Estudio de hormigones con bajo contenido en cemento y áridos reciclados

Tesis doctoral presentada por

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para la obtención del título de doctor por la Universidad de Córdoba

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TITULO: *ESTUDIO DE HORMIGONES CON BAJO CONTENIDO EN CEMENTO Y ÁRIDOS RECICLADOS*

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TÍTULO DE LA TESIS:

ESTUDIO DE HORMIGONES CON BAJO CONTENIDO EN CEMENTO Y ÁRIDOS RECICLADOS

DOCTORANDO:

Antonio López Uceda

INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS

La sostenibilidad del medioambiente, debido al desarrollo industrial y demográfico desde la segunda mitad del siglo XX hasta nuestros días, es y será un objetivo prioritario mundial. Debido a ello, son muchos los estudios científicos dedicados a disminuir el impacto medioambiental que el consumo de recursos naturales genera.

Desde Europa, a través de la Directiva Marco de Residuos 2008/98/CE, se estableció como "flujo prioritario de residuos" los procedentes de construcción y demolición (RCD), fijando una tasa mínima para el año 2020, del 70% en peso de los RCD, la preparación para la reutilización y el reciclado. En la actualidad en España, la tasa es muy inferior al objetivo establecido (<15%). Por ello, se hace necesario realizar estudios conducentes a mejorar la calidad de los áridos reciclados (AR) de RCD y encontrar nuevas aplicaciones que fomenten el uso de estos materiales para cumplir el objetivo marcado en la Directiva Europea.

Los RCD tienen dos procedencias: el denominado como mixto, con un origen y composición heterogénea, generalmente proveniente de la demolición y rehabilitación de edificios, y otro derivado de la demolición de hormigón. Ambos copan la mayoría de los RCD producido en España, 70-80% y 10-15% respectivamente.

Se ha comprobado que los AR procedentes de RCD: mixtos y de hormigón, tienen un buen comportamiento en usos no ligados como son la construcción de terraplenes e incluso en capas estructurales de firmes de carreteras de poco tráfico; sin embargo, son escasos los estudios realizados con los AR mixtos en usos ligados con cemento. En relación a los AR de hormigón, ha sido ampliamente estudiado en uso ligado y no ligado, exceptuando su empleo en hormigón seco compactado con rodillo.

Por ello, en la presente Tesis se pretende estudiar las posibilidades de utilizar en usos ligados: los AR mixtos como hormigones no estructurales con bajo contenido en cemento y los AR de hormigón como hormigón seco compactado con rodillo para capas estructurales de firmes de carreteras.

La Tesis se presenta como un compendio de tres artículos científicos publicados en revistas internacionales indexadas, dos de ellas del primer cuartil, y la tercera del segundo cuartil del Journal Citation Report:

1. López-Uceda, A., Ayuso, J., López, M., Jiménez, J. R., Agrela, F., Sierra, M. J. (2016). Properties of non-structural concrete made with mixed recycled aggregates and low cement content. *Materials*, *9*(2), 74.
2. López-Uceda, A., Ayuso, J., Jiménez, J. R., Agrela, F., Barbudo, A., De Brito, J. (2016). Upscaling the Use of Mixed Recycled Aggregates in Non-Structural Low Cement Concrete. *Materials*, *9*(2), 91.
3. López-Uceda, Agrela, F., Cabrera, M., Ayuso, J., López M. (2016). Mechanical performance of roller compacted concrete with recycled concrete aggregates. *Road Materials & Pavement Design*, 1-20.

Para la realización de estos estudios se ha contado con la participación de investigadores externos a la Universidad de Córdoba. En el primer artículo ha colaborado la jefa de la Unidad de Control Técnico de Obras de la Agencia de Obra Pública de la Junta de Andalucía, María José Sierra López, y en el segundo artículo del profesor Dr. Jorge de Brito (Instituto Superior Técnico, Universidad de Lisboa, Portugal).

Por todo ello, se autoriza la presentación de la Tesis Doctoral "Estudio de hormigones con bajo contenido en cemento y áridos reciclados".

Córdoba, 12 de Diciembre de 2016

Firma de los directores

Fdo.:Prof. Dr. Martín López Aguilar

Fdo.: Prof. Dr. Francisco Agrela Sainz

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Abstract

In this Doctoral Thesis, the use of Recycled Aggregates (RA) from Construction Waste and Demolition (CDW) was studied as coarse fraction, in the manufacturing of concrete, such as the Non-Structural Concrete (NSC) and the Roller Compacted Concrete (RCC), with low cement content.

In Spain, there are two majority RA from CDW; Mixed Recycled Aggregate (MRA), with a diverse composition, generally from demolition and rehabilitation of buildings; and other from demolition of concrete, named Recycled Concrete Aggregate (RCA). Both represent approximately 70-80% and 10-15% respectively of RA produced.

The application of RA is normally for road (backfilling application, subgrade, subbase and base), with a low added value. Therefore, in order to add greater value to RA, three investigations have been conducted to assess the possibilities of using RA with cement.

In the first research, NSC with MRA in the coarse fraction and low cement content was studied. The effect on the mechanical and physical properties of the MRA incorporation rate (0, 20, 40 and 100%), the proportion of ceramic particles of two MRA, obtained directly from plant, and the amount quantity of cement (180 to 200 kg/m^3) was analysed. Once it was determined the viability of NSC manufacturing with 200 kg of cement per m^3 and full coarse replacement. Four on-site slabs were executed, all of them with 200 kg of cement per m^3 and one for each coarse aggregate replacement aforementioned. The concrete was supplied by a nearby ready-mix concrete plant. The mechanical performance was studied in long term on-site and after curing in laboratory. This is shown in the second publication.

Furthermore, in the third paper was analyzed the use of RCA in the coarse fraction in RCC. Four series with different amounts of cement (110, 175, 250 and 350 kg/m^3) were used. Each serie consisted of one mixture per replacement ratio in the coarse fraction; 100%, 50% and 0%, the latter one was used as reference mixture in each serie. Physical and mechanical properties were studied, highlighting a method for manufacturing prismatic moulds for flexural strength and drying shrinkage tests.

En la presente Tesis Doctoral se estudia el uso en la fracción gruesa de Áridos Reciclados (AR) procedentes de Residuos de Construcción y Demolición (RCD) en la fabricación de hormigones con bajo contenido en cemento, como son los Hormigones No Estructurales (HNE) y los Hormigones secos Compactados con Rodillo (HCR).

En España, hay dos tipos mayoritarios de AR provenientes de RCD, el denominado como los Áridos Reciclados Mixtos (ARM), con un origen y composición heterogénea, generalmente provenientes de la demolición y rehabilitación de edificios, y otro derivado de la demolición de hormigón, nombrado Áridos Reciclados de Hormigón (ARH). Ambos suponen el 70-80% y 10-15% respectivamente, de los AR de RCD producido.

La aplicación más común de estos AR es en carreteras (ejecución de rellenos localizados, formación de explanadas, bases y subbases), siendo estas aplicaciones de bajo valor añadido. Por ello, con el fin de dar un mayor valor añadido a estos AR se han realizado tres investigaciones que pretenden evaluar las posibilidades de utilizar estos materiales en usos ligados con cemento.

En la primera publicación se estudió el uso de los ARM en HNE con bajo contenido en cemento. Analizando el efecto de la tasa de sustitución (0, 20, 40 y 100%) de la fracción gruesa, de la proporción de partículas cerámicas de dos ARM, obtenidos directamente de planta, y de la cantidad de cemento (180 y 200 kg/m^3), en las propiedades mecánicas y físicas. A raíz de la viabilidad de fabricación de los HNE con 200 kg/m^3 de cemento y 100% de sustitución. Se fabricaron cuatro losas, cada una con los porcentajes de sustitución antes mencionados de la fracción gruesa de árido natural por ARM, y con 200 kg de cemento por m^3 de hormigón. Los cuatro hormigones diferentes fueron suministrados por una planta de hormigón preparado. Estudiándose el comportamiento mecánico a largo plazo una vez puesto en obra, y el curado en laboratorio. Esto se muestra en la segunda publicación.

Por otra parte, en el tercer artículo se analizó del uso de ARH en la fracción gruesa para fabricación de HCR. En este artículo se utilizaron cuatro series con diferentes cantidades de cemento (110, 175, 250 and 350 kg/m^3).

En cada serie se fabricaron tres amasadas por cada tasa de sustitución de la fracción gruesa: 100%, 50%, y 0%, ésta última fue usada como amasada de referencia. Se estudiaron las propiedades físicas y mecánicas, destacando un método para la fabricación de probetas prismáticas para los ensayos de flexión y retracción.

Índice

Índice de tablas

Índice de figuras

Abreviaturas

AN	Áridos Naturales
AR	Áridos Reciclados
ARA	Áridos Reciclados de Asfalto
ARH	Áridos Reciclados de Hormigón
ARM	Áridos Reciclados Mixtos
CDW	Construction waste and demolition
CER	Catálogo Europeo de Residuos
EHE-08	Instrucción de Hormigón estructural
FEDER	Fondo Europeo de Desarrollo Regional
GERD	Asociación Española del Gremio de Entidades del Reciclaje de Derribos
HCR	Hormigones secos compactados con rodillo
HNE	Hormigones no estructurales
MRA	Mixed recycled aggregates
NSC	Non-structural concrete
PAIDI	Plan Andaluz de Investigación, Desarrollo e Innovación
PEMAR	Plan Estatal Marco de Gestión de Residuos
PG-3	Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes
PNRCD	Plan Nacional de Residuos de Construcción y Demolición

RA	Recycled aggregates
RCA	Recycled concrete aggregates
RCC	Roller compacted concrete
RCD	Residuos de construcción y demolición
RILEM	Reunión Internacional de Laboratorios y Expertos en Materiales, Sistemas de Construcción y Estructuras

1. Introducción

El año estimado para que la población mundial llegue a 9.7 mil millones de habitantes es el 2050 (Worldometers, 2016). La población mundial en el año 2015 alcanzó más de 7.3 mil millones de habitantes (Population Reference Bureau, 2016). Se estima que la demanda global de áridos para la construcción en 2015 alcanzó 48 mil millones de toneladas (Freedonia, 2012), estimándose una demanda por habitante de más de 6.5 toneladas. Para el año 2050 el consumo habrá aumentado un tercio más que en la actualidad, suponiendo que la demanda no aumente. El árido es la segunda materia prima más consumida por el hombre después del agua, siendo la principal materia prima para la construcción de infraestructuras. Por lo que se hace indispensable el estudio para la reducción del consumo de árido.

Por otra parte, los materiales de construcción al finalizar su vida útil, se convierten en residuos que pueden ocasionar graves problemas ambientales. El reciclado y reutilización de éstos como nuevos materiales de construcción, contribuye a la sostenibilidad del sector.

Los Residuos de Construcción y Demolición (RCD) están constituidos por partículas cerámicas, mortero, hormigón y áridos naturales no ligados principalmente, y en menor medida asfalto, yeso, madera, metales, papel y plásticos. Una vez tratados en las plantas de tratamiento de RCD, se obtiene los Áridos Reciclados (AR). En España hay dos tipos de AR mayoritarios: los Áridos Reciclados de Hormigón (ARH), procedentes de la demolición del hormigón, y los Áridos Reciclados Mixtos (ARM), con un contenido de partículas cerámicas no menor del 10 %, siendo éste último el predominante, con un 80% aproximadamente de la producción de AR (CEDEX, 2010).

Las aplicaciones de los AR, provenientes de RCD, en obra civil son bases y subbases de carreteras, rellenos localizados, morteros, hormigones y camas de tuberías, siendo los dos primeros los usos mayoritarios (GERD, 2012).

Recientemente, en Andalucía se ha elaborado una "Guía de áridos reciclados de Andalucía central" como instrumento útil para los agentes intervinientes en los usos y aplicaciones de los AR. Esta Guía nace a raíz de un proyecto de investigación financiado por la Agencia de la Obra Pública de la Junta de Andalucía con fondos FEDER (Fondo Europeo de Desarrollo Regional denominado): "Aplicaciones de los Áridos Reciclados de Residuos de Construcción y Demolición (RCD) para la construcción sostenible de infraestructura viaria en Andalucía Central". Éste fue liderado por el grupo de investigación de Ingeniería de la Construcción de la Universidad de Córdoba (UCO), en el que han participado la empresa CEMOSA (Centro de Estudios de Materiales y Control de obra, SA) y la Asociación de Empresas Gestoras de RCD de Andalucía (AGRECA).

Los RCD son responsables de un tercio de todos los residuos generados en la Unión Europea (Brito y Silva, 2016) y su tasa de reciclaje varía entre el 90 y el 10% en la UE. España es uno de los países con esta tasa más baja (Comisión Europea, 2011), por lo que se hace indispensable la necesidad de estudios para la viabilidad de encontrar nuevas aplicaciones de estos materiales que fomenten su empleo, y así conseguir el objetivo establecido del 70% marcado por la Directiva 2008/98/CE del Parlamento Europeo para el año 2020.

1.1. Ámbito legal

La primera normativa europea motivada por la preocupación de los gobiernos en implementar legislación para prevenir o corregir problemas medioambientales es la Directiva 75/442/EEC. En esta normativa ya se estableció la definición de residuo, "cualquier sustancia u objeto del cual su poseedor se desprenda o tenga la intención o la obligación de desprenderse", definición que usa la normativa vigente europea, que es la Directiva 2008/98/CE del Parlamento Europeo y del Consejo del 19 de noviembre de 2008 sobre los residuos, en la cual se derogan todas las anteriores. En esta Directiva se establece como objetivo alcanzar una tasa mínima de reutilización, reciclado u otras operaciones de valorización del 70% en peso para los RCD para el año 2020. Siendo RCD todos aquellos que pertenezcan al capítulo 17 del Catálogo Europeo de Residuos (CER), aprobada por Orden MAM/304/2002 (BOE número 43 del 19 de febrero de 2002), excluyendo los materiales clasificados en la categoría de 170504, "Tierra, piedras y lodos de drenaje no peligrosos".

En España, el plan actual que establece las líneas estratégicas y las medidas necesarias para avanzar hacia la denominada economía circular e impulsar la preparación para la reutilización y el reciclado, es el Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016-2022, elaborado por el Ministerio de Agricultura, Alimentación y Medio Ambiente. Antes de este Plan, se establecieron otros Planes Nacionales de Residuos de Construcción y demolición (PNRCD): el Primer PNRCD del 2001 al 2006 y el Segundo PNRCD del 2007 al 2015, en éste último se fijó una tasa del 40% de reciclaje para el final de dicho Plan.

El objetivo final del PEMAR, en paralelo a la política comunitaria de residuos, es convertir a España en una sociedad eficiente en el uso de los recursos, que avance hacia una economía circular (Figura 1.1). Se trata, en definitiva, de sustituir una economía lineal basada en producir, consumir y tirar, por una economía circular en la que se reincorporen al proceso productivo una y otra vez los materiales que contienen los residuos para la producción de nuevos productos o materias primas.

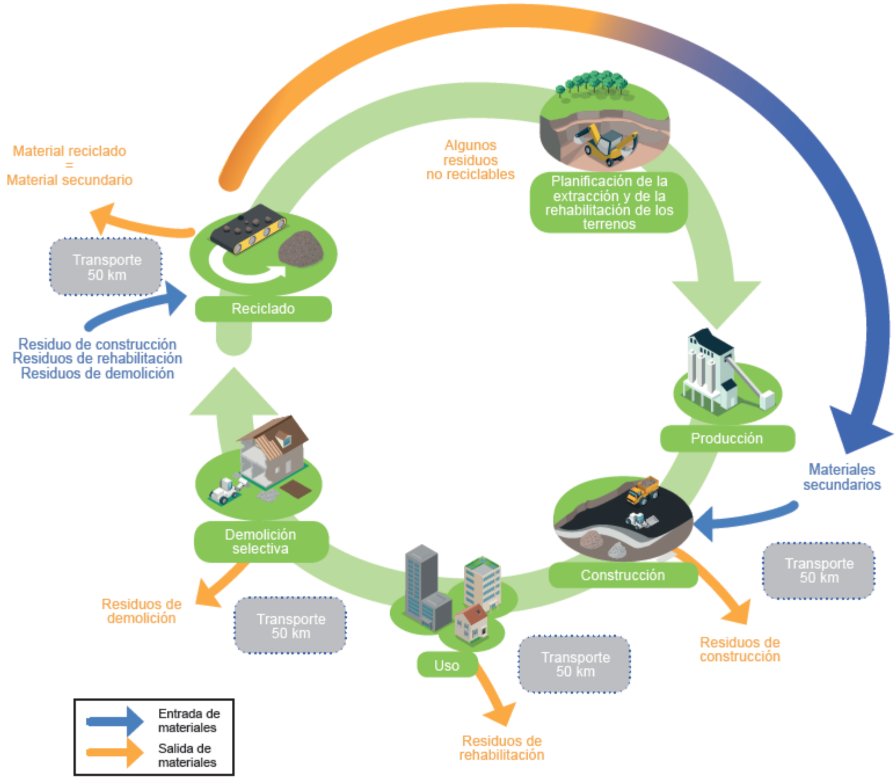

Figura 1.1. Hacia un economía circular para los áridos. (Fuente: Publicación de la Asociación Nacional de Empresarios del Árido (ANEFA), Año 10, Número 4/ Enero-Febrero-Marzo 2016.

En este plan conviene resaltar que se establece como un objetivo un Acuerdo Marco Sectorial para impulsar la utilización de AR procedentes de RCD en obras de construcción (Tabla 1.1), proponiendo la inclusión de éstos en los proyectos de construcción de obra pública con un porcentaje mínimo de un 5%, tanto en obras públicas como privadas, siempre que sea posible.

Tabla 1.1: Objetivos del PEMAR para los RCD hasta el 2020.

Año	2016	2018	2020
% RCD mínimo no peligrosos destinados a la preparación para la reutilización, el reciclado y otras operaciones de valorización	60	65	70
Eliminación de RCD no peligroso en vertedero	40	35	30

En España, se estima que el porcentaje que se eliminan RCD de manera descontrolada en escombreras es superior al 60% (PNIIR 2007-2015). Siendo de los países de la U.E. con una tasa de reciclaje más baja (<15%), la media europea se encuentra entorno al 30-60% (Comisión Europea, 2011).

Quedando todavía camino por recorrer para el objetivo del 70% marcado para el 2020 por la la Directiva 2008/98/CE.

En el Decreto 397/2010 de 2 de noviembre de la Junta de Andalucia se aprueba el Plan Director Territorial de Gestión de Residuos No Peligrosos de Andalucía 2010-2019, por ser competencia de las CCAA la elaboración de los planes de gestión de RCD no peligrosos, y establece como objetivos la reducción, reutilización, reciclado y dar otras formas de valorización a los residuos.

En la normativa vigente, 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 (Ministerios de Fomento, 2015), para conseguir la adaptación a la normativa europea, se fomenta la sostenibilidad y el respeto al medio ambiente mediante la utilización de una serie de residuos, subproductos inertes y materiales reciclados. En esta normativa se permite para cargas de tráfico pesado T2 a T4 (< 800 vehículos pesados/día) el uso de AR procedentes de RCD como material granular en la formación de firmes, también están permitidos sus usos en materiales tratados con cemento y en la capa inferior de pavimentos bicapa de hormigón. Para su uso, los productores de AR de RCD deberán aportar documento acreditativo de su origen, de la idoneidad de sus características para el uso propuesto y que no se encuentran mezclados con otros contaminantes.

En la Instrucción de Hormigón estructural (EHE-08), aprobado por el R.D. 1247/2008, de 18 julio (Ministerio de Obras Públicas, 2008), motivado por la adaptación a los criterios europeos se incorpora el uso de materiales reciclados, recogiendo el término de hormigón reciclado, definido en el anejo 15 "Recomendaciones para la utilización de hormigones reciclados", como "aquel hormigón fabricado con árido grueso reciclado procedente del machaqueo de residuos de hormigón". En este anejo, se establece que se podrá incorporar hasta un 20% de árido reciclado de hormigón en la fracción gruesa en sustitución del árido natural en la fabricación tanto de hormigón armado como en masa siempre y cuando la resistencia característica del hormigón sea menor de 40 N/mm^2. Queda excluido el empleo del árido reciclado en la fracción fina y los áridos reciclados con distinta procedencia que la del machaqueo de residuos de hormigón. Para dicho uso, la combinación en la fracción gruesa del árido natural y el reciclado, deberán cumplir las especificaciones del Artículo 28 de la EHE-08, "Áridos". En la Tabla 1.2 se muestran estas especificaciones.

Tabla 1.2: Especificaciones para el árido reciclado en la EHE-08

Especificaciones		**Árido**
Contenido en partículas < 4 mm		≤ 5%
Contenido de terrones de arcilla		≤ 0,6%
Contenido de desclasificados		≤ 10%
Los Ángeles (para clase resistente ≤30 MPa)		≤ 40 (≤50)
Impurezas	Material cerámico	≤ 7%
	Asfalto	≤ 1%
	Partículas Ligeras	≤ 1%
	Otros materiales (vidrio, plásticos, metales, etc.)	≤ 1%
Cloruros		≤ 0.05%
Sulfatos solubles en ácido (SO3)		≤ 0.8%
Compuestos totales de azufre (S)		≤ 1%

En el caso, de que el hormigón sea para uso no estructural, se deberá cumplir lo indicado en el anejo 18. En este caso, se permite la sustitución completa de la fracción gruesa por árido reciclado, siempre y cuando éste sea procedente de machaqueo de hormigón. Hay dos tipos de hormigón de uso no estructural, el hormigón de limpieza, cuyo contenido de cemento debe ser mayor de 150 kg/m3 y que tiene como fin evitar la desecación del hormigón estructural durante su vertido así como una posible contaminación de éste durante las primeras horas de su hormigonado, y el hormigón no estructural, cuya resistencia característica mínima deberá ser mayor a 15 N/mm^2 y que tiene como fin conformar volúmenes de material resistente. Ejemplos de éstos son los hormigones para aceras, hormigones para bordillos y los hormigones de relleno.

Países como Alemania, Reino Unido, Holanda y Portugal permiten el uso de árido reciclado mixto en hormigón no estructural, a diferencia de la normativa vigente española. El árido reciclado de hormigón si está permitido en la mayoría de los países, siempre y cuando cumpla unos requerimientos, los más comunes son densidad, absorción y contenido de hormigón y mortero adherido.

1.2. Clasificación de los Áridos Reciclados

Las plantas de gestión y tratamiento de RCD valorizan estos residuos. En España éstas presentan una variabilidad amplia en términos de nivel tecnológico. Hay tres tipos de plantas atendiendo a su movilidad, las fijas, que representan el 60%, las semimóviles el 30% y las móvilesel 10% (GERD, 2012). En 2012, España contaba con 282 plantas (Rodriguez-Robles y col., 2015).

En la "Guía de buenas prácticas" para la Gestión Y Tratamiento de Residuos de la Construcción de reciente publicación, desarrollada por el Grupo de Investigación Ingeniería de la Construcción de la UCO del Plan Andaluz de Investigación, Desarrollo e Innovación (PAIDI), se establecen una serie de recomendaciones para mejorar la calidad de los AR producidos. En éstas se hacen procesos fundamentales como: un triaje manual a la entrada del RCD a la planta para la retirada de todos aquellos elementos peligrosos e impurezas que puedan perjudicar la calidad de los AR, y la realización de un pre-cribado para retirar los elementos mas finos que es donde se concentra una parte importante de tierras y yeso. Despues de estas operaciones el RCD resultante pasaría al tratamiento mecánico mediante machadora de mandibulas y/o molino de impacto.

La demolición selectiva en origen es de suma importancia, previo al envío del RCD a la planta de tratamiento, para mejorar la calidad de los AR posteriormente producidos (Barbudo, 2012, Silva y col., 2014).

La clasificación de los AR producido por las plantas de gestión y tratamiento de RCD se hace atendiendo a la naturaleza de los AR y a la granulometría, la cual podremos modificar a través de los equipos de trituración y de los sistemas de cribas y tamices. La Reunión Internacional de Laboratorios y Expertos en Materiales, Sistemas de Construcción y Estructuras (RILEM) propuso una de clasificación de los AR (RILEM TC 121-DRG, 1994) atendiendo a propiedades físicas tales como la densidad seca de las partículas y la absorción de agua, y químicas como el contenido en sulfatos. De manera más recientemente, Silva y col. (2014) clasificó los AR en base a 236 publicaciones con diferentes designaciones atendiendo a la densidad seca, la absorción de agua a las 24 horas y la resistencia a la fragmentación determinada por el ensayo de Los Angeles.

No obstante, la manera más común de clasificar los AR es por su composición, principalmente por el contenido de material cerámico, bituminoso, no ligado (natural) y de hormigón. Agrela y col. (2011) propusieron que para contenidos de partículas de árido natural, de hormigón y de mortero adherido mayores del 90% se clasificarían como ARH; para contenidos en partículas cerámicas menores del 30%, ARM, y para mayores del 30% de éstas sería Árido Reciclado Cerámico (ARC). En La Guía Española de AR procedentes de RCD (GERD, 2012) se establece varios tipos de AR también en relación a su composición: ARH y ARC, con la misma composición que en Agrela y col. (2011); áridos reciclados mixtos de hormigón, con un contenido de hormigón y árido natural menor al 90% y de material cerámico menor al 30%; áridos reciclados mixtos cerámicos, con un contenido de material cerámico mayor al 30%, y Áridos Reciclados Asfálticos (ARA), con un contenido en material bituminos comprendido entre el 5% y el 30%.

