UNIVERSIDAD DE CÓRDOBA

Departamento de Ingeniería Rural
Área de Ingeniería de la Construcción

USE OF INDUSTRIAL WASTE IN MASONRY MORTAR MANUFACTURING

PhD Thesis

by

ENRIQUE FERNÁNDEZ LEDESMA

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TITULO: *Aplicación de residuos en la fabricación de morteros industriales*

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Aplicación de residuos en la fabricación de morteros industriales

"Use of industrial waste in masonry mortar manufacturing"

Tesis doctoral presentada por

Enrique Fernández Ledesma

para la obtención del título de

DOCTOR CON MENCIÓN INTERNACIONAL POR LA UNIVERSIDAD DE CÓRDOBA

Directores

Dr. José Ramón Jiménez Romero (Profesor Contratado Doctor)
Dr. Jesús Ayuso Muñoz (Profesor Titular de Universidad)

TÍTULO DE LA TESIS:

APLICACIÓN DE RESIDUOS EN LA FABRICACIÓN DE MORTEROS INDUSTRIALES

DOCTORANDO: Enrique Fernández Ledesma

INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS

En los últimos años son cada vez más los estudios enfocados a conseguir una construcción que sea sostenible y aumentar todo lo posible el ciclo de vida de los materiales.

Los residuos de construcción y demolición (RCD) generados como consecuencia de la actividad del sector de la construcción tienen un gran potencial para su reutilización en ingeniería civil y edificación. Actualmente la mayor parte de los estudios encauzados a la reutilización de estos residuos están centrados en la fracción gruesa de RCD, es por ello que surge la necesidad de estudiar más profundamente una alternativa para la fracción fina.

Hay que destacar que la Directiva Marco de Residuos 2008/98/CE del Parlamento Europeo establece que los países de la Unión Europea (UE) en el año 2020 deben alcanzar una tasa mínima de recuperación del 70% en peso para los RCD y que España está muy lejos de alcanzar este objetivo.

La presente Tesis Doctoral surge de la idea de reducir el consumo de un recurso natural no renovable como es la arena, sustituyéndola total o parcialmente por arena reciclada de RCD. De este modo, además se contribuye a aumentar la tasa de recuperación de residuos.

La Tesis se presenta como un compendio de artículos científicos, los cuales han sido publicados en revistas internacionales indexadas incluidas en los dos primeros cuartiles del JCR:

1. Ledesma, E. F., Jiménez, J. R., Fernández, J. M., Galvín, A. P., Agrela, F., & Barbudo, A. (2014). Properties of masonry mortars manufactured with fine recycled concrete aggregates. *Construction and Building Materials*, *71*, 289-298.
2. Ledesma, E. F., Jiménez, J. R., Ayuso, J., Fernández, J. M., & de Brito, J. (2015). Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production–Part-I: ceramic masonry waste. *Journal of Cleaner Production*, *87*, 692-706.
3. Fernández-Ledesma, E., Jiménez, J. R., Ayuso, J., Corinaldesi, V., & Iglesias-Godino, F. J. (2016). A proposal for the maximum use of recycled concrete sand in masonry mortar design. *Materiales de Construcción*, *66*(321), e075.

Para la realización de estos estudios se ha contado con la participación de investigadores externos a la Universidad de Córdoba, destacando la colaboración en el segundo trabajo del profesor Dr. Jorge de Brito (Instituto Superior Técnico, Universidade de Lisboa, Portugal) y en el tercer trabajo de la profesora Dra.Valeria Corinaldesi (Department of Materials and Environment Engineering and Physics, Università Politecnica delle Marche, Ancona, Italy).

Por todo ello, se autoriza la presentación de la Tesis Doctoral "Aplicación de residuos en la fabricación de morteros industriales".

Córdoba, 2 de Marzo de 2016

Firma de los directores

Fdo.:Prof. Dr. José Ramón Jiménez Romero

Fdo.: Prof. Dr. Jesús Ayuso Muñoz

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Abstract

This thesis studies the use of fine fraction of construction and demolition waste (CDW) in the manufacturing of masonry mortars.

The main use of recycled aggregates from CDW is for road construction, although its use in the manufacturing of concrete or mortars would give it a greater added value. Worldwide there are numerous studies on the use of coarse fraction of recycled aggregates from CDW for manufacturing concrete. However, very few exist in the evaluation of fine fraction. Currently in Spain it is underused and in most cases simply deposited in recycling plants.

In this study two types of fine recycled aggregates have been used, one from concrete waste (FRCA), and the other of mixed waste material from partition walls with a high percentage of ceramic red-brick (FMRA). All the materials have been characterized physically, chemically and mineralogically in order to attribute the effect of their incorporation in the manufacturing of industrial masonry mortars.

Studied in the first phase were the properties of fresh and hardened mortar made with FRCA and five volumetric substitution levels of natural sand by FRCA: 0%, 5%, 10%, 20% y 40%. A type CEM-IV puzzolanic cement was used and the short and long term properties of low-strength mortars (M5) were evaluated.

In the second phase a type CEM-II cement was used, and mortars of greater strength (M-10) were made using FRMA. During this stage natural sand was substituted by recycled sand in five levels: 0%, 25%, 50%, 75% and 100%. The waste was evaluated environmentally by means of a conformity test before and after binding with cement (leaching test). The results were completed with durability studies.

With the aim of completing the previous studies, a third phase was carried out in which up to 100% of natural sand was substituted by FRCA, using a type CEM-II cement to make a type M-10 mortar, mixed in a similar way to that used in the second phase of this study.

As a general conclusion to this thesis, it can be said that replacement rates of up to 50% of natural sand by recycled materials can be used in industrial masonry mortars for indoor use without their properties being significantly affected. The results obtained contribute to a reduction in the extraction of natural sand from quarries and rivers, thus minimizing energy consumption and CO_2 emissions, mitigating global warming and avoiding the dumping of fine fraction CDW.

Resumen

La presente Tesis Doctoral estudia el uso de la fracción fina de los residuos de construcción y demolición (RCD) en la fabricación de morteros de albañilería.

El principal uso de los áridos reciclados de RCD es la construcción de rellenos o firmes de carreteras, aunque su uso como áridos para la fabricación de hormigones o morteros le daría un mayor valor añadido. A nivel internacional existen numerosos estudios sobre la utilización de la fracción gruesa de los áridos reciclados de RCD en la fabricación de hormigones. Sin embargo son escasos los trabajos llevados a cabo para valorizar la fracción fina. Actualmente en España la fracción fina de los áridos reciclados de RCD está infrautilizada y en la mayoría de los casos depositada sin uso en los vertederos de las Plantas de reciclaje.

En este trabajo se han utilizado dos tipos de áridos reciclados, uno procedente de residuos de hormigón (FRCA) y otro de residuos mixtos de tabiquería con un alto porcentaje de ladrillo rojo cerámico (FMRA). Todos los materiales han sido caracterizados desde un punto de vista físico, químico y mineralógico para justificar el efecto de su incorporación a la fabricación de morteros industriales de albañilería.

En una primera fase se estudiaron las propiedades del mortero fresco y endurecido fabricado con FRCA y cinco niveles de sustitución volumétrica de arena natural y FRCA: 0%, 5%, 10%, 20% y 40%.Se utilizó un cemento puzolánico tipo CEM-IV y se evaluaron las propiedades a corto y largo plazo de morteros de baja resistencia (M5)

En una segunda fase, se utilizó un cemento tipo CEM-II y se fabricaron morteros de mayor resistencia (M-10) utilizando FRMA. En

esta etapa se llevaron a cabo sustituciones de arena natural por arena reciclada de 0%, 25%, 50%, 75% y 100%. El residuo fue evaluado medioambientalmente mediante el test de conformidad antes y después de ser ligado con cemento (lixiviación). Los resultados fueron completados con estudios de durabilidad.

Con el objetivo de completar los estudios anteriores, se llevó a cabo una tercera fase, donde se sustituyó hasta un 100% de arena natural por FRCA, utilizando un cemento tipo CEM-II para fabricar un mortero tipo M-10, dosificado de manera similar al empleado en la segunda fase de este trabajo.

Como conclusión general de esta tesis, se puede decir que pueden admitirse tasas de sustitución de hasta un 50% de arena natural por árido reciclado en morteros industriales de albañilería para usos de interior sin que sus propiedades puedan verse afectadas significativamente. Los resultados obtenidos contribuyen a reducir la extracción de arena natural de canteras y ríos, minimizar el consumo de energía y emisiones de CO_2, mitigar el calentamiento global y evitar el depósito en vertedero de la fracción fina de RCD.

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List of abbreviations

CCB	Coarse crushed brick aggregates
CDW	Construction and Demolition Waste
CEN	Comité Europeo de Normalización
DRX	X-ray diffraction
EHE	Instrucción Española del Hormigón Estructural
FCB	Fine crushed brick aggregates
FRCA	Fine recycled concrete aggregate
I+D+i	Investigación Desarrollo e Innovación
LCA	Life cycle analysis
L/S	Liquid to solid ratios
MMt	Millones de toneladas
MRA	Mixed recycled aggregate
NAs	Natural aggregates
PG-3	Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes
PNIR	Plan Nacional Integrado de Residuos para el período
PNRCD	Plan Nacional de Residuos de Construcción y Demolición
PSD	Particle size distribution
PXRD	Powder X-ray diffraction
RAs	Recycled aggregates
RCA	Recycled concrete aggregate

RCD	Residuos de Construcción y Demolición
RMA	Recycled masonry aggregates
SEM	Scanning Electron Microscopy
SP	Superplastificante
UE-28	Estados miembros de la Unión Europea

1. Introducción

La construcción es uno de los sectores de producción más importantes del mundo y por tanto, genera un gran impacto en la producción de residuos (Solís-Guzman y col., 2009). Los residuos de Construcción y Demolición (RCD) son generados como consecuencia de la actividad del sector de la construcción y se producen a lo largo de todo el ciclo de vida de la obra. Proceden mayoritariamente de derribos de edificios o de rechazos de los materiales de construcción en obras de infraestructuras, obras de nueva planta y de pequeñas obras de reformas en viviendas y urbanizaciones.

Los datos más recientes de la oficina de estadística de la Unión Europea (Eurostat, 2016), estiman la producción de RCD en Europa (UE-28) durante el año 2012 en 821 millones de toneladas (MMt), lo que supuso el 33% del total de residuos generados en la UE-28. España se encuentra en la sexta posición de países más productores con un total de 26 MMt.

No obstante, en el año 2007 la tasa de producción de RCD generada en España superó los 42 MMt coincidiendo con el periodo de mayor intensidad del sector de la construcción, según los datos oficiales aportados por el Ministerio de Agricultura, Alimentación y Medio Ambiente (2010), con un ritmo de crecimiento anual del 8,7% desde el año 2001, aunque esta tendencia de crecimiento cambió drásticamente a partir de 2008 debido a la crisis económica y la fuerte bajada del sector de la construcción.

El aumento de la producción de este tipo de residuos, generados principalmente en los países desarrollados, ha desencadenado el desarrollo de numerosos estudios científico-técnicos para evitar su depósito en vertederos y fomentar su reciclado. Esto contribuiría notablemente a evitar la extracción de materias primas y el agotamiento de un recurso natural no renovable como son los áridos empleados en construcción (Topcu y Guncan 1995; Debieb y col., 2009). A su vez, se han promulgado Directivas Europeas, Leyes, Decretos, Reales Decretos, Planes, Programas y Guías con el fin de gestionar adecuadamente los RCD y fomentar la reutilización, reciclaje y otras formas de valorización de los mismos. La implantación de un plan de gestión de RCD supone una mejora en la eficacia ambiental del área donde se implantan (Del Río Merino y col. 2009).

1.1. Marco normativo

Las principal normativa a nivel europeo en materia de gestión de los RCD es la Directiva Marco de Residuos 2008/98/CE del Parlamento Europeo, la cual, establece que los países de la Unión Europea (UE) en el año 2020 deben alcanzar una tasa mínima de recuperación del 70% en peso para los RCD, y ser destinados a operaciones de reutilización, reciclado u otras operaciones de valorización. La Directiva europea se basa en el principio de jerarquía: prevención, reutilización, reciclado, recuperación con otros fines (como la valorización energética) y eliminación o depósito en vertedero.

En España la producción y gestión de los RCD está regulada por el Real Decreto 105/2008 del Ministerio de la Presidencia. Este Real Decreto define a los RCD como cualquier sustancia u objeto que, cumpliendo la definición de "residuo", incluida en el artículo 3.a) de la Ley 10/1998-modificada por la Ley 22/2011-se genera en una obra de construcción y demolición. Asimismo, en España se han elaborado dos Planes Nacionales de Residuos de Construcción y demolición hasta la fecha: el Primer PNRCD (2001-2006) y el Segundo PNRCD (2007-2015) incluido en el Plan Nacional Integrado de Residuos para el periodo 2008-2015 (PNIR). Este último Plan Nacional estableció como objetivo conseguir una tasa de reciclaje del 40% de los RCD en el año 2015 y que el 100% de todos los materiales peligrosos contenidos en los RCD sean gestionados correctamente (Ministerio de Medio Ambiente, y Medio Rural y Marino, 2009).

Sin embargo, la falta de normas específicas de uso hace que España sea uno de los países de la Unión Europea con menor tasa de reciclado de RCD de la UE-28, muy por debajo de la media europea que está en torno al 50%. Según la disuelta asociación Española del Gremio de Entidades del Reciclaje de Derribos (GERD), en su último informe emitido del periodo 2008-2011, indica que el 50% de la gestión de RCD se realiza de forma ilegal por empresas no autorizadas, se vierten directamente al medio natural o se deposita en vertederos. Esto coincide con las conclusiones emitidas por la Federación Española de Gestores de Residuos de Construcción y Demolición (FERCD), que indican que en España el mayor problema sigue siendo el vertido incontrolado que asciende a un 49% en el periodo 2009-2013, aunque pone de manifiesto que esta tendencia es descendente. Por lo tanto, queda mucho por hacer para conseguir el objetivo marcado por la Unión Europea en el año 2020.

El actual Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3), en vigor a partir de la Orden FOM/2523/2014 de 12 de diciembre, así como el anterior (Orden FOM/891/2004), permite el uso de áridos reciclados como zahorras en la formación de firmes para categoría de tráfico pesado T2 a T4, gravacemento, suelo cemento, pavimentos de hormigón, hormigón magro vibrado y además permite en algunos casos emplear proporciones superiores al 60% en la fabricación de mezclas bituminosas para capas de base e intermedias. Sin embargo, la mayoría de los límites que deben cumplir los áridos reciclados de RCD que establece el PG-3 fueron establecidos tras años de experiencia para áridos naturales, y no tienen por qué aplicarse directamente a los materiales reciclados, lo que está limitando su uso. La adaptación de normativas existente o la aprobación de normativas específicas que comtemplen el uso de áridos reciclados de RCD, incrementaría su uso, su valor añadido y haría que estos fueran cada vez sean más competitivos respecto a los áridos naturales.

La Instrucción de Hormigón Estructural (EHE-08), incorpora el anejo 15 (Recomendaciones para la utilización de hormigones reciclados) que permite sustituir parte de la fracción gruesa del árido natural por árido reciclado de hormigón en un máximo del 20% de sustitución y con contenido de material cerámico menor del 5%, pero no permite utilizar la fracción fina.

Actualmente la fracción fina es un problema en las plantas de gestión de RCD, existiendo grandes cantidades acopiadas o directamente depositadas en los vertederos de las mismas, con el riesgo de colmatación prematura y el despilfarro de un recurso valorizable como es la arena reciclada. Como consecuencia de ello, es necesario investigar una aplicación alternativa de esta fracción que contribuya a mejorar la tasa de reciclaje de RCD de España.

1.2. Tipología y producción de RCD

A partir de los RCD convenientemente gestionados y tratados en plantas de reciclaje autorizadas se pueden obtener áridos reciclados para su empleo en obras de ingeniería civil o edificación.

En España había censadas unas 200 instalaciones de gestión RCD (IDAE, 2011), aunque casi la mitad estaban en proceso de legalización. Además habría que añadir aproximadamente un número similar de plantas móviles simples que operan directamente en obras al margen de cualquier control público. A partir del año 2013 no se han publicado datos fiables actualizados sobre el número de plantas, la gestión o la producción de RCD.

Las plantas de tratamiento de RCD son aquellas instalaciones acondicionadas con la maquinaria y equipos específicos para el reciclaje de RCD, que disponen de sistemas de control de calidad, para maximizar el valor añadido de los áridos reciclados. Hay dos tipos según su construcción: fijas y móviles, pudiendo ser estás últimas semi-móviles.

Las plantas fijas ofrecen un servicio continuo en zonas concretas con la posibilidad de gestionar residuos muy heterogéneos. En cambio las plantas móviles están diseñadas para tratar los residuos directamente en obra, y así evitar los costes derivados de transporte, aunque resultan más caras que las fijas por unidad de peso procesado (Barbudo, 2012), debido al equipo compacto utilizado.

Las plantas semi-móviles se diseñan con el objeto de desplazarse dentro de las escombreras, según la disposición de los materiales en la misma. Se caracterizan por un sistema autoportante normalmente de orugas que contienen los distintos elementos de tratamiento de los RCD (criba, machacadora,...). Este sistema es idéntico al utilizado en las plantas móviles.

Conforme a las operaciones unitarias realizadas en el proceso, las plantas de tratamiento de RCD son clasificadas en diferentes niveles de tecnología en función de la tipología del residuo, su ritmo de generación y el lugar de origen. En el año 1999 en el informe Symonds se definieron 3 niveles tecnológicos en función de la movilidad, el proceso productivo y el número de líneas de las instalaciones.

A día de hoy, el sistema más novedoso son las plantas de Nivel 4, cuyo funcionamiento está constituido a base de moliendas selectivas y clasificaciones en húmedo, aunque por el momento no son de aplicación en España.

La mayoría de las normas y especificaciones internacionales establecen las diferentes tipologías de áridos reciclados en función de su composición (Vazquez y col., 2006), que dependerá de la naturaleza y origen de los RCD de los que proceden.

En España, la mayor parte de los áridos reciclados están constituidos por partículas de hormigón, pétreos y materiales cerámicos, más del 95%, y por otros componentes como asfalto, yeso y otras impurezas (Solis-Guzman y col., 2009; Rodríguez-Robles et al., 2015).

La Guía Española de áridos reciclados procedentes de RCD, (Proyecto GEAR 2007-2010), establece cuatro tipos o categorías de áridos reciclados en función de la composición: ARH (Áridos Reciclados de Hormigón), ARMh (Áridos Reciclados Mixtos de Hormigón), ARMc (Áridos Reciclados Mixtos cerámicos), ARC (Áridos Reciclados Cerámicos). Además incluye a los ARMa (Áridos Reciclados Mixto con asfalto).

El Proyecto I+D+i 2011-2013"Aplicaciones de los áridos reciclados de residuos de construcción y demolición (RCD) para la construcción sostenible de infraestructuras viarias en Andalucía Central", liderado por el Grupo del Plan Andaluz de Investigación TEP-227 de la Universidad de Córdoba, ha establecido 3 tipos de áridos reciclados: ARH (Áridos reciclados de hormigón), ARM (Áridos reciclados mixtos) en dos calidades diferentes (I y II) en base al contenido de partículas no deseables y absorción, y ARA (Áridos reciclados asfálticos).

Estudios recientes demuestran que la calidad final del árido reciclado dependerá del tratamiento recibido en la planta de valorización (Coelho y Brito, 2013-a; Coelho y Brito, 2013-b). Los distintos procesos de trituración y el tamaño (cribado simple, trituración y molienda) influyen en las características del árido reciclado resultante (Gomes y col., 2015). Una demolición selectiva en origen permitiría obtener un material con un nivel mínimo de contaminación, lo que proporciona un valor añadido al empleo de áridos reciclados en construcción (Silva y Brito, 2014).

1.3. Usos de los áridos de RCD

Los áridos reciclados están compuestos principalmente por partículas de hormigón, áridos no ligados, material cerámico, etc., con un gran potencial de ser reciclados. En este apartado se van a describir los diferentes usos y aplicaciones de los áridos reciclados de RCD en ingeniería civil y edificación, y los objetivos alcanzados en diferentes estudios.

La concienciación cada vez mayor por parte de las Administraciones por motivos medioambientales ha desencadenado en una mejora de la gestión de los RCD. A partir de la generación de conocimiento científico-técnico, a partir de proyectos de investigación de carácter nacional e internacional, se han ido ampliando los usos y aplicaciones de los áridos reciclados de RCD y se han llevado a cabo modificaciones de las especificaciones técnicas o normativas específicas que contemplan su uso.

En los últimos 15 años se ha venido investigando intensamente el uso de la fracción gruesa de los áridos reciclados de hormigón. El principal uso de los áridos reciclados de RCD es la ejecución de capas estructurales de firmes de caminos rurales o carreteras (Poon y Chan, 2006; Poon y Chan, 2007; Jiménez y col. 2011; Leite y col., 2011; Agrela y col., 2012; Barbudo y col., 2012, Jiménez y col. 2012-a; Jiménez y col., 2012-b; Jiménez, 2013), los resultados obtenidos indican que los áridos reciclados presentan una menor densidad y una mayor humedad óptima de compactación. Se han identificado como propiedades limitantes la resistencia a la fragmentación y el contenido de sulfatos de los áridos reciclados (Vegas y col., 2008; Jiménez y col., 2011); Jiménez 2013), sin embargo, ofrecen una excelente capacidad portante. Algunos autores han puesto de manifiesto una mejora de la capacidad portante con el tiempo, lo que atribuyen a diversas reacciones puzolánicas entre las diversas fases que constituyen este tipo de material reciclado o a la propia hidraulicidad latente de las partículas cementíceas (Vegas y col., 2011; Jiménez 2013).

De igual modo, ha sido objeto de estudio la posibilidad de emplear la fracción gruesa de los áridos reciclados ligados con cemento para la formación de firmes de carreteras (Xuan y col., 2011; Agrela y col., 2012) mediante la fabricación de suelo cemento y grava cemento (Del Rey y col., 2015-a).

La mayoría de los estudios recientes se han centrado principalmente en las posibilidades del uso de áridos reciclados de hormigón en la elaboración de hormigón reciclado (Sánchez de Juan y Alaejos, 2009; Martín-Morales y col., 2010; Evangelista y Brito, 2010). Los resultados demuestran que es posible la sustitución parcial de la fracción gruesa del árido natural por árido reciclado de hormigón (Etxeberría y col., 2007; Tabsh y Abdelfatah, 2009; Corinaldesi, 2010) para la fabricación de elementos estructurales. No obstante, el empleo de áridos reciclados mixtos en la fabricación de hormigones aún no está contemplado en ninguna normativa española. Existen estudios que ofrecen la alternativa de que los áridos reciclados mixtos pueden ser utilizados en la fabricación de hormigones no estructurales (Brito y col., 2005; Correia y col., 2006; Gomes y Brito, 2009; López-Uceda y col., 2016-a; López-Uceda y col., 2016-b). La alta heterogeneidad de los áridos reciclados influye en la calidad del hormigón fabricado, por lo que es necesario la determinación de la composición y las propiedades físicas del árido reciclado antes de su uso (Silva y Brito, 2014).

Sin embargo, la mayoría de los países no permiten el uso de la fracción fina de los áridos reciclados a pesar de que hay estudios que ponen de manifiesto que con tasas de hasta un 20% de arena reciclada procedente de material cerámico (Poon y Chan, 2004) y un 30% de la fracción fina de árido reciclado procedente de la trituración de ladrillos (Cachim, 2009) se obtienen resultados factibles para su uso en hormigones. Por otro lado Rodrigues y col. (2013) demostraron que eliminando la fracción por debajo de 0,063mm, por ser la fracción donde existe mayor concentración de yesos, sería viable el uso de áridos reciclados finos.

Como consecuencia de ello, es necesario buscar una aplicación alternativa de la fracción fina de los áridos reciclados de hormigón y mixtos que permita su valorización.

1.4. Propiedades y aplicaciones de la fracción fina de RCD

La fracción fina por lo general presenta una menor densidad y mayor absorción de agua que la fracción gruesa (Debied y col., 2008; Jiménez y col. 2013), en el árido reciclado de hormigón (FRCA) es debido al mortero adherido que otorga una superficie rugosa y mayor número de poros (Geng y Sun, 2013). La capacidad de absorción aumenta con el menor tamaño de partícula (Evangelista y Brito, 2014), además muestra forma irregular y mayor angulosidad (Evangelista y col, 2013). Asimismo, la fracción fina posee un mayor contenido en materia orgánica y concentración de cloruros y sulfatos (Rodrigues y col., 2013).

Hay estudios que manifiestan la viabilidad de utilizar la fracción fina de RCD en la fabricación de hormigones con el uso de aditivos (Evangelista y de Brito, 2007; Evangelista y de Brito, 2010; Cartuxo y col., 2015; Cartuxo y col., 2016). El empleo de superplastificantes ayuda a disminuir la relación efectiva de agua/cemento, aumentar la densidad y resistencia mecánica, reducir la absorción de agua por capilaridad y la profundidad de carbonatación (Cartuxo y col., 2016). Sin embargo el comportamiento de las propiedades rehológicas tales como la retracción y la fluencia no han sido del todo satisfactorias, lo que puede limitar su uso en hormigones estructurales (Cartuxo y col., 2015). Una alternativa viable para el uso de la fracción fina de los RCD sería la fabricación de morteros de albañilería cuyas requerimientos mecánicos son inferiores a los materiales estructurales.

A día de hoy existe un escaso conocimiento científico y técnico sobre el uso de áridos reciclados de RCD en la fabricación de morteros. La mayoría de los estudios publicados se limitan al empleo de áridos reciclados de hormigón. En España, como trabajos previos a esta tesis doctoral cabe destacar el trabajo de Vegas y col. (2009) que concluyeron que es posible sustituir en peso hasta un 25% de arena natural por arena reciclada de hormigón sin que se produzcan pérdidas significativas de prestaciones mecánicas, trabajabilidad y retracción. Dapena y col (2011) utilizando también áridos reciclados de hormigón, llegando a conclusiones similares, pero estos autores limitaron el porcentaje de sustitución en peso al 20% en morteros de altas resistencias.

A nivel Internacional, entre los trabajos previos a esta tesis caben destacar a Corinaldesi y col. (2002) quien obtuvieron una excelente adherencia con los ladrillos de morteros fabricados con árido reciclado mixto, lo cual atribuyeron a la alta calidad de la zona interfacial, aunque las resistencias a flexión y compresión se vieron perjudicadas. Otras investigaciones demuestran que tasas del 15% de sustitución de arena natural por arena reciclada procedente de la trituración de ladrillos pueden utilizarse en la fabricación de morteros sin verse reducidas las prestaciones mecánicas (Corinaldesi y Moriconi, 2009). También cabe destacar los trabajos de Silva y col (2010) que con sustituciones volumétricas de hasta el 20%, de árido natural por árido reciclado procedente de la trituración de restos de la industria del ladrillo cerámico consiguieron mejoras de la resistencia a compresión y flexión, menor absorción de agua por capilaridad, menor módulo de elasticidad y un mayor coeficiente de permeabilidad al vapor de agua, presentando como característica negativa su mayor retracción.

No obstante, lo más interesante es la evidencia de una cierta actividad cementante de la fracción fina de los áridos reciclados de RCD, al igual que ocurría en los trabajos de carreteras se atribuye a cierta actividad puzolánica de los materiales cerámicos o a la hidraulicidad latente de los cementos de hormigones y morteros presentes de los áridos reciclados (Arm, 2001; Sánchez de Rojas y col., 2001; Lin y col., 2010; Vegas y col., 2011). Esto podría reducir la cantidad de cemento a emplear. Además, tendría un beneficioso efecto ambiental al reducir las emisiones de CO_2 antropogénicas derivadas de la producción de cemento (Gregg y col., 2008; Lei y col., 2011).

Los RCD pueden contener componentes tóxicos (metales pesados, hidrocarburos, aniones,…), que si no se retiran en la planta de tratamiento pueden incorporarse a los áridos reciclados. Cuando se usan esos áridos y entran en contacto con agua, algunos componentes tóxicos se solubilizan generando un lixiviado que puede contaminar el suelo o a las aguas superficiales y subterráneas (Van der Sloot, 2000; Galvín y col., 2012; Del Rey y col., 2015-b). La lixiviación está afectada por el tamaño de partícula. La fracción fina de RCD al tener mayor superficie de contacto, puede liberar mayor concentración de elementos tóxicos, la cual puede controlarse cuando el material está en forma de monolíto (Van der Sloot y col., 2003). Para evitarlo es necesario analizar el lixiviado de los áridos reciclados empleados en la elaboración de morteros tanto en su estado inicial no ligado, como una vez endurecido el mortero, y estudiar la capacidad de los morteros para inmovilizar componentes perjudiciales.

En base a lo expuesto anteriormente, se pone de manifiesto la necesidad de valorizar la fracción fina de RCD, siendo la fabricación de morteros industriales, de menor requerimiento mecánico que los hormigones, una alternativa viable poco investigada hasta el momento.

La presente tesis doctoral estudia el efecto de la incorporación de dos tipos de áridos reciclados finos procedentes de residuos de hormigón y residuos de tabiquería con un alto porcentaje de material cerámico en las propiedades físico-mecánicas y de durabilidad de morteros de albañilería base cemento a corto y largo plazo, además de analizar el efecto de la inmovilización de elementos tóxicos y peligrosos contenidos en los áridos reciclados de los morteros.

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2. **Objetivos y estructura de la presente tesis doctoral**

2.1. Objetivos

El objetivo general de la presente tesis doctoral es diseñar y fabricar morteros industriales de albañilería partir de la fracción fina de los áridos reciclados de residuos de construcción y demolición (RCD), contribuyendo al desarrollo de una construcción sostenible y dar un valor añadido a este tipo de materiales.

