additive production takes place in a factory located in Madrid (Spain). In its manufacture, chemical products are combined in different amounts to achieve the features required for the plastifying additive.

The transportation distances considered in this study have been determined using the map application server on the website Google Maps (Alphabet Inc, 2016). Those transportation processes with a variable distance have been estimated using the average value, taking into account the area of influence.

It is necessary to take into account the following considerations on data sources, foreground data and background data that are specified below:

- Inventories on the NFA, RFA, and mortar production were carried out by combining the data given by producers with Ecoinvent v.2.2 database (Ecoinvent, 2010) unit processes. This allowed the authors to develop the corresponding inventories in depth, mainly regarding the equipment used in the production of aggregates and mortar, tagged under "Processing".
- Inventories on cement and filler production were created using Ecoinvent v.2.2 database (Ecoinvent, 2010) data; regarding the additive, the inventory was carried out using EPD data (EFCA, 2006).
- As for production facilities (quarry, C&DW treatment plant and mortar production plant), new processes were created taking Ecoinvent v.2.2 database (Ecoinvent, 2010) unit processes as a reference. Here, the subprocesses related to the equipment required for aggregate and mortar process, shown in "Processing", were eliminated.
- The equipment inventory was created by using the unit processes available in the Ecoinvent v.2.2 database (Ecoinvent, 2010); those processes are listed in the inventory tables.
- In order to adapt the electric consumption to the Spanish electrical network, a unit process from the Ecoinvent v.2.2 database (Ecoinvent, 2010) was used: "Electricity, medium voltage, production Spain, at grid/ES U".
- The aggregates external storage was temporary and consumed no energy; therefore, only land occupation was computed and considered inside the quarry facilities and C&DW treatment plant.
- Data sources were assessed according to data quality indicators such as reliability,

completeness, temporal correlation, geographical correlation, technological correlation and sample size. The following data uncertainty estimations were considered:

- Ecoinvent v.2.2 database (Ecoinvent, 2010) unit process data include consistent specification of uncertainty data, such as lognormal distribution with standard deviation as described in Frischknecht and Jungbluth (2007). If uncertainty was not known (because it was not stated in the sources used or because it was not known by the Company providing the data) a standardized estimation procedure was used. The standard approach included a qualitative assessment of data quality indicators based on a pedigree matrix (Weidema and Wesnaes, 1996). This approach transforms the data quality indicators to probability distributions by representing the data quality indicator value using a default lognormal distribution.
- Similarly, uncertainty of foreground data only represented by a single value and EPD (EFCA, 2006) were characterized by lognormal distribution whose standard deviation was estimated using the same pedigree matrix.

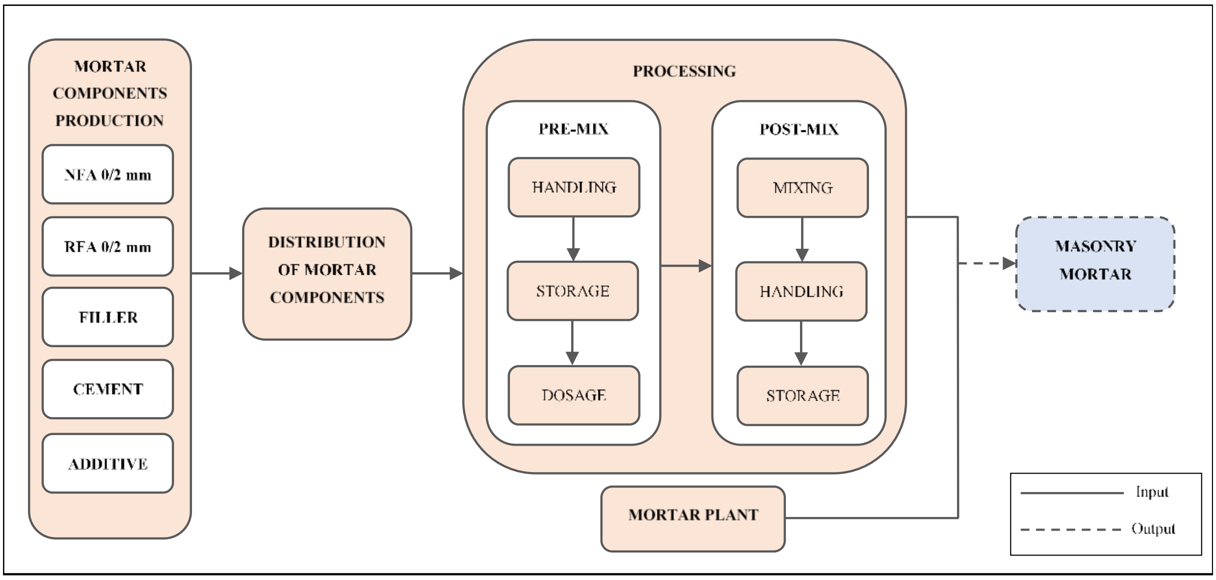

Figure 39. Diagram showing masonry mortar production processes

13.2.2. Computing data and allocation

The quantification of inputs and outputs was determined taking into account the relation between the data collected, unit processes and functional unit reference flow. In the same way, energy and material flows were computed according to the equipment efficiency and the energy consumption during its service life, which is estimated at 25 years or 50,000 h. Production data and power data of the equipment, as well as the corresponding process are shown in Table 17. Data validation was carried out through mass balance and according to the company technicians during data collection.

As mentioned previously, the use of RA from C&DW avoids the consumption of raw materials, as well as the transportation and final disposal of the waste in landfills. In order to quantify this environmental benefit in the future LCA it is necessary to include the processes in the product system that are avoided. The following considerations should be taken into account:

- The disposal of the C&DW in landfills as well as transportation of the C&DW from the demolition site to the landfills constitute the avoided processes that occur as a consequence of recycling C&DW in the treatment plant. These processes have been included within the RFA production subsystem. It was considered that 95% of the C&DW that is processed in the treatment plant is transformed into RA. So this is the same amount that is not disposed of in landfill. The transportation distance from the demolition site to landfill was estimated at 15 km.
- The use of RFA as a replacement for NFA in the manufacture of masonry mortar avoids the consumption of raw materials, in other words, NFA production. In this study a 1:1 replacement of NFA by RFA has been used; so, the quantity of RFA production increases by the same amount as the NFA decreases. The credit for not producing NFA will thus show up in the product system for dry masonry mortar based on the lower input of NFA required.

Table 17. Features of the equipment for masonry mortar production

Process		*Equipment*	*In item*	*Amount*	*Power*	*Fuel consumption*		*Production*
					(kW)	*(kg/m^3)*	*(kg/km)*	*(t/h)*
NFA 0/2 mm								
	Extraction	Buldozzer with ripper	3.1	1	-	0.131	-	1249.30
	Handling	Loading shovel	3.2, 3.7	2	-	0.130	-	38.17
		Conveyor belt, 100 m	3.4	1	22.08	-	-	140.85
		Conveyor belt, 24 m	3.9, 3.11	2	5.15	-	-	140.85
		Conveyor belt, 40 m	3.13	1	8.10	-	-	140.85
	Crushing	Jaw crusher	3.3	1	160.00	-	-	325.00
		Rod mill	3.5	1	92.00	-	-	120.00
		Cone mill	3.10	1	323.84	-	-	210.00
	Storage	Hopper (20 m^3/ 56.4 t)	3.8	1	-	-	-	15.63
	Screening	Vibrating screen	3.6, 3.12	2	18.50	-	-	225.00
RFA 0/2 mm								
	C&DW generation	Backhoe loader with	7.1	1	-	0.131	-	100.00
		Loading shovel	7.1	1	-	0.130	-	100.00
	C&DW transport	Truck, 28 t	7.2	1	-	-	0.245	-
	Handling	Loading shovel (V)	9.1, 9.15,	3	-	0.247	-	100.00
		Chains feeder	9.2, 9.16	2	11.04	-	-	1184.21
		Conveyor belt, 4 m	9.4	1	3.68	-	-	197.37
		Conveyor belt, 10 m	9.4, 9.6	2	5.52	-	-	144.74
		Conveyor belt, 3 m	9.4	1	3.68	-	-	144.74
		Conveyor belt, 15 m	9.4, 9.8	2	5.52	-	-	144.74
		Conveyor belt, 8 m	9.6	1	5.52	-	-	144.74
		Conveyor belt, 6 m	9.8	1	5.52	-	-	144.74
		Conveyor belt, 15 m	9.8	1	7.36	-	-	197.37
		Conveyor belt, 12 m	9.10	1	5.52	-	-	144.74
		Conveyor belt, 20 m	9.12	1	7.36	-	-	144.74
		Conveyor belt, 5 m	9.14, 9.18	2	3.68	-	-	144.74
		Overband	9.4	1	3.68	-	-	144.74
	Crushing	Hammer mill	9.3	1	110.40	-	-	100.00
		Jaw crusher	9.9	1	55.20	-	-	250.00
		Rod mill	9.11	1	73.60	-	-	120.00
	Screening	Vibrating screen	9.5, 9.13,	3	22.08	-	-	250.00
	Storage	Vibrating feeder	9.7	1	8.83	-	-	500.00
		Hopper (20 m^3/ 52.6 t)	9.7	1	-	-	-	197.37
Mortar production								
NFA		Loading shovel	17.2	1	-	0.130	-	200.00
		Truck, 28 t	17.2	1	-	-	0.245	-
NFA pre-mix	Handling	Belt unloader, 11.55 m	17.3.1	1	14.72	-	-	183.10
		Hopper (20 m^3)	17.3.1	1	0.54	-	-	20.25
		Bucket elevator, 26.2 m	17.3.2	1	36.80	-	-	150.00
		Conveyor belt, 5 m	17.3.3	1	4.05	-	-	154.93
		Conveyor belt, 3.6 m	17.3.3	1	2.21	-	-	154.93
	Storage	Hopper (508 m^3)	17.3.4	1	0.54	-	-	20.25
	Dosage	Screw conveyor, 4 m,	17.3.5	1	9.20	-	-	11.42
RFA		Loading shovel (V2)	18.2	1	-	0.124	-	200.00
		Truck, 28 t	18.2	1	-	-	0.245	-
RFA pre-mix	Handling	Belt unloader, 11.55 m	18.3.1	1	14.72	-	-	171.05
		Hopper (20 m^3)	18.3.1	1	0.54	-	-	20.25
		Bucket elevator, 26.2 m	18.3.2	1	36.80	-	-	150.00
		Conveyor belt, 5 m	18.3.3	1	4.05	-	-	144.74
		Conveyor belt, 3.6 m	18.3.3	1	2.21	-	-	144.74
	Storage	Hopper (508 m^3)	18.3.4	1	0.54	-	-	20.25
	Dosage	Screw conveyor, 4 m,	18.3.5	1	9.20	-	-	11.42
Filler		Loading telescopic chute	19.2	1	2.20	-	-	178.00
		Truck, 24 t	19.2	1	-	-	0.245	-
Filler pre-mix	Handling	Loading telescopic chute	19.3.1	1	2.20	-	-	178.00
	Storage	Hopper (50 m^3)	19.3.2	1	-	-	-	2.25
	Dosage	Screw conveyor, 6 m,	19.3.3	1	9.20	-	-	80.00
Cement		Loading telescopic chute	20.2	1	2.20	-	-	220.00
		Truck, 28 t	20.2	1	-	-	0.245	-
Cement pre-mix	Handling	Loading telescopic chute	20.3.1	1	2.20	-	-	220.00
	Storage	Hopper (50 m^3)	20.3.2	1	-	-	-	2.50
	Dosage	Screw conveyor, 6 m,	20.3.3	1	9.20	-	-	80.00
Additive distribution		Loading telescopic chute	21.2	1	2.20	-	-	180.00
		Truck, 18 t	21.2	1	-	-	0.180	-
Additive pre-	Handling	Loading telescopic chute	21.3.1	1	2.20	-	-	180.00
	Storage	Hopper (3.2 m^3)	21.3.2	1	-	-	-	0.12
	Dosage	Screw conveyor, 5 m,	21.3.3	1	2.21	-	-	0.07
Post-mix	Mixing	Mortar mixer	22.1	1	45.00	-	-	72.50
	Handling	Screw conveyor, 6.3 m,	22.2	1	11.04	-	-	10.23
		Bucket elevator	22.2	1	29.44	-	-	150.00
		Screw conveyor, 5 m,	22.2	1	9.20	-	-	8.11
	Storage	Hopper with motor (90 m^3)	22.3	1	0.12	-	-	25.00

In accordance with ISO 14044 (2006) requirements, the allocation approach must be applied in those processes causing more than one final product (coproducts). In the production system under study, there are two different subsystems with multiple outputs. NFA production and RFA production subsystems generate aggregates of different fractions, among them NFA 0/2 mm and RFA 0/2 mm. It was decided to conduct a mass allocation procedure, taking into account the amount of each aggregate fraction produced compared to the total production in each subsystem. The applied allocation percentages for each subsystem are specified below:

- NFA production subsystem: The processing of 5 t of dolomite generates 1 t of NFA 0/2 mm, 1.5 t of NFA 2/4 mm and 2.5 t of NA>8 mm. The allocation percentages correspond to: i) 20% for NFA 0/2 mm; ii) 30% for NFA 2/4 mm; iii) 50% for NA>8 mm.
- RFA production subsystem: The processing of 12.5 t of C&DW generates 1 t of RFA 0/2 mm,1.425 t of RFA 2/8 mm, 2.375 t of RA 8/32 mm, 1.187 t of RA 32/60 mm, and 5.888 t of RA 0/40 mm. The allocation percentages correspond to: i) 8% for RFA 0/2 mm; ii) 12% for RFA 2/8 mm; iii) 20% for RA 8/32 mm; iv) 10% for RA 32/60 mm; v) 50% for RA 0/40 mm.

14. LCA inventory

The inventory for LCA of masonry mortar production has been carried out by using tables where inputs (natural resources, mass and energy) and outputs (emissions, waste, avoided product and product/coproducts) are correlated and shown for every process; unit processes, quantities and reference processes are also specified. The word “item” assigned to inputs and outputs in inventory tables shall allow to relate every process to its impact on the upcoming evaluation phase of LCA. The inventory development is shown for every subsystem and distinguishes between components production and the mortar production process itself.

14.1. LCI of mortar components

14.1.1. NFA production subsystem

The inventory developed for the production of 1 t of NFA is shown in Table 18, in accordance with the processes taking part in the NFA production 0/2 mm (Figure 37). Inputs, outputs and their characteristics are shown below:

- As can be seen, inputs include dolomite as a nature resource, and mass and energy inputs corresponding to the dolomite quarry facilities (Table 19) and to the processing equipment. The amount of input of processes was computed considering that processing 5 t of dolomite is required in order to obtain 1 t of NFA 0/2 mm.
    - The process “Dolomite quarry” includes the data used for the quarry inventory, shown in Table 19. Such process was created taking as a reference the unit process “Dolomite, at plant” by Ecoinvent v.2.2 database (Ecoinvent, 2010); here, some inputs were eliminated, such as dolomite and subprocesses related to processing equipment. Thus, the created process only includes those subprocess related to land use as occupation, transformation and recultivation of dolomite quarry.
    - “Processing” includes those subprocesses regarding equipment required for producing NFA 0/2 mm. The equipment taking part in the process and its energy consumption is shown in detail. As can be seen, the manufacture begins with the extraction of dolomite that due to its fracture characteristics in this quarry (Valverde-Espinosa, 1992), it can be extracted by using a bulldozer with ripper. Afterwards, the material undergoes several crushing and screening processes, enabling to classify the particles size and obtaining several fractions of aggregate, such as NFA 0/2 mm.
- On the other hand, outputs include products and coproducts; that is, 1 t of NFA 0/2 mm and 4 t of other fractions of NA. In accordance to those amounts, the allocation percentage was determined.

Table 18. Inventory data of NFA 0/2 mm production (1 t)

Item	*Process*	*Processed amount (t)*	*Unit process*	*Amount*	*Unit*	*Reference process*
Input						
			Natural resources			
1	Dolomite	5	Dolomite	1.00E+00	t	“Dolomite, in ground” (a)
			Materials/Energy			
2	Dolomite quarry	5	Dolomite quarry	1.00E+00	p	Table 19.
3	Processing					
3.1	Extraction	5	Bulldozer with ripper	3.55E-01	m^3	“Excavation, hydraulic digger/RER U” (a)
3.2	Handling	5	Loading shovel	3.55E-01	m^3	“Excavation, skid-steer loader/RER U” (a)
3.3	Crushing	5	Jaw crusher	1.00E+00	t	“Crushing, rock/RER U” (a)
			Electricity	4.92E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.4	Handling	5	Conveyor belt, 100 m	1.42E-05	m	“Conveyor belt, at plant/RER/I U” (a)
			Electricity	1.57E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.5	Crushing	5	Rod mill	1.00E+00	t	“Crushing, rock/RER U” (a)
			Electricity	7.66E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.6	Screening (8 mm)	5	Vibrating screen	5.64E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (a)
			Electricity	8.22E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.7	Handling	2.5	Loading shovel	3.55E-01	m^3	“Excavation, skid-steer loader/RER U” (a)
3.8	Storage	2.5	Hopper	4.01E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (a)
3.9	Handling	2.5	Conveyor belt, 24 m	3.41E-06	m	“Conveyor belt, at plant/RER/I U” (a)
			Electricity	3.66E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.10	Crushing	2.5	Cone mill	1.00E+00	t	“Crushing, rock/RER U” (a)
			Electricity	1.54E+00	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.11	Handling	2.5	Conveyor belt, 24 m	3.41E-06	m	“Conveyor belt, at plant/RER/I U” (a)
			Electricity	3.66E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.12	Screening (0/2 mm)	2.5	Vibrating screen	5.64E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (a)
			Electricity	8.22E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
3.13	Handling	1	Conveyor belt, 40 m	5.68E-06	m	“Conveyor belt, at plant/RER/I U” (a)
			Electricity	5.75E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a)
Output						
			Emissions (b)			
			Waste (c)			
			Avoided product (d)			
			Products and co-products		*Unit*	*Allocation (%)*
4			NFA 0/2 mm	1.00E+00	t	20
5			NFA 2/4 mm	1.50E+00	t	30
6			NA >8 mm	2.50E+00	t	50

(a) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).
(b) Emissions included in the reference processes.
(c) Waste included in the reference processes.
(d) Not considered.

Table 19. Inventory data of unit process “Dolomite quarry (1 p)”

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources			
	Occupation, mineral extraction site	8.48E-05	m^2a	
	Transformation, to mineral extraction site	6.52E-06	m^2	
	Transformation, from forest	6.52E-06	m^2	
	Water, well, in ground	2.93E-05	m^3	
	Materials/Energy			
	Recultivation(a)	6.52E-06	m^2	
	Mine(b)	5.25E-11	p	
Output				
	Emissions (c)			
	Waste (d)			
	Avoided product (e)			
	Products and co-products			
	Dolomite quarry	1	p	“Dolomite, at plant/RER U” (f) (for the whole unit process).

(a) This process includes only transformation from mineral extraction site to forest and diesel
(b) This process includes the "land-use" of the built part of the mine and therefore the production places and the paved roads. The mine has an annual yield of
(c) Emissions included in the subprocesses.
(d) Waste included in the subprocesses.
(e) Not considered.
(f) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).

14.1.2. RFA production subsystem

RFA 0/2 mm production (Figure 38) begins with C&DW creation after demolition, such waste is taken to the management and valuation plant of C&DW. Once the waste is in the treatment plant, the material is unloaded and stored temporarily. As it is concrete waste from a civil construction, it is not necessary to carry out a previous classification treatment to clear any defects which could affect the quality of the recycled aggregate. Therefore, the material is put on a chains feeder by using a loading shovel; then the crushing process begins, followed by magnetic separation and screening. The recovery percentage of C&DW is 95% and the rest (5%) is disposed to landfill, that is, the 95% turns into avoided product since it is not taken or disposed to landfill.

Table 20 shows the inventory developed for producing 1 t of RFA. Inputs, outputs and their characteristics are the following:

- Inputs are from the C&DW treatment plant facilities (Table 21), C&DW production and the required processes for the C&DW treatment and for obtaining RFA 0/2 mm, which are included in “processing”. Determining the amount of every one of these processes was possible as it is known that it takes 12.5 t of C&DW to obtain 1 t of RFA 0/2 mm.
    - Inventory data of C&DW treatment plant are shown in Table 21. The unit process “Sorting plant for construction waste” by Ecoinvent v.2.2 database (2010) was taking as a reference, and the equipment subprocesses for treating C&DW were eliminated as they are developed in “processing”. The created process was called “C&DW treatment plant” and the subprocesses included were: land use as occupation and transformation, and fuel oil demand from small administrative building.
    - C&DW production process includes the creation, load and transport of waste to the treatment plant where they are to be recycled; for this study an average distance of 20 km was estimated.
    - “Processing” shows the processes that C&DW undergoes at the treatment plant in order to obtain the recycled aggregate; equipment and energy consumption are also indicated.

- Outputs include:
    - Waste, meaning a non-recyclable 5% out of 12.5 t, that is 0.625 t of C&DW to be disposed to landfill.
    - The avoided product, as recycling C&DW avoids it from being taken and disposed to landfill (Blengini and Garbarino, 2010; Knoeri et al., 2013). That is 11.875 t of C&DW which is not taken nor disposed to landfill, and the average distance of 15 km from the demolition site to the landfill.