En España, los ARM representan un 80% aproximadamente de los AR producidos (CEDEX, 2010), y los ARH apenas un 15% (GERD, 2012).

Las propiedades del AR dependen en mayor medida de la naturaleza y proporción de los elementos que lo componen. De Juan y Alaejos (2009) establecieron que los ARH presentan menor calidad que los Áridos Naturales (AN) debido al mortero adherido, encontrándose éste en mayor proporción en la fracción fina que en la fracción gruesa. La absorción, densidad, resistencia a la fragmentación (ensayo de Los Angeles) y contenido en sulfatos son las principales propiedades a tener en cuenta en su uso, sugiriendo un límite de 44% en contenido de mortero adherido para su uso en hormigones estructurales de 25 N/mm^2. Padmini y col. (2009) estudiaron la influencia de la resistencia del hormigón del cual se obtuvo los ARH, concluyendo que la absorción de agua era mayor en aquellos ARH obtenidos de hormigones con mayor resistencia, y a menor tamaño máximo de árido.

En el estudio de Bardudo y col. (2012) con 31 áridos, cuatro de ellos naturales, seis ARH y el resto ARM, se mostró que el contenido de sulfato solubles está fuertemente influenciado por el contenido de yeso y el contenido de partículas cerámicas.

1.3. Aplicaciones de los áridos reciclados

1.3.1. Áridos reciclados no ligados con cemento

El uso de los AR para su aplicación en obra civil ha sido muy estudiado. Como ya se ha comentado anteriormente el uso mayoritario del árido reciclado es no ligado en capas estructurales de firmes y rellenos. Dos recientes publicaciones hacen una revisión bibliográfica de ello (Cardoso y col., 2016; Vieira y Pereira, 2015) destacando que las propiedades de los AR no sólo dependen de su composición, sino también del tratamiento recibido en la planta, mejorando mucho en caso de que se hayan realizado las operaciones previas de triaje y pre-cribado . Por otra parte, la compactación por vibrado se determinó preferible a la compactación por impacto, para evitar la generación de finos por el mortero adherido. Los ARM y los ARH presentaron mayor absorción de agua y menor densidad que los AN. También se concluye que los ARH presentan un CBR similar o incluso mejor que los AN, y que aquellos ARH usados en el paquete de firme mostraron mejor comportamiento a largo plazo.

Poon y Chan (2006) estudiaron el uso de AR en capas de subbase. Estos AR manifestaron menor densidad seca máxima y mayor humedad óptima, aunque por otra parte mostraron menor sensibilidad a los cambios de humedad en la densidad seca máxima, comparando con la de referencia fabricado con áridos naturales. Todas los AR estudiados alcanzaron valores mayores de 35 en el ensayo de CBR. En el estudio llevado a cabo por Garach y col. (2015) se mostró que los valores de CBR a largo plazo en AR mostraron mejor comportamiento que los áridos naturales.

El estudio del uso de AR en cama de asiento de tuberías (Rahman y col., 2014) y aplicado en pavimento permeable junto con geotextil (Rahman y col., 2015), resultó viable como alternativa a los AN. En aplicaciones reales en caminos rurales sin pavimentar (Jiménez y col., 2012a y Jiménez y col., 2012b) cumplió con la normativa vigente.

1.3.2. Áridos reciclados ligados con cemento

La posibilidad de utilizar los AR ligados con un porcentaje de cemento de entre un 3% a un 7% en masa para su aplicación en capas estructurales de firmes con mayores requerimientos ha sido investigada por diversos autores. Este material, requiere de una correcta cantidad de agua para su compactación e hidratación del cemento (Xuan y col., 2012a). Este material en España, se puede clasificar como suelocemento o gravacemento.

En el estudio de materiales granulares tratados con cemento con AR, Xuan y col. (2012b) determinaron que a menor contenido de partículas cerámicas en los AR, y a mayor contenido de cemento y grado de compactación, las propiedades mecánicas mejoraron. Del Rey y col. (2015) investigaron la posibilidad del uso de AR con tamaño máximo de 8 mm en la fabricación de suelocemento, resultando viable su aplicación con un buen comportamiento mecánico y de durabilidad.

Respecto a las variaciones dimensionales (Xuan, 2015) comprobó que en cámara de secado, se produjo retracción mientras que en condiciones de humedad elevadas, expansión, siendo mayor esta expansión con ARM que con ARH (Agrela y col., 2014).

Perez y col. (2013) llevaron a cabo una aplicación real en la que se puso en obra un tramo experimental de un suelocemento como subbase de una carretera con AR. Presentando el suelocemento fabricado con ARH mejor respuesta al deflectómetro de impacto y valores levemente más bajos en resistencia a compresión que el suelocemento fabricado con AN. Girbes y col. (2013) realizaron una experiencia similar. En ésta, no se encontraron diferencias en términos de resistencia a compresión, aun siendo la densidad del Próctor Modificado del suelocemento con árido reciclado un 11% menor que el fabricado con AN.

Otro tipo de AR ligados con cemento es el Hormigón seco Compactado con Rodillo (HCR). Este material está constituido por los mismos materiales que un hormigón convencional, cemento, árido (fracción fina y gruesa), agua, y eventualmente aditivo, pero su puesta en obra es mediante equipos de compactación, análoga a los materiales granulares tratados con cemento (suelocemento y gravacemento).

El estudio del uso de AR en los HCR, en la revisión bibliográfica realizada, ha sido con materiales reciclados de pavimento de firme. Settari y col. (2015) encontraron que la incorporación de ARA en la fabricación de

HCR tiene una fuerte influencia en la compactación y densidad debido a que las partículas asfálticas tienen menor densidad y mayor absorción de agua que los áridos naturales. La resistencia a compresión a 28 días también fue afectada por la incorporación de ARA, con pérdidas comprendidas entre el 32.5% y el 55%. Debieb y col. (2009) estudiaron la afección del uso de árido reciclado fabricado en laboratorio curado en ambientes agresivos (cloruros, sulfatos y agua de mar) y obtuvieron una pérdida del 30% en la resistencia a compresión entre el HCR fabricado con áridos naturales y el fabricado con AR (fracción fina y gruesa) no contaminados. Modarres y Hosseini (2014) encontraron que la sustitución de AN por ARA en la fracción gruesa y/o fina en HCR reducía la resistencia a compresión, siendo esta reducción un 30% mayor en la fracción gruesa que en la fina. En la investigación de Modarres y Hosseini (2014) también se estudió el uso de la adición de cenizas de cáscara de arroz como sustitución al cemento. Meddah y col. (2014) evaluó el uso de neumáticos fuera de uso triturado y tratado en la fracción gruesa de hasta un 30% de sustitución del árido natural. Se obtuvieron pérdidas entre un 50% y un 25% en las propiedades mecánicas con la máxima sustitución respecto al de control, fabricado con áridos naturales.

Courard y col. (2010) estudiaron el uso de AR procedente de pavimentos de hormigón en la fracción gruesa de HCR, no encontrando influencia en la compacidad variando el contenido de cemento entre 175 y 250 kg/m^3. Hazaree y col. (2011) establecieron que la contribución óptima de cantidad de cemento a la resistencia a compresión se encuentra en torno a 250 kg por m^3.

Más ampliamente estudiado ha sido el uso de AR en hormigón convencional, como sustitución parcial o total de la fracción gruesa. La mayoría de las publicaciones han sido realizadas con ARH. Beltrán y col. (2014) concluyeron que para obtener la misma resistencia que con AN, habría que añadir un 12% en peso de cemento más si se sustituye la fracción gruesa de AN por ARH. Rahal (2007) obtuvo unas pérdidas de alrededor del 10% en resistencia a compresión y tracción indirecta, comparando los valores de los ensayos en el hormigón de referencia con AN con la sustitución del 100% de la fracción gruesa por ARH, mientras que Etxeberria y col. (2007) obtuvieron pérdidas de resistencia a compresión entre el 20-25% en el mismo caso.

Mefteh y col. (2013) establecieron que se podía sustituir hasta el 40% de la fracción gruesa por ARH sin pérdida de resistencia.

Soares y col. (2014) estudiaron el uso de ARH provenientes de la industria de la prefabricación de hormigón, concluyendo que la sustitución total de la fracción gruesa no supuso mermas en la mayoría de las propiedades estudiadas, menos en absorción de agua por capilaridad y por inmersión. Kou y Poon (2012) establecieron que a mayor cantidad de ARH menor resistencia mecánica ofrecida por el hormigón, al igual que la retracción por secado y la absorción de agua por capilaridad. Domingo-Cabo y col. (2009) observaron que la retracción por secado en el hormigón fabricado con ARH en la fracción gruesa fue un 70% mayor que el fabricado con AN. En términos de durabilidad, González y Etxeberría (2014) estudiaron hormigones con baja relación agua/cemento y con ARH procedente de hormigones con distintas resistencias, no encontrando diferencias en la absorción de agua por capilaridad entre los hormigones con ARH y los de referencia, 0.014 ± 0.001 mm/min$^{1/2}$. En el estudio de Pedro y col. (2014) se encontró que el ARH usado para la fabricación de hormigones, procedente de diferentes clases resistentes, baja, media y alta, aumentó la retracción por secado; un 47%, 43% y 68% respectivamente, respecto al de control. Al igual que la absorción de agua por inmersión se incrementó en un 29, 23 y 48% respectivamente.

Como se ha comentado antes, el ARM es mayoritario en producción en España, siendo aproximadamente el 80% de todo el árido reciclado. Por ello autores españoles (Martin-Morales y col., 2011; Agrela y col., 2011, Rodríguez-Robles y col., 2014a) ensayaron diferentes muestras de ARM procedentes de plantas de RCD de acuerdo con la EHE-08, concluyendo que en lo relativo a los ensayos químicos, se podría establecer que el contenido en yeso se limite a 1.5% en peso, para cumplir el contenido en sulfatos solubles en ácido de 0.8%. Otras proposiciones son reducir el contenido en yeso pre-tratándolo de manera manual y disminuir el contenido en cloruros sumergiendo los ARM en agua en la planta. Para evitar exceder los valores de contenido en finos, se recomienda efectuar un pretratamiento de los RCD, y que para evitar la absorción de agua reduzca la trabajabilidad del hormigón, se sugiere la presaturación de éste antes de su aplicación.

En los diferentes estudios en el uso de ARM en la fabricación de hormigón, se pueden establecer dos tipos, aquellos cuyo origen son las plantas de tratamiento de RCD, y los que no. En relación a éstos últimos Brito y col. (2005) usaron diferentes porcentajes de ARM para la fabricación de hormigón no estructural con un contenido de cemento de casi 350 kg/m^3, obteniendo una pérdida en resistencia a compresión de 44%, mientras que la pérdida a flexión fue casi de la mitad que ésta. Yang y col. (2011) y Cachim (2009), en estudios con ARH mezclado con ladrillo machacado, encontraron que no había pérdidas significativas hasta 15-20% de sustitución de la fracción gruesa por ladrillo machado, a partir de este porcentaje se acentuaron las pérdidas en trabajabilidad, permeabilidad y resistencia. Otros autores han estudiado el uso de materiales cerámicos de otra índole, como Guerra y col. (2009), quien estudió la incorporación de porcelana sanitaria machacada en la fracción gruesa del hormigón, no obteniendo pérdidas mecánicas hasta un 9% de sustitución, Pachecho-Torgal y Jalali (2010) obtuvo similares resultados. Medina y col. (2012) obtuvieron una mejora para sustituciones del 25% en este tipo de residuo del 10% y del 20% en la resistencia a compresión y la tracción indirecta respectivamente.

En el otro tipo de estudios en hormigones, en los que los ARM incorporados son procedentes de planta de tratamiento de RCD, de manera resumida, se puede indicar que a medida que aumentamos la tasa de sustitución hay mayor pérdida en las propiedades mecánicas y físicas, disminuyendo también la durabilidad.

Mas y col. (2012a, 2012b) concluyeron en sus estudios que a mayor clase resistente, mayor pérdida de resistencia, e indicó que la pérdida resistencia a 90 días fue menor que a 7 y a 28 días, comparando los valores obtenidos con el hormigón de referencia y los de hormigón con ARM.

Medina y col. (2014, 2015) observaron que la interfase fracción gruesa – pasta de cemento en el hormigón reciclado dependía de la composición del ARM, mostrando más estrecha y compacta interfase con materiales inorgánicos (áridos naturales, partículas cerámicas y de hormigón) que con materiales orgánicos (partículas asfálticas y flotantes). También observó el aumento de la capilaridad, aumentando la tasa de sustitución, excepto en el caso del 25%.

Martinez-Lage y col. (2012) observaron una pérdida de alrededor del 7% en la densidad, del 20-30% en la resistencia de compresión y del 30-40% en el módulo de elasticidad, del hormigón con ARM en la fracción gruesa respecto del hormigón de referencia. Rodríguez-Robles y col. (2014b) encontró pérdidas del 10% (±3.5%) en la resistencia a compresión, tracción indirecta y resistencia a flexión, en hormigones reciclados con 25 y 50% de ARM en la fracción gruesa respecto al hormigón de referencia.

Bravo y col. (2015a, 2015b) estudiaron el uso diferentes AR de plantas de tratamiento de RCD en la fabricación de hormigón reciclado. Encontrando pérdidas del 30% en la resistencia a compresión, entre el 4.7% y el 7.7% en la densidad de hormigón fresco, y de alrededor del 50% en absorción de agua por capilaridad y por inmersión en hormigón fabricado con ARM en la fracción gruesa respecto del hormigón de referencia.

En la normativa vigente española relativa a las exigencias al hormigón, EHE-08, no se permite el uso de ARM en ningún caso. En otros países tales como Alemania, Reino Unido o Portugal, se permite el uso parcial o total en la fracción gruesa para la fabricación de hormigón de uso no estructural. En la revisión bibliográfica realizada, se han encontrado pocas publicaciones en el estudio de hormigones con bajo contenido en cemento y ARM obtenido directamente de planta de tratamiento de RCD. Por ello, en esta tesis doctoral se ha estudiado la afección de la incorporación de ARM de planta en la fracción gruesa en hormigones no estructurales con bajo contenido en cemento, en las propiedades físicas y mecánicas en el hormigón endurecido. En el trabajo realizado se contempla una parte de fabricación en laboratorio, otra parte en la que se estudia un hormigón fabricado en una planta de hormigón preparado tras su puesta en obra.

Por otra parte, también se ha estudiado el uso de ARH procedente de planta de RCD en la fracción gruesa del HCR. En base al buen comportamiento ofrecido en la fabricación de suelocemento en las publicaciones revisadas, y dado que no se han encontrado publicaciones aplicando el ARH en HCR, sino con ARA, se estudiaron las propiedades físicas y mecánicas en la incorporación de ARH en la fracción gruesa del HCR.

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2. Objetivos, metodología y estructura

2.1. Objetivos

El objetivo de la presente tesis doctoral es estudiar Hormigones no Estructurales (HNE) y Hormigones secos Compactado con Rodillo (HCR) con Áridos Reciclados (AR) procedentes de los Residuos de Construcción y Demolición (RCD) y bajo contenido en cemento. En el caso de HNE, se buscó el contenido mínimo de cemento con la máxima tasa de sustitución de AR, y una vez determinado y estudiado, se realizaron 4 losas de hormigón con las diferentes tasas de sustitución con el contenido mínimos de cemento determinado. En el caso de HCR, se realizaron amasadas con diferentes cantidades de cemento y tasas de sustitución.

Para cumplir con este objetivo general se han desarrollado los siguientes objetivos parciales:

1. Estudiar las características de la fracción gruesa de los AR procedentes de RCD usados en este trabajo; Árido Reciclado Mixto (ARM) y Árido Reciclado de Hormigón (ARH). Para ello se realizaron ensayos necesarios para sus correspondientes aplicaciones relativas a las propiedades físicas y químicas tales como, granulometría, absorción de agua, densidad seca y saturada, índice de lajas, coeficiente de los Ángeles, contenido total de azufre o cloruros.

2. En el caso de los HNE, determinar el contenido mínimo de cemento con el máximo tasa de sustitución de la fracción gruesa por ARM, y la afección de las partículas cerámicas del ARM, obtenido directamente de la planta de tratamiento de RCD. Estudiando propiedades mecánicas, físicas y relativas a la durabilidad

3. Una vez determinado lo señalado en el punto anterior, llevar a cabo una experiencia con una puesta en obra de diferentes losas de HNE con diferentes tasas de sustitución y con la cantidad de cemento indicada, suministrado por una planta de hormigón preparado. Estudiar sus propiedades, tanto en curado en laboratorio, como en condiciones reales.

4. En el caso de los HCR, estudiar la afección de la cantidad de cemento y la tasa de sustitución de la fracción gruesa de árido natural por ARH en las propiedades físicas y mecánicas.

2.2. Metodología

Para alcanzar los objetivos arriba mencionados se siguió el esquema posterior (Figura 2.2.1). En éste se indican la duración de las actividades y lo más reseñable de éstas para la consecución de la tesis doctoral.

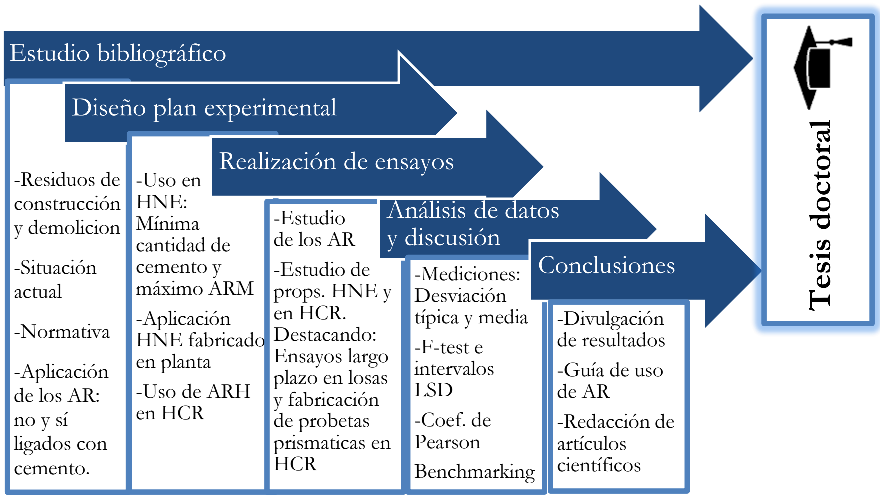

Figura 2.2.1. Esquema metodología

2.3. Estructura de la presente tesis doctoral

Esta tesis doctoral se presenta como un compendio de artículos y se ha estructurado en seis capítulos. El capítulo 1 corresponde a la introducción, mientras que los objetivos, la metodología y la estructura de la tesis se recogen en el capítulo 2. Los tres siguientes capítulos (3, 4 y 5), corresponden a los tres artículos publicados en revistas internacionales indexadas. 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.

El capítulo tercero corresponde al primer artículo "Properties of Non-Structural Concrete Made with Mixed Recycled Aggregates and Low Cement Content", los autores son: A. López-Uceda, J. Ayuso, M. López, J.R.

Jiménez, F. Agrela, M.J. Sierra. Publicado en: *Materials,* en 2016, volumen 9, número 2, página 74. IF: 2.728 (Q1). En este estudio se han utilizado dos gravas recicladas mixtos de diferentes porcentajes de material cerámico, las tasas de sustitución de grava natural de ambos fueron 0, 20, 40 y 100%, con dos bajos contenidos diferentes de cemento 180 kg/m^3 y 200 kg/m^3, el cemento utilizado es el común en las plantas de hormigón preparado CEM II A/V 42,5 R. Con lo que se pudo establecer la afección del contenido de material cerámico del árido reciclado mixto, la cantidad de cemento y la tasa de sustitución de la fracción gruesa en las propiedades mecánicas y físicas en diferentes propiedades del hormigón (objetivos 1 y 2).

El cuarto capítulo corresponde al artículo denominado "Upscaling the Use of Mixed Recycled Aggregates in Non-Structural Low Cement Concrete" los autores son: A. López-Uceda, .J. Ayuso, J.R. Jiménez, F. Agrela, Barbudo, A., De Brito, J. Publicado en: *Materials,* en 2016, volumen 9, número 2, página 91. IF: 2.28 (Q1). En este artículo se lleva a cabo un estudio en el que se llevaron a cabo la ejecución de 4 losas de hormigón con diferentes tasas de sustitución de la fracción gruesa (0%, 20%, 40% y 100%) con árido reciclado mixto (objetivo 3). El hormigón preparado fue suministrado por una empresa local próxima a la UCO. Viendo así las diferencias de las propiedades estudiadas en cada losa, entre las condiciones de puesta en obra en condiciones exteriores reales y las de laboratorio. También se realizó una campaña a largo plazo de ensayos para las condiciones exteriores reales.

El quinto capítulo corresponde al artículo "Mechanical performance of Roller Compacted Concrete with Recycled Concrete Aggregates" los autores son: A. López-Uceda, F. Agrela., M. Cabrera, J. Ayuso, M. López. Publicado en: *Road Materials and Pavement Design,* en 2016, volumen 0, página 1-20. IF: 1.547 (Q2). En esta publicación se llevó a cabo un estudio de diferentes de amasadas de HCR, en las que se elaboraron 4 series con diferentes cantidades de cemento; 110, 175, 250, 350 kg de cemento por m^3. En cada serie se estudiaron 3 tasas de sustitución de la fracción gruesa por ARH; 0%, 50% y 100%. Evaluándose así la afección de la cantidad de cemento y el porcentaje de sustitución (objetivos 1 y 4). También es destacable el desarrollo de un método para la fabricación de probetas para el estudio de la resistencia a flexión de este material.

En el último capítulo se presentan las conclusiones más relevantes y las futuras líneas de investigación motivadas por la presente tesis.

3. Properties of Non-Structural Concrete Made with Mixed Recycled Aggregates and Low Cement Content

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Abstract

In spite of not being legally accepted in most countries, mixed recycled aggregates (MRA) could be a suitable raw material for concrete manufacturing. The aims of this research were as follows: (i) to analyze the effect of the replacement ratio of natural coarse aggregates with MRA, the amount of ceramic particles in MRA, and the amount of cement, on the mechanical and physical properties of a non-structural concrete made with a low cement content; and (ii) to verify if it is possible to achieve a low-strength concrete that replaces a greater amount of natural aggregate with MRA and that has a low cement content. Two series of concrete mixes were manufactured using 180 and 200 kg/m^{3g} of CEM II/A-V 42.5 R type Portland cement. Each series included seven concrete mixes: one with natural aggregates; two MRA with different ceramic particle contents; and one for each coarse aggregate replacement ratio (20%, 40%, and 100%). To study their properties, compressive and splitting tensile strength, modulus of elasticity, density, porosity, water penetration, and sorptivity, tests were performed. The results confirmed that the main factors affecting the properties analyzed in this research are the amount of cement and the

replacement ratio; the two MRAs used in this work presented a similar influence on the properties. A non-structural, low-strength concrete (15 MPa) with an MRA replacement ratio of up to 100% for 200 kg/m^3 of cement was obtained. This type of concrete could be applied in the construction of ditches, sidewalks, and other similar civil works.

Keywords: Mixed Recycled Aggregate; ceramics; low cement content; non-structural concrete; mechanical properties; physical properties.

3.1. Introduction

Most of the CO_2-equivalent produced to manufacture concrete comes from cement production; over 400 kg of CO_2-equivalent is generated per m^3 of concrete [1,2], and is also responsible for 5% of all anthropogenic CO_2 emissions [3]. In the European Union (EU), 900 million tonnes of cement were produced in 2008 [4]. In the same year, CO_2 equivalent emissions reached 101 million tonnes in the cement production sector [5]. This results in a high contribution to the emission of greenhouse gases, and contributes greatly to global warming.

Construction and demolition waste (CDW) represents almost a third of the total waste generated in the EU [5]. If CDW is not properly managed and is instead deposited in landfills, it can cause serious environmental problems, such as the release of contaminants that pollute surface and ground water [6,7]. Moreover, the recycling and reuse of CDW in new building materials require less energy consumption, reduce CO_2 equivalent emissions, and, as a result, benefit the environment. Knoeri et al. [8] significantly reduced the environmental impact of recycled lean concrete by using 100% mixed rubble aggregates instead of conventional lean concrete. To promote the recycling and reuse of CDW, the Waste Framework Directive 2008/98/EC has mandated a 70% minimum CDW reuse and recycling rate by 2020. In Spain, the Second National Plan for CDW 2008–2015 [9] was developed to promote the recycling of this waste. This plan set a goal of achieving a recycling rate of 35% in 2015.

CDW consists of ceramic particles, mortar, concrete, and natural aggregates, as well as minor amounts of asphaltic material, gypsum, and impurities such as wood, metal particles, paper, and plastics. There are two major classifications of CDW aggregates, depending on their origin: recycled concrete aggregate (RCA), produced by crushing concrete, and mixed recycled aggregate (MRA), including at least 5% ceramic particles by weight. In Spain, RCA represents approximately 15%–20% and MRA approximately 80% of the total CDW aggregates produced [10].