El objetivo general está desarrollado en los siguientes objetivos específicos:

1. Caracterizar la fracción fina de los áridos reciclados de las principales tipologías de RCD (árido reciclado de hormigón y árido reciclado mixto).
2. Estudiar el efecto que la incorporación de la fracción fina de áridos reciclados de RCD tiene sobre las prestaciones del mortero de albañilería en estado fresco y endurecido.
3. Determinar la presencia de componentes tóxicos en los materiales reciclados, tanto en su forma no ligada como en los morteros endurecidos.

2.2. Estructura de la presente tesis doctoral

Esta tesis doctoral es presentada en la modalidad de compendio de publicaciones. La organización está estructurada en seis capítulos. Los capítulos 3, 4 y 5 incluyen los tres artículos publicados en revistas internacionales indexadas (requisito en la modalidad de la presente tesis).Los artículos de los capítulos 3 y 4 están publicados en revistas pertenecientes al primer cuartil y el artículo del capítulo 5 pertenece a una revista del segundo cuartil del Journal Citation Reports.

Después de la introducción (capítulo 1) y los objetivos buscados en esta tesis (capítulo 2), los capítulos siguientes son:

El capítulo 3 corresponde a la publicación "Properties of masonry mortars manufactured with fine recycled concrete aggregates". Ledesma, E. F., Jiménez, J. R., Fernández, J. M., Galvín, A. P., Agrela, F., & Barbudo, A. (2014). *Construction and Building Materials*, *71*, 289-298. Impact Factor: 2.296 (Q1). En este trabajo se caracteriza la fracción fina de un árido reciclado de hormigón (objetivo 1).Con una relación volumétrica 1:7 (cemento: árido), y usando un cemento puzolánico CEM-IV/A (V) 32,5N con un 29% de cenizas volantes, se evalúa la sustitución de RCA por arena natural en las siguientes relaciones: 0%, 5%, 10%, 20% y 40%. Con los datos obtenidos de las propiedades del mortero fresco y mortero endurecido, se lleva a cabo un estudio estadístico para determinar si produce un efecto significativo la tasa de sustitución. (objetivo 2)

El capítulo 4 corresponde a la publicación "Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production–Part-I: ceramic masonry waste". Ledesma, E. F., Jiménez, J. R., Ayuso, J., Fernández, J. M., & de Brito, J. (2015).*Journal of Cleaner Production*, *87*, 692-706. Impact Factor: 3.844 (Q1). En este estudio se caracteriza la fracción fina de un árido reciclado mixto y se fabrica un mortero más rico en cemento, con el fin de alcanzar mayores resistencias (M-10), utilizando el cemento más común usado en España CEM II/ BL 32,5N con una relación volumétrica 1:5 (cemento: árido), (objetivos 1 y 2). Además correspondiendo al objetivo 3 es evaluada medioambientalmente la composición del árido reciclado antes y después de ser ligado con cemento, mediante el test de lixiviación. Los niveles de sustitución del árido reciclado fueron 0%, 25%, 50%, 75% y 100%.

El capítulo 5 corresponde a la publicación "A proposal for the maximum use of recycled concrete sand in masonry mortar design". Fernández-Ledesma, E., Jiménez, J. R., Ayuso, J., Corinaldesi, V., & Iglesias-Godino, F. J. (2016). *Materiales de Construcción*, *66*(321), e075.Impact Factor: 0.961 (Q2). Con objeto de completar el estudio presentado en el capítulo 3, se estudia la fabricación de morteros con la fracción fina de árido reciclado de hormigón hasta tasas de sustitución del 100%, con CEM II/ BL 32,5N y relación volumétrica 1:5 (cemento: árido), con el fin de comparar los resultados obtenidos en el capítulo 4 con árido reciclado mixto.

Para finalizar, se presentan las principales conclusiones obtenidas en el conjunto de toda la investigación. Asimismo, se proponen unas futuras líneas de investigación de aquellos aspectos susceptibles de mejora para poder alcanzar una construcción sostenible cada vez más eficaz.

3. Properties of masonry mortars manufactured with fine recycled concrete aggregates

This chapter has been published entirely in the journal" Construction and Building Materials": **E.F. Ledesma [a], J.R. Jiménez [a,*], J.M. Fernández [b], A.P. Galvín [a], F. Agrela [a], A. Barbudo [a]. 2014.**

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Abstract

This research evaluates the short- and long-term properties of masonry mortar manufactured with different replacement ratios of natural sand by fine recycled concrete aggregates. The recycled materials were collected from a recycling plant and after passage through a 4 mm sieve, were directly used to make the mixtures, maintaining their original particle size distribution. A pozzolanic CEM-IV/A (V) 32.5 N, with 29% fly ash in its compositions, was used at a 1:7 volumetric cement-to-aggregate ratio. Five mortars with different replacement ratios by volume were tested: 0%, 5%, 10%, 20% and 40%. The data were analysed using one-way analysis of variance to determine whether the "replacement ratio" had a statistically significant effect on the different fresh and hardened properties. DRX and electron microscope techniques were used to examine the morphologies and evolution of the main mineral phases over time during a curing period of 180 days. The results proved that a replacement ratio of up to 40% is a viable alternative for producing environmentally friendly masonry mortar.

Keywords: Construction and demolition waste; Fine recycled concrete aggregate; Masonry mortar; Concrete waste; Sustainable construction; Recycled aggregates

3.1. Introduction

Construction and demolition waste (CDW) is one of the largest types of waste generated in developed countries. Many studies have been carried out over the last decade to avoid landfilling and promote recycling this waste. In Europe, the recent Waste Framework Directive requires a minimum recycling rate of 70% by 2020 for CDW (Directive 2008/98/EC, 2011). These wastes are mostly composed of concrete and masonry wastes, which have a high potential for recycling (European Comission, 2011). Two types of recycled aggregates (RAs) can be obtained from such CDW: recycled concrete aggregate (RCA) and mixed recycled aggregate (MRA).

Recent studies have demonstrated that RAs are an alternative to natural aggregates (NAs) in road construction, which is the most common use for these materials (Poon & Chan, 2006; Vegas et al., 2008; Xuan et al., 2010; Vegas et al., 2011; Jiménez et al., 2011; Barbudo el al., 2012; Jiménez et al., 2012-a; Jiménez et al., 2012-b; Agrela et al., 2012), although specific technical recommendations and specific construction techniques adapted to their physico-mechanical and chemical properties must be developed (Jiménez, 2013).

A higher added value can be achieved with selected RA through the manufacture of structural or non-structural concrete and mortar. The physico-mechanical and chemical properties of coarse RCA and the feasibility of its use in the manufacture of concrete have been widely studied over the last decade (Sánchez de Juan & Alaejos, 2009; Martín- Morales et al., 2010; Gokce et al., 2011), and the results have indicated that coarse natural aggregate (NA) can be replaced with coarse RCA (Etxeberría et al., 2007; Gomes & de Brito, 2009; Corinaldesi, 2010; Kou et al., 2012; Manzi et al., 2013) . However, the replacement of natural sand by fine RCA reduces the new concrete's compressive strength, increases its shrinkage and affects its durability (increased porosity and permeability of concrete) (Evangelista & de Brito, 2007; Kou & Poon, 2009). For this reason, most standards do not consider the replacement of natural sand by fine RA in the manufacturing of structural concrete (Instrucción de Hormigón Estructural EHE-08, 2008).

However, the manufacture of low-strength masonry mortar may constitute an alternative means of recycling the fine fraction of RCA, although scientific and technical studies on the use of RA in the manufacture of mortar are scarce. For this reason the University of Cordoba is conducting extensive research to determine the technical feasibility of replacing natural sand with different types of fine RA in the manufacturing of masonry mortars. A first study on the use of fine ceramic aggregate from partition rubble has been published previously (Jiménez et al., 2013). The aim of this paper is to analyse the effect of replacing natural sand with fine RCA on masonry mortars properties.

3.2. State of the art

RCAs are obtained from concrete waste properly processed in a recycling plant. According to the authors' previous work, the concrete particle and unbound aggregate content, determined in accordance with the European Standard UNE-EN 933-11:2009, should be above 90% for the material to be considered RCA (Agrela et al., 2011).

From a purely mechanical point of view, the main characteristics of RCA that affect the properties of fresh and hardened mortar and concrete is its decreased resistance to fragmentation, lower density and higher water absorption in comparison to natural sand. In relation to its chemical characterization, RCA has a greater amount of total sulphur compounds (Vegas et al., 2008).

The most relevant studies on which this work was based were developed in Southern European countries, such as Italy, Portugal and Spain. Only work that used fine RCA in masonry mortars are described in detail below; studies using ultrafine particles (< 0.150 mm) (Braga et al., 2012) or fine ceramic aggregates are not detailed in this section (Silva et al., 2009; Silva et al., 2010; Corinaldesi, 2012).

In Italy, Corinaldesi and Moriconi (2009) replaced 100% of natural sand with three different types of RA with a maximum grain size equal to 5 mm. The first RA was obtained from precast concrete waste, the second from red bricks and the third from a recycling plant processing material composed mainly of concrete (75%) and masonry (25%). The cement-to-fine aggregate ratio was 1:3 (by weight), and CEM II/B-L 32.5 R was used. The experimental results demonstrated that mortars containing RA showed lower mechanical strength with respect to the reference mortar. Nevertheless, the bond strength at the interface between the mortar and the brick was found to be greater for mortars prepared with RA, due to the high quality of the interfacial zone (Corinaldesi et al., 2002). These authors also demonstrated that masonry assemblages generated using recycled mortar showed an excellent mechanical behaviour (Corinaldesi, 2009).

In Portugal, Neno et al. (2013) replaced river sand with fine RCA. Four types of mortar were made with different replacement levels (0%, 20%, 50% and 100%). All mixtures were prepared with volumetric proportions of a cement-to-aggregate ratio of 1:4, and cement CEM II/B-L Class 32.5 R was used. The recycled aggregates were previously sieved in the laboratory to obtain identical particle size distribution curves in the 0.149/4 mm fraction, although the particles below 0.149 mm showed a very different particle size distribution. The fine content (< 0.063 mm) was 16 times higher in fine RCA than in river sand.

In Spain, Vegas et al. (2009), using a cement content equal to 9% of the total material by dry weight, made seven types of mortar with various replacement levels (0%, 10%, 20%, 25%, 50%, 75% and 100%) of natural sand by fine RCA sieved to under 2 mm and concluded that up to 25% natural sand could be replaced by recycled concrete aggregate by weight without decreasing mechanical strength, workability and shrinkage in masonry mortar. CEM II /B-M (V-S-LL) 42.5 R was used. Dapena et al. (2011), using a ratio of 1:3 (cement to aggregate) by weight, tested six replacement levels (0%, 5%, 10%, 15%, 20% and 50%) of two types of natural sand (siliceous and limestone) with fine RA containing 81% concrete and various impurities such as asphalt, brick, gypsum and quartz. The cement used was CEM I 42.5 N/SR. The results obtained with the mortars indicate that the use of up to 20% recycled sand caused a drop in the compressive and flexural strength (0.7 times the percentage of recycled sand used).

In a previous work, Jiménez et al. (2013) replaced natural sand with fine recycled aggregate from ceramic partition wall rubble composed mainly of ceramic (54%) and masonry mortar (40%). Five mortars with various replacement levels were tested (0%, 5%, 10%, 20% and 40%), and CEM-IV/A (V) 32.5 N was used with a 1:7 volumetric cement-to-aggregates ratio. The results indicated that replacement ratios of up to 40% by volume did not significantly affect the properties of fresh and hardened mortar, with the exception of density and workability.

3.3. Materials and experimental procedure

3.3.1. Material characterisation

Siliceous river sand (NA) with a maximum particle size of 4 mm was used to manufacture the reference mortar. The recycled material was collected from a recycling plant located in northern of Cordoba (Spain), where concrete blocks waste from different sources (pavement and structures) were crushed in an impact crusher and subsequently sieved with a vibration screen to produce three different fractions: 0/8 mm, 8/40 mm and > 40 mm. The reinforced steel and other impurities were removed beforehand.

A sample of the coarse fraction (8/40 mm) was collected to determine the composition of the RCA according to UNE-EN 933-11:2009. The RCA can be considered to be very pure because more than 95% of its constituents were aggregates with and without mortar adhered from concrete waste (Table 3.1). The few impurities such as asphalt, ceramic and masonry mortar are typical in a commercial recycling plant.

Table 3.1. Composition of RCA (coarse fraction) based on UNE-EN 933-11.

Class	Type	Weight (%) RCA
R_A	Asphalt	1.70
R_B	Ceramics	0.40
R_{C1}	Concrete [(a)]	60.7
R_{C2}	Masonry mortar	2.20
R_L	Lightweight particles	0.00
R_U	Unbound aggregates [(b)]	35.0
X_1	Natural soil	0.00
X_2	Others [(c)]	0.00
X_G	Gypsum	0.00
	Total	100

[(a)] Natural aggregates with cement mortar attached.

[(b)] Natural aggregates without cement mortar attached.

[(c)] Wood, glass, plastic, metals

The fine RCA used in this study was obtained in the laboratory by sieving the collected fine fraction (0/8 mm) through a 4 mm sieve. With this treatment, both sands were of the same maximum particle size, although not identical particle size distribution (PSD). Fig. 3.1 shows the PSD of the NA and FRCA, determined according to the European Standard UNE-EN 933-1:2006. As observed, the NA were more in accordance with the limits proposed by ASTM C-144 for masonry mortar.

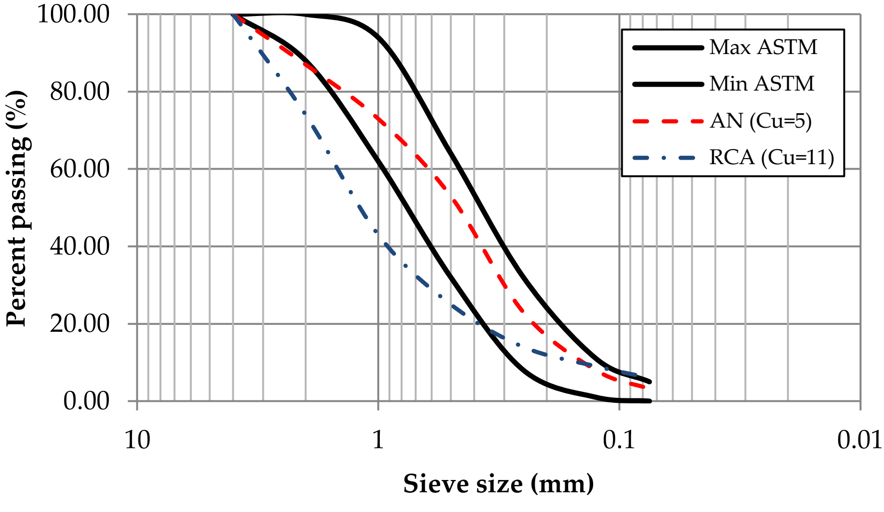

Figure 3.1. Particle size distribution and range determinated by ASTM C 144 (average of three samples).

Table 3.2 shows the main physico-mechanical and chemical properties of both aggregates and the standards used to determine them. The fine RCA compared to NA had twice the amount of fines particles (< 0.063 mm), similar sand equivalent, lower dry density, much higher water absorption, greater friability coefficient and loss of ignition. The soluble salts and total sulphur content (%SO_3) did not exceed the limit of 1% set by Standard UNE-EN 13139:2002 for mortar manufacturing. Humic compounds or fulvic acid were not detected, so the setting time of the cement would not be altered. No alkali-silica or alkali-silicate reactivity was detected (Fig. 3.2). These results are in agreement with the literature (Vegas et al., 2011; Jiménez et al., 2011; Barbudo el al., 2012; Jiménez et al., 2012-a; Jiménez et al., 2012-b;

Sánchez de Juan & Alaejos, 2009; Martín-Morales et al., 2010; Jiménez et al., 2013).

Table 3.2. Characterisation of the NA and RCA.

Characteristic	Standard	AN	RCA	Limit set by UNE-EN 13139
Fine content (%) [(a)]	UNE-EN 933-1	3.2	6.1	≤ 8
Sand equivalent (%)	UNE-EN 933-8	83	88	No limit
Dry sample density [(b)] ϱ_{rd} (g/cm^3)	UNE-EN 1097-6	2.63	2.2	No limit-Valor declarado
Water absorption [(b)] (%)	UNE-EN 1097-6	0.79	8.26	No limit-Valor declarado
Friability coefficient (%)	UNE 83115	15	23	No limit
Acid soluble sulphates (% SO_3)	UNE-EN 1744-1	< 0.01	0.4	≤ 0.8
Total sulphurs (% SO_3)	UNE-EN 1744-1	< 0.01	0.4	≤ 1
Humic content (%)	UNE-EN 1744-1	ND[(c)]	ND[(c)]	No limit
Fulvic acid (%)	UNE-EN 1744-1	ND[(c)]	ND[(c)]	No limit
Water soluble chlorides (% Cl)	UNE-EN 1744-1	< 0.01	0.07	≤0.15
Loss of ignition (%)	UNE-EN 1744-1	6.56	11.12	No limit
Soluble salts 1:2 (%)	Gravimetric	0.128	0.545	≤1

[(a)] Finer than 0.063 mm

[(b)] Fraction 0.063/4 mm

[(c)] Not detected

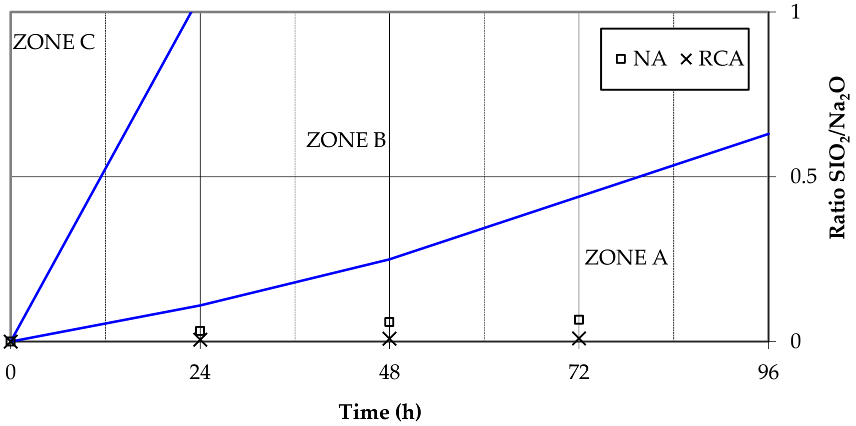

Figure 3.2. Alkali-silica and alkali-silicate reactivity according to UNE 146507-1:99 EX.

Zone A: non-reactive aggregates; Zone B: potentially reactive aggregates; Zone C: potentially reactive aggregates with harmful effects.

With the aim of comparing the results of this study with those obtained by Jiménez et al. in a previous work (Jiménez et al., 2013), the same cement CEM IV/A (V) 32.5 N and plasticiser admixture (RHEOMIX 550) were used. The characteristics of the cement and admixture used were described in detail in this previous article.

X-ray diffraction (DRX) technique was used to identify the main mineral phases. A Siemens D-5000 instrument with CuKα radiation was used. Fig. 3.3 shows the PXRD patterns of the aggregates and cement. The main crystalline phase identified was quartz for the NA and the fine RCA. The presence of illite, sanidine, albite and calcite was residual, and in the NA, dolomite was also detected. Both aggregates exhibited similar X-ray diffraction patterns. In the case of recycled concrete aggregates, the mineral phases depend on the aggregates used in the manufacture of the source concrete. In our case, the NA used in this work and the original aggregates used in the manufacture of the source concrete came from the same geological region, which explains the similarities between both fine aggregates of this study (Rodrigues et al., 2013). The EDAX data (Table 3.3) agree with the mineralogical characterizations; the predominant elements were oxygen (O) and silicon (Si) from the quartz and less calcium (Ca) from the calcite. The low amount of sulphur (S) was not detected with this qualitative technique. From a mineralogical point of view, both aggregates can be classified as siliceous materials and their similar characteristics suggest that both aggregates have a similar behaviour.

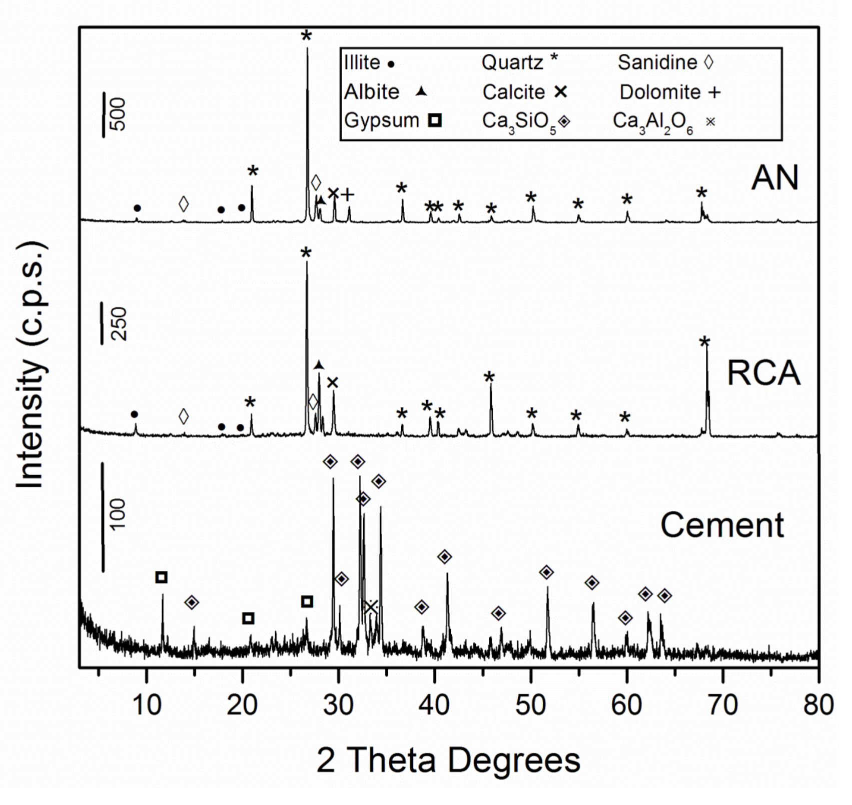

Figure 3.3. PXRD patterns for the NA, RCA and cement.

Table 3.3. EDAX results for the NA, RCA and cement.

Element	NA*	RCA*
C	12.1	19.2
O	63.7	60.5
Na	0.5	0.4
Mg	0.5	0.4
Al	2	2.2
Si	16.8	9.5
S	0	0
K	0.7	0.5
Ca	2.9	6.4
Fe	0.8	0.7
Ba	0	0.2
Total	100	100

*Atomic %

3.3.2. Mortar mixture proportions

To compare the results obtained with those of a previous study by Jiménez el al. (2013), in which ceramic recycled sand was used, the same reference mortar with a cement-to-aggregate volume ratio of 1:7 was used. The reference mortar was classified as M-5 according to UNE-EN 998-2:2012.

Table 3.4 shows the nomenclature of the five mortars tested (A, F, G, H and I) and the mix proportions in dry weight used to make 1600 cm^3 of mortar, calculated according to the following expression:

$$Dry weight of cement = \frac{V \cdot 1 \cdot \text{ρrdCEM}}{8}$$

$$Dry weight of RCA = \frac{V \cdot X \cdot 7 \cdot \text{ρrdRCA}}{8}$$

$$Dry weight of NA = \frac{V \cdot (1 - X) \cdot 7 \cdot \text{ρrdNA}}{8}$$

$$X = \frac{Percentage of NA replaced with RCA}{100}$$

where X was the replacement ratio by volume. The dry density of the cement was 2.83 g/cm^3 (Jiménez et al., 2013).

Table 3.4. Mortar mixture proportions.

tar type	AN/RCA (Volume)	Mix proportions - dry mass							
		NA (g)	RCA (g)	CEM (g)	Water (g)	Admixture (cm^3)	Consistency (mm)	w/c	)ef
)0/0	100/0	3682.00	0.00	566	531	0.8	177	0.94	
/05	95/05	3497.90	154.00	566	542	0.8	170	0.96	
)/10	90/10	3313.80	308.00	566	552	0.8	176	0.98	
)/20	80/20	2945.60	616.00	566	579	0.8	174	1.02	
'40	60/40	2209.20	1232.00	566	607	0.8	172	1.07	

Because of the RCA's lower density, the amount of fine RCA by dry weight was lower than that of NA. A volume of 0.8 cm^3 of admixture was added to each mixture, and the water content was set experimentally to achieve a consistency of 175 mm ± 10 mm according to UNE-EN 1015-3:1999.

As shown in Table 3.4, the amount of water required for the mixtures increased with an increasing percentage of recycled aggregate. This result concurs with those observed by most authors (Jiménez et al., 2013; Neno et al., 2013). The total water/cement ratio ranged between 0.94 for the reference mortar (A-100/0) and 1.07 for the mortar with the highest replacement ratio (I-60/40). To calculate the effective water/cement ratio, the water absorption of the fine aggregates needed to be taken into account. Pereira et al. (2012) calculated that, after 10 min and 2.5 hours, the fine-RCA had absorbed 50% and 90%, respectively of its potential capacity, so during mixing and subsequent hardening of mortars, the aggregates can absorb 90% of their capacity. With these considerations, the estimated effective water/cement ratio was similar in all mortars, ranging between 0.89% in A-100/0 and 0.88% in I-60/40. Considering the total water absorption capacity, the effective water/cement ratio decreased from 0.89% in mortar A-100/0 to 0.86% in mortar I-60/40. The reference mix had the highest consistency mean values, which means that this mortar (A-100/0) has more free water. In contrast, the lowest consistency was obtained in mortar with 5% of replacement ratio (F-95/05). The mixing procedure was described by Jiménez et al. (2013).

3.3.3. Tests

The consistency of the fresh mortar fulfilling the value of 175 ± 10 mm was verified in all mixes in accordance with the procedure described in UNE-EN 1015-3:1999. The mixtures that failed to meet the standards were rejected.

Three properties of the fresh mortar were characterised: density, air content and workability. The hardened mortar was characterised according to six properties: dry bulk density, compressive and flexural strength, dimensional instability (shrinkage), adhesive strength, water absorption due to capillary action and water vapour permeability. Four different mixes of each mortar type were made. Table 3.5 shows the testing standard used and the climatic conditions of the three climatic chambers used in these tests. Previous work by Jiménez et al. (2013) describes the test methods.

Table 3.5. Mortar characterisation test.

Properties of fresh mortar	Standard	Specimens and dimensions	Climatic chamber	Curing time
Bulk density of the fresh mortar	UNE-EN 1015-6	4	--	--
Entrained air	UNE-EN 1015-7	4	--	--
Workability	UNE-EN 1015-9	4	--	--
Properties of hardened mortar	**Standard**	**Specimens and dimensions**	**Climatic chamber**	**Curing time**
Dry bulk density	UNE-EN 1015-10	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Flexural strength	UNE-EN 1015-11	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Compressive strength	UNE-EN 1015-11	8 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Shrinkage	UNE 83831	6 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	Up to 365 days
Adhesive strength	UNE-EN 1015-12	4 Circular – 50 mm diameter, 10 mm-thick	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Water absorption due to capillary	UNE-EN 1015-18	12 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Water vapour permeability	UNE-EN 1015-19	4 Circular – 160 mm (0,02 m^2 surface) diameter, 15 mm-thick	Chamber-1 (2 days) Chamber-3 (rest of curing time)	28 days

3.3.4. Statistical analysis

To determine whether the replacement ratio had a statistically significant effect on the fresh and hardened mortar properties, a one-way analysis of variance (ANOVA) was conducted. The F-test in the ANOVA analysis determined whether any significant differences between the properties' mean values existed. If the p-value of the F-test was less than 0.05, the factor replacement ratio had a significant effect on the analysed property at the 95% confidence level; conversely, if the p-value was greater than 0.05, the replacement ratio did not show a significant effect. A multiple range test was also conducted to determine which means were significantly different from the others.

3.4. Results and discussion

3.4.1. Bulk density of fresh mortar

Because the p-value of the F-test was lower than 0.05 (p-value = 0.0439), the replacement ratio showed a statistically significant effect on the mean bulk density fresh values at the 95% confidence level. The multiple range tests indicated the existence of two homogeneous groups with significant differences in the mean values of the bulk density of fresh mortar: (i) A-100/0 and F-95/05 and (ii) F-95/05, G-90/10, H-80/20 and I-60/40. Fig. 3.4 plots the range of the means for each mortar tested. The bars that do not overlap indicate a significant difference between the two means, whereas bars that overlap indicate no significant difference between the means.

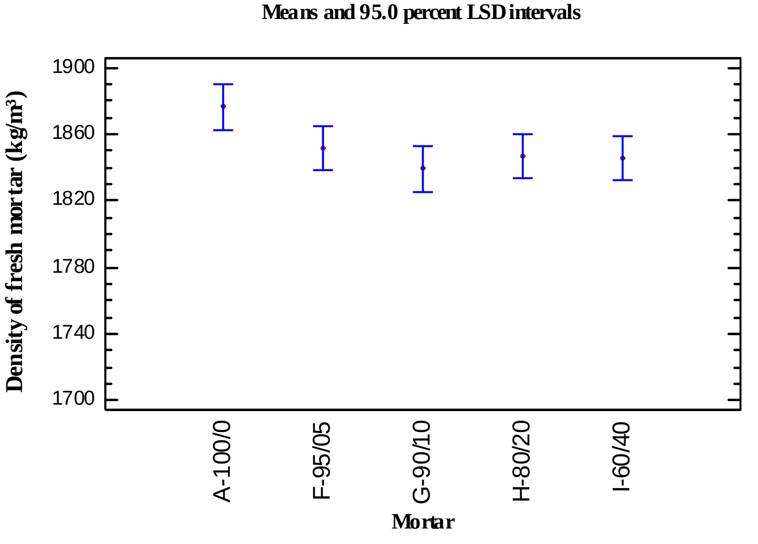

Figure 3.4. LSD range of the mean bulk density of the fresh mortar.

