UNIVERSIDAD DE CÓRDOBA

EVALUACIÓN AMBIENTAL Y APLICACIONES DE ÁRIDOS PROCEDENTES DE RCD LIGADOS CON CEMENTO EN INGENIERÍA CIVIL

Tesis Doctoral presentado por:

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TÍTULO DE LA TESIS:

EVALUACIÓN AMBIENTAL Y APLICACIONES DE ÁRIDOS PROCEDENTES DE RCD LIGADOS CON CEMENTO EN INGENIERÍA CIVIL.

DOCTORANDO: Isaac Alejandro Del Rey Tirado

INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS:

Tradicionalmente, los modelos de desarrollo de los países se han realizado desde el punto de vista económico, sin tener en cuenta otras variables de tipo social, ambiental, etc. El modelo de desarrollo económico aumenta la demanda de suministros (materiales, agua y energía), lo que conlleva una mayor huella sobre el medio.

En contraposición a este modelo, la tendencia actual es hacia un modelo de desarrollo sostenible que presente mayor eficiencia ambiental, equidad social y dinamización económica.

En el caso de la construcción, la búsqueda hacia la sostenibilidad se enfoca en la utilización de técnicas que reduzcan el consumo de recursos naturales, así como una disminución de los residuos generados, de manera que se minimice el impacto causado medioambiental causado.

Los Residuos de Construcción y Demolición (RCD) son un flujo prioritario de residuos para la Unión Europea (UE), fijando a los países pertenecientes a la UE una tasa de reciclaje del 70% en peso para el año 2020.

En la actualidad, la tasa de reciclado en España es muy inferior (<15%) al objetivo establecido por el horizonte 2020. Sin embargo, las políticas ambientales de algunas Comunidades Autónomas como Andalucía, unido al gran potencial de los áridos reciclados (AR) procedentes de RCD para su reutilización, reciclaje y/o valorización en edificación y, principalmente, en ingeniería civil, se está traduciendo en un incremento progresivo de la tasa de reciclaje, pudiendo llegar a cumplir los objetivos establecidos.

Los principales RCD proceden de derribos de edificios y de los restos de materiales de construcción de obras de nueva construcción y, en su mayor parte, de pequeñas obras de reformas. La mayor parte de los RCD producidos en España son mixtos, de composición heterogénea (70 – 80%), y de hormigón (10 – 15%).

La mayor parte de los estudios realizados se centra en la utilización de la fracción gruesa de los AR, por lo que para poder llegar a cumplir los objetivos marcados se hace necesario el estudio de la fracción fina, especialmente los procedentes de RCD mixtos, con mayor tasa de producción.

El objetivo fundamental de la presente Tesis Doctoral es analizar la viabilidad del uso y aplicaciones de AR mixtos en ingeniería civil. Por ello, en la presente Tesis se pretende estudiar las posibilidades de utilizar en usos ligados la fracción fina de los AR mixtos como suelo-cemento en capas estructurales de firmes de carreteras de escaso tráfico. Por viabilidad se entiende no sólo el aspecto físico, químico o mecánico del material, sino, además el aspecto ambiental. Es por ello que la presente Tesis, enmarcada en la aplicación de la economía circular, integra en el estudio la evaluación ambiental de los AR, estimando las posibles emisiones de metales pesados y aniones en el lixiviado, así como un análisis de la procedencia de los elementos más limitantes.

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. Del Rey, I., Ayuso, J., Galvín, A.P., Jiménez, J.R., López, M., García-Garrido, M.L. (2015). Analysis of chromium and sulphate origins in construction recycle materials based on leaching test results. Waste Management, 46, 278-286.
2. Del Rey, I., Ayuso, J., Galvín, A.P., Agrela, F., de Brito, J. (2016). Feasibility study of cement-treated 0–8 mm recycled aggregates from construction and demolition waste as road base layer. Road Materials and Pavement Design, 17, 678-692.
3. Del Rey, I., Ayuso, J., Galvín, A.P., Jiménez, J.R., Barbudo A. (2016). Feasibility of using unbound mixed recycled aggregates from CWD over expansive clay subgrade in unpaved rural roads. Materials, 9(11), 931.

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 del Lirio García Garrido. En el segundo artículo se ha contado con la colaboración del profesor Dr. Jorge de Brito (Instituto Superior Técnico, Universidad de Lisboa, Portugal).

Por todo ello, se autoriza la presentación de la Tesis Doctoral "Evaluación ambiental y aplicaciones de áridos procedentes de RCD ligados con cemento en ingeniería civil".

Córdoba, 31 de enero de 2018

Firma de Directores

Jesus Ayuso

Jesús Ayuso Muñoz

Adela Pérez Galvín

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La realización de esta Tesis Doctoral ha sido un verdadero desafío intelectual y emocional, por ello me gustaría expresar mi más profundo agradecimiento a todos aquellos que, con desinterés y ánimo, me generó el compromiso de su finalización:

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De manera íntima y personal, también quisiera dedicar esta Tesis a las personas más importantes de mi vida,

A mis padres y a mi hermano, por todo el apoyo que me han dado durante todo este tiempo, mostrándome que siempre estarán cuando más los necesito.

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Abstract

The present doctoral thesis is focused on providing an original scientific knowledge about the use of recycled aggregates (RA) from Construction and Demolition Waste (CDW) in civil engineering, as well as an evaluation of the potential environmental risk caused by the use of these recycled materials.

The high potential of AR regarding their physical and mechanical properties, implies a good opportunity for being used by the construction sector, the main sector in consumption of raw materials and environmental pollution. Thus, valorization of RA means a step towards sustainability, which entails enormous environmental, social and economic benefits. The main use of RA is road construction (localized fillings, subgrades, bases and subbases).

The coarse fraction of the RA can be used as a substitute for natural gravel in structural and non-structural concrete manufacturing (type of RA application with the highest quality value). However, there are less type of uses for the fine fraction of RA, being the main application the use in pipe bedding. Thus, the fine fraction of the RA is undervalued, so there is an interesting research field in new applications, such as its use in applications treated with cement.

Andalusia (South of Spain), is a mainly agricultural region where rural roads are numerous. The technical feasibility of the use of RA in structural layers of this type of pathways is demonstrated. For this reason, the use of RA should be encouraged, mainly increasing the use of mixed recycled aggregates (MRA), which in Spain represent between 70 and 80% of national production.

The present work is carried out from an environmental point of view, achieving sustainability criteria derived from the application of RA in civil engineering. First, the environmental consequences of the application of

these recycled materials have been evaluated, performing leaching tests as index of sustainability. The release of potential pollutant compounds has been analyzed in short (by compliance test) and long term (by column or percolation tests). In addition, a study on the source of the main conflictive elements present in the RA has been included in the present doctoral thesis.

In a second stage, the application of the fine fraction of the RA as soil-cement for its use in structural layers of road infrastructures, has been studied.

Finally, in order to evaluate the long-term behaviour of RA from mixed CDW and its viability in structural layers, a rural road has been performed on expansive clays subgrade. These soils are very abundant in the Guadalquivir Valley (sited in Andalusia region). The objective has been to evaluate the physical and mechanical behaviour of these recycled materials in comparison with natural materials.

Resumen

La presente tesis doctoral se centra en la generación un conocimiento científico original y de calidad, sobre el uso de los áridos reciclados (AR) procedentes de Residuos de la Construcción y Demolición (RCD) para su uso en ingeniería civil, así como realizar una evaluación de la sostenibilidad de estos materiales reciclados.

El potencial de los AR supone un acercamiento de la construcción, principal sector en consumo de materias primas y contaminación ambiental, hacia la sostenibilidad, lo que supone enormes beneficios ambientales, sociales y económicos.

Tanto a nivel nacional como internacional, el principal uso de los AR es infraestructuras viarias (rellenos localizados, formación de explanadas, bases y subbases).

La fracción gruesa de los AR puede ser utilizada como sustitutivo de grava natural en la realización de hormigones estructurales y no estructurales, utilización que le da un valor añadido a los materiales reciclados. Sin embargo, son escasas las utilizaciones de la fracción fina de los AR, encontrando como principal aplicación como cama de tuberías, proporcionándole un escaso valor añadido. La fracción fina de los AR está infravalorada, por lo que existe un interés en la búsqueda de nuevas aplicaciones, como son su uso en aplicaciones ligadas con cemento.

Andalucía (España), es una región fundamentalmente agrícola donde existen numerosos caminos rurales. La viabilidad técnica del uso de AR en capas estructurales de este tipo de vías está demostrada. Por esta razón, se debe fomentar la utilización de AR, principalmente áridos reciclados mixtos (ARM), que en España representan entre un 70 y un 80% de la producción nacional.

El presente trabajo se realiza desde el punto de vista de la sostenibilidad ambiental en la aplicación de AR en ingeniería civil. Por ello, primero se han evaluado las consecuencias medioambientales de la aplicación de estos materiales reciclados, utilizando los ensayos de lixiviación como índice de sostenibilidad. La liberación de compuestos contaminantes se ha analizado a corto (test de conformidad) y a largo plazo (test de columna o percolación). Además, se ha realizado un estudio sobre el origen de los principales elementos contaminantes presentes en los AR.

En una segunda etapa, se ha estudiado la aplicación de la fracción fina de los AR como suelo-cemento para su utilización en capas estructurales de infraestructuras viarias.

Por último, para evaluar el comportamiento a largo plazo de AR procedentes de RCD mixtos y su viabilidad en capas estructurales, se ha ejecutado un camino rural sobre arcillas expansivas, que son suelos muy abundantes en el Valle del Guadalquivir, evaluando el comportamiento de estos materiales reciclados en relación con los materiales naturales.

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Abreviaturas

AASHTO	American Association of State Highway and Transportation Officials
AN	Árido Natural
ANEFA	Asociación Nacional de Empresarios Fabricantes de Áridos
ANOVA	Analisys of Variance
AOPJA	Agencia de Obras Públicas y Vivienda de la Junta de Andalucía
AR	Áridos Reciclados
ARA	Árido Reciclado Asfáltico
ARC	Árido Reciclado Cerámico
ARH	Árido Reciclado de Hormigón
ARM	Árido Reciclado Mixto
B	Bluebird
CBR	California Bearing Ratio
CDW	Construction & Demolition Waste
CMRA	Coarse Mixed Recycled Aggregates
CRA	Coarse Recycled Aggregates
CRCA	Coarse Recycled Concrete Aggregates
CTGM	Cement Treated Granular Materials
EHE - 08	Instrucción Española de Hormigón Estructural, 2008
EU	Unión Europea/European Union
FASS	Flame Atomic Absortion Spectometry
FMRA	Fine Mixed Recycled Aggregates
FRA	Fine Recycled Aggregates
FRC	Arena Reciclada Cerámica
FRCA	Fine Recycled Concrete Aggregates
FRH	Arena Reciclada de Hormigón
FRM	Arena Reciclada Mixta
FWD	Falling Weight Deflectometer
GEI	Gases de Efectos Invernadero
GIASA	Gestión de Infraestructuras de Andalucía, S.A.
GN	Grava Natural
GRC	Grava Reciclada Cerámica
GRH	Grava Reciclada de Hormigón
GRM	Grava Reciclada Mixta
HB	Hollow Brick
HCR	Hormigón Compactado con Rodillo
I+D+i	Investigación Desarrollo e Innovación
ICP-MS	Inductively Coupled Plasma Mass Spectrometry

KP	Kilometer Point
L.A.	Los Ángeles
L/S	Líquido/Sólido; Liquid/Solid
MGTC	Materiales Granulares Tratados con Cemento
MPT	Modified Proctor Test
MRA	Mixed Recycled Aggregates
MRA-NS	Mixed Recycled Aggregates Non-Selected
MRA-S	Mixed Recycled Aggregates Selected
MRCA	Mixed Recycled Concrete Aggregates
MRCeA	Mixed Recycled Ceramic Aggregates
NA	Natural Aggregates
NS	Non-selected
PB	Perforated Brick
PEMAR	Plan Estatal Marco de Gestión de Residuos
PG - 3	Pliego de Prescripciones Técnicas Generales para Obras de Carreteras, 2015
PLT	Static Plate Load Test
PNRCD	Plan Nacional de Residuos de Construcción y Demolición
RA	Recycled Aggregates
RCA	Recycled Concrete Aggregates
RCD	Residuos de la Construcción y Demolición
S	Stoneware
SC	Suelo-cemento
SPT	Standard Proctor Test
SR	Suelos Reciclados
SRC	Suelo Reciclado Cerámico
SRH	Suelo Reciclado de Hormigón
SRM	Suelo Reciclado Mixto
T	Tile
UCS	Unconfined Compressive Strength
ZN	Zahorra Natural
ZRC	Zahorra Reciclada Cerámica
ZRH	Zahorra Reciclada de Hormigón
ZRM	Zahorra Reciclada Mixta

CAPÍTULO 1. INTRODUCCIÓN

La sostenibilidad del medioambiente, debido al desarrollo industrial y demográfico desde la segunda mitad del siglo XX hasta nuestros días, ha ido adquiriendo mayor peso a medida que las consecuencias se han mostrado más tangibles. La compatibilidad del consumo de recursos, producción de residuos y emisiones con la sostenibilidad del sistema a largo plazo es el reto del siglo XXI.

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. 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. Por lo que se hace indispensable el estudio para reducir el consumo de áridos.

Así pues, el sector de la construcción es uno de los sectores que más influye en la degradación del medio ambiente, representando en los países desarrollados más del 40% del consumo de energía durante su vida útil (materias primas, construcción, operación, mantenimiento y desmantelamiento). Esto da lugar a una alta contribución a la emisión de gases de efecto invernadero contribuyendo en gran medida al cambio climático (Directiva 2010/31 del Parlamento Europeo). Sin embargo, tiene la capacidad de hacer una importante contribución a un futuro más sostenible, convirtiéndose en uno de los pilares fundamentales para asegurar la viabilidad ambiental, económica y social.

El concepto de sostenibilidad se presenta relacionado al equilibrio de las demandas ambientales, sociales y económicas (United Nations General Assembly, 2005). Para que una acción humana sea sostenible, ella debe ser ecológicamente correcta, económicamente viable y socialmente y culturalmente justa.

La construcción sostenible incorpora elementos como eficiencia económica, el desempeño ambiental y la responsabilidad social. Las cuestiones de sostenibilidad son preocupaciones actuales ya que se utilizan gran cantidad de recursos naturales para la producción de materiales. El agotamiento de los recursos naturales es uno de los principales temas que se deben de abordar de manera eficiente.

Los materiales de construcción al finalizar su vida útil se convierten en residuos que pueden ocasionar graves problemas ambientales. Mediante la reutilización, reciclado y valorización de los residuos de construcción y demolición (RCD) se obtienen nuevos materiales de construcción que requieren un menor consumo energético, contribuyendo a una reducción de emisiones de CO_2 y por lo tanto a la sostenibilidad del sector.

1. RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN

Se define como RCD a "cualquier sustancia, u objeto que, cumpliendo con la definición de residuo del artículo 3.a) de la Ley 10/1998, de 21 de abril, se genere en una obra de construcción o demolición" (II Plan Nacional de Residuos de Construcción y Demolición, 2008 - 2015).

Una obra de construcción o demolición consiste en la construcción, reparación, reforma o demolición de un bien inmueble. También se incluye en el concepto de obra la modificación de la forma del terreno o el subsuelo. Independientemente de otros factores, estos orígenes inducen diferentes características en los áridos reciclados (AR) (Hendriks, Ch., 2000).

A pesar de que, conceptualmente, la definición de RCD abarca a cualquier residuo generado en una obra de construcción o demolición, se excluyen (R.D. 105/2008):

- Las tierras y piedras no contaminadas por sustancias peligrosas reutilizadas en la misma obra, en una obra distinta o en una actividad de restauración, acondicionamiento o relleno, siempre y cuando pueda acreditarse de forma fehaciente su destino a reutilización.
- Los residuos regulados por la Directiva 2006/21/CE, sobre la gestión de los residuos de las industrias extractivas.
- Los lodos de dragado no peligrosos reubicados en el interior de las aguas superficiales derivados de las actividades de gestión de las aguas y de las vías navegables, de prevención de las inundaciones o de mitigación de los efectos de las inundaciones o las sequías, reguladas por el Texto Refundido de la Ley de Aguas, por la Ley 48/2003, de 26 de noviembre, de régimen económico y de prestación de servicios de los puertos de interés general, y por los tratados internacionales de los que España sea parte

Los RCD son considerados inertes, en su mayor parte, o no peligrosos, estando compuestos principalmente por hormigón, cerámicos, pétreos, asfalto y, en algunos casos, tierras de excavación. Además, pueden tener otras impurezas como yesos, maderas, papel y cartón, plásticos, vidrios y otros. Los RCD aparecen codificados en un Lista Europea de Residuos (códigos LER), aprobada por Orden MAM/304/2002, en el capítulo 17, de la siguiente manera:

17 01 Hormigón, ladillos, tejas y materiales cerámicos.

17 02 Madera, vidrio y plástico.

17 03 Mezclas bituminosas, alquitrán de hulla y productos alquitranados.

17 04 Metales (incluidas sus aleaciones).

17 05 Tierra (incluida la excavada de zonas contaminadas), piedras y lodos de drenaje.

17 06 Materiales de aislamiento y materiales de construcción con amianto.

17 08 Materiales de construcción a partir de yeso.

17 09 Otros residuos de construcción y demolición.

1.1. ORIGEN, PRODUCCIÓN Y TRATAMIENTO DE LOS RCD

La gestión de RCD no comienza en la planta de tratamiento, sino que comienza desde el lugar de producción, es decir, en cualquier obra de construcción o demolición:

- La construcción, rehabilitación, reparación, reforma o demolición de un bien inmueble, así como cualquier obra en ingeniería civil.
- La realización de trabajos que modifiquen la forma o sustancia del terreno o del subsuelo.

El R.D. 105/2008, de 1 de febrero, regula la producción y gestión de los residuos de construcción y demolición, obliga a llevar un correcto control de la producción de los RCD, desde su construcción hasta su demolición.

A partir de esta fecha, todas las obras de ejecución incluyen un estudio de gestión de RCD en el que se incluye una estimación de la cantidad de RCD que se generarán en la obra, codificados con arreglo a la lista de los códigos LER. Además, establece que deberán separarse de forma individualizada según su naturaleza cuando, de forma individualizada para cada una de las fracciones, la cantidad prevista de generación de residuos sea superior a las siguientes cantidades:

- Hormigón: 80 t.
- Ladrillos, tejas, cerámicos: 40 t.
- Metal: 2 t.
- Madera 1 t.
- Vidrio: 1 t.
- Plástico: 0,5 t.
- Papel y cartón: 0,5 t.

Dicha separación es de vital importancia para conseguir un RCD de calidad, en especial cuando se está realizando una obra de demolición. En este proceso, es importante realizar una demolición selectiva en el origen, evitando así materiales no deseables como escombros de mampostería, vidrio, maderas, tuberías, cables, etc. (Sánchez de Juan, M., 2004).

Aunque la realización de este proceso favorece el conocimiento del futuro árido reciclado, su excesivo coste puede limitar su realización. Cuando los costes del procesamiento de los materiales mezclados son superiores a los del tratamiento de los materiales separados, se presenta una clara ocasión de aplicar la demolición selectiva.

Asimismo, para favorecer la realización de una demolición selectiva, es importante imponer restricciones al vertido de residuos contaminados, elevando sus tasas. De esta manera, el transporte y vertido de los RCD tendrá un coste mayor que su reutilización o reciclaje, evitando los inconvenientes que conlleva el vertido de residuos, principalmente en el ámbito medioambiental y paisajístico. Así mismo, es importante determinar la presencia de amianto antes de la demolición, puesto que, en caso de detectar este residuo, debe de tratarse con extrema precaución y dejar que los traten empresas autorizadas, al ser un residuo peligroso. Si no se elimina podría llegar a contaminar los futuros AR (Hendriks, Ch., 2000).

Para poder realizar correctamente una demolición selectiva, de manera que se minimice la cantidad de RCD que se destine a vertedero, se deberá seguir un proceso ordenado y por etapas:

1. Desmontar los elementos clasificados como residuos peligrosos, de manera que no contaminen el resto de residuos (amianto, tubos fluorescentes, refrigerantes, etc.)
2. Desmontar la instalación eléctrica, de saneamiento, climatización, etc.

3. Desmontar la carpintería y cerrajería (puertas, ventanas y mobiliario).
4. Desmontar falsos techos, revestimientos de paredes, tabiquería y cerramientos.
5. Demoler la estructura (pilares, forjados, muros de carga, etc.).
6. Demoler la cimentación.

Los elementos desmontados durante las tres primeras etapas se deben depositar en contenedores o acopios independientes para su posterior entrega a gestores autorizados. El resto de residuos irán dirigidos a plantas de tratamiento de RCD, donde según su grado de contaminación, así como su naturaleza serán clasificados.

1.2. MARCO LEGISLATIVO

1.2.1. Marco Legal Comunitario

La Unión Europea, desde finales de los años 90, considera a los RCD como un "flujo prioritario de residuos". La legislación comunitaria que regula su producción y gestión es la Directiva 2008/98/CE, del Parlamento y del Consejo, de 19 de noviembre de 2008, sobre los residuos, conocida como Directiva Marco de Residuos, con la que se derogan directivas anteriores. Con esta directiva se pretende proteger el medioambiente y la salud pública mediante la prevención o la reducción de los impactos adversos a la gestión y generación de residuos. Esta directiva establece una jerarquía que servirá de orden de prioridades en la legislación: prevención, preparación para la reutilización y reciclado, otro tipo de valorización y en última instancia, su eliminación.

Los residuos que deben cumplir esta Directiva aparecen en la lista establecida en la Decisión 2000/532/CE de 3 de mayo de 2000, dentro de la que se encuentran los residuos de construcción y demolición, en el capítulo 17, modificada por la Decisión 2001/118/CE de 16 de enero de 2001.

1.2.2. Marco Legal Estatal

La legislación básica que regula la producción y gestión de los RCD en España, es el R. D. 105/2008 ya mencionado en el apartado 1.1. Los productos que van a vertedero, además del decreto mencionado anteriormente, se regulan por el R. D. 1481/2001.

El Gobierno de España, en conformidad con la Directiva Marco de residuos, aprobó el Plan Nacional Integrado de Residuos para 2008-2015, donde se enmarca el II Plan de Residuos de Construcción y Demolición (II), con el objetivo de prevenir la producción de RCD en origen, aplicación del régimen de jerarquía y mejora de las infraestructuras de tratamiento de RCD.

Con el objetivo de convertir España en una sociedad eficiente y sostenible en el uso de los recursos naturales, se ha elaborado el Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016-2020, en el que se establecen las líneas estratégicas y medidas necesarias para avanzar hacia una economía circular e impulsar la reutilización y reciclado de los residuos.

En España, se han realizado modificaciones a las diversas especificaciones técnicas para poder utilizar este tipo de árido. En el Pliego de Prescripciones Técnicas Generales para Obras de Carreteras (PG-3, 2015) se realiza una modificación para permitir el uso de AR como material granular en capas estructurales. Igualmente, en la Instrucción Española de Hormigón Estructural (EHE, 2008), se permite sustituir la grava por la fracción gruesa de AR de hormigón en la elaboración de nuevos hormigones.

1.2.3. Marco Legal Autonómico

La Comunidad de Andalucía, con el Decreto 73/2012, se pretende regular la producción, posesión y gestión de los residuos que se generen y se gestionen en la Comunidad de Andalucía., así como, prevenir su generación y fomentar la prevención, reutilización, reciclado y valorización.

El Decreto 397/2012, de 2 noviembre, por la que se aprueba el Plan Director Territorial de residuos no peligrosos de Andalucía 2010-2019, tiene por objetivos los de reducción, reutilización, reciclado y dar otras formas de valorización a los residuos. Entre los residuos estudiados por este plan se encuentra los RCD.

La Consejería de Obras Públicas y Vivienda de la Junta de Andalucía ha redactado unas recomendaciones para el uso de AR: Recomendaciones para la redacción de Pliegos de Especificaciones técnicas para el uso de materiales reciclados de RCD, realizado por la empresa pública Gestión de Infraestructuras de Andalucía, S.A. (GIASA, 2010).

Posteriormente, la Agencia de Obra Pública de la Junta de Andalucía (AOPJA) ha financiado con fondos FEDER el proyecto: “Aplicaciones de los Áridos Reciclados de Residuos de Construcción y Demolición (RCD) para la construcción sostenible de infraestructura viaria en Andalucía Central”, proyecto liderado por el grupo de investigación de Ingeniería de la Construcción TEP 227 de la Universidad de Córdoba donde se enmarca la presente tesis doctoral. Como resultados de este proyecto de investigación se han publicado la Guía de áridos reciclados de construcción y demolición (RCD) de Andalucía Central (2015), Una Guía de buenas prácticas en la Gestión y tratamiento de residuos de construcción y demolición (RCD) (2015) y el Catálogo de firmes y unidades de obra con áridos reciclados de Residuos de Construcción y Demolición (RCD) (2016), las publicaciones derivadas de dicho proyecto se muestran en la figura 1.1.

Figura 1.1: Publicaciones derivadas del citado proyecto

1.3. PROCESO DE TRATAMIENTO DE LOS RCD

Con el fin de mejorar la calidad de los áridos reciclados, en la entrada a la planta de tratamiento, se debe realizar una clasificación exhaustiva de los RCD que dependerá principalmente de dos factores, naturaleza y grado de contaminación o impurezas.

Los RCD se clasifican según su naturaleza en tres clases: hormigón, mixto y asfáltico. Se recomienda la disposición de tres acopios diferentes según la naturaleza del RCD. La Ley 22/2011, de 28 de julio de residuos y suelos no contaminados, considera las tierras de excavación no contaminadas que no se utilicen en la misma obra como residuos. Estas tierras no experimentan ningún tratamiento, por lo que se acopian y son expedidas como tierras de relleno para obras cercanas a la planta de tratamiento o en la propia planta.

El grado de impurezas (yeso, plásticos, vidrio, madera, etc.) que contengan los RCD depende principalmente de la gestión llevada a cabo durante la demolición. Los RCD con un grado de impurezas o contaminantes muy bajo o nulo se consideran limpios, y se colocarán directamente en el acopio que corresponda según su naturaleza. Cuando el contenido de impurezas sea importante de modo que pueda afectar a la calidad de los AR se debe realizar una limpieza previa de los RCD. Una vez realizada la limpieza se trasladan a su correspondiente acopio. Si el coste de limpieza del RCD es superior al valor del material reciclado, no se consideran valorizables y se destinan directamente a vertedero.

Una vez los RCD han sido clasificados se procede a la entrada en la línea de tratamiento, en la que se distinguen tres fases: pre – tratamiento, tratamiento primario y tratamiento secundario.

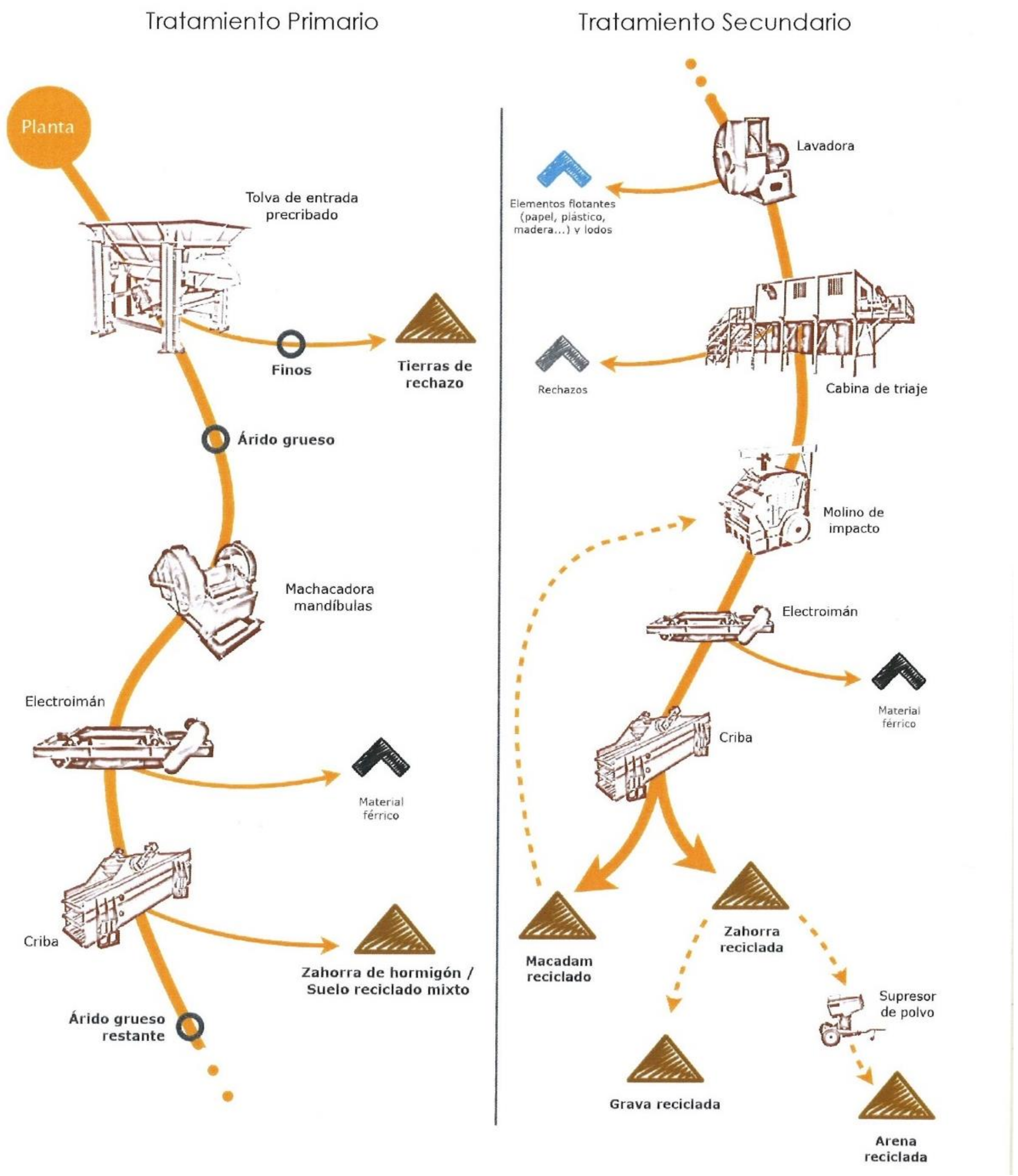

Figura 1.2: Sistema de Gestión de RCD.