In Spain, Structural Concrete Code EHE-08 [11] is the regulatory framework that sets the requirements for all materials used in concrete manufacturing, including recycled aggregates (RA). Among them, the fine fraction of RA is not allowed to be used in concrete manufacturing. The code only permits the use of the coarse fraction of RCA, which limits the replacement ratio of structural concrete to 20%. For non-structural concrete, coarse natural aggregates can be replaced by RCA up to 100%. Both cases exclude concretes manufactured using MRA. The standards in other countries, such as Germany, the United Kingdom, and Portugal, permit the partial or total use of MRA as the coarse fraction in non-structural concrete manufacturing, with different requirements in each country [12]. EHE-08 limits the minimum characteristic strength of non-structural concrete to 15 MPa and minimum cement content to 150 kg/m^3. Because non-structural concretes are not steel reinforced, the EHE-08 code does not include any reference to the environment.

3.2. Literary review

The possibility of using the coarse fraction of RCA for the partial or total replacement of the coarse fraction of natural aggregates (NA) in the manufacture of structural concrete has been studied by many researchers. It has been observed [13,14] that replacement ratios up to approximately 20% of RCA have marginal effects on the development of strength in concrete. Exteberría et al. [15] found that the strength of concrete made entirely with RCA was 20%–25% lower than conventional concrete after 28 days. Thomas et al. [13] found that a 20% replacement ratio led to minimal differences in water penetration under pressure and density values, approximately 5% lower than those of the control concrete. Malešev et al. [16] found a 44% increase in water absorption by sorptivity with total replacement using RCA with respect to the control concrete.

The effect of recycled aggregates made of pure ceramics has been explored by several authors, who used crushed bricks to replace the coarse fraction of NA. Their results are somewhat diverse. Brito et al. [17] measured strength losses of 45% with a replacement ratio of 100%, while Cachim [18] found up to 20% strength losses with 30% replacement. Similar results were found by Yang et al. [19], who observed a 10% reduction in strength with 20% replacement compared to the control concrete. Guerra et al. [20] obtained similar values when replacing up to 9% of the NA with recycled ceramic materials from sanitary porcelain debris.

However, a few studies have also been dedicated to the possibility of using MRA as a total or partial replacement material for the coarse fraction in the manufacture of concrete [21–27].

The objective of these studies was to obtain a structural concrete with a compressive strength greater than 25 MPa. The amount of cement used ranged from 240 kg/m^3 to more than 300 kg/m^3, so the amount of cement under 240 kg/m^3 remains unexplored in studies with MRA incorporation in concrete. It was found that concrete made with MRA has a higher porosity, water absorption, and permeability and a lower strength than the control concretes that were made with NA and the same concrete mix composition.

The objectives of this work were as follows: (i) to analyze the mechanical and physical properties of a non-structural concrete made with MRA and a low cement content, and to study the effect of three factors: the replacement ratio of natural coarse aggregate by coarse MRA at four levels (0%, 20%, 40%, and 100%), the amount of ceramic particles in the MRA at two levels (14% and 30%) and the amount of cement at two levels (180 and 200 kg/m^3 of concrete); and (ii) to verify if it is possible to achieve a low strength concrete that replaces a greater amount of natural aggregate with MRA that has a low cement content. This non-structural concrete could be applied to build ditches, floors, sidewalks, and paving blocks, for which a high mechanical strength is not necessary. The results of this research might have the double environmental benefit of reducing CO2 emissions by reducing the amount of cement and by recycling an RA of low quality, which represents the highest percentage of the CDW aggregates produced.

3.3. Materials and experimental details

3.3.1. Materials

3.3.1.1. Mixed Recycled Aggregate

Two mixed recycled aggregates (MRA1 and MRA2) with different percentages of ceramic particles collected on different days from a CDW treatment plant located in Córdoba (South of Spain) were used. These aggregates were by-products of the demolition of residential buildings. The grain size distribution of the materials is shown in Figure 3.1. Both materials were obtained by sieving the 0–25 mm fraction produced in the treatment plant.

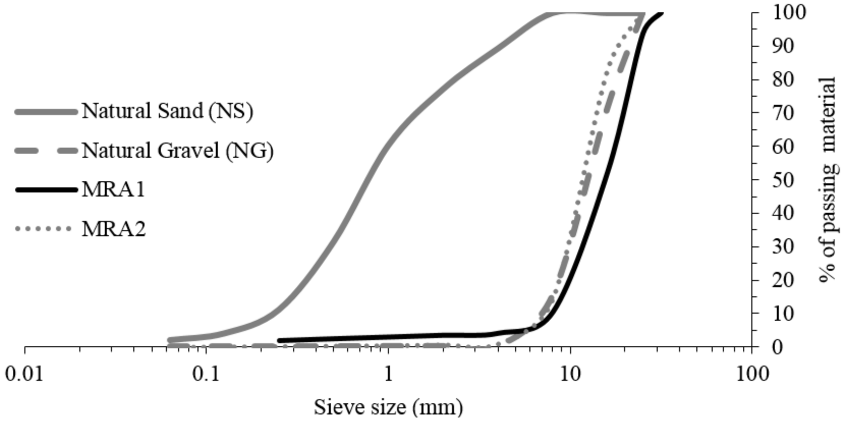


Figure 3.1. Particle size distribution of aggregates. Mixed recycled aggregates (MRA1 and MRA2)

Table 3.1 shows the physical and chemical properties as well as the main constituents of the recycled coarse aggregate with the RA constraints of the Spanish Code EHE-08. Only the water absorption requirement was not satisfied by MRA2, although, for RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures) [28], the limit is less restrictive and up to 20% is allowed. It was noted that the amount of ceramic particles in MRA2 was greater than that in MRA1, so that, the absorption was higher in MRA2. MRA2 complies with the EHE-08 requirements, whereas MRA1 does not, as its total sulfur content slightly exceeds the EHE-08 limit. In the literature review, different classifications have been proposed based on properties or compositions of the two MRA. Agrela et al. [29] established a classification for RA that depends on the ceramic andh concrete particle content. In this scheme, MRA1 was classified as mixed recycled aggregate (MixRA), because its ceramic content was between 10%–30% by weight. MRA2 was classified as a ceramic recycled aggregate (CerRA) because its ceramic content was over 30% by weight. Silva et al. [30] suggested a different RA classification based on te oven-dried density, water absorption, and Los Angeles (LA) abrasion value. In the latter scheme, MRA1 was classified as B-II because its oven-dried density was higher than 2.2 Mg·m^{-3}, and its water absorption and LA values were lower than 6.5% and 45, respectively. Conversely, MRA2 was classified as C-I because its oven-dried density was over 2.0 Mg·m^{-3}, and its water absorption and LA values were lower than 10.5% and 50, respectively.

Table 3.1. Physical, chemical properties and components of mixed recycled aggregates (MRA). SSD: Saturated surface dry.

Physical Properties	**According to Standard**	**MRA1**	**MRA2**	**EHE-08 Requirements**
Water absorption (%)	UNE-EN 1097-6:2014 [31]	6.1	9.0	<5% General <7% RCA
Oven-dried density (Mg/m^3)	UNE-EN 1097-6:2014 [31]	2.24	2.08	-
SSD density (Mg/m^3)	UNE-EN 1097-6:2014 [31]	2.38	2.27	-
Flakiness index (%)	UNE-EN 933-3:2012 [32]	10.8	14.7	<35
Los Angeles test	UNE-EN 1097-2:2010 [33]	35.6	32.3	<40
Freeze-thaw resistance (%)	UNE-EN 1367-2:2010 [34]	5.2	14.0	<18%
Chemical properties	**According to Standard**	**MRA1**	**MRA2**	**EHE-08 Requirements**
Total sulfur content (% S)	UNE-EN 1744-1-11:2010 [35]	1.02	0.96	<1
Acid-soluble sulfates (% SO_3)	UNE-EN 1744-1-12:2010 [36]	0.65	0.62	<0.8
Chlorides (%)	UNE-EN 1744-1-7:2010 [37]	<0.01	<0.01	<0.05
Components (%):	UNE-EN 933-11:2009 [38]	-	-	-
Asphalt	-	0.9	0.5	-
Ceramics	-	13.9	30.2	-
Mortar and concrete	-	49.0	44.6	-
Unbound aggregates	-	34.9	24.0	-
Gypsum	-	0.4	0.5	-
Others (wood, glass, plastic, and metal)	-	0.9	0.2	-

3.3.1.2. Natural aggregates

Figure 3.1 illustrates the grain size distribution of natural siliceous sand (NS) with a maximum size of 4 mm, and siliceous gravel (NG) with a 6–25 mm fraction. The most important physical and chemical properties of natural aggregates for concrete production are summarized in Table 3.2.

Table 3.2. Physical and chemical properties of natural aggregates (NA).

NS = natural siliceous sand, NG = siliceous gravel

Physical Properties	According to Standard	NS	NG
Water absorption (%)	UNE-EN 1097-6:2014 [31]	0.92	0.73
SSD density (Mg/m^3)	UNE-EN 1097-6:2014 [31]	2.66	2.70
Flakiness index (%)	UNE-EN 933-3:2012 [30]	-	20.60
Los Angeles abrasion test	UNE-EN 1097-2:2010 [33]	-	18.10
Friability test	UNE 83115:1989 [39]	12.40	-
Chemical properties	**According to Standard**	**NS**	**NG**
Total sulfur content (% S)	UNE-EN 1744-1-11:2010 [35]	0.36	0.57
Acid-soluble sulfates (% SO_3)	UNE-EN 1744-1-12:2010 [36]	0.17	0.51
Chlorides (%)	UNE-EN 1744-1-7:2010 [37]	<0.01	<0.01

3.3.1.3. Cement

A CEM II/A-V 42.5 R type Portland cement was used. The cement properties are shown in Table 3.3. The cement used for this study had a fly ash content of 17%, which was produced from the emissions of a nearby coal-fired power plant. This represents a significant benefit in CO2 emission reduction [40].

Table 3.3. Chemical composition and physical properties of cement.

Loss on ignition (%)	Specific Mass (Mg/m^3)	Blaine Specific Surface Area (m^2/kg)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O
			(%)						
1.38	2.89	351.9	26.49	8.70	3.31	1.41	54.36	3.26	1.43

3.3.1.4. Admixtures

Two admixtures were used in this study. The plasticizer Conplast MR260 is formulated as a mixture of synthetic and natural polymers. Its main function is to increase the workability of a material. The superplasticizer Conplast SP420 is based on organic polymers. Its main function is to reduce the water-to-cement ratio.

3.3.2. Experimental details.

3.3.2.1. Mix Proportions

The mix proportion was a commercial design provided by PREBESUR SL (Córdoba, Spain), an industrial concrete plant located in Córdoba (Spain).

The concrete mixes were designed to evaluate the influence of the following factors on the mechanical and durability properties of concrete:

- Amount of cement. Two cement contents were used: 180 and 200 kg/m^3.
- Replacement ratio of coarse aggregate. Four levels were used: 0%, 20%, 40%, and 100%. The replacement percentage was calculated using the equivalent volume.
- Type of MRA. Two MRA (MRA1 and MRA2) were tested, with different percentages of ceramic particles.

Two series of concrete mixes were produced with a constant water-to-cement ratio of 0.65: one for a cement content of 180 kg/m^3 and the other for a cement content of 200 kg/m^3. Each series consisted of seven concrete mixes: one with natural aggregates that acted as control concrete (CC); one for each type of MRA (CMRA1 and CMRA2); and one for each replacement ratio (20%, 40%, and 100%). Tables 3.4 and 3.5 illustrate the concrete mix proportions for each series.

Table 3.4. Composition of the concrete mixes for Series I (180 kg of cement/m^3).

Control concrete (CC), R. R. Replacement Ratio, Pl. = Plasticizer, Spl. = Superplasticizer.

Samples	R. R. (%)	Proportions (kg/m^3)						
		Cement	Water	NS	NG	MRA	Pl.	Spl.
CC-I	0	180	117	1100	950	0	1.92	2.15
CMRA1-20-I	20	180	117	1100	759	147	1.92	2.15
CMRA1-40-I	40	180	117	1100	569	294	1.92	2.15
CMRA1-100-I	100	180	117	1100	0	735	1.92	2.15
CMRA2-20-I	20	180	117	1100	817	144	1.92	2.15
CMRA2-40-I	40	180	117	1100	613	288	1.92	2.15
CMRA2-100-I	100	180	117	1100	0	720	1.92	2.15

Table 3.5. Composition of the concrete mixes for Series II (200 kg of cement/m^3).

Control concrete (CC), R. R. Replacement Ratio, Pl. = Plasticizer, Spl. = Superplasticizer.

Samples	R. R. (%)	Proportions (kg/m^3)						
		Cement	Water	NS	NG	MRA	Pl.	Spl.
CC-II	0	200	130	1070	950	0	2.13	2.39
CMRA1-20-II	20	200	130	1070	759	147	2.13	2.39
CMRA1-40-II	40	200	130	1070	569	294	2.13	2.39
CMRA1-100-II	100	200	130	1070	0	735	2.13	2.39
CMRA2-20-II	20	200	130	1070	817	144	2.13	2.39
CMRA2-40-II	40	200	130	1070	613	288	2.13	2.39
CMRA2-100-II	100	200	130	1070	0	720	2.13	2.39

To increase the workability and reduce the amount of water, two additives were used in all the mixes: plasticizer, with a density of 1.184 g/cm^3, and superplasticizer, with a density of 1.195 g/cm^3, were added at 9 mL/kg and 10 mL/kg of cement, respectively. The target was to achieve an S3 slump class, according to UNE-EN-206-1:2008 [41].

3.3.2.2. Mixing Process

MRA have a high water absorption capacity that reduces the workability of fresh concrete and water available for cement hydration. Therefore, some authors [25,42] recommend an initial wetting of the MRA before the mixing process. As such, the MRA were flooded for 10 minutes prior to mixing. It was estimated that during this wetting period MRA absorb 80% of their total capacity [24].

Figure 3.2 presents the scheme of the mixing process.

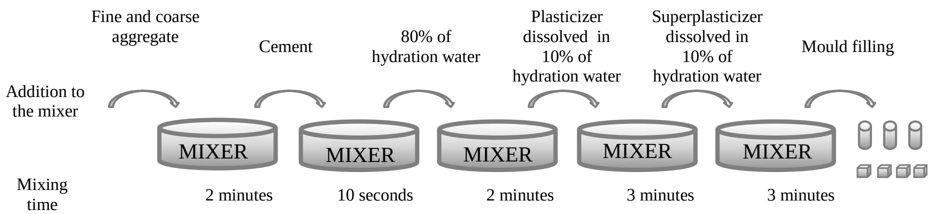


Figure 3.2. Mixing process diagram.

3.3.2.3. Test Method

The mechanical and physical properties were measured at an age of 28 days. Three samples were tested for each test. All the specimens were demoulded at 24 h and then cured in a chamber at constant temperature (23 °C ± 2 °C) and relative humidity (95% ± 5%). Table 3.6 summarizes all the tests that were performed.

Table 3.6. Tests performed to study the properties of concrete.

Test	Standards	Form and Sample Dimensions
Slump test for workability	UNE-EN 12350-2:2009 [43]	Cubic: 100 × 100 × 100 mm
Compressive strength	UNE-EN 12390-3:2009 [44]	Cylindrical: Ø 150 × 300 mm
Tensile splitting strength	UNE-EN 12390-6:2009 [45]	Cylindrical: Ø 100 × 200 mm
Static modulus of elasticity in compression	UNE 83316:1996 [46]	Cylindrical: Ø 150 × 300 mm
Density of hardened concrete	UNE-EN 12390-7:2009 [47]	Cubic: 150 × 150 × 150 mm
Porosity of hardened concrete	UNE-EN 12390-7:2009 [47]	Cubic: 150 × 150 × 150 mm
Penetration of water under pressure	UNE-EN 12390-8:2009 [48]	Cylindrical: Ø 150 × 300 mm
Determination of sorptivity	UNE- EN 1925:1999 [49]	Cubic: 100 × 100 × 100 mm

3.4. Results and discussion

The mean values of the results of all tests carried out for each concrete mix with the coefficients of variation are shown in Table 3.7. All the coefficients of variation were low, which justifies the use of only three replicates. To assess the significance of the effect of the three categorical factors on each of the properties, an analysis of variance (ANOVA) was conducted with the statistical software Statgraphics Centurion XVI (Version 16.1.18, StatPoint Technologies, Inc., Warrenton, VA, USA). The F-test in the ANOVA analysis was used to evaluate whether one factor had statistically significant effects on the properties studied, with a 95% confidence level. If the p-value was lower than 0.05, the factor showed a significant effect on the property studied. To check whether there was a significant difference between the groups for each factor, Fisher's Least Significant Difference (LSD) test was conducted to examine the mean plot and identify the LSD intervals that did not overlap.

Table 3.8 shows a summary of the results obtained with the ANOVA. The results indicate that the percentage of replacement has an influence on all the mechanics and physical properties analyzed and the type of aggregate has no influence on any of the properties, which proves that the two recycled aggregates used in this research were of comparable characteristics. The amount of cement has influence on compressive and splitting tensile strength, as well as on the density and penetration of water under pressure. Additionally, the degrees of freedom n1 and n2 (n1 is equal to factor levels minus one and n2 is equal to the number of observations minus factor levels) considered for the F-Snedecor contrast are indicated.

Table 3.7. Means values of the results of all tests.

Samples	f_{ccub}, MPa	*c.v.*	f_{ccyl}, MPa	*c.v.*	Splitting Tensile Strength, MPa	*c.v.*	Modulus of Elasticity, GPa	*c.v.*	SSD-Density, Mg m^{-3}	*c.v.*	Porosity, %	*c.v.*	Water Penetration, mm	*c.v.*	Sorptivity, mm h$^{-1/2}$	*c.v.*
CC-I	29.0	1.37	20.8	2.53	2.42	2.74	15.3	3.94	2.31	0.74	11.7	1.41	57.0	6.24	0.57	7.17
CMRA1-20-I	23.8	1.01	19.6	1.68	2.36	3.78	14.5	2.35	2.29	0.50	11.8	2.16	89.0	3.31	0.59	6.92
CMRA1-40-I	20.5	4.26	18.6	0.90	2.02	3.52	12.5	5.94	2.25	0.44	13.3	1.62	96.0	3.90	0.76	6.45
CMRA1-100-I	18.5	1.14	17.3	4.86	1.58	15.68	10.5	9.06	2.24	0.10	14.1	0.72	97.5	7.26	0.94	4.84
CMRA2-20-I	21.7	1.95	20.0	1.45	2.35	6.02	14.4	2.96	2.26	0.19	12.2	1.39	63.0	9.07	0.62	12.58
CMRA2-40-I	21.1	0.56	19.2	0.21	2.10	2.26	12.8	3.58	2.24	0.42	13.1	1.27	74.7	7.91	0.81	9.07
CMRA2-100-I	20.5	0.82	19.0	0.77	1.97	10.58	11. 9	1.56	2.20	0.47	13.9	0.37	76.5	3.74	0.99	7.05
CC-II	34.6	2.74	25.8	0.54	2.81	1.28	17.6	3.87	2.38	0.51	10.9	1.35	34.0	8.66	0.25	14.93
CMRA1-20-II	32.7	1.20	24.8	1.43	2.60	3.02	15.8	2.84	2.36	0.23	11.3	1.10	45.3	9.24	0.36	9.46
CMRA1-40-II	30.1	0.42	23.6	0.97	2.29	3.97	15.5	2.86	2.33	0.31	13.2	0.88	52.7	5.44	0.55	3.93
CMRA1-100-II	22.8	4.26	20.5	0.90	2.18	3.52	11.6	8.60	2.25	0.54	13.9	1.43	78.0	6.28	0.89	6.66
CMRA2-20-II	34.5	0.63	25.0	1.77	2.63	2.19	16.7	2.29	2.30	0.62	11.5	1.97	36.3	7.16	0.56	5.15
CMRA2-40-II	33.8	3.66	24.5	1.29	2.35	2.83	16.2	2.47	2.29	0.16	13.1	0.94	45.3	7.28	0.73	5.59
CMRA2-100-II	27.6	3.94	23.4	1.20	2.21	7.23	13.1	4.83	2.25	0.50	13.5	0.10	76.5	6.94	1.03	3.76

f_{ccub} = Compressive strength in cubic specimens; f_{ccyl} = Compressive strength in cylindrical specimens; *c.v.* = Coefficient of variation (%).

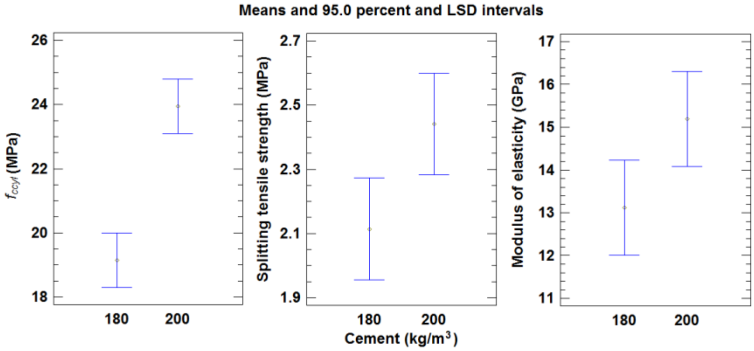
Table 3.8. Summary results of ANOVA and coefficient of variation.

Properties		**Factors**							
		Amount of Cement (kg/m³)		**(%) of Replacement**				**Type or MRA**	
	Factor levels	180	200	0	20	40	100	1	2
	Degrees of freedom	(1;12)		(3;10)				(1;10)	
Compressive strength (f_{ccyl})	*p*-value	<0.0001		<0.0001				0.5477	
	c.v.	5.3	6.7	7.4	3.6	2.1	9.9	8.1	2.9
Tensile splitting strength	*p*-value	0.0439		<0.0001				0.6006	
	c.v.	13.0	9.2	13	8.5	4.5	16.4	12.9	7.5
Modulus of elasticity in compression	*p*-value	0.0647		<0.0001				0.5225	
	c.v.	11.9	12.9	13.9	8.0	4.4	21.6	14.5	9.5
Density of hardened concrete	*p*-value	0.0443		<0.0001				0.2568	
	c.v.	1.5	2.0	2.7	1.4	0.7	2.3	1.6	1.5
Porosity of hardened concrete	*p*-value	0.5132		<0.0001				0.9602	
	c.v.	7.1	9.0	12.3	8.5	4.0	8.5	8.2	6.3
Penetration of water under pressure	*p*-value	0.0023		0.0016				0.1081	
	c.v.	18.5	31.6	44.9	22.3	14.1	24.1	20.1	22.6
Sorptivity	*p*-value	0.3218		<0.0001				0.3875	
	c.v.	20.8	41.3	72.0	32.4	9.9	29.6	27.3	26.2

3.4.1. Effect of cement content

3.4.1.1. Mechanical properties

As seen in Figure 3.3, the mean values for all of the mixes of cylindrical specimens (f_{ccyl} values) with 200 and 180 kg of cement/m^3 were 24.0 and 19.2 MPa, respectively, with a decrease of 19.8%. There were statistically significant differences at a 95% confidence level, as is indicated by the non-overlapping bars in Figure 3.3. Mas *et al.* [23] obtained a greater compressive strength decrease of 46.4% between 360 and 240 kg of cement/m^3 series, due to a higher cement content.



(a) (b) (c)

Figure 3.3. (a) Mean values of compressive strength in cylindrical specimens and 95% LSD intervals vs. amount of cement; (b) Mean values of splitting tensile strength and 95% LSD intervals vs. amount of cement; (c) Mean values of modulus of elasticity 95% LSD intervals vs. amount of cement.

According to the ACI Code 318-08 [50], the mean compressive strength value (f_{cm}) at 28 days for concrete with a characteristic compressive strength (f_{ck}) under 21 MPa, when there are insufficient data to establish a standard deviation of the sample, is given by the following expression:

$$f_{cm} = f_{ck} + 7 \tag{3.1}$$

The values of f_{ck} estimated by equation [3.1] for each concrete mixture are shown in Table 3.9. Six of the mixes, corresponding to a cement content of 200 kg/m^3, had an f_{ck} greater than 15 MPa, which complies with the requirements of the Spanish standard EHE-08 for non-structural concrete. Only the concrete made with 100% MRA1 replacement had a slightly lower f_{ck} value (14 MPa). None of the other mixes (180 kg/m^3) complied with the EHE-08 requirement. This fact does not mean that they cannot be used in applications such as drainage ditches, sidewalks, trench filling and other non-structural uses, whose strength requirements are very low.

Table 3.9. The fck values estimated by ACI Code 318-08.

Cement content	180 kg of Cement/m³						
Samples	CC	CMRA1-20	CMRA1-40	CMRA1-100	CMRA2-20	CMRA2-40	CMRA2-100
f_{cm}	21	20	19	17	20	19	19
f_{ck}	14	13	12	10	13	12	12
Cement content	200 kg of Cement/m³						
Samples	CC	CMRA1-20	CMRA1-40	CMRA1-100	CMRA2-20	CMRA2-40	CMRA2-100
f_{cm}	26	25	24	21	25	25	23
f_{ck}	19	18	17	14	18	18	16

The relationship between the compressive strengths of cylindrical and cubic specimens is plotted in Figure 3.4, with a good linear relationship (R^2 = 0.92).