The mean bulk density of the fresh mortar decreased slightly using fine RCA because the dry density of the fine RCA was 16% lower than that of the NA. These results were consistent with those found in the literature. Neno et al. (2013) observed a linear decrease as the fine RCA content increased and obtained higher decreases than those reported in this work, as the density of the fine RCA used possessed a density 25% lower than that of natural sand. In the work by Jiménez et al. (2013), the fine ceramic aggregates generated a higher decrease in density, a result which is also attributable to the fact that the dry density of the ceramic aggregates was 19% lower than that of NA.

3.4.2. Entrained air

Because the p-value of the F-test was slightly greater than 0.05 (p-value = 0.5175), the replacement ratio showed no statistically significant effect on the mean entrained air values at the 95% confidence level. All bars overlap in the range of means (Fig. 3.5), which ranged from 13.7 and 14.4. The presence of entrained air improves mortars' freeze-thaw resistance but decreases their compressive and flexural strength.

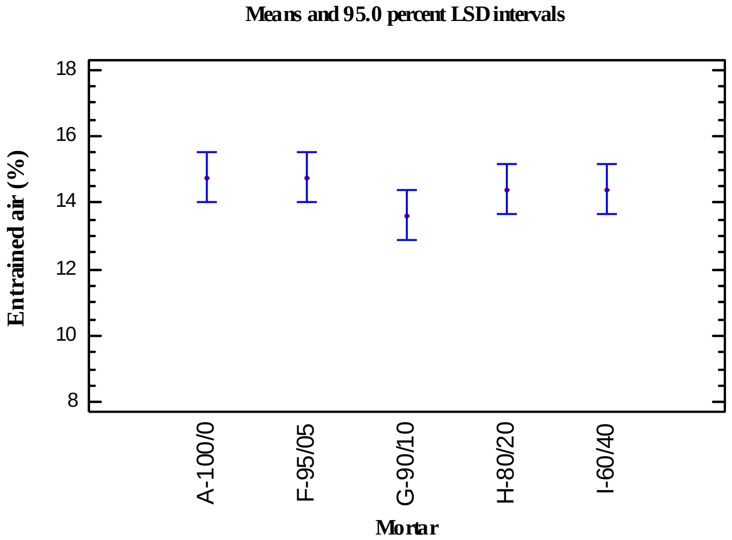

Figure 3.5. LSD range of the mean entrained air.

Most previous studies do not provide entrained air values, with the exception of Vegas et al. (2009), who found no significant differences in the entrained air values of mortars with a 25% replacement of natural sand by fine RCA. Similar values and conclusions were obtained by Jiménez et al. (2013) with ceramic aggregates.

3.4.3. Workable life

The workable life of the fresh mortar is the time in minutes during which the mortar shows a resistance of penetration of 0.5 N/mm^2 using a standard rod.

Because the p-value of the F-test was p-value = 0.0000, the replacement ratio had a statistically significant effect on the mean workable life at the 95% confidence level. As seen in Fig. 3.6, four homogeneous groups whose bars do not overlap were identified: (i) A-100/0, (ii) F-95/05 and G-90/10, (iii) G-90/10 and H-80/20 and (iv) I-60/40. A clear decrease in workable time was observed when the replacement ratios were increased.

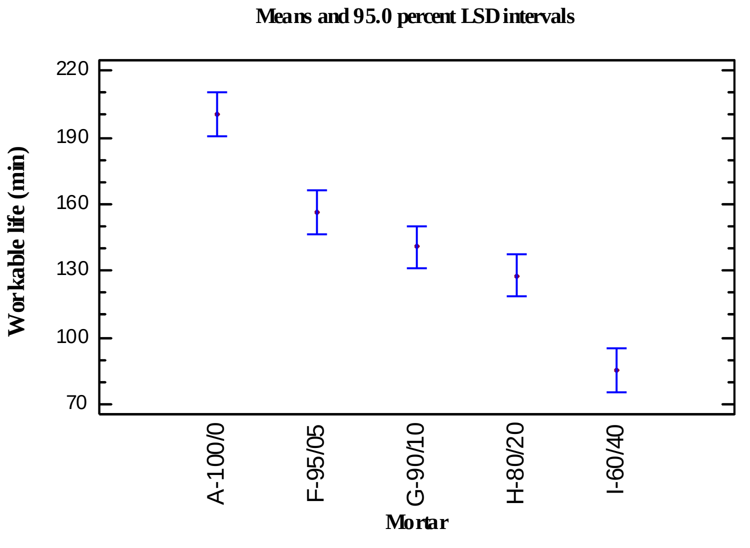

Figure 3.6. LSD range of the mean workable life

These results suggest a negative feature of the use of fine RCA in masonry mortars, as it reduces the time during which the fresh mortar retains adequate workability to be handled by masons. This property has seldom been evaluated by researchers, except by Jiménez et al. (2013), who obtained similar results with the use of recycled ceramic aggregates. To improve this property, further studies with the use of retarding admixtures would be necessary.

3.4.4. Dry bulk density of hardened mortar at 28 days

Because the p-value of the F-test was p-value = 0.0000, the replacement ratio had a statistically significant effect on the dry bulk density of the hardened mortar at the 95% confidence level. Three homogeneous groups with non-overlapping bars were identified (Fig. 3.7): (i) A-100/0, B-95/05 and C-90/10, ii) D-80/20 and iii) E-60/40. The mean dry bulk density was slightly increased with replacement ratios of up to 10% and decreased with replacement ratios of up to 20%. This result was attributed to the fact that higher fine content (<0.063 mm) in fine RCA allows for filling voids at replacement ratios of up to 10%, while for higher replacement ratios, the lower dry density of the fine RCA decreases the dry density of hardened mortar.

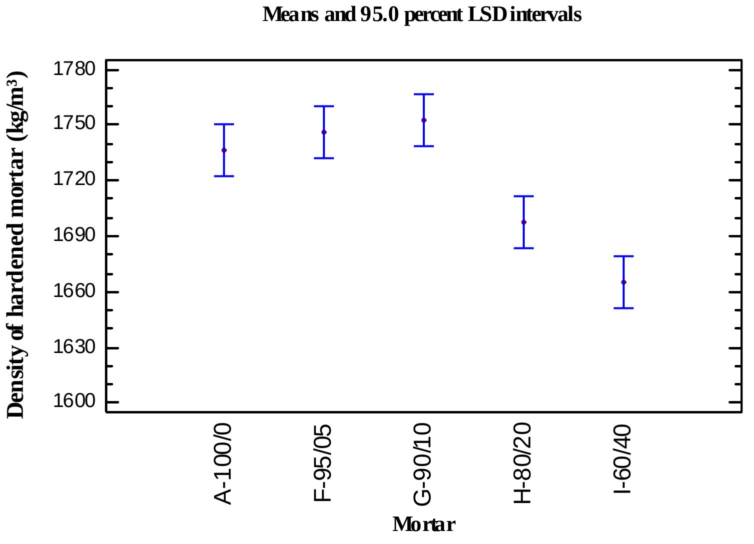

Figure 3.7. LSD range of the mean dry density of the hardened mortar.

These results agree with those of Neno et al. (2013), who demonstrated small increases in the dry bulk density of mortars made with a 20% replacement ratio and a downward linear trend with higher replacement ratios. Dapena et al. (2011) found no significant differences in replacement ratios below 20% and significant decreases with replacement ratios of 50% RCA. Vegas et al. (2009) also found a difference at a replacement ratio of 25%. In the work by Jiménez et al. (2013), no differences were found with the replacement of NA by ceramic aggregates at ratios up to 5%, and linear declines in dry bulk density were observed with replacement ratios above 5%.

3.4.5. Compressive and flexural strength of hardened mortar

Fig. 3.8 shows the evolution over time of the compressive and flexural strength mean values. All mortars tested exhibited a similar trend, with considerably increases in compressive and flexural strength until 28 days of curing and then slightly increases after that period.

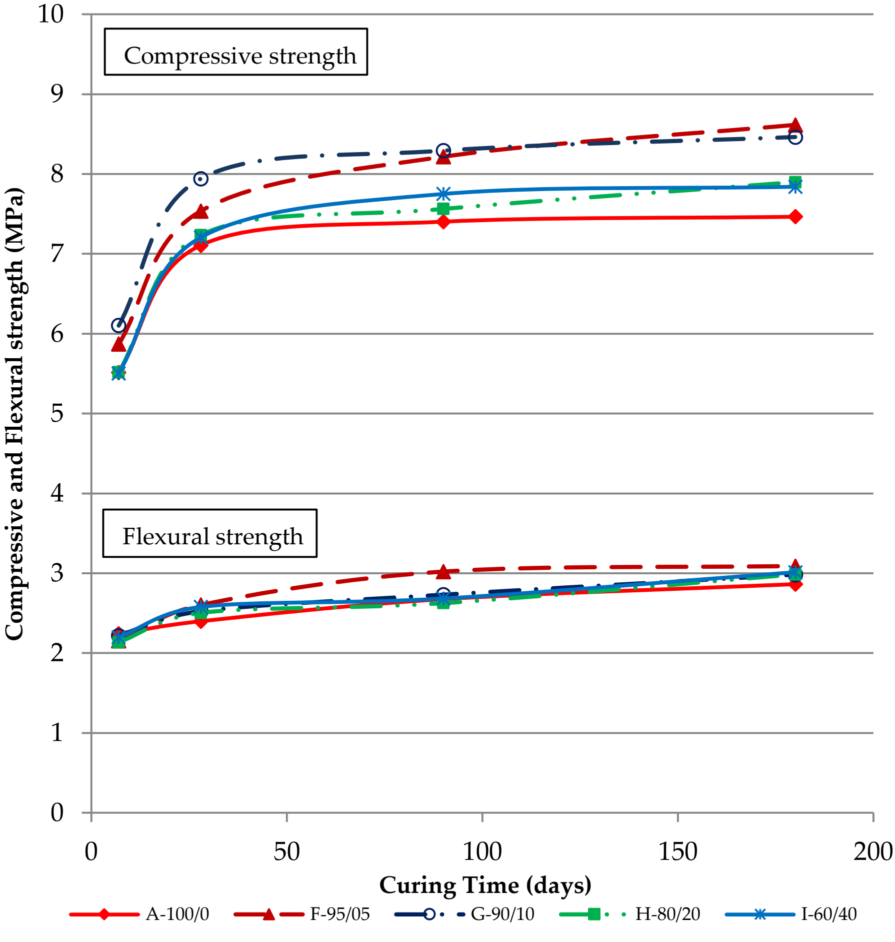

Figure 3.8. Compressive and flexural strength of the hardened mortar over time.

The reference mortar (A-100/0) showed lower mean values for compressive and flexural strength, while replacement ratios of up to 10% resulted in higher mean values for all curing times. This slight increase in the mean values of mechanical strength could be explained by the greater amount of fine materials in the mortars made with fine RCA, which could fill voids and may be due to the remaining hydraulic potential of the cement in the concrete waste (Arm, 2001; Shui et al., 2008). Similar results were obtained by Jiménez et al. (2013) when NA was replaced by fine recycled aggregate from ceramic waste. Braga et al. (2012) demonstrated that mortar with incorporation of up to 15% of very fine aggregates from RCA showed improved mechanical properties.

To determine whether the replacement ratio had a statistically significant effect on mortar mechanical strength properties, a one-way ANOVA was conducted for different periods of curing: 7, 28, 90 and 180 days. Tables 3.6 and 3.7 show the p-values obtained for the F-test. All p-values were greater than 0.05, so the replacement ratio had no statistically significant effect on the compressive and flexural strengths over a period of 7 to 180 days at the 95% confidence level. Multiple range tests were also conducted to determine the homogeneous groups, for each curing time only one homogeneous group was identified by the column of Xs (Tables 3.6, 3.7).

Table 3.6. Multiple range test for compressive strength with different replacement ratios and curing times. Method: 95% LSD.

Mortar	Count	LS mean (MPa)	SD (MPa)	Homogeneous groups			
7 Days (p-value = 0.3104)							
A-100/0	4	5.5	0.3	X			
F-95/05	4	5.9	0.6	X			
G-90/10	4	6.1	0.5	X			
H-80/20	4	5.5	0.1	X			
I-60/40	4	5.5	0.7	X			
28 Days (p-value = 0.3783)							
A-100/0	4	7.1	0.3		X		
F-95/05	4	7.5	1		X		
G-90/10	4	7.9	0.4		X		
H-80/20	4	7.2	0.2		X		
I-60/40	4	7.2	0.7		X		
90 Days (p-value = 0.2021)							
A-100/0	4	7.4	0.5			X	
F-95/05	4	8.2	0.7			X	
G-90/10	4	8.3	0.8			X	
H-80/20	4	7.6	0.3			X	
I-60/40	4	7.7	0.5			X	
180 Days (p-value = 0.3085)							
A-100/0	4	7.5	0.5				X
F-95/05	4	8.6	1.1				X
G-90/10	4	8.5	0.7				X
H-80/20	4	7.9	0.6				X
I-60/40	4	7.8	1.0				X

Table 3.7. Multiple range test for flexural strength with different replacement ratios and curing times. Method: 95% LSD.

Mortar	Count	LS mean (MPa)	SD (MPa)	Homogeneous groups			
7 Days (p-value = 0.9881)							
A-100/0	4	2.2	0.2	X			
F-95/05	4	2.1	0.2	X			
G-90/10	4	2.2	0.1	X			
H-80/20	4	2.1	0.2	X			
I-60/40	4	2.2	0.6	X			
28 Days (p-value = 0.9172)							
A-100/0	4	2.4	0.4		X		
F-95/05	4	2.6	0.4		X		
G-90/10	4	2.5	0.2		X		
H-80/20	4	2.5	0.2		X		
I-60/40	4	2.6	0.3		X		
90 Days (p-value = 0.2926)							
A-100/0	4	2.7	0.1			X	
F-95/05	4	3.0	0.2			X	
G-90/10	4	2.7	0.2			X	
H-80/20	4	2.5	0.2			X	
I-60/40	4	2.7	0.3			X	
180 Days (p-value = 0.8140)							
A-100/0	4	2.9	0.1				X
F-95/05	4	3.1	0.4				X
G-90/10	4	3.0	0.2				X
H-80/20	4	3.0	0.0				X
I-60/40	4	3.0	0.3				X

These results concurred with SEM images and PXRD pattern of hardened mortar. All hardened mortars tested showed a similar surface morphology, and an example is shown in Fig. 3.9. No significant differences were found in the PXRD diagrams of hardened mortars. Fig. 3.10 shows the PRXD diagrams of mortars A-100/0, H-

80/20 and I-60/40 at 90 days. In addition to the aggregates' mineral phases identified previously, the presence of characteristic phases of hardened cements such as portlandite and $Ca_4Al_2O_6(SO_4)\ 14H_2O$ were detected. No ettringite was observed, which agree with the undetected Sulphur element from gypsum in the EDAX analysis. The results are consistent with the raw materials used, because the NA and the fine RCA have a similar composition (Fig. 3.3).

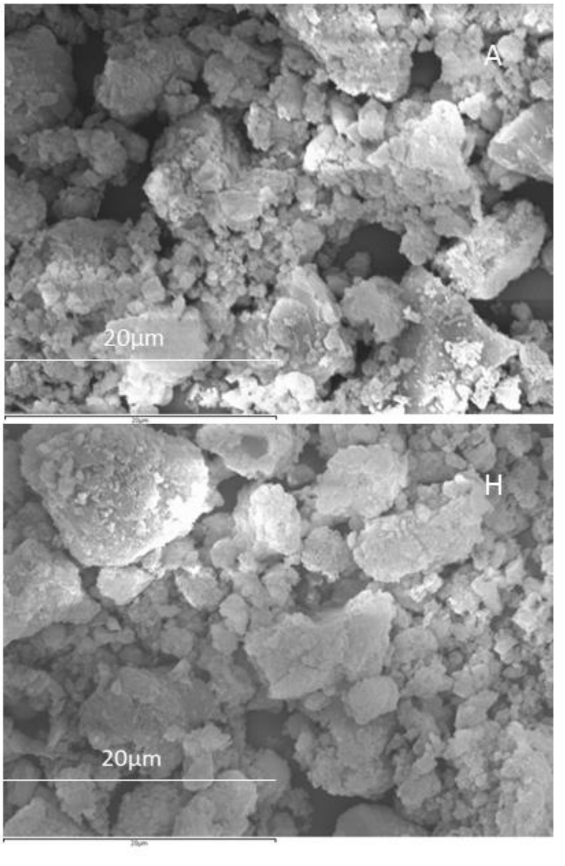

Figure 3.9. SEM micrographs of samples A-100/0 (top) and H-80/20 (bottom).

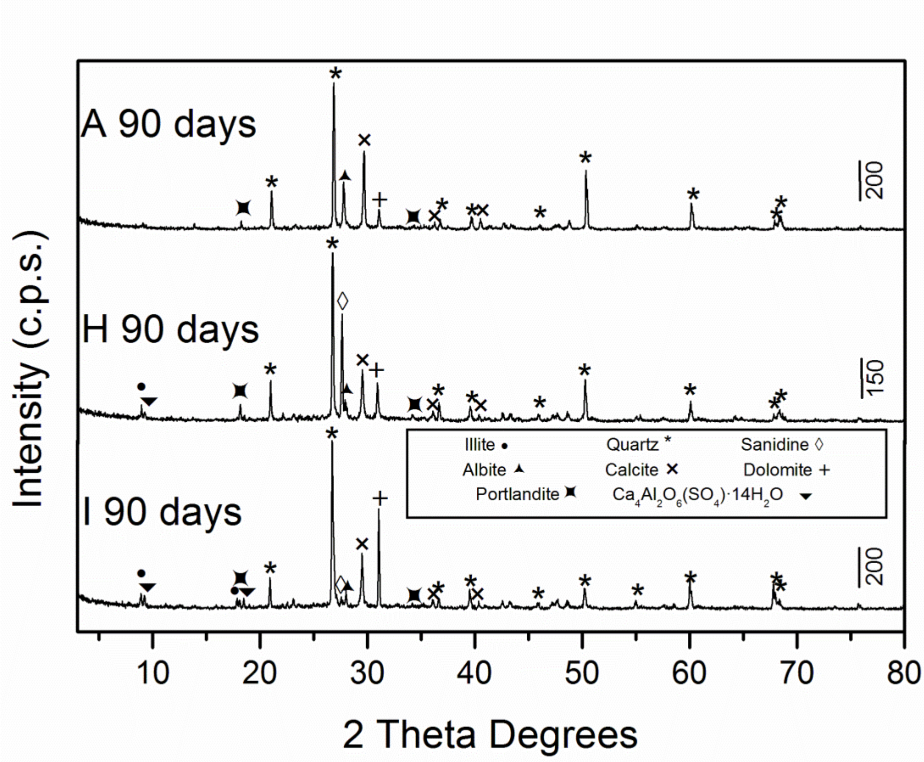

Figure 3.10. PXRD diagrams of mortars A-100/0, H-80/20 and I-60/40 after 90 days.

Neno et al. (2013) obtained higher compressive and flexural strengths in mortars made with 20%, 40% and 100% replacement ratios, in comparison to reference mortars; these results were explained by the higher specific surface of fine RCA, the amount of non-hydrated cement that completes its hydraulic reaction in contact with water, the greater cohesion between particles and the higher water retention in mortar containing RCA. These superior results obtained by Neno et al. (2013) in relation to those obtained in this work may be explained by three causes: 1) these authors produced the fine RCA from selected concrete block (class 30/37) crushed in the laboratory, while in this study concrete waste from different sources were collected and crushed in a recycling plant; 2) the amount of non-hydrated cement was probably higher in the recycled materials used by Neno et al. (2013), while in this work the old concrete waste used probably had little non-hydrated cement content and 3) the effective w/c ratio used by Neno et al. (2013) was lower in mortars made with fine RCA, while in this work the effective w/c ratios were similar in all mortars.

In contrast, Dapena et al. (2011) demonstrated that the compressive strength of mortars in which siliceous sand was replaced with fine RCA decreased between 0.5–0.7 times the percentage of the RCA, and Vegas et al. (2009) reported that mechanical strength decreased significantly when natural sand was replaced with fine RCA above 25%. These differences can be explained largely by the different proportion methods employed and, to a lesser extent, by the different cements used. This study, similar to that by Neno et al. (2013), replaced aggregates by volume, while the previously mentioned authors replaced the NA with RCA by weight. Due to the lower density of the RCA, replacing materials by weight produces a larger volume of lower quality mortar.

3.4.6. Dimensional instability (shrinkage)

The results show a similar trend in the linear shrinkage (mm/m) over time (Fig. 3.11). To determine whether the replacement ratio had a statistically significant effect on the shrinkage, a one-way ANOVA was conducted for samples allowed to cure for varying times: 28, 90, 180 and 360 days. All p-values were greater than 0.05, so the replacement ratio had no statistically significant effect on shrinkage at the 95% confidence level. From the multiple range tests, only one homogeneous group was identified by column of Xs for each curing time (Table 3.8).

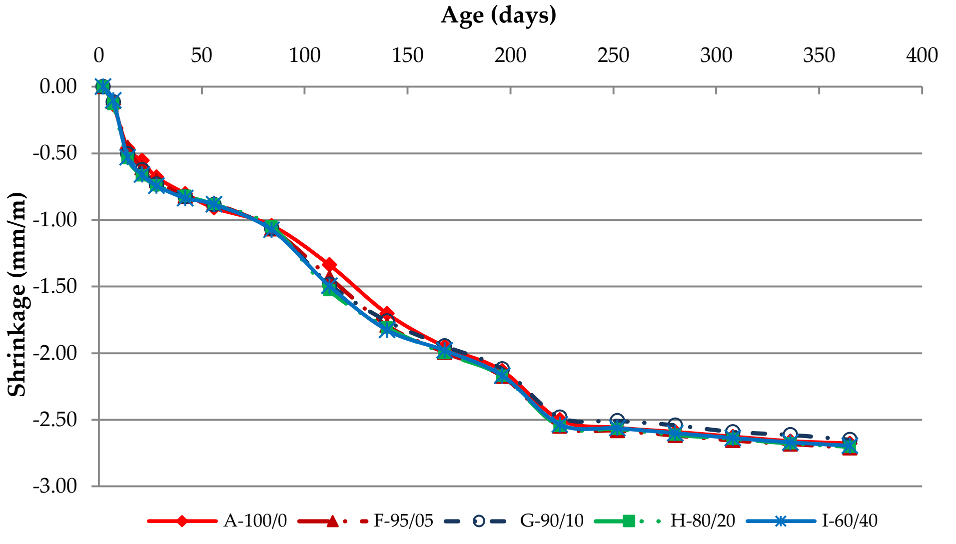

Figure 3.11. Shrinkage of the mortar as a function of age in days (HR = 65 % and T = 20ºC).

Table 3.8.Multiple range test for shrinkage with different replacement ratios and curing times. Method: 95% LSD.

Mortar	Count	LS mean (mm/m)	SD (mm/m)	Homogeneous groups			
28 Days (p-value = 0.7575)							
A-100/0	6	-0.68	0.05				X
F-95/05	6	-0.7	0.10				X
G-90/10	6	-0.73	0.15				X
H-80/20	6	-0.74	0.10				X
I-60/40	6	-0.74	0.07				X
90 Days (p-value = 0.9943)							
A-100/0	6	-1.04	0.07			X	
F-95/05	6	-1.07	0.16			X	
G-90/10	6	-1.06	0.20			X	
H-80/20	6	-1.05	0.13			X	
I-60/40	6	-1.07	0.11			X	
180 Days (p-value = 0.9922)							
A-100/0	6	-1.95	0.07		X		
F-95/05	6	-1.99	0.21		X		
G-90/10	6	-1.94	0.27		X		
H-80/20	6	-2	0.38		X		
I-60/40	6	-1.98	0.18		X		
365 Days (p-value = 0.9948)							
A-100/0	6	-2.68	0.07	X			
F-95/05	6	-2.71	0.20	X			
G-90/10	6	-2.65	0.33	X			
H-80/20	6	-2.7	0.39	X			
I-60/40	6	-2.69	0.19	X			

The results obtained in this work differ from those found in the literature; most of the other studies found that shrinkage increases in mortar and concrete with recycled aggregates from CDW (Miranda &

Selmo, 2006; Kou et al., 2012; Manzi et al., 2013). Vegas et al. (2009) reported that shrinkage increased significantly when natural sand was replaced with fine RCA above 25%, and Braga et al. (2012) observed greater shrinkage in mortar with the addition of 15% very fine concrete aggregate. Neno et al. (2013) also found higher shrinkage in mortar with replacement ratios of 20% in comparison to the reference mortar; this result may be associated with the higher cement and powdered paste content in mortar generated using RCA.

The similar shrinkage mean values obtained in this experimental study can be attributed to the following reasons: the type of cement CEM-IV with fly ash (29%) and low heat of hydration used. Most of the reviewed studies used CEM-I or CEM-II. Moreover all tested mixes had similar effective water/cement ratio (Table 3.4). The reference mortar (A-100/0), had the highest consistency, indicating the presence of more free water in this mix and consequently a greater shrinkage. Based on the study of Ferreira et al. (2011) the aggregates were not previously pre-saturated. RCA were used with their natural moisture (2.7%), with which better properties of hardened mortars can be obtained. And finally, the volumetric dosage method used to design the mixes. Zega and Di Maio (2011) also concluded that concrete with equal effective w/c ratio and fine aggregate volume has similar shrinkage. These authors used replacement ratios of NA by fine RCA up to 30%. Furthermore, similar results were obtained in a previous work in which NA was replaced by fine recycled aggregate from ceramic waste; the same admixture and cement were used (Jiménez et al., 2013).

3.4.7. Adhesive strength

Because the p-value of the F-test was p-value = 0.0118, the replacement ratio had a statistically significant effect on the adhesive strength of hardened mortar at the 95% confidence level. Fig. 3.12 does not show a clear trend for the five mortar types. Mortars made with

10% and 20% replacement ratios showed the highest values of adhesive strength, although the mean values of all mortars tested are within the same order of magnitude (0.38-0.58 MPa).

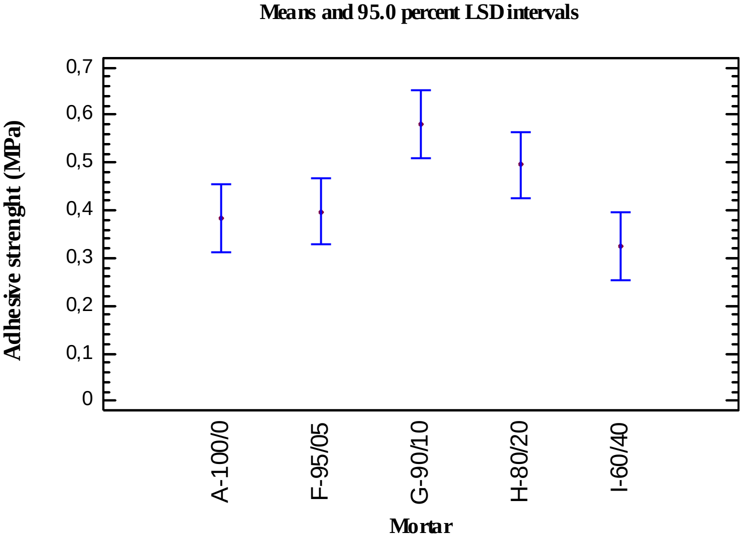

Figure 3.12. LSD range of the mean adhesive strength of the hardened mortar.

These results agree with those obtained by Neno et al. (2013); these authors reported that mortar made with a 20% replacement ratio of fine RCA showed similar adhesive strength in comparison with the reference mortar. Jiménez et al. (2013) also demonstrated that mortar made with a 10% replacement ratio of recycled ceramic aggregate showed the highest mean value, although there was no statistically significant difference between the mean values of the adhesive strength for the different replacement levels tested.

In contrast, Corinaldesi et al. (2002, 2009) found that RA mortars improved the mortar brick bond strength. Braga et al. (2012) also obtained significant improvement in mortar adherence capacity with the incorporation of 15% ultrafine concrete. Other authors did not include this parameter in their studies (Vegas et al., 2009; Dapena et al., 2011).

3.4.8. Water absorption due to capillary action of hardened mortar

Because the p-value of the F-test was lower than 0.05 (p-value = 0.0003), the replacement ratio had a statistically significant effect on water absorption due to capillary action of the hardened mortar at the 95% confidence level. Fig. 3.13 does not show a clear trend for the five mortar types. In accordance with a previous study (Jiménez et al., 2013), the lower mean values corresponded to replacement ratios of 5% and 10%, which may be related to the fine RCA containing more particles smaller than 0.063 mm and ability of those particles to fill voids between larger particles. When the replacement ratio was above 20%, the mean values were of the same order of magnitude as the reference mortar.

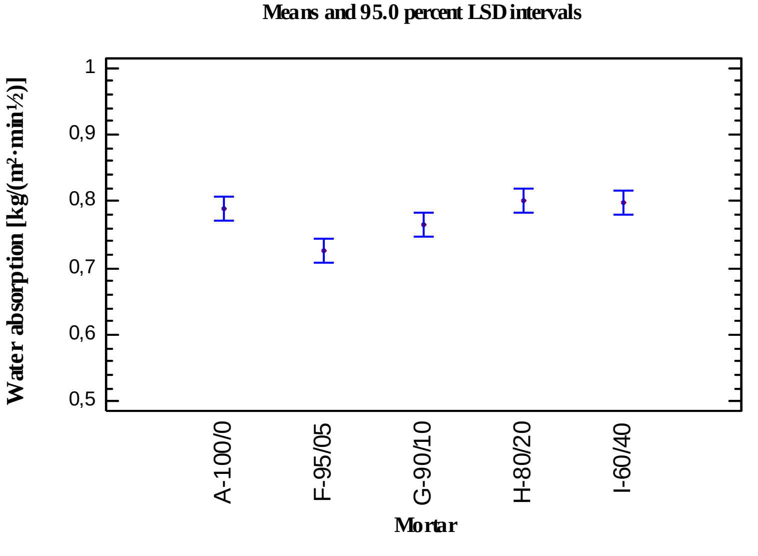

Figure 3.13. LSD range of the mean water absorption due to capillary action of the hardened mortar.