Table 20. Inventory data of RFA 0/2 mm production (1 t)

Item	*Process*	*Processed amount (t)*	*Unit process*	*Amount*	*Unit*	*Reference process*
Input						
			Natural resources (a) *Materials/Energy*			
7	C&DW production					
7.1	C&DW generation	12.5	Backhoe loader with hammer	3.80E-01	m3	“Excavation, hydraulic digger/RER U” (b).
			Loading shovel	3.80E-01	m3	“Excavation, skid-steer loader/RER U” (b).
7.2	C&DW transport	12.5	Truck 28 t, 20 km	2.00E+01	tkm	“Transport, lorry 20-28t, fleet average/CH U” (b). Average distance
8.	C&DW treatment plant	12.5	C&DW treatment	1.00E-07	p	Table 21. Amount computed according to 200,000 t/year and 50
9	Processing					
9.1	Handling	12.5	Loading shovel (V)	3.80E-01	m^3	“Loading shovel (V)_Excavation, skid-steer loader/RER U”. This process derives from the process “Excavation, skid-steer loader/RER U” by Ecoinvent v.2.2 database (Ecoinvent, 2010). Diesel consumption was modified (from 0.13 kg to 0.247 kg) according to the equipment used.
9.2	Handling	12.5	Chains feeder	1.69E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	9.32E-03	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.3	Crushing	12.5	Hammer mill	1.00E+00	t	“Crushing, rock/RER U” (b)
			Electricity	1.10E+00	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.4	Handling	12.5	Conveyor belt, 4 m	4.05E-07	m	“Conveyor belt, at plant/RER/I U” (b)
			Conveyor belt, 10 m	1.38E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Overband	1.45E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Conveyor belt, 3 m	4.15E-07	m	“Conveyor belt, at plant/RER/I U” (b)
			Conveyor belt, 15 m	2.07E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	1.46E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.5	Screening (40/200 mm)	12.5	Vibrating screen	6.88E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	8.83E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.6	Handling	6.25	Conveyor belt, 8 m	1.11E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Conveyor belt, 10 m	1.38E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	7.63E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.7	Storage	6.25	Vibrating feeder	3.24E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Hopper	2.28E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	1.77E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.8	Handling	6.25	Conveyor belt, 6 m	8.29E-07	m	“Conveyor belt, at plant/RER/I U” (b)
			Conveyor belt, 15 m	1.52E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Conveyor belt, 15 m	2.07E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	1.14E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.9	Crushing	6.25	Jaw crusher	1.00E+00	t	“Crushing, rock/RER U” (b)
			Electricity	2.21E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.10	Handling	6.25	Conveyor belt, 12 m	1.66E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	3.81E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.11	Crushing	6.25	Rod mill	1.00E+00	t	“Crushing, rock/RER U” (b)
			Electricity	6.13E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.12	Handling	6.25	Conveyor belt, 20 m	2.76E-06	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	5.09E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.13	Screening (0/32 mm)	6.25	Vibrating screen	6.88E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	8.83E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.14	Handling	5	Conveyor belt, 5 m	6.91E-07	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	2.54E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.15	Handling	5	Loading shovel (V)	3.80E-01	m^3	“Loading shovel (V)_Excavation, skid-steer loader/RER U”.
9.16	Handling	5	Chains feeder	1.69E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	9.32E-03	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.17	Screening (0/2 mm)	5	Vibrating screen	6.88E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	8.83E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
9.18	Handling	1	Conveyor belt, 5 m	6.91E-07	m	“Conveyor belt, at plant/RER/I U” (b)
			Electricity	2.54E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
10.1	Waste handling	0.625	Loading shovel (V)	3.80E-01	m^3	“Loading shovel (V)_Excavation, skid-steer loader/RER U”.
			Truck 28 t, 15 km	1.50E+01	tkm	“Transport, lorry 20-28t, fleet average/CH U” (b). Average distance from treatment plant to landfill is 15 km.
Output						
			Emissions (c)			
10			*Waste*			
10.2	Waste treatment	1	Disposal, inert waste	6.25E-01	t	“Disposal, inert waste, 5% water, to inert material landfill/CH U”

(a) Natural resources included in the reference processes; b) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010); c) Emissions included in reference processes

Table 20. Inventory data of RFA 0/2 mm production (1 t) (continued)

Item	*Process*	*Processed amount (t)*	*Unit process*	*Amount*	*Unit*	*Reference process*
Output						
11			*Avoided product*			
11.1	Transport	11.875	Truck 28 t, 15 km	1.50E+0	tkm	“Transport, lorry 20-28t, fleet average/CH U” (b). Average distance
11.2	Landfill	11.875	Disposal, inert waste	1.00E+00	t	“Disposal, inert waste, 5% water, to inert material landfill/CH U” (b)
			Products and co-products		*Unit*	*Allocation (%)*
12			RFA 0/2 mm	1	t	8
13			RFA 2/8 mm	1.425	t	12
14			RA 8/32 mm	2.375	t	20
15			RA 32/60 mm	1.187	t	1
16			RA 0/40 mm	5.888	t	50

(a) Natural resources included in the reference processes; b) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010); c) Emissions included in reference processes

Table 21. Inventory data of unit process “C&DW treatment plant (1 p)”

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources			
	Occupation, industrial area	7.50E+05	m^2a	
	Transformation, from unknown	1.50E+04	m^2	
	Transformation, to industrial area	1.50E+04	m^2	
	Materials/Energy			
	Light fuel oil/CH U (a)	6.52E-06	m^2	
Output				
	Emissions(b)			
	Waste (c)			
	Avoided product (d)			
	Products and co-products			
	C&DW treatment plant	1.00E+00	p	“Sorting plant for construction waste/CH/I U” (e) (for the whole unit process). Sorting plant with a construction waste throughput of 200,000 t/year and 50 years operation time.

(a) Fuel oil demand from small administrative building.
(b) Emissions included in the subprocesses.
(c) Waste included in the subprocesses.
(d) Not considered.
(e) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).

14.1.3. Inventory data from the filler, cement and additive production subsystems

Production data regarding 1 t of filler are shown in Table 22. In order to create this process the unit process “Limestone, milled, loose, at plant” by Ecoinvent v.2.2 database (Ecoinvent, 2010) was taken as a reference. The included subprocesses were: milling, sieving, filtering, storing, one part of the total heating energy for “production” and “administration”, and land use.

For the inventory on the production of 1 t of cement, the unit process “Portland cement, strength class Z 42.5, at plant” by Ecoinvent v.2.2 database (Ecoinvent, 2010) was used. This is shown in Table 23, and it includes the mixing and grinding manufacturing processes, internal processes (transportation, etc.) and infrastructure (specific machines and plant).

EPD (EFCA, 2006) of additive was used as reference data for the inventory. This Eco-profile is derived from data supplied by European Federation of Cement Admixtures Associations and covers cradle to gate production of 1 t of normal plasticisers in Europe. The unit process "Additive" was created by using the data included in EPD (EFCA, 2006). Inventory data are shown in Table 24.

Table 22. Inventory data of unit process of filler production (1 t)

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources [a]			
	Materials/Energy			
	Electricity, hydropower, at run-of-river power plant/CH U	1.60E+01	kWh	
	Electricity, medium voltage, production ES, at grid/ES U	1.60E+01	kWh	
	Heat, light fuel oil, at industrial furnace 1 MW/CH U	8.98E+01	MJ	
	Industrial machine, heavy, unspecified, at plant/RER/I U	2.25E-01	kg	
	Light fuel oil, burned in boiler 100kW, non-modulating/CH U	1.50E+00	MJ	
	Limestone, crushed, for mill [b]	1.00E+00	t	
Output				
	Emissions (air)			
	Heat, waste	1.15E+02	MJ	
	Waste [c]			
	Avoided product [d]			
	Products and co-products			
	Filler	1.00E+00	t	"Limestone, milled, loose, at plant/CH U" [e] (for the whole unit process).

[a] Natural resources included in the subprocesses.
[b] This process includes land use of the mine, of the paved roads and buildings within the mine and for recultivation.
[c] Waste included in the subprocesses.
[d] Not considered.
[e] Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).

Table 23. Inventory data of unit process of cement production (1 t)

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources [a]			
	Materials/Energy			
	Cement plant/CH/I U [b]	5.36E-08	p	
	Clinker, at plant/CH U	9.03E+02	kg	
	Electricity, medium voltage, production ES, at grid/ES U	2.92E+01	kWh	
	Ethylene glycol, at plant/RER U	1.90E-01	kg	
	Steel, low-alloyed, at plant/RER U	5.00E-02	kg	
	Transport, lorry 3.5-20t, fleet average /CH U	4.86E+00	tkm	
Output				
	Emissions (air)			
	Heat, waste	1.05E+02	MJ	
	Waste [c]			
	Avoided product [d]			
	Products and co-products			
	Cement	1.00E+00	t	"Portland cement, strength class Z 42.5, at plant/CH U" [e] (for the whole unit process).

[a] Natural resources included in the subprocesses.
[b] This process includes the infrastructure (buildings, paved roads, etc.) and the land-use for the cement production.
[c] Waste included in the subprocesses.
[d] Not considered.
[e] Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).

Table 24. Inventory data of unit process of additive production (1 t)

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources			
	coal, brown	8.20E+03	g	
	coal, hard	6.50E+03	g	
	crude oil	5.20E+04	g	
	natural gas	1.80E+04	dm^3	
	Materials/Energy			
	Total energy	1.28E+03	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (a). “Total Energy = 4.6 MJ” by 1 kg of additive according to EPD (EFCA, 2006) has turned into “Electricity, kWh” by 1 t of additive (1 MJ = 0.2778 kWh).
Output				
	Emissions (air)			
	CO_2	2.20E+02	kg	
	CO	1.10E+02	g	
	NO_x	5.20E+02	g	
	SO_x	8.50E+02	g	
	Methane	3.80E+02	g	
	Butane	3.50E+03	mg	
	Pentane	4.40E+03	mg	
	Benzene	1.00E+03	mg	
	Non-methane VOC	1.70E+02	g	
	PAH’s	7.80E+03	µg	
	Arsenic (As)	4.70E+04	µg	
	Chromium VI (Cr)	6.80E+02	µg	
	Mercury (Hg)	2.80E+03	µg	
	Nickel (Ni)	9.30E+02	mg	
	Vanadium (V)	1.90E+03	mg	
	Sodium dichromate	2.00E+03	µg	
	Dioxins	7.90E+03	ng	
	Halon-1211	5.80E+02	µg	
	Halon-1301	2.80E+03	µg	
	Emissions (water)			
	Chemical Oxygen Demand	3.40E+02	g	
	PAH’s	1.30E+04	µg	
	Oils, unspecified	6.20E+02	mg	
	Phosphate	9.40E+02	mg	
	Barite	4.00E+03	mg	
	Emissions (soil)			
	Chromium VI (Cr)	2.80E+02	mg	
	Oils, unspecified	4.60E+04	mg	
	Waste			
	No-hazardous waste	3.40E+03	g	“Disposal, inert waste, 5% water, to inert material landfill/CH U” (a)
	Hazardous waste	1.70E+02	g	“Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U” (a)
	Avoided product (b)			
	Products and co-products			
	Additive	1.00E+00	t	EPD (EFCA, 2006) of plasticising admixture derived from data supplied by European Federation of Concrete Admixtures Associations (for the whole unit process).

(a) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010).

(b) Not considered.

14.2. LCI of mortar production subsystem

As can be seen in Figure 39, mortar manufacture begins by distributing its components to the factory, where they undergo different processes before obtaining the dry mortar. The processing is divided into two general processes called pre-mix and post-mix: the first one includes those processes previous to mixing, that is, handling, storage and dosage of raw materials; the latter includes the components mixing, handling and storage of final product. According to the production processes diagram (Figure 39), the inventory developed for the production of 1 t of masonry mortar is shown in Table 25 and explained below:

- The following have been considered as inputs: raw materials and energy corresponding to mortar components production and distribution, as well as the processes included in "processing" and mortar production plant.
  - Production, distribution and pre-mix processing have been specified for every mortar component, as every component has its own processes, such as equipment used for loading and transportation as well as the distance from the place of production to the mortar manufacture plant. The amount of input flow of these processes shall be determined in accordance with the mortar components dosage.
    - The aggregates (NFA and RFA) distribution process includes loading materials with a loading shovel into a 28 t truck, transportation to the mortar production plant, and gravity unloading of the aggregates. Filler, cement and additive distribution processes include loading materials to the tank truck by using a loading telescopic chute, as well as the transportation to the mortar factory. Trucks features as well as distances are shown in the inventory table (Table 25).
    - The aggregates (NFA and RFA) pre-mix process begins with the handling process, which includes equipment such as a conveyor belt and bucket elevators which distribute the aggregates to the storage hopper. Then, in the dosage process the material is distributed with the screw conveyor. As for filler, cement and additive, the pre-mix process includes unloading materials with a loading chute to the hopper, where they are stored up to the moment of distribution by using a screw

conveyor for the subsequent dosage process.

- In the general post-mix process, the mortar components are mixed into the mortar mixer according to the dosage chosen. After the required mixing period, mortar is distributed with the screw conveyor and bucket elevator to the storage hopper where it shall stay until commercialization. Input flows have been computed for 1 t of dry mortar.
- The process created to collect inventory data on the mortar plant is shown in Table 26. The unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010) “Concrete mixing plant/CH/I U” was taken as a reference, and subprocesses regarding machinery were eliminated. The created process was called “Mortar plant” and includes the area of the infrastructure (buildings, roads, etc.). The lifespan of the infrastructure and the land occupation is assumed to be 50 years, and the average yearly production is about 100,000 t/y.
- The inventory output flow is the product, in this case 1 t of dry masonry mortar with a minimum compressive strength of 5 N/mm^2 according to EN 998-1 (CEN, 2010) and EN 998-2 (CEN, 2012a).

Table 25. Inventory data of mortar production (1 t)

Item	*Process*	*Processed amount (t)*	*Unit process*	*Amount*	*Unit*	*Reference process*
Input						
			Natural resources (a)			
			Materials/Energy			
17.1	NFA 0/2 mm production	*	NFA production	1.00E+00	t	Table 18.
17.2	NFA 0/2 mm distribution	*	Loading shovel	3.55E-01	m^3	"Excavation, skid-steer loader/RER U" (b)
			Truck, 28 t, 4 km	4.00E+00	tkm	"Transport, lorry 20-28t, fleet average/CH U" (b). Distance from quarry to mortar manufacture plant is 4 km.
17.3	NFA 0/2 pre-mix	*				
17.3.1	Handling	1	Belt unloader, 11.55 m	1.26E-06	m	"Conveyor belt, at plant/RER/I U" (b)
			Hopper	3.09E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.07E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
17.3.2	Handling	1	Bucket elevator, 26.2 m	3.49E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	2.45E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
17.3.3	Handling	1	Conveyor belt, 5 m	6.45E-07	m	"Conveyor belt, at plant/RER/I U" (b)
			Conveyor belt, 3.6 m	4.65E-07	m	"Conveyor belt, at plant/RER/I U" (b)
			Electricity	4.04E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
17.3.4	Storage	1	Hopper	1.31E-05	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	2.67E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
17.3.5	Dosage	1	Screw conveyor	1.05E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	8.05E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
18.1	RFA 0/2 mm production	*	RFA production	1.00E+00	t	Table 20.
18.2	RFA 0/2 mm distribution	*	Loading shovel (V2)	3.80E-01	m^3	"Loading shovel (V2)_Excavation, skid-steer loader/RER U". This process derives from the process "Excavation, skid-steer loader/RER U" by Ecoinvent v.2.2 database (2010). Diesel consumption was modified (from 0.13 kg to 0.124 kg) according to the equipment used.
			Truck, 28 t, 10 km	1.00E+01	tkm	"Transport, lorry 20-28t, fleet average/CH U". Distance from treatment plant to mortar manufacture plant is 10 km.
18.3	RFA 0/2 pre-mix	*				
18.3.1	Handling	1	Belt unloader, 11.55 m	1.35E-06	m	"Conveyor belt, at plant/RER/I U " (b)
			Hopper	3.09E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	2.67E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
18.3.2	Handling	1	Bucket elevator, 26.2 m	3.49E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	2.45E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
18.3.3	Handling	1	Conveyor belt, 5 m	6.91E-07	m	"Conveyor belt, at plant/RER/I U " (b)
			Conveyor belt, 3.6 m	4.97E-07	m	"Conveyor belt, at plant/RER/I U " (b)
			Electricity	4.32E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
18.3.4	Storage	1	Hopper	1.31E-05	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	2.67E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
18.3.5	Dosage	1	Screw conveyor	1.05E-06	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	8.05E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
19.1	Filler production	*	Filler production	1.00E+00	t	Table 22.
19.2	Filler distribution	*	Loading telescopic chute	5.62E-08	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.24E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
			Truck, 24 t, 75 km	7.50E+01	tkm	"Transport, lorry 20-28t, fleet average/CH U" (b). Distance from filler manufacture plant to mortar manufacture plant is 75 km.
19.3	Filler pre-mix	*				
19.3.1	Handling	1	Loading telescopic chute	5.62E-08	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.24E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
19.3.2	Storage	1	Hopper	6.96E-05	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
19.3.3	Dosage	1	Screw conveyor	1.37E-07	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.15E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
20.1	Cement production	*	Cement production	1.00E+00	t	Table 23.
20.2	Cement distribution	*	Loading telescopic chute	4.55E-08	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.00E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
			Truck, 28 t, 200 km	2.00E+02	tkm	"Transport, lorry 20-28t, fleet average/CH U" (b). Distance from cement manufacture plant to mortar manufacture plant is 200 km.
20.3	Cement pre-mix	*				
20.3.1	Handling	1	Loading telescopic chute	4.55E-08	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.00E-02	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)
20.3.2	Storage	1	Hopper	6.26E-05	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
20.3.3	Dosage	1	Screw conveyor	1.37E-07	t	"Industrial machine, heavy, unspecified, at plant/RER/I U" (b)
			Electricity	1.15E-01	kWh	"Electricity, medium voltage, production Spain, at grid/ES U" (b)

Table 25. Inventory data of mortar production (1 t) (continued)

Item	*Process*	*Processed amount (t)*	*Unit process*	*Amount*	*Unit*	*Reference process*
Input						
21.1	Additive production	*	Additive production	1.00E+00	t	Table 24.
21.2	Additive distribution	*	Loading telescopic chute	5.56E-08	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	1.22E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
			Truck, 18 t, 440 km	4.40E+02	tkm	“Transport, lorry 3.5-20t, fleet average/CH U” (b). Distance from plasticizing additive manufacture plant to the mortar manufacture plant is 440 km.
21.3	Additive pre-mix	*				
21.3.1	Handling	1	Loading telescopic chute	5.56E-08	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	1.22E-02	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
21.3.2	Storage	1	Hopper	8.43E-05	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
21.3.3	Dosage	1	Screw conveyor	4.72E-05	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	3.07E+01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
22	Post-mix	1				
22.1	Mixing	1	Mortar mixer	2.48E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	6.21E-01	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
22.2	Handling	1	Screw conveyor	1.85E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Bucket elevator	2.92E-07	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Screw conveyor	1.85E-06	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	2.41E+00	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
22.3	Storage	1	Hopper	1.13E-05	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Motor	2.88E-09	t	“Industrial machine, heavy, unspecified, at plant/RER/I U” (b)
			Electricity	4.92E-03	kWh	“Electricity, medium voltage, production Spain, at grid/ES U” (b)
23	Mortar plant	1	Mortar plant	2.00E-07	p	Table 26. The amount is computed according to 100,000 t/year and 50 years of service life: 1/5,000,000.
Output						
			Emissions (c)			
			Waste (d)			
			Avoided product (e)			
			Products and co-products			
24			M5 Masonry mortar	1.00E+00	t	

* Amount in accordance to mortar dosage; (a) Natural resources included in the reference processes; (b) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010); (c) Emissions included in the reference processes; (d) Waste included in the reference processes; (e) Not considered.

Table 26. Inventory data of unit process of “Mortar plant (1 p)”

	Subprocess	*Amount*	*Unit*	*Reference process*
Input				
	Natural resources			
	Occupation, industrial area, built up	9.99E+04	m^2a	
	Occupation, industrial area, vegetation	1.18E+05	m^2a	
	Occupation, traffic area, road network	1.50E+05	m^2a	
	Transformation, from unknown	7.37E+03	m^2	
	Transformation, to industrial area, built up	2.00E+04	m^2	
	Transformation, to industrial area, vegetation	2.37E+03	m^2	
	Transformation, to traffic area, road network	3.01E+03	m^2	
	Materials/Energy			
	Building, all, steel construction/CH/I U (a)	1.40E+03	m^2	
	Building, multi-storey/RER/I U (b)	7.19E+03	m^3	
Output				
	Emissions (c)			
	Waste (d)			
	Avoided product (e)			
	Products and co-products			
	Mortar plant	1	p	“Concrete mixing plant/CH/I U” (f) (for the whole unit process). The lifespan of the infrastructure and the land occupation is assumed to be 50 years. The average yearly production is about 100000 t.

(a) This process represents current metal industrial structures. Includes the most important materials used and their disposal, the transportation of the parts to the building site and to the final disposal at the end of life. Also included is the requirement of electricity for construction, maintenance and demolition. Operation is not included. The service life is assumed to be 50 years.

(b) This process represents a concrete multi-storey building. Includes the most important materials used and their disposal, the transportation of the parts to the building site and to the final disposal at the end of life. Also included is the requirement of electricity for construction, maintenance and demolition. Operation is not included. The life of the building is assumed to be 80 years.

(c) Emissions included in the reference processes; (d) Waste included in the reference processes; (e) Not considered; (f) Unit process by Ecoinvent v.2.2 database (Ecoinvent, 2010)

15. Discussion

To carry out a LCA, there is a need for LCI data to ensure a representative assessment. The life cycle inventory should include personalised data, as far as possible, for the product analysed. This can be done using measurements, calculations or estimations, which can be complemented by the already existing database inventories and EPD. In this study, the inventory developed for the manufacture of masonry mortars was created from specific data from the mortar production process, unit processes of Ecoinvent v.2.2 database (Ecoinvent, 2010) and EPD (EFCA, 2006). The data quality was furthermore increased by taking into account the specific production process of masonry mortar (as well as the production processes of components such as NFA and RFA); these production processes were modelled process by process, in order to obtain a more accurate and reliable inventory. In the absence of specific production process data, the inventory data of unit processes of Ecoinvent v.2.2 database database (Ecoinvent, 2010) and EPD (EFCA, 2006) were used. The analysis of data quality indicators provided the following information:

- Temporal correlation was represented by the degree of accordance between the year of the study and the year of the available data. As some industrial technologies develop very quickly, the use of old secondary data in current studies can significantly distort the results. This corresponded to less than 3 years of difference for site specific data and less than 10 years for data from the Ecoinvent v.2.2 database (Ecoinvent, 2010) and the EPD (EFCA, 2006).
- Geographical correlation was correct as the production conditions in the area of the study and those in the geographical area to which the secondary data were referred corresponded to the European Union.
- Further technological correlation describes the representativeness of secondary data for a specific technology, company or process of production. The methodology applied in this study has enabled the development of LCI with broad temporal and geographical representation, by applying the Ecoinvent v.2.2 database (Ecoinvent, 2010) and EPD (EFCA, 2006).
- The data used were representative of the product system, owing to their reliability and completeness. The transportation distances are unique for this study, but can easily be replaced by local-specific data to adapt the inventory to similar system products.

Data quality and uncertainty are related. Greater data quality brings with it lower uncertainty and increased robustness of the LCA. The inclusion of specific data from the product system decreased the uncertainty concerning the available data. Furthermore, as the amount of data increases, uncertainty decreases and improves the robustness of the LCA. Nevertheless, uncertainty at the LCI level does exist due to data variability and the necessary assumptions made to build the product system. Uncertainties in the inventory created were due to:

- Parameter uncertainty related to the data variability for both foreground and background inventory data.
- The uncertainty related to choices or assumptions. In this study due to uncertainty in data on transportation, related to truck and average distances considered: i) unit process that defines transportation in the production processes of NFA and RFA, "Transport, lorry 20-28 t, fleet average/CH U"; ii) the transportation distance of the waste from its site of generation to the treatment plant, 20 km; ii) and the transportation distance of the waste from its site of generation to the landfill for its final disposal, 15 km.

Inventories presented in this paper were elaborated using data uncertainty estimations in order to understand the reliability of the future LCA in masonry mortar production more clearly. In assessing the impact of the life cycle that would be developed in future research, uncertainty analysis will be used to determine the uncertainty related to the data variability and, consequently, the degree of exactitude and the magnitude of error of the estimations made for the different inventory sources. This procedure will be conducted using the Monte Carlo method, which enables quantification of uncertainty and will determine the transparency and robustness of the LCA. Furthermore, sensitivity analyses will be carried out to determine how any changes in the data or assumptions might affect the results of the life cycle impact assessment.