FUENTE: Gestión y tratamiento de residuos de construcción y demolición (RCD). Guía de buenas prácticas (2015)

1.3.1. Pre – Tratamiento

El objetivo de este tratamiento es la reducción de los RCD de gran volumen. Suele ser exclusivo de los acopios de hormigón, no siendo siempre necesario su realización. Para un adecuado tratamiento de los RCD de gran volumen, estos deben de reducirse en su tamaño. Para ello, suele utilizarse un martillo o pinzas de demolición, siendo el segundo más eficaz en hormigón armado. Esta operación se realiza en el acopio, previo a la entrada a la línea de tratamiento.

1.3.2. Tratamiento Primario

El objeto de este tratamiento es la de realizar una eliminación de tierra vegetal y partículas finas (principalmente yeso). El tratamiento primario, descrito en la figura 1.2, consiste en:

- Pre-cribado: criba anterior a la tolva de entrada de la machacadora. El material pasante son las tierras de rechazo y se destina a obras de relleno en el propio vertedero.
- Reducción de tamaño: una machacadora de mandíbulas reduce el tamaño de los RCD, el tamaño máximo del árido lo determina la abertura de la machacadora. Tras la machacadora un separador magnético separa los elementos de acero.
- Primer cribado: una criba vibratoria separa árido fino y árido grueso. El material pasante o árido fino puede ser utilizado como suelo adecuado o tolerable. Al material retenido o árido grueso se le elimina los elementos de baja densidad mediante sopladora o lavadora hidráulica. Este cribado no es necesario en RCD de hormigón.

En RCD de hormigón no es necesaria la realización del pre-cribado y el primer cribado. El árido grueso pasa al tratamiento secundario.

1.3.3. Tratamiento Secundario

El objetivo del tratamiento secundario es la obtención de un material reciclado apto para su utilización en obras de ingeniería. Los pasos del tratamiento secundario se pueden ver en la figura 1.2, y consiste en:

- Triaje manual: el árido procedente del tratamiento primario pasa por una cinta donde uno o varios operarios retiran las impurezas no eliminadas. Este proceso no es necesario en RCD de hormigón.
- Reducción de material: un molino de impacto reduce el material, obteniendo un árido con una granulometría y caras de fracturas adecuadas. A su salida, un separador magnético elimina el acero liberado durante el fraccionamiento de las partículas.
- Segundo cribado: una segunda criba vibratoria, con diferentes tamices intercambiables, permite obtener los áridos reciclados con la granulometría deseada. Para evitar nubes de polvo y una contaminación atmosférica, se colocará supresores de polvo al final de la cinta transportadora.

2. MATERIALES OBTENIDOS: ÁRIDOS RECICLADOS

Una vez realizado el tratamiento a los RCD, los materiales producidos se denominan áridos reciclados (AR). Las propiedades de los AR, así como sus aplicaciones, dependen de su composición, y del procesamiento recibido en planta (Cardoso y col., 2016; Vieira y Pereira, 2015).

Basándose en la proporción de sus componentes, los AR se pueden clasificar como muestra la Tabla 1.1.

Según la granulometría obtenida durante el tratamiento de los RCD, los AR se clasifican como: zahorra reciclada, suelo reciclado, grava reciclada y arena reciclada.

Tabla 1.1: Clasificación AR según su naturaleza FUENTE: Alaejos P., 2008; Agrela F. y col., 2011.

Tipo de Árido	% Hormigón	% Cerámico
Árido reciclado de hormigón (ARH)	≥ 90%	-
Árido reciclado cerámico (ARC)	< 70%	>20%
Árido reciclado mixto (ARM)	70-90%	≤ 20%
Árido reciclado asfáltico (ARA)	Alto porcentaje de partículas asfálticas	

2.1. PROPIEDADES Y APLICACIONES DE LOS ÁRIDOS RECICLADOS

2.1.1. Zahorra reciclada

La granulometría es de gran importancia en los materiales granulares para su utilización en sub-bases y bases de carreteras, no siendo una propiedad limitante en las zahorras recicladas. (Jiménez y col.,2011; Vegas y col., 2011).

Las zahorras recicladas de hormigón (ZRH) alcanzan valores entre 20 – 31 % en el coeficiente de desgaste de Los Ángeles. Sin embargo, las zahorras recicladas mixtas (ZRM) y cerámicas (ZRC) superan el límite del coeficiente de Los Ángeles establecido en el PG-3, obteniendo valores en torno al 40%. La resistencia a la fragmentación tiene una relación con la composición de los AR, las partículas cerámicas muestran una menor resistencia a la fragmentación, mientras que las partículas de asfalto, árido natural y de mortero adherido muestran una mayor resistencia a la fragmentación (Jiménez y col., 2011; Vegas y col., 2008; Vegas y col., 2011: Barbudo y col., 2012; Sánchez y Alaejos, 2009).

Todos los áridos reciclados de RCD son no plásticos y su coeficiente de forma, partículas trituradas, coeficiente de limpieza y equivalente de arena no son limitantes para su utilización en firmes de carreteras (Jiménez y col., 2011; Vegas y col., 2011).

La mayor parte de las zahorras recicladas de RCD son mixtas. Las ZRM y ZRC cumplen la mayoría de los límites establecidos en el PG-3 para categorías de tráfico T3 y T4 para las propiedades físico-mecánicas. Habiéndose identificado como propiedad más limitante la resistencia a la fragmentación (Jiménez y col., 2011; Vegas y col., 2008; Vegas y col., 2011). El mayor contenido de partículas cerámicas de este tipo de áridos aumenta el coeficiente de desgaste de Los Ángeles.

En cuanto a las propiedades químicas, el contenido de compuestos de azufre totales es una propiedad crítica de los AR (Vegas y col., 2008; Barbudo A. y col., 2012). El contenido de compuestos de azufre totales de los ARH está por debajo del límite del PG- 3 (Jiménez y col., 2011). Sin embargo, los ARM y ARC contienen más del 1% de compuestos de azufre totales, llegando a presentar, en casos aislados, un máximo de un 6%. Este máximo contenido en una muestra de árido mixto se atribuye a la mayor proporción de yeso en las fracciones más gruesas y al proceso de tratamiento en la planta de procedencia (Barbudo A. y col., 2012). Sin embargo, el contenido de materia orgánica está en todos los AR por debajo de 0.8% (Vegas y col., 2008). Un correcto tratamiento de los RCD mixtos (Apartado 1.3.), mediante la realización de un pre-cribado de la fracción fina antes de la trituración de los RCD mixtos, reduciría el contenido de azufre total y mejoraría la calidad de los AR.

Las zahorras recicladas tienen un enorme potencial para la construcción de capas estructurales de firmes de carreteras (base y sub-base), siendo un perfecto sustituto del árido natural en ingeniería civil como materiales no ligados.

Jiménez y col. (2012a) realizaron un tramo experimental donde utilizaron ZRM no seleccionada que no cumplían los requisitos del PG-3 (2015), como capa estructural del firme (base), sobre una capa de sub-base de árido natural (AN). Además, Jiménez y col. (2012b) también llevaron a cabo otro tramo experimental usando ZRM seleccionada (sub-base) y ARH (base). En ambos tramos experimentales se utilizaron zahorra natural (ZN) como materiales de referencia, no habiéndose encontrando diferencias significativas entre el comportamiento de los materiales reciclados y los naturales.

Por lo tanto, para vías de baja intensidad y/o carreteras con pequeño volumen de tráfico, se podrían disminuir las restricciones normativas, lo que conllevaría a un mayor uso de ZRM y ZRC (Sherwood, 2001).

Las zahorras recicladas también pueden ser utilizadas como material ligado con cemento como materiales granulares tratados con cemento (MGTC). Siendo las propiedades más limitantes, al igual que para su utilización como materiales no ligados, el coeficiente de desgastes de Los Ángeles y el contenido en sulfatos. Dentro de los MGTC, las zahorras recicladas, debido a su granulometría, podrían ser utilizadas como suelo-cemento según el Art. 513 del PG-3 (2015).

Los MGTC son una mezcla homogénea, en proporciones adecuadas de árido, cemento y agua que, compactado adecuadamente, se usa como capa estructural en los pavimentos de carreteras (Xuan y col., 2011).

Dongxing y col. (2010) propusieron la utilización de AR en la fabricación de suelo-cemento (SC). Las propiedades mecánicas de las zahorras recicladas son aptas para su utilización en mezclas de MGTC (Herrador y col., 2012, Poon y Chan, 2006, Jiménez y col., 2011, Vegas y col., 2011). Los materiales reciclados (ZRH y ZRM) presentan resistencias a comprensión similares a las ZN (Xuan y col., 2012; Agrela y col. 2014).

El alto contenido en sulfatos de los ARM y ARC genera un alto riesgo de inestabilidad dimensional y patologías en las capas adyacentes cuando son tratados con cemento (Xuan y col., 2012; Agrela y col. 2014). Además, afecta el proceso de endurecimiento, y esto podría ser una limitación importante en materiales reciclados tratados con cemento (Sakai y col., 2004, Pavoine y col., 2006, Tovar-Rodríguez y col., 2013).

Para garantizar la estabilidad dimensional se deben establecer límites en el contenido de sulfatos para los AR (Agrela y col. 2014).

Recientemente, varios autores han realizado tramos experimentales utilizando zahorras recicladas como MGTC, obteniendo comportamientos similares a las ZN tanto en capas de base como de sub-base (Pérez y col., 2013; Agrela y col., 2012). Estos estudios demuestran que la utilización de zahorras recicladas como áridos para SC es factible.

2.1.2. Suelo reciclado

Si debido a la granulometría, el material reciclado no puede clasificarse dentro de alguna de las clases de zahorra indicadas en el PG-3 por un exceso de finos, este puede ser utilizado como suelo reciclado en la construcción de rellenos tipo terraplén.

Los suelos reciclados (SR) tienen una alta capacidad de carga medida a través del CBR. Los suelos reciclados de hormigón (SRH) presentan valores de CBR comprendidos entre 97- 138%, mientras que los suelos reciclados mixtos y cerámicos (SRM, SRC) tienen valores inferiores comprendidos entre 62- 94%, probablemente debido a la menor resistencia de las partículas de cerámicas (Jiménez y col., 2011, Vegas y col. 2011; Poon y Chan, 2006). Esto permite su utilización como materiales de relleno tipo terraplén en firmes de carreteras (Sánchez M. y Alaejos, P., 2009, Vegas y col., 2011; Barbudo y col., 2012). A largo plazo la capacidad de carga de los SR muestra mejor comportamiento que los áridos naturales (Garach y col., 2015).

Atendiendo al Art.330 del PG-3 (2015), los SRH y SRM (con un bajo contenido de yeso se clasifican como suelos adecuados, incluso en algunos casos pueden ser clasificados como suelos seleccionados. Los SRC y SRM no seleccionados se clasifican como suelos tolerables aptos para la construcción de terraplenes, incluso en algunos casos se pueden clasificar como suelo seleccionado.

Al igual que en su utilización como zahorras recicladas, las principales propiedades limitantes esperadas para los SR son el contenido de sales solubles y el porcentaje de yeso (sulfatos).

El índice de colapso e hinchamiento libre de los SR aún con altos contenidos en sales solubles se encuentran dentro de los límites impuestos por el PG-3. Esta evidencia constituye el argumento básico para explicar la ausencia de efectos nocivos para la inestabilidad asociada a un contenido de sales solubles superiores a un 4% (Vegas y col., 2011).

2.1.3. Grava reciclada

La única utilización de la fracción gruesa de los AR en usos no ligados es como material drenante. El Art. 421 del PG-3 (2015), define el material drenante como rellenos localizados que consisten en la extensión y compactación de materiales drenantes en zanjas, trasdoses de obras de fábrica, o cualquier otra zona, cuyas dimensiones no permitan la utilización de los equipos de maquinaria pesada. El PG-3 (2015) no contempla la utilización de grava reciclada como material drenante.

Sin embargo, teniendo en cuenta las propiedades de la grava reciclada (Jiménez y col., 2011; Vegas y col., 2008; Vegas y col., 2011: Barbudo y col., 2012; Sánchez y Alaejos, 2009), cumplen los requisitos del Art.421 "Rellenos localizados de material drenante. La propiedad más limitante es el coeficiente de desgaste de Los Ángeles, los ARH y ARM se encuentran dentro de los límites exigidos por el PG-3 (2015), obteniendo valores superiores a 40 en el caso de ARC y ARM con un alto porcentaje de material cerámico y mortero adherido (Jiménez y col., 2011; Vegas y col., 2008; Vegas y col., 2011). Para fomentar la utilización de AR como material drenante, dichos porcentajes podrían ser elevados, en especial cuando el material no esté sometido a cargas.

Los usos ligados con cemento de las gravas recicladas, son los que mayor valor añadido da a los materiales reciclados. Estudios realizados por diversos autores demuestran que es posible la sustitución parcial de del árido natural por grava reciclada de Hormigón (GRH) en la realización de hormigón estructural (Evangelista y Brito, 2010; Corinaldsi, 2010). La sustitución de GRH por grava natural (GN) en las proporciones adecuadas no muestra pérdidas de resistencia del hormigón reciclado (Beltrán y col., 2014; Mefheh y col., 2013). Los factores que más influyen en las propiedades del hormigón son la calidad del AR y el porcentaje de sustitución (Silva y col., 2014).

La EHE (2008), incorpora la utilización de materiales reciclados para la realización de hormigón reciclado. Esta norma establece que se podrá utilizar hasta un 20% de GRH en sustitución de GN en la fabricación de hormigón estructural, y hasta un 100% en la fabricación de hormigón no estructural. La normativa española no permite en ninguno de los casos el uso de grava reciclada mixta (GRM) o grava reciclada cerámica (GRC), siendo este tipo de AR el más producido en las plantas de tratamiento.

El uso de GRM ha sido investigado para su uso en hormigón y otros elementos de construcción. Los hormigones realizados con GRM presentan una mayor porosidad, absorción, permeabilidad y una menor resistencia que los realizados con GN (Martínez-Lage y col., 2012; Etxeberria y col., 2007; Tabsh y Abdelfata, 2009; Topçu y Sengel, 2004; López-Uceda y col. 2016a). En altos porcentajes de material cerámico (GRC), las pérdidas de trabajabilidad, permeabilidad y resistencia se ven incrementadas (Yang y col., 2011; Cachim, 2009).

En hormigones de mayor clase resistente, las pérdidas de resistencia son mayores (Mas y col., 2012a, Mas y col., 2012b; Lopez-Uceda y col., 2016a). En dosificaciones bajas de cemento y con un bajo porcentaje de sustitución, no se muestran pérdidas significativas en las propiedades mecánicas del hormigón reciclado (López-Uceda y col., 2012a).

Otro tipo de aplicación de la grava reciclada ligada con cemento es el Hormigón Compactado con Rodillo (HCR). Se trata de un material compuesto por los mismos elementos que el hormigón convencional (cemento, agua y árido), que se pone en obra de forma análoga a la grava-cemento. La proporción de agua utilizada en el HCR es menor que en el hormigón convencional, de manera que sea lo suficientemente seco para ser compactado mediante rodillo.

Según Art.516 del PG-3 (2015), los requisitos técnicos a exigir al árido utilizado para la realización de HCR serán los mismos que para grava-cemento. El Art. 513 recoge los requisitos técnicos que debe cumplir el árido para la capa de grava-cemento. Por lo tanto, las limitaciones en la utilización de AR son el coeficiente de desgaste de Los Ángeles y el contenido en azufre.

Pocas son las experiencias de HCR con AR, estando la mayoría de ellas centradas en la sustitución total o parcial de la fracción gruesa por GRH o GRM. La utilización de ARA en la fabricación de HCR tiene una fuerte influencia en la compactación y densidad del material debido a que las partículas asfálticas tienen una mayor densidad y mayor absorción que los AN (Settari y col., 2015). La mala compactación del ARA muestra una pérdida de resistencia a comprensión en el HCR reciclado, obteniendo pérdidas de resistencia entorno al 30% (Debieb y col., 2009; Modarres y Hosseini, 2014).

La utilización de GRH no influye en la compacidad del HCR (Courard y col., 2010). La sustitución de la fracción gruesa por GRH no muestra diferencias significativas (incluso se aprecia mejora), en la relación densidad-humedad, lo que se traduce en un buen comportamiento en la compactación en obra (López-Uceda y col., 2016b). Estos mismos autores concluyeron que para vías de baja intensidad de tráfico se puede realizar una sustitución del 100% de la GN por GRH con una dosis de cemento de 175 kg/m^3 cumpliendo con los requisitos mecánicos exigidos por el PG-3. En el caso de mayor intensidad de tráfico recomiendan utilizar una dosis de 250 kg/m^3 de cemento, y una sustitución del 50% sin afectar significativamente a las características mecánicas del HCR, cumpliendo con las exigencias técnicas de este material.

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 del cemento a la resistencia a compresión se encuentra en torno a 250 kg por m^3.

2.1.4. Arena reciclada

La fracción fina de los AR presenta una menor densidad y absorción de agua que la fracción gruesa (Debied y col., 2008; Jiménez y col. 2013). El mayor porcentaje de mortero adherido presente en la arena reciclada de hormigón (FRH) y material cerámico en la arena reciclada mixta (FRM) otorga una superficie rugosa y mayor número de poros (Geng y Sun, 2013). Las arenas recicladas presentan una granulometría con partículas de menor tamaño, esto unido a partículas con forma más irregular y mayor angulosidad aumenta la capacidad de absorción de agua. La alta absorción que posee la fracción fina puede ser un factor limitante para su utilización en usos ligados con cemento.

En cuento a las propiedades químicas, las arenas recicladas poseen un mayor contenido en materia orgánica y concentración de cloruros y sulfatos (Rodrigues y col., 2013; Barbudo A. y col., 2012).

En usos no ligados, las arenas recicladas únicamente pueden utilizarse como material de relleno en zanjas o como cama de tuberías. Las recomendaciones técnicas para la utilización de áridos finos para su uso como cama de tuberías están basada en el Manual of Contract Documents for Highway Works: Volumen 1, Specification for Highway Works, Series 500 de noviembre de 2009. Las propiedades más limitantes de las arenas recicladas, principalmente de las FRM, son el contenido en sulfatos y en cloruros (Rodrigues y col., 2013; Barbudo A. y col., 2012). Rahman y col. (2014) obtuvo resultados satisfactorios en la utilización de AR como cama de tuberías como alternativa a los AN.

El uso de arena reciclada ligada con cemento ha sido menos estudiado que la utilización de la fracción gruesa. La utilización de arena reciclada como sustitución de AN en el hormigón tiene un efecto negativo tanto en la vida útil del hormigón fresco (Pereira y col., 2012a), como en las propiedades mecánicas y de durabilidad del hormigón endurecido (Pereira y col., 2012b; Evangelista y de Brito, 2010). Por estas razones en la mayoría de países, entre los que se incluye España, no se permite la utilización de arenas recicladas en la realización de hormigón.

Una alternativa para el uso de la fracción fina en materiales ligados con cemento es su utilización en morteros de albañilería, cuyos requerimientos mecánicos son inferiores a los del hormigón estructural. Se puede sustituir hasta un 25 % en peso de arena natural por FRH sin que se produzcan pérdidas significativas en las prestaciones mecánicas, trabajabilidad y retracción (Vegas y col., 2009; Dapena y col., 2011). Corinaldesi y col. (2002) obtuvieron buenos resultados en la sustitución de AN por FRM, aunque hubo una disminución en la resistencia a flexión y compresión. Otras investigaciones, han demostrado que la sustitución de AN por ladrillos triturado (FRC), no reducen las prestaciones mecánicas (Corinaldesi y Moriconi, 2009), o incluso consiguen mejoras de las resistencias a compresión y flexión, aunque presentan mayores retracciones (Silva y col., 2010).

Las buenas prestaciones que proporciona la utilización de AR en sus usos ligados con cemento, al igual que ocurre en su utilización en carreteras, se atribuye a la actividad puzolánica de los materiales cerámicos o a la hidraulicidad latente de los cementos de hormigones y morteros presentes en los AR (Arm 2001; Sánchez de Rojas y col., 2001; Lin y col., 2010; Vegas y col., 2011).

Otra aplicación ligada con cemento que no ha sido estudiada y que daría un valor añadido a las arenas recicladas, es su aplicación en capas de subbase y base de carreteras como MGTC, siendo uno de los objetivos de la presente tesis.

3. EVALUACIÓN DEL IMPACTO AMBIENTAL DE MATERIALES RECICLADOS PARA UNA CONSTRUCCIÓN SOSTENIBLE

3.1. ECONOMIA CIRCULAR Y SOSTENIBILIDAD

Teniendo en cuenta que los AR son aplicados, después de su tratamiento, durante su segundo ciclo de vida, es necesario evaluar el efecto ambiental de su puesta en obra en el marco de la economía circular, iniciativa de la Unión Europea que busca reducir el consumo de materias primas a través de la aplicación de políticas de gestión de los residuos y de reciclado. ANEFA, Asociación Nacional de Empresarios Fabricantes de Áridos dispone del diagrama acerca de la economía circular que se muestra en la Figura 1.3:

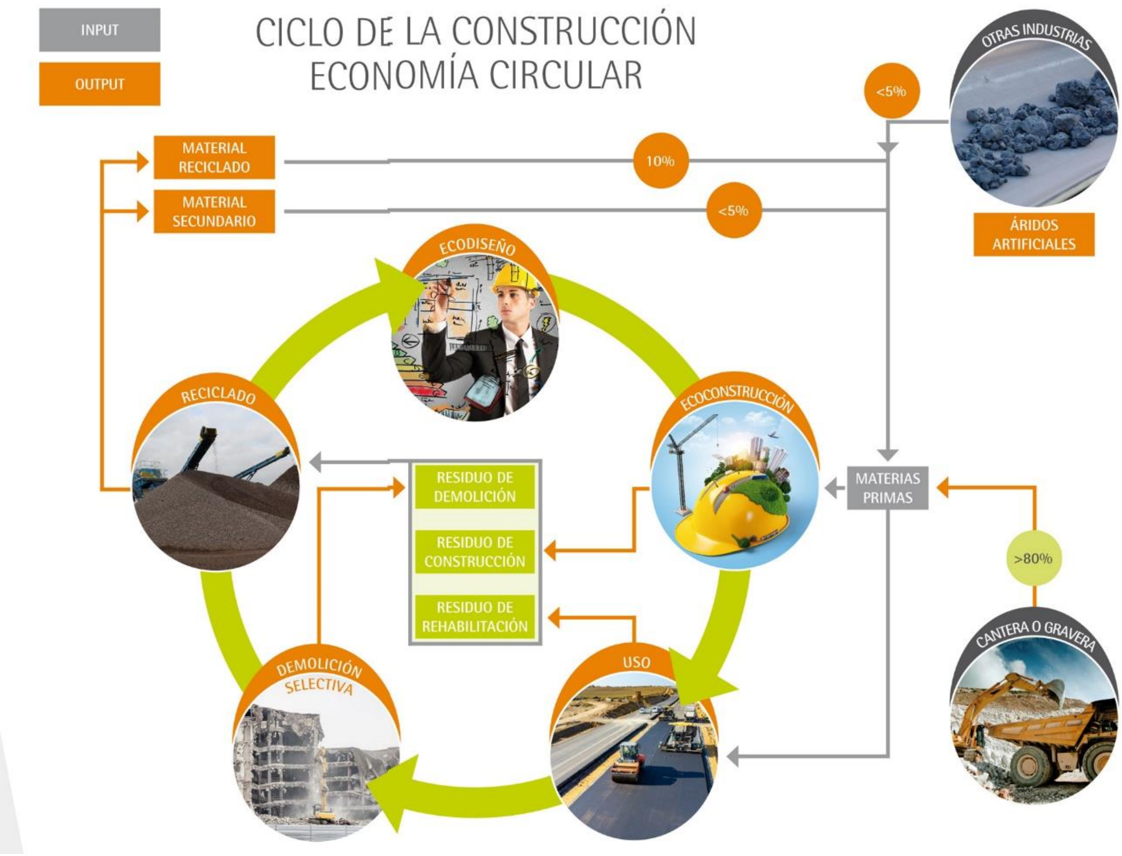

Figura 1.3: Ciclo de construcción en economía circular. FUENTE: ANEFA

La estrategia Europa 2020 tiene entre sus iniciativas emblemáticas que se utilicen eficazmente los recursos. A su vez, una de las prioridades de Horizonte 2020, bloque en el que se reflejan las prioridades políticas y los retos de la estrategia Europa 2020, tiene por objetivos prioritarios la acción por el clima, medio ambiente, eficiencia de los recursos y materias primas, con el fin de estimular la investigación e innovación para que se genere un crecimiento inteligente, sostenible e integrador.

Mediante estas iniciativas se pretende convertir a la UE en una economía circular, es decir, crear una economía eficiente en el uso de los recursos y baja emisión de gases de efecto invernadero (GEI), principalmente dióxido de carbono (CO_2), basada en una sociedad del reciclado a fin de reducir la producción de residuos y utilizarlos como recursos. Esto nos llevaría a pasar de la actual economía lineal (tomar, utilizar y desechar) a una economía circular, basada en el principio de cerrar el ciclo de vida de los productos, lo que ayudaría a reducir el uso de recursos naturales no renovables, impulsar iniciativas de innovación y competitividad de la UE, garantizar la seguridad de suministro de recursos esenciales y luchar contra el cambio climático y limitar los impactos medioambientales del uso de los recursos.

La economía circular es la intersección de los aspectos ambientales y económicos, siendo un concepto ligado a la sostenibilidad. Su objetivo es que, los materiales y los recursos se mantengan durante el mayor tiempo posible en la economía, a la vez que producir una reducción en la generación de residuos. Por tanto, en la presente Tesis Doctoral se pretende abordar los aspectos ambientales a considerar a la hora de aplicar AR en el sector de la construcción e ingeniería. El punto de partida es el hecho de que estos áridos pueden contener elementos tóxicos solubles procedentes de algunos de los componentes listados en apartados anteriores, que pueden dar lugar a la liberación de metales pesados, sulfatos, cloruros y compuestos orgánicos, ya que cuando el agua entra en contacto con ellos, se producen procesos de lixiviación produciendo una amenaza para el medioambiente.

La lixiviación se define como la extracción de un material soluble de una mezcla mediante la acción de un disolvente líquido (principalmente el agua). Así pues, el proceso que tiene lugar, una vez que el árido reciclado es utilizado en obra y entra en contacto con el medio, es que aparece en la Figura 1.4.