These results agree with those of Neno et al. (2013), who demonstrated similar water absorption coefficients in mortar with replacement ratios of fine RCA below 50%. Braga et al. (2012) concluded that water absorption decreases significantly as the ultrafine RCA incorporation ratio increases up to at least 15%, a finding which was attributable to the fact that the ultrafine particles filled the voids between greater particles, leaving mostly very small pores with lower water absorption capacity. Other authors did not include this parameter in their studies (Vegas et al., 2009; Dapena et al., 2011).

3.4.9. Water vapour permeability of hardened mortar

Water vapour permeability helps to dry the wall and reduce the condensation of water on its surface. Mortars with low vapour permeability retain water in its pores for longer, which is related to pathologies such as excess condensation or dampness, mildew on the walls or freeze-thaw damage on the masonry.

The F-test showed a p-value lower than 0.05 (p-value = 0.0000), so the replacement ratio had a statistically significant effect on the water vapour permeability of the hardened mortar at the 95% confidence level. Fig. 3.14 shows that mortars made with fine RCA decreases of around half of the mean water vapour permeability values. The reference mortar (A-100/0) showed an unexpected high value, which could be explain by the higher effective water/cement ratio (Table 3.4) or the higher uniformity of the NA (Fig. 3.1). Aggregates with uniform particle size distribution have lower compactness and consequently the amount of macropores increases. To relate this property with the pore structure of mortars, new studies following the methodology described by Corinaldesi (2012) should be carried out.

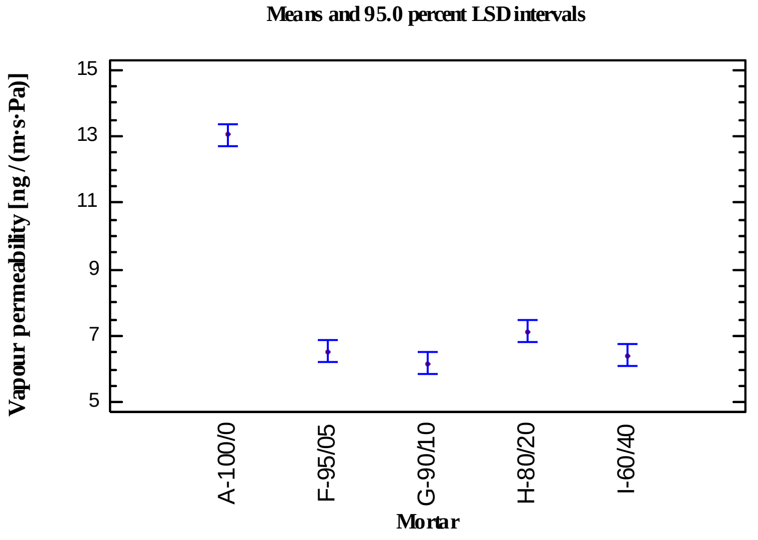

Figure 3.14. LSD range of the mean water vapour permeability of the hardened mortar.

This property could be limiting for the use of the mortar for external rendering, where high vapour permeability and low capillary absorption are required (Corinaldesi, 2012), but these results are not limiting for internal walls or bonding bricks.

These results concur with those reported in the literature. Braga et al. (2012) demonstrated that mortar with a 15% concrete fine material incorporation ratio exhibited approximately 18% lower water vapour permeability. Neno et al. (2013) observed similar water vapour permeability mean values between the reference mortar and mortar made with a 20% replacement ratio. Jiménez et al. (2013) reported similar decreases in vapour permeability in mortar made with ceramic aggregates at replacement ratios above 10%.

3.5. Conclusions

This research evaluates the short- and long-term properties of M-5 masonry mortar manufactured with five replacement ratios of natural siliceous sand by fine RCA: 0%, 5%, 10%, 20% and 40%. A dosage method with a cement-to-aggregate ratio of 1:7 by volume was used.

To identify whether the replacement ratio had a statistically significant effect on the measured properties, a one-way analysis of variance was conducted. The following conclusions were obtained, for both the fresh and hardened states.

The mean bulk density of fresh and hardened mortar decreased as the replacement ratio increased because the dry density of the fine RCA was lower than that of natural aggregate. This change is not a limiting property.

The replacement ratio did not affect the mean values of the entrained air in the fresh mortar. The workable time decreased when the replacement ratios increased, which is an undesirable effect that requires further studies using retarding admixtures to improve this property and render this recycled mortar more serviceable for masons.

Concerning the hardened-state properties, replacement ratios of up to 40% improved the compressive and flexural strengths measured up to 180 days, and the shrinkage showed a similar trend after one year of measurement. The adhesive strength and water absorption due to capillary action of the hardened mortar were within the same order of magnitude of that of the reference mortar, but the water vapour permeability of the hardened mortar decreased by half, even at low replacement ratios, which could be a limiting property for the use of fine RCA-containing mortar as external rendering material.

No differences between the mortars were found in PXRD diagrams, and similar morphologies of the hardened mortars were observed over time. No traces of ettringite were detected.

In conclusion, a replacement ratio of natural sand with up to 40% fine RCA by volume is a viable alternative to manufactured masonry mortar. However, to avoid future dampness problems with its lower vapour permeability, indoor uses are recommended. Studies to improve the workable life are necessary. The results of this research can contribute to increasing the recycling rates of the fine fraction of

CDW, increase the life cycle of building materials, reduce the amount of dumped waste and the consumption of non-renewable resources and lead to the promotion of sustainable construction materials.

3.6. Acknowledgment

The authors are grateful to the Andalusian Research Groups TEP-227 and FQM-214 of the University of Cordoba for funding part of this research.

3.7. Standards used in the experimental work

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4. Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production - Part-I: ceramic masonry waste

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Abstract

Over half of all construction and demolition wastes generated in the European Union are classified as masonry waste, mainly composed of red ceramic brick and adhered mortar. The recycling of these types of masonry waste has been studied to a lesser extent than that of concrete waste. Currently a large quantity of masonry waste, or recycled aggregates from masonry waste, is stored in recycling plants with no recovery alternatives, especially that of the fine fraction. This paper analyses the maximum feasible replacement ratio of natural sand by recycled sand from masonry waste for mortar production. Cement

CEM II/BL 32.5 N, commonly used in Spain for mortar production, in volumetric proportion cement-to-aggregate of 1:5, was used to manufacture an M-10 reference mortar. Five replacement levels were tested: 0 %, 25 %, 50 %, 75 % and 100 %. Both sands were sieved through a 4 mm sieve and used maintaining their original grading curves. The mortars were made with constant admixture content and the tap water content necessary to achieve a consistency of 175 ± 10 mm. The effect of recycled masonry aggregates on fresh and hardened mortars' properties was analysed. The evolution over time of mechanical strength and dry shrinkage was studied up to 180 and 203 days respectively. Trend lines were adjusted to better visualize the effect of the recycled sand on mortar properties and the results were compared with two previous works of the authors. In conclusion a maximum replacement ratio of 50 % can be achieved in mortar for indoor use, although specific studies to increase the workable life and decrease the shrinkage should be carried out before use.

Keywords: Construction and demolition waste; Fine recycled aggregates; Masonry mortar; Ceramic waste; Sustainable construction; Recycled aggregates.

4.1. Introduction

The Waste Framework Directive 2008/98/EC of the European Parliament establishes that countries in the European Union (EU) should achieve a minimum recycling rate of 70 % for construction and demolition waste (CDW) by 2020. The estimated production of CDW in the EU-27 was 461 million tons in 2005, which represents approximately 33 % of the total waste produced in the EU (European Commission DG ENV, 2011). This waste was mainly composed of concrete and masonry waste, both components with a high potential for being re-used or recycled as unbound materials or cement-treated materials in road construction, recycled aggregates (RA) for the production of concrete, mortar, drainage materials and also for asphalt materials. The Waste Framework Directive 2008/98/EC of the European Parliament establishes that countries in the EU should achieve a minimum recycling rate of 70 % for CDW by 2020.

Recycled concrete aggregates (RCA) are obtained from concrete waste, after being crushed and screened in recycling plants. The coarse fraction of RCA has been thoroughly investigated over the past decade to make structural and non-structural concrete (Katz, 2003; Topçu and Sengel, 2004; Poon et al., 2004-a; Poon et al., 2004-b; Tam et al., 2005; Etxeberria et al., 2007; Fonseca et al., 2011; Ferreira et al., 2011; Vieira et al., 2011; Barbudo et al., 2013, Matias et al., 2013). In fact some international standards already allow the use of coarse-RCA concrete production, although technical specifications for the use of coarse-RCA differ from country to country (Martín-Morales et al., 2013; Gonçalves & de Brito, 2010).

The use of fine recycled concrete aggregates (FRCA) to make concrete and mortar has been researched to a lesser extent. It has become evident that the use of FRCA has a negative effect on its workable life in fresh concrete (Pereira et al., 2012a) and mechanical (Pereira et al., 2012b) and durability performance in hardened concrete (Evangelista & de Brito, 2010), which is why in most countries FRCA is not allowed in structural concrete production. This hinders its recycling and it is likely that it ends up in a landfill.

As for masonry waste, its composition varies from country to country (European Commission DG ENV, 2011). In the EU masonry waste is made of ceramic bricks, mortar and other components some of which are recognised as harmful for recycling, such as gypsum. Masonry waste mixed with RCA has always been sought after for recycling purposes.

The possible use of pure ceramic waste has been researched by various authors. Most of these studies do not include ceramic waste from CDW, but rather from ceramic industry waste: clay roof tiles

(Sánchez de Rojas et al., 2006), ceramic sanitary ware (Medina et al., 2012) and brick (Silva et al., 2009; Silva et al., 2010; Gomes & de Brito, 2009). Finely crushed ceramic waste has been used for making cement (Puertas et al., 2008), as a substitute of cement for mortar production (Naceri et al., 2009; Silva et al., 2008) and as an addition to mortar (Silva et al., 2009). The coarse fraction of ceramic waste has been used as recycled aggregate in concrete production (Medina et al., 2012; Medina et al., 2013; Gomes & de Brito, 2009) and fine fraction as recycled sand in mortars (Corinaldesi, 2012; Silva et al., 2010).

Most ceramic waste is found as compounds from masonry waste. In Mediterranean countries such as Spain, masonry-ceramic waste accounts for 54 % of the total of CDW (European Commission DG ENV, 2011). For this reason, it is important to study alternative uses for this kind of ceramic waste. In a previous study, Jiménez et al. (2013) concluded that replacement ratios up to 40 % in volume of natural sand for recycled masonry waste sand would not have a significant effect on mortar properties; however, further studies with larger percentages were not carried out. In this second study the effect of the replacement ratio of natural sand by recycled sand from masonry waste in fresh and hardened mortar, including studies over a long period of time and of durability were included. By comparison with the first study, a different type of cement, cement-to-aggregate ratio and type of admixture was used. The maximum replacement ratio for indoor and outdoor uses was established for each of the tested properties. To the best of the authors' knowledge, these studies, together with the Silva el al. works (2008, 2009, 2010), are the most extensive studies carried out at an international level for recycling ceramic masonry waste in the production of mortars.

From an environmental point of view, the use of fine recycled aggregates (FRA) has the following advantages: i) it minimizes the sand mining from rivers and seashores, which is causing serious environmental problems in many parts of the world; ii) it minimizes energy consumption and CO2 emissions generated by crushing quarry rocks for sand production, mitigating the global warming and iii) it prevents illegal deposits and landfill of the fine fraction of CDW.

In contrast to these environmental benefits, the use of FRA involves a series of activities such as the transportation of the CDW to the recycling plant, processing at the recycling plant and transportation to the place of use that may offset the advantages accrued from recycling. Based on the life cycle analysis (LCA), the use of recycled aggregates from CDW has great environmental benefits over natural aggregates (Estanqueiro, 2012; Knoeri et al., 2013).

4.2. Literature review

This section deals with approaches and conclusions from the studies where natural sand has been replaced by recycled sand from ceramic or masonry waste, which were used as a reference for this study. The majority of the studies described were carried out in the Mediterranean Area.

In Italy, Corinaldesi and Moriconi (2009) used recycled ceramic aggregate from red brick waste (BRI-aggregate) as a replacement for natural sand. The recycled material was crushed in a laboratory to obtain a similar grading curve of less than 4.8 mm. The BRI-aggregate had a greater fine content than the natural sand used as a reference. Cement CEM-II/B-L 32.5 R with a cement-to-aggregate ratio 1:3 (by mass) was used. Enough water to obtain a consistency of 110 ± 5 mm was added. The water/cement (w/c) ratio was greater in mortar made with BRI-aggregate than in the reference mortar. The compressive and flexural strength was less in mortar made with BRI-aggregate, while the bond strength at the interface between mortar and brick was higher.

In a second study, Corinaldesi (2012) used ceramic aggregates from crushed red brick in two different particle sizes (‘fine’ and 'coarse') to replace quartz sand in the production of cement and hydraulic lime mortars. As in the previous study, cement CEM-II/B-L 32.5 R with a cement-to-sand ratio 1:3 (by mass) was used. The aggregates were added to the mixes in saturated-surface-dried condition. No admixtures were used and enough water was added to reach a consistency of 120 ± 10 mm. The author concluded that mortar made with fine crushed brick aggregates (FCB) had a worse mechanical performance than mortar made with coarse crushed brick aggregates (CCB), because of the greater angularity of CCB. FCB led to the best mortar-brick bond strength because of the better rheology of fresh mortar and the greater possibility to permeate the brick surface. Lower values of vapour permeability and higher capillary water absorption were obtained using FCB. Both properties were related to the pore microstructure. Mortars made with FCB showed higher content of micropores (< 0.1 μm) and mesopores (0.1-1 μm) and lower macropores (> 1 μm) than CCB.

In Portugal, Silva et al. (2009) in a first study added ultrafine crushed red clay brick to a siliceous sand mortar. Three incorporation ratios were tested (0 %, 5 % and 10 %) maintaining a volumetric proportion 1:4 (cement: aggregate). The authors concluded that incorporation ratios up to 10 % improved the properties of the reference mortar, with the exception of shrinkage and water vapour permeability. In a second work Silva et al. (2010) replaced siliceous sand by crushed red clay brick, exactly reproducing the grading curve. Four replacement ratios were tested (0 %, 20 %, 50 % and 100 %) keeping constant the 1:4 volumetric proportions (cement-to-aggregate). Replacement ratios of 100 % performed worse than the reference mortar while the replacement ratio of 20 % led to the improvement of all reference mortar's properties. Replacement ratios of 50 % generally presented positive characteristic and better performance than reference mortar, with the exception of shrinkage.

In Spain, Jiménez et al. (2013) replaced natural sand by recycled sand from ceramic masonry waste up to 40 % in volume. Pozzolanic cement CEM-IV/A (V) 32.5 N with 29 % fly ash content was used in volumetric proportion cement-to-aggregate of 1:7. The authors concluded that the masonry mortar properties were not significantly affected, with the exception of density and workability.

Martínez et al. (2013) published a comparative analysis of the mortar's properties made with three kinds of natural sand and three sands recycled from concrete, ceramic and masonry waste. Portland cement (35 MPa) with a volumetric cement-to-aggregate ratio of 1:6 and a 100 % replacement ratio were used. The mortars made with recycled sand showed the worst mechanical strength properties, except in a reference mortar made with low quality natural sand from Cuba. The capillary water absorption and shrinkage was higher in mortars with recycled sands than in reference mortars.

4.3. Experimental program

With the aim of comparing results with a previous study of Jiménez et al. (2013), the same common quartz sand (NA) and recycled sand from ceramic masonry waste were used. Fig. 4.1 shows the ceramic masonry waste from which the recycled masonry aggregates (RMA) used in this study was obtained. This is one of the most common masonry waste generated in Spain. The masonry waste was crushed and sieved in a recycling plant to obtain two fractions: 8/40 mm and 0/8 mm. The main components from the coarse fraction of the RMA determined in accordance with the UNE EN 933-11:2009 were red ceramic bricks (53.9 %) and masonry mortar (39.8 %). Others minor components were also present, such as unbound aggregates (5.7 %), concrete (0.4 %) and gypsum particles (0.2 %).

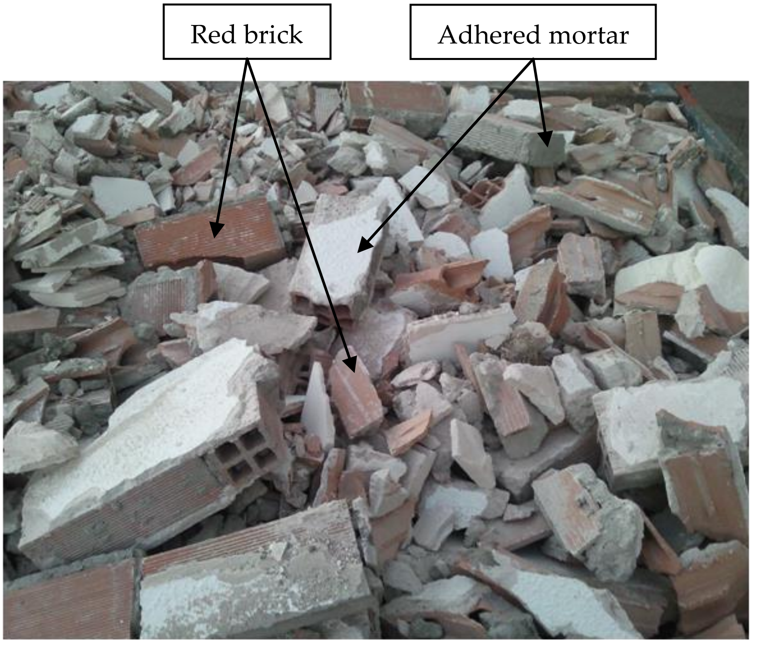

Figure 4.1. Ceramic masonry waste.

The following criteria were established for manufacturing the mixes:

1) Sieve the natural sand (NA) and fine fraction of the recycled masonry aggregates (RMA) with a 4 mm sieve using the original 0/4 mm size distribution of the quarry and recycling plant respectively;

2) Use commercial cement CEM II/BL 32.5 N in a volumetric proportion cement-aggregate of 1:5;

3) Replace in volume the natural sand (NA) by recycled sand (RMA) with the following ratios: 0 %, 25 %, 50 %, 75 % and 100 %;

4) Use a commercial admixture to improve workability.

The mixing process was described in a previous study of Jiménez et al. (2013), using a standard mixer according to UNE-EN 196-1:1996.

4.3.1. Materials

Table 4.1 shows the grading curves of both sands. The RMA had almost three times more particles smaller than 0.063 mm than the NA. Table 2 shows the physical-mechanical characteristics of both aggregates. NA showed a greater sand equivalent, greater dry density, less water absorption and lower friability coefficient. From a chemical point of view both sands were characterised in accordance with UNE-EN 1744-1:1998. The RMA exceeded the limit of 1 % in acid soluble sulphates (1.04 %), total sulphurs (1.04 %), both expressed in SO_3, and soluble salts (1.159 %), established by standard UNE-EN 13139:2002 for aggregates used in the mortars production. These properties agree with those described in other studies on the characteristics of fine recycled sands from CDW (Rodrigues et al., 2013).

Table 4.1. Grading curves of NA and RMA (UNE-EN 933-1:2006)

Sieve size (mm)	Percent passing (%)	
	NA	RMA
4	100.00	100.00
2	87.00	85.00
1	73.00	59.00
0.5	53.00	39.00
0.25	23.00	21.00
0.125	8.00	12.00
0.063	3.20	9.00

Table 4.2.Physico-mechanical properties of NA and RMA.

Characteristic	Standard	NA	RMA
Sand equivalent (%)	UNE-EN 933-8:2000	94	86
Dry sample density [(a)] ρ_{rd} (g/cm^3)	UNE-EN 1097-6:2000	2.63	2.14
Water absorption [(a)] (%)	UNE-EN 1097-6:2000	0.79	9
Friability coefficient (%)	UNE 83115:1989 EX	15	32

[(a)] Fraction 0.063/4 mm

Table 4.3 shows the mineralogical composition determined by X-Ray diffraction (DRX). The major component in both cases was quartz. Small quantities of gypsum were detected in RMA, which coincided with the chemical characteristics in accordance with UNE-EN 1744-1:1998, previously mentioned.

Table 4.3. Mineral phases of NA and RMA.

Mineral phase	**Mineral relative abundance**	
	NA	**RMA**
Albite $Na(Si_3Al)O_8$	*	**
Calcite $CaCO_3$	**	**
Dolomite $CaMg(CO_3)_2$	**	
Illite $KAl_2Si_3AlO_{20}(OH)_2$	*	*
Quartz (SiO_2)	******	*****
Sanidine $(Na,K)(Si_3Al)O_8$	**	***
Gypsum $CaSO_4{\cdot}2H_2O$		*

From an environmental point of view, standard UNE-EN 12457-3:2002 was used to determine whether the contents could leach and hence be potentially hazardous to the environment. The dry sample's mass was 0.175 kg. Two steps were examined in the leaching test to simulate short- and long-term exposure scenarios. In Step 1 an amount of deionised water was added to obtain a liquid/solid ratio (L/S) of 2 L/kg; the sample was mixed for 6 hours at a speed of 5 to 10 rpm and afterwards was filtered with 0.45 μm filters. In Step 2 more deionised water was added to the previous sample to obtain a ratio of L/S =10 L/kg. The sample was mixed for 18 hours and afterwards was filtered with 0.45 μm filters. The elements of the eluate were determined in a laboratory using an ICP-MS (Perkin Elmer ELAN DRC-e).

Table 4.4 shows the concentrations (mg/kg) of leached elements obtained in the NA and RMA, compared to the standard limits established by the European Directive 2003/33/CE (Annex 2) for their classification as inert and non- hazardous. The NA was classified as inert. The RMA was classified as non-hazardous because the concentration of sulphates ions from the eluate was over the limit established by the European Directive to inert materials. The majority of these sulphates derived from gypsum particles, detected during the composition test and the DRX analysis. This also agrees with the greater percentage of acid soluble sulphates and total sulphurs detected in the chemical characterisation tests. The classification as non inert materials could limit its use as unbound materials in places where it could come into contact with water. Therefore its use with cement is a viable alternative.

Table 4.4. Leached concentrations of NA and RMA (mg/kg) and waste acceptance criteria (EU Council Decision 2003/33/EC).

ent (mg/kg)	NA		RMA		Criteria EU Landfill Directive 2003/33/EC					
					Inert		Non-hazardous		Hazardous	
	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10
hromium)	0.001	0.000	0.172	0.344	0.2	0.5	4	10	25	70
ickel)	0.000	0.000	0.012	0.026	0.2	0.4	5	10	20	40
opper)	0.000	0.003	0.031	0.039	0.9	2	25	50	50	100
inc)	0.001	0.002	0.006	0.010	2	4	25	50	90	200
rsenic)	0.013	0.061	0.013	0.030	0.1	0.5	0.4	2	6	25
elenium)	0.003	0.013	0.028	0.042	0.06	0.1	0.3	0.5	4	7
Molybdenum)	0.001	0.000	0.055	0.088	0.3	0.5	5	10	20	30
admium)	0.000	0.000	0.000	0.000	0.03	0.04	0.6	1	3	5
ntimony)	0.001	0.002	0.014	0.035	0.02	0.06	0.2	0.7	2	5
arium)	0.025	0.091	0.107	0.498	7	20	30	100	100	300
Mercury)	0.000	0.000	0.000	0.000	0.003	0.01	0.05	0.2	0.5	2
ead)	0.000	0.000	0.000	0.000	0.2	0.5	5	10	25	50
ride	< 2	< 10	< 2	< 10	4	10	60	150	200	500
ride	14.2	< 50	119.624	104.41	550	800	10000	15000	17000	25000
hate	34.5	< 50	3616	9590	560	1000	10000	20000	25000	50000
litions of the test sample										
luctivity (µS/cm)	56.5	22.5	1426	785						

Table 4.5 show the characteristics of the cement used. Cement CEM II/BL 32.5 N was chosen because it is the most common cement in mortar production in Southern Spain. This cement differed from the one used in previous studies by Jiménez et al. (2013).

Table 4.5. Characteristics of CEM II / BL 32.5 N.

Constituents	
Clinker (%)	≥ 65 %
Limestone (%)	≥ 35 %
Minority (%)	≤ 5 %
Chemical characteristics	
Sulphates	< 3.5 %
Chlorides	< 0.04 %
Chromium VI in water soluble	< 0.0002 %
Physical characteristics	
Density (g/cm^3)	2.84
Expansion (Le Chatelier)	< 2.5 mm
Initial set (min)	> 75 min
Final set (min)	< 275 min
Mechanical characteristics	
Compression strength at 7 days (MPa)	> 24.0 MPa
Compression strength at 28 days (MPa)	> 34.0 MPa
	< 52.5 MPa

A commercial plasticiser NEOPLAST with density of 1.040 gr/cm^3 and pH = 8 was used (UNE-EN 934-2:2010). The plasticiser was mixed directly in the tap water during mixing at a ratio of 0.1 cm^3 per mix.

4.3.2. Mortar mixes' composition

The mortar mixes' composition and nomenclature used is presented in Table 4.6. The mixing water was determined experimentally to ensure a consistency of 175 ± 10 mm (UNE-EN 1015-3:1999).

Table 4.6. Mortar mixes composition.

tar type	NA/RMA			Mix proportions - dry weight			
	in volume	NA (g)	RMA(g)	CEM(g)	Water (g)	Admixture(cm³)	Consistency index(mm)
100/0	100/0	3508.00	0.00	757.00	596.00	0.1	175 ± 10
75/25	75/25	2631.00	713.00	757.00	645.00	0.1	175 ± 10
50/50	50/50	1754.00	1427.00	757.00	701.00	0.1	175 ± 10
25/75	25/75	877.00	2140.00	757.00	753.00	0.1	175 ± 10
)/100	0/100	0.00	2853.00	757.00	796.00	0.1	175 ± 10

The following formulas were used to calculate the dry mass of each component:

$$Drymassofcement = \frac{V \cdot 1 \cdot \text{ρrdCEM}}{6}$$

$$DrymassofRMA = \frac{V \cdot X \cdot 5 \cdot \text{ρrdRMA}}{6}$$

$$DrymassofNA = \frac{V \cdot (1 - X) \cdot 5 \cdot \text{ρrNA}}{6}$$

$$X = \frac{PercentageofreplacementofNAbyRMA}{100}$$

4.3.3. Tests on mortar mixes

Table 4.7 shows the fresh and hardened mortar's properties tested, the standard tests and number of specimens used, as well as the climatic conditions and curing time for each property. The methodology of the tests was described previously by Jiménez et al. (2013), with the exception of durability and leaching tests.

Table 4.7. Standards used to characterize the mortars.

Properties of fresh mortar	Standard	Specimens and size	Climatic chamber [a]	Curing time
Bulk density of the fresh mortar	UNE-EN 1015-6:1998	4	--	
Entrained air	UNE-EN 1015-7:1999	4	--	
Workability	UNE-EN 1015-9:2000	4	--	
Properties of hardened mortar				
Dry bulk density	UNE-EN 1015-10:1999	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Flexural strength	UNE-EN 1015-11:1999	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Compressive strength	UNE-EN 1015-11:1999	8 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Shrinkage	UNE 83831 EX:2010	3 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	Up to 203 days
Adhesive strength	UNE-EN 1015-12:2000	4 Circular - 50 mm diameter, 10 mm-thick	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Water absorption due to capillary	UNE-EN 1015-18:2002	6 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Durability	UNE-EN 12370:1999	4 Prismatic 40 x 40 x 160 mm	--	180 days
Leached specimen	XP X31-211:2000	1 Cylindrical 40 mm diameter x 80 mm height	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days

[a] Climatic conditions: Chamber-1: Tª = 20±2 ºC – HR= 95±5 %; Chamber-2: Tª = 20±2 ºC – HR= 65±5 %

The durability of hardened mortar was determined by its resistance to salts crystallization described in Vegas et al. (2009), according to UNE-EN 12370:1999. Starting with a constant mass, the 40x40x160 mm prismatic samples were submerged for 2 hours in a sodium sulphate decahydrated at 14 % solution, then oven-dried and left to cool at normal laboratory temperature. This cycle was repeated 15 times and the difference in weight of the specimens before and after the tests provides the loss of mass and resistance to salts crystallization of the mortar.

To analyze the leaching of mortars made with RMA, French Standard XP X 31-211:2000 was used. Cylindrical specimens with a diameter of 40 mm and 80 mm in height were immersed in deionised water, stirred for 24 hours and continuously vibrated throughout the test by means of a magnetic stirrer (120 rpm). This is followed by the filtering stage with filters of 0.45 μm. The quantity of leached elements was determined in a laboratory using an ICP-MS (Perkin Elmer ELAN DRC-e).

4.3.4. Data analysis

For each of the studied properties, a multiple range test was conducted to determine whose mean values were statistically different. For ‘replacement ratios’ whose mean values had statistically significant differences, a trend line was adjusted with the aim of studying the effect of the amount of RMA on the 'measured property'. The results of each of the 'measured properties' were compared with those of Jiménez et al. (2013) and Silva et al. (2010).

4.4. Results and discussion

4.4.1. Properties of fresh mortar

4.4.1.1. Bulk density of fresh mortar

The bulk density of fresh mortar decreased linearly with the replacement ratio (Fig. 4.2). This was due to the lower density of RMA with respect to NA. Fig. 2 shows that this trend agrees with those obtained by Jiménez et al. (2013) and Silva et al. (2010). The lower density in mortars made by Jiménez et al. (2013) is due to the lower quantity of cement between both studies, the previous work used a cement-aggregate ratio of 1:7 while in this second study a cement-aggregate ratio of 1:5 was used. Silva et al. (2010) used a cement-aggregate ratio of 1:4 and obtained similar density values to our study's. The density drop in fresh mortars with the use of RMA was greater in Silva et al. (2010), possibly because the ceramic aggregates were lighter.