16. Conclusions

The LCI developed in this study in accordance with ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) to be used in masonry mortar made of NFA and RFA, includes the production of raw materials and masonry mortar manufacture, and its system boundaries are considered to be from the cradle to gate level. In order to create the inventory, the data used were those given by producers, as well as data included in the unit processes by Ecoinvent v.2.2 database (Ecoinvent, 2010) and EPD (EFCA, 2006). Data collection included: raw materials, equipment used for the production processes, production facilities, means of transport and distances, the products resulting from production processes, waste and emissions. Combining production data with unit processes data by Ecoinvent v.2.2 database (Ecoinvent, 2010) allowed to develop aggregate production inventories (natural and recycled) and masonry mortar inventories in greater detail, especially regarding the equipment used for the production processes; that made the result of the life cycle inventory match the reality of the process. The methodology used for developing the inventory was clear; this makes its reproducibility possible and allows to identify and quantify the input and output flows which are really related to the masonry mortar life cycle. That makes it essential for the future quality of the life cycle assessment, which shall be developed in a future research aiming at assessing the main impacts related to the natural aggregate and recycled aggregate life cycles, as well as the masonry mortar life cycle made of those aggregates.

CHAPTER 4. Environmental assessment of masonry mortars made with natural and recycled aggregates[6]

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[6] *The results shown in this Chapter were presented in: G. M. Cuenca-Moyano, M. Martín-Morales, A. Bonoli, I. Valverde-Palacios. Environmental assessment of masonry mortars made of natural and recycled aggregates. The International Journal of Life Cycle Assessment (2019) 24: 191-210. https://doi.org/10.1007/s11367-018-1518-9.*

17. Introduction

Construction in Europe uses half of the raw materials extracted and generates around a third of the total amount of waste (European Commission, 2011). In 2014, for example, the aggregates demand amounted to 2.7 billion tonnes in Europe, and 90 million tonnes in Spain in particular, which were used mainly for the production of concrete, prefabricated products and mortars (ANEFA 2016; UEPG 2016). Specifically, the aggregate constitutes as much as 90% in weight of the composition of masonry mortar, which is one of the most extensively used materials in the construction sector. In addition, according to data published by Eurostat (2017), in the EU-28 countries 276 million tonnes of mineral waste from construction and demolition were treated; 82% of such waste was recycled, 14% was disposed in landfills and 6% used for backfilling. In Spain, 7 million tonnes were processed by authorized waste managers (treatment plants and/or landfills), of which 7% was used for backfilling, 30% was disposed in landfills and 63% was recycled. However, these data differ from those provided by the Spanish Association of Recycling of Construction and Demolition Wastes (2017). According to this Association, 70% of the total C&DW generated in Spain was processed by authorized waste managers (39% recycled, 24% deposited in landfill and 7% stock piled) while the remaining 30% was unsupervised and dumped at unauthorized sites. This 39% of recycled material is still far from the minimum 70% target to be achieved by 2020, according to the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008). According to these data, C&DW can still be treated as waste in Spain, and not as an entirely re-used secondary raw material.

European Union’s waste management policies aim to reduce waste environmental impacts and improve resources’ efficiency. In this way, circular economy maintains the added value of products for as long as possible and reduces waste; it keeps products in the economy when they reach the end of their lifespan in such a way that they can be re-used over and over again in order to create more value (European Commission, 2014c). In this context, turning waste into raw materials is a way of increasing the efficiency of using resources and closing the materials’ cycle. In the last four decades, the use of RA from C&DW as a replacement for NA has been widely developed in a large number of investigations, both regarding structural concrete (Etxeberria et al., 2007; Frondistou-Yannas, 1977; Hansen and Narud, 1983), pre-cast concrete (Hossain et al., 2016a; Martín-Morales et al., 2017; Sánchez-Roldán et al., 2016), road construction (Martín-Morales et al., 2013a; Mroueh et al., 2001; Poon and Chan, 2006; Vegas et al., 2011), masonry mortar production (Bektas et al., 2009; Corinaldesi and Moriconi, 2009; Jiménez et al., 2013) or as extensive green roof substrate material (Mickovski et al., 2013; Molineux et al., 2015). Such studies have shown the possibility to widen the application range of RA, increasing possibilities for assessment and recycling of C&DW. Adding C&DW as a technological nutrient in a circular economy, helps to reduce the use of resources, waste production and limit energy consumption, while generating benefits. Similarly, aiming to reduce the impact of waste creation and management on the environment, the Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008) has incoporated a new approach which takes into account products' life cycle, from generation to destruction, reinforcing in this way the economic value of waste. Consumption of resources in the building sector and related environmental impacts can be reduced by considering the principles of circular economy and adopting an eco-design approach that promotes more resource-efficient methods of manufacturing construction products using recycled materials. This, in turn, will reduce the amount of waste sent to landfill (European Commission, 2014a). The existence of regulations that allow the use of RA in the manufacture of construction materials encourages and justifies research into recycled materials. In that context, LCA is increasingly being used to identify strategies that will improve the environmental performance of C&DW management systems and, therefore, to support the eco-design of construction materials.

The LCA methodology (ISO, 2006a, 2006b) is used to measure the environmental impact of a product, process or system along its life cycle. Many studies have assessed the environmental impact of C&DW management systems (Blengini and Garbarino, 2010; Coelho and De Brito, 2012; Dahlbo et al., 2015; Mercante et al., 2012; Ortiz et al., 2010; Penteado and Rosado, 2016; Vossberg et al., 2014). These studies showed how recycling C&DW was environmentally feasible as the impacts avoided from the non-disposal of waste in landfills exceeded the number of impacts from their processing. The environmental benefit was greater when the recycling process was performed at the place of waste generation or close treatment plants, showing the big environmental burden generated by transport processes. Environmental burdens generated during RA production coming from C&DW were also assessed and compared to those impacts caused by NA production. Results obtained by Simion et al. (2013) showed that the recycling process generated lower environmental impact compared to that resulted from the NA processing, as regards the emission of pollutants, the consequences on human health and ecosystems, in terms of global warming potential and the amount of energy consumed. In the same way, Hossain et al. (2016b) concluded that RA from C&DW reduced 65% greenhouse gases emission with a saving of 58% non-renewable energy consumption compared to NA. Similar results were obtained when assessing the use of RA as a replacement of NA for different construction applications, such as concrete production (Knoeri et al., 2013; Serres et al., 2016; Turk et al., 2015), road construction (Butera et al., 2015; Mroueh et al., 2001) and concrete blocks production (Hossain et al., 2016a). However, despite the numerous studies carried out that have demonstrated the technical feasibility of mortars manufactured with RA (Bektas et al., 2009; Corinaldesi and Moriconi, 2009; Jiménez et al., 2013), the application of LCA to confirm its environmental feasibility has only been developed in studies where cement or sand have been replaced with recycled materials such as rice husk ash (Mendes Moraes et al., 2010) or liquid cristal displays scrap (Ruello et al., 2016). For the literature search, the authors used the search items “masonry mortars”, “recycled aggregate” and “LCA” in the Web of Science (Clarivate Analytics 2017) and Scopus (Elsevier B.V. 2017) databases, no LCA studies addressing the use of RA from C&DW in masonry mortars were found. As a consequence, it appears necessary to use LCA to develop an environmental evaluation on masonry mortars manufactured with these aggregates.

The aim of this study is to apply LCA methodology to quantify and assess the different environmental impacts associated with the production of masonry mortars made with NFA and RFA from C&DW. As we are dealing with mineral waste originating from demolition and construction, the best recycling option is via processing at a C&DW treatment plant. After recycling, therefore, C&DW can be reintroduced into the system as a secondary raw material. However, the fine fraction (RFA 0/2 mm) obtained at the end of the process is not used and is ultimately sent to landfill. Nevertheless, European Standard EN 13139 (CEN, 2002a) “Aggregates for mortars” permits the use of RA in the manufacture of masonry mortars without restrictions on the percentage used, thereby creating a potential outlet for this fine fraction of RA from C&DW whose use is limited by more restrictive standards (Martín-Morales et al., 2013c). This fact, combined with the large amount of aggregate which forms part of the composition of masonry mortar (as much as 90%), constitutes the optimum situation for developing the technical and environmental feasibility of this well know and extensively used construction material. In this case, the authors used 25% and 50% of RFA in the manufacture of masonry mortars. This means that the use of RFA in the manufacture of masonry mortars will mitigate the environmental impact by reducing the amount of C&DW sent to landfill and saving natural resources, and thereby contribute to increasing the rate of recycling of C&DW in Spain. This research seeks to assess the environmental feasibility of masonry mortars, the technical feasibility of which has been set out by the authors and published in part in Chapter 1 and Chapter 2 of this document. For that purpose, in this study the environmental burdens generated during the production of NFA and RFA were examined and compared in order to identify those processes which generate the environmental benefits associated with the use of RFA as a replacement for NFA. The environmental performance of mortars manufactured with different amounts of NFA, RFA and admixture were subsequently assessed and checked. The use of LCA methodology highlights the novelty and originality of this research. The results are presented in a clear and transparent manner and are supported by thorough sensitivity and uncertainty analyses. Although this study presents a specific case in the south of Spain, the results can be adapted to other geographical areas by adjusting the inventory to the manufacturing processes, energy consumption and transport distances specific to each area. This research is aimed at public authorities, technical personnel, builders and manufacturers, for the purpose of overcoming the barriers to applying RA, boosting the consumption of these aggregates and increasing environmental and economic benefits in the construction sector.

18. Materials and methods

18.1. Materials

Masonry mortars assessed in this study meet the requirements established in EN 998-2 (CEN, 2012a) for masonry mortars with a minimum compressive strength of 5 N/mm^2. Mortar samples were manufactured according to the dosage recommendations for commercial masonry mortar provided by the manufacturer ARGOS D.C. The product is commercialized as a premixed dry mortar (ready to be mixed with water and applied).

The components are described below:

- Fine aggregate for masonry mortars according to EN 13139 (CEN, 2002a):
    - A dolomitic NFA of 0/2 mm size, with a bulk density of 2.818 t/m^3.
    - A RFA of 0/2 mm size produced in a C&DW treatment and recovery plant. It was obtained from civil engineering concrete waste, the components of which,

determined according to EN 933-11 (CEN, 2009b), included: 87% concrete, 7.5% NA, 2.5% brick, 1.6% asphalt and 0.2% other impurities. Its bulk density value is 2.630 t/m^3.

- Filler. A limestone filler of 0.890 t/m^3 bulk density was added to the aggregate to adjust the fineness modulus according to EN 13139 (CEN, 2002a).
- Cement. A Portland cement of 1.100 t/m^3 bulk density was used, EN 197-1- CEM II/A-L 42.5 R according to RC-16 (Ministerio de la Presidencia, 2016).
- Admixture. A commercial air-entraining/plasticizer admixture (RHEOMIX 932) was used to improve workability. Its bulk density value is 0.900 t/m^3.

The composition of RFA (NA bonded with cement mortar) reduces its density and increases the water absorption capacity with respect to NA (Martín-Morales et al., 2013c). These properties have an effect on the consistency, reducing workability of masonry mortar in fresh state, and also the mechanical performance in the hardened state. However, the partial replacement of NFA by RFA in masonry mortars provided enough workability, improved mechanical strength and reduced the water absorption coefficient due to capillary action values (Bektas et al., 2009; López Gayarre et al., 2017). According to these statements, in the masonry mortars studied NFA was replaced by RFA in different percentages (0%, 25% and 50%). In order to compare the environmental impact of mortars either made of NFA or RFA, it is necessary for these mortars to meet similar functional requirements. As mortar is supplied as dry dough, different dosages of mortar were tested with different amounts of admixture, the aim being that of obtaining recycled mortars with a suitable level of workability which allows its application to works (plastic consistency ≥ 140 mm) and a minimum compressive strength of 5 N/mm^2. The mortars studied comply with these requirements, which are the minimum established in European Standard EN 998-2 for a masonry mortar with class M5 compressive strength.

Mortar samples were designed with the letter G which indicates a masonry mortar for normal use according to EN 998-2 (CEN, 2012a), followed by the NFA replacement percentage and the admixture content ratio. Table 27 shows the designation and dosage of mortars (per t of product), as well as their consistency and compressive strength values. In order to determine the LCA, ISO 14040 (ISO, 2006a), ISO 14044 (ISO, 2006b), SimaPro 8.0.2 software format (PRé Consultants, 2014) and the mortar production system were taken into account.

Table 27. Dosage table of mortars studied (per 1 t of mortar) and properties

Mortar	*NFA replacement (%)*	*Component*					*Property (unit)*	
		NFA (t)	*RFA (t)*	*Filler (t)*	*Cement (t)*	*Admixture (t)*	*Consistency (mm)*	*Compressive strength (N/mm^2)*
G-0-1	0	0.810	0	0.090	0.100	0.001	153	7.00
G-25-1	25	0.612	0.198	0.090	0.100	0.001	143	8.68
G-25-3	25	0.612	0.198	0.090	0.100	0.003	142	8.22
G-25-6	25	0.612	0.198	0.090	0.100	0.006	155	9.09
G-25-9	25	0.612	0.198	0.090	0.100	0.009	155	9.73
G-50-9	50	0.405	0.405	0.090	0.100	0.009	144	9.86

18.2. Methods

18.2.1. Goal and scope of the LCA

The goal of this LCA study is to determine and compare the environmental impact associated with the production of six masonry mortars made with varying amounts of NFA, RFA and admixture, according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). The masonry mortars considered are those determined by mortar dosage in Table 27. The functional unit used as a reference to compare mortar samples is 1 t dry masonry mortar with a minimum compressive strength of 5 N/mm^2, according to the functional requirements specified in section 18.1 (Materials). Furthermore, the environmental burdens generated during the production of aggregates (NFA and RFA) were determined in order to identify their critical production phases as well as those processes giving rise to the environmental benefit associated with the use of RFA as a replacement for NFA. Therefore, LCA methodology was also applied to the production of NFA and RFA, for 1 t functional unit.

The system boundaries of the six masonry mortars include production of the components, transport from production site to mortar plant and manufacture of the masonry mortar; the procedures included in the commercialization, construction, use and mortar demolition phases have not been taken into account. Thus, the LCA is limited to cradle to gate level. If recycling is considered as a strategy for valorising certain CDW fractions, the downstream system boundary can be expanded in order to consider the avoided burdens (credits) due to the production of a secondary material as a partial replacement for a primary (virgin) material (Bovea and Powell, 2016). In this study, we have considered C&DW to be burden-free. Therefore, the full environmental impact of the raw material from C&DW has been attributed to the product in which it was first used, i.e. construction, while the impact caused during the demolition, transport and recycling processes has been allocated to the production of RFA. This is one way of allocating impact. We are aware, however, that there are other ways and this one of the limitations of this study. Recycling C&DW generates an environmental benefit as the impacts caused by waste disposal to landfill and consumption of raw materials are avoided (Blengini and Garbarino, 2010; Ferreira et al., 2016; Knoeri et al., 2013; Turk et al., 2015; Yazdanbakhsh et al., 2017). This benefit is quantified when those processes avoided as a consequence of replacing NFA by RFA are included in the system. In this study, C&DW disposal and transport to landfill were included as avoided processes in the RFA production subsystem. The material resulting from the recycling process (RFA) replaces virgin material (NFA) on a 1:1 ratio in mortar production. Thus, as the amount of RFA increases, the quantity of NFA decreases and this is the avoided consumption of raw materials in the system.

The mortar production system (Figure 40) is divided into the following subsystems:

- The aggregate production subsystem which includes the NFA and RFA production subsystems. In accordance with the dosage of the mortars (Table 27), in the case of the mortar manufactured using only NFA (G-0-1), just the NFA production subsystem was taken into consideration. For the recycled mortars, both production subsytems were included, the features of which are defined as follows:
    - i) The NFA production subsystem includes the extraction of dolomite and the processing thereof in order to obtain NFA 0/2 mm (Figure 41). The dolomite on the site is already fractured (Valverde-Espinosa, 1992) so this peculiar form of mining is carried out without explosives; bulldozers simply rip out the dolomite rock and push it downhill. The material is gathered above ground and treated using a series of crushing and screening processes, thereby enabling the particles to be classified by size and several fractions of aggregate to be obtained. According to data provided by the quarry, it is necessary to process 5 t of dolomite to generate 1 t of NFA 0/2 mm and 4 t of other fractions (2/4 mm and >8 mm). The dolomite quarry is located in Padul (Granada, southern Spain), and transport distance to the mortar plant is 4 km. On average, the quarry produces

380,000 t of manufactured NA per year.

- ii) The RFA production subsystem encompasses the work of demolishing and loading the C&DW, transport from demolition site to C&DW treatment plant, the processing required for obtaining RFA 0/2 mm, and transport to, and disposal at, a landfill site of non-recyclable material (Figure 42). Taking into account system expansion, it also includes the processes which are avoided by recycling C&DW at the treatment plant, i.e. the disposal of the C&DW at landfills as well as transport of the C&DW from demolition site to landfill (Blengini and Garbarino, 2010; Hossain et al., 2016b; Knoeri et al., 2013; Yazdanbakhsh et al., 2017). The area of influence of the landfill is 30 km, so the transport distance from demolition site to landfill was estimated as an average distance of 15 km. These avoided impacts can be subtracted from the total impact related to the production of recycled mortar mix. It was considered that 95% of the C&DW processed at the treatment plant is transformed into marketable materials ranging from finely graded recycled aggregates for the manufacture of concretes and mortars (fractions of 0/2 mm, 2/8 mm, 8/32 mm and 32/60 mm) to filler materials (fraction of 0/40 mm). According to data supplied by the treatment plant, the processing of 12.5 t of C&DW generates 1 t of RFA 0/2 mm and 10.875 t of other fractions (2/8 mm, 8/32 mm, 32/60 mm and 0/40 mm). Thus, the total amount which is not disposed of at landfill is 11.875 t. The remaining 5% of C&DW (0.625 t) is not recoverable and is disposed of at landfill. The recycling machinery is similar to that used in the production of NA as this involves the same structural elements (crushing, screening, conveyor belts, etc.). It also has a section where employees manually sort through the material that passes along the conveyor belts and an overband magnet for the removal of ferric materials. The non-recyclable material is transported to a landfill located 15 km away for final disposal. As the area of influence of the treatment plant is 40 km, the average distance (20 km) was considered as the transport distance from demolition site to C&DW treatment plant. This treatment plant collects 210,000 t of C&DW in an area of influence of 40 km and the average annual production of RA is 200,000 t. The plant is located in Alhendín (Granada, southern Spain) and transport distance to the mortar plant is 10 km.

- The filler production subsystem encompasses the extraction of limestone of great chemical purity which is processed using high-technology equipment to obtain milled calcium carbonate (filler). The factory is located in Darro (Granada, southern Spain) and transport distance to the mortar plant is 75 km. The annual average production of filler is 6,000 t.
- The cement production subsystem commences with the extraction of the raw material, mainly limestone, which is subjected to various crushing, dehydration, carbonatation and sintering processes to obtain clinker. The cement is obtained after milling the clinker, gypsum and added mineral component. It is then either stored in silos awaiting bagging or transported in bulk. The cement is produced at a factory located in Córdoba (Spain) and transport distance to the mortar plant is 200 km. The annual average production of cement is 1,000,000 t.
- The admixture production subsystem encompasses the production of raw materials, transport to the factory and admixture manufacture. Chemical products are combined in varying amounts to achieve the features required for the plastifying admixture. The admixture is manufactured in a factory located in Madrid (Spain) and transport distance to the mortar plant is 440 km.
- The transport subsystem consists of the process of loading each component and transporting it from production site to mortar plant. The process of loading the aggregates (NFA and RFA) is performed with a loading shovel onto a 28 t truck; other materials (filler, cement and admixture) are loaded onto the tank truck using a telescopic loading chute. The transport distances of mortar components were determined using the map application server on the website Google Maps (Alphabet Inc, 2016) and are shown in Figure 40.
- The manufacturing subsystem encompasses the processing of components to obtain masonry mortar and the mortar plant facilities. The manufacturing process is representative of dry mortar factories and follows the standardized protocol for obtaining masonry mortar in accordance with EN 998-2 (CEN, 2012a). The processing begins with the components being handled by equipment such as conveyor belts and bucket elevators or loading chutes, which distribute the materials to different storage hoppers. In the dosage process, materials are distributed via screw conveyors to the mortar mixer. After the required mixing period, mortar is conducted by screw conveyor

and bucket elevator to the storage hopper, where it remains until sale. The dry mortar factory is located in Padul (Granada, southern Spain). The average annual production is 100,000 t of dry masonry mortar.