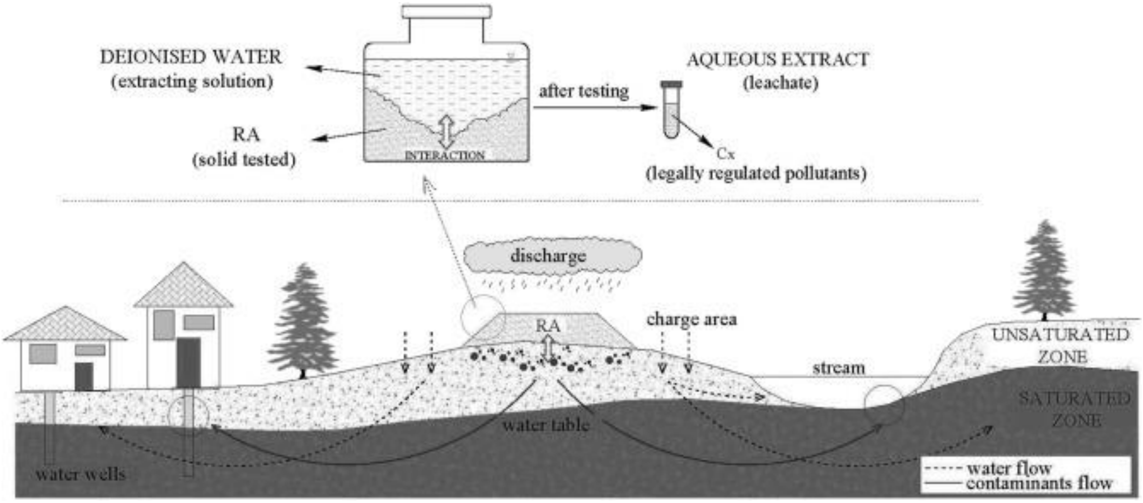

Figura 1.4: Diagrama del proceso de lixiviación en una aplicación tipo de AR en carreteras. FUENTE: Galvín y col., 2014

Como se observa en dicha figura, el proceso que tiene lugar "in situ" es similar al que tiene lugar en condiciones de laboratorio, siendo por tanto los ensayos de lixiviación una herramienta indispensable para caracterizar este proceso de forma controlada y poder evaluar el comportamiento de estos materiales una vez son utilizados en la ejecución de una infraestructura.

Es por tanto clave en la evaluación ambiental de estos materiales, evaluar el proceso de lixiviación durante su segundo ciclo de vida y por el cual, contaminantes orgánicos o inorgánicos, son liberados de una fase sólida a una fase acuosa. Así, para tomar decisiones respecto al tratamiento y al posterior uso de los áridos reciclados que son estudiados por la presente Tesis Doctoral, se incluyen pruebas de laboratorio objetivas para evaluar el impacto ambiental que generarían las distintas alternativas.

3.2. NORMATIVA AMBIENTAL

La Decisión del Consejo Europeo (2003/33/CE), de 19 de diciembre de 2002, por la que se establecen los criterios y procedimientos de admisión de residuos en los vertederos con arreglo al artículo 16 y al anexo II de la Directiva 1999/31/CEE , se distinguen tres tipos de vertederos: vertederos para residuos inertes, para no peligrosos y para residuos peligrosos.

Para la admisión de residuos en los vertederos hay que realizar una primera caracterización básica sobre el residuo (liberación de elementos peligrosos al lixiviado). La concentración de las especies químicas críticas desde un punto de vista ambiental, se miden sobre el lixiviado obtenido mediante una **prueba o test de conformidad**. En base a los resultados obtenidos por dicho ensayo, se obtendrá el nivel de liberación del material y por tanto, se determinará la clase de vertedero en el que el residuo se considera admisible.

En cuanto a las especies químicas reguladas por la normativa vigente por ser considerados potencialmente peligrosos para el medio ambiente, son las siguientes: As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, sulfatos, cloruros y fluoruros. Así pues, dicha normativa indica la concentración máxima (expresada en mg/kg) de cada uno de esos elementos, para cada uno de los tres tipos de vertederos: los de residuos inertes, los de no peligrosos y los de peligrosos. Estos niveles se calcularán, en términos de liberación total, para las proporciones entre líquido y sólido (L/S) de 2 l/kg y de 10 l/kg y una vez medidos los niveles liberados en el lixiviado de cada material, se compararán con los valores límite de concentración que se indican en las Tablas 1.2 y 1.3 para poder clasificar el material según su potencial contaminante.

Tabla 1.2: Clasificación de peligrosidad de residuos en función de la cantidad lixiviada (para L/S=2 l/Kg) para admisión en vertedero.

Componentes	**Valores admisibles de la Directiva para una relación L/S de 2 l/kg para el Test de Conformidad para materiales granulares Niveles liberados por elemento (mg/kg)**		
	Residuo Inerte	**Residuo No Peligro**	**Resido Peligroso**
As	0.1	0.4	6
Ba	7	30	100
Cd	0.03	0.6	3
Cr	0.2	4	25
Cu	0,9	25	50
Hg	0.003	0.05	0.5
Mo	0.3	5	20
Ni	0.2	5	20
Pb	0.2	5	25
Sb	0.02	0.2	2
Se	0.06	0.3	4
Zn	2	25	90
Cloruro	550	10000	17000
Fluoruro	4	60	200
Sulfato	560	10000	25000

Tabla 1.3: Clasificación de peligrosidad de residuos en función de la cantidad lixiviada (para L/S=10 l/Kg) para admisión en vertedero.

Componentes	**Valores admisibles de la Directiva para una relación L/S de 10 l/kg para el Test de Conformidad para materiales granulares Niveles liberados por elemento (mg/kg)**		
	Residuo Inerte	**Residuo No Peligro**	**Resido Peligroso**
As	0.5	2	25
Ba	20	100	300
Cd	0.04	1	5
Cr	0.5	10	70
Cu	2	50	100
Hg	0.01	0.2	2
Mo	0.5	10	30
Ni	0.4	10	40
Pb	0.5	10	50
Sb	0.06	0.7	5
Se	0.1	0.5	7
Zn	4	50	200
Cloruro	800	15000	25000
Fluoruro	10	150	500
Sulfato	1000	20000	50000

Tabla 1.4: Clasificación de peligrosidad de residuos en función de la cantidad lixiviada (para L/S=0.1 L/kg) para admisión en vertedero

Componentes	**Valores admisibles de la Directiva para la primera relación L/S de 0.1 l/kg para el Test de Columna para materiales monolíticos Niveles liberados por elemento (mg/l)**		
	Residuo Inerte	**Residuo No Peligro**	**Resido Peligroso**
As	0.006	0.3	0.3
Ba	4	20	20
Cd	0.002	0.3	0.3
Cr	0.01	2.5	2.5
Cu	0.06	30	30
Hg	0.0002	0.03	0.03
Mo	0.02	3.5	3.5
Ni	0.012	3	3
Pb	0.015	3	3
Sb	0.01	0.15	0.15
Se	0.004	0.2	0.2
Zn	0.12	15	15
Cloruro	45	850	850
Fluoruro	0.25	4	4
Sulfato	150	700	700

Además del test de conformidad, que es un ensayo básico de caracterización del comportamiento frente a lixiviación de un material granular, se puede realizar otro tipo de ensayo: el **test de lixiviación en columna o también denominado test de percolación**. La diferencia con el anterior es que éste simula en el laboratorio de una forma más exacta el proceso de lixiviación real que tendría lugar cuando el material en forma granular es aplicado en una infraestructura como puede ser una carretera (utilizando el AR, por ejemplo, como subbase de la misma). Esto se debe a que, como su propio nombre indica, el ensayo simula el proceso de percolación del agua a través de unas columnas de metacrilato en las cuales se deposita el material en estudio, y de esta manera se simula cómo se infiltraría el agua de lluvia a través de las capas del material que conforma la infraestructura. Por tanto, la legislación da unos límites distintos para cada uno de los tres tipos de vertederos y que se observan en la Tabla 1.4. En este caso, la liberación de contaminantes en el lixiviado se expresará directamente en mg/l en la columna C_0 (el primer eluato de un ensayo de percolación en columna con una proporción L/S = 0,1 l/kg). Cabe indicar que para la caracterización básica de materiales granulares se utiliza el Test de Conformidad por ser más simple, rápido y económico (Van der Sloot, 1998).

Ante la carencia de normativa y procedimiento de evaluación ambiental a nivel nacional, se recurran a las metodologías aprobadas por la Comisión Europea (v.g. test de cumplimiento UNE-EN 12457-3)

A nivel europeo, se han creado 40 comités técnicos de materiales de construcción, donde cada uno de ellos ha desarrollado su propio ensayo de lixiviación. Por ejemplo, la normativa holandesa (Dutch Building Materials Decree 1995) regula la utilización de materiales de construcción indicando valores límites particularizados para este tipo de material. Otros países como Alemania, Francia o Suiza también disponen de procedimientos propios para la evaluación de la lixiviación particularizados para residuos concretos como son tratamientos de aguas residuales o residuos sólidos municipales.

Por tanto, el objetivo fundamental de la presente Tesis Doctoral es analizar la viabilidad del uso y aplicaciones de AR en ingeniería civil. Para ello, se incluye el estudio del impacto ambiental derivado de la puesta en obra de estos materiales, incluyendo un estudio y análisis de la procedencia de los elementos más limitantes en este tipo de materiales.

3.3. ESTUDIOS DE LIXIVIACIÓN EN ÁRIDOS RECICLADOS

La presente Tesis Doctoral comenzaba resaltando que el concepto de construcción sostenible debe abarcar los aspectos económico, social y ambiental. Por lo tanto, para poder hablar de sostenibilidad, es necesario abordar la evaluación ambiental de los materiales reciclados, previo a su reutilización en un segundo ciclo de vida.

En función de la calidad de partida del material reciclado que se vaya a utilizar en una nueva infraestructura durante su segundo ciclo de vida, se causará o no un efecto negativo en el medio en el cual interacciona. De esta forma es el agua de lluvia el que da lugar a la disolución de elementos solubles presentes en los AR, los cuales podrían ser tóxicos y causar la contaminación de aguas superficiales y subterráneas (Van der Sloot y col., 2003). En este proceso, la cantidad total de un elemento no es el factor crítico, sino su capacidad para ser liberado al medio, definido como “potencial lixiviable” y que aparece en azul en la figura 1.5:

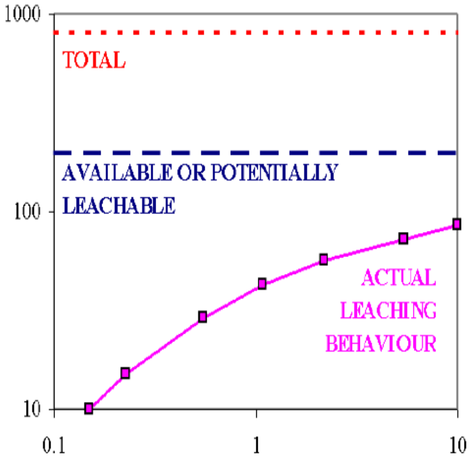

Figura 1.5: Representación gráfica entre Lixiviación vs Concentración total (Van der Sloot y Kosson (2003))

En cuanto a los parámetros que le afectan, la lixiviación está afectada por varios factores físicos: tamaño de la partícula expuesto, tiempo, condiciones de flujo lixiviante, temperatura, porosidad, forma geométrica y tamaño de los materiales, permeabilidad de la matriz, condiciones hidrogeológicas, etc. Así como una serie de factores químicos: pH del material, equilibrio o control cinético de la liberación, formación de complejos inorgánicos u orgánicos, condiciones redox del material, etc.

Además, en términos de comportamiento frente a la lixiviación, se debe distinguir según el tipo de material y/o de infraestructura de la cual formará parte: materiales monolíticos (materiales base cemento, hormigón, ladrillos, materiales recubiertos, etc.) y materiales granulares (áridos, cenizas, escorias, etc.). En los materiales monolíticos la lixiviación está controlada por difusión, mientras que en los materiales granulares, la liberación está dominada por mecanismos de percolación (Van der Sloot y col., 2003). Los factores físicos, químicos y ambientales y, a su vez, el tipo de uso o aplicación del material afectan a la liberación de elementos potencialmente contaminantes (Figura 1.6 Y 1.7)

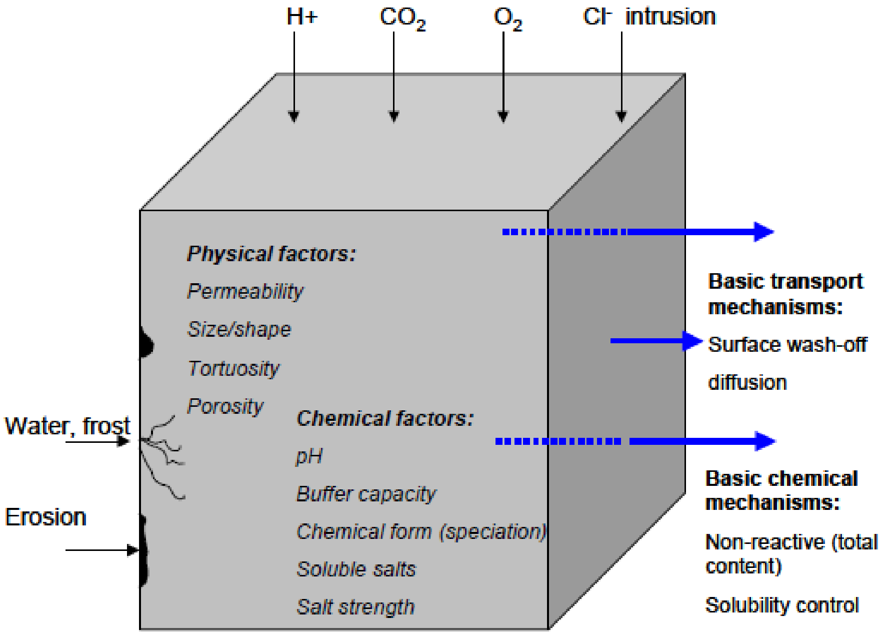

Figura 1.6: Factores externos (químicos y físicos) que influyen en la liberación de contaminantes en materiales monolíticos (hormigón, bloques, ladrillos, etc.)

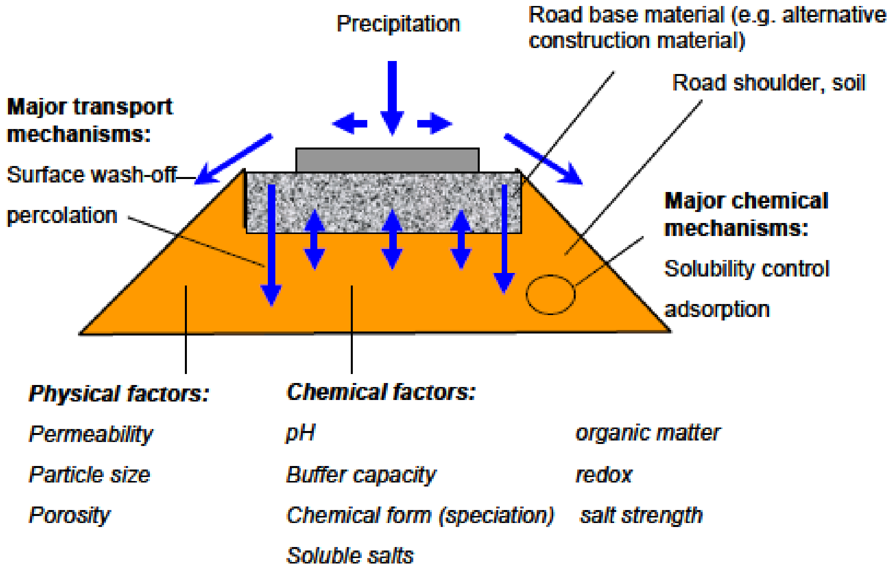

Figura 1.7: Factores externos (químicos y físicos) que influyen en la liberación de contaminantes en materiales granulares (arena, grava, zahorra, etc.)

Los ensayos de lixiviación son los más indicados para reproducir en laboratorio los procesos físico-químicos que tienen lugar bajo las condiciones de exposición que el material reciclado tendrá en campo u obra. (Vázquez E., 2009). Se pueden distinguir los siguientes tipos de ensayos de lixiviación:

i. Test de conformidad: análisis a corto plazo donde el material en estado granular se pone en contacto con agua y se somete a una agitación mecánica en dos relaciones líquido/sólido (L/S) (2 y 10 l/kg). (UNE EN 12.457-3).

ii. Test de Columna o de percolación: el material en estado granular es depositado en el interior de columnas por las que se hace circular un flujo de agua, analizando a largo plazo con siete relaciones L/S (0,1; 0,2; 0,5; 1; 2; 5; y 10 l/kg). Durante este ensayo se simula los mecanismos de percolación por los que se produce la liberación de elementos químicos en materiales granulares puesto en obra (NEN 7343:2004).

iii. Test de Tanque o de difusión: test de lixiviación que evalúa a largo plazo los materiales monolíticos, tomando muestras a 8 edades distintas (6 h.; 1; 1,25, 4, 9, 19, 36 y 64 días). Se reproduce en el laboratorio el mecanismo de liberación que rige la difusión superficial de especies químicas en materiales sólidos (NEN 7345: 2004).

La realización de un completo estudio del proceso de lixiviación y, por lo tanto, de la liberación de contaminantes, permite utilizar los ensayos de lixiviación como indicadores de sostenibilidad, necesarios para dejar patente la idoneidad de poder reutilizar AR en obras de ingeniería civil. Los resultados de los ensayos de lixiviación son determinantes en la decisión de utilización o no de materiales reciclados. Por este motivo, estos ensayos han sido incluidos en las investigaciones realizadas en la presente Tesis Doctoral, siendo sus resultados determinantes para analizar el origen de los contaminantes en los AR.

Existen muchos factores que influyen en la lixiviación, y todos ellos deben ser considerados al elegir el tipo de test. Si se omite alguno de estos factores, se corre el riesgo de obtener resultados no extrapolables a situaciones reales.

Engelsen y col., 2012 estudió que, los factores externos a los que está sometido el material, una vez puesto en obra, nos va a introducir más variables que afectan a este fenómeno. Galvín y col. (2012), estudiaron los principales factores que afectaban a la liberación de contaminantes por parte de áridos reciclados en forma granular, concluyendo que los más relevantes son: la relación líquido sólido directamente relacionada con la cantidad de líquido en contacto con el árido, tiempo de contacto del agua con el material, y el valor del pH (siendo este factor es más influyente de los tres en la liberación de elementos contaminantes).

El estudio en profundidad de los condicionantes que afectan al lixiviado concluyen que una vez puesto en obra, factores como la formación de circuitos preferenciales en los materiales granulares, está condicionando la lixiviación de elementos tóxicos, y todo ello dependerá además del tipo de escenario, es decir, del tipo de infraestructura civil en cuestión, no siendo igual la respuesta del material formando parte de la subbase de una carretera asfaltada en la cual la capa de rodadura actúa de aislante a inclemencias meteorológicas, que una carretera sin asfaltar, camino de tierra o caminos rurales (Galvín Y col., 2014b, Galvín y col., 2017) .

Los últimos estudios demuestran que, para extrapolar los resultados del laboratorio a las condiciones de campo, se deben tener en cuenta todos estos factores que se han citado, de lo contrario, sería muy difícil extrapolar los datos experimentales a campo (Van der Sloot y Kosson, 2012, López-Uceda y col., 2017).

La evaluación del riesgo ambiental resultante de la aplicación de AR en diferentes escenarios (vertederos, terraplenes, pendientes o sub-base en pavimentos), implica el análisis del potencial de lixiviación del material en su aplicación específica. Así, trabajos previos demuestran que, en general, la lixiviación de los AR en condiciones de campo es relativamente menor que en condiciones controladas en laboratorio. Este hecho se ha observado en varias aplicaciones en ingeniería: infraestructuras viarias (Engelsen y col., 2017, Lidelöw y col., 2017, Bestgen y col., 2016, Galvín y col., 2014, Butera y col., 2014, Engelsen y col., 2012) relleno o terraplenes (Coudray y col., 2017, Cristelo y col., 2016) u hormigón endurecido (Puthussery y col., 2017, Galvín y col., 2014, Erdem y Blankson, 2014). Así como en aplicaciones reales: material de carreteras (Paulus y col., 2016), en la fracción fina utilizada en la construcción de estructuras geosintéticas reforzadas (Vieira y col., 2016) o en material de relleno para aguas pluviales y tuberías de alcantarillado (Rahman y col., 2014).

Los numerosos factores que intervienen en la lixiviación, tanto físicos como químicos, juegan un papel fundamental en el comportamiento a largo plazo de los materiales (cuando son puestos en obra). Esto hace necesario realizar un desarrollo y estandarización de los ensayos de laboratorio para que se reproduzca fehaciente lo que ocurre en la aplicación real.

A pesar de que las liberaciones de contaminantes al lixiviado son controladas por un número limitado de parámetros como se ha comentado, existe un patrón similar que se repite en diferentes tipos de residuos a pesar de sus diferencias inherentes, facilitando a los investigadores predecir el comportamiento ambiental de materiales secundarios o subproductos una vez que son puestos en obra (Van der Sloot y col., 1996).

Por tanto, el procedimiento de evaluación ambiental de cualquier material reciclado que vaya a ser utilizado en el ámbito de la construcción sostenible, se puede resumir en el siguiente ciclo de 5 fases:

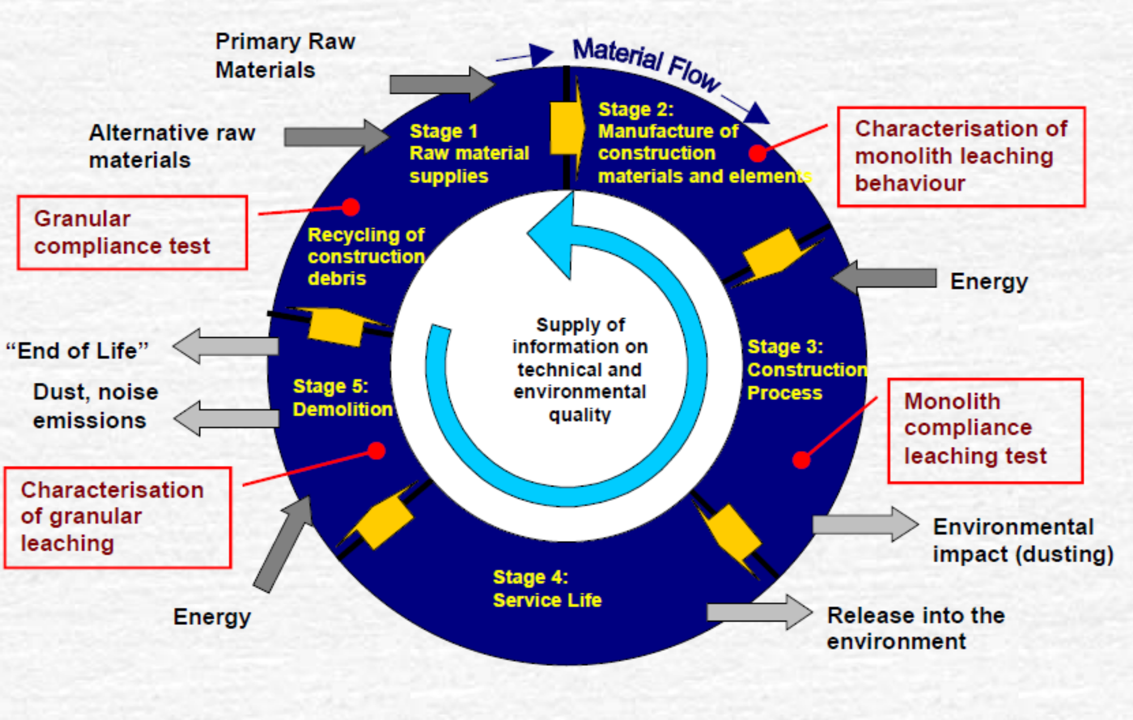

Figura 1.8: Characterization and compliance leaching tests in different stages of the building cycle supply. FUENTE: WASCON 2003. An Overview of Leaching Assessment for Waste Disposal and Materials Use. Hans A. van der Sloot, Hans Meeussen, David S. Kosson, Florence Sanchez

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CAPÍTULO 2. OBJETIVOS Y ESTRUCTURA DE LA PRESENTE TESIS DOCTORAL

1. OBJETIVOS

El objetivo principal que se plantea en esta tesis es la evaluación ambiental de los áridos reciclados procedentes de residuos de construcción y demolición para su aplicación en obras de infraestructura civil, contribuyendo al desarrollo de una construcción sostenible y dar un valor añadido a este tipo de materiales.

Para la consecución del objetivo principal, la investigación se centrará en los siguientes objetivos específicos:

1. Caracterización física y química de los áridos reciclados de diferente procedencia (árido reciclado de hormigón y árido reciclado mixto): se realizará un exhaustivo estudio de las propiedades físico-químicas (granulometría, composición, coeficiente de descaste de Los Ángeles, absorción y densidad, índice de lajas, sulfatos solubles en agua y en ácido, compuestos totales de azufre, etc.).
2. Estudiar las posibles consecuencias medioambientales que puede conllevar la utilización de áridos reciclados en ingeniería civil: Se realizarán ensayos de lixiviación para l evaluar el comportamiento de los áridos reciclados a corto plazo (test de conformidad) y a largo plazo (test de columna o percolación)
3. Detectar el origen de los elementos contaminantes presentes en los áridos reciclados: se analizará el origen de los principales elementos contaminantes presentes en los áridos reciclados.

4. Estudiar el comportamiento mecánico de la fracción fina de los áridos reciclados ligados con cemento en capas estructurales de firme de carreteras mediante la fabricación de suelo-cemento.
5. Análisis de la viabilidad de utilizar zahorras recicladas mixtas en capas estructurales del firme de un camino rural. para ello, se ejecutará un tramo experimental en un camino rural sobre suelos típicos de la campiña cordobesa (arcillas expansivas). Se evaluará "in situ" el comportamiento a largo plazo de las principales características del tramo (densidad y humedad, deflexiones y regularidad superficial).

La metodología seguida para lograr la consecución de los objetivos anteriormente expuestos, se resume en las siguientes etapas, las cuales se describen según el orden cronológico que se siguió durante la realización de la presente Tesis Doctoral, y se esquematiza en la Figura 2.1:

Figura 2.1: Esquema y metodología de la presente tesis doctoral

2. ESTRUCTURA DE LA PRESENTE TESIS DOCTORAL

Esta tesis doctoral se presenta en la modalidad de compendio de artículos. La estructura está compuesta por seis capítulos. El capítulo 1 corresponde a la introducción, donde se realiza una recopilación de información y un análisis de la bibliografía. Una vez se ha determinado los antecedentes de la temática escogida. En el capítulo 2, se describen los objetivos generales y específicos, así como la metodología a adoptar. Los tres siguientes capítulos (3, 4 y 5), corresponden a los tres artículos publicados en revistas internacionales indexadas en el Journal Citation Reports. Los artículos de los capítulos 3 y 5 están publicados en revistas pertenecientes al primer cuartil y el artículo del capítulo 4 pertenece a una revista del segundo cuartil.

El capítulo tercero corresponde al artículo " ANALYSIS OF CHROMIUM AND SULPHATE ORIGINS IN CONSTRUCTION RECYCLED MATERIALS BASED ON LEACHING TEST RESULTS", los autores son: I. Del Rey, J. Ayuso, A.P. Galvín, J.R. Jiménez, M. López, M.L. García-Garrido. Publicado en: *Waste Management,* en 2015, volumen 46, páginas 278-286. IF: 4.669 (Q1). En este estudio se ha realizado la caracterización física y ambiental de veinte muestras de AR de RCD con diferentes composiciones (objetivo 1). El cromo y los sulfatos fueron detectados como compuestos más críticos en los lixiviados (objetivo 2). Posteriormente se realizó un análisis de los lixiviados de ocho materiales de construcción (cinco cerámicos, dos hormigones de diferente edad y un mortero de nueva fabricación) para detectar la procedencia de los compuestos más críticos. (objetivo 3).

El cuarto capítulo corresponde al artículo denominado " FEASIBILITY STUDY OF CEMENT-TREATED 0-8 MM RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE AS ROAD BASE LAYER " los autores son: I. Del Rey, J. Ayuso, A. Barbudo, A.P. Galvín, F. Agrela, J. de Brito. Publicado en: *Road Materials and Pavement Design,* en 2016, volumen 17, número 3, páginas 678-692. IF: 1.717 (Q2). En este artículo se estudió la viabilidad del uso de la fracción fina de los áridos reciclados como capa de base de carreteras como material granular tratado con cemento (suelo-cemento) (objetivo 4). La fracción fina, se usa comúnmente en camas de tuberías, una aplicación que proporciona poco o ningún valor añadido. Se caracterizaron seis materiales reciclados, que incluyeron tres realizadas con fracción fina, dos áridos reciclados mixtos y uno de hormigón, para su uso como SC20 y tres con fracción gruesa, dos áridos reciclados mixtos y uno de hormigón, para su uso como SC40 (objetivo 1). Se estudiaron las principales propiedades mecánicas (resistencia a compresión y módulo de elasticidad) y de durabilidad (cambios dimensionales), analizando el efecto del tamaño de partícula y procedencia del AR (objetivo 4).

El quinto capítulo corresponde al artículo "FEASIBILITY OF USING UNBOUND MIXED RECYCLED AGGREGATES FROM CDW OVER EXPANSIVE CLAY SUBGRADE IN UNPAVED RURAL ROADS" los autores son: I. Del Rey, J. Ayuso, A.P. Galvín, J.R. Jiménez, A. Barbudo. Publicado en: *Materials,* 9, 931. 2016. IF: 3.236 (Q1). En esta publicación se pretende evaluar el comportamiento "in situ" de zahorras recicladas mixtas en usos no ligados en capa estructurales del firme de un camino rural sin pavimentar con baja intensidad de tráfico (objetivo 5). Los comportamientos de las capas estructurales en el camino experimental se determinaron controlando la compactación (densidad "in situ" y humedad) y midiendo las deflexiones y la capacidad de carga (deflectómetro) durante los 18 meses posteriores a la construcción. Los resultados muestran que las secciones hechas con AR cumplen con las especificaciones técnicas requeridas por la normativa española de carreteras (PG-3, 2015).