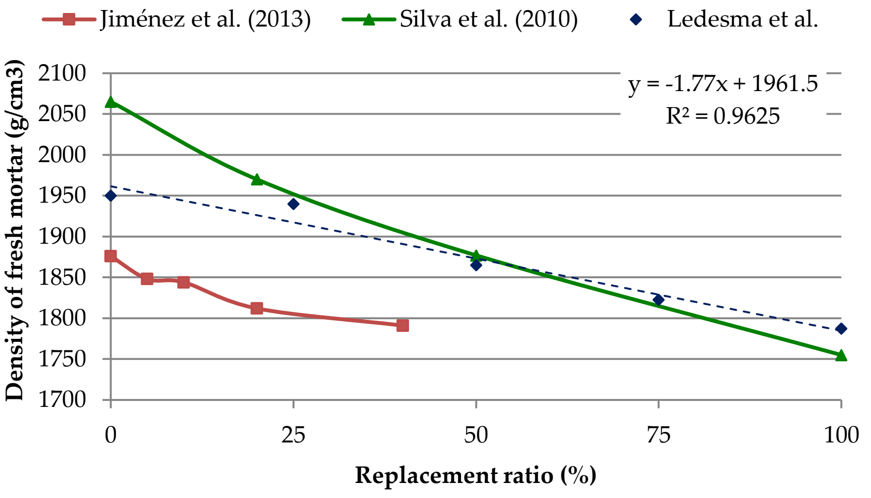

Figure 4.2. Bulk density of fresh mortar vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

The European standards do not set a minimum or maximum value for the masonry mortars' fresh density, so the use of RMA is not a limiting factor for this property. The main advantage of a lighter mortar is that for the same volume of mortar the amount of mass to be transported is smaller. For the same mass of aggregates, the use of recycled sand produces a greater volume of mortar. By contrast, a lighter mortar absorbs more water than usual as consequence of a greater volume of porous materials (Lanzón and García-Ruiz, 2008). This phenomenon can have a negative effect on the durability of mortar in outdoor environments. For indoor uses, to use lighter mortar is not a limiting property.

4.4.1.2. Occluded air content

Due to the high dispersion of the data, the multiple range test analysis shows that no statistically significant difference was observed for replacement ratios below 75 %. However a linear fall in mean values of occluded air with respect to replacement ratio was observed (Fig. 4.3).

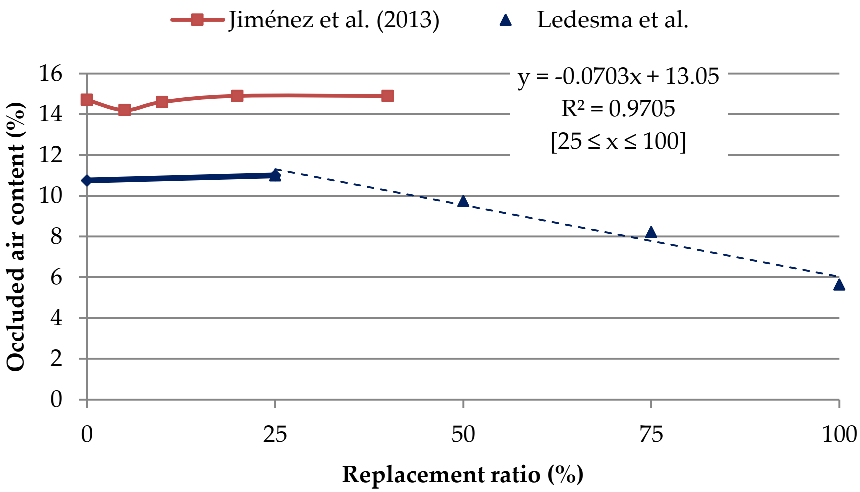

Figure 4.3. Occluded air content vs. replacement ratio and comparison with Jiménez et al. (2013).

According to Corinaldesi (2012), when recycled aggregates with a greater percentage of fine particles (< 0,063 mm) are used, the number of macropores (>1 μm) decreases due to the filler effect of these fine particles and so does the volume of occluded air. The recycled sand used in this study had more than three times the fine particles than the reference natural sand (Table 4.1). Additionally the friability coefficient of the recycled sand was more than twice that of natural sand (Table 4.2), which increases the amount of fine particles broken during the mixing process. This explains why the mean values of the occluded air were slightly lower with the incorporation of RMA. Jiménez et al. (2013) found no statistically significant difference in the mean values of occluded air for replacement ratios up to 40 %. These authors showed higher mean values of occluded air that could be due to the lower cement content in their study.

4.4.1.3. Workable life

Statistically significant differences between mean values were found for replacement ratios greater than 25 %. Fig. 4.4 shows a linear decline in the measured mean values of workable life with the amount of RMA. This was due to greater water absorption of the recycled sand and because no extra water was added during mixing.

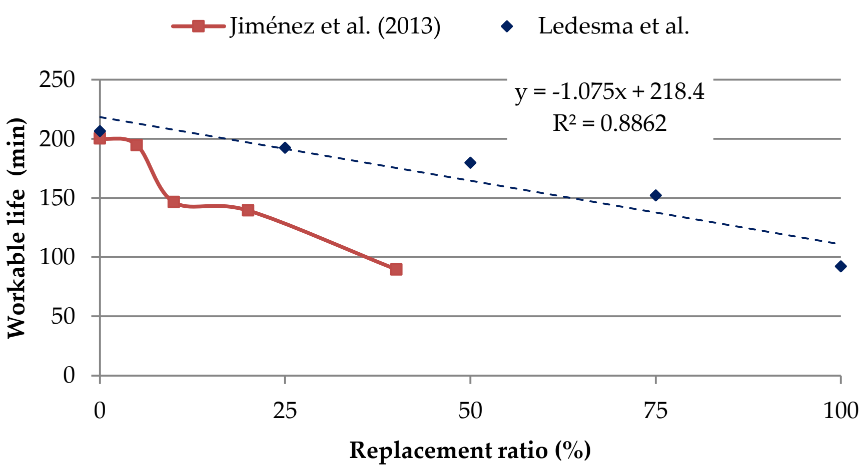

Figure 4.4. Workable life vs. replacement ratio and comparison with Jiménez et al. (2013).

Mortars need to retain workability for a reasonable length of time, although European Standards do not establish any limit for this property. Jiménez et al. (2013) obtained a workable life of 200 min for the reference mortar, slightly lower than the value of 206 min obtained in this study. These values are similar from a practical point of view. Workability loss was much greater in the first work (Jimenez et al., 2013) as seen in Fig. 4.4. This could be due to the cement content and type of admixture used that were different in both studies. The authors cited in the literature review section have not studied this property, even though workability is a key issue for the mason to be able to make a quality masonry construction. Other authors, such as Gadea et al. (2010) obtained a higher workable life value of 270 min in the reference mortar.

Pereira et al. (2012a) mentioned the need to understand the evolution of the FRA’s water absorption during mixing, because approximately 50 % of potential water absorption by recycled aggregates occurs in the first 10 min and approximately 90 % after 90 min. After the mortars tested were produced, the RMA continued absorbing water, thus reducing the workable time of the fresh mortar.

4.4.2. Properties of hardened mortar

4.4.2.1. Bulk density of hardened mortar at 28 days

Fig. 4.5 shows a linear fall of the mean values of bulk density of hardened mortar, which was due to the lower density of RMA. Jiménez et al. (2013) and Silva el al. (2010) also showed a linear fall of the bulk density of hardened mortar as the replacement ratio increased (Fig. 4.5). Fig. 4.6 shows the distribution of ceramic particles in the matrix of the five types of mortar tested and how the amount of visual ceramic particles increases with the replacement ratio. The trend of the two authors and our results was very similar. Martínez et al. (2013) also noted a lower density in mortars made with recycled ceramic aggregate. European Standards do not establish any limit for this property, so no maximum replacement ratio can be recommended.

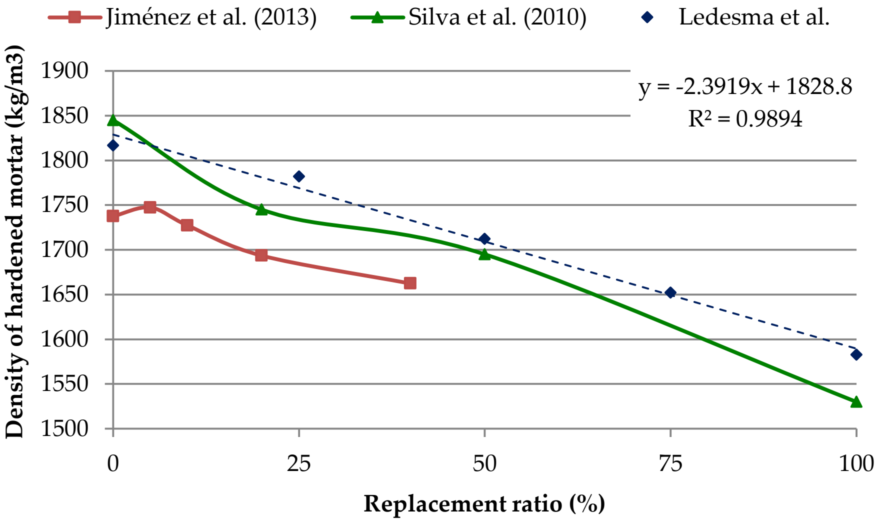

Figure 4.5. Bulk density of hardened mortar vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

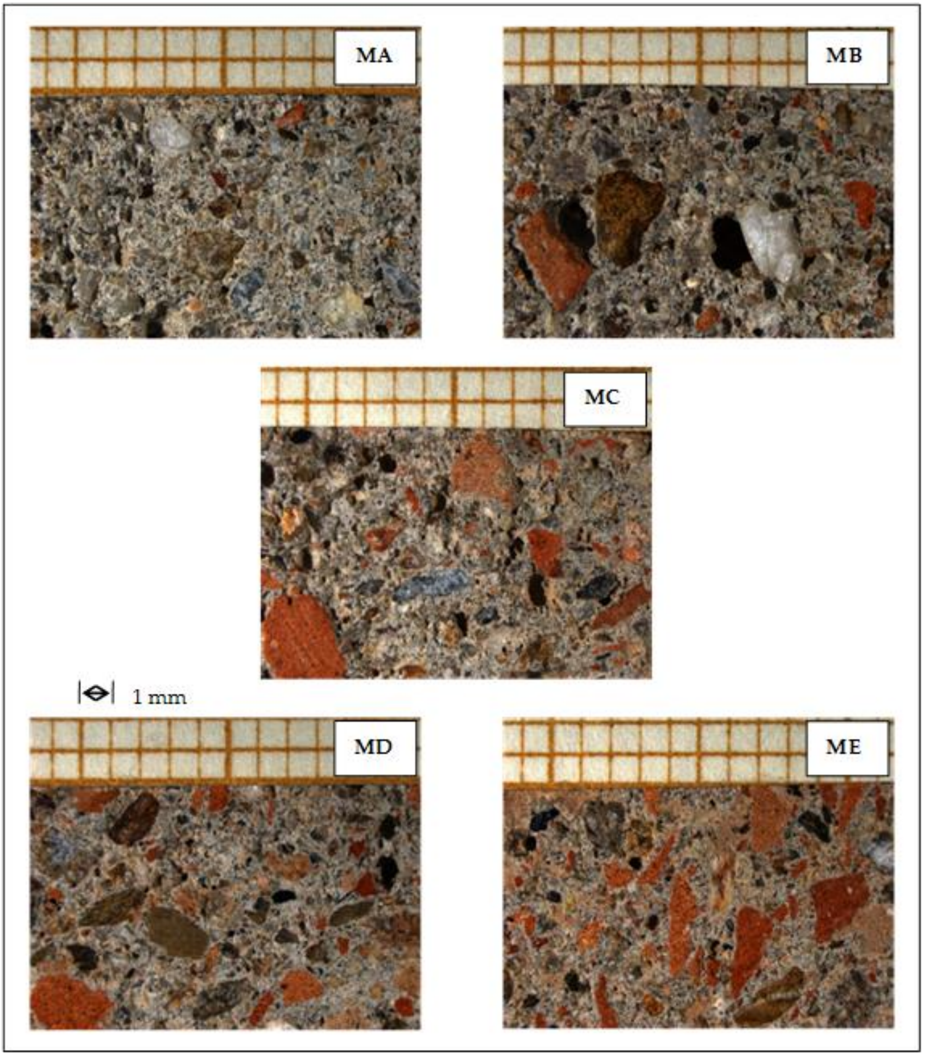

Figure 4.6. Distribution of NA and RMA particles in prism specimens.

4.4.2.2. Compressive and flexural strengths

The compressive and flexural strengths were measured at various curing times: 7, 28, 90 and 180 days. Fig. 4.7 shows the evolution over time of the compressive and flexural strengths' mean values for all types of mortar tested. The evolution of the curves was similar for all mortars, showing an increase in mechanical strength as a function of time. The mechanical strength decreased as the replacement ratio of RMA increased, except for the mix MC-50/50 that showed a flexural strength at 7 days 8.5 % lower than that of the mix MD-25/75. This breaks the general trend of a total of 20 mixes and there is no reason for this value, so it should be considered spurious data.

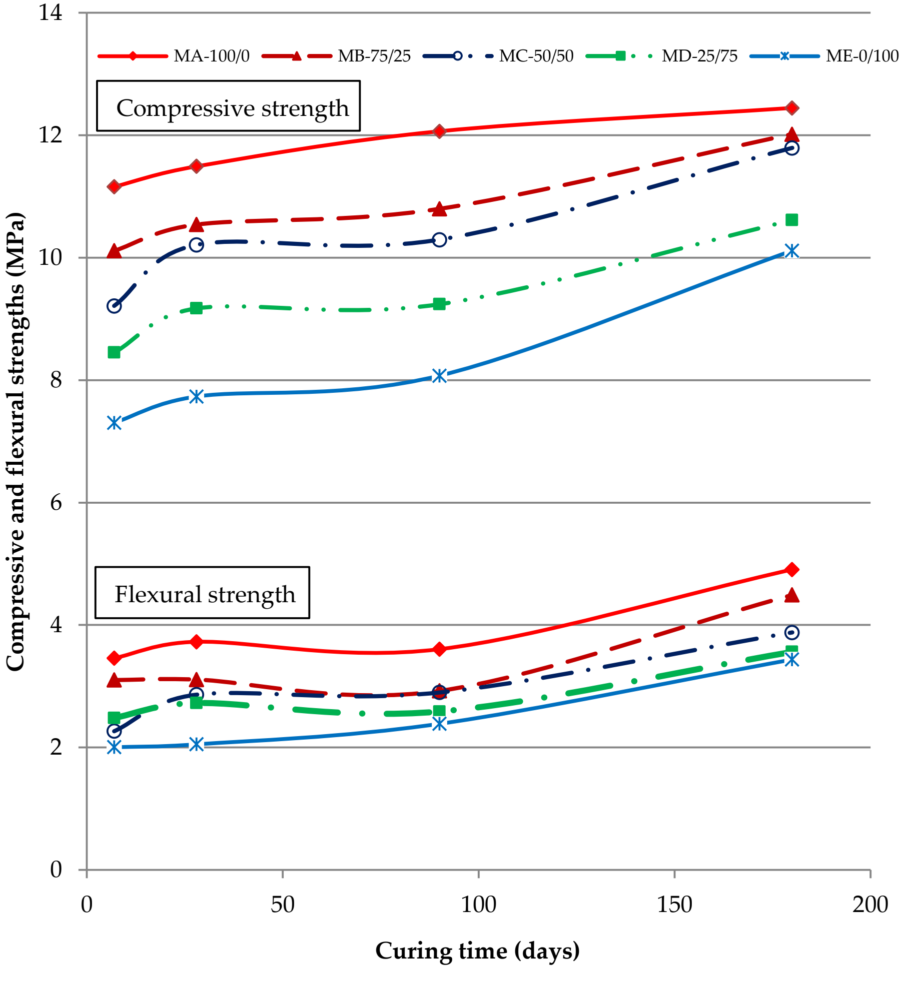

Figure 4.7. Compressive and flexural strengths of hardened mortar over time.

For replacement ratios up to 50 % the mean values of compressive strength exceeded 10 MPa after 28 days, 11.3 % less than for the reference mortar. The differences between the mechanical strength of the reference mortar and of the mortar with 50 % replacement level decreased with the curing time. That did not occur when the replacement ratio was 100 %, since the compressive strength fall relative to the reference mortar was sustained over time. This may justify that from a mechanical point of view, replacement ratios up to 50 % may be viable for mortar type M-10 production.

Fig. 4.8 compares the results of compressive strength at 28 day of curing with those obtained by Jiménez et al. (2013) and Silva et al. (2010). Jiménez et al. (2013) found no statistically significant differences of mechanical strength for replacement ratios up to 40 % in mortar type M-7, whilst Silva et al. (2010) observed an increase in mechanical strength for replacement ratios up to 50 % and a decrease for replacement ratios of 100 %. Corinaldesi (2012) noted mechanical strength falls of about 58 % when natural sand was replaced in weight by ceramic recycled aggregates. However, Corinaldesi's results are not directly comparable with those of our study, as different methods of substitution in weight or volume were used.

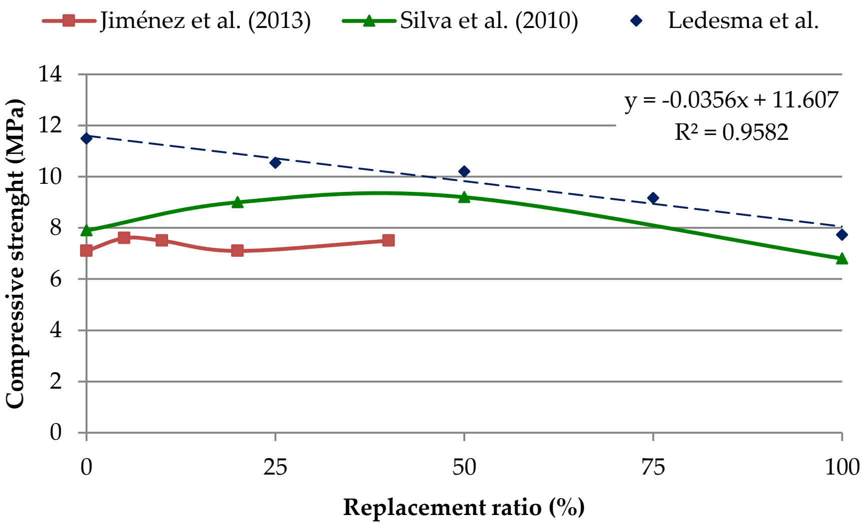

Figure 4.8. Compressive strength of hardened mortar at 28 days vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

The compressive and flexural strengths also decreased linearly as the replacement ratio increased (Fig. 4.9). Jiménez et al. (2013) found no significant differences in the flexural strength with replacement ratios up to 40 %, while Silva et al. (2010) did not show a clear effect of the incorporation of RMA on the flexural strengths. Corinaldesi (2012) also noted falls of 60 % of the flexural strength with total replacement in weight of natural sand by recycled ceramic aggregate. Martínez et al. (2013) observed that, when the quality of natural sand used in mortars production was good, the use of recycled aggregate from CDW reduced the mechanical properties of the mortars, and vice-versa.

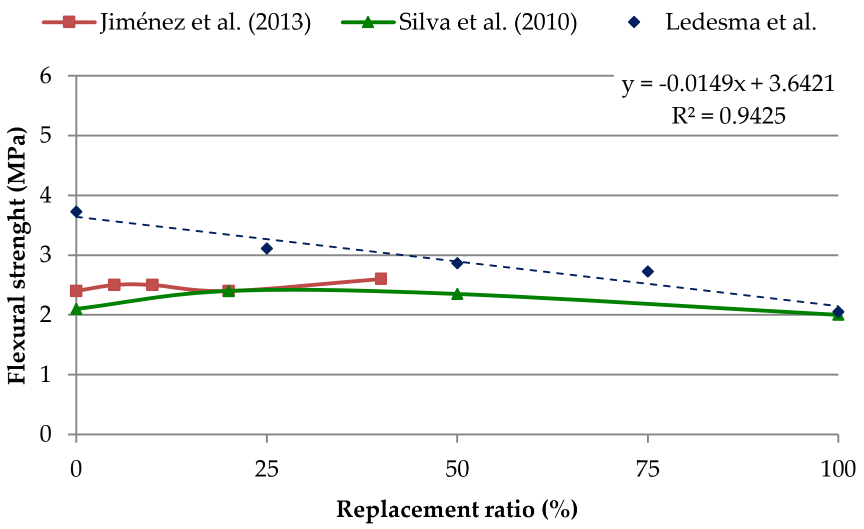

Figure 4.9. Flexural strength of hardened mortar at 28 days vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

The best results obtained by Jiménez et al. (2013) can be attributed to the type of cement used, CEM-IV with 29 % of fly ash. The pozzolanic activity of fly ash and its smooth and spherical particles improved the compaction of the mortars. This agrees with the evidence of Torkittikul and Chaipanich (2010), who showed that the replacement of natural sand by recycled sand from ceramic products from Thailand made the compressive strength of the mortars fall by 9 % when the replacement ratio went from 50 % to 100 %, while, when substituting 30 % of cement by fly ash, no decreases were observed for the same increase of the replacement ratio of natural by recycled aggregates. The use of pozzolanic cement with fly ash (CEM-IV) improved the mechanical properties of the mortars made with recycled aggregates from CDW.

After the compressive strength test, the moisture content of the broken specimens was measured. Even though all samples underwent the same environmental conditions (chamber-2), a linear increase of moisture in the samples as the replacement ratio increased can be observed (Fig. 4.10). This can be explained by the greater water absorption of RMA relative to NA. This interesting factor had not been revealed by other authors and can increase humidity or freeze-thaw resistance problems if these mortars are used in outdoor environment.

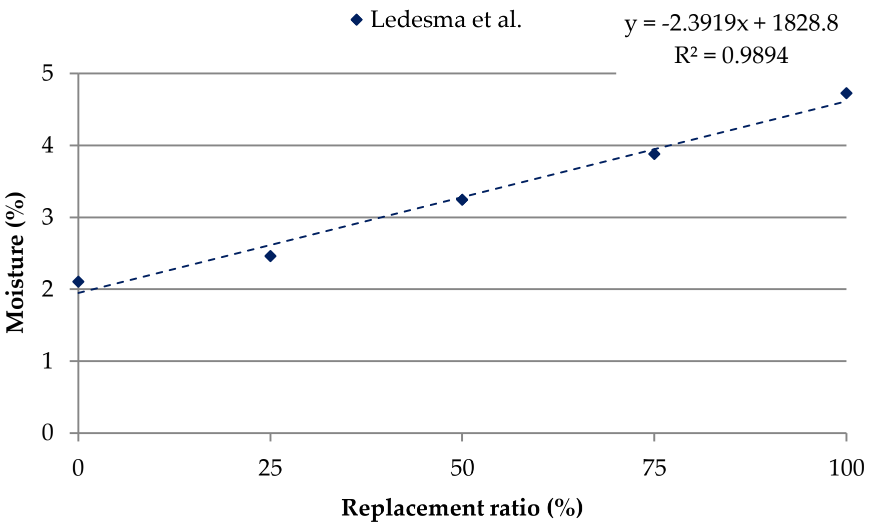

Figure 4.10. Moisture of the specimens vs. replacement ratio at 28 days.

4.4.2.3. Shrinkage

The dimensional stability of the mortars was measured for up to 203 days. The mortars all behaved in a similar way over that period of time resulting in greater dry shrinkage in the mortars with greater amount of RMA. This can be due to the greater w/c ratio needed by these mortars during mixing. Fig. 4.11 shows that the largest dimensional changes occurred in the first 28 days of curing coinciding with the loss of water by evaporation. Fig. 4.12 shows the loss of mass of the specimens tested. The weight of the specimens stabilised after 28 days of curing. The evolution of the loss of mass was similar in all mortars, but the greater loss of mass occurred in those with the greatest replacement ratio. This was explained by the greater w/c ratios of the mortars with RMA.

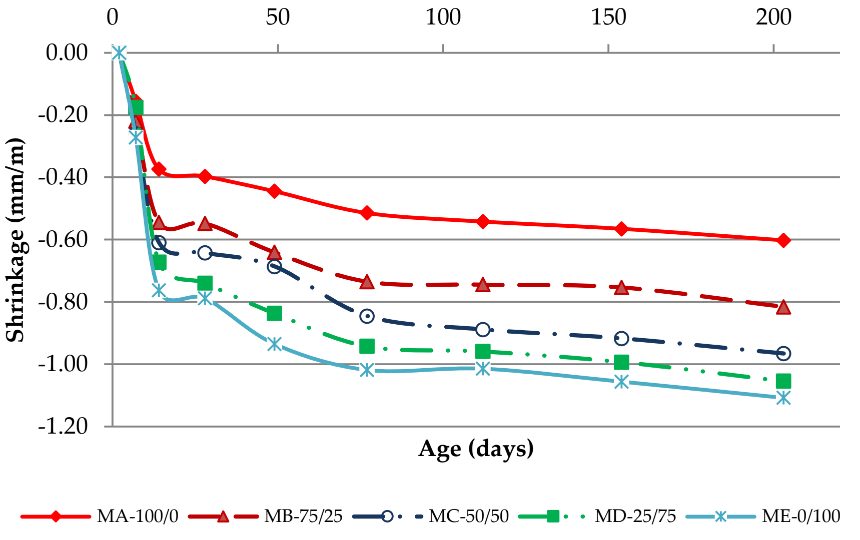

Figure 4.11. Shrinkage of mortar as a function of age in days (HR = 65% and T = 20 ºC).

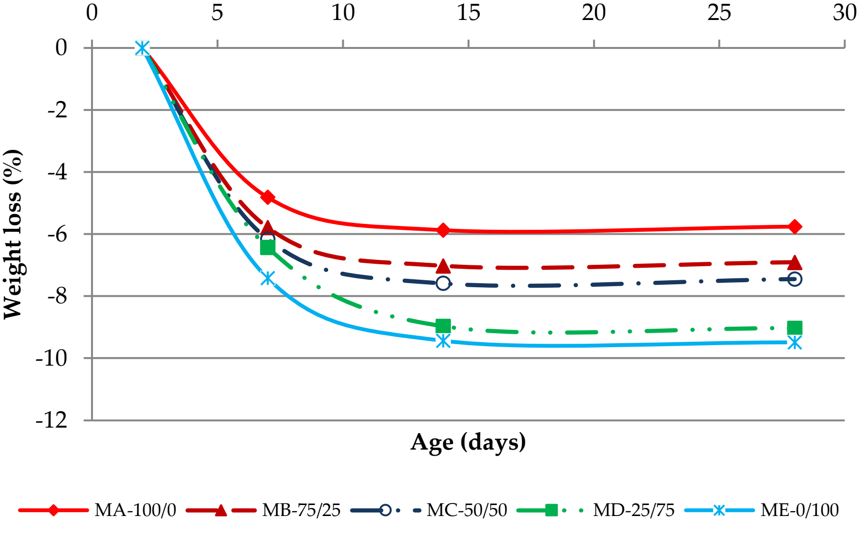

Figure 4.12. Weight loss of specimens mortar until 28 days (HR = 65% and T = 20 ºC).

Fig. 4.13 shows that after 28 days of curing the dry shrinkage linearly increased when the amount of RMA increased. Silva et al.

(2010) showed that replacement ratios of 20 % increased the shrinkage, but above this value only a slight increase was observed. Jiménez et al. (2013) showed higher shrinkage mean values, possibly because their w/c ratio was greater than in our study.

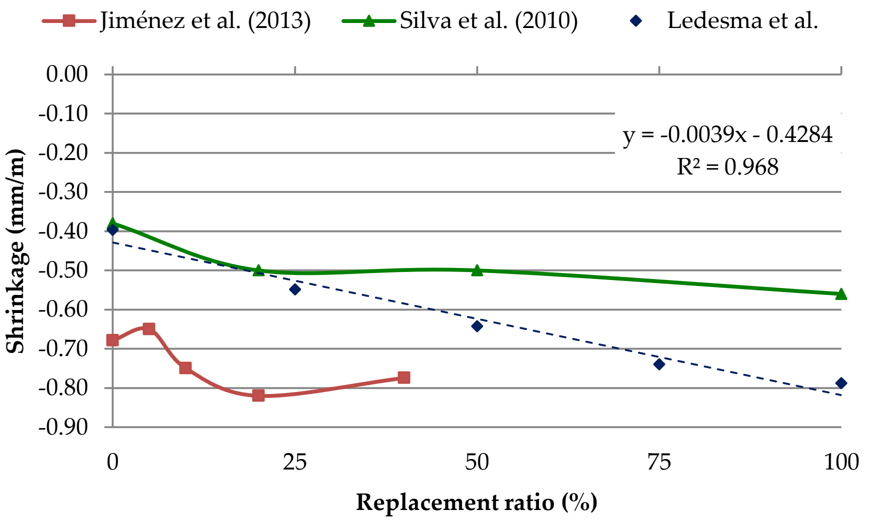

Figure 4.13. Shrinkage of hardened mortar at 28 days vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

In order to establish the maximum replacement ratio, two criteria were used: 1) according to standard UNE 83831 EX: 2010 during the shrinkage test a maximum difference of 0.5 mm/m is allowed between specimens of the same mortar type, and 2) the mean dry shrinkage value must not exceed 1 mm/m. The maximum replacement ratio that fulfilled these criteria for any curing age was 50 %.