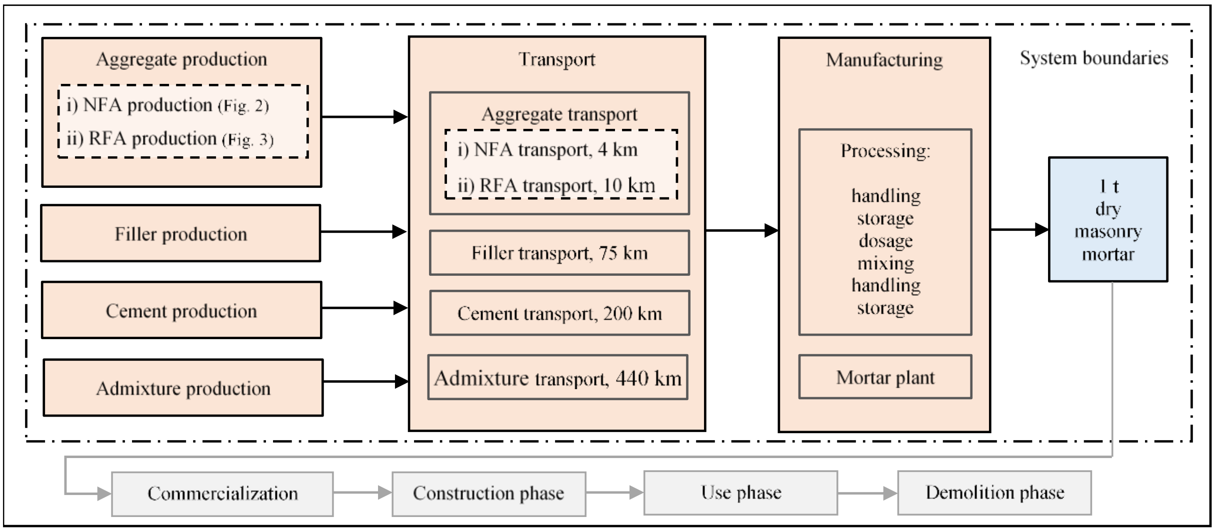

Figure 40. LCA of masonry mortar and system boundaries

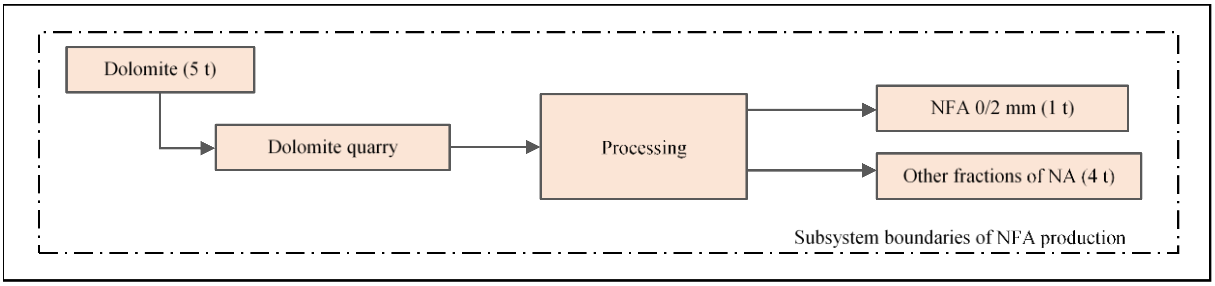

Figure 41. Subsystem boundaries of NFA 0/2 mm production

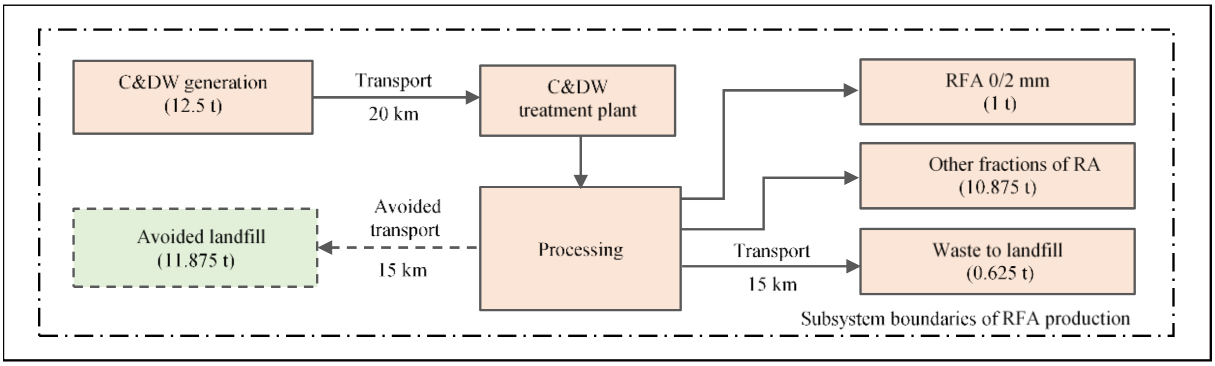

Figure 42. Subsystem boundaries of RFA 0/2 mm production

18.2.2. Life cycle inventory data quality and data collection

The collection of the data required for the masonry mortar life cycle inventory was dealt with extensively by the authors in Chapter 3, where the main input and output of each process encompassed in the product system (Figure 40) were taken into account for the functional unit of 1 t dry masonry mortar. Given the importance of the exhaustiveness in the inventory phase regarding a subsequent application of LCA, it is also necessary to highlight the fact that this needs to be detailed in order to be reproduced by an independent practitioner (ISO, 2006b; Rebitzer et al., 2004). Thus, mortar production processes were defined in depth in more than 145 processes combining foreground data with background data. Foreground data were site specific and collected by means of surveys, interviews and technical visits to the local producers (Spain) which formed part of the process of producing mortar and its components, as related to average production from 2012 to 2014. The data collected included the amount of raw materials, the equipment used in the production processes and the characteristics thereof, the description of production processes and production facilities, means of transport and distances, and the resulting products and waste. The Ecoinvent v.3.01 database (Ecoinvent, 2014) and the Environmental Product Declaration (EPD) (EFCA, 2006) were used as background data for generic materials, energy, transport and waste management. In order to guarantee data quality requirements, including temporal, geographical and technological representativeness, the processes data of Ecoinvent were modified according to information provided by producers and electricity consumption was adapted to the Spanish electricity network. The technology applied to the production of masonry mortar and its components corresponds to the current modal technologies implemented in Spain. Inventory data and production processes corresponding to the production of NFA, RFA and masonry mortars are detailed in Table A2 to Table A6 in Annex; in addition, the elementary flows with a relevance of more than 1% in the final assessment are quantified.

18.2.3. Methodology and selection of impact categories

The impact assessment was carried out using the impact categories recommended in EN 15804+A1 (CEN, 2013a) concerning sustainability of construction works for construction products and services, including masonry mortars. These impact categories are: abiotic depletion of elements (ADe), abiotic depletion of fossil fuels (ADf), global warming (GW), ozone layer depletion (ODP), photochemical oxidation (POF), acidification of soil and water

(A) and eutrophication (E). For these categories, the characterization factors of the CML-IA method (Guinée et al., 2002) were used as established in EN 15804+A1 (CEN, 2013a). In addition to these impact categories, and in order to complete the environmental profile and assess their relevance for masonry mortars, the following impact categories were also analysed: human toxicity for cancer effects (HTc) and for non-cancer effects (HTnc), particulate matter (PM), ecotoxicity (ET), land use (LU) and water depletion (WD). These categories were assessed according to the ILCD 2011 Midpoint method characterization factors (EC-JRC-IES, 2012).

The data collected during the inventory phase were loaded into the SimaPro 8.0.2 software (PRé Consultants, 2014) and processed using the CML-IA method (Guinée et al., 2002) and ILCD 2011 Midpoint method (EC-JRC-IES, 2012). The results of characterization were presented for the impact categories selected. Furthermore, contribution analysis was assessed to determine which processes were playing a significant role in the results. Firstly, the environmental burdens generated during the production of NFA and RFA were examined and compared in order to identify those processes which produce the environmental benefit associated with the use of RFA as a replacement for NFA. After that, the results obtained from the impact assessment of masonry mortars were presented.

18.2.4. Uncertainty and sensitivity analysis

Data uncertainty was carried out to verify the uncertainty related to the data variability for both foreground and background inventory data. This procedure was conducted using the Monte Carlo method, which enables quantification of uncertainty. The simulations were performed with an iteration of the independent variables for 10,000 cases and with a confidence interval of 95%.

A series of sensitivity analyses were performed in order to determine how any changes in the data or assumptions might affect the results of the life cycle impact assessment. Raw material transport processes can have a significant effect on energy consumption and environmental indicators. For the most part, the fuel required to operate trucks is the reason for the high amount of emissions, both during fuel production (at the refinery) and consumption (combustion in the truck engine). These factors depend on the assumptions established in relation to transport distance, as well as on the type of truck used as a means of transport.

Therefore, due to the existing uncertainty in data regarding transport, this study evaluated whether changes in the transport distances of C&DW and the type of truck would alter the results. The parameters studied in the sensitivity analysis are presented in Table 28 and defined below:

- "Transport distance of C&DW from site of generation to treatment plant" and "Transport distance of C&DW from site of generation to landfill". These variables were selected due to the fact that, in the production subsystem of RFA, average distances were used for the transport of C&DW on the basis of the area of influence of the treatment plant (from 1 km to 40 km) and the landfill (from 1 km to 30 km). Therefore, new scenarios were assessed regarding different combinations of transport distances.
- "Type of transport truck". The transport processes in the inventory were replaced by the process "Transport, lorry 16-32 t, EURO5 {GLO}, U". This transport process can reduce nitrogen oxides and sulfur dioxide emissions by up to 65% and 14% per t and km, respectively.

Table 28. Parameters of the sensitivity analysis

Parameters	*Process*	*Scenario*									
		Data used in the model	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	S9
Transport distance (km)	From C&DW generation to treatment plant	20	1	1	1	20	20	40	40	40	20
	From C&DW generation to landfill	15	1	15	30	1	30	1	15	30	15
Transport truck	Lorry, fleet average	yes	yes	yes	yes	yes	yes	yes	yes	yes	-
	Lorry, EURO 5	-	-	-	-	-	-	-	-	-	yes

19. Results and discussion

19.1. Life cycle impact assessment of NFA vs RFA

Characterization values from the production of NFA and RFA are shown in Table 29, which also expresses the variation in the impact of RFA compared with NFA as a percentage (in brackets). The results showed that the production of NFA generated positive values in all categories which produce a negative impact. For RFA production, negative values showed environmental benefits for all impact categories except HTc, HTnc, ET and WD. As can be seen, burdens resulting from the production of NFA were higher than those obtained during the production of RFA in all impact categories. The most significant reduction occurred in the LU category as recycling C&DW avoided its disposal in landfills, which lead to a reduction in land occupation and transformation for inert landfill construction. There were also significant reductions in the other categories (from -438% for ADf to -62% for ET) due to the impacts avoided by re-using C&DW, i.e. by avoiding the transport of waste and the disposal thereof in landfills. The largest reductions corresponded to: i) consumption of raw materials such as oil (crude), gas (natural), cadmium, silver and lead; ii) emissions to air of substances such as butane, pentane, halon 1301, carbon monoxide, methane, nitrogen oxides, particulates <2.5 µm, carbon dioxide, cadmium and chromium; iii) emissions to water of chemical oxygen demand (COD), zinc, chromium VI and nickel; and iv) emissions to ground of chromium VI. These results amounted to an important environmental benefit as impacts were reduced compared with NFA.

Table 29. Characterization results of NFA and RFA production (per 1 t)

Impact category	*Units*	*NFA*	*RFA*	*(Δ%)*
ADe	kg Sb eq.	2.59E-06	-1.75E-06	(-168)
ADf	MJ	2.59E+01	-8.75E+01	(-438)
GW	kg CO_2 eq.	1.81E+00	-1.88E+00	(-204)
ODP	kg CFC-11 eq.	1.35E-07	-3.72E-07	(-376)
POF	kg C_2H_4 eq.	5.77E-04	-6.04E-04	(-205)
A	kg SO_2 eq.	1.59E-02	-1.22E-02	(-177)
E	kg PO_4 eq.	3.35E-03	-1.98E-03	(-159)
HTc	CTUh	1.66E-07	2.08E-08	(-87)
HTnc	CTUh	4.29E-07	7.92E-08	(-82)
PM	kg PM2.5 eq.	1.67E-03	-2.92E-03	(-275)
ET	CTUe	9.77E+00	3.76E+00	(-62)
LU	kg C deficit	4.02E+00	-1.37E+02	(-3505)
WD	m^3 water eq.	1.73E+00	1.76E-01	(-90)

The contribution analysis of NFA production processes is shown by impact category in Figure 43a. As can be seen, the dolomite quarry generated the highest impact in categories ADe (55%) and LU (42%) due to the occupation of the mineral extraction site, the second highest in HTnc (12%) and the third highest in ET (12%); it caused impacts of less that 3% in the remaining categories. Therefore, the processing of the dolomite was responsible for the highest impacts in almost all categories, with values which ranged from 45% to 99%. To be specific, crushing processes generated the highest environmental burden in all categories except ADe (20%) and LU (23%) where they were responsible for the second highest impact; the contribution ranged between 48% for ODP and 80% for WD as a consequence of the electricity consumption required for the crushing equipment (jaw crusher, rod mill and cone mill). Likewise, the distribution of the aggregates by conveyor belt caused the second greatest contribution in all categories except ADe (12%) and LU (9%), where it generated the third greatest impact; the values ranged from 10% for WD and 17% for ODP. These results can be attributed to the burdens generated by the consumption of the “steel, low-alloyed, hot-rolled” necessary for manufacturing the 188 m of conveyor belts installed in the quarry. The extraction of dolomite generated the third greatest impact in categories ADf (12%), GW (11%), ODP (17%), POF (7%), A (9%), E (10%), HTc (6%), PM (14%) and LU (12%) and contributions of less than 3% for ADe, HTnc, ET and WD due to consumption of the diesel fuel necessary for the functioning of the bulldozer. Moreover, the handling of dolomite by loading shovel up to the processing area caused the third impact in ODP (17%) and burdens of less than 3% in the other categories. Screening processes generated the third greatest impact for WD (5%) and burdens of less than 4% for the other categories. Finally, storage in the hopper generated impacts of less than 5%.

Likewise, contributions made by the RFA production processes are shown in Figure 43. With regard to environmental burdens (positive values) the transport of waste from generation site to treatment plant caused the greatest impact in all categories except WD where it generated the second highest contribution at 41%; the values ranged between 8% for LU and 72% for ET and ADe, as a consequence of fossil fuel consumption by the trucks. These results were according to Mercante et al. (2012), which found transportation from on-site generation to treatment plant to generate the greatest contribution to the environmental impact of the C&DW life cycle. Furthermore, C&DW processing at the treatment plant was the main factor responsible for the burdens in WD (52%) and the second greatest impact in categories ADe (8%), ADf (13%), GW (17%), ODP (11%), POF (23%), A (24%), E (22%), HTc (41%), HTnc (28%), PM (18%) and ET (22%), mainly due to the consumption of electricity by the crushing equipment (hammer mill, jaw crusher and rod mill). After that, the treatment plant generated the second greatest impact in the LU category (6%) and values lower than 1% in the other categories, due to land occupation by the industrial area. The transport and disposal of non-recyclable waste at the landfill site caused burdens of around 5% with the third greatest impact in categories ADe, ADf, GW, ODP, POF, HTc, ET, LU and WD; these burdens were generated by the consumption of diesel fuel by the truck and from process-specific burdens (energy, land use) and infrastructure from inert material landfill. Finally, C&DW generation was responsible for the third highest impact in categories A (6%), E (6%), HTc (5%) and PM (7%) and contributions of less than 5% in the remaining categories, mainly due to the consumption of fossil fuel by the demolition and loading equipment (backhoe loader with hammer and loading shovel). In contrast, the process which most contributed to generating an environmental benefit (negative values) was the avoided disposal of C&DW in landfill, with values ranging between -49% for ADe and -94% for LU; in the same way, avoiding transportation from the C&DW generation site to the landfill caused an environmental benefit in all categories with values of between -6% for LU and -51% for ET. According to Blengini and Garbarino (2010), the impact avoided by these processes is higher than the total obtained by adding all the negative impacts, thus proving the existence of net environmental gains.

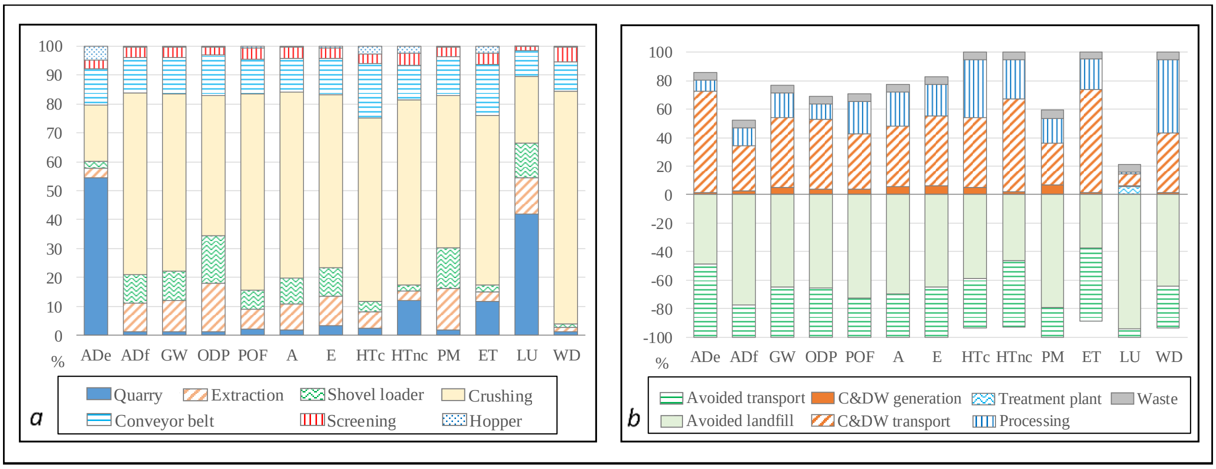

Figure 43. Contribution of NFA (a) and RFA (b) production processes to the impact

19.2. Life cycle impact assessment of masonry mortars

Characterization values of 1 t functional unit of the masonry mortars assessed are shown in Table 30 and, in brackets, the percentage of the impact variation caused by recycled mortars in comparison with G-0-1 mortar. The main raw materials consumed and substances emitted during the manufacturing of these mortars are listed according to the corresponding impact category in Table A7 in Annex, with a cut-off criterion of 1%. As can be seen in Table 30, the results of characterization for each category are very similar, although they show that G-25-1 mortar generated the lowest impact values and G-25-9 mortar the highest in all categories, except for ET and LU. For ET, the lowest value was 210.2 CTUe for G-0-1 mortar compared with 221.9 CTUe for the G-50-9 mortar, which means a difference of 6% due to the fact that the transport distance for NFA is shorter than for RFA (4 km as opposed to 10 km). As regards the LU category, the lowest value was observed in G-50-9 mortar with a 3.2 kg C deficit as opposed to the 54.3 kg C deficit corresponding to G-0-1 mortar; these values showed a variation of 94% as a consequence of the higher amount of RFA in mortar dosage, thus leading to an increase in impacts avoided when transporting C&DW to landfill and disposing of it therein. If we compare the results of the mortar manufactured using only NFA (G-0-1), the reduction in impact for G-25-1 mortar ranged between -49.8% for LU and -0.2% for HTnc, while in the case of G-25-9 mortar, the increase in impact ranged between 1.9% for PM and 34.3% for WD. In addition, the higher amount of admixture increased the values of G-25-9 mortar with respect to G-25-1 mortar mainly in WD (35%), ODP (22%), LU (16%), ADf (11%) with increases of less than 6% in the other categories. These results were due to substances with a high atmospheric acidification potential such as nitrogen dioxide, sulfur dioxide and sulfur monoxide which are released into the air during the synthesis of the admixture. The results of characterization are illustrated in Figure 44.

Table 30. Characterization results for impact categories of masonry mortars (1 t)

Category	*Unit*	*Mortar*										
		G-0-1	*G-25-1*	*(Δ%)*	*G-25-3*	*(Δ%)*	*G-25-6*	*(Δ%)*	*G-25-9*	*(Δ%)*	*G-50-9*	*(Δ%)*
ADe	kg Sb eq.	8.66E-05	8.62E-05	(-0.4)	8.69E-05	(0.4)	8.78E-05	(1.5)	8.88E-05	(2.7)	8.85E-05	(2.3)
ADf	MJ	593.7	574.8	(-3.2)	590.1	(-0.6)	613.1	(3.3)	636.0	(7.1)	616.1	(3.8)
GW	kg CO_2 eq.	102.4	101.9	(-0.5)	103.0	(0.6)	104.6	(2.2)	106.2	(3.8)	105.7	(3.3)
ODP	kg CFC-11 eq.	2.92E-06	2.85E-06	(-2.3)	3.01E-06	(3.1)	3.25E-06	(11.2)	3.48E-06	(19.2)	3.41E-06	(16.9)
POF	kg C_2H_4 eq.	1.19E-02	1.17E-02	(-1.6)	1.18E-02	(-0.2)	1.21E-02	(1.8)	1.23E-02	(3.8)	1.21E-02	(2.2)
A	kg SO_2 eq.	3.28E-01	3.24E-01	(-1.3)	3.28E-01	(0.0)	3.34E-01	(1.9)	3.40E-01	(3.8)	3.36E-01	(2.5)
E	kg PO_4 eq.	6.36E-02	6.29E-02	(-1.1)	6.38E-02	(0.3)	6.51E-02	(2.4)	6.65E-02	(4.5)	6.57E-02	(3.3)
HTc	CTUh	1.65E-06	1.63E-06	(-1.2)	1.65E-06	(0.2)	1.69E-06	(2.3)	1.72E-06	(4.4)	1.70E-06	(3.1)
HTnc	CTUh	1.16E-05	1.15E-05	(-0.2)	1.16E-05	(0.6)	1.18E-05	(1.9)	1.19E-05	(3.2)	1.19E-05	(3.0)
PM	kg PM2.5 eq.	2.39E-02	2.31E-02	(-3.3)	2.35E-02	(-2.0)	2.39E-02	(-0.1)	2.44E-02	(1.9)	2.36E-02	(-1.6)
ET	CTUe	210.2	210.4	(0.1)	213.2	(1.4)	217.4	(3.5)	221.7	(5.5)	221.9	(5.6)
LU	kg C deficit	54.3	27.2	(-49.8)	28.3	(-47.8)	30.0	(-44.8)	31.6	(-41.8)	3.2	(-94.1)
WD	m^3 water eq.	37.7	37.5	(-0.6)	40.8	(8.1)	45.7	(21.2)	50.7	(34.3)	50.4	(33.6)

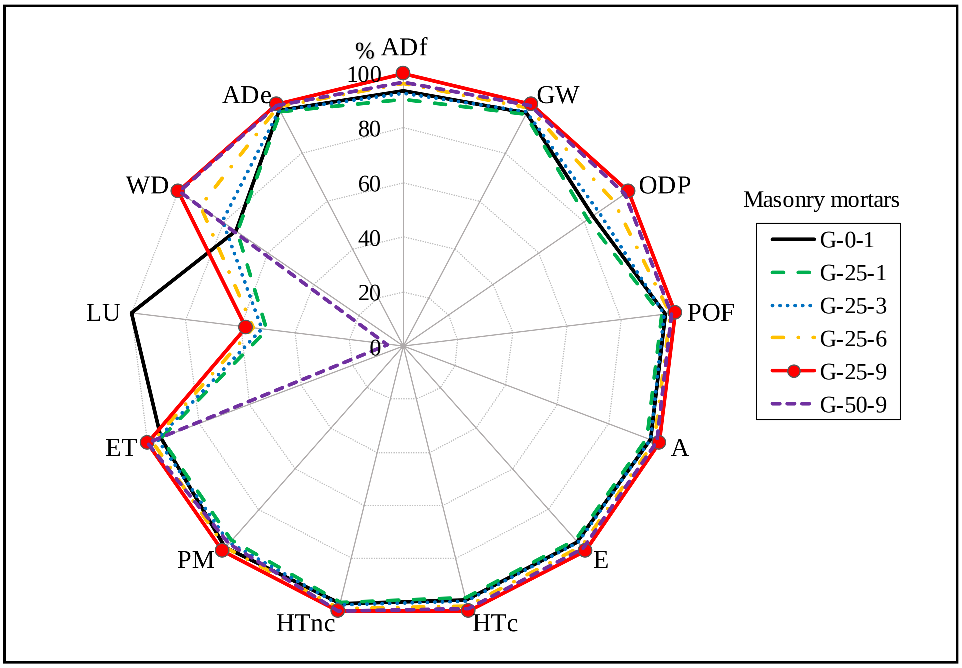

Figure 44. Comparative chart of the impact assessment of masonry mortars

With regard to the contribution of production subsystems to impact categories, the results are presented in Figure 45. As can be seen, the cement production subsystem generated the highest impacts in all categories except ADe and LU, where it generated the second highest contribution. The values ranged from 34% to 35% for ADe and from 84% to 88% for GW. According to other authors who developed the LCA of concrete (Knoeri et al., 2013; Marinković et al., 2010; Serres et al., 2016), these results occurred as a consequence of a large amount of CO_2 emissions caused by the production of clinker and the burning of fuels to fire the kiln and power the other manufacturing processes (Huntzinger and Eatmon, 2009).