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

CAPÍTULO 3. ANALYSIS OF CHROMIUM AND SULPHATE ORIGINS IN CONSTRUCTION RECYCLED MATERIALS BASED ON LEACHING TEST RESULTS

This chapter has been published entirely in the journal "Waste Management", vol.46, p.278-286. 2015:

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ABSTRACT

Twenty samples of recycled aggregates from construction and demolition waste (CDW) with different compositions collected at six recycling plants in the Andalusia region (south of Spain) were characterised according to the Landfill Directive criteria. Chromium and sulphate were identified as the most critical compounds in the leachates. To detect the sources of these two pollutant constituents in recycled aggregate, environmental assessments were performed on eight construction materials (five unused ceramic materials, two old crushed concretes and one new mortar manufactured in the laboratory). The results confirmed that leached sulphate and Cr were mainly released by the ceramic materials (bricks and tiles).

To predict the toxicological consequences, the oxidation states of Cr (III) and Cr (VI) were measured in the leachates of recycled aggregates and ceramic materials classified as non-hazardous. The bricks and tiles mainly released total Cr as Cr (III). However, the recycled aggregates classified as non-hazardous according to the Landfill Directive criteria mainly released Cr (VI), which is highly leachable and extremely toxic. The obtained results highlight the need for legislation that distinguishes the oxidative state in which chromium is released into the environment. Leaching level regulations must not be based solely on total Cr, which can lead to inaccurate predictions.

KEYWORDS

Environmental management; Construction materials; Leaching assessment; Chromium, Sulphates,

1. INTRODUCTION

The reuse, recycling and revalorization of construction and demolition waste (CDW) are essential from an environmental point of view. They help to conserve natural resources, and in turn, they reduce the amount of waste disposed in landfills. As many authors have shown (Agrela et al., 2012; Kumar et al., 2008; Jiménez et al., 2012), the mechanical properties of recycled aggregates (RA) do not limit their reuse in roads as sub-bases or embankments. The feasibility of RA for making concrete and cement-treated materials has also been demonstrated (André et al., 2014; Agrela et al., 2012; Martin-Morales et al., 2011).

However, the main problem is that CDWs are not completely inert materials. Generally, they present potential hazardous risks to the environment due to containing adhesives, paints, sealants, PCBs, asbestos and/or lead-based paint (Del Río et al., 2010). The contact of these compounds with construction materials causes a pollution risk and their classification as potentially contaminated secondary materials. However, Spain currently has no specific national regulations that assess potential contaminants or that classify wastes based on their potential environmental risk. Council Decision 2003/33/EC about the acceptance criteria for landfill waste was entered into force without transposition into Spanish law starting on July 16, 2004. Since July 16, 2005, these criteria have been the only ones recognized by the Spanish Government, which is why they are the criteria used in this study.

To assess the potential environmental risk of applying RA on a site, the leaching availability should be analysed instead of the total content because the release of substances from a given material depends on their solubility, which is influenced by numerous factors including material composition, pH, permeability, contact time and water/solid ratio (Van der Sloot, 2004, Townsend et al., 2003, Medina et al., 2014, Tiruta-Barna, 2013).

Previous studies report the leaching behaviour of different RA from CDW. (Galvín et. al, 2013) revealed that the compounds that present a leachability close to the limits for inert waste according to the EU landfill directive are Ni, Cr, Sb, Zn, Cu, and sulphate. (Butera et al., 2014) concluded that Se, Cr, Sb and sulphate are the most critical components. However, (GEAR, 2012) analysed RA from a wide number of treatment plants in Spain and detected only Cr and sulphate as more critical components.

Hence, within the framework of these previous investigations, the objectives of the present research were as follows: (i) Analyse which metals and anions present higher release in the leachate than the limits for inert waste according to the EU Landfill directive. To cover the variability of recycled aggregates produced in Andalusia (located in southern Spain), six different treatment plants were selected and several concrete, mixed and asphalt recycled aggregates were collected. (ii) Study the origin of those compounds. For this purpose, unused CDW components will be analysed to determine which originate high releases in leachate, thereby assisting and facilitating the elaboration of technical recommendations for managers of treatment facilities and furthering the technical potential of aggregates.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Recycled aggregates

Twenty samples of recycled aggregates were collected from six different CDW treatment plants to provide a representative sampling of the main RAs produced in the Andalusia region of the South of Spain. The samples consisted of seven recycled aggregates from crushed concrete (C1-C7), ten mixed materials (M1-M10) including different proportions of concrete, asphalt and ceramic particles (bricks, tiles, bluebirds and stoneware) and three asphaltic RAs from the milling of bituminous pavement layers (A1-A3). The RAs was classified following the recommendations of the GEAR (2012): recycled concrete aggregates (RCA) containing natural aggregate, concrete and mortar above 90%; mixed recycled concrete aggregate (MRCA) containing less than 90% concrete and natural aggregates and in which the ceramic material does not reach 30%; mixed recycled ceramic aggregate (MRCeA) in which the content of the ceramic exceeds 30%; and asphalt recycled aggregates in which the predominant material is bitumen (more than 30%). Table 3.1 shows the percentage in weight of each component of the 17 RAs (according to the standard UNE-EN 933-11: 2009). The composition of asphalt recycled aggregates does not appear because the nature of the material is entirely asphalt. The physical and chemical properties (A-1) and grain size distribution (A-2) are reported in Appendix A, support information.

Table 3.1: Composition of the recycled aggregates

			Composition (% in weight)					
		RA source	**Bitumen**	**Ceramic**	**Concrete and mortar**	**Natural aggregates**	**Gypsum**	**Others**
Recycled concrete aggregate	C1	RCA	0.85	0.74	52.89	45.37	0	0.15
	C2	RCA	1.12	0	59.34	39.56	0	0.88
	C3	RCA	4.79	4.34	41.13	49.74	0	0
	C4	RCA				*		
	C5	RCA	3.8	3.7	62.9	29.6	0	0
	C6	RCA	0	1.3	80.9	17.8	0	0
	C7	RCA	0	0	95.6	4.4	0	0
Mixed recycled aggregates	M1	MRCeA	9.56	32.75	40.36	15.92	1.15	0.26
	M2	MRCA	2.48	20.41	45.91	30.73	0.12	0.35
	M3	MRCA	2.88	25.72	35.25	35.46	0.45	0.24
	M4	MRCA	4.1	29.73	49.69	14.54	1.55	0.39
	M5	MRCA	0.9	13.8	49.3	34.9	0.2	0.9
	M6	MRCA	3.07	26.23	54.02	16.24	0.28	0.16
	M7					*		
	M8					*		
	M9	MRCA	2.47	8.7	81.44	7.05	0.13	0.21
	M10	MRCeA	0	33.8	59.5	6.6	0	0.1

** non-determined parameter due to the grain size distribution of the material*

2.1.2. Ceramics materials and concretes

To deepen the origin of critical compounds in the leachate of recycled aggregates from CDW, eight materials were analysed for environmental evaluation. Five of the materials were unused ceramic materials from a construction material factory located in Bailén (south of Spain). Perforated brick (PB), hollow brick (HB), and tile (T) are composed of clay (80-95%) and grog (5-10%). Bluebird (B) is composed of clay (70-80%), feldspar (15-20%) and quartz (10-20%); stoneware (S) is composed of clay (60-80%), feldspathic sands (15-20%) and feldspar (5-10%) (Spanish Association of Technical Ceramics and SACMI, 2004). The remaining tested materials were two concretes with different manufacturing years (pre- and post-Directive 2003/53/EC), one of them dating from the 1960s (RC-1) and the other dating from the 1990s (RC-2), and a new mortar (NM) manufactured in the laboratory during the present research. Table 3.2 describes all of the materials analysed.

Table 3.2: Description of construction materials tested for detection of Cr and sulphate origins.

	Materials	Description
Type 1: unused ceramic materials from factory	Perforated brick (PB)	Made of clay with holes greater than 25% of the brick volume
	Hollow brick (HB)	Made of clay. The holes are less than 25% of the brick volume
	Tile (T)	Made of clay used in the manufacture of pitched roofs.
	Bluebird (B)	Thin flat pieces made of clay, silica, fluxes (feldspars), coloring and other raw materials. Generally used to pave floors and cover walls and facades.
	Stoneware (S)	Ceramic tile made of malleable clay or a combination of clays that have been fired at high temperature. It has a fine texture with a glassy finish.
Type 2 concretes of different manufacturing years	New Mortar (NM)	Mortar made of a natural sand (NS) with a CEM II/B-L 32.5-R.
	Recycled Concrete Aggregate (RC-1)	Concrete provided by a CDW treatment plant of Andalusia. The concrete comes from the demolition of a foundation of a house early 60s. Based on the classification of the Spanish legislation of Concrete for that period (EH-68). The concrete presented a minimum strength of 6 (MPa).
	Recycled Concrete Aggregate (RC-2)	Concrete provided by a CDW treatment plant of Andalusia. The concrete comes from the demolition of a foundation of a house on the decade of 90s. Based on the classification of the Spanish legislation of Concrete for that period (EH-73). The concrete presented a minimum strength of 12.5 (MPa).

2.2. METHODS

2.2.1. Sample preparation

Laboratory samples were obtained by methods for sampling, according to UNE-EN 192-1:1997. The material was divided into quarters to obtain a sample of 2 kg. The tests have to be done with a size of less than 4 mm particles. Therefore, the samples were sieved. The coarse fraction retained on the sieve was crushed by a jaw crusher. Later, the sample moisture was determined by oven-drying (UNE 103300:1993). Finally, a portion of moist soil containing the desired dry matter was selected. Two replicates were made for each test.

2.2.2. Compliance test

A compliance test or batch test according to the standard UNE-EN 12457-3: 2003 was conducted to estimate whether the 20 recycled materials satisfy European regulations. To classify those materials according to the Landfill Directive (Council Decision DC/2003/33/CE, 2002), both heavy metals and inorganic anions were measured.

The procedure consists of a two-step batch leaching test resulting in two liquid/solid ratios (L/S). This method use a solution of 175 g of dry mass of material (particle size < 4 mm) with deionised water. In the first step, the solution is shaken for 6 ± 0.5 h with an L/S of 2 l/kg. In the second step, water is added to stablish an L/S of 10 l/kg, and the solution is then shaken for another 18 ± 0.5 h. In both stages, the samples are left to decant during 15 min, the eluate is filtered (0.45 µm membrane filters), a subsample of 40 ml of eluate is collected for testing, and the pH, conductivity and temperature are measured.

2.2.3. Column test.

The column test described by the standard NEN 7343: 1994 is designed to simulate the leaching behaviour of a material by relating the accumulated pollutant release (expressed as mg/kg leached) to the liquid/solid ratio. The procedure consists of a seven-step column test resulting in seven liquid/solid ratios (0.1, 0.2, 0.5, 1, 2, 5, and 10 L/kg). The column (inner diameter of 5 cm and length of 20 cm) is filled with the test material (particle size < 4 mm) and the initial dry matter is calculated (with the in weight difference between the full and empty column and soil moisture). The deionised water quantity for each step is calculated from the dry matter and the L/S relationship. In the first step, a peristaltic pump (flow rate of 18 ml/h) fills the column with deionised water until the material is saturated, the eluate passes through two filters (1.5-µm prefilter and a

0.45-µm filter) to prevent entrainment of fine particles, and a collections flask picks up the leachate corresponding to each L/S ratio. From each flask, a subsample of 40 ml of eluate is collected for testing, and the pH, conductivity and temperature are measured.

2.2.4. Sample composition of leachate

The leachates were analysed by inductively coupled plasma mass spectrometry (ICP-MS) using a PerkinElmer ELAN DRC-e spectrometer. This analysis quantified the 12 heavy metals specified by the European Landfill Directive: Ni, Cr, Sb, Se, Mn, Hg, As, Pb, Cd, Cu, Ba and Zn. In addition, the sulphate, fluoride and chloride anion contents were obtained by ion chromatography according to the standard UNE-EN ISO 10304-1: 2009.

2.2.5. Determination of total chromium by UNE-EN 1233:1997.

The total Cr concentration was determined by flame atomic absorption spectrometry (FASS) according to the procedure described by the standard UNE-EN 1233:1997. This method is based on spectrometric measurement of the atomic absorption of chrome in samples acidified in a flame of nitrous oxide/acetylene. The measurement is realized at a wavelength of 357.9 mm (Monteiro et al., 2002). The leachate sample is acidified with nitric acid to obtain a pH between 1 and 2, and 10 ml of lanthanum chloride is flushed with the filtered sample and acidified in a volumetric flask. The sample is aspirated into the flame, and the chrome absorbance is measured.

2.2.6. Determination of Cr (VI) by UNE 77061:2002.

Cr (VI) was measured according to the water quality standard UNE 77061:2002 for chromium determination, which applies a colourimetric method with diphenylcarbazide. The measurement consists of acidifying and leaching the sample. Then, 50 ml of the sample is introduced into a 100-ml Erlenmeyer flask, using 2.5 ml of diphenylcarbazide as the reagent. The samples are introduced into a spectrophotometer at 540 nm. In a lightly acidified solution, hexavalent chrome reacts quantitatively with the diphenylcarbazide and achieves a violet colouration. Cr (III) can be calculated as the difference between total Cr and Cr (VI).

3. RESULTS AND DISCUSSION

3.1. POLLUTANT EMISSIONS BY RA ACCORDING TO COMPLIANCE TEST.

As previously mentioned, the leaching behaviour was evaluated according to the compliance test proposed by the Landfill Directive for evaluating the leaching of granular waste materials at the compliance level. The legally regulated limit levels are shown in Appendix B. Tables 3.3a, 3.3b and 3.3c show the numeric data on the leachate concentrations of metals and anions as well as the conductivity, pH values and temperature. The data in bold indicate that the value exceeds the limit for inert wastes.

Table 3.3a: Leachate concentrations (mg/kg) from asphaltic recycled aggregate

	A1		**A2**		**A3**	
	L/S 2	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**
C (μS/cm)	178.6	71.9	145.81	54.4	241	104.3
pH	9.05	9.39	10.28	9.95	11.32	11.09
T (˚C)	24.1	23.7	24.3	23.7	22.9	22.6
Cr	0.004	0.008	0.004	0.005	0.002	0.013
Ni	0.008	0.052	0.014	0.049	0.014	0.067
Cu	0.004	0.014	0.015	0.023	0.001	0.004
Zn	0.032	0.11	0.024	0.128	0.024	0.143
As	0.001	0.008	0.005	0.016	<0.001	0.002
Se	0.006	0.0012	0.005	0.036	0.008	0.023
Mo	0.008	0.002	0.007	0.013	0.005	0.013
Sb	0.002	0.005	0.003	0.006	0.001	0.004
Ba	0.080	0.354	0.010	0.064	0.058	0.135
Hg	<0.005	0.001	<0.005	0.001	<0.005	0.001
Pb	0.002	0.001	<0.005	0.002	<0.005	0.002
F-	<2.000	<1.000	<2.000	<1.000	<2.000	<1.000
Cl-	18.3	50	50	50	45.2	59.7
SO4=	206.7	276.1	89.5	80.2	14.3	50.0
I. Fenol	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2

Table 3.3b: Leachate concentrations (mg/kg) from concrete recycled aggregates

	C1		C2		C3		C4		C5		C6		C7	
	L/S 2	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**
C (µS/cm)	2298	1225	1577	1335	987	527	1014	730	730	348	1195	632	1735	850
pH	12.1	11.94	11.7	11.56	12.13	11.88	11.78	11.78	11.73	11.56	12.38	12.05	12.55	12.23
T (˚C)	25.2	24.7	18.6	17.1	21.5	20.6	24.5	23.3	17.7	17.3	17.5	17.1	17.5	17.1
Cr	**0.270**	**0.600**	**0.250**	0.500	**0.230**	0.450	0.180	0.500	0.200	0.500	**0.960**	**1.360**	0.200	0.500
Ni	0.010	0.030	0.020	0.060	0.020	0.040	0.010	0.050	0.010	0.040	0.010	0.030	0.010	0.060
Cu	0.070	0.120	0.050	0.130	0.230	0.300	0.030	0.100	0.010	0.050	0.050	0.120	0.010	0.090
Zn	0.020	0.050	0.030	0.140	0.010	0.040	0.030	0.170	0.020	0.120	0.020	0.120	0.020	0.120
As	<0.001	<0.001	<0.001	0.010	<0.001	<0.001	<0.001	0.010	<0.001	<0.001	<0.001	0.010	<0.001	0.010
Se	0.045	0.074	0.054	0.070	0.052	0.085	0.047	0.075	0.045	0.085	0.040	0.080	0.055	0.087
Mo	0.050	0.160	0.080	0.100	0.180	0.270	0.160	0.170	0.010	0.080	0.130	0.200	0.020	0.160
Sb	<0.001	0.010	<0.001	<0.001	0.001	0.013	<0.001	0.010	<0.001	0.020	<0.001	0.010	<0.001	0.010
Ba	0.470	1.410	0.100	0.420	0.110	0.330	0.110	0.280	0.020	0.200	0.080	0.340	0.150	0.860
Pb	<0.005	<0.005	<0.005	0.010	<0.005	<0.005	<0.005	0.020	<0.005	0.010	<0.005	0.010	<0.005	0.010
F-	1.800	8.700	2.000	8.500	1.300	8.700	1.560	8.500	1.300	9.000	1.200	9.200	1.500	8.800
Cl-	123.7	170.5	209.3	321.3	114.5	166.0	64.8	50.0	13.1	80.6	100.5	95.6	11.2	70.0
$SO_4^{=}$	58.6	270.5	**2730.0**	**12076.0**	554.8	**1089.0**	334.0	620.0	140.0	890.0	406.0	800.0	31.1	235.6

Note: Cd was negligible and below the detection limit. Inert value limits exceeded are given in bold.

Table 3.3c: Leachate concentrations (mg/kg) from mixed recycled aggregates

	M1		**M2**		**M3**		**M4**		**M5**		**M6**		**M7**		**M8**		**M9**		**M10**	
	L/S 2	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**	**L/S 2**	**L/S 10**
C (µS/cm)	1708	906	980	549	1131	473	1635	1193	1504	644	1382	526	1072	532	1499	688	1711	917	1393	1285
pH	11.24	11.16	11.62	11.46	11.53	11.55	12.33	12.42	11.97	11.86	10.93	11.06	12.00	11.75	11.22	11.36	11.58	11.50	11.58	11.40
T (°C)	25.2	24.5	25.2	24.8	18.1	17.3	18.0	17.3	18.0	21.1	24.7	23.3	21.3	20.7	25.1	24.8	24.4	23.2	17.8	17.3
Cr	**0.220**	0.490	**0.380**	0.480	**0.860**	**1.100**	0.160	**0.520**	**0.260**	0.500	**0.530**	**0.740**	0.180	0.450	0.188	0.450	**0.380**	**0.560**	0.200	0.500
Ni	0.010	0.010	0.010	0.010	0.010	0.050	0.010	0.100	0.010	0.050	0.010	0.010	0.020	0.050	0.020	0.140	0.010	0.010	0.010	0.050
Cu	0.060	0.090	0.050	0.070	0.030	0.110	0.030	0.110	0.040	0.120	0.010	0.010	0.090	0.210	0.170	0.260	0.020	0.020	0.030	0.260
Zn	0.010	0.060	0.010	0.040	0.020	0.170	0.020	0.140	0.020	0.130	0.020	0.040	0.020	0.160	0.020	0.050	0.010	0.110	0.030	0.260
As	<0.001	0.010	<0.001	0.010	<0.001	0.010	<0.001	0.010	<0.001	0.020	<0.001	<0.001	0.010	0.020	0.010	0.010	<0.001	<0.001	<0.001	<0.001
Se	0.040	0.080	0.050	0.087	0.056	0.078	0.055	0.070	0.050	0.080	0.055	0.078	0.050	0.080	0.055	0.078	0.055	0.080	0.057	0.090
Mo	0.070	0.080	0.080	0.100	0.060	0.080	0.060	0.140	0.080	0.060	0.050	0.070	0.130	0.220	0.110	0.140	0.120	0.170	0.030	0.150
Sb	<0.001	0.010	<0.001	0.010	<0.001	0.010	<0.001	<0.001	<0.001	0.010	<0.001	0.020	<0.001	0.020	<0.001	0.010	<0.001	<0.001	<0.001	0.010
Ba	0.100	0.360	0.090	0.280	0.080	0.290	0.390	1.200	0.120	0.260	0.070	0.170	0.120	0.350	0.190	0.560	0.180	0.540	0.040	0.380
Hg	<0.005	<0.005	<0.005	0.010	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.007	0.002	0.008	0.002	0.009	<0.005	<0.005	<0.005	<0.005
Pb	<0.005	<0.005	<0.005	<0.005	<0.005	0.020	<0.005	0.020	<0.005	0.020	<0.005	<0.005	<0.005	0.020	<0.005	<0.005	<0.005	<0.005	<0.005	0.030
F^-	1.800	9.000	1.750	8.500	1.680	8.000	3.200	9.200	1.800	9.000	1.700	8.900	1.500	8.000	1.700	8.500	**4.800**	8.000	1.500	8.500
Cl^-	206.5	208.5	102.9	109.0	130.0	122.6	59.4	50.0	35.3	50.0	137.1	173.5	34.4	50.0	63.7	78.0	304.7	247.0	17.4	103.5
$SO_4^=$	**2790.0**	**6450.0**	**840.0**	**1454.9**	**1942.0**	**2270.0**	19.6	50.0	**2620.0**	**3440.0**	**2620.0**	**3450.0**	**1276.0**	**1200.0**	**3340.0**	**4000.0**	**2640.0**	**5750.0**	**2574.3**	**13650.0**

Note: Cd was negligible and below the detection limit. Inert value limits exceeded are given in bold.

According to the results, 14 of the 20 RAs are classified as non-hazardous materials (70% of the tested aggregates). These percentages are similar to those obtained by GEAR (2012), a national research project that analysed different CDW treatment plants (geographically representing all of Spain) and classified 75% of the tested RAs as non-hazardous materials. The three asphalt RAs are classified as inert. Cr and sulphate were the most critical compounds, both exceeding the limit for inert waste imposed by the Landfill Directive in the majority of the materials tested; in addition, the leaching measurements for Se were very close to the inert limit. The leaching values for Cr exceeded the limit for inert waste in 11 of the 20 materials (C1, C2, C3, C6, M1, M2, M3, M4, M5, M6 and M9), and the Cr leached at L/S of two varied between 0.002 and 0.96 mg/kg with a mean value of 0.283 mg/kg. These results agree with the data published by (Butera et al., 2014 and Galvín et al.2013). The sulphate leached exceeded the inert limit in 11 of the materials tested (C2, C3, M1, M2, M3, M5, M6, M7, M8, M9 and M10). Sulphate is released at L/S of two in amounts ranging between 14.3 and 3340 mg/kg with a mean value of 1261.3 mg/kg. These results contrast with the data reported by Butera et al. (2014) with a mean value of 150 mg/kg. This difference may be due to the heterogeneity of CDW and the different management systems in treatment plants of CDW. Therefore, the critical compounds were Cr and sulphate.

3.2. PERCOLATION DATA ACCORDING TO THE COLUMN TEST

Once the release of contaminants has been characterised by a compliance test, a column test is performed to evaluate the release of components under equilibrium or into leachate over time (Roussat et al., 2008) because these are the closest approaches to the processes occurring under field conditions (Van der Sloot, 1996; Dijkstra et al., 2006).

The data from this leaching procedure explain the evolution of long-term Cr and sulphate release. A column test was performed with 14 materials classified as non-hazardous under the compliance test: four concrete RAs and 10 mixed RAs. Figs. 3.1a and 3.1b show the cumulative release of Cr and sulphate leachates from an L/S of 0.1 to 10 L/kg and the regulated limits of the Landfill Directive for the first extraction of the column test at an L/S of 0.1 L/kg.

Regarding sulphate, the directive states that even if the waste does not meet the inert values for sulphate, it may be considered to meet the criteria for admission as an inert material if the leaching does not exceed any of the following values: 1500 mg/L at an L/S of 0.1 L/kg (represented as IL (L/S=0.1) in Figs. 3.1a and 3.1b with black dots) and 6000 mg/kg at an L/S 10 of L/kg (represented as IL (L/S=0.1) in Fig. 3.1a with black triangles). As a consequence, the column test confirms a potential hazard from Cr and sulphate in the tested RA.

According to Fig. 3.1b with cumulative curves of mixed recycled aggregates, only the M2 and M7 materials do not exceed the inert limit. However, all of these materials exceed the inert limit established for Cr, so all of the mixed materials are classified as non-hazardous. This result confirms that 70% (14/20) of the RAs analysed are classified as non-hazardous and that Cr and sulphate are the critical compounds.

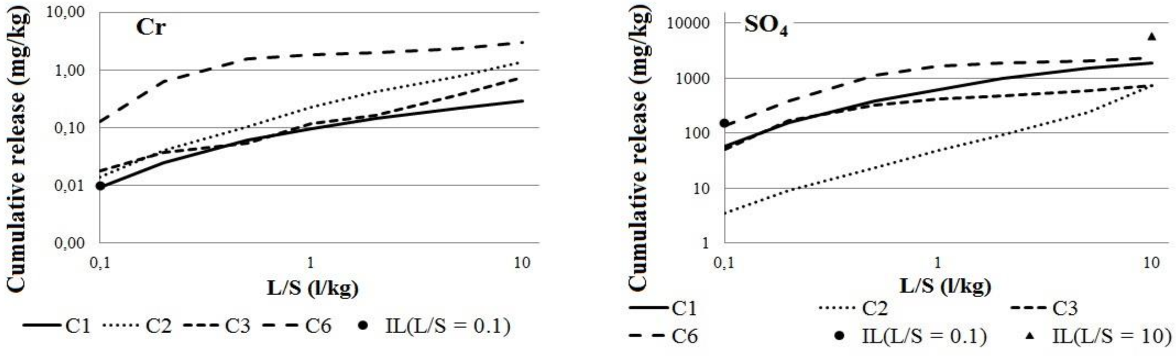

*Figure 3.1*a: Cumulative Cr and sulphate release from concrete RA according to column test.

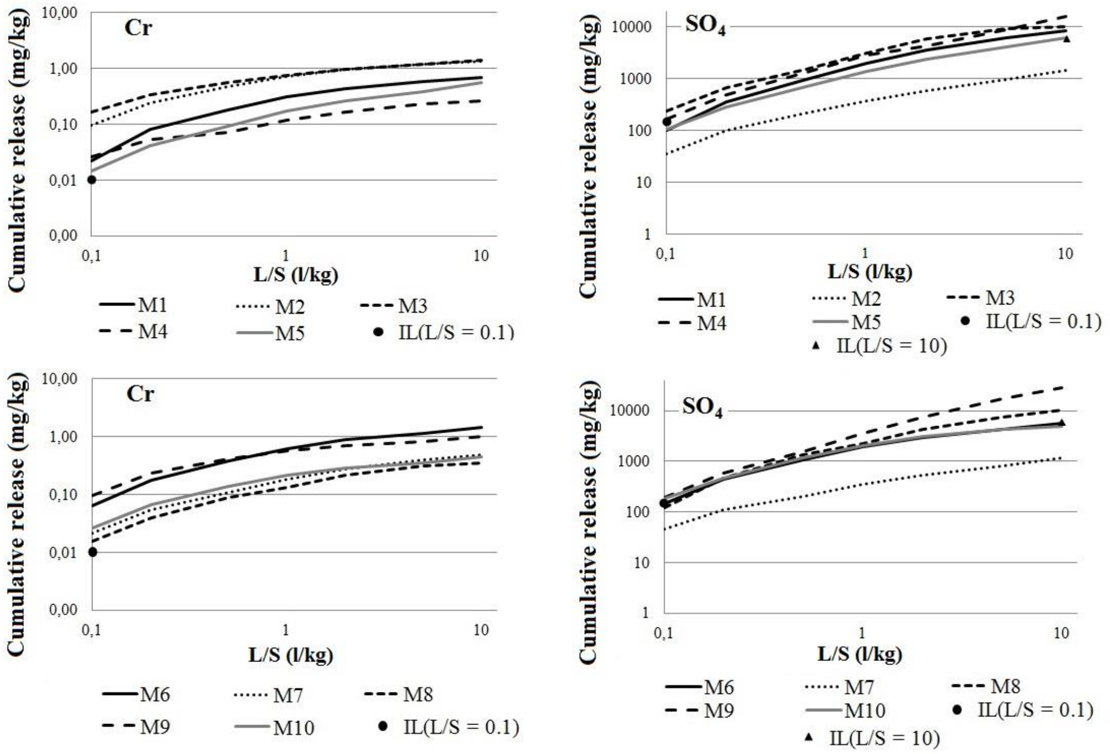

Figure 3.1b: Cumulative Cr and sulphate release from mixed RA according to column test.