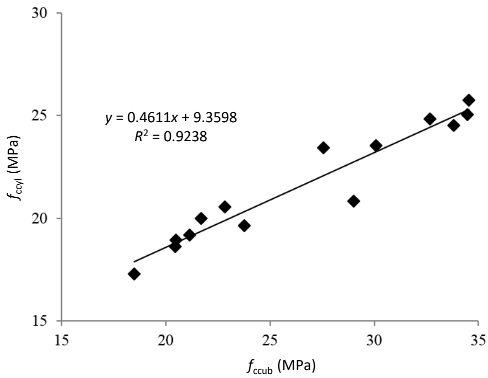


Figure 3.4. Correlation between compressive strength values for cylinder and cubic specimens at 28 days.

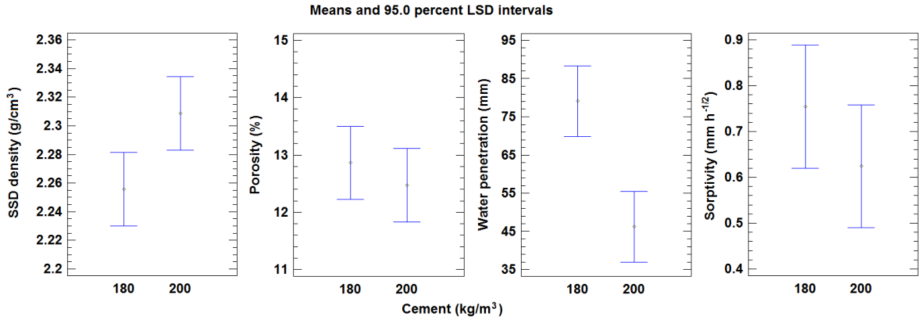
Table 3.7 indicates the mean splitting tensile strength values for each concrete mixture. The non-overlapping bars in Figure 3.3 show that there were statistically significant differences in the splitting tensile strength based on the amount of cement with a 95% confidence level. The mean values of the splitting tensile strength for all of the mixes with 200 and 180 kg of cement/m^3 were 2.44 and 2.12 MPa, respectively, with a decrease of 13.3% from the higher content to the lower one. Mas *et al.* [23] obtained a higher splitting tensile strength decrease (35.9%). This agrees with the statement of Neville [51] who affirmed that the compressive and tensile strengths decline with the cement content, but the latter at a lower rate.

The mean values of the static modulus of elasticity are shown in Table 3.7. The mean values for all of the mixes with 200 and 180 kg of cement/m^3 were 15.2 and 13.1 GPa, respectively. The decrease in the modulus of elasticity between both mixes was 13.8%, which is similar to the splitting tensile strength decrease (13.3%). Figure 3.3 shows that there were no statistically significant differences between the two cement contents in modulus of elasticity property, as indicated by the overlapping bars.

3.4.1.2. Physical properties

Four different physical properties of concrete, namely the saturated surface dry density (SSD density), water penetration under pressure, porosity, and water sorptivity were estimated. The results are shown in Table 3.7. The mean density values for all of the mixes with 200 and 180 kg of cement/m^3 were 2.31 and 2.26 Mg/m^3, respectively. The decrease in the SSD density between the two series was 2.25%. In contrast, Mas *et al.* [23] obtained a decrease of 1.28% between 360 and 240 kg of cement/m^3. The analysis shown in Figure 3.5 did not yield any statistically significant differences at a 95% confidence level, indicated by the lack of overlapping bars.

The mean values of the porosity are given in Table 3.7. Figure 3.5 indicates that a higher cement content reduces the porosity and consequently increases the density. There were no significant differences in porosity with a 95% confidence level. The mean values for all mixes with 200 and 180 kg of cement/m^3 were 12.5% and 12.9%, respectively, with an increase of 3.2% between both series.



(a) (b) (c) (d)

Figure 3.5. (a) Mean values of SSD density and 95% LSD intervals *vs.* amount of cement; (**b**) Mean values of porosity and 95% LSD intervals *vs.* amount of cement; (**c**) Mean values of water penetration and 95% LSD intervals *vs.* amount of cement; (**d**) Mean values of sorptivity and 95% LSD intervals *vs.* amount of cement.

The mean values of water penetration under pressure for all concrete mixtures are given in Table 3.7, and the value for the mixes with 200 and 180 kg of cement/m^3 were 52.6 and 79.1 mm, respectively, (a difference of 50.4%). This is consistent with the higher porosity and lower density of the second series. Figure 3.5 shows that there were significant differences between the series, as the amount of cement had a great effect on the water penetration under pressure. The results of Mas *et al.* [23] showed an increase of 114% between 360 and 240 kg of cement/m^3, which is greater than that seen in our results. This could be attributed to the lower cement content (10%) in the present probes than in those used in their tests (33%).

The mean values of sorptivity for all the mixes with 200 and 180 kg of cement/m^3 were 0.62 and 0.75 mm·h$^{-1/2}$, respectively, with an increase of 20.2%.

Strong linear relationships were found between the sorptivity, density, and porosity, as depicted in Figure 3.6. Sorptivity declines as the density increases and increases as the porosity increases.

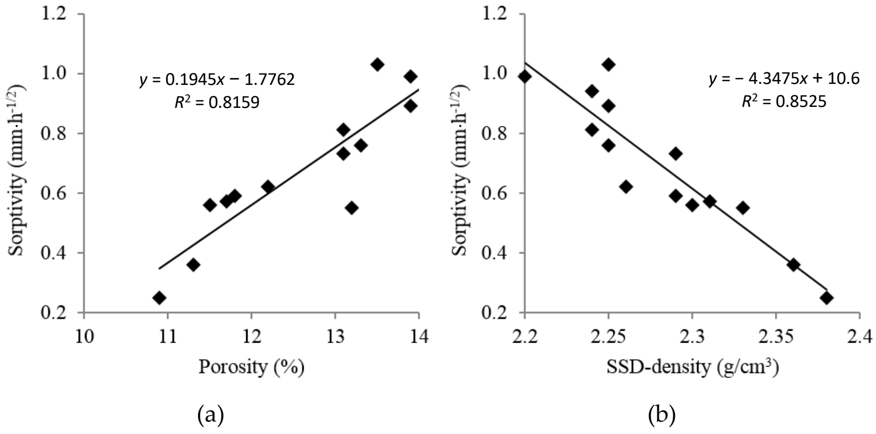


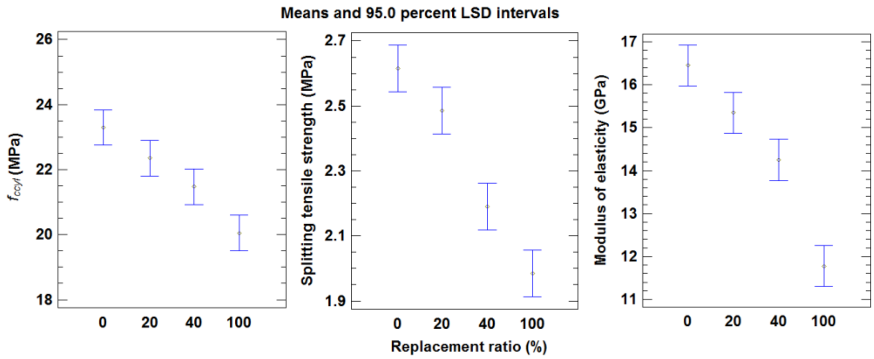
Figure 3.6. (a) Correlation between porosity with sorptivity; (**b**) Correlation between SSD density with sorptivity .

3.4.2. Effect of replacement ratio

3.4.2.1. Mechanical properties

The mean compressive strength of the concrete mixes with 20% of the coarse aggregate replaced was 4% less than the mean value of the control mixes after 28 days. The non-overlapping bars in Figure 3.7 indicate that there was no statistically significant difference between these series of mixes. Mas *et al.* [25] concluded that the reduction in the mean compressive strength after 28 days in concrete made with coarse MRA was 8.1% for a 20% replacement level and 250 kg of cement/m^3. This could be attributed to the fact that in a concrete manufactured with low cement content, the quality of coarse aggregate has a minor influence on strength.

The result was 7.8% less than the mean value of CCs with a 40% replacement ratio, and statistically significant differences in these two series of mixes did occur. These results contrast with those of Medina *et al.* [24], who found an 18.4% difference with 323 kg of cement/m^3 and 50% replacement ratio. Their result could be attributed to the larger amount of cement used.



(a) (b) (c)

Figure 3.7. (a) Mean values of compressive strength in cylindrical specimens and 95% LSD intervals vs. replacement ratio; (b) Mean values of splitting tensile strength compressive strength in cylindrical specimens and 95% LSD intervals vs. replacement ratio; (c) Mean values of modulus of elasticity and 95% LSD intervals vs. replacement ratio.

In the case of the total replacement of coarse aggregate, the decrease was 13.9%, significantly different from the other mixes. Martinez-Lage *et al.* [26] estimated the loss for concrete with 100% replacement was 23%, with values ranging from 20% for 250 kg of cement/m^3 to 31% for 290 kg of cement/m^3. These results were similar to those obtained by Ihobe [21], who found a 25% decrease relative to the control concrete with 250 kg of cement/m^3; Brito *et al.* [17] reached a reduction of 43.48% for total replacement with 346.7 kg of cement/m^3. These results indicate that for a percentage of replacement, the loss of strength was smaller as the amount of cement decreased. This observation agrees with findings by Mas *et al.* [23], who found that concretes with MRA had lower percentages of reduction of unconfined compressive strength than concretes with a higher cement content.

Figure 3.8 represents the loss of mean values of the mechanical properties (f_{ccyl}), splitting tensile strength and modulus of elasticity, with the replacement ratio. A strong linear relationship exists between the loss of mechanical properties relative to CCs and the replacement ratio.

No statistically significant differences in the splitting tensile strength (95% confidence level) between CCs and a 20% replacement level were observed in the data of Figure 7. The loss of strength was 5.0%; this result agrees with findings by Mas *et al.* [23], who measured 6.8% for the same replacement level with 240 kg/m^3 of CEM II.

For 40% replacement, the decrease in splitting tensile strength relative to CCs was 16.2%, which is a statistically significant difference from both a 20% replacement level mix and the CCs. These results contrast with those of Mas *et al.* [25], who concluded that the reduction in average tensile strength was 10% for a 40% replacement level with 240 kg of cement/m^3.

A 24% decrease was measured with total replacement with respect to CC. Yang *et al.* [19] obtained a 30.5% loss for concrete with 100% mixed recycled aggregate for 435 kg of cement/m^3. This higher reduction is due to the larger cement content used in their study.

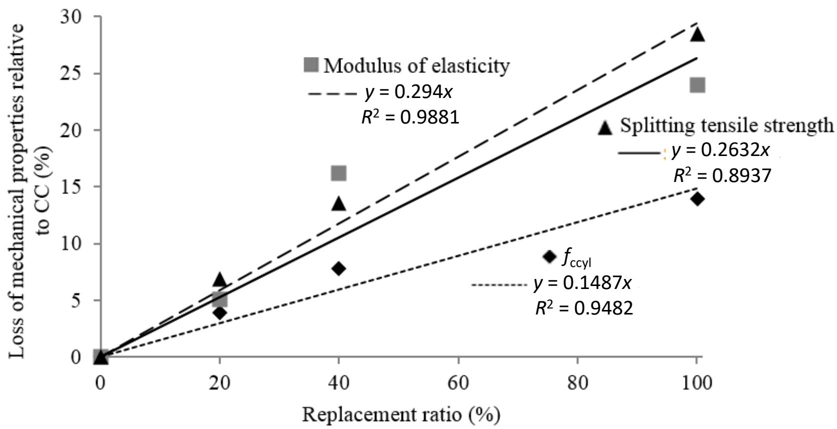


Figure 3.8. Loss of mean compressive strength, tensile strength, and modulus of elasticity relative to control concrete (CC) in relation to the replacement ratio.

The modulus of elasticity varied in the same way as the compressive and splitting tensile strength. The mean value of the modulus of elasticity with a 20% replacement level was 15.34 GPa. This was 6.8% less than the mean value for CCs (16.46 GPa). For a 40% replacement level, the mean value was 14.22 GPa, with a decrease of 13.6% relative to CCs. With full replacement, the decrease was 28.4%. This result is in accordance with the results of Martinez-Lage *et al.* [26] and Ihobe [21], who estimated decreases of 34% and 28%, respectively, for total replacement in concrete manufactured with MRA. Figure 7 shows that there were statistically significant differences between all replacement ratios.

3.4.2.2. Physical properties

Figure 3.9 shows that there were significant differences between the SSD density of CCs and all replacement ratios. The SSD density decreased as the replacement levels of the MRA increased; this was due to the low density of MRA compared to NA. The mean SSD density for 20%, 40%, and 100% replacement ratios, decreased by 1.8%, 2.9%, and 4.4%, respectively. Mas *et al.* [25] found a 3.3% loss of density for a concrete with 240 kg/m^3 of CEM II and 20% MRA replacement. Martinez-Lage *et al.* [26] found a 7.7% decline with a 100% MRA replacement and 250–290 kg/m^3 of CEM II. These higher values could be attributed to the larger cement content used.

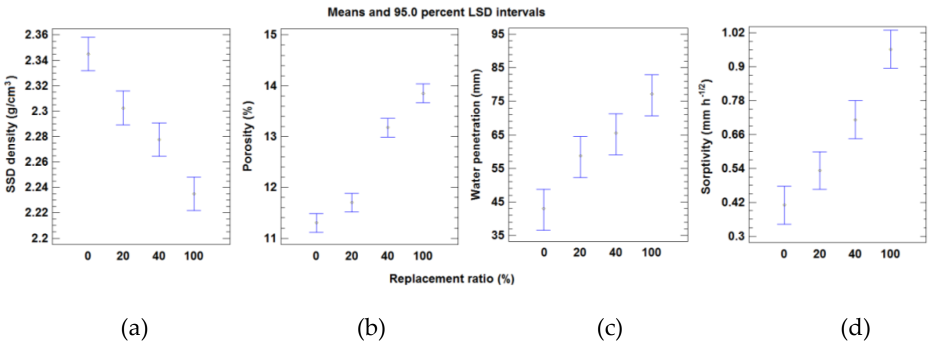


Figure 3.9. (a) Mean values of SSD density and 95% LSD intervals vs. replacement ratio; (b) Mean values of porosity and 95% LSD intervals vs. replacement ratio; (c) Mean values of water penetration and 95% LSD intervals vs. replacement ratio; (d) Mean values of sorptivity and 95% LSD intervals vs. replacement ratio.

As seen in Figure 3.9, there were significant differences in porosity between all replacement levels, showing that this factor had an important effect on porosity. The mean value of porosity for 20%, 40%, and 100% replacement levels increased relative to CCs by 3.4%, 16.3%, and 22.4%, respectively. Beltran *et al.* [52] found 1.75% and 6.3% growth for a concrete manufactured with 300 kg of cement/m^3 and with a 20% and 100% replacement of coarse NA by RCA, respectively. This minor growth could be attributed to the greater density of RCA compared to MRA.

Figure 10 indicates that a strong linear correlation exists between the decrease in SSD density (R^2 = 0.86) and replacement ratio, and the increase in porosity (R^2 = 0.85) and replacement ratio.

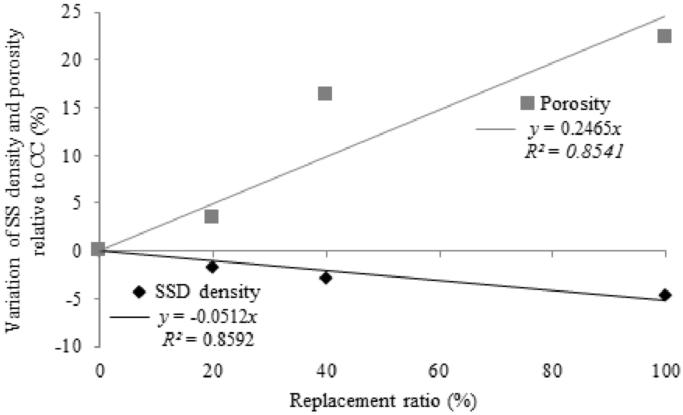


Figure 3.10. Loss of mean of SSD density and porosity variation relative to CC in relation to the replacement ratio.

Figure 3.9 shows that there were no significant differences between CCs and a 20% replacement mix in water penetration under pressure. A 28.4% increment of maximum water penetration under pressure was found with a 20% replacement level relative to the control. Total replacement resulted in an 80.4% increment of maximum water penetration under pressure relative to CCs.

Figure 3.11 indicates that the maximum water penetration under pressure and sorptivity increases linearly with the replacement ratio, with a high correlation index, 0.90 and 0.97, respectively. The maximum water penetration under pressure for the series with 200 kg of cement/m^3 varied between 34 mm for CCs and 78 mm for 100% replacement with MRA1. These results agree with those obtained by Mas *et al.* [25] and Correia *et al.* [53].

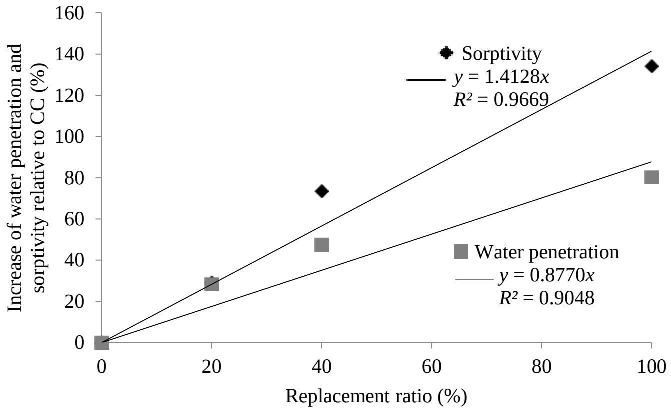


Figure 3.11. Loss of mean of water penetration and sorptivity increase relative to CC in relation to the replacement ratio.

Figure 9 does not show significant differences (95% confidence level) between CCs and 20% replacement in the sorptivity property. A 20% replacement ratio relative to CCs produced a 29.2% increase in sorptivity; this may be due to the higher porosity of concrete with 20% replacement.

For 40% replacement, the increase in sorptivity relative to CCs was 73.4%, similar to Etxeberría *et al.* [27] (65.2%) for similar probes (23% ceramic content of MRA and 240 kg of CEM II/ A-V/m^3). Medina *et al.* [24] found an increase of 13% for 50% substitution; this lower value could be attributed to the larger cement content used (323 kg of CEM I/m^3), resulting in a higher density, as well as the lower ceramic material content (5.3%) in relation to that used in this study (13.9% for MRA1 and 30.2% for MRA2). For total replacement, the gain in sorptivity was 134.1% relative to CCs, which is very similar to the results obtained by Sanchez [22], who found a 133% increase with 240–265 kg of cement/m^3. Conversely, Correia *et al.* [53] found an increase of 70.4%, but with a cement content of 346.7 kg/m^3.

3.4.3. Effect of type of aggregate

3.4.3.1. Mechanical properties

There were no statistically significant differences between the mechanical properties analyzed and the type of aggregate, as shown by the overlapping bars in Figure 12. This statistical result only confirms that the RA used in this work had similar characteristics. As a comparison between the two types of aggregates, the MRA1 mean compressive strength at 28 days was 20.74, and the same value for MRA2 was 21.85 MPa. This may be because the Los Angeles value of MRA1 is higher than that of MRA2, as observed by Ramesh Kumar and Sharma [54].

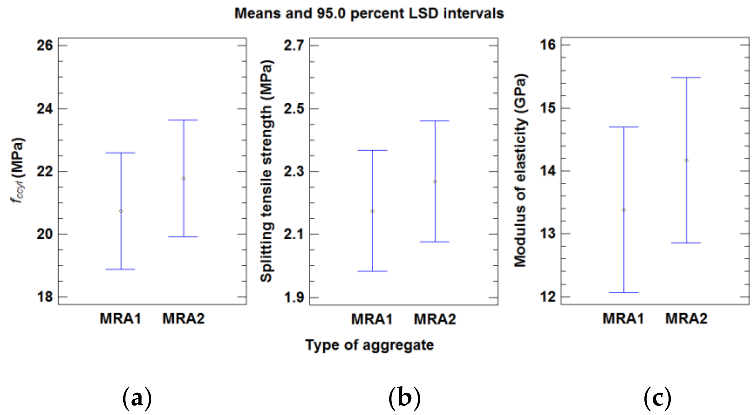


Figure 3.12. (a) Mean values of compressive strength in cylindrical specimens and 95% LSD intervals vs. type of MRA; (b) Mean values of splitting tensile strength compressive strength in cylindrical specimens and 95% LSD intervals vs. type of MRA; (c) Mean values of modulus of elasticity and 95% LSD intervals vs. type of MRA.

Although there is no significant difference in the magnitude of the compressive strength between each type of aggregate, the results suggest a clear trend that does differ by the two types studied (Figure 13). The reduction of the compressive strength between the CMRA1-100-I/II and CC-I/II (9% for both series I and II) is greater than that of CMRA2-100-I/II (17.1% for series I and 20.2% for series II). MRA2 is apparently less harmful to concrete mixtures than MRA1.

The mean splitting tensile strength after 28 days for each type of aggregate was very similar: 2.17 MPa and 2.27 MPa for MRA1 and MRA2, respectively. The higher strength of MRA2 may be due to the minor Los Angeles coefficient of this aggregate, which occurs for the compressive strength. The difference in splitting tensile strength was 4.3%, which is similar to the difference in compressive strength (5.0%).

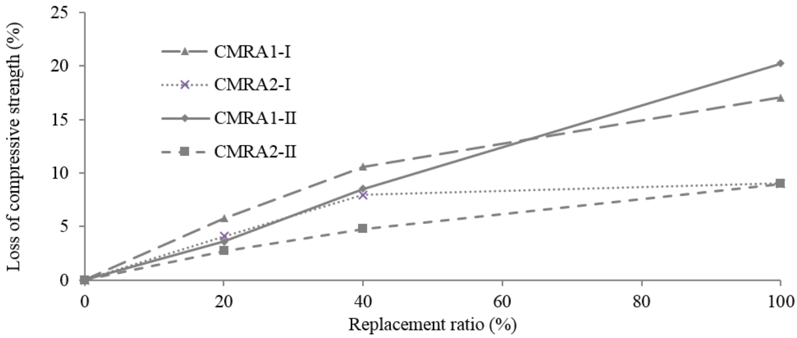
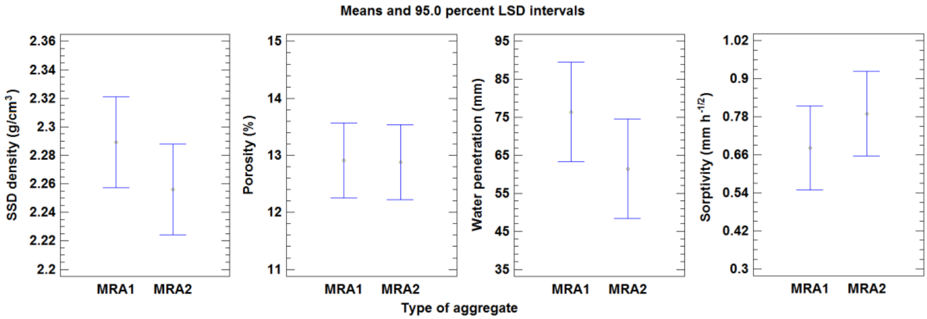


Figure 3.13. Loss of compressive strength, fccyl, relative to CC with the replacement ratio.

The mean value of the modulus of elasticity for the concrete mixtures with MRA1 was 13.38 GPa, which was 5.6% lower than the mean value with MRA2 (14.17 GPa). These results were similar to the compressive strength decrease (5.0%). However, there was no significant difference between the modulus of elasticity and two types of aggregates, although the results show a greater reduction in the modulus of elasticity for CMRA1-100-I/II in relation to CC-I/II (31.5% for I and 33.9% for II) than CMRA2-100-I/II to CC-I/II (22.3% for I and 25.7% for II) due to the minor Los Angeles coefficient of this aggregate.

3.4.3.2. Physical properties

There were no significant differences between the physical properties analyzed and the type of aggregate, as seen in Figure 14. The mean SS densities for MRA1 and MRA2 were 2.29 and 2.26 Mg/m^3, respectively. The low density of concretes with MRA2 was due to the low density of this aggregate, as seen in Table 1.



(a) (b) (c) (d)

Figure 3.14 a) Mean values of SSD density and 95% LSD intervals vs. MRA type. (b) Mean values of porosity and 95% LSD intervals vs. MRA type. (c) Mean values of water penetration and 95% LSD intervals vs. type MRA. (d) Mean values of sorptivity and 95% LSD intervals vs. MRA type.

The mean values of maximum water penetration for MRA1 and MRA2 were 76.4 and 62.1 mm, respectively, with a decline of 18.7%. These great penetration values exert an appreciable influence on the durability of concrete. Nevertheless, this result is not restrictive for the main purpose of this work, which is to manufacture a non-structural concrete to use without steel bars for reinforcement.

Mean sorptivity for MRA1 and MRA2 was 0.68 and 0.79 $mm \cdot h^{-1/2}$, respectively. These results agreed with those of Etxeberría *et al.* [27], who obtained mean sorptivity values of 0.515 $mm \cdot h^{-1/2}$ for MRA with cement content of between 240 and 265 kg/m^3.