Likewise, the transport subsystem generated the highest contribution in category LU (39-43%) due to land occupation and its transformation into a traffic area and road network. Furthermore, it generated the second highest contribution for ADf (15-18%), GW (6-7%), ODP (31-33%), POF (11-13%), A (11-13%), E (14-17%) and PM (14-18%), due to the consumption of oil (crude) and the emissions to air of halon 1301, carbon monoxide, nitrogen oxides, sulfur dioxide and particulates < 2.5µm; these results are associated with the consumption of fossil fuel by the trucks used to transport components from site of manufacture to mortar plant. In addition, the burdens generated by transport increased in all categories with the increase of RFA in the dosage of the mortars, by 4% when the dosage of RFA was 25% and by 24% when the said dosage was 50%, as a consequence of the greater transport distance compared with NFA. Likewise, the burdens increased by around 16% in all categories due to the increase in admixture from 1% to 9%.

After that, the manufacturing subsystem generated the greatest impact in category ADe (44-45%), mainly due to the consumption of raw materials (such as copper, cadmium and lead) used in the construction of the mortar plant and the mortar production equipment (belt unloaders, hoppers, bucket elevators, screw conveyors and mortar mixer). It also caused the second greatest contribution in HTc (23%), HTnc (27-28%) and ET (32-34%) due to the emissions to water (chromium VI, phospate, zinc and arsenic) generated during the process. The subsystem also caused the second greatest impact in category WD (9%) in mortars G-0-1 and G-25-1, and the third (7-8%) greatest for the remaining mortars, as a consequence of the consumption of the electricity required for the functioning of the manufacturing equipment. Furthermore, the burdens generated by the subsystem increased by between 1% and 5% in all categories except ADe, due to the increase in the amount of admixture in the dosage of the mortars.

Regarding to the aggregate production subsystem, its contribution was conditioned by the amount of RFA in the dosage of the mortars. The impacts generated by the subsystem in G-0-1 mortar (0% RFA) ranged between 1% for GW and 8% for HTc, causing the second or third lowest contribution (according to the category) to the total impact of the mortar. The fact that the contribution is so insignificant can be attributed to the way that the dolomite in this quarry is extracted i.e. without using explosives, thereby minimizing the burdens generated during the production of NFA. With recycled mortars, the subsystem's contribution to the impact of the mortar decreased in all categories when RFA was incorporated; the values ranged between -48% and -94% for LU, and between 6% and 4% for HTc, for RFA dosages of 25% and 50%, respectively. These results occurred as a consequence of the reduction of the environmental burdens of the subsystem with the incorporation of RFA in the dosage of the mortar. As a result, the burdens decreased in all categories, mainly for LU where the burden was 8.5 times less with 25% RFA and 17.5 times less with 50% RFA. In contrast, the smallest reduction in impact occurred in the category ET, at -15% and -31% for 25% and 50% RFA, respectively.

In the same way, the admixture production subsystem caused varying contributions according to the amount dosed in the mortar. Specifically, it was observed that in mortars manufactured with 1% admixture (G-0-1 and G-25-1) the subsystem generated the lowest impact in all categories, at less that 4%. For the dosage corresponding to 3% (G-25-3), the admixture was responsible for the second highest impact in category WD (12%), as with the dosage of 6% (G-25-6), where, in addition to the generating the second highest impact for WD (21%), it caused the third highest for ODP (11%). In dosages of 9% admixture (G-25-9, G-50-9), the subsystem was responsible for the second highest contribution in category WD (28%) and the third in categories ADf (8%), GW (3%) and ODP (15%). The burdens were generated mainly due to the consumption of electricity and raw materials such as oil (crude) and gas (natural/m^3) and halon 1301 emissions, generated during the admixture manufacturing process. Therefore, the increase in the amount of admixture increased the contribution to impact in all categories, mainly for WD (from 4% to 28%), ODP (from 2% to 15%) and ADf (from 1% to 8%); for the remaining categories, the variations ranged between 0.1% to 0.8% for ADe and from 0.4% to 4% for POF.

Finally, the consumption of electricity required during the manufacturing of filler was responsible for impacts of around 2-6% in all categories, making this the second or third least significant subsystem in the burdens generated by mortar.

Figure 45. Contribution analysis of production subsystems of masonry mortars for each category

19.2.1. Comparative analysis of mortars: G-0-1 vs G-25-1

This section will focus on the analysis and comparison of the impacts of G-0-1 mortar and G-25-1 mortar, which generated the lowest impact values according to the characterization results (Table 30). The replacement of NFA by RFA produced a reduction in environmental burdens due to the reduction in the consumption of raw materials and substances emitted (Table A7 in Annex), which led to the following improvements:

- The lower level of depletion of minerals such as cadmium and lead generated reductions of -3.26E-07 kg Sb eq. in ADe. Moreover, the lower consumption of fossil fuels (oil, coal and gas) reduced the use of -19 MJ in ADf. These improvements led to a reduction in resource consumption.

- The effects on climate change were minimized after carbon dioxide and methane emissions to air decreased, with a reduction of -0.5 kg CO_2 eq. in GW; this is the warming of the climate system due to human activities. The direct consequence is an increase in the temperature of the atmosphere and oceans, which leads to several types of higher-level impacts such as rising sea levels and extreme meteorological events (Levasseur, 2015). Therefore, the effects on human health and the ecosystem were reduced.

- The reduction in greenhouse gas emissions such as halon 1301, CFC-114 and halon 1211 minimized the impact in OLD by -6.58E-08 kg CFC-11 eq. The transmission of ultraviolet B (UVB) to the Earth's surface was mitigated, which reduced a number of effects on human health and the ecosystem: i) excessive exposure to UVB is strongly linked to the risk of skin cancer and certain types of eye diseases (Norval et al., 2011; UNEP EEAP, 2012); and ii) large reductions in plant productivity.

- Ethylene emissions to air (C_2H_4 eq.) in the POF category were reduced by -1.86E-04 kg, thus diminishing photochemical oxidation. This is caused by the emission of air pollutants such as sulfur dioxide, carbon monoxide and methane mainly emitted by combustion activities, such as thermal energy conversion (electricity and heat) and different transport-technologies such as aviation, shipping and vehicles, which use fossil fuels. According to Preiss (2015), the effects caused by photochemical oxidation mitigated damage to human health (acute and chronic effects, such as irritation of the respiratory system that affects health in different ways and increases mortality) and ecosystem deterioration (crop productivity and biodiversity).

- With regard to category A, SO_2 eq. decreased by -4.20E-03 kg, mainly caused by sulfur and nitrogen depositions resulting from emissions to air of sulfur dioxide, nitrogen oxides and ammonia. Most of these acidifying compounds are derived from anthropogenic activities, such as the combustion of fossil fuels at power stations and industrial plants or vehicle exhausts (Zelm et al., 2015). Excess nitrogen can alter tolerance to disease or other stressors (e.g., drought, frost) and the structure and function of terrestrial ecosystems, resulting in changes to overall biodiversity and productivity (Henderson, 2015). As a consequence, the acidity in water and soil systems and the reduction in biodiversity were mitigated, thus reducing effects on the ecosystem.

- Due to the lower emissions of nitrogen oxides to air, and lower emissions of phosphate and chemical oxygen demand to water, the excess contribution of nutrients was reduced by -7.10E-04 kg PO_4 eq. in category E. As a result, there was a reduction in effects on the ecosystem, such as alterations in species composition, biomass, or productivity (Henderson, 2015).

- In category HTc, emissions of CTUh fell by -1.96E-08 kg for cancer effects and -2.45E-08 kg for non-cancer effects, which means that exposure to chemical substances such as chromium VI, chromium, arsenic, mercury and zinc decreased. This exposure can be either direct, by inhaling air and drinking water, or indirect, by ingesting chemicals that bioaccumulate in the human food chain (Huijbregts et al., 2005; Rosenbaum et al., 2011). Once ingested by humans, chemicals are distributed around the body and can damage organs and induce the onset of various diseases, thus causing periods of disability or loss of life (Jolliet and Fanke, 2015). As a consequence, there was a reduction in damage to human health.

- In PM, there was a reduction of -7.83E-04 kg PM2.5 eq., due to lower emissions to air of substances such as particulates <2.5µm, sulfur dioxide and nitrogen oxides, thus minimizing damage to human health. These particles can cause serious adverse health effects, including reduced life expectancy, lung cancer, chronic and acute respiratory and cardiovascular morbidity (Humbert et al., 2015).

- The impact reduction of -27.05 kg C deficit in the LU category helped mitigate species loss, soil loss or amount of organic dry matter content (Koellner et al., 2013; Milà I Canals et al., 2007). In the same way, in category WD there was a reduction in water consumption of -0.24 m^3 water eq. Thus, effects on the ecosystem and resources were reduced for both categories.

19.3. Uncertainty analysis

Uncertainty related to data variability was assessed through two uncertainty analyses: i) on NFA and RFA production; and ii) on G-0-1 and G-25-1 production. Table 31 shows the results derived from Monte Carlo simulations, it is, the values for the probability, mean, median, standard deviation, coefficient of variation and standard error of mean. The results obtained from each analysis were presented in ascending order of standard error of mean, which indicated how much the mean was changed by the last Monte Carlo run; the lower the standard error of mean, the more reliable the results. The simulation performs the subtraction of two compared systems, where results also indicate the probability that one option generates more impact or damage than the other. The amount of data containing uncertainty values was 76.7% and the remaining 23.3% of the data contained no uncertainty and were therefore considered as fixed data since they derive from direct calculation.

The results showed that the probability that the production of 1 t NFA generates more impact than the production of 1 t RFA was: i) greater than 97% for LU, PM, A, POF, ADf, GW, E and WD; ii) 85% for ODP; iii) 61% for ADe; and iv) between 49% and 54% for the remaining categories (HTc, HTnc and ET). In the comparison between G-0-1 vs G-25-1 mortars, the probability that the impact generated during the production of 1 t G-0-1 was higher than that generated by the production of 1 t G-25-1 was: i) greater than 88% for GW, ADf, ODP, A, POF, E, WD and PM; ii) 73% for LU; and iii) between 50% and 54% for the remaining categories (ADe, HTc, HTnc and ET). For both simulations, categories HTc, HTnc and ET obtained the highest values of the standard error of mean, which resulted in a higher level of uncertainty. According to Rosenbaum (2015) and Jolliet and Fanke (2015), uncertainty of parameters and models is high due to the spatial and temporal variation and time horizon which are linked to these categories. For category ADe, the scale of the impacts depends on the resource in question. Thus, for metals, impacts can be considered on the global scale, as they are generally marketed globally, while minerals such as sand (fine aggregate) tend to be supplied from local sources. Impacts can also be deferred according to location, as the same materials are not available everywhere to the same extent. Short-term temporal variability can be ignored. However, longer term temporal variability can be deemed an important source of uncertainty as humans influence the availability of resources (e.g. by their consumption pattern) but also discover new resources and develop new technologies for resource extraction (e.g. fracking); thus, impacts can be considered to change over time (Swart et al., 2015).

Table 31. Results of Monte Carlo uncertainty analysis

Category	*Probability*	*Mean*	*Median*	*SD*	*CV (Coefficient of variation)*	*2.5%*	*97.50%*	*Standard error of mean*
NFA ≥ RFA								
LU	99.8%	1.40E+02	1.32E+02	6.04E+01	43%	4.46E+01	2.84E+02	0.00430
PM	99.7%	4.62E-03	4.36E-03	2.07E-03	44.8%	1.36E-03	9.39E-03	0.00448
A	98.6%	2.82E-02	2.76E-02	1.28E-02	45.4%	3.91E-03	5.53E-02	0.00454
POF	99%	1.19E-03	1.14E-03	5.79E-04	48.8%	2.03E-04	2.50E-03	0.00488
ADf	99.8%	1.14E+02	1.04E+02	5.69E+01	50%	3.26E+01	2.52E+02	0.00500
GW	97.4%	3.72E+00	3.69E+00	1.90E+00	51.2%	-3.31E-02	7.58E+00	0.00512
E	97.1%	5.35E-03	5.32E-03	2.80E-03	52.4%	-2.72E-04	1.10E-02	0.00524
WD	97.1%	1.56E+00	1.44E+00	9.68E-01	62.2%	-5.25E-02	3.73E+00	0.00622
ODP	85.8%	5.04E-07	4.65E-07	7.09E-07	141%	-6.86E-07	1.92E-06	0.01410
ADe	61.6%	3.57E-06	4.55E-06	5.01E-05	1.4E3%	-9.21E-05	9.25E-05	0.14000
HTnc	49.4%	-1.35E-05	-1.48E-06	7.45E-04	5.5E3%	-1.44E-03	1.38E-03	0.55000
ET	50.4%	-1.56E+01	2.31E+00	1.16E+03	7.41E3%	-2.24E+03	2.15E+03	0.74100
HTc	54.2%	2.62E-08	1.24E-07	6.30E-06	2.4E4%	-1.20E-05	1.18E-05	2.40000
G-0-1 ≥ G-25-1								
GW	99.7%	2.71E+01	2.56E+01	1.21E+01	44.7%	7.73E+00	5.53E+01	0.00447
ADf	98.4%	7.86E-04	7.46E-04	4.26E-04	54.2%	8.44E-05	1.74E-03	0.00542
ODP	98.3%	1.91E+01	1.73E+01	1.20E+01	62.6%	1.20E+00	4.72E+01	0.00626
A	94.2%	4.26E-03	4.24E-03	2.83E-03	66.4%	-1.28E-03	1.00E-02	0.00664
POF	95.4%	1.88E-04	1.79E-04	1.25E-04	66.4%	-3.78E-05	4.58E-04	0.00664
E	89.1%	5.00E-01	5.09E-01	4.28E-01	85.6%	-3.79E-01	1.33E+00	0.00856
WD	91%	2.38E-01	2.23E-01	2.07E-01	87.1%	-1.38E-01	6.84E-01	0.00871
PM	88.4%	7.22E-04	7.38E-04	6.33E-04	87.6%	-5.76E-04	1.92E-03	0.00876
LU	73.2%	6.32E-08	6.01E-08	1.56E-07	246%	-2.30E-07	3.90E-07	0.02460
ADe	53%	2.49E-08	2.35E-08	1.67E-06	6.7E3%	-3.39E-06	3.63E-06	0.67000
HTc	54.6%	8.06E-08	4.48E-07	1.24E-05	1.54E4%	-2.53E-05	2.38E-05	1.54000
ET	50.4%	6.75E-07	3.35E-07	1.97E-04	2.93E4%	-4.02E-04	4.28E-04	2.93000
HTnc	50.4%	7.77E-01	3.74E-01	3.07E+02	3.95E4%	-6.28E+02	6.66E+02	3.95000

19.4. Sensitivity analysis

The sensitivity analysis was performed on G-25-1 mortar as this was the mortar which generated the lowest impact compared with natural mortar. Table 32 shows the impact variation (expressed as a %) of the results for each scenario assessed of the sensitivity analysis compared to the initial results of G-25-1.

19.4.1. Transport distance of C&DW

The results of the contribution analysis of the production of 1 t RFA showed a significant contribution as regards transport processes “C&DW transport from site of generation to treatment plant (item 7.2)” and “Avoided transport from generation site of C&DW to landfill (item 11.1)”. For this reason, a sensitivity analysis was performed to determine the influence of C&DW transport distances on the total impact of the mortar. Eight scenarios were assessed (S1 to S8), regarding different combinations of transport distances of C&DW (Table 28). As expected, the results showed that the greater the transport distance to treatment plant and the lower the transport distance to landfill, the greater the impacts. The highest values were obtained in scenario S6 (40 km as transport distance to treatment plant and 1 km as transport distance to landfill), where burdens increased by up to 18% in LU and 7% in ODP; the remaining categories increased their values by less that 4%. In contrast, the lowest impact occurred in scenario S3 (1 km as transport distance to treatment plant and 30 km as transport distance to landfill), with reductions of up to -18% for LU.

Table 32. Results of the sensitivity analysis (by % of variation)

Impact category	*Scenario*								
	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*
ADe	-0.6	-1.9	-3.4	1.4	-1.5	3.4	2.1	0.6	-0.4
ADf	-0.6	-1.9	-3.3	1.3	-1.4	3.3	2.0	0.6	-2.6
GW	-0.2	-0.7	-1.3	0.5	-0.6	1.3	0.8	0.2	-0.9
ODP	-1.1	-3.8	-6.7	2.7	-2.9	6.7	4.0	1.2	-4.9
POF	-0.4	-1.3	-2.3	0.9	-1.0	2.3	1.4	0.4	-5.1
A	-0.4	-1.3	-2.3	0.9	-1.0	2.3	1.4	0.4	-6.0
E	-0.5	-1.7	-3.0	1.2	-1.3	3.0	1.8	0.5	-7.6
HTc	-0.5	-1.7	-3.1	1.2	-1.3	3.1	1.8	0.5	-1.4
HTnc	-0.4	-1.2	-2.1	0.9	-0.9	2.1	1.3	0.4	0.2
PM	-0.5	-1.7	-2.9	1.2	-1.3	3.0	1.8	0.5	-6.8
ET	-0.6	-2.1	-3.7	1.5	-1.6	3.7	2.2	0.6	-1.4
LU	-3.0	-10.1	-17.6	7.1	-7.6	17.7	10.6	3.0	-17.0
WD	-0.2	-0.6	-1.0	0.4	-0.4	1.0	0.6	0.2	-0.6

Variability in C&DW transport distances would require to determine the limit at which environmental benefit can be obtained for recycled mortar, i.e. to determine where its impact is lower than that of G-0-1 mortar. Values for all categories are represented in Figure 46, where the scenarios are ordered from the lowest to the highest impact and are compared to the values for G-0-1 mortar. The optimal transport distance of C&DW for environmental benefit are determined below. For categories PM and LU, all the scenarios showed lower impacts than G-0-1 mortar, which means that all the transport distances evaluated proved acceptable. In categories ADf, POF and WD, all the scenarios generated lower impacts than G-0-1 mortar except for S6. Therefore, for the maximum distance of C&DW to treatment plant (40 km), the distance to landfill is 15 km. Scenarios S7 and S6 generated higher burdens than G-0-1 mortar in category A, and thus the distance to landfill is 30 km for the maximum distance to the treatment plant (40 km). In categories GW, ODP, E and HTc, scenarios S4, S7 and S6 generated higher impacts than G-0-1. Therefore, if the transport distance to treatment plant is 20 km, transport distance to landfill is 15 km, or 30 km when the C&DW has been generated at 40 km. In categories ADe, HTnc and ET, the impact values of S3, S2, S5 and S1 scenarios were lower than those for G-0-1 mortar. These results indicate a minimum transport distance to landfill of 15 km for a transport distance to treatment plant of 20 km, i.e. G-25-1 mortar.

As maximum distances vary depending on the category, it might be useful to analyse those categories with a higher environmental burden due to the transport subsystem. According to the results of the contribution analysis, the highest impacts occurred in categories LU (39-43%) and ODP (31-33%). Given that all the transport distances proved optimum for category LU, the values assigned for ODP which generated the lowest impact were taken, which in this case were all the combinations containing 1 km transport distance to treatment plant, 15 km transport distance to landfill for 20 km transport distance to treatment plant, and 30 km transport distance to landfill for the maximum transport distance to treatment plant (40 km).

Figure 46. Sensitivity analysis values of the transport distances of C&DW from site of generation to treatment plant and landfill compared to G-0-1 reference mortar, by categories

19.4.2. Type of transport truck

For this sensitivity analysis, scenario S9 was assessed for the purpose of determining the influence that the variable “Type of transport truck” could have on the results of the assessment. The transport processes in the inventory were replaced by the process “Transport, lorry 16-32 t, EURO5 {GLO}, U”. According to the results obtained (Table 32), values were reduced in all categories (from -0.4% for ADe up to -17% for LU), except in HTnc where the impact increased slightly. The lower emissions of substances such as nitrogen oxides, particulates <2.5µm, carbon monoxide, sulfur oxide and halon 1301 were responsible for the reduced impact in categories E, PM, A, POF and ODP.

19.5. Comparison with previous studies

It is difficult to compare the results of this study with previous findings, as the differences between system boundaries, processes, waste management system, energy mix, fuel consideration, transport distances and geographical location must be taken into account. Furthermore, some LCA studies do not present the results in absolute values but rather in contribution percentages, which makes it difficult to compare results. In the bibliographical review carried out, a small number of research works were found which address the environmental assessment of the manufacture of masonry mortar regardless of the material used in the dosage thereof (Melià et al., 2014; Ruello et al., 2016; Zabalza-Bribián et al., 2011). What is more, given that the variation in the results of the indicators of the mortars occur due to the replacement of NFA with RFA, it is useful to know the results obtained in other studies which have applied the LCA in the production of RFA from C&DW (Blengini and Garbarino, 2010; Estanqueiro et al., 2016; Hossain et al., 2016b; Simion et al., 2013). Table 33 summarises the results of these LCAs and those obtained in this study and relates the studies, the method of analysis used and the values obtained in categories GW and ADf. It also specifies those processes included in the system boundaries which may influence the final results, such as the generation of C&DW, the transport thereof to the treatment plant and the processes avoided related to transport to and disposal at landfill or the production and transport of natural aggregates.

The manufacture of 1 t of mortar using NFA generated 102.4 kg CO_2 eq. and required 593.7 MJ of energy, while the values obtained in other studies were higher, ranging between

195.3 kg CO_2 eq. and 8000 kg CO_2 eq. for GW and from 1516 MJ to 2171 MJ for energy consumption thereof (Melià et al., 2014; Ruello et al., 2016; Zabalza-Bribián et al., 2011). With regard to the manufacture of recycled mortars, environmental data were only found in one study in which waste from liquid cristal displays was used in cement mortars (Ruello et al., 2016), thereby producing an environmental benefit of -12000 kg CO_2 as a consequence of the landfill disposal thus avoided. This value is a long way from the result obtained in the present study, corresponding to 101.9 kg CO_2 eq., which may be due to the fact that different types of waste is being dealt with, whose disposal at landfill generates widely differing environmental burdens.

For 1 t NFA production, 1.81 kg CO_2 eq. were emitted and 25.9 MJ were required, while the figures in other studies ranged between 15.4 kg CO_2 eq. and 103 kg CO_2 eq. for GW and from 246.23 MJ to 1664 MJ for energy consumption (Estanqueiro et al., 2016; Hossain et al., 2016b; Simion et al., 2013). As can be seen, the values obtained in the present study are lower, which might be attributable to the fact that the dolomite at this quarry is extracted by bulldozer and avoids the use of explosives, thereby reducing the impact generated during the extraction process. In the case of RFA, 1 t production generated -1.88 kg CO_2 eq. and required -87.5 MJ of energy. These values fall within the variation of values reported which ranged from -14 kg CO_2 eq. to 24.4 kg CO_2 eq. for GW and from -250 MJ to 246.41 MJ for ADf (Blengini and Garbarino, 2010; Estanqueiro et al., 2016; Hossain et al., 2016b; Simion et al., 2013). The lowest values were obtained by Blengini and Garbarino (2010) who included the following as processes avoided: disposal of waste at landfill; the production of natural aggregates; and the transport of both. In contrast, the failure to consider processes avoided increased environmental burdens by as much as 14 times for GW (Estanqueiro et al., 2016) and 9 times for ADf (Simion et al., 2013). In the case of Hossain et al. (2016b) the impacts were high as a consequence of the greater transport distances.