3.3. ORIGINS OF CR AND SULPHATE IN RA

These results show that the most limiting compounds in leachates were Cr and sulphate. Thus, it is necessary to determine the possible origins of both contaminants. Sulphur is present in RA in the sulphate state, most of which appears as water-soluble sulphate, representing a potential contamination risk to ground and surface water. In RA, sulphate originates from gypsum and ceramic particles (Barbudo et al., 2012; Jang and Townsend, 2001). Additionally, the detection of high levels of sulphate due to the presence of other CDW compounds such as mortar particles has been confirmed by authors such as Sanchez and Alaejos (2009) and Ledesma et al. (2014). Therefore, these studies confirm that ceramic particles and adhered mortar are the main sources of sulphate.

Research focused on the leaching behaviour of RA from CDW (Clark and Hunter, 2013; Dutch Environment, Land Use and Planning Agency, VROM 2005) has detected high amounts of total Cr in RA composed primarily of crushed concrete. Additionally, a study developed by Dosho (2007) detected Cr (VI) in concrete aggregates. This author explained that its origin was the cement, which after contact with the aqueous phase releases this metal into the leachate. Cr metal is mainly present as Cr (III), which does not entail the same health and environmental risks as Cr (VI), a sensitizing agent that can cause dermatitis after handling (Gaspar-Tebar et al., 2005). Directive 2003/53/CE of the European Council banned the use and marketing of cements with Cr (VI) content higher than 2 ppm (mg/kg) (Valverde et al., 2005). Pozo et al. (2010) found the presence of Cr in the clays used by factories of ceramic materials located in Bailén in amounts varying from 69.1 to 91.1 mg/kg. This finding confirms that knowing whether the origin of Cr is a ceramic product or cement and distinguishing the oxidation state of Cr released from the leachate is essential. Ceramic materials and concrete were evaluated according to the compliance test, and the leachate concentrations of Cr and sulphate are shown in Table 3.4.

Table 3.4: Leachate concentrations (mg/kg) obtained by compliance test.

		C (µS/cm)	**pH**	**T (˚C)**	**Cr**	**$SO_4^=$**
PB	L/S=2	1301	9.35	22.1	**0.866**	**3040**
	L/S=10	914	9.65	21.7	**0.847**	**10400**
HB	L/S=2	1423	9.20	22.4	**4.266**	**3340**
	L/S=10	872	8.39	22.1	**4.614**	**7840**
T	L/S=2	506	10.09	22.2	**0.213**	**870**
	L/S=10	164.7	10.27	21.7	0.237	990
B	L/S=2	297	11.11	19.6	0.083	250
	L/S=10	146.6	10.97	18.8	0.094	315
S	L/S=2	158.1	9.89	20.0	<0.01	204
	L/S=10	55.3	9.77	18.5	<0.01	287
NM	L/S=2	538	12.84	21.7	0.039	16
	L/S=10	566	12.92	20.9	0.115	67
RC-1	L/S=2	885	11.76	22.1	0.054	120.4
	L/S=10	463	11.97	22.4	0.085	428
RC-2	L/S=2	505	11.54	20.8	0.109	548
	L/S=10	645	11.82	21.6	0.170	970

Note: Values exceeding inert limits are given in bold. Values exceeding non-hazardous limits are given in bold and underlined.

The pH of recycled concrete aggregate is dependent on the carbonation degree of the material, which will obviously vary with the service life exposure of the original concrete structure (Engelsen et al., 2009). As described above, RC-1 and RC-2 were concrete aggregates from the demolition of building foundations from the 60s and 90s, respectively. The manufacturing year could affect the carbonation degree, and in consequence, the material's pH. According to previous research (Engelsen et al., 2009), a typical range for the material pH will be between that of fresh concrete (>13) and the pH of fully carbonated material (<10). Different pH ranges are observed in the data shown in Table 3.4 for RC-1, RC-2 (partially carbonated concretes) and NM (fresh material). However, despite the obviously different carbonation degrees between the carbonated and fresh concretes, small differences were observed in the pH values registered during the leaching test. At an L/S of 10 L/kg, the RC-1 and RC-2 materials presented a pH of approximately 11.9, which may be due to the two concretes having not completed the process of carbonation, whereas the fresh NM presented a pH of approximately 12.9.

High levels of Cr and sulphate were measured in three of the five ceramic materials: PB, T (both materials classified as non-hazardous) and HB (classified as a hazardous material). The main characteristic of these materials is that they are composed of 80-95% clay. The remaining two ceramic materials, namely B and S, are classified as inert and are composed of 60-80% clay. Thus, the results reveal a different behaviour pattern of ceramic materials as a function of clay content. Higher clay content in the material caused higher levels of Cr and sulphate release.

However, low concentrations of Cr were measured in the leachates from concretes of different ages, and all were classified as inert materials. Cr did not appear in the leachate of concrete because it can be immobilized when replacing Al or the SO_4^{2-} in ettringite and calcium monosulfoaluminate hydrate (Laforest and Duchesne, 2005; Giergiczny and Krol, 2008). Thus, the initial assumption that the Cr originated from the cement and influence of concrete age on Cr concentration was not confirmed.

3.4. OXIDATION STATE OF CHROMIUM

The oxidation state of the chromium provides information about different chemical, biological and environmental properties. The most stable oxidation states in RAs are Cr (III) and Cr (VI). The Occupational Safety and Health Administration of the United States analysed in depth the source of hexavalent chromium in previous studies (OSHA, 2009). Cr (VI), rarely found in nature and generally man-made, can be present in different compounds in CDW as pigments for paints and coatings, ceramics, glass, roofing and plastics. Due to the potential contamination of construction materials, there has been a decline in the use of chromates in these construction materials since 2000. As is well known, from a human health point of view, only Cr (VI) is harmful (Gaspar-Tebar, 2005). However, this chemical species is not regulated by the Landfill Directive (only the total Cr present in the leachate). Therefore, due to the high levels of total Cr observed in PB, HB and T, discrimination of the oxidation state of Cr in leachates is essential for estimating what danger these materials may pose to human health.

First, total Cr and it is oxidation state was determined in the unused ceramic materials (PB, HB and T). For this, a hot-extraction with nitric acid 20% in water was performed. This extraction was carried out in an acidified pH due to the relative insolubility of Cr (III) at pH above 5 (Abbas et al., 2001, Quina et al., 2009).

Table 3.5 shows the content of total Cr, Cr (III) and Cr (VI). Cr is mostly present on these materials as Cr (III), which does not imply a health risk to the environment, because Cr (VI) in acid pH can be reduced to Cr (III). Thus, the obtained results confirm that it is essential to distinguish the oxidation state of Cr released from the leachate. In addition, both unused ceramic materials and 13 RA leachates were analysed to determine the Cr oxidation states. Analyses were only performed on the 13 RAs that exceeded the inert limit value for total Cr at an L/S of 0.1 L/kg (see Figs. 1a and 1b). Total Cr, Cr (III) and Cr (VI) are shown in Table 3.6.

Table 3.5: Chromium concentration in unused ceramic materials

Materials	**Chromium content (mg/kg)**		
	Cr total	**Cr (VI)**	**Cr (III)**
PB	26.05	0.92	25.13
HB	51.12	0.94	50.18
T	53.15	0.88	52.27

Table 3.6: Chromium concentration in leachates from unused ceramic materials and RA.

Materials	**L/S**	**pH**	**Chromium content (mg/kg)**		
			Cr total	**Cr (VI)**	**Cr (III)**
PB	2	9.35	0.866	0.806	0.060
HB	2	9.20	4.266	4.226	0.040
T	2	10.09	0.213	0.153	0.050
C2	0.1	7.91	0.009	0.008	0.001
C3	0.1	11.83	0.023	0.016	0.007
C6	0.1	9.35	0.126	0.126	-
M1	0.1	8.43	0.028	0.019	0.009
M2	0.1	9.22	0.017	0.017	-
M3	0.1	9.88	0.096	0.087	0.009
M4	0.1	7.22	0.035	0.021	0.014
M5	0.1	7.87	0.014	0.014	-
M6	0.1	7.75	0.046	0.046	-
M7	0.1	7.62	0.013	0.01	0.003
M8	0.1	7.77	0.019	0.019	-
M9	0.1	7.91	0.059	0.058	0.001
M10	0.1	7.11	0.029	0.014	0.015

The results released in the leachate were present as Cr (VI), which is highly soluble and stable at high pH levels. Cr (VI) is more soluble at a pH range of 7-11. In contrast, when the pH range is 5-7, it is less soluble (Tiruta-Barna, 2013). This finding differs from results shown in Table 3.5, in which most of the total Cr content was Cr (III). The differences observed could be caused by the lower mobility and solubility of Cr (III) and the high leachability of Cr (VI) in neutral or alkaline solutions, which markedly increases its toxicity under all environmental conditions (Panda et al, 2013). However, Cr (III) appeared on the leaching of two RAs (M4 and M10) where the pH was neutral or slightly alkaline because in some cases the sulphides and organic matter present in the material reduce the oxidation state of Cr (James et al., 1995). Considering the environments where RAs are found, the Cr is mainly leached as Cr (VI).

4. CONCLUSIONS

According to the results of the compliance tests, 14 of the 20 materials are classified as non-hazardous waste. However, three concrete RAs and all asphaltic RAs are considered to be inert waste. Therefore, the highest potential environmental risks were posed by high contents of concrete particles, mortar and ceramic. The initial study identified Cr and sulphate as the more limiting compounds.

The experimental procedures were performed to identify the sources of these two compounds and were focused on analysing the leaching behaviour of the conventional components of RA (such as ceramic construction materials and concrete). Thus, high levels of Cr and sulphate were detected in three of the five ceramic materials (perforated and hollow brick and tile), and these presented the highest clay contents (more than 90% by composition weight). Although the Landfill Directive does not consider the Cr oxidation state in the leachate, the present study determined the relative concentrations of Cr (III), Cr (VI) and total Cr. The results showed that essentially all of the total Cr released by the ceramic materials was present as Cr (III), which is less harmful to environmental health.

Regarding the contribution of concrete particles to Cr release, contrary to demonstrations of previous experiments, none of the three studied concretes released significant amounts of Cr or sulphate. These results are understandable in the case of sulphate, which mainly originates from gypsum, ceramic particles and mortar adhered to RA. High levels of Cr were expected to be detected in the concrete RAs tested as they were made from the crushing of cement concrete according to Directive 2003/53/EC, i.e., it was manufactured prior to the enforcement of legislation that banned the use of cements with a high content of water-soluble Cr (VI). According to the results, this low Cr level could be due to the low cement content of the recycled concrete tested (see RC-1 and RC-2 in Table 3.4). Cr release did not occur because Cr is fixed by ettringite at a pH above 11.

The column test characterised the long-term behaviour of the two limiting compounds, and the main mechanisms that govern the release of Cr (wash-out from the second stage) and sulphate (solubility control at first and depletion at the final stages) were identified.

Comparing the release levels obtained in the column tests to the legal limits at an L/S of 0.1 L/kg, a high reduction of sulphate levels in all concrete RAs and in two mixed RAs (lower than the inert limit value) was observed. However, only one material (C1) released Cr in concentrations lower than the inert limit value.

Finally, the present work included the determination of the main oxidation states of Cr in all leachates obtained in the column test. The data showed that most of the total Cr was released as Cr (VI), which is more harmful and leachable than Cr (III) due to the influence of pH on the oxidation state and the leachability of Cr. When the pH is less than 5, most Cr is leached as Cr (III). In contrast, when the pH value is neutral or slightly alkaline, Cr is leached as Cr (VI). Finally, the chromium leachability decreases when the pH is above 12.

Therefore, the study identified the key RA compounds that pose environmental risks after the application of these aggregates as construction materials. To prevent and reduce risks, selective demolition to remove a significant portion of ceramic materials (bricks and tiles), gypsum and plaster from CDW is recommended because they were shown to have a direct relationship with high levels of Cr and sulphate.

Moreover, the applicable regulations related to environmental matters need to assess the levels of Cr (VI) in the leachate produced.

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CAPÍTULO 4. FEASIBILITY STUDY OF CEMENT-TREATED 0-8 mm RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE AS ROAD BASE LAYER

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ABSTRACT

Recently, both nationally and internationally, cement-treated granular materials (CTGM) have been widely used as road base layer. However, all the researches on CTGM with recycled aggregates are limited to the coarse fraction, with a size range of 0-40 mm. In Spain, one of the recycled materials most commonly produced in construction and demolition waste (CDW) treatment plants is a mixture with around 75% of fine aggregates (hereby called FRA), with 5-8 mm nominal maximum size. This material is commonly used in pipe bedding, an application that provides little or no added-value.

The intent of this paper is to study the feasibility of using CTGM made with FRA as road base layer. For this purpose, six mixtures have been produced, comprising 0-8 mm FRA and 0-40 mm coarse aggregates, made of mixed recycled aggregates (MRA) and recycled concrete aggregate (RCA). The main mechanical (unconfined compressive strength and modulus of elasticity) and durability (dimensional changes) properties were studied and the effects of size and aggregates' source were analysed.

To the best of the authors' knowledge, this is the first study on the use of the fine fraction of CDW in the production of CTGM to be used as road base layer. It suggests that it is feasible to produce CTGM with 0-8 mm RA (SC20) from CDW for that purpose. In addition, CTGM with FRA have better mechanical properties and dimensional changes than CTGM with CRA (SC40).

KEYWORDS:

Cement-treated granular materials; Construction and demolition waste; 0-8 mm recycled aggregates; Mechanical properties; Dimensional stability.

1. INTRODUCTION

Cement-treated granular materials (CTGM) are a homogenous mixture, in suitable proportions, of granular materials, cements and water, which, when properly compacted, is used as a structural layer in road pavements (Xuan et al., 2011). They are widely used as a semi-rigid base course in pavements (Terrel et al., 1979). Cement-bonded granular materials have high fatigue strength and bearing capacity (Jofre and Kraemer, 2008).

In order to allow a higher load distribution capacity in pavements, in comparison to unbound materials, the treatment of the granular materials of road bases/sub-bases with cement is a good option (Xuan et al., 2015). The Spanish Code for basic materials on firm pavements (Ministry of Development, 2015) allows the use of recycled aggregates (RA) from Construction and Demolition Waste (CDW) as granular materials bound with cement in structural road layers. Three types of materials are identified: soil-cement, gravel-cement and rolled compacted concrete. Soil-cement is used in light traffic base courses and is classed in two groups, SC20 and SC40. The main differences between them are the size distribution, the nominal size of the aggregates and the maximum size of the aggregates: 20 and 40 mm respectively. Many researchers (Herrador et al., 2012, Poon and Chan, 2006, Jiménez et al., 2011, Vegas et al., 2011) have found that RA from crushed concrete (RCA) or mixed recycled aggregates (MRA) obtained from mixed rubble (containing mostly ceramic and cementitious materials), can be used in structural layers of pavements as unbound granular materials. However, cement treated CDW is hardly applied in situ and little field performance data are available (Xuan et al., 2011, Agrela et al., 2014).

Xuan et al. (2012) studied the mechanical properties of RCA and MRA in the production of CTGM in laboratory and concluded that the compressive strength depends on several variables, such as cement and water content, curing time, degree of compaction and the properties of the recycled aggregates.

Dimensional changes were studied in two research works (Agrela et al., 2014, Xuan, 2012) and in both of them the authors concluded that the curing procedure has a high influence on the dimensional behaviour of CTGM made with RCA and MRA. Xuan (2012) studied the dimensional changes in three curing conditions, a wet chamber, a dry chamber with relative humidity of 50%, and a wet chamber in which the specimens were sealed with aluminium foil. In the dry chamber the specimens showed shrinkage, but when they were in a high humidity environment, as in the wet chamber, the specimens showed expansion.

Agrela et al. (2014) studied CTGM with RCA and MRA cured in a tank, and they observed that high expansion occurred in the mixes with RCA, and even higher in those made with MRA. It was also observed that the dimensional behaviour is greatly influenced by the acid-soluble sulphates content and that it is necessary to use sulphate-resistant Portland cement in CTGM made with MRA or RCA with high sulphate con-tent.

The total sulphur content affects the hardening process in CTGM, and this could be an important limitation in recycled materials treated with cement (Sakai et al., 2004, Pavoine et al., 2006, Tovar-Rodríguez et al., 2013). (Ministry of Development, 2015) for road construction limits the maximum sulphur content expressed in S to 1%, and the acid-soluble sulphate content expressed in SO3 to 0.8%.

In several researches fine recycled aggregates (FRA) have been applied in concrete production, replacing natural sand (Evangelista and de Brito, 2007, Evangelista and de Brito, 2014, Alves et al., 2014). Evangelista and de Brito (2014) determined that it is possible to use higher contents of FRA in non-structural concrete with low cement content.

Generally, CTGM is produced by using either coarse natural or crushed aggregates (Xuan et al., 2011). However, in Spain, one of the recycled materials mostly commonly produced in CDW treatment plants has a nominal maximum size from 5 mm to 8 mm (hereby called FRA). It may result from crushed concrete (FRCA) or mixed CDW (FMRA) and is commonly used in pipe bedding, an application that provides little or no added-value.

Recently, a practical application of recycled aggregates treated with cement has been carried out. Agrela et al. (2012) used two types of MRA with a continuous grading (0-40 mm) treated with 3% cement for the construction of a sub-base in an access ramp to a motorway in Malaga (south of Spain). They concluded that MRA treated with cement has good mechanical properties and can be used as soil-cement SC40 in sub-base layers of a road. However, a CTGM in a pavement structure is sometimes considered the source of shrinkage cracking and such cracks tend to propagate through the overlaying asphalt layer. Therefore, Xuan et al.

(2015) and George (1968) presented a simplified method to estimate the spacing and width of shrinkage cracks in a CTGM base layer. Xuan et al. (2015) concluded that, by increasing the masonry content, the crack spacing increases and the width of the primary cracks strongly decreases.

In the literature review no researches on FRA treated with cement have been found. Therefore, the intent of this paper is to study the feasibility of using cement treated FRA as soil-cement SC20 in sub-base layers of light traffic roads and compare its mechanical and dimensional stability properties with those of cement treated coarse recycled aggregates (CRA) as soil-cement SC40.

Two groups of materials have been used. The first one comprised three FRA with a size range of 0-8 mm: two FMRA and one FRCA. The second group included three CRA with a size range of 0-40 mm: two mixed recycled aggregates (CMRA) and one recycled concrete aggregate (CRCA). The effects of size and aggregates' source on the mechanical properties and dimensional changes of CTGM made with RA were analysed.

2. MATERIALS

2.1. CEMENT

The cement used is a CEM II BL 32.5 N (UNE-EN 197-1: 2011) with 20% fly ash, whose properties are included in Table 4.1.

Table 4.1: Chemical composition and physical properties of cement

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)
26.56	3.89	6.58	58.32	1.12	3.32	1.25	2.96	3978

2.2. RECYCLED AGGREGATES

Six RA from CDW were used. They came from several recycling plants in the Andalusia region, in the South of Spain. Three of them (CMRA1, CMRA2 and CRCA3) were CRA with a 0-40 mm size range, and the other three (FMRA1, FMRA2 and FRCA3) were FRA. Each group consisted of two mixed and one concrete RA. Table 4.2 shows the composition of the CRA according to UNE-EN 933-11:2009, i.e. by visual inspection and manual separation. The FRA's composition could not be deter-mined in the same way, but they come from CDW with high ceramic contents (FMRA) or crushed concrete (FRCA). Tables 4.3 and 4.4 show the main physical and chemical properties of the RA.

Table 4.2: Composition of the coarse recycled aggregate

	CMRA1	**CMRA2**	**CRCA3**
% Ra (Asphalt)	1.2%	2.98%	0.90%
% Rb (Ceramic)	18.04%	25.72%	0.26%
% Rc (Concrete and mortar)	31.20%	35.36%	57.42%
% Ru (Natural aggregate)	49.37%	35.35%	41.39%
% Rg (Glass)	0.10%	0.03%	0.00%
% FL (Floating particles)	0.04%	0.06%	0.02%
% X1 (Gypsum)	0.03%	0.45%	0.00%
% X2 (Wood, plastic and metals)	0.02%	0.04%	0.01%

Table 4.3: Physical properties of the recycled aggregates

			CMRA1	**CMRA2**	**CRCA3**	**FMRA1**	**FMRA2**	**FRCA3**
Water absorption (%)	UNE-EN 1097-6: 2014	> 4 mm	7.84	7.83	4.91	*	*	*
		< 4 mm	3.13	6.50	7.47	2.93	4.93	6.22
Density-SSD (g/cm^3)	UNE-EN 1097-6: 2014	> 4 mm	2.382	2.408	2.180	*	*	*
		< 4 mm	2.674	2.524	2.524	2.670	2.523	2.460
Sand equivalent (%)	UNE-EN 933-8:2012		31	62	62	54.0	49	52
Liquid limit	UNE 103103:1994		No	No	No	No	No	No
Plastic limit	UNE 103104:1993		No	No	No	No	No	No
L.A. Coefficient (%)	UNE-EN 1097-2:2010		39	43	38	*	*	*
Friability (%)	UNE 83115:1989 EX		*	*	*	25.6	23.0	31.6
Flakiness index (%)	UNE-EN 933-3:2012		10.0	20.2	15.1	*	*	*

* Non-determined parameter due to the size of the material

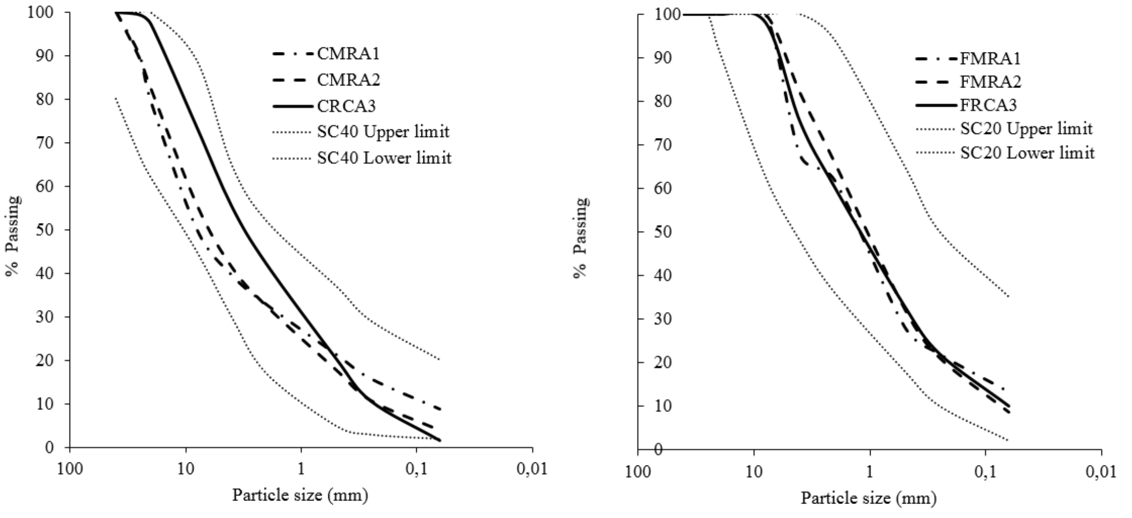
It is highlighted that one type of mixed materials did not comply with all the limits imposed by the Spanish Code (Ministry of Development, 2015): FMRA2 slightly exceeded the limit in acid soluble sulphate (0.8% expressed in SO3).

Table 4.4: Chemical properties of the recycled aggregates

	Organic matter **UNE-EN 1744-1:2013**	**Total sulphur (%S)** **UNE-EN 1744-1:2013**	**Acid soluble sulphate (%SO_3)** **UNE-EN 1744-1:2013**	**Alkali-silica reactivity** **UNE 146507:1999**
CMRA1	0.45	0.42	0.71	No
CMRA2	0.40	0.46	0.77	No
CRCA3	0.37	0.29	0.46	No
FMRA1	0.77	0.31	0.51	No
FMRA2	0.56	0.60	**0.82**	No
FRCA3	0.77	0.32	0.65	No

Note: Limits exceeded are given in bold. The limit for total sulphur is 1%, the one for acid soluble sulphate is 0.8% and the one for organic matter is 1%.

As for the size grading of the materials, the three CRA were classified as SC40 (Figure 4.1a) and the three FRA as SC20 (Figure 4.1b) according to the Spanish code (Ministry of Development, 2015).



(a) (b)

Figure 4.1: Particle size distribution of the recycled aggregates and size limits prescribed by the Spanish Code (Ministry of Development, 2015)

2.3. COMPOSITION AND MIXING OF THE SPECIMENS

The cement content was 3% of the dry weight of the aggregates. The water content corresponding to the optimum moisture of the modified Proctor test was performed according to Standard UNE 103501:1994. The results of maximum dry density and optimum moisture content obtained are shown in Table 4.5. The specimens were compacted with a vibrating hammer. The compaction time is determined by standard NLT 310-90. The vibrating hammer time is determined by subjecting three specimens to different compaction times. All specimens were compacted in three tiers with the optimal moisture content. The density dry-time is represented in a graph. The vibrating hammer time is the time that leads to 100% of maximum dry density (Table 4.5). The mixing procedures that were followed are shown in Figure 4.2. The specimens were covered and left to stand for 25 minutes to distribute the moisture uniformly.

Table 4.5: Modified Proctor values and vibrating hammer time

	CMRA1	**CMRA2**	**CRCA3**	**FMRA1**	**FMRA2**	**FRCA3**
Dry density (g/cm^3)	2.07	1.87	2.00	2.14	1.94	1.99
Optimal moisture content (%)	10.2	12.5	11.3	9.0	11.9	11.0
Vibrating hammer time (s)	12	11	7	21	63	52

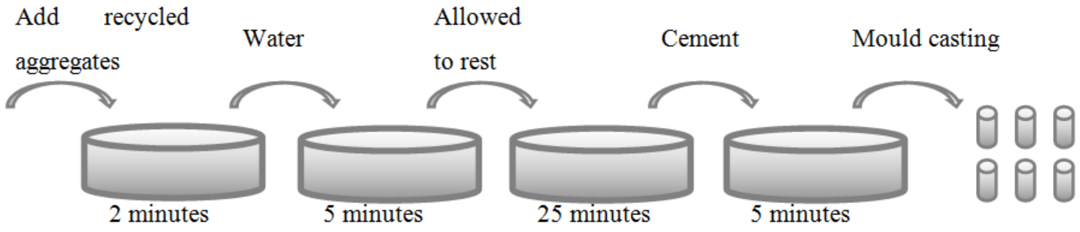


Figure 4.2. Mixing procedure

The optimum moisture content of the coarse materials is similar or slightly greater than that of the fine materials. Since the finer material has larger specific surface area, higher optimum moisture content was expected. This did not happen since the absorption of the coarse aggregate is similar or slightly greater than that of the fine aggregates. Most of the absorption of the coarse aggregate is due to the greater porosity of ceramic materials and adhered mortar.

3. EXPERIMENTAL METHODS

3.1. UNCONFINED COMPRESSIVE STRENGTH (UCS) (UNE-EN 13286-41:2003)

The UCS was determined in specimens in a California Bearing Ratio mould (177.8*152.5 mm). Six specimens were prepared per mixture and cured in a wet chamber at 18-22 °C and relative humidity above 95%. Three of them were tested at 7 days and the three remaining ones at 28 days. Immediately after testing, a representative sample of each specimen was taken and used to determine the moisture content according to Standard UNE 103300:1993. This process is done to ensure that the moisture content of the specimens is similar to the optimal moisture content. The results are the average of three specimens.

3.2. MODULUS OF ELASTICITY (UNE-EN 13286-43:2003)

Three specimens were manufactured in a cylindrical mould 300 mm high and with a 150 mm diameter. At 28 days of curing, the secant modulus of elasticity was measured at 30% of the unconfined compression strength. The deformations were measured during the test with two LVDT sensors. The curing process is the same as for the UCS test. The results are the average of three specimens.

3.3. DIMENSIONAL CHANGES

To study the dimensional changes (shrinkage and expansion), six specimens were manufactured in cylindrical moulds 300 mm high and with a 150 mm diameter. They were cured for 7 days in a wet chamber at 18-22 °C and relative humidity above 95%. The curing process is similar to that for the UCS and modulus of elasticity tests. Once cured, six generatrices were drawn at 60°. The evolution of height over time was measured in each generatrix with a digital sliding gauge with an accuracy of ±0.005 mm. The height of each specimen was determined at 7, 14, 21, 28, 56, 90, 126, 180 and 360 days as the average of the six generatrices measurements (Agrela et al., 2014).

To have results under different environmental conditions, after 7 days of curing, three specimens were left in a dry chamber at 22-25 °C and 46-54% relative humidity. The other three specimens were immersed in a tank with water at 20 °C. In both cases, the conditions remained constant until 360 days. The results are the average of three specimens.

3.4. STATISTICAL ANALYSIS

Two factors were analysed statistically: RA size (with two options SC40 and SC20, i.e. coarser and finer) and RA source (mixed and concrete). To determine the effect of each factor on each of the properties, an analysis of variance (ANOVA) was used. If the p-value of an F-Test is less than 0.05, that factor is statistically significant to the property studied, with a 95% confidence level.