4.4.2.4. Adhesive strength

No statistically significant difference was observed for replacement ratios below 75 %, due to the dispersion of results in the pull-off test. Although the mean values for adhesive strength linearly decreased as the amount of RMA increased (Fig. 4.14). This is in contrast with Jiménez et al. (2013), who found no statistically significant differences for replacement ratios up to 40 %, and with Silva et al. (2010), who obtained an improvement of the adhesive strength with replacement ratios up to 50 %. Based on the results of the multiple range test, a maximum replacement ratio of 75 % can be recommended.

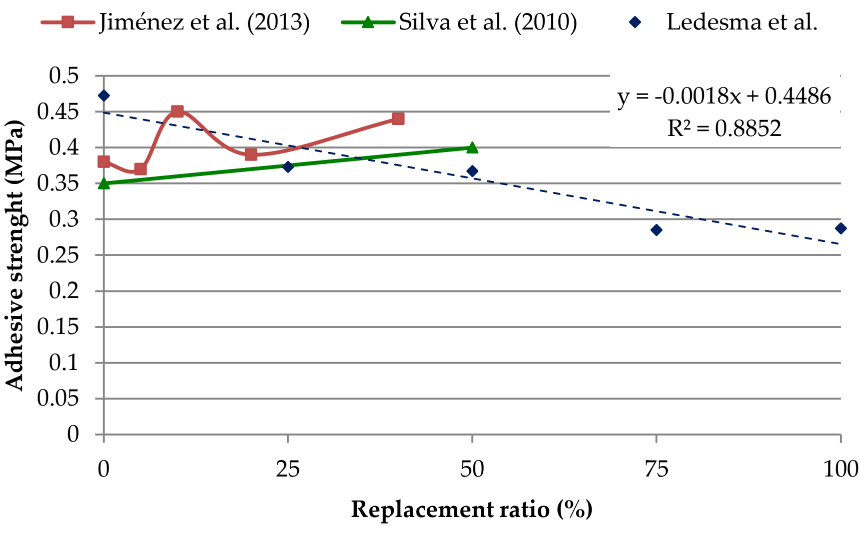

Figure 4.14. Adhesive strength of hardened mortar at 28 days vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

4.4.2.5. Capillary water absorption

Due to the higher water absorption of RMA, the capillary water absorption of the mortars increased linearly as the amount of RMA increased (Fig. 4.15), reaching up to 91 % more than the reference mortar in the case of 100 % replacement ratio. Jiménez et al. (2013) found no major differences in this property with replacement ratios up to 40 %. Silva et al. (2010) showed a similar trend, although they also found that the replacement ratio of 20 % led to a decrease of capillary water absorption. Corinaldesi (2012) also observed an increase of between 54 % and 108 % in the mean values of capillary water absorption in mortars made with coarser crushed brick and finer crushed brick respectively. These variances were attributed to the different fine contents in RA. The capillary water absorption is not a limiting property in indoor uses, but the incorporation of RMA in an outdoor environment may promote pathologies derived from the accumulation of water in mortars.

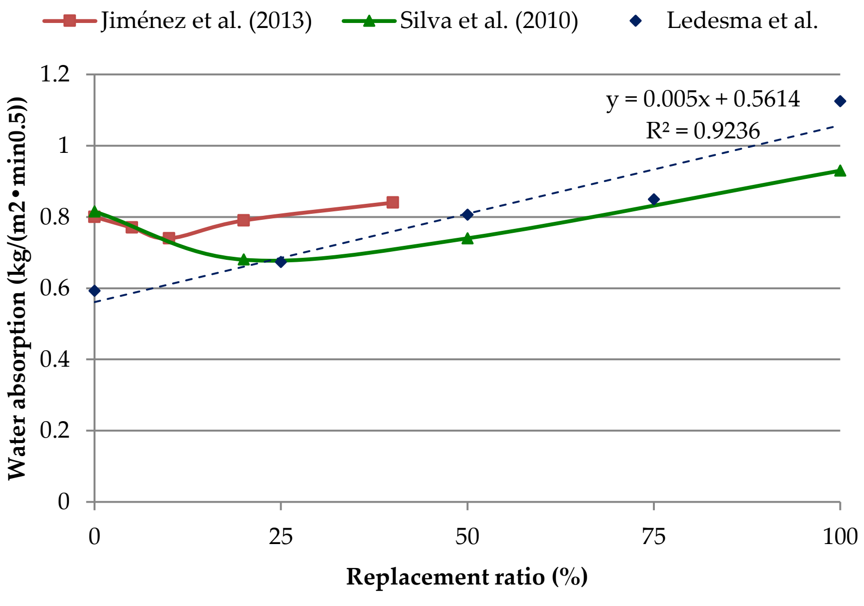

Figure 4.15. Water absorption due to capillary action of hardened mortar vs. replacement ratio and comparison with Jiménez et al. (2013) and Silva et al. (2010).

4.4.2.6. Resistance to sodium-sulphate attack

The salt-crystallization test (UNE-EN 12370:1999) was carried out only in the mortars with 0 %, 50 % and 100 % replacement ratio. Fig. 4.16 shows the aspect of the samples once the tests were completed. At a first glance no greater number of cracks or visible damage in samples made with RMA were observed, although the weight losses were greater in those mortars (Table 4.8). The differences in weight between samples after 15 cycles of immersion in sodium-sulphate solution can be attributed to the disintegration of mortar particles and the crystallisation of salts in pores and fissures.

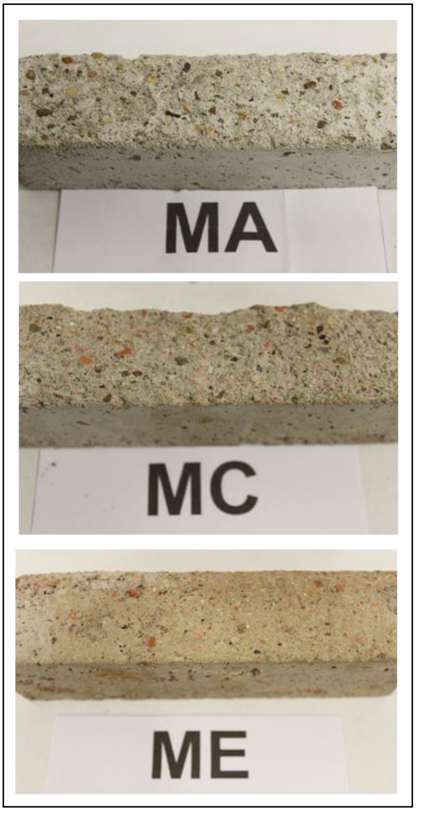

Figure 4.16. Aspect of prism specimens after 15 cycles in sodium sulphate dissolution.

Table 4.8. Percent of weight loss after 15 cycles in sodium sulphate dissolution.

Mortar	Count	LS mean (%)	SD (%)
MA-100/0	4	2.2	0.4
MC-50/50	4	3.65	0.37
ME-0/100	4	4.27	0.25

The results obtained in concrete made with RMA were better than those of Vegas et al. (2009), who used fine-RCA and obtained a weight loss of 5.5 % in a mortar with 25 % replacement ratio.

Cultrone et al. (2007) demonstrated that the response of the mortar samples to the freeze-thaw test was different from their response to sodium-sulphate attack, and therefore freeze-thaw tests should be carried out to draw more accurate conclusions about the mortar's durability and use in outdoor environments.

4.4.2.7. Leaching of hardened mortar

The RMA was not classified as inert material due to its high amount of leached sulphates (Table 4.4). Table 4.9 shows the anions concentrations (mg/kg) in the eluate of the hardened mortar. The results were compared with the limit established in Annex 2 of the 2003/33/CE Council Decision for landfill classification. The sulphate concentrations increased with the increasing RMA content in mortars, although all monolithic specimens were classified as inert.

Table 4.9. Anions concentration in mortars made with RMA (mg/kg).

Element (mg/kg)	MA-100/0	MC-50/50	ME-0/100	Criteria EU Landfill Directive 2003/33/EC		
				Inert	Non-hazardous	Hazardous
	L/S=10	L/S=10	L/S=10	L/S = 10	L/S = 10	L/S = 10
Fluoride	< 10	< 10	< 10	10	150	500
Chloride	< 50	< 50	< 50	800	15000	25000
Sulphate	303.6	522.1	722	1000	20000	50000
Conditions of the test sample						
C (μS/cm)	71.4	95.3	127.6			
Tª (ºC)	24.6	24.8	24.9			
pH	9.43	9.21	9.03			

4.4.2.8. PXRD pattern of hardened mortar

Fig. 4.17 shows the PXRD diagrams of raw samples in hardened mortars MA-100/0, MC-50/50 and ME-0/100 after 220 days of curing. All mineral phases identified previously in NA and RMA were identified in mortars since these were the major components. Typical portlandite in set cement was identified and no ettringite was detected.

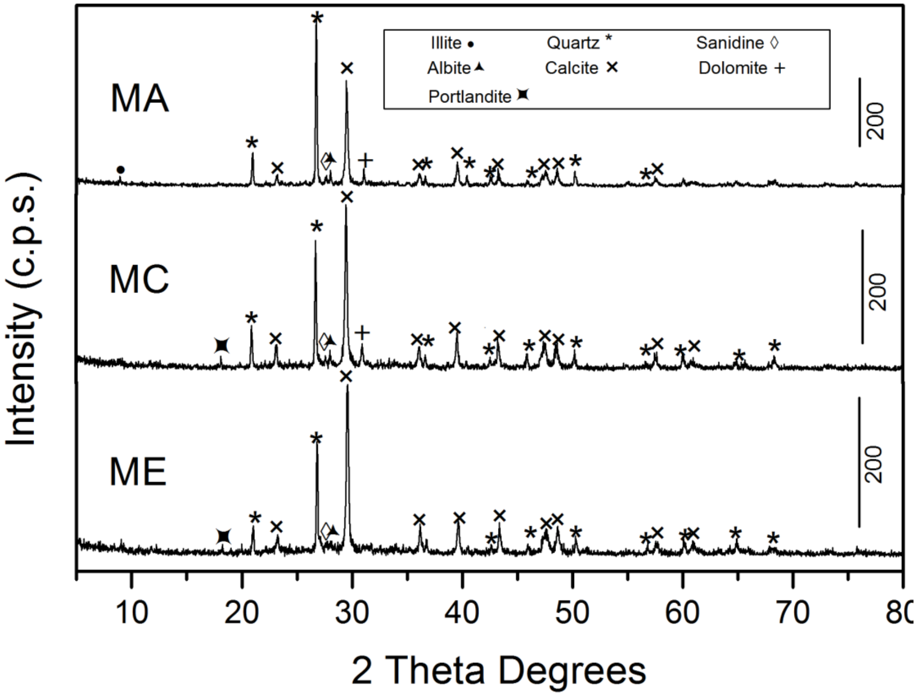

Figure 4.17. Powder X-ray diffraction (PRXD) diagrams of raw samples: MA, MC and ME hardened 220 days.

4.5. Conclusions

Based on the experimental results conducted in this study, the following conclusions related to the effect of recycled masonry aggregates on mortars' properties and the maximum feasible replacement ratio of natural sand by recycled sand can be drawn:

1. The bulk density of fresh and hardened mortars decreased linearly as the use of recycled masonry aggregates increased because of the lower dry density of recycled sand compared to natural sand. This is not a limitation to the use of recycled sand in mortar production.
2. The mean values of the occluded air content showed no statistically significant differences for replacement ratios below

75 %, although a linear decrease when the replacement ratio increased was observed in the mean values.

3. The mean values of workable life showed statistically significant differences for replacement ratios above 25 %. The use of recycled sand in fresh mortars produces a linear decrease in its workable life.
4. The mean values of compressive and flexural strengths decreased linearly as the recycled masonry aggregates content increased, although all mortars with replacement ratios up to 50 % exceeded the value of 10 MPa in the compressive strength test at 28 days of curing. All mortars showed an increase over time of their mechanical strength. The differences between the mean values of the mechanical strengths of the reference mortar and mortars with replacement ratios below 50 % decreased as the curing time increased, reaching a minimum at 180 days.
5. For the same environmental curing conditions, the moisture of the specimens of hardened mortars increased linearly as the recycled masonry aggregates content increased, due to the higher water absorption of recycled sand compared to natural sand. This can be a limitation in outdoor uses.
6. The dry shrinkage increased linearly as the recycled masonry aggregates content increased. The mean values of dry shrinkage were lower than those obtained by other authors.
7. The mean values of the adhesive strength showed no statistically significant differences with replacement ratios below 75 %, due to the dispersion of results in the pull-off test. The mean values decreased linearly as the recycled masonry aggregates content increased.
8. The mean values of the capillary water absorption showed statistically significant differences for replacement ratios above 25 %. The mean values increased linearly as the recycled masonry aggregates content increased.

9. Mortars with recycled ceramic aggregates showed higher weight losses than the reference mortar after 10 cycles of immersion in sodium-sulphate solution, although no greater visible damage was observed. Better results than those of other authors who used recycled concrete aggregates were obtained.
10. No ettringite was detected in PDRX diagrams of mortars.
11. Minor differences between the properties of the reference mortar and mortars made with recycled masonry aggregates were obtained in a previous study where a CEM-IV with 29 % fly ash was used; therefore, the use of this type of cement is recommended instead of CEM-II used in our study for mortar with recycled masonry aggregates production.

Table 4.10 shows the maximum replacement ratio of natural sand by recycled ceramic aggregate for mortar type M-10 production. Total sulphur compounds must be below 1%.

Table 4.10. Maximum replacement ratio of NA by RMA for mortar type M-10 production.

Property	**Maximum replacement ratio (%)**	
	Indoor uses	Outdoor uses
Bulk density of fresh mortar	No limit	No limit
Occluded air content	75	75
Workable life	25	25
Dry bulk density of hardened mortar	No limit	No limit
Compressive strength ([a])	50	50
Flexural strength ([a])	25	25
Dimensional instability (shrinkage)	50	50
Adhesive strength	75	75
Water absorption	No limit	0 Not recommended
Sodium-sulphate attack	No limit	0 Not recommended
Leached specimen	No limit	100

([a]) Considering the long-term results

In conclusion, a maximum replacement ratio up to 50 % of natural sand by recycled masonry sand can be admitted in indoor environments without significantly affecting the hardened mortar properties, although specific studies with different kinds of admixtures to increase the workable life and reduce the water/cement ratio should be carried out. In an outdoor environment freeze-thaw resistance studies should be carried out to confirm that high replacement ratios do not affect the durability of mortar.

The finding of this study can reduce natural sand mining from river and seashores, minimize energy consumption and CO2 emissions and global warming, prevent illegal deposits and landfill of the fine fraction of CDW and meet the limits of the European Waste Framework Directive. This demonstrates the practical relevance of this study to promote cleaner production in the construction sector.

4.6. Standards used in the experimental work

UNE 83115 EX:1989. Friability coefficient (*In Spanish).*

UNE 83831 EX:2010. Methods of test for hardened mortar. Determination of dimensional stability of hardened mortar (*In Spanish).*

UNE 12370:1999. Natural stone test methods. Determination of resistance to salt crystallization (*In Spanish)*.

UNE-EN 196-1:1996. Methods of testing cement. Part 1: Determination of strength.

UNE-EN 933-1:2006. Test for geometrical properties of aggregates Part 1: Determination of particle size distribution. Sieving method.

UNE-EN 933-8:2000. Test for geometrical properties of aggregates. Part 8: Assessment of fines. Sand equivalent test.

UNE-EN 933-11:2009. Test for geometrical properties of aggregates. Part 11: Classification test for the constituents of coarse recycled aggregate.

UNE-EN 934-2:2010. Admixtures for concrete, mortar and grout - Part 2: Concrete admixtures - Definitions, requirements, conformity, marking and labelling.

UNE-EN 998-2:2012. Specification for mortar for masonry. Part 2: Masonry mortar.

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UNE-EN 1015-7:1999. Methods of test for mortar for masonry. Part 7: Determination of air content of fresh mortar.

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UNE-EN 1015-10:1999. Methods of test for mortar for masonry. Part 10: Determination of dry bulk density of hardened mortar.

UNE-EN 1015-11:1999. Methods of test for mortar for masonry. Part 11: Determination of flexural and compressive strength of hardened mortar.

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UNE-EN 13139:2002. Aggregates for mortar.

XP X31 211:2000 Waste - Test for the determination of the leachability of a solid waste material initially massive or generated by a solidification process.

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5. A proposal for the maximum use of recycled concrete sand in masonry mortar design

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Abstract

Natural sand mining from rivers and seashores is causing serious environmental problems in many parts of the world, whereas the fine fraction from recycling concrete waste is underutilized as a construction material. The aim of this paper is to determine the maximum replacement level of natural sand by recycled sand in the manufacturing of masonry mortar (M-10). For this purpose, five replacement levels were tested: 0%, 25%, 50%, 75% and 100% by volume. The mixes were made using cement CEM II/BL 32.5 N in a volumetric proportion of cement-to-aggregate of 1:5. A commercial admixture was used at a constant content. The amount of water was variable to achieve a consistency of 175 ± 10 mm. The short- and long-term mortar properties were evaluated. The data were analyzed using a one-way ANOVA. In conclusion, a maximum percentage of 50% recycled concrete sand can be used in an indoor environment.

Keywords: Mortar, Compressive Strength, Mechanical Properties, Retraction, Waste Treatment

Resumen

La extracción de arena natural de ríos y costas está provocando graves problemas ambientales en muchas partes del mundo, mientras que la fracción fina de los áridos reciclados de residuos de hormigón está infrautilizada como material de construcción. El objetivo de este artículo es determinar el máximo porcentaje de sustitución de arena natural por arena reciclada en la fabricación de morteros M-10. Cinco niveles de sustitución en volumen fueron ensayados: 0%, 25%, 50%, 75% y 100%. Las mezclas fueron hechas con cemento CEM II/BL 32,5 N en una relación volumétrica cemento-árido de 1:5. Se utilizó un aditivo comercial a dosis constante. El agua se ajustó experimentalmente para conseguir una consistencia de 175 ± 10 mm. Se evaluaron las propiedades de los morteros a corto y largo plazo. Los datos se analizaron mediante una ANOVA-simple. En conclusión, un porcentaje máximo del 50% de arena reciclada de hormigón puede usarse en interiores.

Palabras clave: mortero, resistencia a compresión, propiedades mecánicas, retracción, tratamiento de residuos

5.1. Introduction

Concrete is one of the most widely used materials in the world for making architectural structures, foundations, walls, pavements, bridges, dams, reservoirs, pipes and precast elements. Conventional concrete is not considered an environmentally friendly material because of the use of non-renewable natural resources, such as sand and gravel, and its high embodied energy. In most cases, these concrete elements are demolished at the end of their useful life, generating what is known as construction and demolition waste (CDW). Using selective demolition techniques, very pure concrete waste with a high potential for recycling can be obtained (Kamrath, 2013)). For this, all non-mineral dry building materials, such as plasterboards, wood, metals, plastics, should be removed and separated before the demolition of concrete elements. Indeed, in some cases, it may also be worthwhile to separate ceramic elements such as brick and tiles. This has led to the concept of deconstruction techniques (Coelho & de Brito, 2013).

Concrete waste is treated in recycling plants, where the reinforced steel is removed from the concrete rubble. Concrete rubble is crushed in an impact or jaw crusher to reduce the grain size to produce recycled concrete aggregate (RCA). Depending on its subsequent use, the RCA is screened to obtain different sizes. If the RCA is to be used in road pavement, it is screened to obtain 0/22 mm, 0/32 mm or 0/40 mm fractions (Jiménez et al., 2011; Jiménez, 2013), but for its use in the manufacture of new concrete or mortar, the RCA is screened to obtain two different fractions: a coarse fraction (4/16 mm, 4/22 mm, or 4/32 mm) and a fine fraction (0/4 mm). The manufacture of concrete and mortars allows for greater added value to RCA.

The use of fine RCA (recycled concrete sand) has been investigated less than the coarse fraction in concrete manufacturing because of its inferior properties, such as a larger amount of cement paste, higher water absorption and more sulfur compounds (Etxeberria et al., 2007). Evangelista and de Brito (2007) concluded that replacement ratios of up to 30% of natural sand by recycled concrete sand does not jeopardize the mechanical properties of concrete. Kou and Poon (2009) showed that it is possible to use fine RCA in concrete, although the use of fine RCA decreased the compressive strength and increased the drying shrinkage of the concrete. The use of superplasticizers improves the mechanical properties of concrete with fine RCA (Pereira et al., 2012a). However, the water absorption and non-steady-state chloride migration coefficient increase linearly with the replacement ratio of fine natural aggregate by fine RCA, whereas the carbonation resistance is reduced (Evangelista & de Brito, 2010). For durability reasons, the use of fine RCA in structural concrete may pose serious difficulties. Several countries, including China, Germany, Hong Kong, Portugal, Spain and the U.K., forbid the use of fine RCA in the manufacturing of concrete (Gonçalves & de Brito, 2010). In a recent article, Evangelista and de Brito (2014) concluded that, considering the particularities of fine RCA in the method used for the mix design and production, it is possible to replace natural sand with fine RCA to make structural concrete.

The use of fine RCA in the manufacture of non-structural concrete or masonry mortar, to be used in structures or building elements not affected by durability issues (e.g., partition walls in indoor environments), might constitute an alternative way to recycle this fraction as recycled concrete sand. However, scientific and technical studies on the use of fine RCA in the manufacture of mortar are scarce. Corinaldesi and Moriconi (2009) and Corinaldesi (2009) concluded that replacement levels up to 100% by weight of natural sand by recycled concrete sand decreases the flexural and compressive strength with respect to the reference mortar, although the masonry assemblages with recycled mortar displayed excellent mechanical behavior. Dapena et al. (2011) reported that the compressive strength dropped linearly with the percentage of replacement of natural sand by recycled concrete sand. Vegas et al. (2009) proposed that it is possible to replace, by weight, up to 25% of natural sand with recycled concrete sand without decreasing the mechanical strength, workability and shrinkage in masonry mortar. These authors replaced natural sand with recycled concrete sand by weight. Because of the lower density of the fine RCA, substituting materials by weight produces a larger volume of lower-quality mortar (Jiménez et al., 2013).

Martínez et al. (2013) replaced by volume 100% of natural sand with different types of recycled sand and found that most of the natural aggregate mortars achieved higher mechanical properties than the recycled aggregate mortars. Very fine RCA, with particle sizes less than 0.150 mm, have also been used in mortars. Braga et al. (2012) obtained very satisfactory results for most of the mortars prepared with different incorporation levels of fine concrete aggregates. Neno et al. (2014) studied the effect of different replacement levels of river sand by recycled concrete sand on mortar properties, although these authors did not propose a maximum replacement ratio that meets all the performance requirements of mortars. Ledesma et al. (2014) evaluated the short- and long-term properties of masonry mortar and concluded that a replacement ratio of up to 40% is a viable alternative for masonry mortar production. Cuenca-Moyano et al. (2014) studied the influence of pre-soaked recycled fine aggregates from CDW on the properties of masonry concrete and concluded that this method may be more effective to compensate for the higher water absorption of recycled aggregates.

The aim of this work was to establish the maximum feasible replacement level of natural sand by recycled concrete sand in the manufacturing of masonry mortars. For this study, the performances of fresh and hardened mortar with replacement levels of up to 100% by volume were tested. The findings of this article support the use of recycled concrete sand, as it minimizes the consumption of non-renewable natural resources such as natural sand from rivers, reduces the energy consumption and CO_2 emissions that occur when rock and gravel are crushed to produce natural sand and promotes the recycling of construction and demolition waste.

5.2. Materials and Experimental Procedure

5.2.1. Material characterization

Two different aggregates were used in this study: natural siliceous river sand (NA) as a reference and fine RCA from a recycling plant located in northern Córdoba, Spain. The recycling plant was equipped with a mobile crushing unit with a magnetic ferrous metal separator and a mobile vibrating screen with two sieves that could produce three recycled aggregate fractions: 0/8 mm, 8/40 mm and > 40 mm. The fine RCA was collected from the 0/8-mm stockpile, and this sample was sieved in the laboratory to remove particles larger than 4 mm to obtain the same maximum particle size as the NA. The primary constituent of the RCA, determined in accordance with standard UNE-EN 933-11:2009, was concrete (98%). Only a few impurities, such as asphalt (1.7%) and ceramics (0.4%), were found. Thus, the recycled aggregate used can be considered very pure.

Both sands met the specifications of standard UNE-EN 13139:2002 for mortar aggregates. Table 5.1 shows the size distribution determined in accordance with European standard UNE-EN 933-1:2006 and Table 5.2 shows the materials' physico-mechanical and chemical properties. The fine RCA had approximately double the fine content (< 0.063 mm), similar sand equivalents, a higher water absorption, lower dry density and higher friability coefficient than the NA. In the chemical characterization, the fine RCA did not exceed the 1% sulfur and soluble salt ceilings set by standard UNE-EN 13139:2002 for total sulfur compounds (1%). Organic matter or other substances that might have altered the mortar setting time were not detected. The water-soluble chlorides and the loss on ignition were higher than for the NA. Both materials were classified as non-reactive according to UNE 146507-1:1999. All results were in agreement with the properties described in the literature for RA from CDW (Martínez et al., 2013; Ulsen et al., 2013).

Table 5.1. Particle size distribution of materials and uniformity coefficient (Cu).

Sieve size (mm)	Percent passing (%)	
	NA	RCA
4	100.00	100.00
2	87.00	74.00
1	73.00	43.00
0.5	53.00	25.00
0.25	23.00	14.00
0.125	8.00	9.00
0.063	3.20	6.00
Cu	5.00	11.00

Table 5.2. Characterization of aggregate for mortars.

Characteristic	Standard	AN	RCA	Limit set by UNE-EN 13139
Fine content (%) [(a)]	UNE-EN 933-1	3.2	6.1	≤ 8
Sand equivalent (%)	UNE-EN 933-8	83	88	No limit
Dry sample density [(b)] ϱ_{rd} (g/cm^3)	UNE-EN 1097-6	2.63	2.2	No limit
Water absorption [(b)] (%)	UNE-EN 1097-6	0.79	8.26	No limit
Friability coefficient (%)	UNE 83115	15	23	No limit
Acid soluble sulfates (% SO_3)	UNE-EN 1744-1	< 0.01	0.4	≤ 0.8
Total sulfurs (% SO_3)	UNE-EN 1744-1	< 0.01	0.4	≤ 1
Humic content (%)	UNE-EN 1744-1	ND[(c)]	ND[(c)]	No limit
Fulvic acid (%)	UNE-EN 1744-1	ND[(c)]	ND[(c)]	No limit
Water soluble chlorides (% Cl)	UNE-EN 1744-1	< 0.01	0.07	≤0.15
Loss of ignition (%)	UNE-EN 1744-1	6.56	11.12	No limit
Soluble salts 1:2 (%)	Gravimetric	0.128	0.545	≤1

[(a)] Finer than 0.063 mm

[(b)] Fraction 0.063/4 mm

[(c)] Not detected

The aggregates were also analyzed by powder X-ray diffraction patterns (PXRD) using a Siemens D-5000 instrument with CuKα radiation. The equipment used is as described by Jiménez et al. (2013);

the main crystalline phase was quartz for both the NA and RCA (Table 5.3), whereas the other minor phases were calcite, dolomite, illite, albite and sanidine. These results depend on the mineralogical composition of the virgin aggregates used in the manufacture of concrete and reflect the geological environs of the plant location (Rodrigues et al., 2013).

Table 5.3. Mineralogical analysis of NA and fine RCA.

Mineral phase	**Mineral relative abundance (*)**	
	NA	**RCA**
Albite $Na(Si_3Al)O_8$	*	**
Calcite $CaCO_3$	**	**
Dolomite $CaMg(CO_3)_2$	**	
Illite $KAl_2Si_3AlO_{20}(OH)_2$	*	*
Quartz (SiO_2)	******	*****
Sanidine $(Na,K)(Si_3Al)O_8$	**	*

The environmental performance of the fine aggregates was assessed using the UNE-EN 12457-3:2003 leaching test. This standard is a two-step batch leaching test in which 175 g of dry samples of material at liquid to solid ratios (L/S) of 2 and 10 l/kg are used. The quantities of several major and trace elements were determined in the laboratory using inductively coupled plasma mass spectrometry (ICP-MS). Table 5.4 shows the leached concentrations (mg/kg) for L/S=2 and L/S=10 and the limits established in Annex 2 of the 2003/33/CE Council Decision for landfill classification. Both materials were classified as inert. As shown in this table, the amount of Cr and SO_4^- leachate was higher in the fine RCA than NA. These elements come from the cement composition and in some cases exceed the limit of inert materials (Jiménez et al., 2013).

Table 5.4. Leached concentrations of NA and fine RCA (mg/kg) and waste acceptance criteria (EU Council Decision 2003/33/EC).

ɪent	NA		RCA		Criteria EU Landfill Directive 2003/33/EC					
					Inert		Non-hazardous		Hazardous	
	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10	L/S = 2	L/S = 10
hromium)	0.001	0.000	0.172	0.338	0.2	0.5	4	10	25	70
ickel)	0.000	0.000	0.004	0.003	0.2	0.4	5	10	20	40
opper)	0.000	0.003	0.052	0.074	0.9	2	25	50	50	100
Zinc)	0.001	0.002	0.001	0.002	2	4	25	50	90	200
rsenic)	0.013	0.061	0.003	0.017	0.1	0.5	0.4	2	6	25
elenium)	0.003	0.013	0.007	0.005	0.06	0.1	0.3	0.5	4	7
Molybdebum)	0.001	0.000	0.096	0.180	0.3	0.5	5	10	20	30
admium)	0.000	0.000	0.000	0.000	0.03	0.04	0.6	1	3	5
ntimony)	0.001	0.002	0.001	0.019	0.02	0.06	0.2	0.7	2	5
arium)	0.025	0.091	0.195	1.340	7	20	30	100	100	300
Mercury)	0.000	0.000	0.000	0.000	0.003	0.01	0.05	0.2	0.5	2
ead)	0.000	0.000	0.000	0.000	0.2	0.5	5	10	25	50
ride	< 2	< 10	< 2	< 10	4	10	60	150	200	500
ride	14.2	< 50	51.932	69.74	550	800	10000	15000	17000	25000
hate	34.5	< 50	318	840	560	1000	10000	20000	25000	50000
ditions of the test sample										
ductivity (µS/cm)	56.5	22.5	995	641						

A cement type CEM-II/BL 32.5N, according to UNE-EN 197-1:2011, was used to make the mortar. A commercial admixture (NEOPLAST) was mixed directly into the water at a dosage of 0.1 cm^3. This admixture is a conventional plasticizer for mortars used to improve the workability and reduce the amount of mixing water. Pereira et al. (2012a) and Cartuxo et al. (2015) demonstrated that the use of admixtures in concrete made with fine RCA exhibited better mechanical and rheological performance than the reference mixes without admixtures.