As has been verified, taking into account the processes avoided by recycling, such as the transport and disposal of C&DW at landfill and the transport and consumption of raw materials, significantly influences the results obtained. However, it is necessary for these processes to be included in the system under study so that the environmental benefit generated by the recycling of C&DW can be quantified.

Table 33. Comparison of results of different LCA studies

		Impact value		*Assessed processes*		*Avoided processes*			
Reference	*Method*	*GW kg CO_2 eq.*	*ADf MJ*	*C&DW generation*	*C&DW transport*	*Landfill disposal*	*Landfill transport*	*NA production*	*NA transport*
NA mortar (1 t)									
This study	CML-IA (Guinée et al., 2002)	102.4	593.7	-	-	-	-	-	-
Zabalza-Bribián et al. (2011)	Ecoinvent v2.0 (Frischknecht et al., 2005)	241	2171	-	-	-	-	-	-
Melià et al. (2014)	CED (Huijbregts et al., 2010) / GGP (2011)	195.3	1516	-	-	-	-	-	-
Ruello et al. (2016)	ILCD (EC-JRC-IES, 2012)	8000	*	-	-	-	-	-	-
Recycled mortar (1 t)									
This study	CML-IA (Guinée et al., 2002)	101.9	574.8	yes	20 km	yes	15 km	non	non
Ruello et al. (2016)	ILCD (EC-JRC-IES, 2012)	-12000	*	-	-	yes	-	-	-
NA production (1 t)									
This study	CML-IA (Guinée et al., 2002)	1.81	25.9	-	-	-	-	-	-
Estanqueiro et al. (2016)	CML Baseline 2000 (Guinée et al., 2002) / CED (Huijbregts et al., 2010)	15.4	246.23	-	-	-	-	-	-
Hossain et al. (2016b)	IMPACT2002+ (Jolliet et al., 2003)	23/33	341/518	-	-	-	-	-	-
Simion et al. (2013)	EDIP (Hauschild and Potting, 2003) / CED (Huijbregts et al., 2010)	103	1664	-	-	-	-	-	-
RA production (1 t)									
This study	CML-IA (Guinée et al., 2002)	-1.88	-87.5	yes	20 km	yes	15 km	non	non
Blengini and Garbarino (2010)	IMPACT2002+ (Jolliet et al., 2003)	-14	-250	non	15/25 km	yes	yes	yes	15/25/50km
Estanqueiro et al. (2016)	CML Baseline 2000 (Guinée et al., 2002) / CED (Huijbregts et al., 2010)	20.5/24.4	386/450	non	30 km	non	non	non	non
Hossain et al. (2016b)	IMPACT2002+ (Jolliet et al., 2003)	12	235	non	45 km	yes	200 km	non	non
Simion et al. (2013)	EDIP (Hauschild and Potting, 2003) / CED (Huijbregts et al., 2010)	15.5	246.41	non	non	non	non	non	non

*Value not given

20. Conclusions

This study used LCA methodology to quantify and compare the environmental impacts associated with the production of 1 t functional unit of masonry mortar manufactured with varying dosages of NFA, RFA from C&DW and admixture. The system boundaries were considered from cradle to gate level and included the production of raw materials, the transport to mortar plant and masonry mortar manufacture. Furthermore, the production processes for aggregates (natural and recycled) were analysed and compared in order to determine the associated benefit of using RFA from C&DW instead of NFA. Inventory data were loaded into SimaPro 8.0.2 software (PRé Consultants, 2014) and processed using CML-IA and ILCD 2011 methods (EC-JRC-IES, 2012; Guinée et al., 2002). The most important conclusions reached by the study are presented below:

- Results from the assessment showed that using RFA as a replacement for NFA in the manufacture of masonry mortar reduced environmental burdens. The biggest reduction occurred in category LU, as recycling C&DW avoided its disposal at landfills, thereby reducing land occupation and transformation for inert landfill construction and the consumption of natural resources (dolomite). The impacts increased slightly in category ET due to the fact that the transport distance of RFA from C&DW treatment plant to mortar manufacturing plant was greater than the transport distance of NFA, i.e. 10 km compared with 4 km. Furthermore, the increase in admixture in the dosage of the mortars increased impacts in all categories, mainly in WD and ODP, as a consequence of the increase in the consumption of electricity and raw materials required for its manufacture. On the basis of these results, G-25-1 mortar generated the lowest impact values in all categories except ET and LU, where the lowest values were recorded for G-0-1 and G-50-9 mortars. The highest impacts occurred in G-25-9 mortar, except in categories ET and LU, where they were generated by mortars G-50-9 and G-0-1, respectively.
- The contribution analysis of the masonry mortar manufacturing system established that the cement production subsystem generated the highest impacts in nearly all categories, the transport subsystem in LU and the manufacturing subsystem in ADe, while the aggregate, additive and filler production subsystems generated low contributions. Specifically, the impacts of the cement production subsystem were as a consequence of

the large amount of CO_2 emissions from clinker production and energy consumed during the manufacturing process. In addition, the transport subsystem generated the largest contribution for LU, due to land occupation and transformation into traffic area and road network. The manufacturing subsystem generated the highest impact for ADe category, mainly due to the consumption of the raw materials employed in the construction of the mortar plant and the mortar production equipment. The aggregate production subsystem for mortar G-0-1 (100% NFA) generated low contributions (less than 8%) attributable to the mechanical extraction of dolomite which avoided the use of explosives. However, in the case of recycled mortars, burdens decreased in all categories with the incorporation of RFA, mainly for LU, which was up to 8.5 times lower with 25% RFA and 17.5 times lower with 50% RFA. For its part, the admixture production subsystem caused the lowest impacts in nearly all categories with dosages of 1%. However, the burdens intensified with higher dosages of admixture, mainly due to the increased consumption of electricity and raw materials and the increase in emissions. Finally, the consumption of electricity required during the manufacture of filler was responsible for the subsystem generating impacts of around 2-6% for all categories, making this the second or third least significant subsystem as regards burdens generated by mortar.

- Burdens resulting from the production of RFA were substantially lower in all categories than those obtained during the production of NFA, due to the impacts avoided by re-using C&DW, i.e. by avoiding waste transport and disposal in landfills. For NFA production, the dolomite quarry generated the highest impact in categories ADe and LU due to the mineral extraction site occupation. However, for the remaining categories, the highest impacts were generated during the processing of the dolomite, mainly in the crushing processes due to the consumption of electrical energy by the crushing equipment, followed by conveyor belt handling and dolomite extraction due to the consumption of steel and fossil fuel, respectively. With regard to RFA production, the greatest environmental impact in all categories was obtained by C&DW transport from generation site to treatment plant as a result of the consumption of diesel fuel by the trucks. C&DW processing generated the largest contribution in category WD due to the electricity consumption of the crushing equipment, and the treatment plant was the second largest contributor in LU due to land occupation by an industrial area. Nevertheless, the negative burdens generated by the avoided processes of disposal of

C&DW at landfill and transport were higher than the combined total of the negative impacts, which meant a significant reduction in the consumption of raw materials and the emission of substances, thereby representing an important environmental benefit.

- The uncertainty related to data variability was assessed using the Monte Carlo method in two comparative simulations: i) for NFA and RFA production; and ii) for G-0-1 and G-25-1 production. Results showed a high probability that the production of NFA and G-0-1 mortar generates a higher impact than RFA and G-25-1. The magnitude of error of the estimates made for the different inventory sources suggested a high level of accuracy for all impact categories except ADf, HTc, HTnc and ET, which showed a higher level of uncertainty due to the spatial and temporal variability and time horizon linked to these categories.
- The sensitivity analysis performed in order to assess the uncertainty of the model determined how distances and transport processes influenced the environmental impact of masonry mortars. The results showed that the greater the C&DW transport distances from site of generation to treatment plant and the lower the transport distance to landfill, the higher the environmental burdens. The highest increase was 18% in LU and 7% in OLD. Furthermore, the optimum C&DW transport distances were determined for each impact category where the impact of G-25-1 mortar is lower than that of G-0-1 mortar. The use of less pollutant transport trucks represented a reduced impact in all categories except HTnc, where the impact increased slightly.
- In the comparison with previous studies, it was observed how the results varied depending on whether or not the processes avoided by recycling were included in the system. The greater the number of processes avoided taken into consideration, the lower the impacts. This shows clearly that, in order to be able to quantify the environmental benefit generated by the recycling of C&DW, it is extremely important that the processes avoided, such as the transport and disposal of C&DW in landfill, are taken into account in LCA studies.

This study has used LCA methodology to assess the environmental performance of masonry mortar made with recycled fine aggregate from C&DW. The use of this methodology is what makes this study unique, since similar studies have not been found in the literature. The findings of the LCA have been presented in an open, comprehensive and comprehensible manner, thus ensuring that the study is transparent and the results can be reproduced by any other researcher. Detailed data from inventories and elementary flows related to the production processes included in the system boundaries were collected, and this has permitted the authors to fully understand and evaluate the magnitude and significance of the environmental impacts generated during the manufacture of masonry mortars. The conclusions can be extended to other geographical areas by adapting the inventory to the specific processes of each area (manufacturing processes, energy consumption and transport distances). However, the limitations of this study will be addressed in a future research that: i) Extends the scope of the System to include processes involved in the sale, construction, use and demolition of masonry mortars, performing a cradle to cradle LCA; ii) Evaluates different C&DW recovery rates by means of a sensitivity analysis, because, due to the heterogeneity of the material, this rate will depend on the area where the C&DW was generated; iii) Considers a regional or global geographical scope in order to make a comparative analysis of the results, and iv) Uses different methods to allocate impacts to C&DW that would permit an analysis of the sensitivity of each allocation model.

The results have clearly shown the environmental benefits of using the fine fraction of recycled aggregates from C&DW for the production of masonry mortar, as recycling C&DW avoided the disposal of this material in landfills. Environmental feasibility justifies the need to eliminate the current barriers to applying these aggregates and boosting their consumption in order to increase the environmental and economic benefits of the construction sector. Nevertheless, were have also seen that between 34% and 88% of the impacts are associated with the burdens generated during the cement manufacturing process. Therefore, it would seem necessary to further develop techniques which help reduce the environmental impact caused by cement, such as using renewable energies during the production process or adding recycled materials to its composition.

CONCLUSIONES

Las conclusiones de las aportaciones más importantes que se han obtenido del estudio de la viabilidad técnica y ambiental de la utilización de AFR procedente de RCD en morteros de albañilería pueden agruparse en cuatro apartados, de acuerdo con los objetivos secundarios fijados en esta memoria:

1. Estudio de la viabilidad técnica:

1.1. Respecto a la *evaluación de diferentes métodos de compensación de agua para determinar su efectividad sobre las propiedades de los morteros de albañilería*.

- El empleo de AFR en la elaboración de morteros de albañilería sin aumentar la relación a/c total disminuye el valor de la consistencia como consecuencia de su alta capacidad de absorción de agua. Sin embargo, incrementa la resistencia mecánica, lo que permite el reemplazo del 25% de AFN por AFR sin que conlleve un detrimento de las propiedades del mortero.
- El uso de AFR premojado resulta más efectivo que el aumento directo de agua de amasado ya que, aunque reduce ligeramente la consistencia (3,4%) y el contenido en aire del mortero fresco (13,3%), incrementa los valores de la densidad en estado fresco y endurecido (≈9%) y de la resistencia a compresión, que aumenta hasta el 50% para el reemplazo total de AFN.
- La cantidad óptima de agua de premojado para reemplazos parciales de AFN es del 67% de la capacidad de absorción de agua del AFR, mientras que en el caso de realizar un reemplazo total es preferible utilizar el 80% de su capacidad de absorción. En ambos casos, estos valores aportan a los morteros una consistencia plástica y buenos resultados para las propiedades estudiadas.

1.2. En relación al *estudio de los efectos que puede causar la variabilidad de la relación agua/cemento, el AFR y el aditivo inclusor de aire/plastificante en las propiedades de los morteros de albañilería, así como la determinación de las dosificaciones que cumplen los requerimientos técnicos.*

- Se cumplen los requisitos normativos en los morteros de albañilería fabricados con la incorporación total de AFR. No obstante, el reemplazo óptimo de AFN por AFR que no comprometa el comportamiento técnico de los morteros puede ser del 25%. Para incorporaciones de AFR superiores a este valor se han de considerar las opciones de incrementar tanto la relación a/c total a través del mojado de los áridos reciclados previo a su utilización, como la cantidad de AIAP con dosificaciones superiores al 3% que, aunque resultan efectivas técnicamente, podrían no ser viables ni económica ni ambientalmente.
- De acuerdo al Código Técnico de la Edificación Español, estos morteros de albañilería se pueden utilizar en elementos constructivos no sometidos a requisitos estructurales en interiores de edificios protegidos de la intemperie, exteriores protegidos de la lluvia y exteriores no protegidos de la lluvia o sótanos no ventilados, según las clases de exposición I, IIa y IIb.
- A partir del análisis estadístico ANOVA se establece que los factores más determinantes para cada una de las propiedades son los siguientes: relación a/c total para la consistencia, la densidad en estado endurecido, y las resistencias mecánicas; AFR para la densidad en estado fresco; y el aditivo inclusor de aire/plastificante para el contenido en aire y el coeficiente de absorción de agua por capilaridad.

2. Estudio de la viabilidad ambiental:

2.1. En relación al *desarrollo del inventario para la aplicación del análisis de ciclo de vida de los morteros de albañilería.*

- La recopilación de datos para crear el inventario de ACV incluye las materias primas, los equipos utilizados para los procesos de producción, las instalaciones de producción, los medios de transporte y las distancias, los productos resultantes de los procesos de producción, los residuos y las emisiones.

- El inventario del ciclo de vida desarrollado coincide con la realidad del proceso ya que se ha basado en la combinación de datos reales de producción y de datos secundarios, con un alto nivel de detalle con respecto a los equipos utilizados en los procesos de producción de los áridos (natural y reciclado) y en los procesos de fabricación del mortero. De esta manera, el sistema considerado de la cuna a la puerta que engloba la fabricación del mortero de albañilería se define mediante 147 procesos.

- Para garantizar los requisitos de calidad de los datos, incluida la representatividad temporal, geográfica y tecnológica, los valores de algunos procesos de Ecoinvent han sido modificados con la información proporcionada por cada una de las fábricas.

- La metodología utilizada para desarrollar el inventario es clara y totalmente reproducible, lo que permite identificar y cuantificar los flujos de entrada y salida que están realmente relacionados con el ciclo de vida del mortero de albañilería.

2.2 Finalmente, *la cuantificación de los impactos ambientales asociados a los morteros de albañilería fabricados con áridos reciclados de acuerdo al inventario desarrollado para determinar la dosificación más idónea en el cumplimiento de los requisitos ambientales.*

- En la producción de AFN, los impactos más altos corresponden al procesamiento de la dolomía, principalmente por el consumo eléctrico de los equipos de trituración.
- En la producción del AFR los impactos se originan principalmente durante el transporte de los RCD desde el lugar de generación hasta la planta de tratamiento, siendo éstas mayores cuando se aumenta la distancia. No obstante, el reciclaje de los RCD evita su transporte y disposición en el vertedero, por lo que las cargas positivas asociadas a estos procesos evitados son más altas que todos los impactos negativos, lo que se traduce en un importante beneficio ambiental.
- El uso de AFR como reemplazo de AFN disminuye los impactos ambientales generados en la fabricación de morteros de albañilería, alcanzándose los valores de impacto más bajos en el mortero fabricado con el 25% de AFR y la menor dosis de aditivo (1%).
- El análisis de contribución determina que el cemento origina los impactos más altos en casi todas las categorías, seguido por el transporte, el proceso de fabricación del mortero

y el resto de componentes (árido, aditivo y filler). En el caso del árido la contribución es inferior al 8% en el mortero natural, y del 4% en el mortero reciclado con el 50 % de AFR.

Teniendo en cuenta todo lo indicado, finalmente se puede concluir que la fabricación de morteros de albañilería para uso corriente (G) y clase M5 con AFR procedente de residuos minerales de construcción y demolición es técnicamente y ambientalmente viable con la incorporación del 25% de AFR, sin aumentar la cantidad de agua y con el 1% de aditivo inclusor de aire/plastificante.

CONCLUSIONS

The most important conclusions drawn from this study of the technical and environmental feasibility of using of RFA from C&DW in masonry mortars can be grouped into four sections, based on the secondary objectives established in this study:

1. Study of technical feasibility:

1.1. Regarding *the evaluation of different water compensation methods to determine their effect on the properties of masonry mortars*.

- Using RFA in the manufacture of masonry mortars without increasing the total water/cement ratio reduces the value of the consistency as a consequence of its high absorption capacity. However, the use of RFA increases the mechanical strength of the mortar, which allows replacements of 25% NFA without detriment to the properties of the mortar.
- It is more effective to use pre-soaked RFA than increase the quantity of mixing water because, although this slightly reduces the consistency (3.4%) and the air content of the fresh mortar (13.3%), it increases the bulk density in the fresh and hardened state (≈9%) and also compressive strength, which increases up to 50% in the case of total replacement of NFA.
- Ideally, pre-soaking water equivalent to 67% of the water absorption capacity of the RFA should be used. This should be increased to 80% of absorption capacity in the case of total replacement of NFA. In both cases, these values give the study mortars good plasticity and obtains satisfactory results in terms of the properties analysed.

1.2. In relation to *the study of the effect of different water/cement ratios, RFA and air-entraining/plasticizer admixture content on the properties of the masonry mortars, and the determination of dosages that meet technical requirements.*

- Masonry mortars manufactured with 100% RFA meet these technical requirements. However, the optimal percentage replacement of NFA by RFA, without affecting technical performance of the mortars, is 25%. If a higher percentage of replacement RFA is used, the option of increasing the total w/c ratio by pre-soaking the RFA prior to use, and increasing the AEPA dosage over 3% should be considered. Although such doses are technically effective, they may not be economically or environmentally optimal.
- These masonry mortars can be used in constructive elements that are not subject to structural requirements and are placed in the interior of buildings protected from the weather, in the exterior protected from rain and in the exterior not protected from rain, or in unventilated basements, according to exposure classes I, IIa and IIb of the Spanish "Código Técnico de la Edificación".
- Using ANOVA statistical analysis, we found the major determinants for each different property to be: total w/c ratio for the consistency, dry bulk density, and mechanical strength; RFA for bulk density of fresh mortar; and AEPA for air content and capillary water absorption coefficient.

2. Study of environmental feasibility:

2.1. With respect to *the development of the inventory for the life cycle assessment of masonry mortars.*

- Data collected to create the LCA inventory include raw materials, production equipment, production facilities, means of transport and distances, products resulting from production processes, waste and emissions.

- The life cycle inventory compiled reflects the real process, since it has been based on a combination of real production data and secondary data, and includes a highly detailed inventory of the equipment used to produce the aggregates (natural and recycled) and to manufacture the mortar. Thus, the "cradle to gate" system, which includes the manufacture of masonry mortar, is defined by 147 processes.

- To guarantee data quality, including temporal, geographical and technological representativeness, the values of some Ecoinvent processes have been modified on the basis of information provided by each of the factories.

- The methodology used to create the inventory is clear and totally reproducible, and identifies and quantifies the real input and output flows involved in the life cycle of the masonry mortar.

2.2. Finally, *the quantification of the environmental impacts associated with masonry mortars manufactured with RFA, based on the inventory created for this purpose, in order to determine the dosage that best meets environmental requirements.*

- The highest environmental impact associated with NFA production is dolomite processing, mainly due to the electricity consumption of the crushing equipment.
- In RFA production, impacts are mainly derived from the transport of the C&DW from the generation site to the treatment plant; the greater the distance, the higher the impact. However, recycling the C&DW avoids the need for transport and disposal in landfill, and the savings this involves outweigh the negative impact of production, resulting in an important environmental benefit.
- The use of RFA to replace NFA reduces the environmental impacts caused by the manufacture of masonry mortars, with the lowest impact values being associated with mortar manufactured with 25% RFA and the lowest admixture dose (1%).
- The contribution analysis shows that cement causes the highest impacts in almost all categories, followed by transport, mortar manufacturing process, and the remaining components (aggregate, admixture and filler). The contribution of aggregate is less than 8% in natural mortar, and 4% in recycled mortar containing 50% RFA.

In view of the foregoing, we can conclude that the manufacture of masonry mortars, for general purpose (G) and class M5, with RFA from mineral waste of construction and demolition is technically and environmentally feasible with the incorporation of 25% RFA, without increasing the amount of water and with 1% air entraining/plasticizer admixture.

LÍNEAS FUTURAS DE INVESTIGACIÓN

En el desarrollo de este trabajo han surgido una serie de cuestiones técnicas, económicas y ambientales que no han sido abordadas, que se proponen como futuras líneas de trabajo:

Respecto de la viabilidad técnica de los morteros:

- Estudio a escala de laboratorio de morteros fabricados con diferentes proporciones de AFN y AFR, según los ensayos determinados por la norma EN 998-1: Especificaciones de los morteros para albañilería. Parte 1: Morteros para revoco y enlucido, al objeto de determinar la proporción óptima de AFR.
- Fabricación industrial del mortero que permitirá optimizar el proceso de premojado y las técnicas de fabricación. El mortero industrial se podrá someter a diferentes condiciones de uso para determinar la dosificación más adecuada según el ambiente de exposición.

Desde el punto de vista de la viabilidad económica:

- Realización de un análisis de mercado para morteros fabricados con AFR con la finalidad de conocer su mercado potencial, tanto a nivel privado como en entidades locales dispuestos a exigir en sus obras el uso de materiales respetuosos con el medio ambiente.
- Estudio de viabilidad coste/beneficio en la producción industrial de los morteros. Esto es fundamental para garantizar la viabilidad de su aplicación.

Finalmente, en relación a la viabilidad ambiental:

- Evaluación de diferentes tasas de recuperación de RCD mediante un análisis de sensibilidad, ya que, debido a la heterogeneidad del material y su distribución geográfica, esta tasa dependerá del área donde se genere el RCD.
- Aplicación de diferentes métodos para asignar impactos a RCD que permitirían un análisis de la sensibilidad de cada modelo de asignación.
- Ampliación del estudio del ACV de la cuna a la cuna para incluir los procesos involucrados en la venta, construcción, uso y demolición de morteros de albañilería como material de construcción KM0.