4. RESULTS AND DISCUSSION

4.1. UNCONFINED COMPRESSIVE STRENGTH (UCS)

The UCS values, obtained after 7 and 28 days of curing, are shown in Table 4.6. The results are the average of three specimen values.

Table 4.6: Mechanical properties and dimensional changes

		SC40			**SC20**		
		CMRA1	**CMRA2**	**CRCA3**	**FMRA1**	**FMRA2**	**FRCA3**
UCS (MPa)	7 days	2.53 (0.09)	3.51 (0.22)	2.85 (0.13)	2.63 (0.19)	3.38 (0.16)	3.26 (0.06)
	28 days	3.09 (0.03)	4.17 (0.14)	3.36 (0.18)	3.34 (0.02)	4.43 (0.06)	4.16 (0.21)
	% increase	22.1%	18.8%	17.9%	27.0%	31.1%	27.6%
Modulus of elasticity (MPa)		6081 (399)	5361 (255)	5266 (304)	6471 (402)	6171 (356)	6392 (305)
Dimensional changes at 360 days (µm/m)	Dry chamber	1733 (119)	1101 (85)	1275 (76)	1278 (81)	1003 (56)	1232 (115)
	Curing tank	-701 (67)	-1201 (33)	-796 (76)	-658 (29)	-893 (42)	-660 (56)

(*) Standard deviations

The six mixtures tested comply with the Spanish Code (Ministry of Development, 2015), which requires a UCS value at 7 days between 2.5 MPa and 4.5 MPa. Hence, RA could be used as CTGM in roads and curbs. The average UCS values of the SC20 mixtures are 3.09 MPa at 7 days and 3.98 MPa at 28 days. These results are 4.27% and 12.34% higher than those of the SC40 mixtures at 7 and 28 days respectively. Similar results were obtained by Behiry (2013), who studied RCA with various FRA contents (5%, 9%, 12% and 16%). With 4% of cement, the UCS at 3 days was: 1.5 MPa, 1.5 MPa, 1.8 MPa and 2.3 MPa for 5%, 9%, 12% and 16% FRA, respectively. Increasing by 11% the FRA content, the increase in UCS at 3 days was 53%, i.e. the CTGM strength increases for higher contents of FRA. This is due to the fact that the FRA has a greater surface area than the RCA, causing a reduction in the aggregate-cement paste bond stress (Bamforth et al., 2008), which decreased the likelihood of the breakage occurring through this interface. Since the breakage plan had to go through the aggregates the UCS increased. Furthermore, the effect of compaction on the coarse material also reduces the strength of the specimens with higher content of coarse aggregate. Breakage of the coarse particles of the mixtures is produced during compaction.

The average UCS values of the SC40 mixtures with CMRA were 3.02 MPa and 3.63 MPa at 7 and 28 days respectively. They are higher than those with CRCA: 2.85 MPa and 3.36 MPa at 7 and 28 days respectively. The highest UCS values, 3.51 and 4.17 MPa at 7 and 28 days respectively, occurred for CMRA2, which is the aggregate with the highest content of ceramic particles. These results agree with the findings of Agrela et al. (2012), where the mixtures with more ceramic particles had better mechanical behaviour. As a matter of fact, ceramic particles have rougher and more porous surface thus allowing the improvement of the bond with the cement paste. In contrast, Xuan (2012) reported a loss of strength with increasing masonry aggregates content, which could be due to the weaker nature of ceramic particles when compared to relatively high-strength concrete particles.

The average UCS values of the SC20 mixtures with FMRA were 3.01 MPa at 7 days and 3.89 MPa at 28 days. They are lower than those obtained with FRCA, 3.26 and 4.16 MPa at 7 and 28 days respectively. In these mixtures, FMRA showed lower UCS than FRCA by 7.67% at 7 days and 6.49% at 28 days.

As for the evolution of UCS over time, for the SC20 mixtures the 7-day strength was 77% and 78% of the 28-day strength for FMRA and FRCA respectively, whereas for the SC40 mixtures it was 83% and 85% for CMRA and CRCA respectively (Figure 4.3).

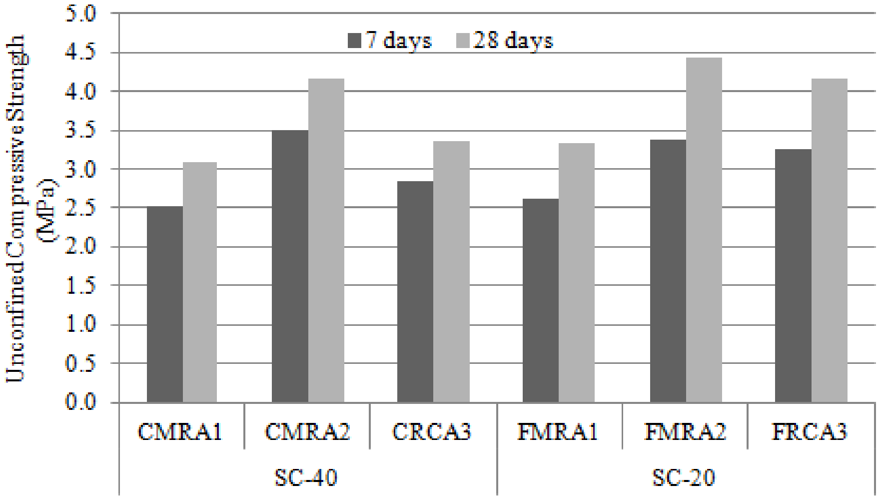


Figure 4.3: Effect of the recycled aggregate size on the 7- and 28-day UCS.

An ANOVA was performed to determinate whether the recycled aggregates size and recycled aggregates source had a statistically significant effect on the UCS at 7 and 28 days. None of the factors was statistically significant, i.e., the p-values were higher than 0.05 (0.79 for particle size distribution and 0.93 for type of recycled aggregate at 7 days; 0.44 for particle size distribution and 0.92 for type of recycled aggregate at 28 days).

Therefore, RA (both mixed and concrete) can be used in the manufacture of CTGM as base or sub-base roads, as long as RA complies with the UCS limits imposed by the Spanish Code (Ministry of Development, 2015), including the RA (FMRA2) that slightly exceeds the limits of acid soluble sulphates.

4.2. MODULUS OF ELASTICITY

The modulus of elasticity after 28 days of curing was determined as the secant modulus at 30% compressive strength of the specimen. The deformation and strength data are in Table 4.7. The modulus of elasticity is shown in Figure 4.4. The results are the average of three specimen values.

Table 4.7: Modulus of elasticity data

	CMRA1	**CMRA2**	**CRCA3**	**FMRA1**	**FMRA2**	**FRCA3**
Strength (MPa)	2,68	3,37	3,07	2,93	3,93	3,87
Strength$_{30\%}$ (MPa)	0,80	1,01	0,80	0,80	1,18	0,80
L (mm)	295,32	285,43	294,96	294,96	283,82	289,54
ΔL (mm)	0,540	0,575	0,631	0,603	0,722	0,631
$\Delta L_{30\%}$ (µm)	39,045	53,832	45,034	36,647	54,223	36,42
$\varepsilon_{30\%}$ (‰)	0,132	0,188	0,153	0,124	0,191	0,126
Modulus of elasticity (MPA)	6081,09	5360,52	5265,91	6471,11	6171,17	6391,64

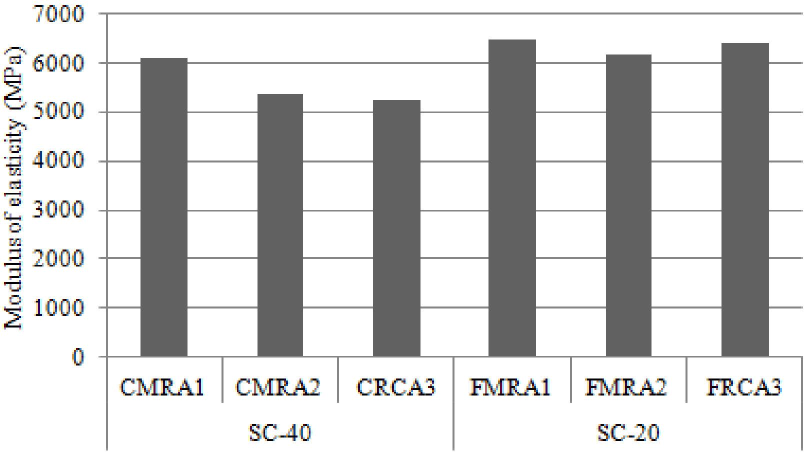


Figure 4.4: Effect of the recycled aggregate size on the modulus of elasticity

The modulus of elasticity values ranged from 5266 MPa to 6471 MPa. Considering the size distribution of RA, the average value of the SC20 mixtures (6345 MPa) was 13.9% higher than that of the SC40 mixtures (5569 MPa). These results are consistent with those obtained for UCS where the average value of the SC20 mixtures at 28 days was 12.34% greater than that of the SC40 mixtures. Breakage of the coarse particles occurs during compaction, producing a weakening of the specimens and reducing their modulus of elasticity.

In terms of the RA source, the average value of the modulus of elasticity of the SC40 mixtures was 5721 MPa for CMRA and 5266 MPa for CRCA (8.64% lower). As for the SC20 mixtures, the average value for FMRA (6321 MPa) was 1.11% lower than that for FRCA (6392 MPa). CTGM's mechanical properties depend mainly on the mechanical, physical and chemical properties of aggregates, the most important of which are dry density, optimal moisture content, degree of compaction and sulphate content (Agrela et al., 2014, Xuan et al., 2012). The most influential property in the modulus of elasticity is the degree of compaction (Xuan et al., 2012). Since the degree of compaction is similar in all samples, in neither case (SC20 or SC40) significant differences were found in terms of the RA source.

In the literature, only one other work (Lim and Zollinger, 2003) determined the modulus of elasticity of CTGM with RCA, and there are no studies of CTGM with MRA or with FRA. In this research, the modulus of elasticity values ranged from 5840 MPa to 6867 MPa for RCA. The higher values were mostly due to the use of higher cement content (4% dry matter), although there is also influence of the graduation and composition of the RA. It is stressed that different proportions of fine aggregates passing through the 4 mm sieve (52% and 42%) were studied and the lower values of the modulus of elasticity correspond to lower fines fraction than in our study.

According to the ANOVA test, and in terms of the RA size, the p-value was lower than 0.05 (0.04), i.e. this factor had a statistically significant effect on the modulus of elasticity (higher for FRA). Moreover, the p-value concerning the RA source was higher than 0.05 (0.72), i.e. this factor did not have a statistically significant effect on the modulus of elasticity.

4.3. DIMENSIONAL CHANGES

Shrinkage is caused by the loss of water by evaporation, hydration and carbonation of cement. In the environmental conditions of a dry chamber, shrinkage increases over time (Tam and Tam, 2007).

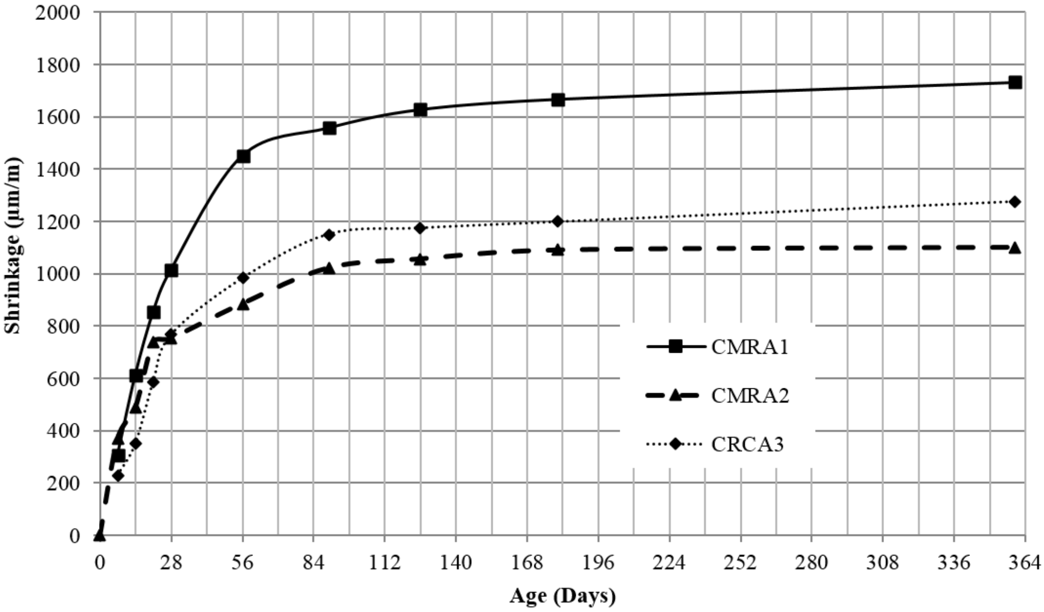


Figure 4.5: Evolution of the shrinkage of the SC40 mixtures in a dry chamber

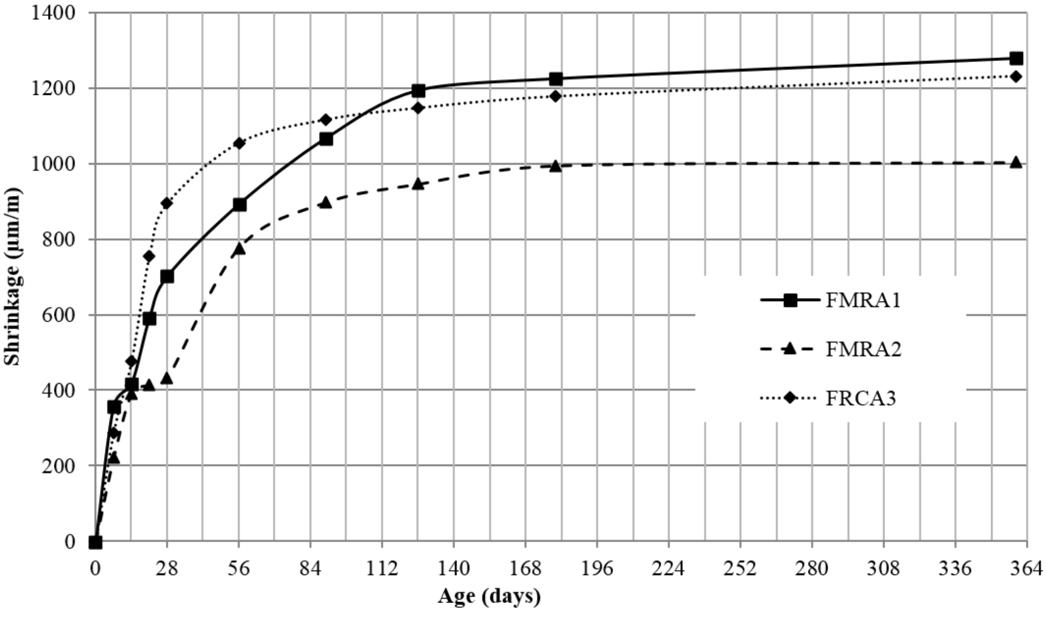


Figure 4.6: Evolution of the shrinkage of the SC20 mixtures in a dry chamber

Figures 4.5 and 4.6 show the evolution of shrinkage, for the mixtures SC40 and SC20 respectively, in a dry chamber over a 360-day period. After 126 days shrinkage tends to stabilize.

The maximum shrinkage of the SC40 mixtures ranged from 1101 μm/m to 1733 μm/m, with an average of 1370 μm/m whereas for the SC20 mixtures it ranged from 1003 μm/m to 1278 μm/m, and the average was 1171 μm/m. The maximum shrinkage value of the SC40 mixtures was 16.99% higher than that of the SC20 mixtures. Additionally, the shrinkage of the SC20 mixtures was more stable and homogenous.

In terms of the RA source, the average maximum shrinkage of the SC40 mixtures was 1417 μm/m for CMRA, i.e. 11.14% higher than that for CRCA (1275 μm/m). As for the SC20 mixtures, the average maximum shrinkage was 1141 μm/m and 1232 μm/m, for FMRA and FRCA respectively. FMRA's maximum shrinkage was 7.98% lower than that of FRCA. Cement content, degree of compaction, moisture content, dry density, ceramic content and sulphate content are the most influential factors in terms of shrinkage of CTGM (Agrela et al., 2014, Xuan et al., 2015). The degree of compaction and the cement content are the same in all the specimens, and the other properties were similar (Tables 4.2, 4.3 and 4.4) in SC20 and SC40 mixtures, except for the ceramic content. The comparison between CTGM with MRA and RCA yields contradicting trends in the SC20 and SC40 mixtures. This is coherent with the fact that the RA source is not statistically significant for shrinkage. Regarding RA size, the higher density of the fine particles and better bond with the cement paste causes a more stable behaviour in the specimens with FRA (Bamforth et al., 2008, Xuan et al., 2015).

Figures 4.7 and 4.8 present the dimensional changes of specimens immersed in a water tank at 20-24 °C for 360 days. All mixtures experienced an expansion that tends to stabilize after 126 days for the SC40 mixtures, whereas for the SC20 mixtures it had not stabilized after 360 days.

The maximum expansion of the SC40 mixtures range between 701 µm/m and 1201 µm/m, with an average of 899 µm/m, whereas that of the SC20 mixtures ranged from 658 µm/m to 893 µm/m, with an average of 737 µm/m (18.02% lower than that of the SC40 mixtures).

In terms of the RA source, the average maximum expansion of the SC40 mixtures was 951 µm/m for CMRA and 796 µm/m for CRCA (19.47% lower). As for the SC20 mixtures, the average maximum expansion was 776 µm/m and 660 µm/m, for FMRA and FRCA respectively, i.e. the FMRA's average maximum expansion was 17.58% higher than that for FRCA). With small differences, the trends found for expansion are a mirror to those found for shrinkage and they are explained in the same way.

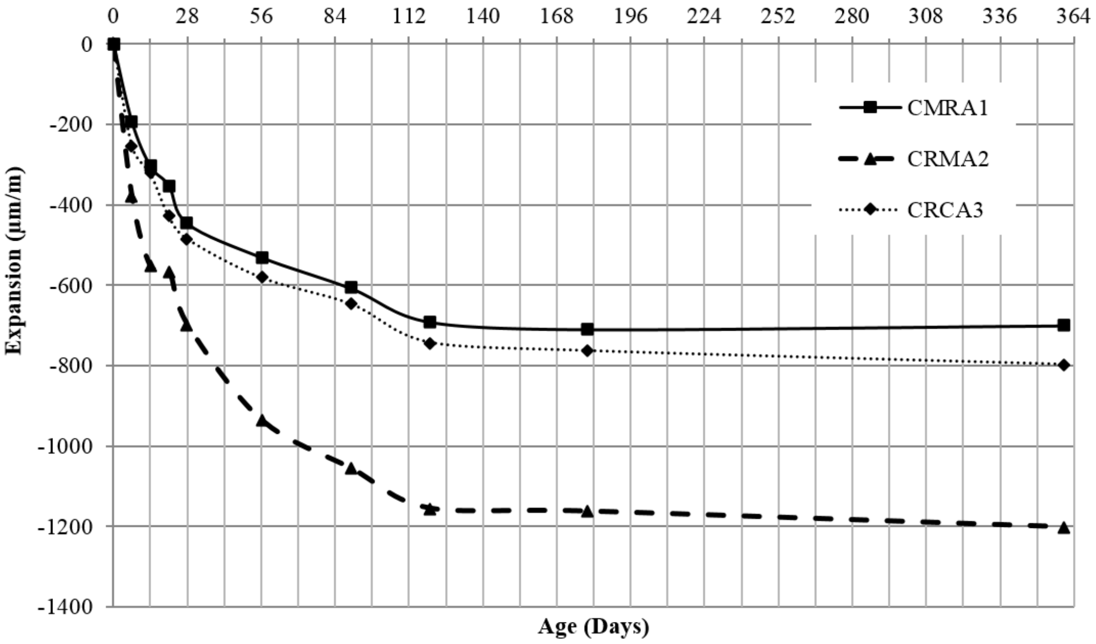


Figure 4.7: Evolution of the expansion of the SC40 mixtures immersed in a tank

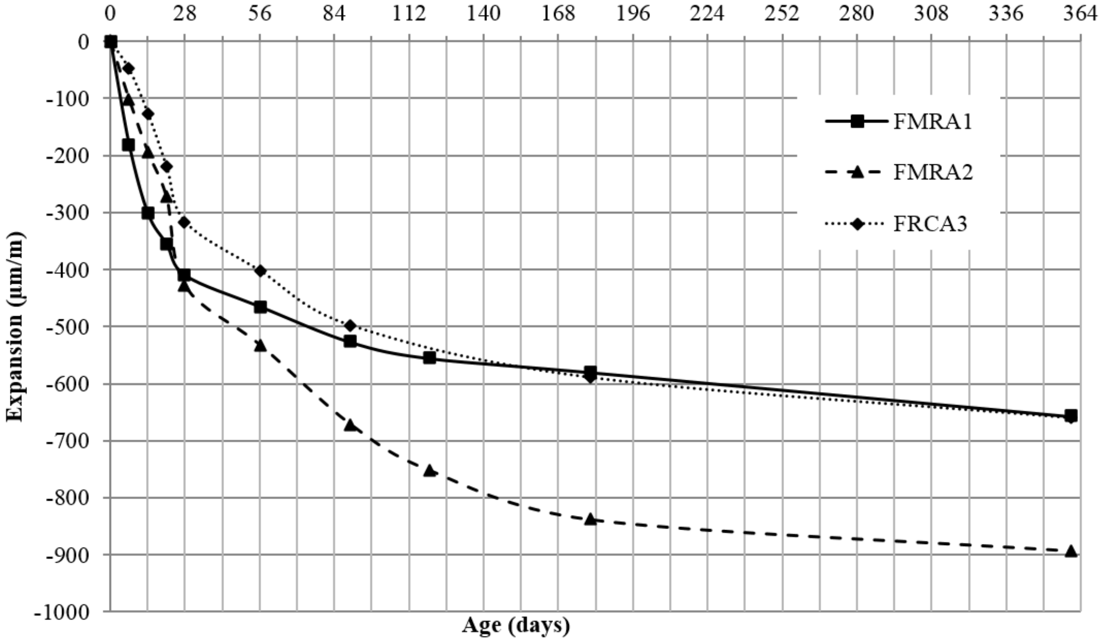


Figure 4.8: Evolution of the expansion of the SC20 mixtures immersed in a tank

The evolution of the dimensional changes is similar to that observed in a previous work. Xuan (2012) analysed the dimensional changes in three environmental conditions, two at high humidity level (wet chamber at 100% humidity) and one at 50% humidity (dry chamber). A CTGM was produced with 65% MRA and 4% cement. In the dry chamber, most of the shrinkage had occurred at 126 days. As for the wet chamber, the high humidity caused expansion. Most of the expansion had occurred at 126 days. In both cases, the deformations occurred at 360 days, resulting in a maximum shrinkage of 360 µm/m in the dry chamber (MRA). This was 62% lower than that obtained in our study, possibly because the MRA content was 35% lower. The maximum expansion in the wet chamber was 140 µm/m and 170 µm/m. This expansion in a high humidity environment was far lower than that of the immersed specimens.

Agrela et al. (2014) immersed the specimens in a curing tank for 126 days. Under these conditions, the specimens suffered higher expansions. The CTGM made with CMRA and 3% CEM II showed an expansion of 1450 µm/m, i.e. 52% higher than the average value in our study for CTGM with

CMRA. Furthermore, the CTGM made with CRCA and 3% CEM II expanded 900 µm/m, which is similar to the results of our study.

An ANOVA test was performed to determinate whether the factors RA size and RA source had a statistically significant effect on shrinkage and expansion. The p-values were higher than 0.05 (0.79 for RA size and 0.93 for RA source at 7 days; 0.44 for RA size and 0.92 for RA source at 28 days), i.e. none of the factors had a statistically significant effect on the dimensional changes.

5. CONCLUSIONS

In this study the mechanical properties and dimensional changes of 0-8 mm and coarse cement treated recycled aggregates (RA) from CDW were studied to understand the feasibility of using them as road base layer, according to the Spanish Code for basic materials on firm pavements (Ministry of Development, 2015). One group of RA consisted of three 0-8 mm RA and the second one of three coarse recycled aggregates (CRA) with a size range of 0-40 mm. The following conclusions were drawn:

- The six RA satisfy the requirements of the Spanish Code in terms of unconfined compressive strength (UCS) with the minimum cement content (3%);
- One mixed recycled aggregate (MRA) (FMRA2) that slightly exceeded the limit of acid soluble sulphates imposed by the Spanish Code shows no loss in the mechanical properties relative to the other RA;
- There are no statistically significant differences with a confidence level of 95% for the two sources of RA used (MRA and RCA) in terms of mechanical (UCS and modulus of elasticity) and durability (dimensional changes) properties;

- There are no statistically significant differences in UCS between cement-treated granular materials (CTGM) made with CRA (SC40) and FRA (SC20);
- CTGM made with FRA have higher modulus of elasticity than CTGM made with CRA. There are statistically significant differences in terms of the RA size, although the modulus of elasticity values in both groups (SC20 and SC40) are suitable for use as base or sub-base roads;
- The environmental conditions have a major influence on the dimensional changes of all cement treated materials studied. In an environment at 50% humidity shrinkage occurs while in a water tank expansion occurs. The SC 20 mixtures show a better behaviour than the SC 40 mixtures. The average shrinkage at 360 days of the SC20 mixtures is 16.91% lower than that of the SC40 mixtures, even though shrinkage tends to stabilize at 126 days. The average maximum expansion of the SC20 mixtures is 18.02% lower than that of the SC40 mixtures.

Aggregates with a size range of 0-8 mm are often used as pipe bedding, a destination with no added-value. This study suggests that it is feasible to produce CTGM with 0-8 mm RA (SC20) from CDW to be used as road bases or sub-bases. In addition, CTGM with FRA have better mechanical properties and dimensional changes than CTGM with CRA (SC40). Even materials with sulphur content higher than the limit established by the Spanish Code meet the requirements. The curing process in field takes 7 days and vehicles traffic is forbidden during this period. The control of the environ-mental effects is difficult, so the of CTGM will not be performed when the ambient temperature is above 35 °C or below 5 °C or when intense atmospheric precipitation occurs. The use of asphalt irrigation or any other technique that prevents moisture loss during curing of the CTGM is recommended, in order to minimize dimensional changes. In addition, when the width of the spread layer is more than four meters it will lead to transversal pre-cracking. Since tension-related properties are critical in pavement design, it is recommended that they are investigated.

To the best of the authors' knowledge, this is the first study on the use of the fine fraction of CDW in the production of cement-treated granular materials to be used as road base layer.

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CAPÍTULO 5. FEASIBILITY OF USING UNBOUND MIXED RECYCLED AGGREGATES FROM CDW OVER EXPANSIVE CLAY SUBGRADE IN UNPAVED RURAL ROADS

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ABSTRACT

Social awareness aims to increase practical skills, such as sustainable development, which seeks to increase the use of different types of waste in construction activities. Although insufficient attention is sometimes given to these actions, it is essential to spread information regarding new studies in the field of waste recycling, which encourages and promotes waste use. Reusing and recycling construction waste in the creation of buildings and infrastructure are fundamental strategies to achieving sustainability in the construction and engineering sectors. In this context, the concept of waste would no longer exist, as waste would become a material resource. Therefore, this study analyses the behaviours of two unbound mixed recycled aggregates (MRA) in the structural layers of an unpaved rural road with low traffic (category T43). The sections were built on inappropriate soil (A-7-6) with a high degree of free swelling. The experimental road consisted of three sections: the first was made with natural aggregates (NA) that were used as a control, the second was composed of MRA in the subbase and NA in the base, and the third section was completely composed of MRA. The materials were characterised in the laboratory. The behaviours of the structural layers in the experimental road were determined by controlling compaction

("in situ" density and moisture) and measuring the deflections and load capacity (deflectometer) during the 18 months after construction. The results show that the sections made with recycled aggregates meet the technical specifications required by General Technical Specifications for Road and Bridge Works (PG-3). Therefore, the water-soluble sulphate content and Los Angeles abrasion coefficient limits can be increased for recycled aggregates without compromising the quality of this type of road with low traffic. To the best of our knowledge, this is the first study regarding the use of unbound MRA made from construction and demolition waste (CDW) in the construction of an unpaved rural road with low traffic on an expansive clay subgrade.

KEYWORDS

Construction materials; mixed recycled aggregates; construction and demolition waste; expansive clays; unpaved rural roads.

1. INTRODUCTION

Waste management is an environmental, social and economic problem. Increasing consumption and the development of economic activities continue to generate large amounts of waste that require greater effort to reduce and prevent. In the past, waste was considered disposable and was disposed of in landfills. The current trends in waste management systems to replace removal with recycling and valorisation reflect the potential of waste as a resource rather than a problem. In 2012, the total amount of waste generated in the European Union (EU) by household activities amounted to 2514 million tons, of which 33% (821 million tons) was construction and demolition waste (CDW), which is the largest waste stream generated in the EU. During that same year, Spain generated a total waste of 119 million tons, of which 22% (26 million tons) was CDW [1].