3.5. Conclusions

The mechanical and physical properties of concrete made with MRA and low cement content were analyzed in manufacturing a non-structural, low-strength concrete (15 MPa) using the highest substitution percentage of MRA in the coarse fraction. Based on the results obtained in this study, the following conclusions can be drawn:

- The main factors that affect the properties analyzed in this research are the amount of cement and the replacement ratio.

- The type of aggregate used in this research had no statistically significant effects on the properties analyzed.

• Excellent linear correlations between the percentage of substitution and loss of compressive strength, tensile strength, and the modulus of elasticity were found. These losses decrease with the amount of cement.

• Excellent linear correlations between the replacement ratio and increases in porosity, depth of water penetration under pressure and sorptivity were found. These are properties that adversely affect the durability, but the correlations do not present a negative impact for the purpose of this study, as a concrete without steel reinforcement is being sought.

• A replacement ratio of up to 20% of coarse natural aggregates by MRA presents no statistically significant differences in strength properties compared with the control concrete.

• It is possible to achieve a non-structural, low-strength concrete (15 MPa) with an MRA replacement ratio of up to 100% with 200 kg/m^3 of cement. Previous studies have used cement quantities exceeding 240 kg/m^3 for manufacturing non-structural concretes with MRA.

• Even though non-structural concrete made with MRA is not allowed by Spanish Code EHE-08, the results obtained here support its viability. Experimentation on a larger scale is required to confirm these results. This concrete could be used in the construction of ditches, sidewalks, and similar works, with the environmental benefits indicated above.

Acknowledgment

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4. Upscaling the Use of Mixed Recycled Aggregates in Non-Structural Low Cement Concrete

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Abstract

This research aims to produce non-structural concrete with mixed recycled aggregates (MRA) in upscaled applications with low-cement content. Four slabs were executed with concrete made with different ratios of coarse MRA (0%, 20%, 40% and 100%), using the mix design, the mixing procedures and the facilities from a nearby concrete production plant. The analysis of the long-term compressive and splitting tensile strengths in concrete cores, extracted from the slabs, allowed the highlighting of the long-term high strength development potential of MRA incorporation. The study of cast specimens produced in situ under the same conditions as the slabs showed, firstly, that the use of MRA has a great influence on the properties related to durability, secondly, that the loss of compressive strength for total MRA incorporation relative to control concrete increases proportionally with the class strength, and, thirdly, that the mechanical properties (including Schmidt hammer results) from the concrete slabs showed no significant differences relative to the control concrete for coarse aggregates replacements up to 40%. Therefore, this upscaled experimental study supports the

application of concrete with 100% coarse MRA incorporation and low cement content in non-structural civil works such as bike lanes, gutters, ground slabs, leveling surfaces, and subgrades for foundations. To the best of the authors' knowledge, there have not been any upscaled applications of concrete with MRA and low cement content.

Keywords: Upscaled experimental study, non-structural concrete, long term mechanical performance, concrete cores, ready-mix plant, low cement content, mixed recycled aggregates.

4.1. Introduction

Given the amount of construction and demolition waste (CDW), approximately 750 million tonnes per year, according to the European Commission, CDW has been recently upgraded to a priority waste stream status in the European Union (EU) [1] in order to reach 70% by weight in re-use, recycling and other recovery operations by 2020, according to Directive 2008/98/CE [2], established at the European level. In a recent study in Spain, Rodríguez-Robles et al. [3] concluded that there are no reliable regional data on yearly generated CDW, and the most recent reliable figure in 2010 is 23 million.

CDW comes from total or partial construction or demolition of buildings and civil infrastructures. Its composition comprises numerous materials: concrete, natural aggregates, bricks, and, to a lesser extent gypsum, wood, glass, metals, and plastics among others. The two major recycled aggregates (RA) from CDW are recycled concrete aggregate (RCA), which are produced by crushing concrete, and mixed recycled aggregate (MRA), which contains an significant percentage of masonry rubble. In Southern European countries, many architectural interior building elements are ceramic. In Spain, MRA represents over 70% of total CDW aggregates [4]. Hence, Agrela et al. [5] established a classification for RA depending on the content of ceramic and concrete particles: If RA's concrete content ≥90%, it is called concrete recycled aggregate; if its ceramic content is between 10% and 30%, it is named mixed recycled aggregate; finally, if its ceramic content is >30%, it is called ceramic recycled aggregate. Additionally, Silva et al. [6] suggested a different RA classification based on the oven-dried density, water absorption and LA abrasion value. Nowadays, the most common application of MRA in Spain is in unpaved rural roads with low daily heavy traffic, with low value added [7,8]. Additionally, Vegas et al. [9] mentioned that MRA have been used so far mostly in applications with low added value.

According to the Spanish Code on Structural Concrete (EHE-08) [10], a minimum strength class of 15 MPa is required for non-structural concrete, but the minimum cement content shall be 150 kg/m^3. MRA is not allowed in any case, but RCA can be used in non-structural concrete up to 100% and up to 20% in structural concrete, in the coarse fraction in both cases. EN 206-1 requires a minimum cement content of 240 kg/m^3 for structural concrete and 150 kg/m^3 for non-structural concrete [11]. Standards of countries like Germany, United Kingdom, Netherlands, and Portugal allow the use of MRA in non-structural concrete [12].

In Spain, the incorporation of MRA in concrete could be an environmental-friendly value-added solution for this type of RA. To the best of the authors' knowledge, few authors have studied MRA from CDW recycling plants, as total or partial replacement of the coarse aggregate fraction in the production of concrete [13–18]. In these studies, the minimum cement content was 240 kg/m^3.

Martinez-Lage et al. [13] found that the decline in density, compressive strength and modulus of elasticity was approximately linear with the replacement ratio, and it amounted to 7%, 20%–30% and 30%–40%, respectively, in concrete containing 100% recycled aggregate.

Mas et al. [14] concluded that a decrease in concrete's compressive and tensile strength takes place as the MRA ratio increases. The relative loss of strength was higher as concrete strength increased. The loss in long-term (90 days) strength, relative to the reference concrete, is less than that in the short term. MRA incorporation up to 20%–25% leads to strength decreases of less than 15%. In relation to durability, MRA mixes' water under pressure penetration showed a linear increase with the replacement level. A long-term experimental campaign on concrete made with MRA was also suggested.

Mas et al. [15] analyzed the influence of the type of cement, concluding that concrete made with cement with fly ash showed a lower decrease in strength and permeability as the MRA ratio increased.

Medina et al. [16] found that the saturated density and mechanical performance of aggregate concrete are moderately lower than those of the reference concrete, particularly at higher RA incorporation ratios and with impurities. MRA incorporation levels up to 25% have no effect on the sorptivity of concrete. Medina et al. [17] found that the coarse aggregate/paste interface varied depending on the components: Mixes with inorganic materials (gravel, concrete waste and clay-based materials) exhibited a narrower and more compact interface than mixes with organic constituents (asphalt and floating particles). Rodríguez-Robles et al. [18] found that there was a greater negative impact on the mechanical properties of recycled aggregate concrete than found by other authors because of the high cement content they used, confirming the results of Mas et al. [15]. Almost all of the authors agree on the use of admixtures in order to balance the loss of workability caused by the incorporation of high-absorption MRA. Additionally, the use of MRA from CDW in concrete was suggested as a feasible option to improve the construction sector's sustainability, as Bravo et al. [19,20] demonstrated.

Kou et al. [21] studied the influence on different properties of concrete mixes of different recycled aggregates sorted from a Hong Kong's CDW treatment plant. Coarse RA incorporation caused a reduction in ultrasonic pulse velocity (UPV) and in compressive strength, but the quality of the different recycled aggregates did not show significant influence on both of them.

Zaharieva et al. [22] obtained an increase of 75% in porosity and a decrease of 3.15% in density, comparing concrete mixes of full coarse replacement of natural aggregates (NA) by MRA from a CDW treatment plant respect to control concrete made with NA.

Sheen et al. [23] evaluated the effect of RA from the earthquake of Chi-Chi in Taiwan on concrete. Compressive strength reduction was found in concrete made with RA relative to control concrete affected by the brick and tile content of the RA. A higher compressive strength development over the long term was also observed in unwashed RA concrete mixes than in washed ones.

Literature on MRA in real applications has not been found, with the exception of one paper by Etxeberría et al. [24], unlike in the case of RCA. In Shanghai, China, almost 400 m^3 of concrete with RCA were used in an ecological green building, mostly in walls and foundations [25]. In Hong Kong, Wetland Park consumed approximately 14,300 m^3 of concrete made with RCA, namely in ground slabs, external works, mass concrete and minor concrete works. Zhang et al. [26] studied the performance of RCA in beams, proving the feasibility in structural concrete of this type of recycled aggregate. Soares et al. [27], by means of the execution of four full-scale two-storey reinforced concrete structures, concluded that RCA from the precasting industry is suitable for incorporation in structural concrete. In Spain, Rodríguez-Robles et al. [28] listed some pilot projects using RCA in concrete such as sub-bases and ripraps located in the Olympic Village in Barcelona, a cable-stayed bridge in Valencia and a footbridge in Barcelona.

This study continues the research of Uceda et al. [29] with the aim of producing non-structural concrete with MRA, sourced directly from a CDW recycling plant in Córdoba (Spain), and low cement content (200 kg/m^3). To the best of the authors' knowledge, there are no upscaled applications of concrete with MRA and low cement content. This material may be applied in bike lanes, gutters, ground slabs, leveling surfaces, subgrades for foundations and similar civil works. Hence, on-site concrete slabs were executed with different ratios of coarse mixed recycled aggregate (0%, 20%, 40% and 100%), using the mix design, the mixing procedures and the facilities from a nearby concrete production plant. Long-term compressive and tensile strength were performed in cores extracted from the slabs. Schmidt hammer tests were performed on the concrete slabs. Furthermore, mechanical and durability-related properties were studied in laboratory conditions (in terms of curing), using specimens cast in situ under the same conditions as the slabs.

4.2. Materials and Experimental Details

4.2.1. Materials

Natural siliceous sand (NS), with a maximum size of 4 mm, and Portland cement-type CEM II/A-V 42.5 R, with a specific gravity of 2.89 g/cm^3, were used in all the mixes. Two types of coarse aggregate were used: a siliceous gravel (NG) with a size range of (6–25 mm) and a mixed recycled aggregate (MRA) from a recycling plant of CDW located in Cordoba (South of Spain), which was used exactly as it came out of the plant. Figure 4.1 shows the grain size distribution of the aggregates used, where both coarse aggregates display similar curves. Table 4.1 shows the physical and chemical properties of the aggregates. A plasticizer (Conplast MR 260) and a superplasticizer (Conplast SP 420) were used simultaneously to reduce the water content and increase workability.

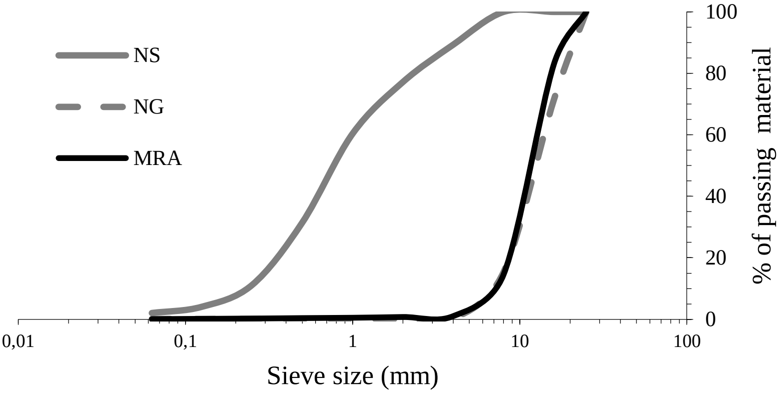

Figure 4.1. Grain size distribution of aggregates used.

Table 4.1. Physical and chemical properties of the aggregates.

Physical Properties:	Test Standard	S	G	RA	EHE-08 Requirements
Water absorption (%)	UNE-EN 1097-6: 2014 [30]	0.92	0.73	9.0	<5% General <7% RCA
Oven-dried density (g/cm^3)	UNE-EN 1097-6: 2014 [30]	2.64	2.68	2.08	-
SSD density (g/cm^3)	UNE-EN 1097-6: 2014 [30]	2.66	2.70	2.27	-
Flakiness index (%)	UNE-EN 933-3: 2012 [31]	-	20.6	14.7	<35
Friability test	UNE-EN 1097-2:2010 [32]	12.4	-	-	-
Los Angeles abrasion test	UNE-EN 1367-2:2010 [33]	-	18.1	32.3	<40
Freeze-thaw resistance (%)	UNE-EN 1097-6:2014 [34]	-	-	14.0	<18%
Chemical properties	**Test Standard**				
Total sulphur content (% S)	UNE-EN 1744-1-11:2010 [35]	0.17	0.2	0.96	<1
Acid-soluble sulphates (SO_3)	UNE-EN 1744-1-12:2010 [36]	0.36	0.56	0.62	<0.8
Chlorides (%)	UNE-EN 1744-1-7:2010 [37]	<0.01	<0.01	<0.01	<0.05

The only test result that did not comply with EHE-08 [10] requirements is the water absorption of MRA. However, according to RILEM [38], this MRA could be classified as Type II aggregates, fit to be used in an up to C50/60 strength class.

Some other Spanish researches were analyzed in order to compare the material used in this study with other of the same geographical area. Rodriguez-Robles et al. [28] studied thirteen samples of MRA with different ceramic contents from several Spanish CDW recycling plants. The ceramic constituents' mean value was 32%, ranging between 16.51% and 64.75%. Vegas et al. [9] analyzed ten different MRA produced in three recycling plants in the Basque Country, North of Spain. The ceramic material mean value was 27.4%, with a range between 12% and 43%. According to Agrela et al. [5], the average ceramic content of 27 MRA samples from 13 CDW recycling plants in Spain was 24%, and it ranged between 12.7% and 53.9%. Thus, in spite of the heterogeneous nature of this type of RA, the RA studied in our research is representative in terms of its ceramic composition (Table 4.2). Sheen et al.

[23] used two MRA with brick and tile contents of 32% and 24%, available in Taiwan.

Table 4.2. MRA composition according to UNE-EN 933-11:2009 [39].

Components	Percentage
Asphalt	0.5
Ceramics	30.2
Mortar and concrete	44.6
Unbound aggregates	24.0
Gypsum	0.5
Others (wood, glass, plastic and metal)	0.2

4.2.2. Mix Design and Procedures

The composition of the mixes (Table 4.3) and the ready-mixed concrete were supplied by a ready-mix plant in Cordoba, Spain. Constant cement content (200 kg/m^3) and water/cement ratio (0.65) were used in all mixes. Four concrete slabs were manufactured, one with natural aggregates (CC), and one for each MRA incorporation ratio: 20%, 40% and 100% (in volume), named RC20, RC40 and RC100, respectively. The slabs dimensions were 3.5 × 3.5 × 0.25 m.

Table 4.3. Composition of the concrete mixes (kg/m^3).

Samples	Cement	Water	NS	NG	MRA	Pl.	Spl.	Slump (cm)
CC	200	130	1070	950	0	2.13	2.39	17
RC20	200	130	1070	817	144	2.13	2.39	14
RC40	200	130	1070	613	288	2.13	2.39	12
RC100	200	130	1070	0	720	2.13	2.39	16

Two admixtures were used in all the mixes, at 9 mL/kg and 10 mL/kg of cement. The plasticizer and superplasticizer were added sequentially in order to have a slump value of 15 ± 3 cm according to UNE-EN-206-1:2008 [40]. Oliveira and Vazquez [41] obtained better results with semi-saturated RA (saturation degree of 85%–90%) than with air-dried or saturated RA. Partially saturated RA has been used in several studies [42–47]. Therefore, the MRA was watered before concrete mixing. To produce the mixes in the ready-mix plant, coarse aggregate and NS were fed into an actual truck mixer, after which the cement and 80% of the water were added sequentially and mixed for two minutes before adding the admixtures with 10% of the water for each one of them.

4.2.3. Specimens, Curing and Test Methods

Cylindrical specimens, Ø 150 × 300 mm, were cast during the slabs execution (Figure 4.2): After 24 h, specimens were demolded and stored in a wet chamber (at 23 ± 2 °C and 95% ± 5% relative humidity). Before casting the specimens, a workability test was performed for each slab (measured with the Abrams cone) (results in Table 3) according to UNE-EN 12350-2:2009 [48].

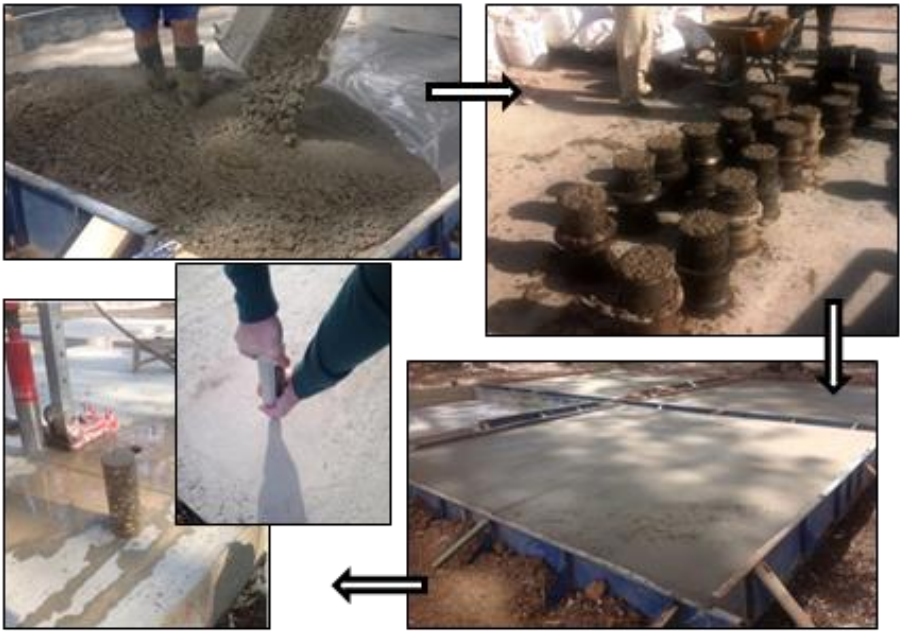

Figure 4.2. Slab execution, specimens cast and core extraction and non-destructive test.

Table 4.4 lists the tests conducted on the cast specimens and their curing time. The value presented for each test and curing time is the average of three replicates.

A non-destructive in situ test, using the Schmidt hammer, was carried out at 7, 28 and 90 days, following standard UNE-EN 12504-2:2013 [49]. Five measurements were made per slab, each one corresponding to the median of ten readings. Six Ø 100 × 200 mm cylindrical concrete cores were extracted from each slab at 7, 28, 90, 180 and 365 days, in accordance with UNE EN 12504-1:2009 [50]. Once extracted, three were tested for compressive strength and three for splitting tensile strength.

Table 4.4. Tests conducted in cast specimens.

Tests (Curing Time in Days)	Standards
Compressive strength (7, 28, 90 and 180)	UNE-EN 12390-3:2009 [51]
Splitting tensile strength (7, 28 and 90)	UNE-EN 12390-6:2009 [52]
Modulus of elasticity in compression (28)	UNE 83316:1996 [53]
Ultrasonic pulse velocity (7, 28, 90 and 180)	UNE 12504-4:2006 [54]
Density of hardened concrete (28)	UNE-EN 12390-7:2009 [55]
Porosity of hardened concrete (28)	UNE-EN 12390-7:2009 [55]
Penetration depth of water under pressure (28)	UNE-EN 12390-8:2009 [56]
Sorptivity (28)	UNE- EN 1925:1999 [57]

4.3. Results and discussions

4.3.1. Compressive Strength

4.3.1.1. Cast Specimens

Figure 4.3 shows the average compressive strength at 7, 28, 90 and 180 days and the corresponding standard deviation. The average values of the mixes with 20% and 40% of MRA incorporation ratio are very similar to those of CC at the same age except those of RC100, whose compressive strength losses relative to CC decreased over the long term: 15.7%, 12.1% and 10.2%, at 28, 90 and 180 days respectively, in agreement with Sheen et al. [23] but at earlier ages. This higher strength gain relative to CC over the long term may be due to the improvement of the microstructure of the interfacial transition zone (ITZ) and the increase of the bond strength between the new cement paste and MRA constituents after continuous hydration because of the presence of the mortar and concrete in the MRA used [58]. It was found that RC40 reached slightly higher compressive strength than RC20, which could be attributed to the higher RC40's slump. Nonetheless, the differences were minor (the average at the four ages of RC40 was higher than that of RC20 by 2.38%, with differences ranging from 0.7% to 4.5%). Mas et al. [14] obtained a compressive strength decrease of 13% for both 20% and 40% MRA incorporation ratio at 28 days, but with more cement content. Bravo et al. [20], with RA with similar ceramic content and 350 kg/m^3 of cement, obtained a ratio equal to 68.5% between the compressive strengths of the mix with total replacement at 7 and 28 days, while in our study the same ratio of the equivalent mix (RC100) was 76.3%.

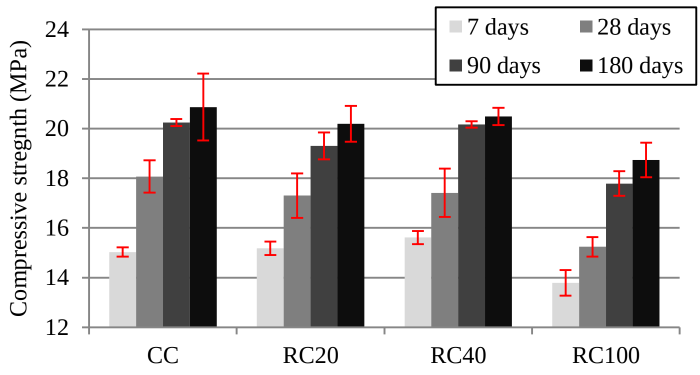

Figure 4.3. Compressive strength in cast specimens at 7, 28, 90 and 180 days of age.

Figure 4.4 shows the loss of compressive strength of total MRA incorporation relative to reference concrete and cement content at 28 days by several authors. Mas *et al.* [15] concluded that the loss of strength is proportionally higher as concrete strength increases. In Figure 4, the idea that the loss of compressive strength in total MRA incorporation relative to control concrete is proportionally higher as cement content increases (class strength) is reinforced. This could be attributed to the fact that the higher the strength class, the higher the influence of the aggregate used on the concrete's compressive strength is.

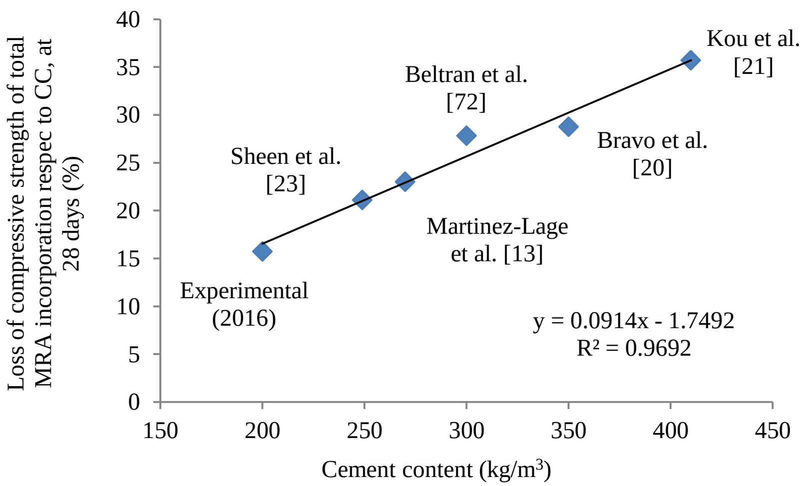

Figure 4.4. Compressive strength in cast specimens at 28 days obtained by several authors in concrete with full MRA replacement.

Silva *et al.* [59] studied, through an extensive literature meta-analysis, the influence of RA on the compressive strength. Figure 4.5 shows that Silva *et al.*'s compressive strength trend reduces the concrete's strength to a greater extent than in our study. As mentioned before, publications were found with lower cement content than the one used here; therefore, this supports the idea that low strength class leads to lower loss of the compressive strength relative to control concrete.

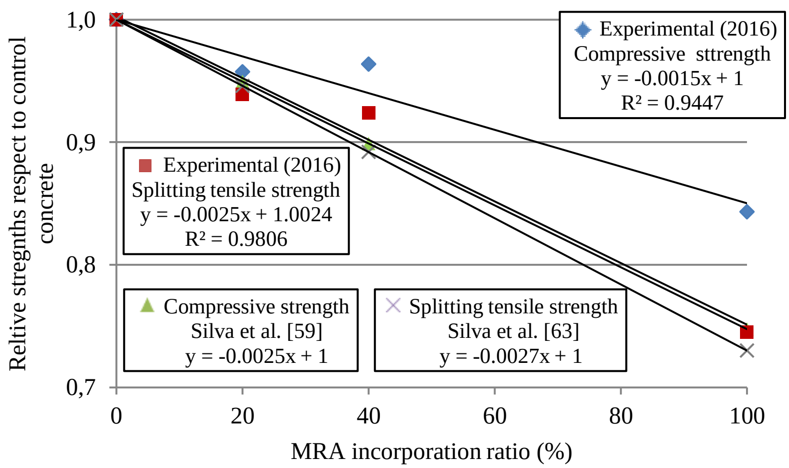

Figure 4.5. Relative compressive and splitting tensile strength in cast specimens obtained by Silva et al.'s review in concrete with MRA.