FUTURE LINES OF RESEARCH

A series of technical, economic and environmental issues arose during this study that have not been addressed, but which suggest future lines of research:

Regarding the technical feasibility of mortars:

- Laboratory-scale study of mortars manufactured with different proportions of NFA and RFA, according to the tests determined by the standard EN 998-1: “Specifications for mortar for masonry. Part 1: Rendering and plastering mortars”, in order to determine the optimal proportion of RFA.
- Industrial manufacturing of the mortar, wich will optimize the pre-soaking process and manufacturing techniques. The industrial mortar can be subjected to different conditions of use to determine the most appropriate dosage for each type of environmental exposure.

From the point of view of economic feasibility:

- A market analysis of mortars made with RFA that will show their market potential both for private use, and for use by local authorities willing to demand the use of environmentally friendly materials for the construction projects.
- Cost-benefit analysis of the industrial production of mortars, primarily to ensure their feasibility as a market product.

Finally, in relation to environmental feasibility:

- Evaluation of different C&DW recovery rates by means of a sensitivity analysis, since, due to the heterogeneity of the material and its geographical distribution, this rate will depend on the area where the C&DW is generated.
- The use of different methods to assign impacts to C&DW that would permit a sensitivity analysis of each allocation model.
- Extension of the system boundaries of LCA, “cradle to cradle”, to include the processes involved in the commercialization, construction, use and demolition of masonry mortars as KM0 construction material.

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ANNEX

Table A1. Compliance with technical requirements of mortars

Mortars	*Technical requirements*								
	Consistency *≥140 mm*	*Compressive strength at 28d* *>5 N/mm²*	*Bulk density*	*Air content*	*Dry bulk density*	*Flexural strength at 7d*	*Compressive strength at 7d*	*Flexural strength at 28d*	*Capillary water absorption coefficient*
D-25-1	✔	✔	≈	≈	≈	≈	≈	≈	≈
D-25-3	✔	✔	≈	≈	≈	≈	≈	≈	≈
D-25-6	✔	✔	≈	≈	≈	≈	≈	≈	≈
D-25-9	✔	✔	≈	≈	≈	≈	≈	≈	≈
D-50-1	✗	✔	≈	≈	≈	≈	≈	≈	≈
D-50-3	✗	✔	≈	≈	≈	≈	≈	≈	≈
D-50-6	✗	✔	≈	≈	≈	≈	≈	≈	≈
D-50-9	✔	✔	≈	≈	≈	≈	≈	≈	≈
D-75-1	✗	–	≈	≈	–	–	–	–	–
D-75-3	✗	–	≈	≈	–	–	–	–	–
D-75-6	✗	–	≈	≈	–	–	–	–	–
D-75-9	✗	–	≈	≈	–	–	–	–	–
D-100-1	✗	–	≈	≈	–	–	–	–	–
D-100-3	✗	–	≠	≈	–	–	–	–	–
D-100-6	✗	–	≠	≈	–	–	–	–	–
D-100-9	✗	–	≠	≠	–	–	–	–	–
P-25-1	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-25-3	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-25-6	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-25-9	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-50-1	✔	✗	≠	≈	≠	≠	≠	≈	≈
P-50-3	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-50-6	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-50-9	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-75-1	✔	✗	≠	≠	≠	≠	≠	≠	≈
P-75-3	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-75-6	✔	✔	≈	≈	≈	≈	≈	≈	≈
P-75-9	✔	✔	≠	≈	≠	≈	≈	≈	≈
P-100-1	✔	✗	≠	≈	≠	≠	≠	≠	≈
P-100-3	✔	✗	≠	≈	≠	≠	≠	≠	≈
P-100-6	✔	✔	≠	≈	≈	≈	≈	≈	≈
P-100-9	✔	✔	≠	≈	≠	≈	≈	≈	≈

✔	Meets the technical requirements
✗	Does not meet the technical requirements
≈	It belongs to the homogeneous group of the reference mortar
≠	Does not belong to the homogeneous group of the reference mortar
–	Property not evaluated

Table A2. Inventory data and elementary flows of NFA 0/2 mm production (1 t)

Item	*Process*	*Unit process* (a)	*Amount*	*Unit*	*Flow*		*Amount*	*Unit*
	Input							
	Materials/Energy				*Resources*	Land occupation	1.39E-01	m^{2}a
1	Dolomite	Dolomite	5.00E+00	t		Land transformation	2.84E-02	m^2
2	Dolomite quarry	Dolomite quarry (b)	5.00E+00	p	*Non renewable energy resources*	Coal, brown	1.03E-01	kg
3	Processing					Coal, hard	3.96E-01	kg
3.1	Extraction	Bulldozer with ripper	1.78E+00	m^3		Oil, crude	1.33E-01	m^3
3.2	Handling	Loading shovel	1.78E+00	m^3		Gas, natural	2.06E-01	kg
3.3	Crushing	Jaw crusher	5.00E+00	t	*Non renewable elements*	Cadmium	3.37E-06	kg
		Electricity	2.46E+00	kWh		Chromium	4.59E-04	kg
3.4	Handling	Conveyor belt, 100 m	7.10E-05	m		Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	7.76E-05	kg
		Electricity	7.85E-01	kWh		Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	5.18E-05	kg
3.5	Crushing	Rod mill	5.00E+00	t		Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	3.07E-05	kg
		Electricity	3.83E+00	kWh		Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	2.95E-04	kg
3.6	Screening (8 mm)	Vibrating screen	2.82E-06	t		Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	8.14E-05	kg
		Electricity	4.11E-01	kWh		Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	4.43E-05	kg
3.7	Handling	Loading shovel	8.88E-01	m^3		Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	7.94E-10	kg
3.8	Storage	Hopper	1.00E-05	t		Lead	5.79E-05	kg
3.9	Handling	Conveyor belt, 24 m	8.53E-06	m		Molybdenum	3.73E-06	kg
		Electricity	9.15E-02	kWh		Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% (c.o)	1.86E-06	kg
3.10	Crushing	Cone mill	2.50E+00	t		Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% (c.o.)	5.78E-06	kg
		Electricity	3.85E+00	kWh		Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% (c.o.)	1.54E-06	kg
3.11	Handling	Conveyor belt, 24 m	8.53E-06	m		Nickel, 1.98% in silicates, 1.04% in crude ore	1.24E-03	kg
		Electricity	9.15E-02	kWh		Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	8.26E-08	kg
3.12	Screening (0/2 mm)	Vibrating screen	1.41E-06	t		Tin	3.66E-06	kg
		Electricity	2.06E-01	kWh		Zinc	1.06E-04	kg
3.13	Handling	Conveyor belt, 40 m	5.68E-06	m	*Renewable resources*	Water	3.01E-02	m^3
		Electricity	5.75E-02	kWh				
	Output							
	Products/Co-products				*Emissions*			
4		NFA 0/2 mm	1	t	*Air*	Arsenic	3.90E-07	kg
5		Other fractions of NA	4	t		Butane	1.73E-05	kg
						Cadmium	1.09E-07	kg
						Carbon dioxide, fossil	1.71E+00	kg
						Carbon monoxide, fossil	3.05E-03	kg
						Chromium	1.64E-06	kg
						Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	1.24E-08	kg
						Lead	1.25E-06	kg
						Mercury	1.04E-07	kg
						Methane, bromochlorodifluoro-, Halon 1211	5.89E-09	kg
						Methane, bromotrifluoro-, Halon 1301	6.95E-09	kg
						Methane, chlorodifluoro-, HCFC-22	5.65E-08	kg
						Methane, fossil	2.97E-03	kg
						Nitrogen oxides	9.81E-03	kg
						Particulates, < 2.5 µm	1.07E-03	kg
						Pentane	2.29E-05	kg
						Sulfur dioxide	9.07E-03	kg
						Zinc	2.02E-06	kg
					Water	Arsenic	5.02E-06	kg
						Chromium VI	1.45E-05	kg
						COD, Chemical Oxygen Demand	3.14E-03	kg
						Copper	2.63E-05	kg
						Nickel	5.86E-05	kg
						Nitrate	5.61E-04	kg
						Phosphate	1.90E-03	kg
						Vanadium	1.02E-05	kg
						Zinc	1.05E-04	kg
					Soil	Chromium VI	4.56E-07	kg
						Zinc	3.06E-07	kg

(a) Ecoinvent database processes (converted from v.2.2 to v.3.01);.

(b) Modified process; for further details, see Chapter 3.

Table A3. Inventory data and elementary flows of RFA 0/2 mm production (1 t)

Item	*Process*	*Unit process* [(a)]	*Amount*	*Unit*	*Flow*		*Amount*	*Unit*
	Input							
	Materials/Energy				*Resource*	Land occupation	-1.52E+00	m^2a
7	C&DW production					Land transformation	-3.11E-01	m^2
7.1	C&DW generation	Backhoe loader with hammer	4.75E+00	m^3	*Non renewable energy resources*	Coal, hard	6.94E-02	kg
						Gas, natural	-7.22E-01	m^3
		Loading shovel	4.75E+00	m^3		Oil, crude	-1.55E+00	kg
7.2	C&DW transport	Truck 28 t, 20 km	2.50E+02	tkm	*Non renewable elements*	Cadmium	-6.19E-06	kg
8	C&DW treatment plant	C&DW treat. plant[(b)]	1.25E-06	p		Chromium	-1.71E-04	kg
9	Processing					Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	-1.44E-05	kg
9.1	Handling	Loading shovel(V)[(b)]	4.75E+00	m^3		Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	-6.29E-05	kg
9.2	Handling	Chains feeder	2.11E-06	t		Dolomite	-1.23E-04	kg
		Electricity	1.17E-01	kWh		Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	7.62E-09	kg
9.3	Crushing	Hammer mill	1.25E+01	t		Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	1.62E-09	kg
		Electricity	1.38E+01	kWh		Lead	-1.02E-04	kg
9.4	Handling	Conveyor belt, 4 m	5.06E-06	m		Molybdenum	-3.23E-06	kg
		Conveyor belt, 10 m	1.73E-05	m		Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% (c.o.)	-2.65E-06	kg
		Overband	1.81E-05	t		Nickel, 1.98% in silicates, 1.04% in crude ore	-5.98E-04	kg
		Conveyor belt, 3 m	5.19E-06	m		Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	-1.51E-07	kg
		Conveyor belt, 15 m	2.59E-05	m		Tin	3.40E-06	kg
		Electricity	1.83E+00	kWh		Zinc	-1.92E-04	kg
9.5	Screening (40/200 mm)	Vibrating screen	8.60E-06	t	*Renewable resources*	Water	3.01E-02	m^3
		Electricity	1.10E+00	kWh				
9.6	Handling	Conveyor belt, 8 m	6.94E-06	m	Output			
		Conveyor belt, 10 m	8.63E-06	m	*Emissions*			
		Electricity	4.77E-01	kWh	*Air*	Acetaldehyde	1.49E-05	kg
9.7	Storage	Vibrating feeder	2.03E-06	t		Arsenic	-5.55E-08	kg
		Hopper	1.43E-05	t		Butane	-1.20E-04	kg
		Electricity	1.11E-01	kWh		Cadmium	-8.15E-08	kg
9.8	Handling	Conveyor belt, 6 m	5.18E-06	m		Carbon dioxide, fossil	-1.67E+00	kg
		Conveyor belt, 15 m	9.50E-06	m		Carbon monoxide, biogenic	-3.11E-04	kg
		Conveyor belt, 15 m	1.29E-05	m		Carbon monoxide, fossil	-1.00E-02	kg
		Electricity	7.13E-01	kWh		Chromium	-6.67E-07	kg
9.9	Crushing	Jaw crusher	6.25E+00	t		Dinitrogen monoxide	-8.07E-05	kg
		Electricity	1.38E+00	kWh		Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	6.17E-09	kg
9.10	Handling	Conveyor belt, 12 m	1.04E-05	m		Ethene	-9.39E-06	kg
		Electricity	2.38E-01	kWh		Formaldehyde	2.74E-05	kg
9.11	Crushing	Rod mill	6.25E+00	t		Heptane	-2.69E-05	kg
		Electricity	3.83E+00	kWh		Hexane	-5.55E-05	kg
9.12	Handling	Conveyor belt, 20 m	1.73E-05	m		Lead	-4.09E-07	kg
		Electricity	3.18E-01	kWh		Mercury	2.30E-09	kg
9.13	Screening (0/32 mm)	Vibrating screen	4.30E-06	t		Methane, bromochlorodifluoro-, Halon 1211	2.81E-09	kg
		Electricity	5.52E-01	kWh		Methane, bromotrifluoro-, Halon 1301	-3.31E-08	kg
9.14	Handling	Conveyor belt, 5 m	3.46E-06	m		Methane, fossil	-7.65E-03	kg
		Electricity	1.27E-01	kWh		Nitrogen oxides	-1.88E-02	kg
9.15	Handling	Loading shovel(V)[(b)]	1.90E+00	m^3		Particulates, < 2.5 um	-2.03E-03	kg
9.16	Handling	Chains feeder	8.45E-07	t		Pentane	-1.47E-04	kg
		Electricity	4.66E-02	kWh		Propane	-1.24E-04	kg
9.17	Screening (0/2 mm)	Vibrating screen	3.44E-06	t		Propene	-6.09E-06	kg
		Electricity	4.42E-01	kWh		Sulfur dioxide	-2.27E-03	kg
9.18	Handling	Conveyor belt, 5 m	6.91E-07	m		Toluene	-1.22E-05	kg
		Electricity	2.54E-02	kWh		Zinc	-9.66E-07	kg
10.1	Waste handling	Loading shovel(V)[(b)]	2.38E-01	m^3	*Water*	Arsenic	1.72E-06	kg
		Truck 28 t, 15 km	9.38E+00	tkm		Barium	-2.87E-05	kg
	Output					Chromium	-3.13E-07	kg
10	*Waste*					Chromium VI	1.87E-06	kg
10.2	Waste treatment	Disposal, inert waste	0.625	t		COD, Chemical Oxygen Demand	-9.00E-03	kg
11	*Avoided product*					Copper	1.35E-05	kg
11.1	Transport	Truck 28 t, 15 km	1.78E+02	tkm		Mercury	5.88E-08	kg
11.2	Landfill	Disposal, inert waste	1.19E+01	t		Nickel	1.94E-05	kg
	Products/Co-products					Phosphate	7.07E-04	kg
		RFA 0/2 mm	1	t		Vanadium	4.85E-06	kg
		Others fractions RA	10.875	t		Zinc	1.16E-05	kg
					Soil	Chromium VI	2.93E-07	kg
						Zinc	2.88E-06	kg

[(a)] Ecoinvent database processes (converted from v.2.2 to v.3.01); [(b)] Modified process; for further details, see Chapter 3.

Table A4. Inventory data of 1 t masonry mortar

Subsystem	*Item*	*Process*	*Unit process* [(a)]	*Amount per functional unit of masonry mortar*						
				G-0-1	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*	*Unit*
Input										
		Materials/Energy								
Aggregate	17.1	NFA production	NFA 0/2 mm [(b)]	8.10E-01	6.12E-01	6.12E-01	6.12E-01	6.12E-01	4.05E-01	t
	18.1	RFA production	RFA 0/2 mm [(c)]	-	1.98E-01	1.98E-01	1.98E-01	1.98E-01	4.05E-01	t
Filler	19.1	Filler production	Filler	9.00E-02	9.00E-02	9.00E-02	9.00E-02	9.00E-02	9.00E-02	t
Cement	20.1	Cement production	Cement	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	t
Admixture	21.1	Admixture production	Admixture	1.00E-03	1.00E-03	3.00E-03	6.00E-03	9.00E-03	9.00E-03	t
Transport	17.2	NFA 0/2 mm transport	Loading shovel	2.88E-01	2.17E-01	2.17E-01	2.17E-01	2.17E-01	1.44E-01	m^3
			Truck, 28 t, 4 km	3.24E+00	2.45E+00	2.45E+00	2.45E+00	2.45E+00	1.62E+00	tkm
	18.2	RFA 0/2 mm transport	Loading shovel (V2) [(d)]	-	7.52E-02	7.52E-02	7.52E-02	7.52E-02	1.54E-01	m^3
			Truck, 28 t, 10 km	-	1.98E+00	1.98E+00	1.98E+00	1.98E+00	4.05E+00	tkm
	19.2	Filler transport	Loading telescopic chute	5.06E-09	5.06E-09	5.06E-09	5.06E-09	5.06E-09	5.06E-09	t
			Electricity	1.12E-03	1.12E-03	1.12E-03	1.12E-03	1.12E-03	1.12E-03	kWh
			Truck, 24 t, 75 km	6.75E+00	6.75E+00	6.75E+00	6.75E+00	6.75E+00	6.75E+00	tkm
	20.2	Cement transport	Loading telescopic chute	4.55E-09	4.55E-09	4.55E-09	4.55E-09	4.55E-09	4.55E-09	t
			Electricity	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	kWh
			Truck, 28 t, 200 km	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	tkm
	21.2	Admixture transport	Loading telescopic chute	5.56E-11	5.56E-11	1.67E-10	3.34E-10	5.00E-10	5.00E-10	t
			Electricity	1.22E-05	1.22E-05	3.66E-05	7.32E-05	1.10E-04	1.10E-04	kWh
			Truck, 18 t, 440 km	4.40E-01	4.40E-01	1.32E+00	2.64E+00	3.96E+00	3.96E+00	tkm
Manufacturing		Processing								
	17.3.1	NFA 0/2 mm Handling	Belt unloader, 11.55 m	1.02E-06	7.71E-07	7.71E-07	7.71E-07	7.71E-07	5.10E-07	m
			Hopper	2.50E-06	1.89E-06	1.89E-06	1.89E-06	1.89E-06	1.25E-06	t
			Electricity	8.67E-02	6.55E-02	6.55E-02	6.55E-02	6.55E-02	4.33E-02	kWh
	17.3.2	NFA 0/2 mm Handling	Bucket elevator, 26.2 m	2.83E-06	2.14E-06	2.14E-06	2.14E-06	2.14E-06	1.41E-06	t
			Electricity	1.98E-01	1.50E-01	1.50E-01	1.50E-01	1.50E-01	9.92E-02	kWh
	17.3.3	NFA 0/2 mm Handling	Conveyor belt, 5 m	5.22E-07	3.95E-07	3.95E-07	3.95E-07	3.95E-07	2.61E-07	m
			Conveyor belt, 3.6 m	3.77E-07	2.85E-07	2.85E-07	2.85E-07	2.85E-07	1.88E-07	m
			Electricity	3.27E-02	2.47E-02	2.47E-02	2.47E-02	2.47E-02	1.64E-02	kWh
	17.3.4	NFA 0/2 mm Storage	Hopper	1.06E-05	8.02E-06	8.02E-06	8.02E-06	8.02E-06	5.31E-06	t
			Electricity	2.16E-02	1.63E-02	1.63E-02	1.63E-02	1.63E-02	1.08E-02	kWh
	17.3.5	NFA 0/2 mm Dosage	Screw conveyor	8.51E-07	6.43E-07	6.43E-07	6.43E-07	6.43E-07	4.25E-07	t
			Electricity	6.52E-01	4.93E-01	4.93E-01	4.93E-01	4.93E-01	3.26E-01	kWh
	18.3.1	RFA 0/2 mm Handling	Belt unloader, 11.55 m	-	2.67E-07	2.67E-07	2.67E-07	2.67E-07	5.47E-07	m
			Hopper	-	6.12E-07	6.12E-07	6.12E-07	6.12E-07	1.25E-06	t
			Electricity	-	5.29E-03	5.29E-03	5.29E-03	5.29E-03	1.08E-02	kWh
	18.3.2	RFA 0/2 mm Handling	Bucket elevator, 26.2 m	-	6.91E-07	6.91E-07	6.91E-07	6.91E-07	1.41E-06	t
			Electricity	-	4.85E-02	4.85E-02	4.85E-02	4.85E-02	9.92E-02	kWh
	18.3.3	RFA 0/2 mm Handling	Conveyor belt, 5 m	-	1.37E-07	1.37E-07	1.37E-07	1.37E-07	2.80E-07	m
			Conveyor belt, 3.6 m	-	9.84E-08	9.84E-08	9.84E-08	9.84E-08	2.01E-07	m
			Electricity	-	8.55E-03	8.55E-03	8.55E-03	8.55E-03	1.75E-02	kWh
	18.3.4	RFA 0/2 mm Storage	Hopper	-	2.59E-06	2.59E-06	2.59E-06	2.59E-06	5.31E-06	t
			Electricity	-	5.29E-03	5.29E-03	5.29E-03	5.29E-03	1.08E-02	kWh
	18.3.5	RFA 0/2 mm Dosage	Screw conveyor	-	2.08E-07	2.08E-07	2.08E-07	2.08E-07	4.25E-07	t
			Electricity	-	1.59E-01	1.59E-01	1.59E-01	1.59E-01	3.26E-01	kWh
	19.3.1	Filler Handling	Loading telescopic chute	5.06E-09	5.06E-09	5.06E-09	5.06E-09	5.06E-09	5.06E-09	t
			Electricity	1.12E-03	1.12E-03	1.12E-03	1.12E-03	1.12E-03	1.12E-03	kWh
	19.3.2	Filler Storage	Hopper	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	t
	19.3.3	Filler Dosage	Screw conveyor	1.23E-08	1.23E-08	1.23E-08	1.23E-08	1.23E-08	1.23E-08	t
			Electricity	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	kWh
	20.3.1	Cement Handling	Loading telescopic chute	4.55E-09	4.55E-09	4.55E-09	4.55E-09	4.55E-09	4.55E-09	t
			Electricity	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	kWh
	20.3.2	Cement Storage	Hopper	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	t
	20.3.3	Cement Dosage	Screw conveyor	1.37E-08	1.37E-08	1.37E-08	1.37E-08	1.37E-08	1.37E-08	t
			Electricity	1.15E-02	1.15E-02	1.15E-02	1.15E-02	1.15E-02	1.15E-02	kWh
	21.3.1	Admixture Handling	Loading telescopic chute	5.56E-11	5.56E-11	1.67E-10	3.34E-10	5.00E-10	5.00E-10	t
			Electricity	1.22E-05	1.22E-05	3.66E-05	7.32E-05	1.10E-04	1.10E-04	kWh
	21.3.2	Admixture Storage	Hopper	8.43E-08	8.43E-08	2.53E-07	5.06E-07	7.59E-07	7.59E-07	t
	21.3.3	Admixture Dosage	Screw conveyor	4.72E-08	4.72E-08	1.42E-07	2.83E-07	4.25E-07	4.25E-07	t
			Electricity	3.07E-02	3.07E-02	9.21E-02	1.84E-01	2.76E-01	2.76E-01	kWh
	22.1	Mixing	Mortar mixer	2.48E-06	2.48E-06	2.48E-06	2.48E-06	2.48E-06	2.48E-06	t
			Electricity	6.21E-01	6.21E-01	6.21E-01	6.21E-01	6.21E-01	6.21E-01	kWh

Table A4. Inventory data of 1 t masonry mortar (continued)

Subsystem	*Item*	*Process*	*Unit process* [(a)]	*Amount per functional unit of masonry mortar*						
				G-0-1	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*	*Unit*
Input										
		Materials/Energy								
Manufacturing		Processing								
	22.2	Handling	Screw conveyor	1.85E-06	1.85E-06	1.85E-06	1.85E-06	1.85E-06	1.85E-06	t
			Bucket elevator	2.92E-07	2.92E-07	2.92E-07	2.92E-07	2.92E-07	2.92E-07	t
			Screw conveyor	1.85E-06	1.85E-06	1.85E-06	1.85E-06	1.85E-06	1.85E-06	t
			Electricity	2.41E+00	2.41E+00	2.41E+00	2.41E+00	2.41E+00	2.41E+00	kWh
	22.3	Storage	Hopper	1.13E-05	1.13E-05	1.13E-05	1.13E-05	1.13E-05	1.13E-05	t
			Motor	2.88E-09	2.88E-09	2.88E-09	2.88E-09	2.88E-09	2.88E-09	t
			Electricity	4.92E-03	4.92E-03	4.92E-03	4.92E-03	4.92E-03	4.92E-03	kWh
		Mortar plant								
	23	Mortar plant	Mortar plant[(d)]	2.00E-07	2.00E-07	2.00E-07	2.00E-07	2.00E-07	2.00E-07	P
Output										
		Products/Co-products								
		Masonry mortar		1	1	1	1	1	1	t

(a) Ecoinvent database processes (converted from v.2.2 to v.3.01);

(b) According to Table A2;

(c) According to Table A3;

(d) Modified process; for further details, see Chapter 3.