The construction sector contributes significantly to environmental degradation, and it must move towards sustainability. Construction in developed countries accounts for 40% of global energy consumption over the use-life of materials (raw materials, construction, operations and dismantling) [2]. This results in a large contribution to greenhouse gas emissions, which contribute considerably to climate change [3]. In addition, the construction industry is responsible for 50% of the depletion of natural resources [4]. Therefore, reusing, recycling and revalorising CDW can conserve natural resources and reduce the volume of waste disposal in landfills.

The best practices for creating conditions that increase CDW recycling and improve the quality of recycling and recovery are being identified to present a set of recommendations to member states of the EU. It is necessary to address the potential barriers that maximise the generation of recycled aggregates (RA) from CDW. RA can be used in various civil engineering applications, such as in soil improvement projects and in the bases and subbases of roads. Additionally, CDW is used as a pipe bedding, backfilling and aggregate material for concrete and mortar.

Thus, RA are an excellent substitute for natural aggregate (NA) in civil engineering as unbound materials [5, 6]. As many authors have shown [7–11], the mechanical properties of RA do not limit their use as unbound materials in roads. They can be used as base, subbase or embankment material. To allow a higher load distribution capacity in pavements, the use of RA in cement-treated granular materials (CTGM) provides excellent performance compared to using traditional unbound materials [12–14]. Additionally, RA can be used in recycled concrete [15–17] and mortar [18, 19].

Although RA research has considerably progressed, the Spanish structural concrete code [20] only allows natural gravel to be replaced by recycled gravel, and RA can only be used in concrete (RCA). The code does not allow the use of mixed recycled aggregates (MRA) or ceramic recycled aggregates. Furthermore, recycled materials must meet the specifications of NA for the manufacturing of structural concrete. Not allowing the use of RA is a significant problem for CDW processing plants because most RA in Spain are MRA, representing over 80% of all CDW [21].

The Spanish General Technical Specification for Road and Bridge Works (PG-3) [22] using basic materials for pavements allows the use of RA, both MRA and RCA, as unbound materials, and CTGM can be used in structural layers and embankments. The use of MRA is vital in reducing landfill deposits. Experiments must be conducted to verify the performance of RA in the field. Jiménez et al. [8] performed an experiment with non-selected MRA (surface and base layers) on NA (subbase) and a subgrade classified as A-6 in accordance with the American Association of State Highway and Transportation Officials (AASHTO) [23]. Jiménez et al. [9] also conducted experiments using selected MRA (surface and base layers) on NA (subbase) and a subgrade classified as A-1-B in accordance with AASHTO. In both cases, the behaviour of the RA was similar to the behaviour of NA, and they found no significant differences between them.

The experimental road used in these studies is located in southern Spain (Andalusia). This rural area has abundant clay soils with high water-holding capacity, making them suitable for agriculture. Nevertheless, these clays are expansive and cause numerous structural failures in pavements [24].

Studies of the behaviour of recycled materials on expansive clay subgrades (inappropriate soil) have not been performed. Therefore, the response of RA over subgrades with high swelling capacity and low bearing capacity must be investigated.

The aim of this research is to study the behaviours of two MRA in the structural layers of an unpaved rural road with low traffic (category T43), i.e., less than 11 heavy vehicles per day, over a subgrade of expansive clays. The results are then compared to those when NA are used. To carry out this experiment, an 825 m experimental road was constructed with three different sections: one made with NA, another with MRA and a third section with both NA and MRA.

2. MATERIALS AND METHODS

2.1. DESIGN OF THE EXPERIMENTAL UNPAVED ROAD SECTIONS

The experimental road was constructed in southern Cordoba (Andalusia, Spain) in May 2014. It consists of a single carriageway with one lane five metres wide in both directions. The design of the structural layer was based on the bearing capacity of the subgrade and the estimated traffic density. The asphalt pavement manual for roads of low traffic intensity [25] was used to determine the thickness of the layers. Figure 5.1 shows the structural layers, cross slope, and the slope of the embankments of each section.

The experimental road was divided into three sections:

- Section I spans from Kilometer Point (KP) 0 + 0 to KP 0 + 275. Section I consists of two conventional materials; the subbase is an artificial graded aggregate with a 40 mm maximum size (NA-40), and the base is an artificial graded aggregate with a 25 mm maximum size (NA-25). This section will be used to compare the behaviours of recycled materials.

- Section II spans from KP 0 + 275 to KP 0 + 550. Section II consists of one conventional material and one non-selected recycled material. The aim of this section is to study the behaviour of a non-selected (NS), mixed recycled graded aggregate, with a 40 mm maximum size (MRA-NS) as the subbase layer. The base layer of this subsection is the same as that used in section I (NA-25).

- Section III (Figure 5.2) spans from KP 0 + 550 to KP 0 + 825. Section III consists of two recycled materials; the subbase is a non-selected, mixed, recycled, graded aggregate with a 40 mm maximum size (MRA-NS), the same as that used in Section II, and the base is a selected (S), mixed, recycled, graded aggregate with a 25 mm maximum size (MRA-S). The aim of this section is to study the behaviour of a structural layer built completely with recycled materials and to compare these behaviours with those of Section I, which uses conventional materials.

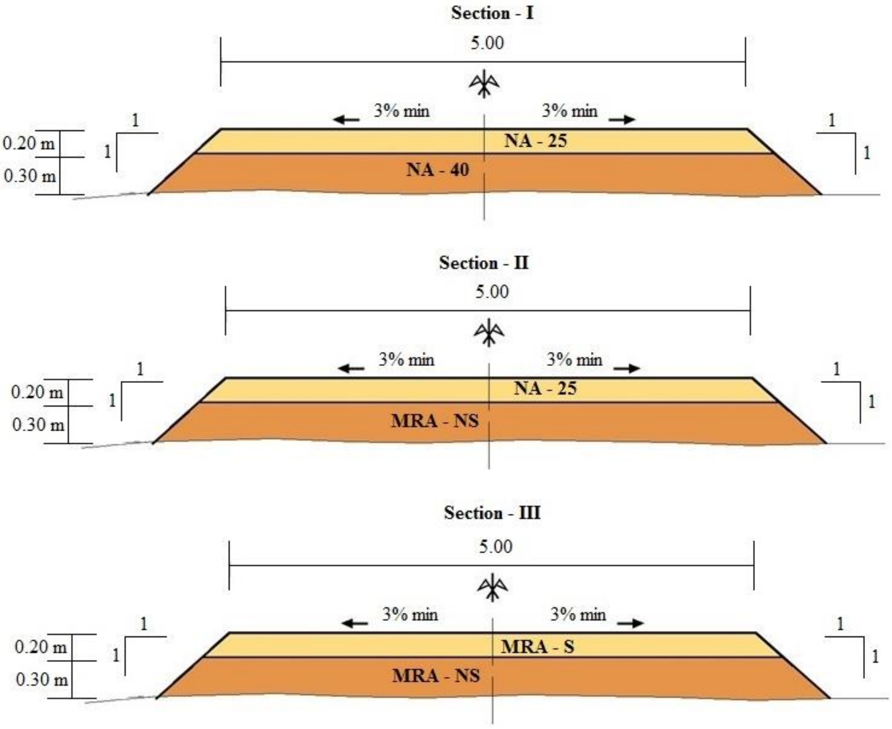


Figure 5.1: Illustration of the experimental sections of unpaved rural road.

Figure 5.2: Section III of experimental unpaved rural road.

Structural layers of Section I were chosen as reference, Section III was carried out to evaluate the behaviour of MRA with respect to NA, and Section II was chosen to evaluate the behaviour of the subbase layer of MRA in case of finding structural failures in Section III.

2.2. RECYCLING PROCESS OF CDW

Two aggregates of mixed debris were used in the experimental sections, and the treatment process was different for each of them. MRA-NS was obtained without any pre-treatment. Mixed debris was crushed without any selection process to remove unwanted waste. By contrast, MRA-S is from selected waste. Furthermore, the mixed debris was pre-screened (20 mm) to remove unwanted impurities and topsoil (0–20 mm fraction), which can create plasticity and increase the sulphate content. After crushing, MRA-NS and MRA-S were screened to 40 mm and 25 mm, respectively.

The aggregate retained by the sieve was transported to the crusher again for reduction.

In both recycled materials, metallic elements were removed using a magnetic conveyor belt. Lightweight materials were removed using a blower. Before the crushing process, a visual inspection was conducted to manually remove plastic, wood, paper, and other types of inappropriate materials.

2.3. MATERIAL CHARACTERIZATION

A complete characterisation of the materials that constitute the unpaved road sections of the subgrade, subbase, and base layers was performed. To perform the characterisation, 200 kg of each material was collected according to UNE-EN 932-1 [26]. The samples were taken during the construction of the experimental section before they were on-site. The tests performed were required under PG-3 [22]. Thorough reduction and sample preparation procedures were performed for each test in accordance with UNE-EN 932-2 standard [27].

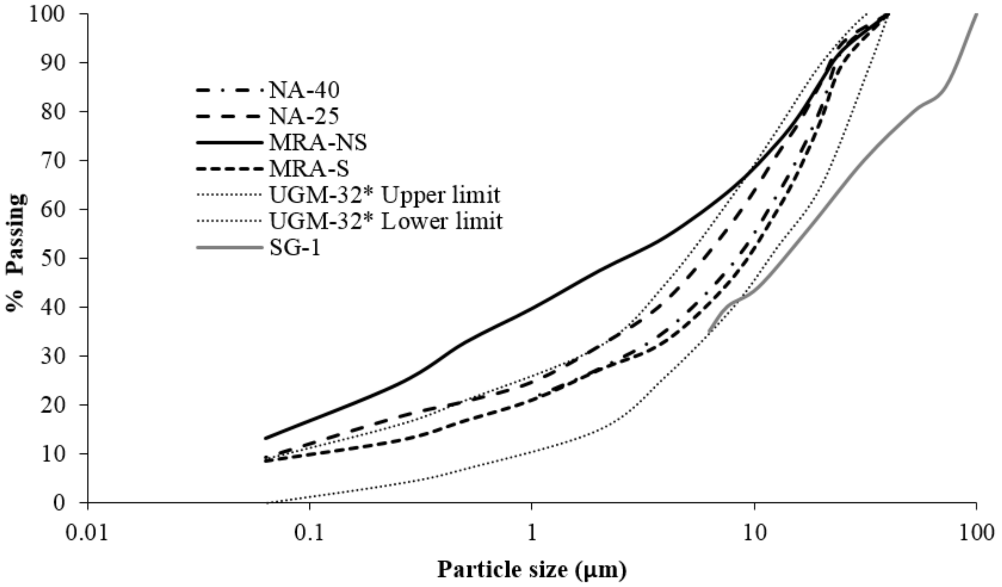
2.3.1. Subgrade Materials

The physical, mechanical and chemical properties of the subgrade were determined based on article 330 of PG-3 [22] which establishes the natural soil classifications and limit specifications used to formulate roadbeds and fills. The following factors were tested: the particle size distribution by sedimentation [28], plasticity index [29,30], the content of water-soluble sulphate [31], standard Proctor test (SPT) [32], California Bearing Ratio (CBR) [33], free swelling and collapse [34]. Table 5.1 shows the physical and mechanical properties studied. The particle size distribution is displayed in Figure 5.3.

The subgrade (SG-1) had a low bearing capacity, a CBR value less than 3, a low density, a high free swell (greater than 5%) and a collapse rate close to 2%. The organic matter content was below 1%. In accordance with the PG-3 [22], SG-1 was classified as inappropriate soil. According to the AASHTO [23], the soil is classified as A-7-6. In these soils, weather could produce shrinkage or swelling. This reduces the bearing capacity of the pavement and the failure of these type of roads by the action of traffic loads.

Table 5.1: Physical, mechanical and chemical properties.

Properties	Particle size	SG-1	NA-40	NA-25	MRA-NS	MRA-S
Water absorption (%)	>4 mm	–	4.3	3.8	8.9	9.4
	<4 mm	–	3.8	3.7	7	7.2
Density-SSD (g/cm3)	>4 mm	–	2.423	2.393	2.11	2.18
	<4 mm	–	2.467	2.471	2.25	2.24
Liquid limit (LL)	–	52.7	–	–	–	–
Plastic limit (PL)	–	29.3	–	–	–	–
Plasticity index (PI)	–	23.4	No	No	No	No
Sand equivalent (%)	–	–	35	37	45	68
Clean coefficient (%)	–	–	2.7	1.4	8.7	7.3
Los Angeles (L.A.) Coefficient (%)	–	–	30.3	31.6	47	40
Flakiness index (%)	–	–	10.5	13.5	24	12.8
Crushed particles (%)	–	–	100	100	91	97
Maximum dry density (MPT) (g/cm3)	–	–	2.29	2.28	1.91	1.85
Maximum dry density (SPT) (g/cm3)	–	1.52	–	–	–	–
Optimum moisture content (%)	–	27.3	7.4	6.4	11.4	11.6
CBR (%)	–	2.7	48.9	78.4	67.3	63.7
Free swelling (%)	–	6.96	–	–	–	–
Collapse (%)	–	1.93	–	–	–	–
Organic matter (%)	–	0.74	0	0	0.02	0.01
Water soluble sulphate (%SO4)	–	0.01	0.01	0.01	0.27	0.22
Total sulphur content (%S)	–	0.27	0.02	0.01	1.15	0.65



* UGM-32 = Unbound granular material. Maximum aggregate size is 32 mm.

Figure 5.3: Particle size distribution.

As can be seen in Figure 5.3, MRA-NS was outside the granulometric zones imposed by PG-3 [22]. MRA-NS, being a non-selected recycled waste material, had a higher percentage of fines required by the Spanish code.

2.3.2. Subbase and Base Materials

The materials used in the experiments included two NA and two mixed MRA. The physical, mechanical and chemical properties of the NA and RA were determined based on article 510 of

PG-3 [22], which regulates the properties and limits of materials used in the unbound structural layers of roads. The following factors were tested: the particle size distribution using a sieve [35], plasticity index [29,30], modified Proctor test (MPT) [36], the CBR [33], the flakiness index [37], the percentage of crushed particles [38], the sand equivalent [39], Los Angeles abrasion coefficient [40], and the contents of water-soluble sulphates and total sulphur [41]. Table 5.1 shows results of the physical and mechanical properties studied. The particle size distribution is displayed in Figure 5.3. The constituents of the RA were determined in accordance with UNE-EN 933-11 standard [42], and the results are shown in Table 5.2.

Table 5.2: Compositions of coarse recycled aggregates.

Compositions	**MRA-NS**	**MRA-S**
% Ra (Asphalt)	0.9	1.6
% Rb (Ceramic)	28.9	33.7
% Rc (Concrete and mortar)	45.7	40.7
% Ru (Natural aggregate)	22.4	23.2
% Rg (Glass)	0.0	0.0
FL (Floating particles) (cm^3/kg)	2.4	1.0
% X1 (Gypsum)	0.8	0.3
% X2 (Wood, plastic and metals)	0.9	0.4

Similar to other studies, the CBR values obtained by RA are slightly lower than those obtained by NA [43, 44]. L.A. abrasion coefficient of RA are above the limits of the PG-3 [22] (<35%) due to the high content of masonry waste [45]. Regarding the clean coefficient, all materials exceed the limit imposed by PG-3 [22] (<1%). These results are in accordance with findings by [10, 46] in which the most limiting physical and mechanical properties of RAs are the L.A. coefficient and the clean coefficient.

The RA have higher contents of both water-soluble sulphate and total sulphur content compared to those of NA. MRA-NS has a total sulphur content that is higher than that allowed by PG-3 [22] (<1%); this occurs because the aggregate did not receive previous treatment to remove unwanted elements. In addition, the main source of sulphate in RA comes from gypsum [47]. Additionally, previous studies have found high levels of sulphate due to the presence of other CDW compounds such as mortar and ceramic particles [48–50].

2.4. FIELD TEST AND QUALITY CONTROLS

2.4.1. Field Density and Moisture Content

During road construction, the field density and moisture content were determined using nuclear density equipment according to ASTM D6938 [51]. One measurement was conducted every 25 metres, i.e., 11 measurements were taken in each section. This test method is a quick and non-destructive technique for measuring the water content and dry density of the aggregate. The results were compared with the maximum dry density and optimum moisture values obtained from the modified Proctor test. The dry density and moisture content of the surface layer were measured at the completion of the experimental section (July 2014), after 12 months (July 2015) and after 18 months (January 2016).

2.4.2. Plate Load Test

Static plate load tests (PLT) were used to determine the load-strain curves. The elastic modulus, which indicates the deformability characteristics of the soil, can be obtained from the slope of the secant through the points corresponding to 0.3 σ_{max} and 0.7 σ_{max}, where σ_{max} is the maximum pressure applied. The load plate had a diameter of 300 mm, and the plate bearing test device had a load of 200 kN. One measurement of the subgrade and three measurements of the base and subbase layers were taken in each section in accordance with NLT-357/98 standard [52].

2.4.3. Falling Weight Deflectometer

Tests were performed by applying a load and measuring the strain produced at the surface by the effect of the load. Deflection was measured using seven sensors (geophones). One sensor was positioned below the loading plate, and six were positioned at 0, 300, 450, 600, 900, 1200, and 1500 mm from the point of load application. The falling weight deflectometer (FWD, manufactured by Dynatest, Soborg, Denmark) was used to apply an impulse load to the road surface by dropping a steel bearing plate with a diameter of 450 mm. The drop height was adjusted to ensure a dynamic load of 40 kN. Two strokes were produced at each point. Measurements were made every 12.5 metres, i.e., 22 measurements were taken in each layer in all the sections. The measurements were taken according to ASTM D4694 standard [53]. The deformation of the base layer was measured at the completion of the experimental section (July 2014), after 12 months (July 2015) and after 18 months (January 2016).

2.4.4. Rut Depth Measurement

One of the most useful tests in assessing the possible failure or degradation of the pavement of a road is the measurement of rut depth on its surface. The permanent vertical deformations of the road surface along the unpaved rural road were registered following the standard of ASTM E1703/1703M [54]. This test was carried out in October 2016.

Assuming that the road surface in the middle has no rutting, the maximum rut depth in the left and right wheel path was measured manually with two straight edges of two meters long (Figure 5.4) and a steel rule calibrated with an accuracy of 0.5 mm (Figure 5.5). Measurements were performed every 30 meters (10 transverse profiles in each of the three Sections).

Figure 5.4: Rut depth measurement manually with straight edge and steel rule.

Figure 5.5: Straight edge of 2 m in each wheel path.

3. EXECUTION QUALITY CONTROL AND EXPERIMENTAL BEHAVIOUR

3.1. FIELD QUALITY CONTROL OF THE EXECUTION

In each section, quality control tests were carried out to assess the application of the materials in the subgrade, subbase, and base layers. Three “in situ” tests were conducted: dry density and moisture content tests using a Troxler nuclear gauge (manufactured by Troxler Electronics Lab. Durham, North Caroline, USA), a bearing capacity test using a PLT, and deflection measurements using a FWD.

3.1.1. Field Control of the Compaction

The degree of compaction is the most influential factor in the mechanical characteristics of the unbound material [55]. Therefore, the compaction process was controlled in the field. "In situ" moisture and density values were measured in the subgrade, subbase, and base. The degree of compaction was defined in accordance with the reference Proctor test. MPT was used for the pavement layers, and the SPT was used for the subgrade. SPT was used in the subgrade due to its advantage in expansive soils. PG-3 [22] indicates that the degree of compaction in the subgrade should meet SPT and MPT values of 95% and 98%, respectively, in pavement layers. The density and moisture values after compaction are shown in Table 5.3.

The compaction degree generally complied with PG-3 [22]. Hence, the experimental section was designed correctly. The average values in the subgrade sections were 97.7%, 96.4%, and 98.3% for sections I, II, and III, respectively. These results were higher than the 95% threshold required by PG-3 [22]. In the subbase sections, the average values were 99.8% in Section I, which used NA-40, and 100.2% and 99.9% in sections II and III, respectively, which used MRA-NS. In the base sections, the average values were 99.3% and 99.1% in sections I and II, respectively, which used NA-25, and 100.9% in Section III, which used MRA-S. In all the subbase and base layers, the results were higher than the 98% threshold required by PG-3 [22].

Table 5.3: *"In situ" assessments of density and humidity*

KP	Subgrade			Subbase			Base		
	Dry Density (g/cm^3)	**Moisture (%)**	**Compaction (% SPT)**	**Dry Density (g/cm^3)**	**Moisture (%)**	**Compaction (% MPT)**	**Dry Density (g/cm^3)**	**Moisture (%)**	**Compaction (% MPT)**
0 + 12.5	1.48	27.6	97.4	2.26	4.7	98.7	2.26	3.4	99.1
0 + 37.5	1.51	24.3	99.3	2.27	4.7	99.1	2.27	2.6	99.6
0 + 62.5	1.50	26.6	98.7	2.25	3.4	98.3	2.30	2.6	100.9
0 + 87.5	1.43	17.1	94.1	2.36	4.0	103.1	2.27	2.5	99.6
0 + 112.5	1.46	28.2	96.1	2.30	3.2	100.4	2.28	4.1	100.0
0 + 137.5	1.47	22.7	96.7	2.26	4.0	98.7	2.25	3.8	98.7
0 + 162.5	1.58	20.8	103.9	2.26	3.8	98.7	2.25	2.5	98.7
0 + 187.5	1.55	18.0	102.0	2.30	3.2	100.4	2.26	2.4	99.1
0 + 212.5	1.44	26.8	94.7	2.36	4.0	103.1	2.23	2.6	97.8
0 + 237.5	1.42	23.3	93.4	2.26	4.1	98.7	2.25	3.3	98.7
0 + 262.5	1.49	25.6	98.0	2.26	3.8	98.7	2.29	3.3	100.4
Average	1.48 ± 0.05	23.73 ± 3.78	97.7 ± 3.2	2.29 ± 0.04	3.90 ± 0.51	99.8 ± 1.8	2.26 ± 0.02	3.01 ± 0.59	99.3 ± 0.9
0 + 287.5	1.41	29.6	92.8	2.02	7.1	105.8	2.25	3.7	98.7
0 + 312.5	1.55	23.4	102.0	1.93	9.6	101.1	2.27	2.9	99.6
0 + 337.5	1.51	22.5	99.3	1.94	9.4	101.6	2.25	3.6	98.7
0 + 362.5	1.51	22.5	99.3	1.91	11.1	100.0	2.22	3.7	97.4
0 + 387.5	1.48	23.0	97.4	1.93	10.2	101.1	2.25	3.6	98.7
0 + 412.5	1.44	25.0	94.7	1.86	8.2	97.4	2.24	3.3	98.3
0 + 437.5	1.48	18.7	97.4	1.87	8.2	97.9	2.23	3.4	97.8
0 + 462.5	1.42	28.3	93.4	1.93	9.6	101.1	2.27	3.9	99.6
0 + 487.5	1.43	17.8	94.1	1.87	8.2	97.9	2.23	3.7	97.8
0 + 512.5	1.42	28.1	93.4	1.94	9.7	101.6	2.25	3.2	98.7
0 + 537.5	1.47	20.9	96.7	1.86	9.8	97.4	2.40	3.6	105.3
Average	1.47 ± 0.05	23.62 ± 3.85	96.4 ± 3.0	1.91 ± 0.05	9.19 ± 1.14	100.2 ± 2.5	2.26 ± 0.05	3.51 ± 0.28	99.1 ± 2.2
0 + 562.5	1.45	23.8	95.4	1.90	9.8	99.5	1.91	9.7	103.2
0 + 587.5	1.48	19.3	97.4	1.91	10.1	100.0	1.90	9.6	102.7
0 + 612.5	1.52	23.5	100.0	1.91	8.4	100.0	1.89	11.7	102.2
0 + 637.5	1.45	21.7	95.4	1.92	10.7	100.5	1.85	12.2	100.0
0 + 662.5	1.51	23.3	99.3	1.86	8.8	97.4	1.82	11.4	98.4
0 + 687.5	1.44	17.8	94.7	1.94	10.6	101.6	1.82	10.7	98.4
0 + 712.5	1.46	25.2	96.1	1.89	9.5	98.9	1.88	11.5	101.6
0 + 737.5	1.42	27.7	93.4	1.95	8.4	102.1	1.85	11.7	100.0
0 + 762.5	1.47	19.9	96.7	1.89	11.0	98.9	1.89	11.5	102.2
0 + 787.5	1.62	15.3	106.6	1.90	11.1	99.5	1.91	10.4	103.2
0 + 812.5	1.61	17.3	105.9	1.92	10.9	100.5	1.82	10.7	98.4
Average	1.49 ± 0.07	21.35 ± 3.76	95.3 ± 4.4	1.91 ± 0.02	9.94 ± 1.03	99.9 ± 1.3	1.87 ± 0.04	11.01 ± 0.85	100.9 ± 2.0

3.1.2. Field Control of the Plate Load Test (PLT)

Based on the data obtained by the PLT, the elastic modulus was calculated for each load cycle. Table 5.4 shows the elastic modulus values in the second load cycle in each of the test sections according to NLT 357/98 standard [52]. Figures 5.6–5.8 show the vertical stress-settlement diagrams of the subgrade, subbase, and base layers in each experimental section. The results are the average of two measurements per section.

Table 5.4: Elastic modulus in MPa.

Section	**Subgrade**			**Subbase**			**Base**		
	Ev_1	**Ev_2**	**Ev_2/Ev_1**	**Ev_1**	**Ev_2**	**Ev_2/Ev_1**	**Ev_1**	**Ev_2**	**Ev_2/Ev_1**
Section I	13.7	28.4	2.1	77.5	162.0	2.1	83.1	170.1	2.1
Section II	10.8	19.3	1.2	52.6	101.4	1.9	73.2	159.2	2.2
Section III	13.9	25.9	1.9	45.9	95.9	2.1	70.0	144.7	2.1

The subgrade had an extremely low bearing capacity of less than 30 MPa, which is well below that required by the PG-3 [22] (≥100 MPa for selected soils and ≥60 for other soils). These values are consistent with a CBR that is less than 3 (Table 5.1). The bearing capacity was well below values obtained in previous studies that used soils with bearing capacity 10 times larger than those of the soils used in this study [8,9].

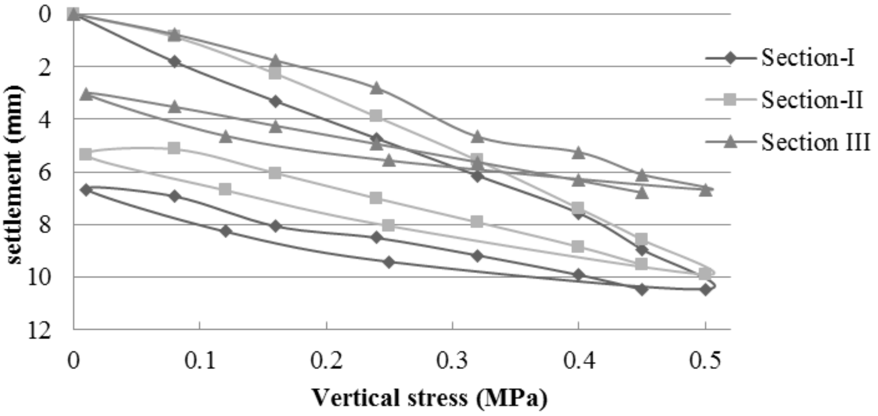


Figure 5.6: Vertical stress–settlement diagram of the subgrade layer.

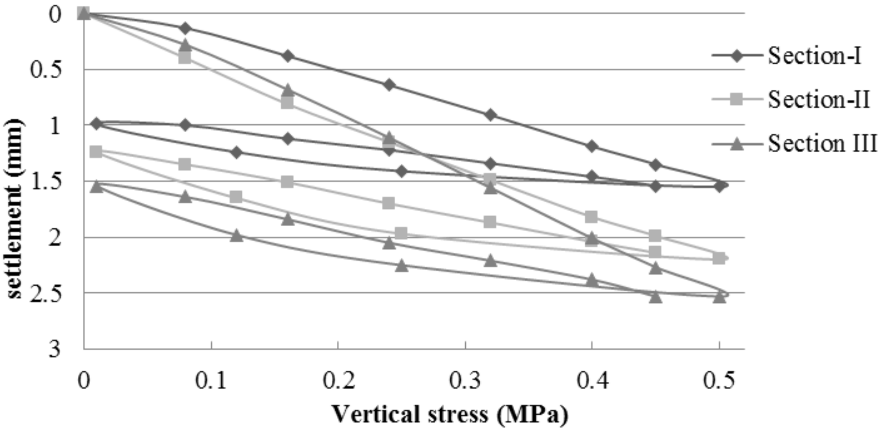


Figure 5.7: Vertical stress–settlement diagram of the subbase layer.