4.3.1.2. Core Concrete

As in cast specimens, compressive strength average values of the mixes with 20% and 40% of MRA are very similar to those of CC (15.8 MPa). As seen in Figure 4.6, RC100's compressive strength took one year to reach CC's at 28 days, as in Kou and Poon [60], but with RCA and higher cement and fly ash content.

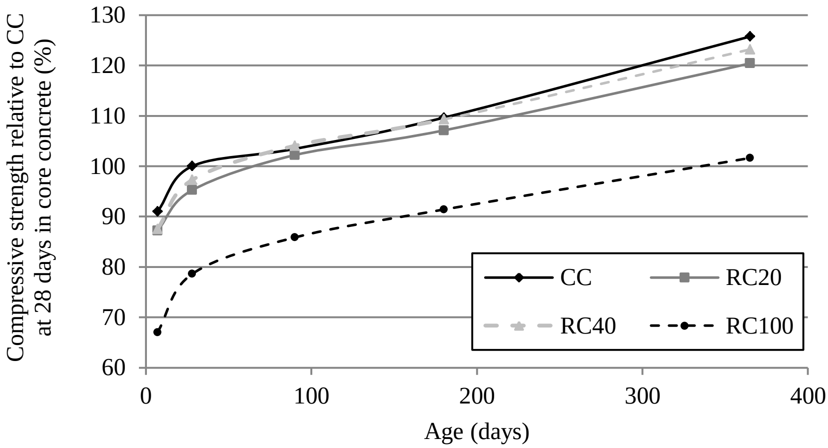

Figure 4.6. Compressive strength in core concrete relative to that of CC at 28 days.

Figure 4.7 shows different correlations between compressive strength obtained in cast specimens and concrete core for all ages studied. By separating RC100 values, a better correlations index was found than with all the mixes (R2 = 0.7983), 0.8502 with CC, RC20 and RC40 mixes and 0.954 with RC100 mix. The higher ratio between compressive strength in cast specimens and concrete cores in RC100 (1.29) than that of up to 40% MRA incorporation (1.17) can be attributed to the fact that damage from drilling increases for poor-quality concrete [61].

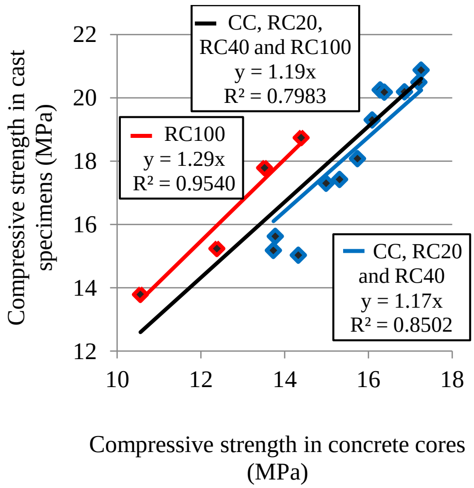

Figure 4.7. Correlation between compressive strength of concrete cores and cast specimens.

4.3.2. Spiltting tensile strength

4.3.2.1. Cast Specimens

Figure 4.8 shows the average splitting tensile strength at 7, 28 and 90 days and the corresponding standard deviation. At 7 days, the strength variations registered were 0.2%, −1.26% and 0.53% for RC20, RC40 and RC100 mixes respectively, relative to CC mix. There was a decrease of 25.5% relative to control concrete with full replacement after 28 days, whereas Bravo et al. [20] found over 30%, and Kou et al. [58] found a 36% loss of splitting tensile strength with 100% full MRA incorporation.

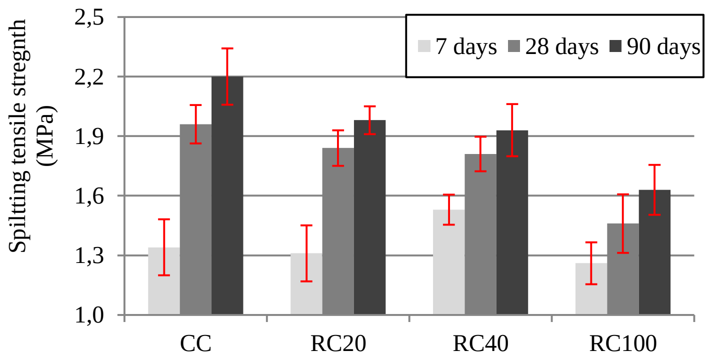

Figure 4.8. Splitting tensile strength in cast specimens at 7, 28 and 90 days.

The splitting tensile strength decreased as the replacement ratio increased (Figure 4.5). This trend regarding MRA incorporation ratio was in agreement with Silva *et al.*'s [62] study, derived from the results of nearly 50 concrete mixes with different coarse substitution ratios of NA with MRA.

4.3.2.2. Core Concrete

Figure 4.9 shows the splitting tensile strength relative to CC at 28 days. It shows that the average values of the mixes with 20% and 40% of MRA are very similar to those of CC (1.28), as for compressive strength. RC100's splitting tensile strength took less than 180 days to reach that of the control concrete at 28 days. Kou and Poon [60] observed that, after one year, concrete with full RCA replacement had higher strength than that of the corresponding control concrete. This increasing long-term trend may be attributed to an improvement of the interstitial transition zone's microstructure between coarse RCA and new cement paste [27]. There was a lower difference relative to control concrete over the long term in mixes with MRA incorporation. Not only does MRA induce the same effect, but it also improves it. At 7, 28, 90, 180 and 365 days, RC100's splitting tensile strength relative to CC was 37.2%, 29.5%, 17%, 11.3% and 8.1%, respectively.

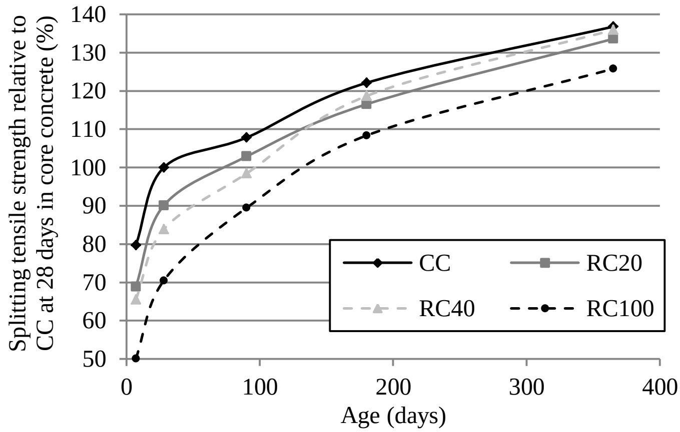

Figure 4.9. Splitting tensile strength in core concrete relative to that of CC at 28 days.

4.3.3. Modulus of elasticity

The modulus of elasticity decreases as the MRA replacement ratio increases (Figure 4.10), similarly to compressive and splitting tensile strengths. Sheen *et al.* [23] obtained a higher loss of modulus of elasticity (27%, whereas in our research 23% was obtained) for full coarse replacement of NA, with similar MRA and higher cement (249 kg/m^3 of cement). Behnood *et al.* [63] established, through extensive data collection, a model for the prediction of the modulus of elasticity according to several factors such as compressive strength, SSD density, water absorption, water-cement, coarse aggregate-cement and fine aggregate-total aggregate ratio. Using our values in their equation, the estimated modulus of elasticity is around 50% higher on average than the experimental results, but the slope of the two linear regressions is very similar (Figure 10). Silva *et al.* [64] also studied the influence of the MRA incorporation on the modulus of elasticity, through an extensive review with 33 mixes (with diverse cement contents but always higher than the one used in this research). Based on CC's modulus of elasticity, Silva *et al.*'s loss relative to MRA incorporation ratio was plotted.

Silva *et al.*'s experimental regressions show very similar slopes, which could lead to the conclusion that the effect of incorporating increasing MRA content is higher than that of the cement content.

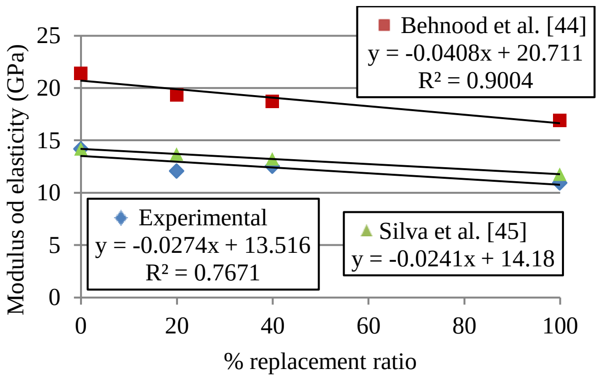

Figure 4.10. Modulus of elasticity in cast specimens with MRA incorporation ratio at 28 days.

4.3.4. UPV

The evolution of the UPV test over the long term of all mixes is displayed in Figure 4.11. As expected, the UPV decreased for specimens produced with higher replacement ratio and increased with longer curing times [65,66]. A higher increase over the long term was found in RC100's UPV than in the rest of the mixes. Kou et al. [58] found similar UPV values after 28 days (3.65 km/s) with full coarse replacement of NA with low-grade RA.

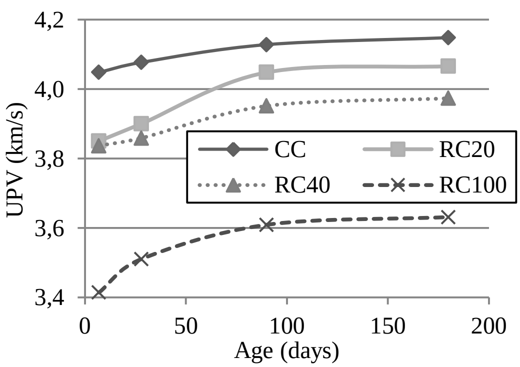

Figure 4.11. Evolution of the UPV test over the long term.

UPV values at 28 days relative to MRA's incorporation ratio compared with those of other authors are presented in Figure 4.12. Concrete mixes with RCA incorporation [27,67,68] presented less decrease as the replacement level increases than those with MRA incorporation of Kou *et al.* [21], Gonzalez-Corominas and Etxeberría [69] and our results. These trends may be due to the higher quality of the RCA than the MRA, in accordance with Breysse [70], who stated that the main influence on the UPV test results is that of the aggregate and that of other, smaller parameters (e.g., type of cement, cement percentage).

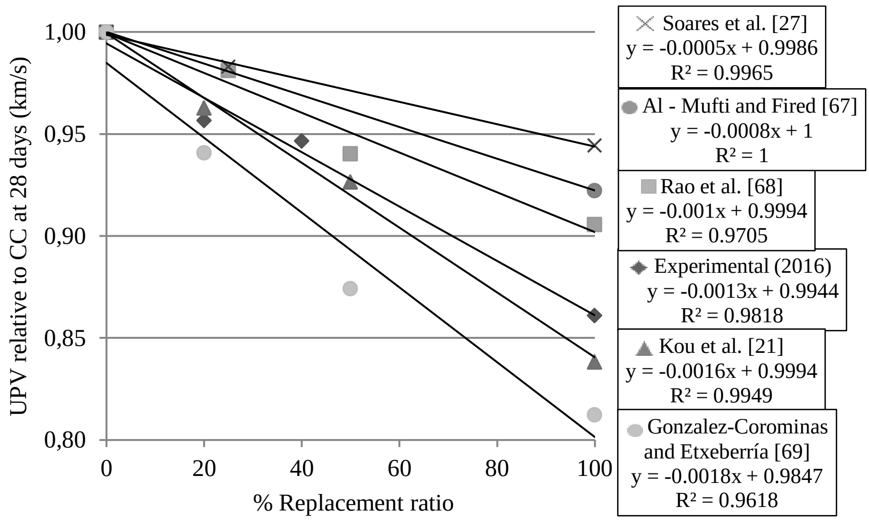

Figure 4.12. Comparison of UPV relative to that of CC with that of other authors.

4.3.5. Schimdt Hummer

Figure 4.13 shows the rebound number of the Schmidt hammer test at 7, 28 and 90 days and the corresponding standard deviation. In spite of the high scatter of this test [71], it was found that the replacement ratio up to 40% had no significant influence on this property, and RC100's rebound number is lower than that of the rest of the mixes, as for compressive strength.

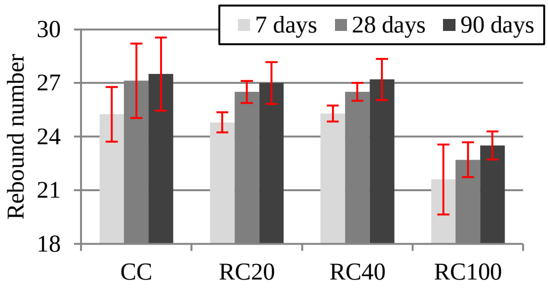

Figure 4.13. Rebound number at 7, 28 and 90 days.

Figure 4.14 shows a better correlation between rebound number and compressive strength in concrete cores than in cast specimens. This can be attributed to the fact that cast specimens were cured in wet chamber and that concrete cores have been subjected to the same meteorological conditions.

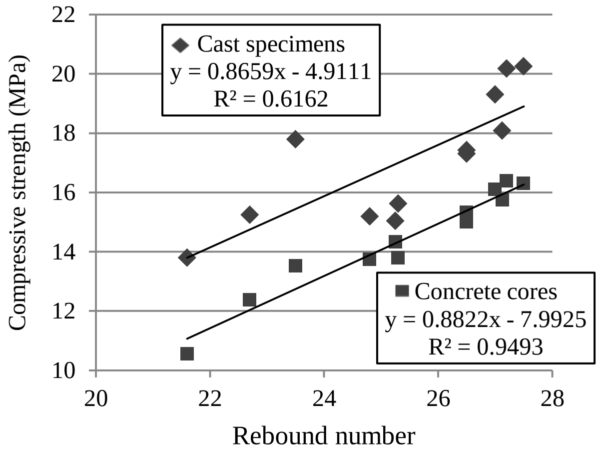

Figure 4.14. Rebound number at 7, 28 and 90 days.

4.3.6. Physical properties

Four physical properties related to the durability of concrete, namely saturated surface dry density (SSD density), water penetration under pressure, porosity and water sorptivity, were tested (Table 4.5). The decrease in SSD density with higher incorporation ratio is due to the lower density of the MRA than the NA. Zaharieva *et al.* [22] obtained, for full MRA incorporation, a similar porosity increase (75%) relative to control concrete and a lower density variation (−3.15%) than in our research. Martinez-Lage *et al.* [13] and

Beltrán *et al.* [72] found similar decreases relative to control concrete in SSD density for MRA total replacement: 7.7% and 6.3%, respectively. The values of porosity and water penetration under pressure increased as the incorporation ratio rose. Thomas *et al.* [73] studied the influence of concrete with RCA from CDW with various incorporation ratios on both properties: The variations relative to control concrete with 20% and 100% replacement are lower than those obtained in our research, which could be due to Thomas *et al.*'s study's having higher cement content and higher-quality RA. Beltrán *et al.* [72] reported 36.3 mm and 70.7 mm in water penetration under pressure of control concrete and full MRA incorporation concrete respectively, which is consistent with our results. Etxeberría *et al.* [24] obtained a sorptivity of 0.74 $mm \cdot h^{-1/2}$ with the same type of cement, similar MRA and 260 kg of cement per m^3 in concrete produced in a truck mixer, with 50% incorporation ratio, similar to those presented in Table 5. The greater water absorption by capillarity of the mixes with MRA incorporation may have been caused by the higher absorption capacity of the MRA ceramic than that of the NA used in the control mix.

Table 4.5. Physical properties tests conducted in cast specimens.

Physical properties	**SSD-Density**		**Porosity**		**Water Penetration**		**Sorptivity**	
Samples	$g \cdot m^{-3}$	V. (%)	%	V. (%)	m	V. (%)	$mm \cdot h^{-1/2}$	V. (%)
CC	2.174	0.00	11.4	0.00	55	0.00	0.24	0.00
RC20	2.135	1.79	13.73	0.44	70.3	27.82	0.59	145.8
RC40	2.139	−1.61	13.15	15.35	73.3	33.27	0.61	154.2
RC100	2.038	−6.26	18.05	58.33	91	65.45	0.87	262.5

4.4. Conclusions

This paper presents an upscaled application of recycled concrete slabs to determine the influence of MRA from CDW on the long-term compressive and splitting tensile strengths of concrete cores extracted from the slabs and on the mechanical and durability properties of specimens cast in situ with the same conditions as the slabs. Based on the experimental results obtained and their discussion, the conclusions drawn are as follows:

- Compressive strength was similar to that of control concrete by up to 40% incorporation ratio at the same age, in cast specimens and concrete cores.

- Full MRA incorporation concrete cores took one year and 180 days to reach control concrete at 28 days values in compressive and splitting tensile strengths respectively, and high long-term development strength potential was found.

- Comparing the relative strength of the total MRA incorporation compressive strength in cast specimens relative to the control concrete and that of other authors with varying cement content, it was found that the loss of compressive strength is proportionally higher as the strength class increases. The compressive strength in cast specimen reached more than 15 MPa in the total MRA incorporation mix at 28 days, i.e. 15.7% lower than that of the control concrete.

- The ratio between the compressive strength of cast specimens and concrete cores depends on the incorporation ratio, leading to two values; one up to 40% incorporation ratio (1.17) and another for 100% replacements (1.29), in order not to underestimate the latter.

- A reduction in UPV test results associated with MRA incorporation was observed, reaching 16% for full MRA incorporation relative to the control concrete, very similar to that observed in compressive strength.

- The Schmidt hammer test results decreased with MRA incorporation, as expected. A good correlation (0.95) between this parameter and core concrete compressive strength was obtained.

- The use of MRA in concrete has a significant influence on the physical properties related to durability. Nevertheless, this material can be used without steel reinforcement in non-structural applications.

CDW were declared a priority stream waste, and MRA is the most abundant RA produced. In light of the results of this upscaled experimental study, using an MRA that is representative in terms of its ceramic composition by comparison with data from other Spanish authors, the feasibility of the use of concrete with full coarse MRA incorporation and low cement content in non-structural applications, such as bike lanes, gutters, ground slabs, leveling surfaces, subgrades for foundations and similar civil works, is clearly demonstrated.

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5. Mechanical performance of Roller Compacted Concrete with Recycled Concrete Aggregates

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Abstract

Because the recycling of construction and demolition waste (CDW) has been deemed to be a priority, the use of a recycled aggregate has been widely demonstrated as a sustainable contribution among different materials applied in civil projects. Roller compacted concrete applications (RCC) offer technical, economic and ecological solutions in many civil construction projects. To the best of the authors' knowledge, there has been little research on the use of RCC with a coarse recycled aggregate that does not originate from pavement. This research evaluates the use of recycled concrete aggregates (RCA) from a CDW recycling plant in RCC mixtures. Four series of RCC mixtures were produced with different cement contents (110, 175, 250 and 350 kg/m^3). Each series consisted of three mixtures with different RCA incorporation ratios (0%, 50% and 100%) of natural coarse aggregates, thus producing 12 RCC mixtures to evaluate the effect on the compaction, the mechanical and physical properties while highlighting a new laboratory casting method for flexural strength and drying shrinkage tests. Based on the obtained results, the use of coarse RCA in RCC production is feasible at a replacement level of 100% when using these materials in road pavement bases.

Keywords: Recycled concrete aggregates, Roller Compacted Concrete, prismatic mould casting method, mechanical properties, drying shrinkage.

5.1. Introduction

Roller Compacted Concrete (RCC) is a homogenous mixture of water, sand, aggregate and cement that is best described as a zero-slump concrete placed with compacting equipment. It is used for dams (Abu-Khashaba et al., 2014; Zarrinkafsh & Shirazi, 2015; Ashtankar & Chore, 2014; Berga at al., 2003), heavy-duty parking and storage areas (Lhur, 2004; Jofre & Kramer, 2008; Courard et al., 2010), and most commonly as a base for rigid pavements (Vancura et al., 2009). In general, the behaviour of RCC is similar to that of conventional concrete, but the mechanical properties of RCC, including its compressive strength, flexural strength, shear strength, and toughness, have been proven superior over long timespans (Burns, 1976; Piarc 1993; Schrader, 1996;Kohn &Tayabji, 2003; Delatte, 2007).

RCC offers technical, economic and ecological qualities that make it an optimal solution in many situations. Its use reduces time and resource consumption, resulting in savings of 10% to 40% compared to conventional concrete (ACI Committee 325, 2011; Naik et al., 2001). Santero et al. (2011) suggested that the application of concrete pavement decreases the heat island effect in urban areas in hot-weather climates. In addition, it has been shown that vehicles require 50% more lighting power on asphalt pavement than concrete pavement to achieve adequate illumination for driving (AzariJafari et al., 2016)

Construction and demolition waste (CDW) can cause serious environmental problems at the end of its service life. Recycling and reusing this waste in new construction materials could diminish energy consumption, thus reducing CO2 emissions and achieving better sustainability in civil construction projects. This sector consumes approximately 40% of primary energy, and CDW represents approximately 50% of sector waste (Behera et al., 2014). Directive 2008/98/CE established that a minimum of 70% of CDW be reused, recycled, or recovered by weight in the European Union by 2020. Additionally, natural aggregate sources are becoming scarcer and further from cities (Marinkovic et al., 2010), hence the use of recycled aggregates should be promoted.

Recycled concrete aggregate (RCA) come from a CDW treatment plant, with a composition of natural aggregate and crushed concrete achieving over

90% by weight (Cardoso et al. 2015). RILEM (1994) established a minimum dry density and maximum water absorption for recycled aggregate in concrete rubble of 2 g/cm^3 and 10%, respectively. Tošić et al., (2015) noted that RCA has a minor density of 10% in relation to natural aggregates (NA). The water absorption of RCA lies between 3.5% and 9%, depending on the amount of adhered mortar (Exteberría et al., 2007). In the Spanish Code for basic materials of firm pavements (Ministry of Development, 2015), sustainability and respect for the environment is promoted through the use of recycled materials and other by-products, thus allowing for the use of CDW aggregates as coarse fractions in road pavement bases.

The use of RCA has been extensively applied in construction materials such as concrete, unbound granular materials and cement-treated granular materials (CTGM). Numerous studies have examined the application of RCA in road bases and sub-bases (O'Mahony & Milligan, 1991; Bennert, 2000; Agrela et al., 2013; Poon & Chan, 2006, Poon et al., 2006; Xuan et al., 2012; Perez et al., 2013, Arulrajah et al., 2014, Del Rey et al., 2015).

There have been various studies that evaluated the properties of RCC with recycled asphalt pavement (RAP), which primarily comes from bituminous road pavement. Settari et al. (2015) concluded that the mechanical properties were reduced in mixtures with partial and full RAP replacement compared to the control RCC, except for the 50% levels of both fine and coarse RAP replacement mixtures, which resulted in higher splitting tensile strength. Courard et al. (2010) did not find significant differences between 250 and 175 kg of cement per m3 in terms of the solid compactness in RCC mixtures with full coarse replacement in concrete road recycled aggregates. Modarres & Hosseini (2014) concluded that RAP incorporation reduced compressive strength and rupture modulus while improving flexibility in relation to control RCC; they also studied the influence of rice husk ash in RCC. Other authors (Meddah et al., 2014) analysed the effect of replacing coarse NA with shredded rubber tyres in RCC mixtures and (Debied et al., 2009) the influence of RCA contaminated with aggressive solutions (chlorides, sulphates and sea water). In addition, RCC has been studied using supplementary cementitious materials such as fly ash (Cao et al., 2000; Atiş 2005; Yerramala & Babu, 2011). The frost resistance of RCC has also been studied by partially substituting cement with natural pozzolan, silica fumes, pumice (Vahedifard et al., 2010), and expansive agents (Gao et al., 2006); the mixture composition has also been evaluated (Hazaree et al., 2011).

Chowdhury et al., 2010, studied the life-cycle impact assessment of industrial by-products used in pavement such as coal fly ash, coal bottom ash and recycled concrete pavement. It was found that the use of recycled concrete pavement had much lower toxicity in increasing transportation ratios; in addition, fly ash and bottom ash had higher impacts compared to NA.

This study evaluates the use of RCA from a CDW recycling plant in the manufacture of RCC as a coarse fraction. Three replacement levels of coarse natural aggregate by RCA (0, 50 and 100%) were crafted in four different series, with each series utilizing four different cement contents (110, 175, 250 and 350 kg/m3). All 12 RCC mixtures were tested to study their mechanical and physical properties, thus highlighting a new laboratory casting method for flexural strength and drying shrinkage tests.

5.2. Materials

5.2.1. Cement

Portland cement CEM II/A-L 42.5 R was used in this investigation (6-20% of limestone addition). The properties of the cement are shown in Table 5.1.