5.2.2. Mortar batching

To design the mortar mixture proportions, the following criteria were established.

a) Maintaining the original grading curves below 4 mm for NA and fine RCA.

b) Maintaining a volumetric proportion of cement-to-aggregate of 1:5 in all mixes.

c) A gradual increase in the incorporation of fine RCA: 0%, 25%, 50%, 75% and 100%. Five mortars were tested: MA-100/0, MF-75/25, MG-50/50, MH-25/75 and MI-0/100.

d) A replacement by volume of the NA by RCA. The dry mass of each component was calculated using the formulas [1] to [4].

$$Drymassofcement = \frac{V \cdot 1 \cdot \mathrm{\rho rdCEM}}{6} \quad (1)$$

$$DrymassofRCA = \frac{V \cdot X \cdot 5 \cdot \rho \mathrm{rdRCA}}{6} \quad (2)$$

$$DrymassofNA = \frac{V \cdot (1-X) \cdot 5 \cdot \rho \mathrm{rNA}}{6} \quad (3)$$

$$X = \frac{PercentageofreplacementofNAbyRCA}{100} \quad (4)$$

Table 5.5 shows the dry mass of 1600 cm^3 of components. Due to RCA’s lower density, the dry mass of RCA was lower than that of NA for the same volume of mixed material.

Table 5.5. Mortar mixture proportions.

Mortar type	NA/RCA	Mix proportions - dry weight							
		NA (g)	RCA (g)	CEM (g)	Water (g)	Admixture (cm^3)	Consistency (mm)	w/c	$(w/c)_{ef}$
MA	100/0	3508	0	757	596	0.1	181	0.78	0.75
MF	75/25	2631	734	757	629	0.1	174	0.83	0.72
MG	50/50	1754	1467	757	667	0.1	178	0.87	0.69
MH	25/75	877	2201	757	701	0.1	175	0.92	0.67
MI	0/100	0	2935	757	754	0.1	172	0.97	0.65

e) No pre-saturation of the fine RCA. Based on the study of Ferreira et al. (2011), the aggregates were not previously pre-saturated. RCA were used with their natural moisture (2.7%).

f) Use of a fixed amount of admixture in all mixes. The admixture was added directly into the water at a dosage of 0.1 cm^3.

g) The water content was set experimentally to achieve a consistency of 175 ± 10 mm (UNE-EN 1015-3:1999). As the replacement ratio increased, it was necessary to increase the amount of water because of the higher water absorption of fine RCA. The total water/cement ratio (w/c) ranged from 0.78 in the MA-100/0 to 0.97 in the MI-0/100 mortar, whereas the effective w/c ratio obtained by subtracting the difference in water absorbed by the NA and RCA over 24 h ranged from 0.75 in MA-100/0 to 0.65 in MI-0/100. The decrease in the $(w/c)_{ef}$ ratio with the incorporation of the fine RCA is explained by the recycled aggregates not absorbing their potential capacity (24 h) during the mixing period (3–4 min). Pereira et al. (2012a, 2012b) showed the fine RCA's water absorption over time and found that after 10 min the fine RCA had absorbed 50% of its potential capacity.

5.2.3. Mixing procedure

The mortars were mixed in a standard mixer (UNE-EN 196-1:1996) according to the procedure described by Jiménez et al. (2013).

5.2.4. Tests

Three properties were tested to evaluate the fresh mortar: density, air content and workability. The hardened mortar was characterized by studying seven properties: dry bulk density, flexural strength, compressive strength, dimensional instability (shrinkage), adhesive strength, water absorption due to capillary action and durability. Four different mixes of each mortar type were made. Table 5.6 shows the testing standards used and the climatic conditions of the three climatic chambers used in these tests. The test methods are described in their correspondent standard, except for the durability test.

Table 5.6. Standard used to characterise the mortar properties.

Properties of fresh mortar	Standard	Specimens and dimensions	Climatic chamber [1]	Curing time
Bulk density of the fresh mortar	UNE-EN 1015-6:1998	4	Chamber-2	
Entrained air	UNE-EN 1015-7:1998	4	Chamber-2	
Workability	UNE-EN 1015-9:2000	4	Chamber-2	
Properties of hardened mortar				
Dry bulk density	UNE-EN 1015-10:1999	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Flexural strength	UNE-EN 1015-11:1999	4 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Compressive strength	UNE-EN 1015-11:1999	8 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	7, 28, 90, 180 days
Shrinkage	UNE 83831 EX:2010	3 Prismatic 40 x 40 x 160 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	Up to 203 days
Adhesive strength	UNE-EN 1015-12:2000	4 Circular – 50 mm diameter, 10 mm-thick	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
Water absorption due to capillary	UNE-EN 1015-18:2002	6 Prismatic 40 x 40 x 80 mm	Chamber-1 (7 days) Chamber-2 (rest of curing time)	28 days
[illegible]	[illegible]	[illegible]		[illegible]

According to Vegas et al. (2009), the durability test was focused on determining resistance to salt crystallization (UNE-EN 12370:1999). This test method, described in the standard for natural stone, was applied to 40 x 40 x 160-mm prismatic specimens. After drying to constant mass, the specimens were immersed in a sodium sulfate solution and then dried in an oven and left to cool to laboratory temperature. This cycle was repeated 15 times, and the percentage change in mass was determined.

5.2.5. Statistical analysis

To determine whether the replacement ratio had a statistically significant effect on the mortar's properties, a one-way ANOVA was conducted. If the p-value of the F-test is greater than 0.05, there is no statistically significant difference between the mean values from one level of replacement to another at the 95.0% confidence level. If the p-value of the F-test is less than 0.05, there is a significant difference between the mean values from one level of replacement to another at the 95.0% confidence level. A multiple range test was also conducted to determine which means were significantly different from the others. Homogeneous groups were identified using columns of Xs. For replacement ratios whose mean values had statistically significant differences, a trend line was adjusted with the aim of studying the effect of the incorporation of fine RCA on the 'measured property'.

5.3. Results and Discussion

5.3.1. Bulk density of fresh mortar

The p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the bulk density of fresh mortar was affected by the incorporation of fine RCA. From a statistical standpoint, three homogeneous groups were identified in the multiple range tests. Table 5.7 shows that there were no statistically significant differences between the mean values of mixes with replacement ratios below 50%. Analyzing the evolution of these mean values (Fig.5.1), the fresh bulk density slightly increased with a replacement ratio of 25% and decreased linearly with higher replacement levels.

Table 5.7. Multiple Range Test for the bulk density of fresh mortar. Method: 95 % LSD.

Mortar	Count	LS mean (kg/m³)	SD (kg/m³)	Homogeneous groups		
MA-100/0	4	1950	23			X
MF-75/25	4	1963	25			X
MG-50/50	4	1943	17			X
MH-25/75	4	1910	8		X	
MI-0/100	4	1867	22	X		

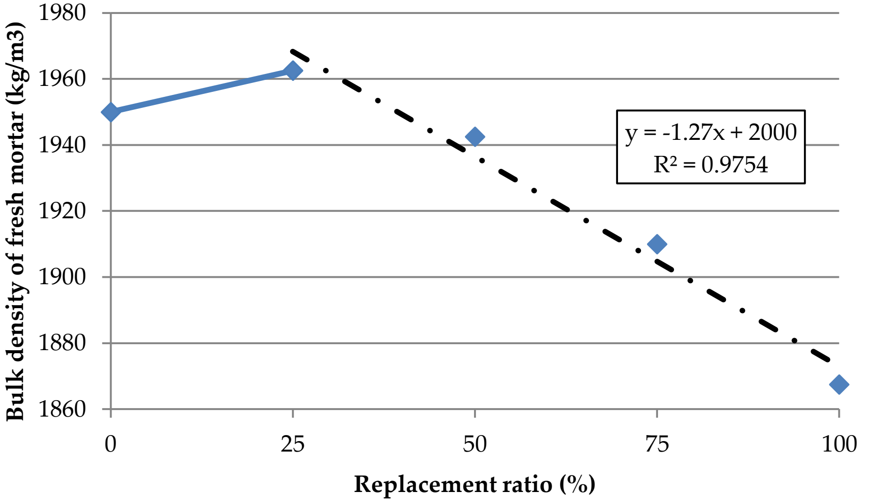

Figure 5.1. Bulk density of fresh mortar vs. replacement ratio.

These results can be explained three different ways. The higher amount of very fine particles (< 0.063 mm) of RCA that at low rates of replacement has a filler effect on the matrix of mortar consequently produces a higher density. The higher uniformity coefficient of RCA gives greater compactness to the mix (Jiménez et al., 2012a; Jiménez et al., 2012b). The lower particle density of RCA, at replacement rates above 25%, has a greater effect than the previous two.

Neno et al. (2014) showed that fresh bulk density decreased linearly as the content of RCA increased. These authors did not observe a higher fresh bulk density in mixes with low replacement rates of NA by fine RCA. This can be explained because these authors kept the particle size distribution constant in all mixes. The maximum loss observed by Neno et al. (2014) was 6.8%, whereas in this study the maximum loss was 4.2%. The use of fine RCA caused less of a decrease than the fine ceramic aggregates. Jiménez et al. (2013) demonstrated that the use of fine RA from ceramic waste caused significant differences from the reference mortar, with replacement rates above 5%.

This is not a limiting property because the European standards do not set a minimum or maximum value for masonry mortar. A maximum replacement ratio of 100% could be suggested for masonry mortar production to ensure proper performance in terms of the bulk density of fresh mortar.

5.3.2. Entrained air content

The p-value of the F-test was greater than 0.05 (p-value = 0.061); thus, the replacement ratio did not have a significant effect on this property. Due to the high dispersion of the data, the multiple-range test showed only one homogeneous group (Table 5.8). The replacement ratio of 25% that showed the highest fresh bulk density also showed the lowest entrained air content, which is a consistent result. From a statistical standpoint, this is not a limiting property and a maximum replacement ratio of 100% can be proposed for masonry mortar production to ensure proper performance in terms of entrained air content. Although the statistical results, the entrained air content mean values, decreased linearly as the fine RCA content increased (Fig. 5.2).

Table 5.8. Multiple Range Test for entrained air content. Method: 95 % LSD.

Mortar	Count	LS mean (%)	SD (%)	Homogeneous groups
MA-100/0	4	10.8	0.7	X
MF-75/25	4	8.5	1.3	X
MG-50/50	4	9.8	1.3	X
MH-25/75	4	9	3.1	X
MI-0/100	4	8.5	0.9	X

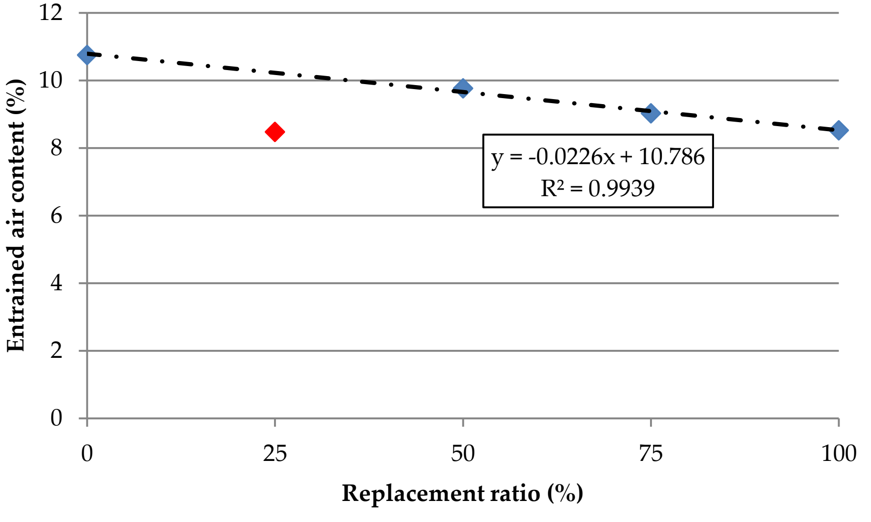

Figure 5.2. Entrained air content vs. replacement ratio.

Ledesma et al. (2014) and Vegas et al. (2009) found no significant differences in the entrained air values of mortars with a 25% and 40% replacement of natural sand by fine RCA, respectively. Cuenca-Moyano et al. (2014) found that the use of pre-soaked recycled fine aggregate reduced the air content slightly. These authors also observed a clear influence of the w/c ratio on the air content of masonry mortar: the air content increased with the total w/c ratio. In contrast, the air content decreased with bulk and dry bulk density. Most researchers have not included this test in their work.

5.3.3. Workability

The p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on this property. Four homogeneous groups were identified in the multiple range tests. Table 5.9 shows that there were no statistically significant differences between the mean values of mixes with replacement ratios below 25%. Fig. 5.3 shows that the mean workability values decreased linearly as the content of fine RCA increased. This phenomenon occurs because RCA's absorption capacity of water was higher than that of NA, and the amount of water required to saturate the aggregates was not added during the mixing process. Fig. 5.4 shows how the effective water/cement ratio decreased linearly as the replacement ratio increased.

Table 5.9. Multiple Range Test for workability. Method: 95.0 % LSD.

Mortar	Count	LS mean (min)	SD (min)	Homogeneous groups			
MA-100/0	4	206.5	7.9				X
MF-75/25	4	189.3	12.9			X	X
MG-50/50	4	185.5	14.8			X	
MH-25/75	4	148.8	10.9		X		
MI-0/100	4	121.3	14.7	X			

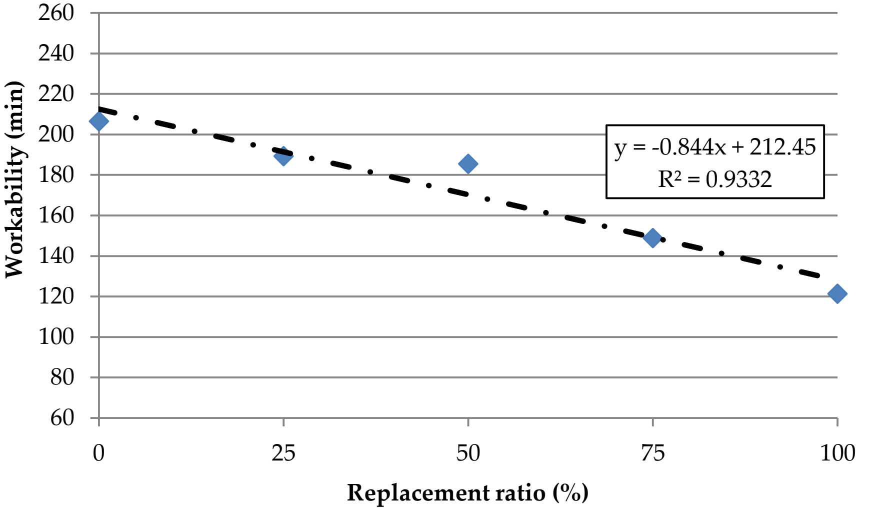

Figure 5.3. Workability vs. replacement ratio.

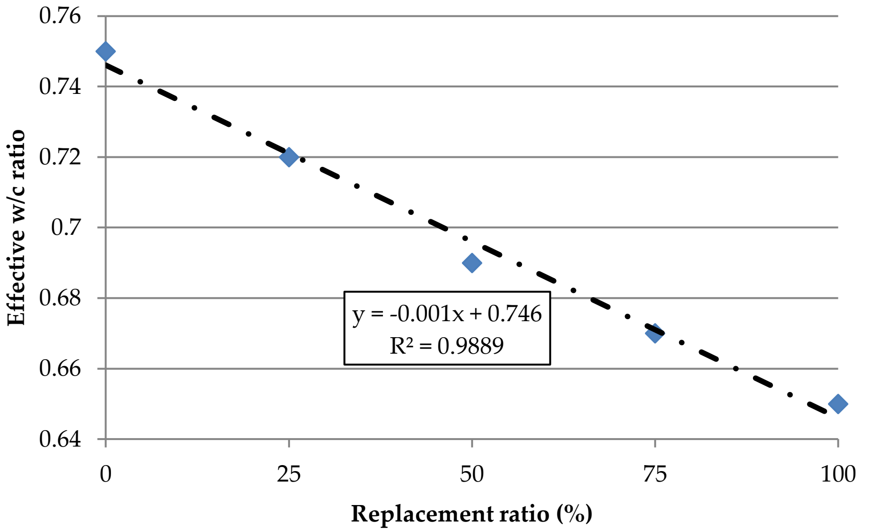

Figure 5.4. Effective w/c ratio vs. replacement ratio.

Workability is a key aspect for the mason to be able to produce quality masonry work. However, few authors have studied the effect of the incorporation of fine RCA on this property. Ledesma et al. (2014) found a maximum loss on the workability of 57.5%, using a replacement ratio of fine RCA of 40%. In a previous work, Jiménez et al. (2013) found a maximum loss of 55% with the same replacement ratio, but in this case using ceramic masonry aggregates. The maximum loss found in this study was 41.3% with a replacement ratio of 100%. The best results of this study are related to the best control of the environmental conditions in chamber-2 (Table 5.6), under which the test was performed. Other authors studied water retentivity (prEN 1015-8:1998), a property related to workability. Vegas et al. (2009) showed that replacement ratios below 25% of natural sand by fine RCA did not affect the water retentivity of fresh mortar, and Martínez et al. (2013) found minimum differences in mortars manufactured with a total replacement level of low-quality natural sand with different types of recycled aggregates from CDW.

One alternative to improve the workability of fresh mortar is pre-saturating the fine RCA (Poon et al., 2004; Mefteh et al., 2013). The authors believe that pre-saturating the fine RCA is not a viable alternative because fine RCA retain considerable water on their surfaces and pores when wet, increasing the effective water/cement ratio. Cuenca-Moyano et al. (2014) proposed pre-soaking the fine recycled aggregates, but these authors did not study this property. Moreover, there is neither a good technique nor proper facilities to manipulate the wet fine RCA for use in mortar production. If fine RCA is used with its natural moisture, the use of chemical admixtures can be used to improve the workability. Pereira et al. (2012b) demonstrated that the efficiency of superplasticizers in terms of workability falls as the fine RCA incorporation ratio increases in concrete manufacturing.

From a statistical standpoint, a maximum replacement ratio of 25% can be proposed for masonry mortar production to ensure proper performance in terms of workability.

5.3.4. Dry bulk density of 28-day hardened mortar

The p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on this property. Four homogeneous groups were identified in the multiple range tests. Table 5.10 shows that there were no statistically significant differences between the mean values of mixes with replacement ratios below 25%. Fig. 5.5 shows that the mean dry bulk density values again decreased linearly after the 25% replacement ratio. The reason for the decrease in the dry bulk density is the same as that for the decrease of the fresh bulk density.

Table 5.10. Multiple range test for dry bulk density of hardened by mortar type. Method: 95 % LSD.

Mortar	Count	LS mean (kg/m³)	SD (kg/m³)	Homogeneous groups			
MA-100/0	4	1817	14				X
MF-75/25	4	1811	24				X
MG-50/50	4	1777	14			X	
MH-25/75	4	1714	9		X		
MI-0/100	4	1658	19	X			

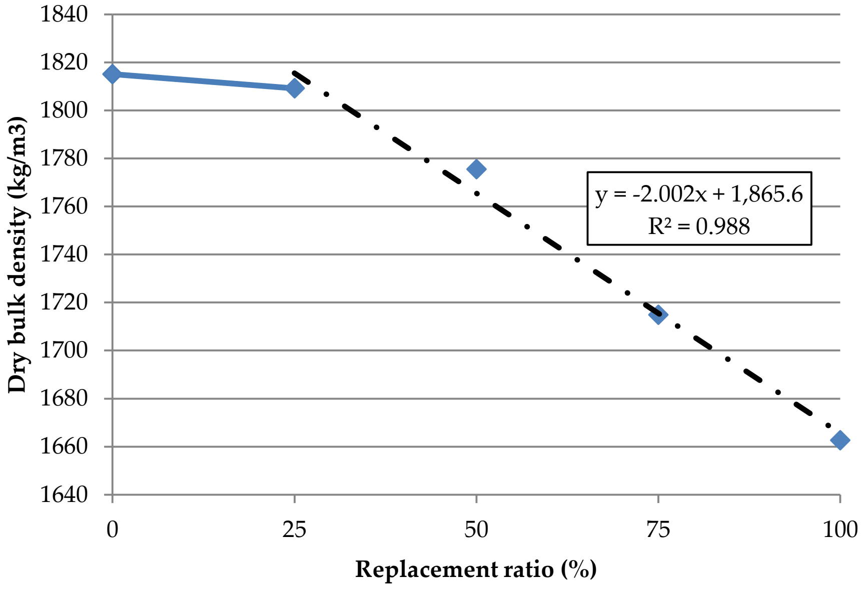

Figure 5.5. Dry bulk density vs. replacement ratio.

These results are consistent with those reported in the literature. Vegas et al. (2009) and Dapena et al. (2011) found no significant differences with replacement ratios below 20% and 25%, respectively. Martínez et al. (2013) found lower densities in mortars manufactured with RA from CDW. Neno et al. (2014) showed a similar trend, although in that case the authors found a small increase with a 20% replacement ratio. The maximum losses observed by Neno et al. (2014) and in this study were similar (9.0% vs. 8.7%). Ledesma et al. (2014) found slight increases with replacement ratios of up to 10% and decreases with replacement ratios of up to 20%.

For the same reason given for the fresh bulk density, a maximum replacement ratio of 100% can be proposed for masonry mortar production.

5.3.5. Compressive strength of hardened mortar

From a statistical standpoint, a one-way ANOVA test was conducted at 7, 28, 90 and 180 days of curing. In all cases, the p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on the compressive strength. Table 5.11 shows the homogeneous groups identified in the multiple-range test. As shown, at early ages more homogeneous groups were identified than at older ages. For all curing times there were no statistically significant differences between the compressive strength mean values in mixes with replacement ratios below 50%. At 180 days, replacement ratios up to 75% did not show statistically significant differences with respect to the reference mortar.

Table 5.11. Multiple Range Test for compressive strength of hardened mortar by mortar type and curing time. Method: 95 % LSD.

Mortar	Count	LS mean (MPa)	SD (MPa)	Homogeneous groups		
7 Days (p-value = 0.0004)						
MA-100/0	4	11.2	0.4			X
MF-75/25	4	10.9	0.8			X
MG-50/50	4	10.3	0.3		X	X
MH-25/75	4	9.6	0.3	X	X	
MI-0/100	4	8.9	0.8	X		
28 Days (p-value = 0.0000)						
MA-100/0	4	11.5	0.7		X	
MF-75/25	4	11.6	0.3		X	
MG-50/50	4	10.9	0.7		X	
MH-25/75	4	9.7	0.5	X		
MI-0/100	4	9.1	0.5	X		
90 Days (p-value = 0.0020)						
MA-100/0	4	12.1	0.6			X
MF-75/25	4	11.8	0.9			X
MG-50/50	4	11.2	0.2		X	X
MH-25/75	4	10.3	1.1	X	X	
MI-0/100	4	9.7	0.6	X		
180 Days (p-value = 0.0128)						
MA-100/0	4	12.4	0.5		X	
MF-75/25	4	12.9	0.3		X	
MG-50/50	4	12.8	1.2		X	
MH-25/75	4	12	0.6		X	
MI-0/100	4	10.7	1.1	X		

The five mortars displayed a similar pattern in compressive strength. The compressive strength for mortars with replacement ratios up to 50% exceeds the value of 10 MPa required for mortar type M-10 (UNE-EN 998-2:2012) at 28 days of age, whereas the mortars with replacement ratios above 50% did not reach this value. The mortar with fine RCA showed a greater increase in compressive strength mean values over time. For example, a 10.7% increase in compressive strength was recorded between the 7- and 180-day reference mortar (MA-100/0), whereas the rise recorded for mortar MG-50/50 was 24.3% and for mortar MI-0/100 the rise was 20.2%. This demonstrates that the effect of the fine RCA incorporation is greater at early ages than later ages, which is consistent with the statically homogeneous groups identified in Table 5.11. In relative terms, the 180-day compressive strength was less affected by the incorporation of fine RCA because the slope of the linear trend was slightly lower than for the 7-day material (Fig. 5.6). These results can be explained by the higher specific surface of the fine RCA and the amount of non-hydrated cement that completes its hydraulic reaction when in contact with water.

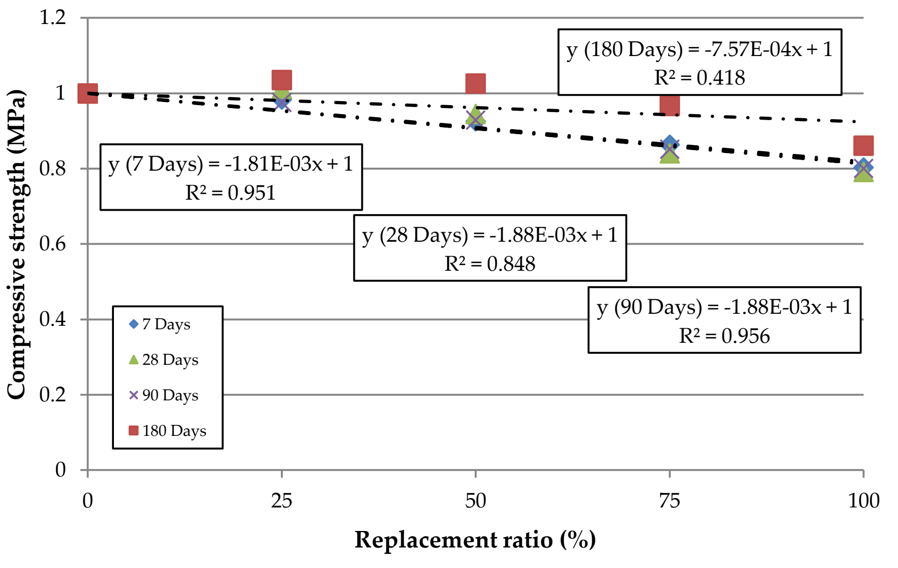

Figure 5.6. Influence of fine RCA replacement ratio on the relative compressive strength at 7, 28, 90 and 180 days.

Neno et al. (2014) found that the incorporation of 100% fine RCA resulted in a compressive strength improvement of 48.3% at 28 days of age, whereas in this study the total replacement of NA by fine RCA resulted in a decrease of 20.9%. Ledesma et al. (2014) described in detail the reasons for these differences. The most significant reason is that Neno et al. (2014) used fine RCA from selected concrete blocks (class 30/37) manufactured in the laboratory and crushed at early ages; therefore, the amount of non-hydrated cement was probably higher than in the recycled aggregates used in this study.

Ledesma et al. (2014) demonstrated that replacement ratios of NA by fine RCA up to 40% did not affect the mechanical properties of M-5 masonry mortar. The best results obtained by Ledesma et al. (2014) can be attributable to the cement CEM-IV, which used 29% fly ash. The combined effect of coal fly ash and RCA improves the properties of concrete (Kim et al., 2013). These results are explained by the pozzolanic reaction between coal fly ash and $Ca(OH)_2$ of the RCA. Kou and Poon (2013) found improvements in the long-term properties of concrete made with fly ash and RCA. These authors proposed that a combination of 50% of RCA and 25% replacement ratio of Portland cement by coal fly ash is an optimal solution for recycled concrete production.

Vegas et al. (2009) and Dapena et al. (2011) concluded that the mechanical strength decreases significantly in mortars when natural sand is replaced by fine RCA. These differences can be explained by the different proportion method employed. This study replaced aggregates by volume, whereas the previous authors replaced NA with RCA by weight. Because of the lower density of the RCA, substituting materials by weight produces a larger volume of lower-quality mortar. Martínez et al. (2013) found that the use of fine recycled aggregates, independent of the composition of the CDW origin, improved the compressive strength of the mortar manufactured with the most accessible natural sand in Havana because of the low quality of this natural aggregate.

The moisture of the specimen was measured after fracture. Although all specimens were cured under the same conditions (HR= 65±5% and Tª = 20±2 ºC), mixes with more fine RCA incorporation had a higher moisture content (Fig. 5.7). This can be explained by the higher water absorption capacity of the recycled aggregates, which may limit their use in outdoor environments.

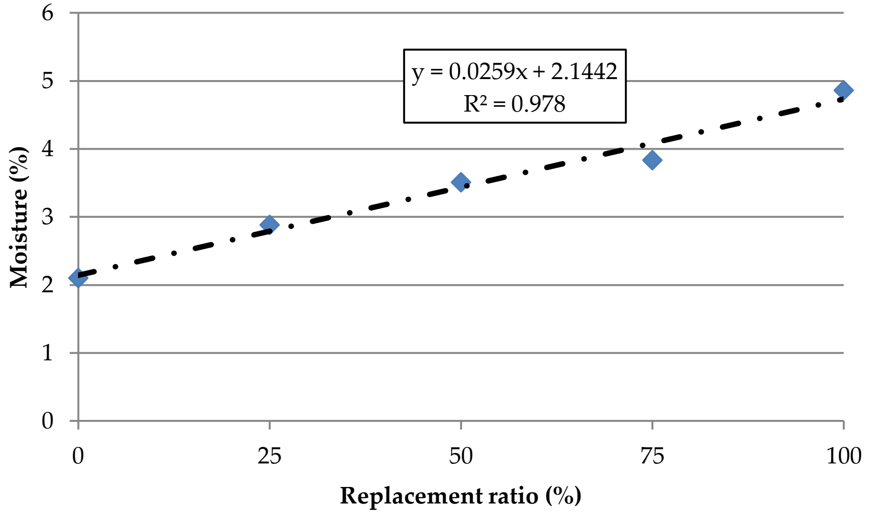

Figure 5.7. Influence of fine RCA replacement ratio on the moisture of the specimen.