Table A5. Inventory flows (inputs) of masonry mortars

		Amount per functional unit						*Unit*
Input flows		*G-0-1*	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*	
Resources	Land occupation	2.02E+00	1.72E+00	1.75E+00	1.79E+00	1.84E+00	1.52E+00	m^2a
	Land transformation	1.55E-01	8.82E-02	9.18E-02	9.71E-02	1.02E-01	3.26E-02	m^2
Non renewable energy resources	Coal, brown	9.38E-01	9.32E-01	9.56E-01	9.92E-01	1.03E+00	1.02E+00	kg
	Coal, hard	8.24E+00	8.18E+00	8.28E+00	8.42E+00	8.57E+00	8.51E+00	kg
	Gas, natural	3.04E+00	2.88E+00	3.00E+00	3.19E+00	3.38E+00	3.21E+00	m^3
	Oil, crude	5.74E+00	5.46E+00	5.65E+00	5.93E+00	6.21E+00	5.92E+00	kg
Non renewable elements	Cadmium	7.94E-05	7.81E-05	7.88E-05	7.97E-05	8.07E-05	7.94E-05	kg
	Chromium	5.74E-03	5.64E-03	5.69E-03	5.76E-03	5.84E-03	5.74E-03	kg
	Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	3.60E-03	3.59E-03	3.60E-03	3.62E-03	3.65E-03	3.63E-03	kg
	Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	2.08E-03	2.07E-03	2.08E-03	2.09E-03	2.11E-03	2.10E-03	kg
	Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	7.29E-04	7.25E-04	7.29E-04	7.35E-04	7.41E-04	7.36E-04	kg
	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	1.52E-02	1.52E-02	1.52E-02	1.53E-02	1.54E-02	1.54E-02	kg
	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	2.96E-03	2.95E-03	2.96E-03	2.98E-03	3.00E-03	2.99E-03	kg
	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	1.58E-03	1.58E-03	1.59E-03	1.60E-03	1.61E-03	1.60E-03	kg
	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	1.16E-07	1.20E-07	1.23E-07	1.27E-07	1.31E-07	1.36E-07	kg
	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	2.59E-08	2.68E-08	2.75E-08	2.84E-08	2.94E-08	3.04E-08	kg
	Lead	1.36E-03	1.34E-03	1.35E-03	1.37E-03	1.38E-03	1.36E-03	kg
	Molybdenum	8.45E-05	8.34E-05	8.39E-05	8.46E-05	8.54E-05	8.42E-05	kg
	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% (c.o.)	8.63E-05	8.60E-05	8.64E-05	8.69E-05	8.74E-05	8.72E-05	kg
	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% (c.o.)	2.95E-04	2.94E-04	2.95E-04	2.97E-04	2.98E-04	2.97E-04	kg
	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% (c.o.)	5.84E-05	5.82E-05	5.84E-05	5.89E-05	5.93E-05	5.90E-05	kg
	Nickel, 1.98% in silicates, 1.04% (c.o.)	1.44E-02	1.42E-02	1.43E-02	1.45E-02	1.48E-02	1.45E-02	kg
	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	1.93E-06	1.90E-06	1.92E-06	1.94E-06	1.96E-06	1.93E-06	kg
	Tin	1.14E-04	1.14E-04	1.15E-04	1.17E-04	1.18E-04	1.19E-04	kg
	Zinc	2.44E-03	2.40E-03	2.42E-03	2.46E-03	2.49E-03	2.45E-03	kg
Renewable resources	Water	9.14E-02	8.54E-02	8.57E-02	8.62E-02	8.67E-02	8.04E-02	m^3

Table A6. Inventory flows (outputs) of masonry mortars

		Amount per functional unit						*Unit*
Output flows		*G-0-1*	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*	
Emissions to air	Ammonia	4.18E-03	4.16E-03	4.17E-03	4.19E-03	4.20E-03	4.18E-03	kg
	Arsenic	1.58E-05	1.57E-05	1.59E-05	1.62E-05	1.65E-05	1.64E-05	kg
	Butane	4.82E-04	4.59E-04	4.74E-04	4.97E-04	5.19E-04	4.95E-04	kg
	Cadmium	5.51E-06	5.49E-06	5.51E-06	5.55E-06	5.59E-06	5.56E-06	kg
	Carbon dioxide, fossil	9.95E+01	9.91E+01	9.96E+01	1.01E+02	1.01E+02	1.01E+02	kg
	Carbon monoxide, fossil	9.69E-02	9.49E-02	9.57E-02	9.70E-02	9.83E-02	9.62E-02	kg
	Chromium	1.87E-05	1.83E-05	1.85E-05	1.88E-05	1.91E-05	1.87E-05	kg
	Ethane, CFC-114	4.55E-07	4.55E-07	4.73E-07	4.99E-07	5.26E-07	5.26E-07	kg
	Formaldehyde	2.71E-04	2.83E-04	2.95E-04	3.13E-04	3.30E-04	3.44E-04	kg
	Lead	4.75E-05	4.73E-05	4.76E-05	4.80E-05	4.84E-05	4.81E-05	kg
	Mercury	3.77E-06	3.75E-06	3.77E-06	3.80E-06	3.83E-06	3.82E-06	kg
	Methane, Halon 1211	4.35E-08	4.30E-08	4.81E-08	5.56E-08	6.32E-08	6.27E-08	kg
	Methane, Halon 1301	1.69E-07	1.63E-07	1.72E-07	1.85E-07	1.98E-07	1.93E-07	kg
	Methane, HCFC-22	1.42E-06	1.43E-06	1.47E-06	1.54E-06	1.61E-06	1.62E-06	kg
	Methane, CFC-12	9.77E-08	9.82E-08	9.99E-08	1.02E-07	1.05E-07	1.05E-07	kg
	Methane, fossil	9.25E-02	9.07E-02	9.19E-02	9.37E-02	9.55E-02	9.36E-02	kg
	Nitrogen oxides	2.65E-01	2.62E-01	2.66E-01	2.72E-01	2.78E-01	2.74E-01	kg
	Particulates, < 2.5 um	1.52E-02	1.47E-02	1.49E-02	1.52E-02	1.55E-02	1.50E-02	kg
	Pentane	6.12E-04	5.84E-04	6.02E-04	6.30E-04	6.58E-04	6.28E-04	kg
	Sulfur dioxide	1.55E-01	1.53E-01	1.54E-01	1.57E-01	1.60E-01	1.58E-01	kg
	Zinc	4.40E-05	4.37E-05	4.41E-05	4.48E-05	4.55E-05	4.51E-05	kg
Emissions to water	Antimony	2.53E-05	2.51E-05	2.53E-05	2.56E-05	2.58E-05	2.56E-05	kg
	Arsenic	9.52E-05	9.48E-05	9.56E-05	9.68E-05	9.80E-05	9.76E-05	kg
	Chromium VI	1.38E-04	1.37E-04	1.38E-04	1.41E-04	1.43E-04	1.41E-04	kg
	COD, Chemical Oxygen Demand	4.71E-02	4.53E-02	4.68E-02	4.90E-02	5.12E-02	4.94E-02	kg
	Copper	7.10E-04	7.14E-04	7.27E-04	7.47E-04	7.67E-04	7.72E-04	kg
	Nickel	6.94E-04	6.89E-04	6.98E-04	7.11E-04	7.24E-04	7.19E-04	kg
	Nitrate	7.90E-03	7.84E-03	7.94E-03	8.10E-03	8.25E-03	8.18E-03	kg
	Phosphate	2.55E-02	2.53E-02	2.56E-02	2.61E-02	2.65E-02	2.63E-02	kg
	Vanadium	1.05E-04	1.04E-04	1.05E-04	1.07E-04	1.09E-04	1.08E-04	kg
	Zinc	3.13E-03	3.13E-03	3.17E-03	3.22E-03	3.27E-03	3.27E-03	kg
Emissions to soil	Chromium VI	3.53E-06	3.51E-06	4.17E-06	5.16E-06	6.15E-06	6.12E-06	kg

Table A7. Main raw materials consumed and substances emitted during the manufacturing of 1 t functional unit mortar

Impact category (unit)	*Compartment*	*G-0-1*	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*
Raw material consumed / Substance emitted							
Abiotic depletion of elements (kg Sb eq.)							
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	Crude	2.08E-05	2.08E-05	2.09E-05	2.10E-05	2.11E-05	2.11E-05
Cadmium	Crude	1.25E-05	1.23E-05	1.24E-05	1.25E-05	1.27E-05	1.25E-05
Lead	Crude	8.62E-06	8.49E-06	8.56E-06	8.66E-06	8.76E-06	8.63E-06
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	Crude	6.01E-06	6.24E-06	6.39E-06	6.61E-06	6.84E-06	7.08E-06
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	Crude	5.25E-06	5.23E-06	5.25E-06	5.28E-06	5.31E-06	5.29E-06
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	Crude	4.93E-06	4.91E-06	4.93E-06	4.97E-06	5.00E-06	4.98E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	Crude	4.05E-06	4.04E-06	4.06E-06	4.09E-06	4.11E-06	4.10E-06
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	Crude	2.85E-06	2.84E-06	2.85E-06	2.87E-06	2.89E-06	2.87E-06
Chromium	Crude	2.54E-06	2.50E-06	2.52E-06	2.55E-06	2.59E-06	2.54E-06
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	Crude	2.28E-06	2.24E-06	2.26E-06	2.29E-06	2.31E-06	2.28E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	Crude	2.17E-06	2.16E-06	2.17E-06	2.19E-06	2.20E-06	2.19E-06
Tin	Crude	1.84E-06	1.85E-06	1.87E-06	1.89E-06	1.92E-06	1.92E-06
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	Crude	1.54E-06	1.53E-06	1.54E-06	1.55E-06	1.56E-06	1.55E-06
Molybdenum	Crude	1.50E-06	1.49E-06	1.49E-06	1.51E-06	1.52E-06	1.50E-06
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	Crude	1.35E-06	1.39E-06	1.43E-06	1.48E-06	1.53E-06	1.58E-06
Zinc	Crude	1.31E-06	1.29E-06	1.30E-06	1.32E-06	1.34E-06	1.32E-06
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	Crude	1.04E-06	1.04E-06	1.04E-06	1.05E-06	1.05E-06	1.05E-06
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	Crude	9.99E-07	9.93E-07	9.98E-07	1.01E-06	1.02E-06	1.01E-06
Nickel, 1.98% in silicates, 1.04% in crude ore	Crude	9.43E-07	9.26E-07	9.36E-07	9.50E-07	9.65E-07	9.46E-07
Substances remaining		4.05E-06	4.04E-06	4.07E-06	4.12E-06	4.17E-06	4.16E-06
Abiotic depletion of fossil fuels (MJ)							
Oil, crude	Crude	240.52	228.73	236.63	248.47	260.32	247.94
Coal, hard	Crude	229.80	228.23	230.94	234.99	239.04	237.40
Gas, natural/m3	Crude	106.32	100.80	105.15	111.68	118.21	112.41
Coal, brown	Crude	13.13	13.04	13.38	13.88	14.39	14.30
Substances remaining		3.98	3.96	3.99	4.03	4.07	4.05
Global Warming (kg CO_2 eq.)							
Carbon dioxide, fossil	Air	99.50	99.06	99.64	100.52	101.40	100.94
Methane, fossil	Air	2.31	2.27	2.30	2.34	2.39	2.34
Substances remaining		0.59	0.59	1.05	1.76	2.46	2.45
Ozone layer depletion (kg CFC-11 eq.)							
Methane, bromotrifluoro-, Halon 1301	Air	2.02E-06	1.96E-06	2.06E-06	2.22E-06	2.38E-06	2.31E-06
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	4.28E-07	4.27E-07	4.44E-07	4.69E-07	4.95E-07	4.95E-07
Methane, bromochlorodifluoro-, Halon 1211	Air	2.61E-07	2.58E-07	2.88E-07	3.34E-07	3.79E-07	3.76E-07
Methane, dichlorodifluoro-, CFC-12	Air	9.77E-08	9.82E-08	9.99E-08	1.02E-07	1.05E-07	1.05E-07
Methane, chlorodifluoro-, HCFC-22	Air	7.12E-08	7.15E-08	7.37E-08	7.71E-08	8.04E-08	8.08E-08
Substances remaining		3.97E-08	3.99E-08	4.08E-08	4.20E-08	4.33E-08	4.35E-08
Photochemical oxidation (kg C_2H_4 eq.)							
Sulfur dioxide	Air	7.42E-03	7.33E-03	7.41E-03	7.54E-03	7.67E-03	7.57E-03
Carbon monoxide, fossil	Air	2.62E-03	2.56E-03	2.58E-03	2.62E-03	2.65E-03	2.60E-03
Methane, fossil	Air	5.55E-04	5.44E-04	5.51E-04	5.62E-04	5.73E-04	5.62E-04
Pentane	Air	2.42E-04	2.31E-04	2.38E-04	2.49E-04	2.60E-04	2.48E-04
Butane	Air	1.70E-04	1.61E-04	1.67E-04	1.75E-04	1.83E-04	1.74E-04
Formaldehyde	Air	1.40E-04	1.47E-04	1.53E-04	1.62E-04	1.71E-04	1.78E-04
Substances remaining		7.20E-04	7.05E-04	7.32E-04	7.73E-04	8.13E-04	7.97E-04
Acidification (kg SO_2 eq.)							
Sulfur dioxide	Air	1.86E-01	1.83E-01	1.85E-01	1.89E-01	1.92E-01	1.89E-01
Nitrogen oxides	Air	1.33E-01	1.31E-01	1.33E-01	1.36E-01	1.39E-01	1.37E-01
Ammonia	Air	6.69E-03	6.66E-03	6.68E-03	6.70E-03	6.72E-03	6.69E-03
Substances remaining		2.93E-03	2.92E-03	2.93E-03	2.95E-03	2.97E-03	2.96E-03

Table A7. Main raw materials consumed and substances emitted during the manufacturing of 1 t functional unit mortar (continued)

Impact category (unit)	*Compartment*	*G-0-1*	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*
Raw material consumed / Substance emitted							
Eutrophication (kg PO_4 eq.)							
Nitrogen oxides	Air	3.45E-02	3.40E-02	3.45E-02	3.54E-02	3.62E-02	3.57E-02
Phosphate	Water	2.55E-02	2.53E-02	2.56E-02	2.61E-02	2.65E-02	2.63E-02
Ammonia	Air	1.46E-03	1.46E-03	1.46E-03	1.47E-03	1.47E-03	1.46E-03
COD, Chemical Oxygen Demand	Water	1.04E-03	9.97E-04	1.03E-03	1.08E-03	1.13E-03	1.09E-03
Nitrate	Water	7.90E-04	7.84E-04	7.94E-04	8.10E-04	8.25E-04	8.18E-04
Substances remaining		3.64E-04	3.53E-04	3.61E-04	3.73E-04	3.86E-04	3.73E-04
Human toxicity (cancer effects) (CTUh)							
Chromium VI	Water	1.47E-06	1.45E-06	1.47E-06	1.49E-06	1.52E-06	1.50E-06
Chromium	Air	3.95E-08	3.87E-08	3.91E-08	3.97E-08	4.03E-08	3.95E-08
Arsenic	Water	3.51E-08	3.49E-08	3.52E-08	3.57E-08	3.61E-08	3.60E-08
Mercury	Air	2.66E-08	2.65E-08	2.67E-08	2.69E-08	2.71E-08	2.70E-08
Nickel	Water	2.66E-08	2.64E-08	2.67E-08	2.72E-08	2.77E-08	2.75E-08
Chromium VI	Soil	1.89E-08	1.87E-08	2.23E-08	2.75E-08	3.28E-08	3.27E-08
Substances remaining		3.49E-08	3.49E-08	3.56E-08	3.68E-08	3.80E-08	3.79E-08
Human toxicity (non-cancer effects) (CTUh)							
Zinc	Water	3.88E-06	3.89E-06	3.93E-06	4.00E-06	4.06E-06	4.07E-06
Mercury	Air	3.15E-06	3.14E-06	3.15E-06	3.18E-06	3.20E-06	3.19E-06
Arsenic	Water	2.60E-06	2.58E-06	2.61E-06	2.64E-06	2.67E-06	2.66E-06
Zinc	Air	6.91E-07	6.86E-07	6.93E-07	7.03E-07	7.14E-07	7.08E-07
Lead	Air	4.53E-07	4.51E-07	4.53E-07	4.57E-07	4.61E-07	4.59E-07
Arsenic	Air	2.62E-07	2.61E-07	2.64E-07	2.68E-07	2.73E-07	2.72E-07
Cadmium	Air	2.55E-07	2.54E-07	2.55E-07	2.57E-07	2.58E-07	2.57E-07
Substances remaining		2.84E-07	2.82E-07	2.87E-07	2.94E-07	3.01E-07	2.99E-07
Particulate matter (kg PM2.5 eq.)							
Particulates, < 2.5 µm	Air	1.22E-02	1.15E-02	1.17E-02	1.20E-02	1.22E-02	1.16E-02
Sulfur dioxide	Air	9.55E-03	9.43E-03	9.54E-03	9.70E-03	9.87E-03	9.73E-03
Nitrogen oxides	Air	1.92E-03	1.90E-03	1.93E-03	1.97E-03	2.02E-03	1.99E-03
Ammonia	Air	2.79E-04	2.78E-04	2.78E-04	2.79E-04	2.80E-04	2.79E-04
Substances remaining		4.03E-08	4.03E-08	1.19E-07	2.36E-07	3.54E-07	3.54E-07
Freshwater ecotoxicity (CTUe)							
Zinc	Water	115.89	116.31	117.52	119.35	121.17	121.61
Copper	Water	39.15	39.37	40.12	41.23	42.34	42.58
Chromium VI	Water	14.52	14.34	14.51	14.77	15.03	14.84
Vanadium	Water	11.85	11.77	11.90	12.09	12.28	12.20
Nickel	Water	10.34	10.26	10.39	10.59	10.79	10.71
Antimony	Water	4.80	4.76	4.80	4.85	4.91	4.87
Arsenic	Water	3.84	3.82	3.86	3.91	3.96	3.94
Substances remaining		9.77	9.73	10.10	10.65	11.20	11.16
Land use (kg C deficit)							
Transformation, to mineral extraction site	Crude	83.32	68.82	69.47	70.45	71.43	56.20
Transformation, to arable, non-irrigated, intensive	Crude	10.43	10.19	10.53	11.03	11.53	11.28
Transformation, to traffic area, road network	Crude	10.43	-14.40	-14.27	-14.08	-13.88	-39.96
Transformation, to industrial area	Crude	9.51	11.31	11.38	11.49	11.60	13.49
Transformation, to arable	Crude	8.77	8.77	9.13	9.67	10.21	10.22
Occupation, traffic area, road network	Crude	8.22	7.44	7.65	7.96	8.27	7.45
Occupation, mineral extraction site	Crude	1.79	1.46	1.46	1.47	1.47	1.12
Transformation, to dump site	Crude	1.68	1.66	1.69	1.74	1.79	1.76
Occupation, forest, intensive	Crude	1.64	1.41	1.42	1.44	1.46	1.22
Occupation, traffic area, rail/road embankment	Crude	1.25	1.29	1.32	1.36	1.41	1.45
Transformation, to traffic area, rail/road embankment	Crude	1.07	1.08	1.11	1.14	1.18	1.20
Occupation, industrial area	Crude	0.95	1.13	1.13	1.15	1.16	1.34
Occupation, dump site	Crude	0.89	-0.30	-0.29	-0.26	-0.24	-1.49
Transformation, from arable, non-irrigated	Crude	-0.91	-0.93	-0.95	-0.98	-1.01	-1.02
Transformation, from arable, non-irrigated, intensive	Crude	-7.34	-7.14	-7.43	-7.86	-8.29	-8.07
Transformation, from arable	Crude	-10.83	-10.80	-11.20	-11.79	-12.38	-12.35
Transformation, from unknown	Crude	-10.99	-10.34	-10.45	-10.60	-10.76	-10.08
Transformation, from mineral extraction site	Crude	-56.44	-45.57	-45.58	-45.60	-45.61	-34.19
Substances remaining		0.86	2.14	2.17	2.21	2.25	3.60

Table A7. Main raw materials consumed and substances emitted during the manufacturing of 1 t functional unit mortar (continued)

Impact category (unit) *Raw material consumed / Substance emitted*	*Compartment*	*G-0-1*	*G-25-1*	*G-25-3*	*G-25-6*	*G-25-9*	*G-50-9*
Water depletion (m^3 water eq.)							
Water, turbine use, unspecified natural origin, RoW	Crude	10.71	10.70	10.72	10.74	10.76	10.75
Water, turbine use, unspecified natural origin, FR	Crude	10.42	10.44	10.49	10.56	10.64	10.66
Water, turbine use, unspecified natural origin	Crude	7.49	7.46	7.53	7.63	7.73	7.70
Water, turbine use, unspecified natural origin, CH	Crude	3.72	3.72	3.73	3.73	3.73	3.74
Water, turbine use, unspecified natural origin, ES	Crude	1.96	1.96	5.15	9.94	14.72	14.72
Water, turbine use, unspecified natural origin, DE	Crude	1.65	1.65	1.66	1.67	1.68	1.68
Water, turbine use, unspecified natural origin, CN	Crude	1.45	1.27	1.28	1.30	1.31	1.13
Water, cooling, unspecified natural origin, SA	Crude	1.34	1.33	1.34	1.36	1.38	1.36
Water, turbine use, unspecified natural origin, IT	Crude	0.66	0.66	0.66	0.67	0.67	0.67
Water, turbine use, unspecified natural origin, US	Crude	0.64	0.63	0.64	0.65	0.66	0.65
Water, CH	Water	-3.70	-3.70	-3.71	-3.71	-3.71	-3.72
Substances remaining		1.39	1.37	1.30	1.20	1.10	1.08