Table 5.1. Properties of cement used

SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	LOI (%)	Specific mass (g/cm^3)	Specific surface area Blaine (cm^2/g)
18.22	3.06	4.27	62.21	0.9	3.17	6.56	2.96	4198

5.2.2. Natural aggregates

Two natural aggregates were used in this study: natural siliceous sand (NS) with a maximum size of 4 mm, and natural limestone coarse aggregate (NG) in the range 4-20 mm from crushed rocks. Their particle size distribution is presented in Figure 5.1 and their properties are summarized in Table 5.2.

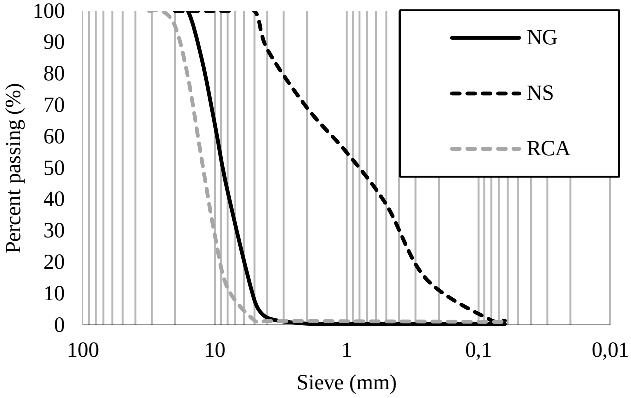


Figure 5.1. Particle size distribution

Table 5.2. Properties of natural and recycled aggregates

Properties	RCA	NS	NG	Test method
SSD density (g/cm³)				UNE - EN 1097 – 06:2014
0-4 mm	-	2.65	-	
4-31.5 mm	2.51	-	2.64	
Water absorption (%)				UNE - EN 1097 – 06:2014
0-4 mm	-	0.77	-	
4-31.5 mm	4.69	-	0.91	
Los Angeles abrasión test	29.4	-	25.6	UNE - EN 1097-2:2010
Water-soluble sulphate content (% SO_3)	0.27	<0.01	<0.01	UNE - EN 1744-1:2013
Acid-soluble sulphate content (% SO_3)	0..36	<0.01	<0.01	UNE - EN 1744-1:2013

5.2.3. Recycled aggregates

RCA was manufactured in the Gecorsa Company treatment plant in Córdoba (South of Spain). Prior to material treatment, all concrete blocks were previously subjected to a cleaning process. Manual and mechanical selections were also performed to separate different compounds from the waste such as wood, plastic or iron. The clean material was then introduced into the production line, beginning with a pre-screening of 25 mm to remove particles below this size to assure quality; it was subsequently sent to a crusher. Production control was performed according to the UNE-EN: 13242:2003 Standard. The RCA composition is shown in Table 5.3.

Table 5.3. RCA composition according to UNE-EN 933-11:2009

	Composition (%)
Bituminuos	1.3
Ceramic particles	2.5
Concrete and mortars	71.0
Natural aggregates	24.9
Gypsum	0

The RCA presented a lower surface saturated density and higher water absorption compared to NG (Table 5.2). The water-soluble and acid-soluble sulphate contents of the RCA complied with the Spanish Code (Ministry of Development, 2015). The RCA presented the same size range (4-20 mm) and coarser particle size distribution than the NG (Figure 5.1).

5.2.4. Dosage and mixing process

In carrying out the dosing of the mixtures, a Fuller curve was followed to seek maximum compactness in the aggregate mixture and filling the emptiness of the granular skeleton, as shown in Figure 5.2. The gradation of the combined aggregate that matches the Fuller curve is very close to 50% for each fraction, fine and coarse; this is similar to the ideal grading plotted followed by Mardani-Aghabaglou et al. (2013). Three coarse RCA incorporation ratios (in volume) were used (0%, 50% and 100%) for the coarse NA.

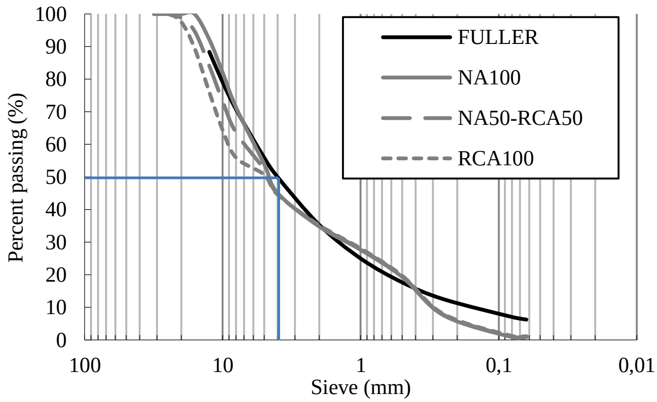


Figure 5.2. Fuller and mixtures distributions

Table 5.4 shows the proportions of the 12 RCC mixtures produced. Four different series were produced, one for each cement content used (110, 175, 250 and 350 Kg/m3). Each series consisted of three mixtures with the aforementioned RCA replacements. The dosages of the mixtures were similar to those used in the works of Vahedifard et al. (2010) and Nili & Zaheri (2011).

Table 5.4. Composition of the mixtures

		Proportions (Kg/m³)				
Series	**Samples**	**NS**	**NG**	**RCA**	**Water**	**Cement**
Serie1 (S1)	S1-NA100	1105	1099	-	90	110
	S1-RCA50	1091	543	530	99	110
	S1-RCA100	1078	-	1047	110	110
Serie 2 (S2)	S2-NA100	1066	1061	-	97	175
	S2-RCA50	1047	521	509	112	175
	S2-RCA100	1027	-	997	127	175
Serie 3 (S3)	S3-NA100	1022	1017	-	105	250
	S3-RCA.50	989	492	480	130	250
	S3-RCA100	965	-	993	127	250
Serie 4 (S4)	S4-NA100	957	962	-	118	350
	S4-RCA50	936	466	454	132	350
	S4-RCA100	913	-	940	145	350

The necessary amounts of water required to manufacture the mixtures were determined by the Proctor modified test (5.3.1). It can be seen that mixtures with RCA required more water than mixtures with NA because of the porous nature of the RCA constituents (Exteberria et al., 2007). Moreover, as can be seen in Table 5.4, the water-cement ratio is lower as cement content increases, in accordance with the study by Hazaree et al. (2011).

The scheme of the mixing procedure is presented in Figure 5.33.

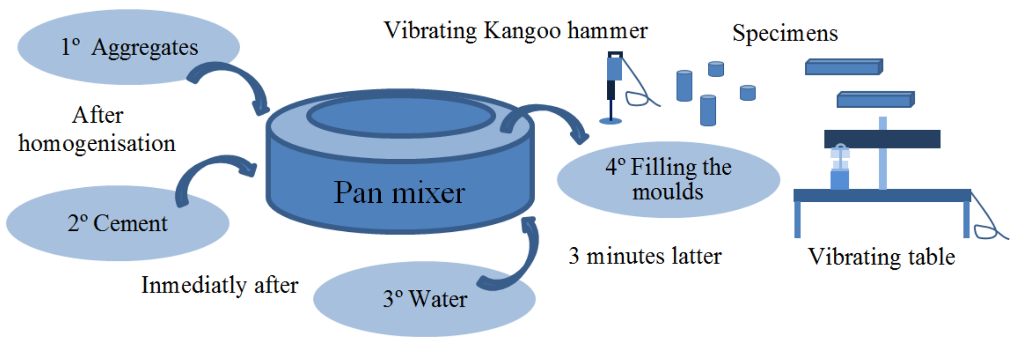


Figure 5.3. Mixing procedure.

5.3. Experimental tests

5.3.1. Compaction tests

An analysis of compaction characteristics of the mixtures with varying compaction moisture was performed according to the UNE-EN 13286-2:2011 modified Proctor test. A Ø 152.5 × 129.8 mm Proctor mould was used to compact five layers, with 60 blows per layer. The relationship between moisture and dry density was obtained. The resultant curve represents the changes in dry density when varying the moisture of the mixture. The optimum moisture corresponds to the maximum dry density.

The compaction time for all of the mixtures was calculated using a vibrating Kango hammer in accordance with the Spanish Standard 310/90 NLT. The specimens were compacted using the moisture content determined in the modified Proctor test. Different compaction energies were used, thus varying the time of application of the load exerted by the vibrating hammer (10, 20 and 30 seconds). Compaction was applied in three layers. The dry-density time is plotted in a graph. The vibrating hammer denoted the time needed to reach 98% of the maximum dry density obtained in the modified Proctor test.

5.3.2. Mechanical property tests in hardened RCC

The compressive strength test was performed using a CBR cylinder mould (Ø 152.5 × 179.8 mm). Nine moulds were filled in three layers, and each layer was compacted with the previously calculated optimum vibrating hammer time. After approximately 24 hours, the specimens were demoulded and stored in a moist chamber at 18-22 ºC and a relative humidity above 95%. After 7, 28 and 90 days, three specimens were tested; the loading direction was perpendicular to the concrete compacting surface. Specimens were subjected to the compressive strength test standard described in the UNE-EN 13286-41:2003.

The splitting tensile strength test was performed according to UNE-EN 12390-6:2010. The loading direction was parallel to the concrete compacting surface. The development of elastic modulus in the RCC mixtures was investigated using the stress-strain relationships of the mixtures in the strength tests; identifying the tangent of the modulus of elasticity was obtained according to UNE 83316:1996. For each of the two latter tests, three cylindrical moulds (Ø 150 x 300 mm) were cast in five layers, and each layer was compacted (Mardani-Aghabaglou & Ramyar, 2013) with the previously calculated previously calculated optimum vibrating hammer time. After approximately 24 hours, the specimens were demoulded and stored in a moist chamber at for 28 days prior to testing.

The flexural strength test was conducted according to UNE-EN 12390-5:2009, for which three prismatic specimens were subjected to a four-point bending moment. The maximum loads perpendicular to the concrete compacting surfaces were recorded and flexural strengths at 28 days was calculated using Eq. [5.1]:

$$R = \frac{P\ x\ l}{d_1\ x\ {d_2}^2} \qquad [5.1]$$

where

- P – maximum load (N)
- l – distance between supports (mm)
- d_1 – specimen dimension perpendicular to the load (mm)
- d_2 – specimen dimension parallel to the load (mm)
- R – flexural strength rupture (MPa)

To produce the prismatic specimen, the following steps were performed; the specimens were then demoulded and stored in a moist chamber after 24 hours.

Prismatic moulds measuring 100 x 100 x 400 mm were used as described in UNE-EN 12390-5:2009.

Givens include the mould volume, the dry density to achieve a minimum of 98% of the maximum dry density obtained in modified Proctor test, and their corresponding moisture. The mass of material to be introduced into the mould was determined.

An IPN-180 I-beam was used to apply a compaction energy similar to that applied in the vibration hammer time test (NLT 310/90 standard) by welding steel plates to the web (Figure 5.4) until 600 N (15 kpa) was reached. Using the I-beam as a surcharge and a vibrating table, specimens were manufactured.

The process of filling moulds was performed in two layers: once the first layer was filled with 60% of the material (due to the compaction energy, the second layer is attenuated to receive part of the first), it was subjected to the compaction process; the remaining material was then introduced.

After several attempts with different dosages, it was determined that the estimated average time to achieve the desired density was 1 minute per layer. Thus, the method was justified.

Figure 5.4. I-beam with welded steel plates plates to the web to produce prismatic specimens.

5.3.3. Density and porosity in hardened RCC

The SSD density, dry density and the porosity of the specimens at 28 days were determined by UNE-EN 12390-7:2009. Three cubic specimens of

10 x 10 x 10 cm were used to calculate both densities, and another three specimens used to obtain the porosity. These specimens were obtained from the flexural strength tested samples. After failure occurred, each of the two extreme parts of the specimens was cut with a cutting saw to the aforementioned cubic specimen dimensions.

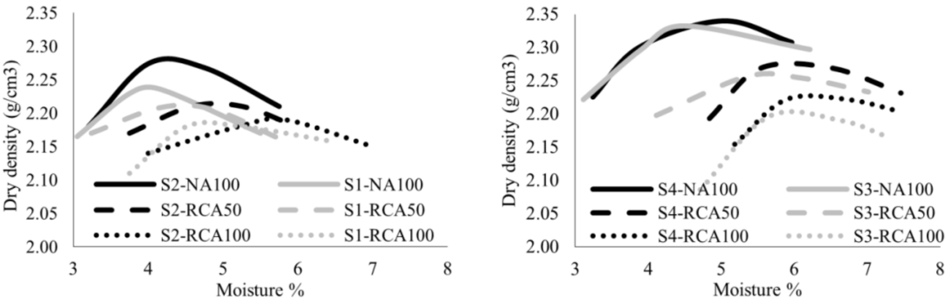
5.3.4. Drying shrinkage

Retraction measurements were obtained on the 100 x 100 x 500 mm RCC prisms according to ASTM C157:2003. Three specimens were manufactured for each mixture following the specifications given for casting the prismatic specimens (5.3.2) for flexural strength; a steel compacting plate slightly smaller than the corresponding mould dimensions was used to homogenously distribute the load. Once the first layer was set, the plate proceeded to the placement of the screw retraction and compacted to subsequently fill the second layer and compact again. The specimens were stored in a dry chamber at 22–25 °C and 46–54% relative humidity 24 hours after production. Measurements were taken at 1, 7, 28, and 90 days of curing to determine retraction.

5.4. Results and discussion

5.4.1. Compaction tests

The relationship between water content and dry density for each mixture is shown in Figure 5.5. Curves of RCA100 mixtures presented flatter slopes than in NA100 mixtures in low cement content series, S1 and S2, S3 and S4 mixtures presented similar slopes. This suggests that the RCC mixtures with RCA replacements can tolerate the same or greater variations in moisture content than the RC mixtures with NA without compromising their dry density during compaction.



a) b)

Figure 5.5 Modified Proctor curves; a) for series S1 and S2; b) for series S3 and S4.

Table 5.5 shows the results of the modified Proctor test, maximum dry density and optimum moisture, and the optimum time compaction. All of the maximum dry density values ranged from 2.34 to 2.19 g/cm^3, in accordance with Mardani-Aghabaglou et al. (2013), Mardani-Aghabaglou & Ramyar (2013) and Modarres & Hoessini (2014). It should be noted that higher RCA incorporation ratios led to lower maximum dry densities and higher moisture levels; this could be attributed to the fact that RCA exhibits lower density and higher water absorption than natural aggregates (Sanchez de Juan & Alaejos 2009). In addition, a higher RCA incorporation ratio led to lower optimum compaction time. Additionally, the three results of the compaction tests were directly proportional to the cement content; this contrasts Hazaree et al. (2011), who obtained an increase in dry density with increasing cement content, although dry density began to decrease beyond 300 kg/m^3.

Table 5.5. Summary of the maximum dry density, optimum moisture and hammer time

	S1 (110 kg/m^3)			**S3 (250 kg/m^3)**		
	NA100	**RCA50**	**RCA100**	**NA100**	**RCA50**	**RCA100**
Max. dry density (g/cm^3)	2.24	2.21	2.19	2.33	2.26	2.21
Moisture (%)	4.00	4.50	5.50	4.50	5.75	6.00
Hammer time (s)	21.	19	16	24	22	18
	S2 (175 kg/m^3)			S4 (350 kg/m^3)		
	NA100	**RCA50**	**RCA100**	**NA100**	**RCA50**	**RCA100**
Max. dry density (g/cm^3)	2.28	2.23	2.20	2.34	2.28	2.23
Moisture (%)	4.25	5.00	5.75	5.00	6.00	6.50
Hammer time (s)	22	20	17	25	23	19

Figure 6 shows the density results for each vibrating hammer time. All RCA100 mixtures presented a similar slope to Agrela et al. (2014), with CTGM produced with RCA and lower cement content.

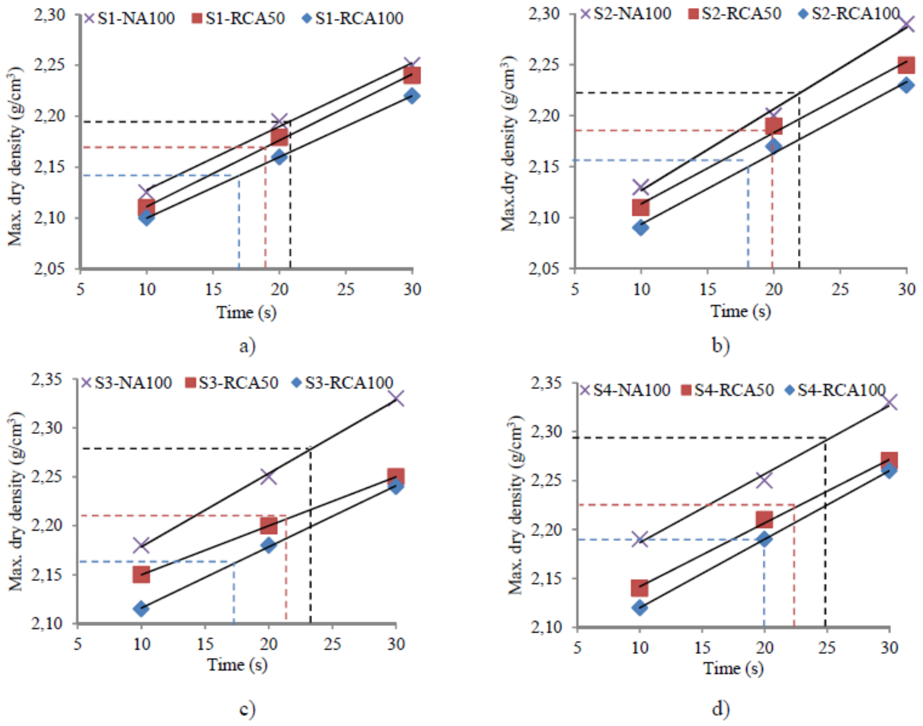


Figure 5.6. Vibrating hammer time of the series; a) S1; b) S2; c) S3; d) S4.

5.4.2. Mechanical properties in hardened RCC

Table 5.6 shows the mean values of the compressive strength at different ages, the splitting tensile strength, the flexural strength and the modulus of elasticity. All mechanical properties decreased as the RCA replacement ratio increased and improved as the cement content increased, as expected.

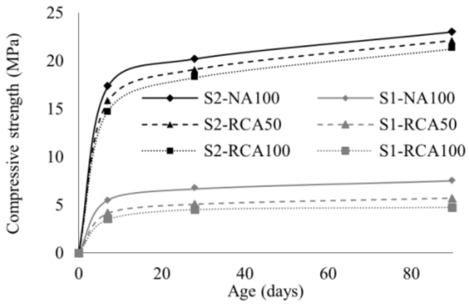
Table 5.6. Mean values of the mechanical properties

Mixtures	Compressive strength (MPa) 7 days	28 days	90 days	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)
S1-NA100	5.5 *(0.47)*	6.7 *(0.87)*	7.5 *(0.53)*	1.25 (0.10)	1.24 (0.12)	11.1 (1.37)
S1-RCA50	4.1 *(0.33)*	5.1 *(0.53)*	5.7 *(0.31)*	1.15 (0.07)	0.96 (0.16)	8.5 *(0.92)*
S1-RCA100	3.5 *(0.30)*	4.5 *(0.45)*	5.1 *(0.43)*	1.09 (0.06)	0.81 (0.14)	7.0 *(0.89)*
S2-NA100	17.3 (1.03)	20.2 (1.13)	23.0 (1.73)	2.41 (1.14)	3.13 (0.23)	18.7 (1.74)
S2-RCA50	15.7 (1.13)	19.1 (1.42)	22.1 (1.41)	2.18 (0.08)	2.57 (0.19)	15.9 (1.24)
S2-RCA100	14.8 (1.41)	18.2 (1.39)	21.2 (0.28)	2.06 (0.06)	2.09 (0.06)	14.2 (1.47)
S3-NA100	28.2 (2.56)	33.2 (1.16)	35.4 (1.03)	3.61 (0.21)	4.93 (0.16)	22.7 (1.50)
S3-RCA50	22.8 (2.31)	25.4 (1.71)	28.9 (1.16)	3.31 (0.22)	4.19 (0.15)	17.8 (1.42)
S3-RCA100	17.9 (1.70)	21.5 (1.81)	24.1 (2.06)	2.67 (0.23)	3.93 (0.07)	16.1 (0.71)
S4-NA100	35.6 (1.82)	40.6 (2.52)	43.9 (2.43)	4.54 (0.14)	6.22 (0.12)	24.3 (1.95)
S4-RCA50	27.6 (1.58)	35.2 (1.47)	40.6 (2.01)	3.85 (0.26)	5.09 (0.32)	20.6 (1.42)
S4-RCA100	23.9 (1.57)	27.6 (2.27)	31.9 (1.24)	3.31 (0.31)	4.90 (0.07)	18.9 (1.73)

[a]Note: Standard deviations given in parenthesis.

The compressive strength at 28 days at varying amounts of cement increase between the series, as expected, obtained mean values of 5.4 MPa, 19.2 MPa 26.7 MPa and 34.5 MPa for S1, S2, S3 and S4, respectively. Bearing in mind the replacement ratio, the mean compressive strength losses between the NA100 and RCA50 mixtures and the NA100 and RCA100 mixtures were 16.5% and 27.5%, respectively. This concurs with Debieb et al. (2009), who found a decrease of 30% in total RCA replacement compared to control RCC mixtures. In comparing the compressive strength in control RCC mixtures with other authors, Lee et al. (2013) obtained 32 MPa and 15 MPa for 250 Kg/m^3 and 180 Kg/m^3 in compressive strength at 28 days, respectively, similar to the results of this research. In contrast, Vahedifard et al. (2010) obtained 28.2 MPa and 25.1 MPa for 281 Kg/m^3 and 238Kg/m^3, respectively. Also in contrast, Debied et al. (2009) found a higher compressive strength at 46 MPa for 250 Kg/m^3 of cement (this could be attributed to the cement used, CEM I 52.5N).

Figure 5.7 shows the compressive strength evolution over time. The mean ratio between the compressive strength of the control mixtures at 7 and 28 days was 85%, equal to that obtained by Abdelaziz Meddah et al. (2014). The increases in compressive strength between 28 days and 90 days in mixtures fully or partially replaced by RCA were higher than in the NA100 mixtures. This increase could be attributed to an improvement of the bond strength in the interstitial transition zone between the old adhered mortar of the RCA and new cement paste over time. Mardani-Aghabaglou & Ramyar (2013) observed a gain of compressive strength over time when partially substituting cement with fly ash in RCC mixtures, thus decreasing the difference in strength between control mixtures and mixtures with fly ash. Modarres & Hoessini (2014) found that compressive strength developed over time in RCC with coarse and fine RAP replacements. Conversely, Settari et al. (2015) found a compressive strength decrease over time in mixtures with RAP replacements.



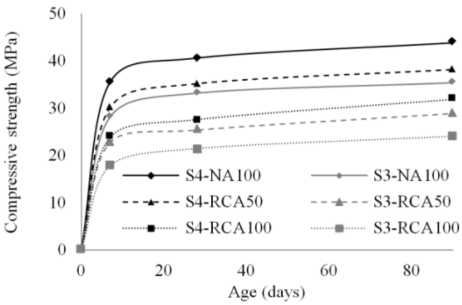


Figure 5.7. Compressive strength evolution in; a) S1 and S2 mixtures; b) S3 and S4 mixtures.

There was a gain in compressive strength between 28 days and 90 days of 6.6% and 8.1% in the NA100 mixtures in S3 and S4, whereas the gain in the RCA replaced mixtures was 13.8%, 15.3%, 12.1% and 15.6% in S3-RCA50, S4-RCA50, S3-RCA100 and S4-RCA100, respectively. The compressive strength development over time was heightened in S3 and S4, almost double that of mixtures fully or partially replaced by RCA mixtures. This effect was not seen in S1 and S2, most likely due to the lower cement content.

As for the splitting tensile strength, the RCA50 mixture losses compared to NA100 mixtures in S1, S2 and S3 were very similar (average loss of 8.6% ±0.9%), whereas the S4 loss was greater (15.2%). In comparing mixtures with full RCA replacement to NA100 mixtures, the losses in splitting tensile strength were 13.6% (±0.9%) in S1 and S2, and 26.7% (±0.9%) in S3 and S4. Debied et al. (2009) obtained a decrease of 56% in splitting tensile strength in full RCA replacement compared to the control mixture of the equivalent series S3; this higher reduction could be attributed to the type of cement (CEM I) used by latter authors.

Figure 5.8 shows the correlation between the splitting test and the compressive strength, demonstrating a good correlation coefficient (R^2=0.92) similar to Berga et al. (2003). Mardani-Aghabaglou & Ramyar (2013) also found similar relationships in RCC mixtures with fly ash substitutions. Their splitting tensile strength corresponded to approximately 10% of their compressive strengths.