Based on the previous results, a maximum replacement ratio of 50% can be proposed for M-10 masonry mortar production to ensure a proper performance in terms of compressive strength.

5.3.6. Flexural strength of hardened mortar

Regarding the flexural strength, in all cases (7, 28, 90 and 180 days) the p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on the flexural strength. The reference mortar displayed greater flexural strength values for all curing times. Between two to four homogeneous groups were identified in the multiple range test (Table 5.12): four for 7 days and 28 days of curing time, two for 90 days and three for 180 days. All mixes had a similar pattern in the flexural strength. At 7 days, the use of 100% fine RCA decreased the flexural strength 36%, with respect to the reference mortar, whereas at 180 days the decrease was 28%. From

7 to 180 days the flexural strength increased 42% in the reference mortar, whereas in mortar with 100% fine RCA the increase was 60%.

Table 5.12. Multiple Range Test for flexural strength of hardened mortar by mortar type and curing time. Method: 95 % LSD.

Mortar	Count	LS mean (MPa)	SD (MPa)	Homogeneous groups			
7 Days (p-value = 0.0000)							
MA-100/0	4	3.5	0.1				X
MF-75/25	4	2.9	0.2			X	
MG-50/50	4	2.8	0.2		X	X	
MH-25/75	4	2.6	0.2		X		
MI-0/100	4	2.2	0.3	X			
28 Days (p-value = 0.0005)							
MA-100/0	4	3.7	0.5				X
MF-75/25	4	3	0.3			X	
MG-50/50	4	3	0.3		X	X	
MH-25/75	4	2.6	0.2	X	X		
MI-0/100	4	2.5	0.3	X			
90 Days (p-value = 0.0063)							
MA-100/0	4	3.6	0.2		X		
MF-75/25	4	2.9	0.3	X			
MG-50/50	4	2.9	0.5	X			
MH-25/75	4	2.9	0.2	X			
MI-0/100	4	2.6	0.3	X			
180 Days (p-value = 0.0083)							
MA-100/0	4	4.9	0.5			X	
MF-75/25	4	4.3	0.1		X	X	
MG-50/50	4	4.1	0.4	X	X		
MH-25/75	4	3.9	0.5	X	X		
MI-0/100	4	3.5	0.6	X			

Flexural strength decreased linearly with a rising replacement ratio (Fig. 5.8). As observed for compressive strength, flexural strength was more affected by the incorporation of fine RCA at early ages. Comparing the slopes of the trend lines in Fig. 5.6 and Fig. 5.8, we noted that the compressive strength was more affected than the flexural strength with the use of fine RCA.

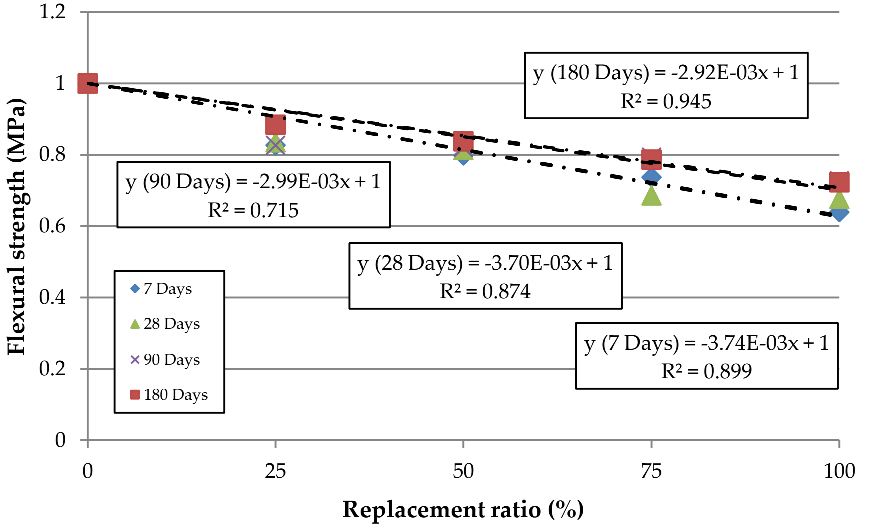

Figure 5.8. Influence of fine RCA replacement ratio on the relative flexural strength at 7, 28, 90 and 180 days.

These results are in agreement with what happens in concrete made with coarse RCA, where flexural strength exhibits lower reduction than compressive strength (Katz, 2003). Neno et al. (2014) showed a similar pattern in flexure and compression.

5.3.7. Dimensional instability (drying shrinkage)

Linear shrinkage (mm/m) was higher in the mortars manufactured with fine RCA than the reference mortar (Fig. 5.9). A one-way ANOVA test was conducted at 28, 112 and 203 days of curing. In all cases, the p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on the dimensional instability. Table 5.13 shows the homogeneous groups identified in the multiple-range test. Fig. 5.10 shows the percentage of weight loss of the mortar specimens during the shrinkage test. The weight loss is attributable to water loss. Mortars made with fine RCA had greater weight loss because these mortars needed more water for mixing. After 60 days, slight increases in weight were measured, which may be due to carbonation reactions (Quattrone et al., 2014).

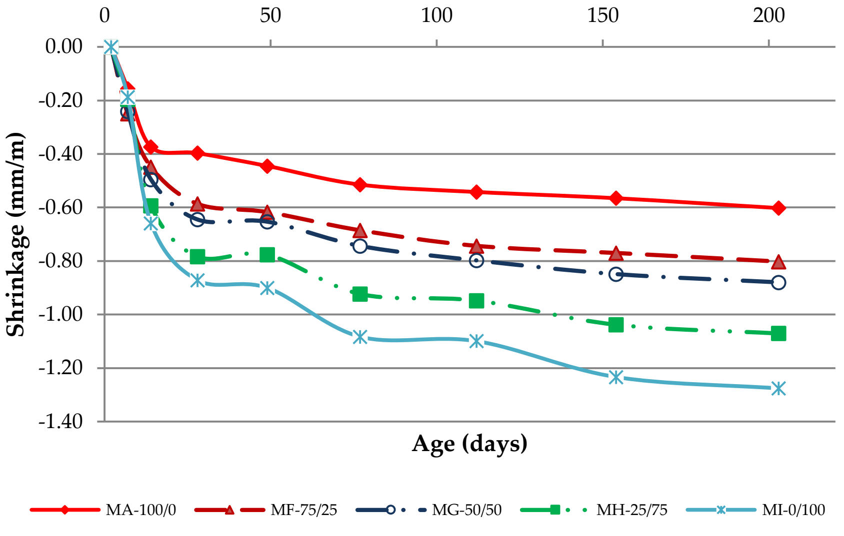

Figure 5.9. Dimensional instability (shrinkage) over time.

Table 5.13. Multiple Range Test for shrinkage of hardened mortar by mortar type and curing time. Method: 95 % LSD.

Mortar	Count	LS mean (mm/m)	SD (mm/m)	Homogeneous groups				
28 Days (p-value = 0.0000)								
MA-100/0	3	-0.397	0.019					X
MF-75/25	3	-0.587	0.015				X	
MG-50/50	3	-0.645	0.02			X		
MH-25/75	3	-0.783	0.005		X			
MI-0/100	3	-0.872	0.024	X				
112 Days (p-value = 0.0000)								
MA-100/0	3	-0.542	0.053				X	
MF-75/25	3	-0.744	0.033			X		
MG-50/50	3	-0.798	0.033			X		
MH-25/75	3	-0.948	0.036		X			
MI-0/100	3	-1.099	0.022	X				
203 Days (p-value = 0.0000)								
MA-100/0	3	-0.602	0.086				X	
MF-75/25	3	-0.802	0.048			X		
MG-50/50	3	-0.879	0.05			X		
MH-25/75	3	-1.071	0.024		X			
MI-0/100	3	-1.276	0.056	X				

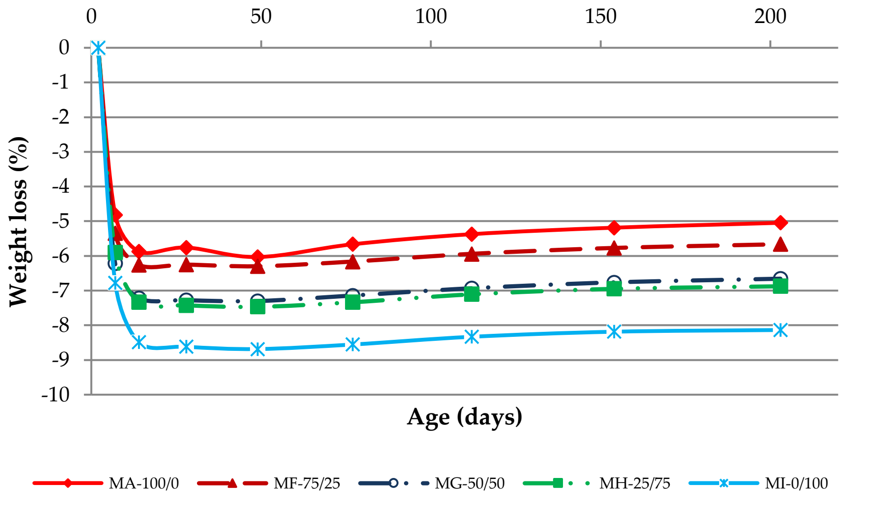

Figure 5.10. Weight loss of the mortar specimens during the shrinkage test.

These results are consistent with the literature. Vegas et al. (2009), Braga et al. (2012) and Neno et al. (2014) indicated that shrinkage increased with the incorporation of fine RCA. The high total water/cement ratio in the mixture is the first cause of the increase in the shrinkage of recycled mortars (Martínez et al., 2013). In contrast, Ledesma et al. (2014) concluded that replacement ratios up to 40% did not affect the shrinkage mean values after one year of measurements. This can be attributed to the type of cement and dosage method.

Based on the shrinkage values, Ledesma et al. (2015) proposed two criteria to set the maximum incorporation ratio: the shrinkage value must not exceed 1 mm/m and the difference with respect to the reference mortar must not exceed 0.5 mm/m. A replacement rate of 50% meets both criteria; thus, a maximum replacement ratio of 50% could be suggested for masonry mortar production to ensure proper performance in terms of drying shrinkage.

Tests to measure the susceptibility to cracking and evaluations in real conditions of the development of cracks are necessary.

5.3.8. Adhesive strength

The p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on this property. The multiple-range test showed two homogeneous groups (Table 5.14): the reference mortar and the recycled mortars. The reference mortar displayed an unreasonably high value compared to the recycled mortars. This can be attributed to the greater amount of free water derived from the higher effective water/cement ratio. However, this would not explain all the results of the recycled mortars; therefore, the high adhesive strength value of the reference mortar may be considered spurious data.

Table 5.14. Multiple Range Test for adhesive strength of hardened mortar by mortar type and curing time. Method: 95% LSD.

Mortar	Count	LS mean (MPa)	SD (MPa)	Homogeneous groups	
MA-100/0	4	0.47	0.11		X
MF-75/25	4	0.26	0.15	X	
MG-50/50	4	0.25	0.03	X	
MH-25/75	4	0.25	0.05	X	
MI-0/100	4	0.29	0.04	X	

Corinaldesi et al. (2002) and Corinaldesi and Moriconi (2009) found that RA mortars displayed higher mortar-brick bond strengths than the reference mortar. Braga et al. (2012) also achieved significant improvement in the mortar's adherence capacity with the incorporation of 15% concrete fines. Ledesma et al. (2014) found that mortars made with 10% and 20% RCA fines exhibited the highest adhesive strength values, although all of the mortars tested exhibited values between 0.38 and 0.58 MPa. Other authors did not include this parameter in their studies (Vegas et al., 2009; Dapena et al., 2011; Cuenca-Moyano et al., 2014).

5.3.9. Capillary absorption

The p-value of the F-test was less than 0.05 (p-value = 0.000); thus, the 'replacement ratio' factor had a significant effect on this property. The multiple-range test showed that no statistically significant differences were observed for replacement ratios below 75% (Table 5.15), although the mean values increased slightly with the use of fine RCA because of the higher water absorption of recycled concrete sand.

Table 5.15. ANOVA table for water absorption due to capillary of hardened mortar by mortar type.

Mortar	Count	LS mean (kg/(m^{2}min$^{-0.5}$))	SD	Homogeneous groups	
MA-100/0	6	0.59	0.02	X	
MF-75/25	6	0.59	0.02	X	
MG-50/50	6	0.62	0.02	X	
MH-25/75	6	0.62	0.05	X	
MI-0/100	6	0.67	0.06		X

These results are in agreement with those obtained by Silva et al. (2010) and Martínez et al. (2013), who demonstrated that mortars manufactured with recycled aggregates had a higher capillary absorption capacity than reference mortars. Neno et al. (2014) found similar capillarity absorption for replacement ratios below 50%. Ledesma et al. (2014) achieved the lowest values with replacement ratios of 5% and 10%. Other authors did not include this parameter in their studies (Vegas et al., 2009; Dapena et al., 2011; Cuenca-Moyano et al., 2014).

A maximum replacement ratio of 75% could be suggested for masonry mortar production to ensure proper performance in terms of capillary absorption.

5.3.10. Durability

Mortars MG-50/50 and MI-0/100, manufactured with 50% and 100% replacement ratios, respectively, displayed a higher percent of weight loss after 15 cycles in sodium sulfate dissolution than the reference mortar, according to UNE-EN 12370:1999 (Table 5.16). These results agree with those obtained by Vegas et al. (2009) who demonstrated a weight loss of 2.6% and 5.5% in the reference mortar and mortar with a 25% replacement ratio, respectively. Accordingly, mortars prepared with fine RCA appear to be less resistant to salt crystallization. Having a more permeable mortar, which is highlighted by increased water absorption by capillarity, sulfates can more easily penetrate into the mortar structure. These sulfates react with portlandite forming secondary gypsum in the presence of the tricalcium aluminate (C3A), giving rise to the formation of expansive ettringite (Aye & Oguchi, 2001; Sahmaran et al., 2007). Dimensional changes at the surface of the concrete generate cracks, which act as capillaries for the transport of water and sulfates deeper into the mortar. This process continues as the mortars disintegrate (Chen & Jiang, 2009). This negative property can limit the use of mortar with recycled aggregate in outdoor environments that are at risk of frost, but this property does not limit their use in indoor environments. Fig. 5.11 shows the appearance of prism specimens after 15 cycles in sodium sulfate dissolution.

Table 5.16. Percent of weight loss after 15 cycles in sodium sulphate dissolution.

Mortar	Count	LS mean (%)	SD (%)
MA-100/0	4	2.2	0.4
MG-50/50	4	3.82	0.41
MI-0/100	4	8.73	2.07

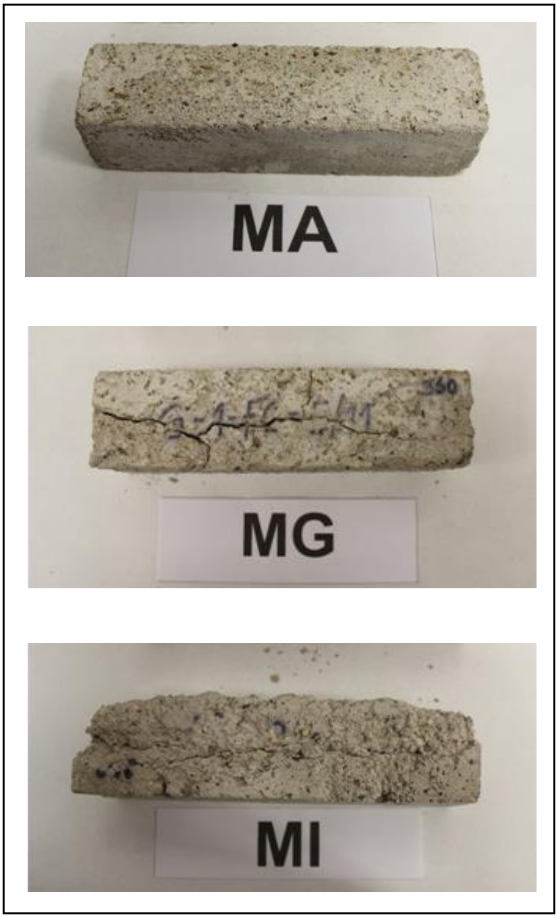

Figure 5.11. Appearance of prism specimens after 15 cycles in sodium sulfate dissolution.

5.4. Conclusions

This study proposes a maximum feasible use of recycled concrete sand in the manufacturing of type M-10 masonry mortars. Five mortars were tested with different replacement ratios of 0%, 25%, 50%, 75% and 100% by volume. The most innovative aspects of this work were the following: a) maintaining the original grading curves of the recycled concrete sand; b) using a volumetric dosage method; c) determining a dosage to obtain a mortar type M-10 using a commercial cement and a commercial admixture in the manufacture of mortars, thereby ensuring a knowledge transfer to industry; and d) not pre-saturating the recycled aggregates. The primary conclusions can be drawn as follows:

The bulk density of fresh mortar was not affected with replacement ratios below 50%, whereas higher replacement ratios caused significant decreases. The use of fine RCA did not have a significant effect on the entrained air, whereas the mean workability values decreased with replacement ratios above 25%.

The dry bulk density of hardened mortar decreased with replacement ratios above 25%. The compressive and flexural strength displayed similar behaviors over time. Replacement ratios of up to 50% did not significantly affect the mean compressive strength values for any of the curing times, whereas replacement ratios of 100% produced significant decreases. Compressive strength displayed a higher reduction compared with flexural strength. For the same environmental conditions, mortars with fine RCA had higher moisture content than the reference mortar.

The shrinkage of hardened mortar displayed a similar trend over time. Mortars made with fine RCA displayed higher shrinkage than the reference mortar. No traces of ettringite were detected. Bonding strength decreased with replacement ratios above 25%. Replacement ratios of up to 75% did not affect the mean values of capillary absorption. Mortars prepared with fine RCA were less resistant to salt crystallization, which may limit their use in outdoor environments that are at risk of frost.

In view of the results of this work and considering the requirements of masonry mortars, the maximum recommended replacement ratio of natural sand by recycled sand from concrete waste in indoor environmental conditions without reducing the properties of the reference mortar can be fixed at 50% by volume. Findings from this study encourage the conservation of non-renewable natural resources and an increase in the recycling rate of the fine fraction of CDW. To encourage an increase in this rate, new studies using different types of cement and admixtures are being conducted by this research group.

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6. Conclusions

6.1. General conclusions

After analyzing the results obtained in detail, the following points are the most relevant conclusions reached in this PhD thesis.

1. In relation to the physico-mechanical properties, the fine recycled aggregates from the CDW (recycled sand) tested have a continuous particle size distribution, greater fine content (<0.0063 mm), less density, greater water absorption, less fragmentation resistance (friability), greater loss of ignition and lower equivalent sand than the natural siliceous sand used as reference.

2. In relation to the chemical properties, the CDW recycled sands tested are composed mainly of quartz, have a greater amount of total sulphur compounds, soluble salts and soluble sulphates in water and in acid than natural sand.

3. The use of CDW recycled sand implies an increase in the water/cement total ratio in order to reach the desired consistency. Although the use of not pre-saturated recycled sand produces a lower effective water/cement ratio than in the reference mortars.

4. The bulk density of the fresh and hardened mortar decreases as the rate of replacement of natural sand by recycled sand increases due to the fact that the bulk density of recycled sand is lower than that of natural sand. This change is not a limiting property for masonry mortars.

5. The percentage of occluded air is practically unaffected by the incorporation of recycled sand.

6. The workability (time of use) decreases lineally with the increase in recycled sand, due to the greater water absorption of the recycled materials as well as the use of sands that are not pre-saturated.

7. The XRD analysis showed no difference between the hardened mortars made with natural sand and recycled sand, and no differences were observed in the morphology of the hardened mortars over time. No trace ettringite were detected; despite the fact that the mixed recycled sand from partition walls slightly exceeded the technical specifications limits of total sulphur compounds.

8. In low strength mortars (M5) with a volumetric ratio of 1:7 (cement: aggregate), the replacement of up to 40% of natural sand by recycled mixed-ceramic sand did not affect the mechanical strength, which increased over time. The adhesive strength, water absorption due to capillary action and dimensional instability (shrinkage) properties were not affected. In contrast, steam water permeability decreased by half, which limited the use of the mortars outdoors.

9. In masonry mortars of greater strength (M10) and volumetric ratio 1:5 (cement: aggregate) up to 50% replacement rates can be reached. A lineal decrease in mechanical strength was observed with the incorporation of recycled materials, although with replacement percentages of up to 50% the mechanical strength remained above 10 MP after 28 days. Mechanical strength increased faster over time in the recycled mortars, producing fewer differences in mechanical strength among mortars with 0%, 25% and 50% as the curing time increased. After 180 days the mortars with up to 100% replacement exceeded compression strength of 10 MPa.

10. The shrinkage increased lineally with the incorporation of recycled materials. The capillarity is more susceptible with the

use of ceramic rather than concrete recycled materials, although better adherence strength results were obtained from it.

11. The mortars made from concrete recycled materials were more sensitive to freeze-thaw cycles by means of magnesium sulphate attacks. With ceramic recycled materials no visible damage was observed in the mortar test specimens.
12. From an environmental point of view, the concentration of sulphates in the leaching of recycled partition walls exceeded the limit of inert material established by the European Directive. However, in the hardened mortars with 100% replacement, the concentration of sulphates decreased to being below the required limit for classification as inert material. The manufacturing of mortars with recycled materials is a good alternative for encapsulating non-inert recycled materials and thus avoiding any potential pollution of the environment.
13. The use of type CEM-IV/A (V) 32.5N pozzolanic cement with 29% fly ash improves the final properties of the mortar, producing minor differences with respect to the reference mortar than with the use of CEM-II cement, besides conferring greater long-term strength, due to the activation of the fly ash present in its composition.

6.2. Future lines of research

This PhD thesis demonstrates that the use of fine fraction CDW in proportions of up to 50% with natural sand is a viable alternative in the manufacturing of industrial masonry mortars for indoor use. The product is open to commercialization (RECYMORT). Two limiting properties have been identified: greater shrinkage owing to a necessary greater water/cement ratio, although there is no regulatory limitation to shrinkage values, and a shorter workability life, both related to the greater absorption of water in recycled materials.

With regard to this, the following lines of research are proposed to be developed in the future in order to continue in the improvement of the valorization of these waste materials:

- Design new industrial mortars using new additives, such as setting-time delayers and superplasticizers, in order to increase workability time in the fresh state and also reduce the amount of water for mixing.
- Study other types of fine recycled aggregates from mixed CDW.
- Study fire resistance and thermal and acoustic insulation of partition walls made with RECYMORT.
- Study the influence of on-site environmental conditions, different relative temperature and humidity conditions, since the tests for this PhD thesis have been carried out in air-conditioned chambers with standard conditions.
- Study the use of powdered recycled materials used as fillers. This may result in an increase in embodied energy of the materials due to the crushing process.
- Manufacture on an industrial scale mortar samples made with 50% natural sand and 50% recycled sand from concrete waste and/or 50% recycled sand from mixed debris (RECYMORT-H / RECYMORT-T). Carry out an experiment (real-scale test) in order to evaluate the medium-long term behaviour under real-life conditions.
- Evaluate by means of a panel of experts the manageability of the recycled mortar as bending mortar in partition-wall construction.

7. Conclusiones

7.1. Conclusiones generales

Tras analizar detalladamente los resultados obtenidos, a continuación se enumeran las conclusiones más relevantes obtenidas en la presente tesis doctoral.

1. En relación a las propiedades físico-mecánicas, las arenas recicladas de RCD ensayadas tienen una granulometría continua, mayor cantidad de finos, menor densidad, mayor absorción de agua, menor resistencia a la fragmentación (friabilidad), mayor pérdida por calcinación y menor equivalente de arena que la arena natural silícea empleada como referencia.

2. En relación a las propiedades químicas, las arenas recicladas de RCD ensayadas están compuestas principalmente por cuarzo, tienen mayor cantidad de compuestos totales de azufre, sales solubles y sulfatos solubles en agua y en ácido que la arena natural.

3. El uso de arena reciclada de RCD implica un aumento de la relación agua/cemento total para alcanzar la consistencia deseada. Aunque la relación agua/cemento efectiva es menor que en los morteros de referencia con el uso de arenas no pre-saturadas.

4. La densidad aparente del mortero fresco y endurecido se reduce a medida que aumenta la tasa de sustitución de arena natural por arena reciclada debido a que la densidad seca de los áridos reciclados es menor que la del árido natural. Este cambio no es una propiedad limitante para los morteros de albañilería

5. El porcentaje de aire ocluido prácticamente no se ve afectado con la incorporación de arena reciclada.

6. La trabajabilidad (tiempo de uso) se reduce linealmente con el aumento de arena reciclada, esto es debido a la mayor absorción de agua de los áridos reciclados y a que se han utilizado sin pre-saturación

7. El análisis DRX no mostró diferencias entre los morteros endurecidos hechos con arena natural y arena reciclada y no se observaron diferencias en la morfología de los morteros endurecidos con el tiempo. No se detectaron rastros de etringita, a pesar de que la arena reciclada mixta de tabiquería superaba ligeramente los límites de compuestos totales de azufre de las especificaciones técnicas.

8. En morteros de baja resistencia (M-5) con relación volumétrica 1:7 (cemento:árido), la sustitución de hasta el 40% de arena natural por arena reciclada mixta-cerámica no afectó a la resistencia mecánica, observando un aumento de la resistencia con el tiempo. Las propiedades de adherencia, capilaridad y retracción no se vieron afectadas. En cambio, la permeabilidad al vapor se redujo a la mitad, lo que limita el uso de los morteros en exteriores.

9. En morteros de albañilería de mayor resistencia (M-10) y relación volumétrica 1:5 (cemento:árido) se pueden alcanzar tasas de sustitución de hasta un 50%.Se observó un descenso lineal de las resistencias mecánicas con la incorporación de áridos reciclados, aunque con porcentajes de sustitución de hasta el 50% la resistencia mecánica se mantuvo por encima de los 10 MPa a los 28 días de edad. La resistencia mecánica aumentó con el tiempo más rápidamente en los morteros con áridos reciclados, obteniendo menores diferencias de resistencia mecánica entre los morteros con 0%, 25% y 50% a medida que aumenta la edad de curación. A los 180 días los morteros con

hasta el 100% de sustitución superan los 10 MPa de resistencia a compresión.

10. La retracción aumentó linealmente con la incorporación de áridos reciclados. La capilaridad es más susceptible con el uso de árido reciclado cerámico que con el árido reciclado de hormigón, en cambio se obtuvieron mejores resultados de adherencia con el primero.
11. Los morteros hechos con árido reciclado de hormigón fueron más sensibles a los ciclos de hielo-deshielo medidos mediante ciclos de ataque con sulfato de magnesio. Con el árido reciclado cerámico no se observaron daños visibles en las probetas de mortero.
12. Desde un punto de vista ambiental, la concentración de sulfatos en el lixiviado del árido reciclado de tabiquería superó el límite de material inerte establecido por la directiva europea. Sin embargo, en los morteros endurecidos conel 100% de sustitución, la concentración de sulfatos bajó hasta clasificarse el material como inerte. La fabricación de morteros con áridos reciclados es una buena alternativa para encapsular áridos reciclados no inertes y evitar la posible contaminación al medio ambiente.
13. El uso del cemento puzolánico tipo CEM-IV/A (V) 32.5N con 29% de cenizas volantes mejora las propiedades finales del mortero, observándose menores diferencias con respecto al mortero de referencia que con el uso de cemento CEM-II, además confiere a largo plazo mayores resistencias debido a la activación de las cenizas volantes presentes en su composición.

7.2. Líneas futuras de investigación

Esta tesis doctoral pone de manifiesto que el uso de la fracción fina de RCD en proporciones de hasta un 50% con respecto a la arena natural es viable en la fabricación de morteros industriales de albañilería para usos interiores. El producto es susceptible de comercialización (RECYMORT). Se han identificado dos propiedades limitantes, la mayor retracción derivada de la mayor relación agua/cemento necesaria, aunque no hay limitación normativa a los valores de retracción y el menor periodo de trabajabilidad, ambas relacionadas con la mayor absorción de agua de los áridos reciclados.

En base a lo anterior, se proponen las siguientes líneas de investigación a desarrollar en el futuro para proseguir con la mejora de la valorización de estos residuos:

- Diseñar nuevos morteros utilizando aditivos de última generación, tipo retardadores de fraguado y superplastificantes con el fin de aumentar el tiempo de uso en estado fresco y de reducir el agua de amasado.
- Estudio de otros tipos de áridos reciclados mixtos procedentes de derribos y/o restos de obra.
- Estudios de resistencia al fuego, aislamiento térmico y acústico de tabiquerías hechas con RECYMORT.
- Estudio de la influencia de las condiciones ambientales de puesta en obra, con diferentes condiciones de temperatura y humedad relativa. Ya que los ensayos de esta tesis se han hecho en cámara climática con condiciones normalizadas.
- Uso de filleres procedentes de áridos reciclados como sustituyentes de cemento. Esto podría suponer un aumento de la energía embebida de los materiales debido a la trituración.
- Fabricación a escala industrial de muestras de mortero hecho con un 50% de árido natural y 50% de áridos reciclado de hormigón y/o 50% de árido reciclado mixto (RECYMORT-H / RECYMORT-T). Ejecución de un demostrativo (ensayo a escala real) para evaluar el comportamiento a medio-largo plazo en condiciones reales.

- Evaluación mediante panel de expertos de la manejabilidad del material en la construcción de tabiquería.