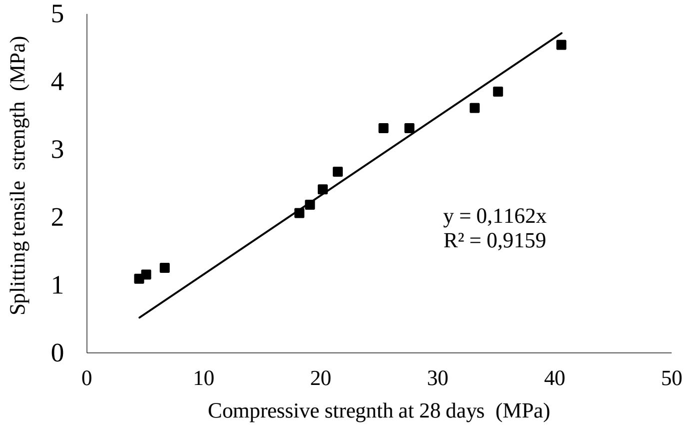
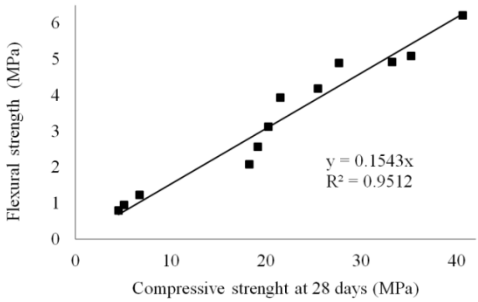


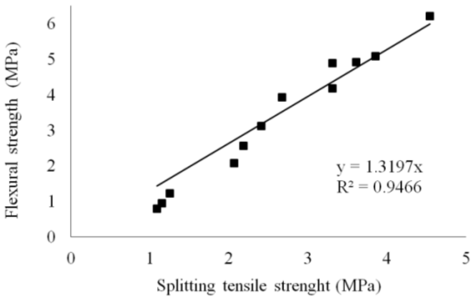
Figure 5.8. Relation between compressive strength at 28 days and splitting tensile strength.

The flexural strength mean values for the four mixtures of S1, S2, S3 and S4 were 1.0 MPa, 2.6 MPa, 4.4 MPa and 5.4 MPa. Taking into consideration the percentage of RCA substitution in flexural strength, the mean loss between the four NA100 mixtures, the four 50% RCA substitution mixtures and the four mixtures with total RCA replacement was 17.7% and 24.4%, respectively, very similar to the compressive strength (15.8% and 28.7%). Abdelaziz Meddah et al. (2014) obtained 5.82 MPa for RCC with natural aggregates mixtures in flexural strength with 295 Kg/m^3, similar to our results.

In Figure 5.9, it can be seen that the flexural strength shows a good correlation with the compressive strength (R^2=0.95) and splitting test (R^2=0.94). Mardani-Aghabaglou & Ramyar (2013) found a relation of 11% and 110% between the flexural strength and the corresponding compressive strength, as well as between the flexural strength and the corresponded splitting tensile strength, respectively.



a)



b)

Figure 5.9. Relation between a) flexural strength and compressive strength at 28 days; b) flexural strength and splitting tensile strength.

The mean values of the modulus of elasticity for the four mixtures of S1, S2, S3 and S4 were 8.9 GPa, 16.3 GPa, 18.9 GPa and 21.3 GPa. The amount of cement did not present as much of an effect as the other mechanical properties, except for S1. The mean loss in the four RCA50 mixtures compared to the four NA100 mixtures was 18.2% and ranged between 17% and 21%, with a mean reduction of 26.8% in full replacement mixtures compared to NA100 mixtures that ranged between 22% and 31%. Debied et al. (2009) obtained a similar modulus of elasticity loss (32%) in RCC with total RCA replacement compared to a control RCC, attributing this decrease to the presence of cement gangue in the RCA. Settari et al. (2015) reached a 44% loss in mixtures with full RAP replacement compared to a control RCC.

A linear correlation between the modulus of elasticity and the compressive strength (Figure 5.10) was calculated and the correlation index obtained was (R^2=0.5465), not as good as the other mechanical properties due to the higher scatter of the modulus of elasticity values obtained.

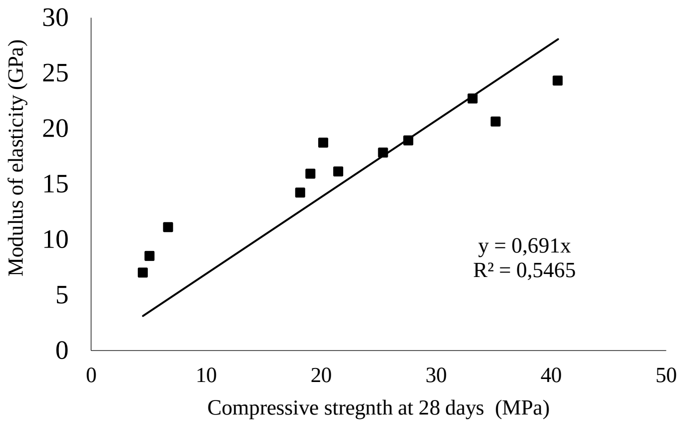


Figure 5.10. Relation between modulus of elasticity and compressive strength at 28 days.

The Spanish Guide of Recycled aggregates from CDW (GERD, 2012) established a minimum compressive strength of 20 MPa at 28 days for RCC and a minimum splitting tensile strength of 3.3 MPa in base pavement applications with a high density of heavy vehicles. All S4, S3-NA100 and S3-RCA50 mixtures complied with these limits. The same minimum splitting tensile strength is also required by Spanish Code (Ministry of Development, 2015). The S2-RCA100 mixture did comply with the compressive strength limit after 90 days but not with the splitting tensile strength minimum; it could be applied in base pavements with a low density of heavy vehicles. Spanish Code (Ministry of Development, 2015) also established that concrete pavements are to be designed based on flexural strength test values, setting the minimum in 3.5 MPa; the S3 and S4 mixtures comply with this standard.

ACI 325.10R-95 (ACI Committee 325, 2001) requires a minimum of 27.6 MPa in RCC used as a surface course. The S4 mixtures met this requirement at 28 days, and S3-NA100 and S3-RCA50 did so after 90 days. For RCC pavements ACI 211.R-02 (ACI Committee 211, 2002) requires a flexural strength of 4 MPa to 5 MPa with a cement content between 12% and 16% by mass of dry aggregate . The S3-NA100, S3-RCA50 and S4-RCA100 mixtures complied with this flexural strength requirement.

Hazaree et al. (2011) used a method often applied in dam construction to realize the strength contribution from a unit quantity of cement. Figure 5.11 shows the contribution of the mechanical properties used in the method latter described. In terms of flexural strength and modulus of elasticity, the optimum values of the amount of cement were 250 kg/m^3, and 175 kg/m^3, respectively, regardless of the RCA incorporation ratio.

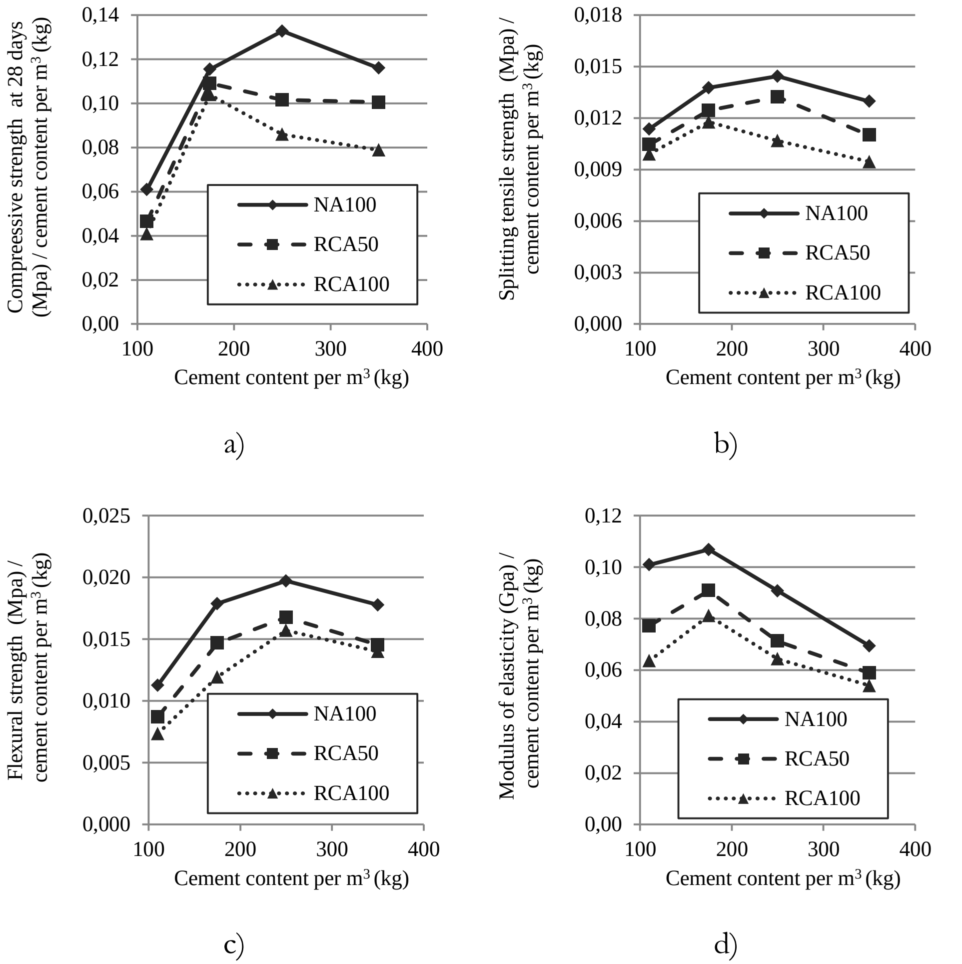


Figure 5.11. Strength contribution from a unit quantity of cement compared to the amount of cement for mechanical properties: a) compressive strength at 28 days; b) splitting tensile strength; c) flexural strength; d) modulus of elasticity.

As for the NA100 mixtures, the optimum value of the amount of cement seems to be close to 250 kg/m^3 for the splitting tensile strength and the compressive strength, which concurs with the previous authors. As for the RCA50 mixtures, the optimum amounts of cement were 175 kg/m^3 and 250 kg/m^3 in compressive and splitting tensile strength, respectively. As for the mixtures with total RCA incorporation, 175 kg/m^3 was the optimum amount of cement for the latter properties.

Thus, bearing in mind the contribution of the amount of cement to the mechanical properties, this material could be applied depending on the resistance requirements of the structural layer of the pavement by applying a cement content ranging between 175 kg/m^3 and 250 kg/m^3. The lowest cement content used, 110 kg/m^3, appears insufficient for use in RCC.

5.4.3. Density and porosity in hardened RCC

Table 5.7 shows the mean values for the density and porosity tests. Dry density values in the hardened RCC mixtures reached 98% (±2%) of the maximum dry density obtained by modified Proctor test. Porosity values ranged between 19% and 9.7%, in contrast to Modarres et al. (2014) and Mardani-Aghabaglou & Ramyar (2013), who found lower values than our results. The porosity mean values for the four mixtures of S1, S2, S3 and S4 were 16.7%, 15.1%, 13.3%, and 12.1%, with greater porosity levels with lower amounts of cement. The RCA incorporation ratio effect concurs with Gomez-Soberón (2002). The reverse occurs with density values; the decrease in both densities with higher incorporation ratios is due to a lower density of RCA versus NA, as expected. Nili & Zaheri (2011) found similar SSD densities in a control RCC.

Table 5.7. Mean values of the physical properties

Mixtures	**SSD Density (g/cm³)**	**Dry Density (g/cm³)**	**Porosity (%)**
S1-NA100	2.321 (0.024)	2.214 (0.030)	14.75 *(1.06)*
S1-RCA50	2.271 (0.010)	2.154 (0.013)	16.32 *(1.32)*
S1-RCA100	2.246 (0.011)	2.101 (0.054)	19.01 *(1.42)*
S2-NA100	2.364 (0.037)	2.256 (0.016)	13.43 *(0.72)*
S2-RCA50	2.304 (0.022)	2.185 (0.016)	14.52 *(0.97)*
S2-RCA100	2.278 (0.022)	2.132 (0.015)	17.32 *(1.56)*
S3-NA100	2.387 (0.025)	2.299 (0.017)	11.32 *(0.96)*
S3-RCA50	2.343 (0.020)	2.233 (0.021)	13.73 *(0.98)*
S3-RCA100	2.339 (0.013)	2.206 (0.008)	14.80 *(1.53)*
S4-NA100	2.450 (0.034)	2.367 (0.014)	9.69 *(0.64)*
S4-RCA50	2.404 (0.018)	2.281 (0.015)	12.42 *(0.40)*
S4-RCA100	2.347 (0.027)	2.223 (0.010)	14.17 *(0.80)*

[a]Note: Standard deviations given in parenthesis.

Figure 5.12 shows the correlations between maximum dry density obtained in the modified Proctor test and the dry density and porosity. Both showed a high correlation index of 0.9 and 0.87, respectively.

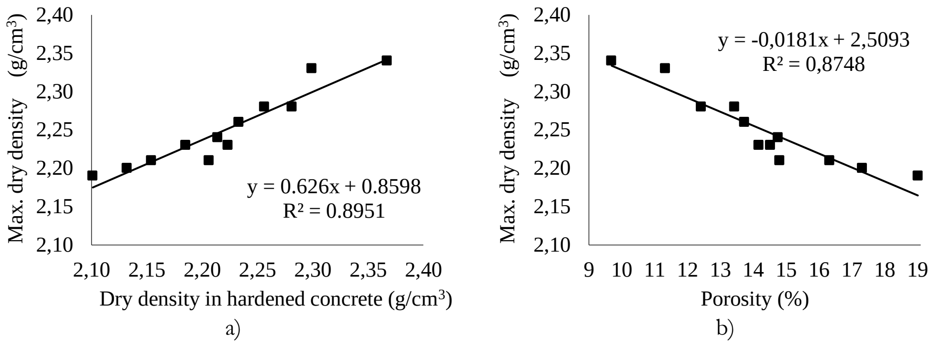


Figure 5.12. Relation between maximum dry density obtained in modified Proctor test and a) dry density in hardened concrete; b) porosity in hardened concrete

Figure 5.13 shows the correlations between dry density and porosity and SSD density and porosity, showing high correlation indexes of 0.97 and 0.93, respectively.

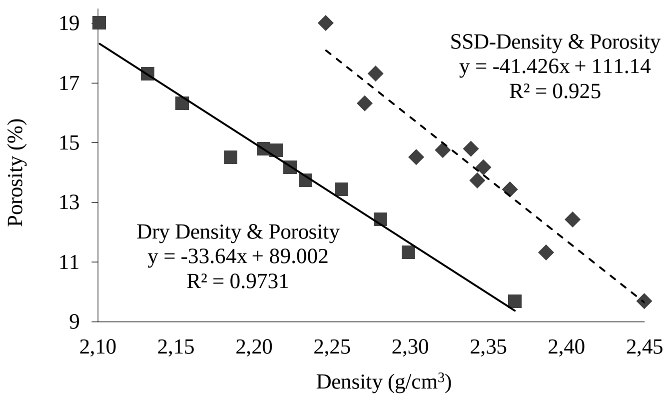
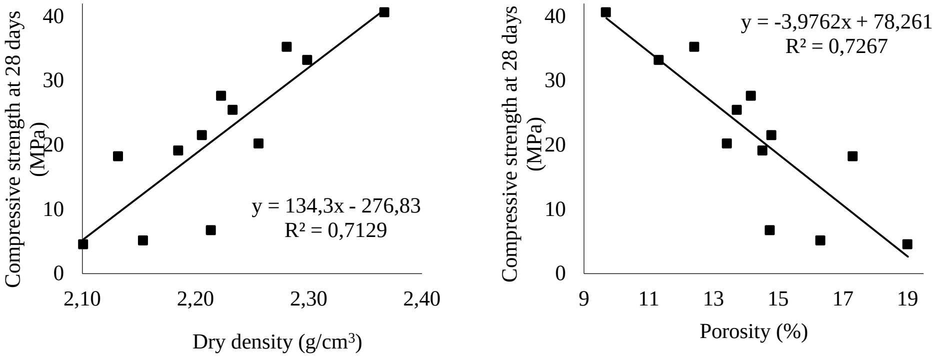


Figure 5.13. Relation between porosity and densities

As shown in Figure 5.14, compressive strength has a good relation with porosity (R^2 = 0.73) and dry density (R^2 =0.71) when comparing all of the series. However, there was a reverse relationship between the mix porosity and the compressive strength. This means that the RCC mix with a more integrated structure or lower porosity exhibited better compressive strength behaviour compared to a mixture with a high air void content. Conversely, the relation between dry density and compressive strength was directly proportional.



a) b)

Figure 5.14. Relation between a) compressive strength and dry density; b) compressive strength and porosity.

5.4.4. Drying srhinkage

The drying shrinkage is shown in Figure 5.15. Sagoe-Crentsil et al. (2001) found that drying shrinkage increased with time and stabilized at approximately 91 days; this justifies our longest measured age of 90 days. The maximum value was 810 μm/m, corresponding to the S1-RCA100 mixture. Based on the results, two trends are apparent: first, it can be suggested that higher cement content diminishes retraction and reduces the shrinkage obtained in these materials, and second, higher cement content leads to a lower relative retraction of NA100 mixtures compared to mixtures with partial or full RCA replacements with the same cement content. The relative retractions in NA100 mixtures compared to mixtures with full RCA replacement were 68%, 65%, 58% and 51% in S1, S2, S3 and S4, respectively.

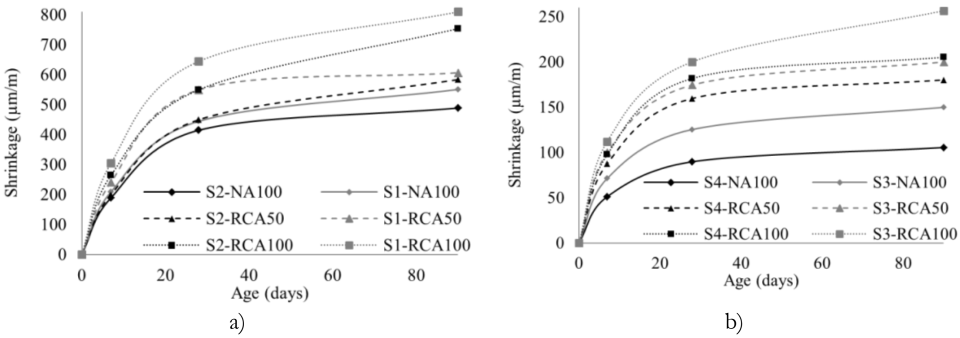


Figure 5.15. Retraction evolution with age: a) in S1 and S2 mixtures; b) in S3 and S4 mixtures.

Joint sawing was necessary because the RCC would crack due to shrinkage and temperature differences. RCC will be easier to maintain by ensuring that cracks form at the proper locations (Vahidi & Malekabadi, 2012). The Portland Cement Association (PCA, 2004) recommends that control joints be spaced at least six metres apart; a solution might be to reduce this to three metres, corresponding to the lowest relative retraction in S4.

5.5. Conclusions

This research presents the results of an investigation into the incorporation of RCA in the manufacture of RCC for possible civil applications, such as the base layers of roads. In light of the results obtained in these experiments, the following conclusions are drawn:

Proctor modified test curves indicate that RCC mixtures with RCA incorporation did not show any significant difference compared to mixtures with NA in terms of sensitivity of the maximum dry density to change in the moisture content.

The method used to cast prismatic specimens through vibration table tests achieved a compaction energy equal to the optimum time of compaction through a vibrating hammer. This could be a useful tool, considering the opportunity to cast samples requiring flexural strength and drying shrinkage evaluation.

There are good correlations between compressive strength and flexural strength and between splitting tensile strength and flexural strength in RCC mixtures with NA and RCA. These correlations warrant future studies for the implementation and monitoring of strength tests because flexural strength is an important feature. The flexural strength was determined to be approximately 15% and 130% of the obtained compressive strength and the splitting tensile strength, respectively.

RCC mixtures with a cement content of 110 kg/m^3 did not demonstrate appropriate properties for civil applications.

RCC with 175 kg/m^3 and 100% of coarse replacement of NA by RCA achieved over 2 MPa in flexural and splitting tensile strength and over 18MPa and 21MPa in compressive strength at 28 days and 90 days, respectively. This RCC could be used as a base for road pavements with a low density of heavy vehicles. Better mechanical properties were obtained in RCC mixtures with a 250 kg/m^3 cement content and full coarse RCA replacement, reaching up to 3.5 MPa in flexural strength. This material could be applied in road pavements bases with a high density of heavy vehicles.

Physical properties were also evaluated in this study. The porosity values may be slightly higher in RCC with natural aggregates than in RCC with RCA incorporation due to increased entrapped voids in the latter. This is not necessarily harmless, given that trapped air can induce better frost resistance. Future investigations should determine whether the use of non-pavement origin recycled aggregates could improve frost resistance.

As for shrinkage, it is recommended that the joint distance for initiating crack locations should be closer in RCC with RCA incorporation than in RCC with natural aggregates. Three metres is recommended in RCC mixtures with full coarse replacement of NA by RCA, as mixtures with RCA incorporation had more retraction.

In conclusion, RCC with 175 kg/m^3 and full coarse replacement of NA by RCA is recommended for use as a base in road pavements with a low density of heavy vehicles such as urban areas. In the case of roads with higher resistance requirements, RCC with approximately 250 kg/ m^3 and a 50% incorporated RCA ratio is suggested. The application of this type of RA is feasible in the construction of road bases with RCC.

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6. Conclusiones

6.1. Conclusiones generales

A la luz del trabajo realizado en la presente tesis doctoral, se presentan las siguientes conclusiones generales:

En relación a las propiedades de los materiales estudiados, las gravas recicladas presentaron granulometrías similares a la fracción gruesa de los AN a reemplazar, y mostraron menores densidades, menor resistencia a la fragmentación y mayor absorción de agua, siendo estas diferencias mayores en los ARM que en el ARH en comparación con los AN, empleados como control.

En relación al estudio efectuado en los HNE con bajo contenido en cemento y ARM destacamos que:

1. Debido a la mayor absorción de agua que presentaron los ARM, es recomendable la presaturación previa a su uso, para evitar la reducción en la trabajabilidad del hormigón.
2. No hubo diferencias significativas en el uso de dos ARM con diferente porcentaje de partículas cerámicas, 14% y 30 %, y las mismas dosificaciones en las propiedades del hormigón. Sin embargo, al usar dos cantidades de cemento, 180 y 200 kg/m^3, si se mostraron diferencias significativas, al igual que con diferente tasas de sustitución de la fracción gruesa, la cual mostró pérdidas lineales en las propiedades mecánicas, aunque también en las propiedades relacionadas con la durabilidad, no siendo limitantes en este caso ya que su destino es no estructural.
3. A largo plazo presentaron buen comportamiento mecánico. El hormigón con total reemplazo de ARM en la fracción gruesa alcanzó resistencias a 180 días mayores valores que el hormigón de referencia a 28 días.
4. Las pérdidas de resistencias en los hormigones reciclados con ARM son mayores a mayor clase resistente.

5. La relación entre las resistencia del hormigón de las probetas cilíndricas fabricadas in situ y posteriormente curadas, y los testigos extraídos es mayor en un 10% aprox. en el caso del 100% de sustitución, lo que se debe tener en cuenta en un futuro para no minorar su resistencia.
6. El uso de ARM en hormigón convencional está contraindicado en la Normativa correspondiente para la construcción de estructuras de hormigón, EHE-08. Para tratar de modificar la normativa vigente, hay que profundizar en el conocimiento científico-técnico de los hormigones con áridos reciclados con bajas dosificaciones de cemento.

En relación al estudio de HCR con diferentes cantidades de cemento y ARH destacamos que:

7. La sustitución de la fracción gruesa por ARH no mostró diferencias significativas, incluso mejoró, con respecto a la de control en relación con la sensibilidad de la densidad seca máxima al cambio de humedad, lo que se traduciría en un comportamiento en la compactación en obra, cuanto menos, igual que HCR con AN.
8. Gracias al sistema de compactación utilizando probetas prismáticas, se mostraron buenas correlaciones entre resistencia a flexión y a compresión, y resistencia a flexión y tracción indirecta, siendo éstas del 15% y del 130% respectivamente. También, gracias a este sistema se determinó que sería conveniente disminuir la distancia entre las juntas de retracción en caso de usar ARH, debido a la mayor retracción por secado.
9. Para base de vías de baja intensidad de tráfico, con una dosificación de cemento de 175 kg/m^3 y total incorporación de ARH, y que para base de vías de mayor intensidad de tráfico, con una dosificación de 250 kg/m^3 y una incorporación de ARH del 50%, ambas cumplieron los requisitos correspondientes.

6.2. Futuras líneas de investigación propuestas

Los aspectos no abordados por la presente tesis, y que a la luz de la misma se muestran interesantes para futuros estudios son:

Realizar una campaña a largo plazo para el estudio de la durabilidad de manera similar a la realizada para las propiedades mecánicas en el capítulo 4, en HNE en condiciones reales de puesta en obra.

Estudiar la sustitución de la fracción fina por arena reciclada con diferente origen, tanto de hormigón como mixto, en el uso de HNE con bajo contenido en cemento de manera conjunta y separada a la sustitución de la grava natural por grava reciclada.

En lo que respecta al estudio del HCR, sería muy interesante ensayar la inclusión de ARM en dosificaciones con bajo contenido en cemento, así como la aplicación real de HCR fabricado con AR para analizar su comportamiento in situ.

Finalmente, sería altamente atractivo para el estudio de su comportamiento, el uso de hormigón con grava reciclada mixta con bajo contenido en cemento en aplicaciones reales de uso no estructural tales como carriles bici, cunetas, hormigón de limpieza y de relleno.

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