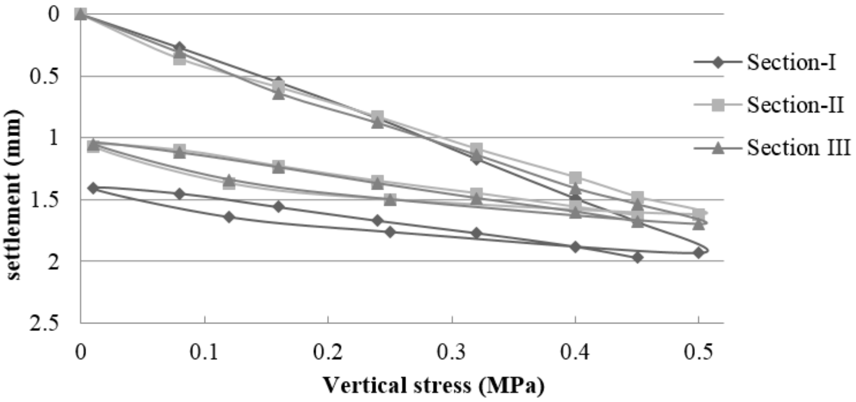


Figure 5.8: Vertical stress–settlement diagram of the base layer.

The elastic modulus values of the pavement are influenced by the subgrade properties. The low bearing capacity of the subgrade decreased the load capacity of the upper layers. The elastic modulus values of the subgrade ranged from 19.3 to 28.4 MPa. Compared to the subbase, the average value of Section I (162.0 MPa), which used NA, was 60% and 69% higher in relation to those of sections II (101.4 MPa) and III (95.9 MPa) respectively, which used MRA. In the base layer, the average value of Section I (170.1 MPa) was 6% greater than that of Section II (159.2) and 18% higher than that of Section III (144.7). The modulus of elasticity values of both NA and MRA were above the 80 MPa minimum, and the ratio of Ev2/Ev1 was less than the value of 2.2 required by PG-3 [22] for traffic category T43.

Jiménez et al. [8] constructed experiments using a subgrade with a modulus of elasticity greater than 300 MPa. Thus, the upper layers exhibited higher elastic modulus. The elastic modulus values of the subbase layers, which used MRA, were between 270 and 405 MPa, and those of the base layer varied between 370 MPa in the layer with RCA and 421 MPa in the layer with NA. As expected, the elastic moduli are higher than those obtained in similar experimental sections (I and II) in this study because they used an appropriate soil in the subgrade layer.

3.1.3. Field Control of the Falling Weight Deflectometer

The main FWD contribution is the analysis of the bearing capacity by reverse calculation of the modulus of elasticity values of the road layers based on the registered deflections. The deflections were measured with a Dynatest HWD 8081 deflectometer (manufactured by Dynatest, Soborg, Denmark). Figures 5.9–5.11 show the values of deflection and the average deflection in the subgrade, subbase, and base in each of the sections.

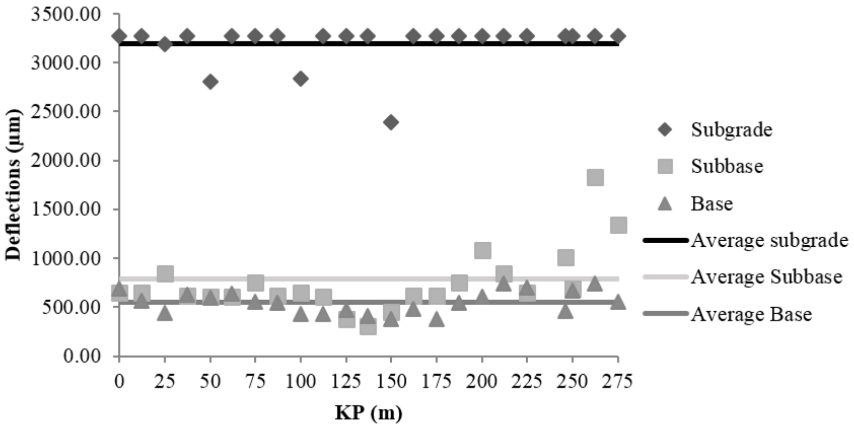


Figure 5.9: Deflections of subgrade, subbase and base in Section I.

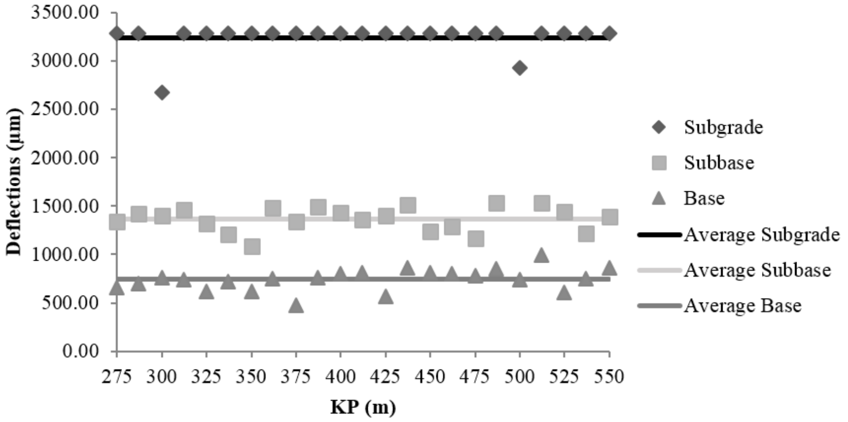


Figure 5.10: Deflections of subgrade, subbase and base in Section II.

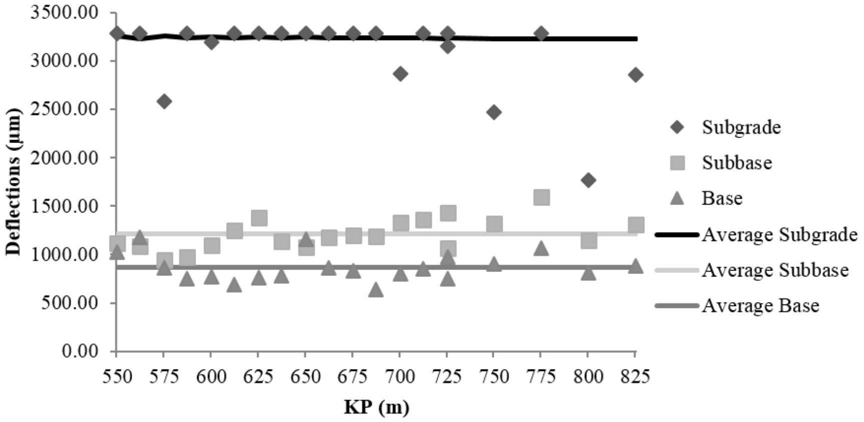


Figure 5.11: Deflections of subgrade, subbase and base in Section III.

The low bearing capacity of the subgrade is reflected by the high deflection values registered at the central geophone, which generally exceed 3000 µm. The average deflections in the subgrade were 3198 ± 37, 3219 ± 23, and 3073 ± 19 µm in sections I, II, and III, respectively.

The average deflections in the subbase layer were smaller relative to those in the subgrade: 74% in Section I (826 µm); 58% in Section II (1348 µm); and 61% in Section III (1209 µm). The values obtained in Sections II and III, which were constructed using MRA, are 63% and 46% higher than that in Section I respectively, which was made with NA. Nonetheless, the results in Sections II and III were admissible for unbound rural roads with low traffic and design speed, not compromising the structural stability of the road.

The decrease in the average deflections in the base layer, relative to those in the subbase, were 33% in Section I (552 μm), 45% in Section II (741 μm), and 32% in Section III (827 μm). In connection with the subgrade decrease were 82% in Section I, 77% smaller in Section II and 73% smaller in Section III. This result suggests that the behaviour of Section I, which was constructed with NA, is similar to the behaviour of Section III, which was constructed with MRA, and it demonstrates that the use of MRA does not compromise the load bearing capacity of the section.

Below the load application point, the equivalent elastic modulus (E) of the pavement structure at the centre of the plate (r = 0 mm) was calculated in each of the sections by applying the function proposed by Brown [56]:

$$\mathrm{E} = \frac{2\,(1-\upsilon^2)\ \times\ \sigma\ \times\ \mathrm{r}}{\delta}$$

where υ is the Poisson ratio of the material (0.35 for unbound granular materials in roads), σ is the stress applied below the plate, r is the plate radius (225 mm), and δ is the deflection at the centre of the plate measured in μm. The results of the elastic modulus are included in Table 5.5. These results were calculated using the average deflection in each section.

Table 5.5: Elastic modulus of the pavement structure in MPa.

Section	Subgrade	Subbase	Base
Section I	26.8	147.1	160.4
Section II	29.1	72.8	135.2
Section III	30.9	81.6	116.9

A decrease in the elastic modulus was observed in the section constructed with MRA, which may be related to the low resistance of the material to fragmentation [10, 43–46]. In the subbase layer, sections II and III exhibited elastic modulus values that were 50.49% and 44.52% lower than those in Section I, which was constructed with NA. In the base layer, the modulus of elasticity in Section I was 15.68% higher than that in Section

II and 27.09% higher than that in Section III. Although MRA undergo more deformation and have lower elastic modulus values than do NA, the MRA used in this study exhibited satisfactory performance.

3.2. FIELD CONTROL OF THE EXPERIMENTAL SECTION BEHAVIOUR

An evaluation of MRA materials in an expansive clay subgrade under low-traffic conditions was conducted from July 2014 to January 2016. The main factors that affect the upper layers of unpaved roads with bases consisting of unbound granular materials are traffic density and weather conditions.

Table 5.6 shows the average monthly maximum and minimum temperatures and monthly total precipitation from execution until the completion of the performance tests. This information was collected from the nearest weather station, which is located in Cabra (Cordoba), with UTM coordinates of (373,516, 4,151,100). The elevation of the station is 547 m.

The temperatures were not extreme. Notably, 2015 was a particularly dry year. Precipitation was concentrated during the months of October to February.

As a service road to an agricultural area, the annual critical period is between September and February. During those months, increased vehicle traffic occurs, as this is the period of greatest agricultural activity. This period also coincides with the transition from a dry spell (summer) at the end of the period to maximum precipitation (winter). Therefore, the beginning of July 2015 and late January 2016 were chosen to perform "in situ" measurements of density, moisture, and falling weight deflection. These tests were carried out to observe the evolutional trends in the deformation, bearing capacity, and elastic modulus values.

Table 5.6: Temperatures and precipitation from execution until completion.

Month	Minimum Temperature (°C)			Maximum Temperature (°C)			Precipitation (mm)		
	2014	2015	2016	2014	2015	2016	2014	2015	2016
January	–	4.43	6.88	–	13.71	13.85	–	49	88.1
February	–	2.88	6.52	–	11.63	14.3	–	55.8	145
March	–	7.03	–	–	18.50	–	–	39.6	–
April	–	10.09	–	–	21.78	–	–	41	–
May	–	14.36	–	–	28.71	–	–	0.6	–
June	–	16.33	–	–	31.08	–	–	7.8	–
July	17.42	22.31	–	31.32	36.81	–	0	0	–
August	18.00	18.37	–	32.10	31.83	–	0	2.3	–
September	15.80	15.19	–	27.22	27.30	–	6.2	25.5	–
October	14.97	13.53	–	25.37	22.56	–	50.2	78.3	–
November	9.09	9.44	–	16.54	19.49	–	130	44.8	–
December	4.98	9.50	–	13.20	18.50	–	21.4	2.2	–
Average	11.34	11.96	6.70	22.07	23.49	14.08	–	–	–
Total	–	–	–	–	–	–	207.8	346.9	233.1

3.2.1. Field Control of Compaction Evolution

To evaluate the behaviour of compaction over time, three “in situ” moisture and density measurements were taken in each section: after execution, at 12 months and at 18 months. Each measurement was the average of 11 tests, and the results in each test section are included in Table 5.7.

Table 5.7: Average values of dry density, moisture and compaction.

Date	Properties	Section I	Section II	Section III
July 2014	Dry Density (g/cm^3)	2.26	2.26	1.87
	Moisture (%)	3.01	3.51	11.01
	% Compaction	99.3	99.1	100.9
July 2015	Dry Density (g/cm^3)	2.23	2.22	1.88
	Moisture (%)	2.07	2.25	5.13
	% Compaction	97.7	97.5	101.7
	Dry Density (g/cm^3)	2.19	2.21	1.85
January 2016	Moisture (%)	5.33	4.55	10.58
	% Compaction	96.0	96.8	100.1

A small decrease in the dry density over time was observed in sections I and II, whose bases were made with NA. Decreased dry density causes a decrease in the degree of compaction. The dry density in Section I decreased by 1.33% and 3.10% in July 2015 and January 2016, respectively. In Section II, the dry density decreased by 1.80% in July 2015 and 2.21% in January 2016. In Section III, a small increase in the dry density (0.53%) was observed in July 2015, and the dry density decreased by 1.07% in January 2016. As in previous investigations, the degree of compaction remained constant in the base layers constructed with recycled aggregates [8], although minimal loss of compaction was observed in the sections constructed with NAs in these studies.

As expected, RA exhibited a higher moisture content than did NA. The high porosity and absorption of MRA increased the moisture content (Table 5.1). This difference was largest after a large precipitation event in January 2016 (88.1 mm).

To assess the significance of the effect of the two factors (composition of each section and date) have on dry density, an analysis of variance (ANOVA) was conducted with the statistical software Statgraphics Centurion XVI (Version 16.1.18, Statgraphics, Madrid, Spain). The F-test in the ANOVA analysis was used to evaluate whether one factor had statistically significant effects on dry density, 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 levels for each factor, Fisher's Least Significant Difference (LSD) test was conducted. In this method there are statistically significant differences at a 95% confidence level when there are non-overlapping bars.

Table 5.8 shows the results obtained with the ANOVA. The results indicate that the composition of sections has a statistically significant influence on dry density ($p < 0.05$). In relation to date, the results show that this factor has statistically significant influence ($p < 0.05$) on Section I and Section II. However, there is no influence in Section III. Figures 5.12 and 5.13 illustrate the average and 95% LSD Interval. No statistically significant differences were found between those levels that share overlapping bars.

The least significant difference (LSD) method was used for this analysis. In this method, 5% is associated with saying that every pair of means is significantly different when the actual difference is equal to 0.

Table 5.8: Dry density results of ANOVA and coefficient of variation.

Properties	**Factor Levels**	**Factor**												
		Composition of Sections			**Date**									
		Section I	**Section II**	**Section III**	**Section I**			**Section II**			**Section III**			
					July 2014	**July 2015**	**January 2016**	**July 2014**	**July 2015**	**January 2016**	**July 2014**	**July 2015**	**January 2016**	
Dry Density (g/cm^3)	*p*-value	<0.0001			<0.0001			0.0073			0.0554			
	Average	2.23	2.23	1.87	2.26	2.23	2.19	2.26	2.22	2.21	1.87	1.88	1.85	
	c.v.	2.02	1.94	1.40	0.89	1.91	1.47	2.17	0.98	1.72	1.95	0.90	0.74	

c.v. = Coefficient of variation (%); bold p-values show significant difference.

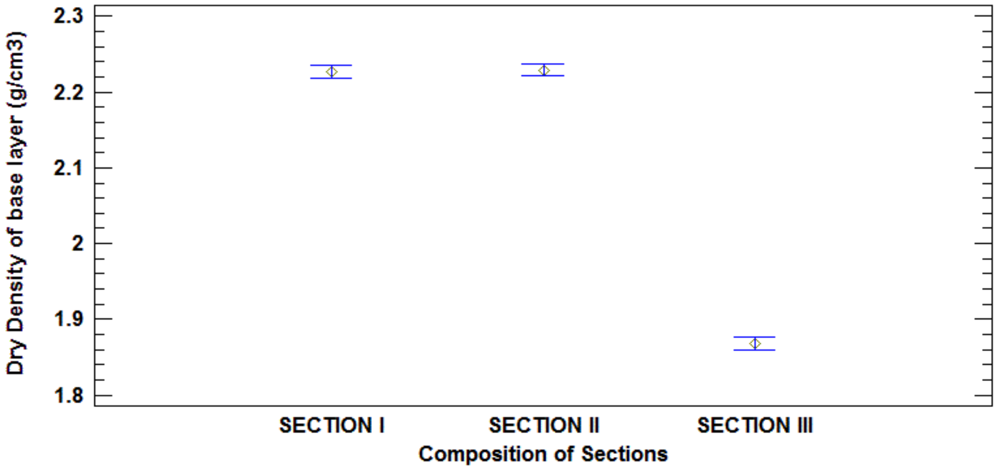


Figure 5.12: Mean values of dry density and 95% LSD intervals vs. composition of sections.

As expected, the mean values of Section III, the base layer was performed with MRA, were lower than the mean values of Section I and II, constructed with NA. There were statistically significant differences at a 95% confidence level between Section I and II compared to Section III, as is indicated by the non-overlapping bars in Figure 5.10.

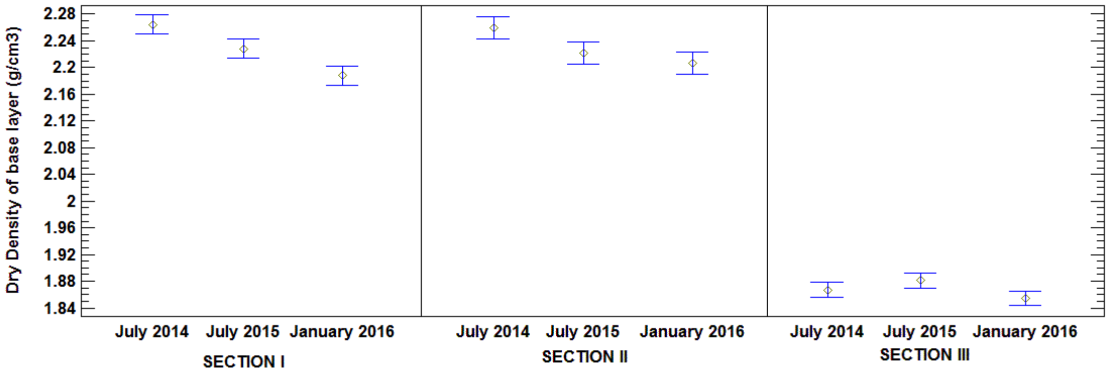


Figure 5.13: Mean values of dry density and 95% LSD intervals vs. date.

As can be seen in Figure 5.13, according to overlapping of bars, Section III did not exhibit a decrease in dry density, there were no statistically significant differences in densities measured over time. However, sections I and II displayed statistically significant differences in their dry density values, which decreased over time. Density loss was mainly due to the base material. Both sections were made with NAs and were differentiated by the subbase materials. Thus, no significant difference was observed between the behaviours of sections I and II. Section I was made completely with NA, while the subbase of Section II was made with MRA. These results could be due to the higher absorption capacity of MRA (Table 5.1), which alleviates the effects of precipitation and humidity.

Similar results were obtained by other authors. In sections with RA base layers, Jiménez et al. [8] found no statistically significant differences over the first two years; however, heavy traffic produced a dry density increase of 4% during the third year. The same results were obtained by Jiménez et al. [9] in sections made with an NA base layer. Although they observed no statistically significant differences, a small decrease in the dry density, approximately 2%, was observed. A similar decrease in the degree of compaction was observed in this study. Based on these results, the degree of compaction of the base layer made with RA exhibited a minor decrease compared to that of the base layer made with NA.

3.2.2. Field Control of the Evolution of the Deflection and Bearing Capacity

The behaviour of the base layer was analysed based on measurements collected using the FWD. The bearing capacity was analysed using reverse calculations of the modulus of rigidity of the road layers based on the registered deflections. Figure 5.14 shows the evolution of deflection over time. The values are the average of 22 measurements per section.

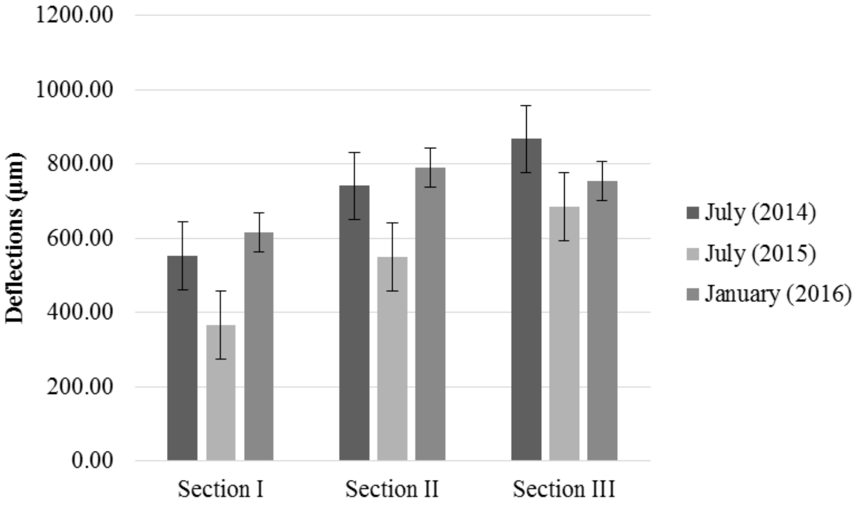


Figure 5.14: Evolution of the deflection for the base layer over time.

The evolution of deflection was similar in Section I and Section II, the deflection decreases in July 2015 and increases in January 2016, the deflections in January 2016 were higher than in July 2014. In Section III, the deflection decreases in July 2015 and increases in January 2016, but does not outnumber January 2016. The deflections were lower in July 2015 than in July 2014, which had dry conditions and low soil moisture. The average deflections observed in sections I (336.51 μm) and

II (549.81 μm) were lower than those observed in Section III (685.41 μm). Reductions of 33.65%, 25.81%, and 20.98% compared to July 2014 were observed in sections I, II, and III, respectively. After a large precipitation event in January 2016, high deflection was observed in all the sections. The average deflections were 616.13, 789.59, and 753.41 μm in sections I, II and III, respectively. In sections with base layers made of NA (Section I and II), the deflection at 18 months was greater than that obtained after completion of the section, as it increased by 11.61% in Section I and 6.54% in Section II. Although an increase in deflection was observed in Section III compared to previous measurements, the deflection at 18 months (January 2016) was 13.14% lower than that observed after completion of the section (July 2014).

To assess the effect of composition of section and date on deflections a similar ANOVA was performed. Table 5.9 presents a summary of the results. No statistically significant differences were found between those levels that share overlapping bars.

Table 5.9: Deflection results of ANOVA and coefficient of variation.

Properties	**Factor Levels**	**Factor**											
		Composition of Sections			**Date**								
					Section I			**Section II**			**Section III**		
		Section I	**Section II**	**Section III**	**July 2014**	**July 2015**	**January 2016**	**July 2014**	**July 2015**	**January 2016**	**July 2014**	**July 2015**	**January 2016**
Deflections (µm)	*p*-value	<0.0001			<0.0001			<0.0001			0.0008		
	Average	511.667	686.164	766.553	552.36	366.51	616.13	741.12	549.81	789.59	867.38	685.41	753.41
	c.v.	0.04	0.02	0.03	20.14	33.84	20.39	15.24	19.64	12.25	17.07	25.29	20.26

c.v. = Coefficient of variation (%); bold p-values show significant difference.

There were statistically significant differences at a 95% confidence level, as can be seen in Figure 5.15.

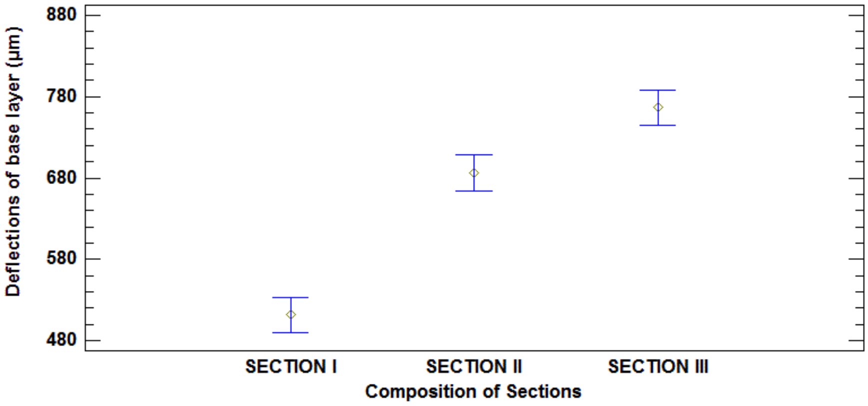


Figure 5.15. Mean values of deflections and 95% LSD intervals vs. composition of sections.

According to overlapping of bars in Figure 5.16, there were significant differences in deflections measured over time in all sections, although it is appreciated that the tendency of deflections was different between them. Section I and II showed an increase of deflections with the onset of rains and, therefore, increased humidity. Deflections in January 2016 were higher than deflections in July 2014, after the execution of the road. However, this did not happen in Section III, in which the deflections increased in January 2016 compared to July 2015, but did not reach the deflections of July 2014. As in dry density, these results are due to the higher absorption capacity of MRA (Table 5.1), which alleviates the effects of precipitation and humidity.

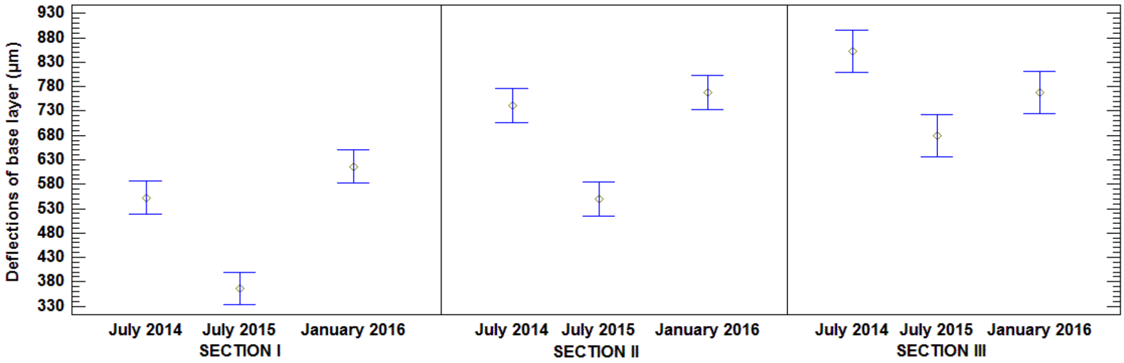


Figure 5.16. Mean values of deflections and 95% LSD intervals vs. composition of sections.

The elastic modulus was calculated from the deflections [56]. Figure 5.17 shows the evolution of the modulus of elasticity over time.

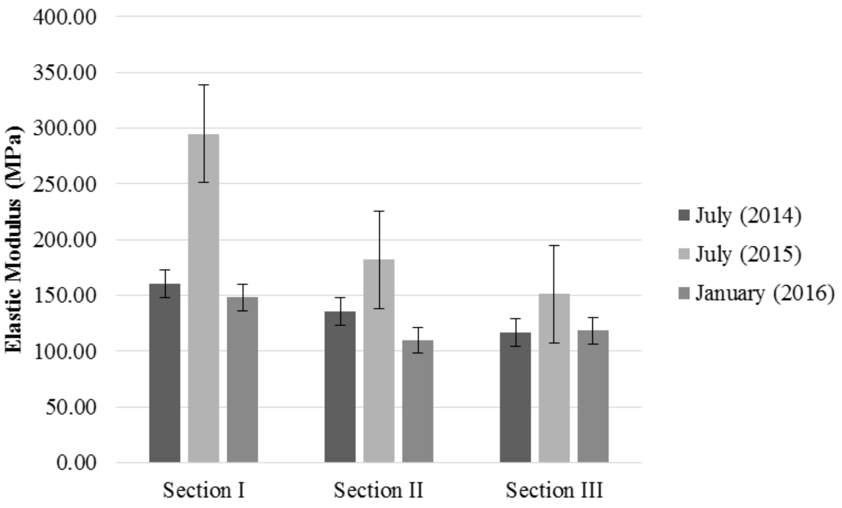


Figure 5.17. Evolution of the elastic modulus for the base layer over time.

All of the elastic modulus values complied with the requirements of PG-3 [22] (>80 MPa).

In Section I, the elastic modulus decreased to 148.2 MPa in January 2016, a reduction of 7.62% from July 2014. In Section II, the elastic modulus was 109.9 MPa in January 2016, a decrease of 18.72% from July 2014. In Section III, the elastic modulus was 118.2 MPa in January 2016, a decrease of 1.04% compared to July 2014. The increase in the elastic modulus in Section III is due to the pozzolanic activity or hydraulic properties of the RA cement [10, 57, 58].

These results are consistent with the moisture data shown in Table 5.7. In July 2015, the soil moisture content was low, and deflections were small; therefore, the material behaved more rigidly. However, deflection increased and the modulus of elasticity decreased when the moisture content increased in January 2016.

3.3. FIELD CONTROL OF THE RUT DEPTH

The permanent vertical deformation of the road surface is the main failure mechanism for unpaved roads. Rutting is due to permanent deformations in any of a pavement's layers or subgrade usually caused by consolidation or lateral movement of the materials due to traffic loading. The combination of these actions, coupled with wet weather conditions, increase the vertical deformations of the road surface resulting in severe rut depth and potholes [59, 60]. Once the wheel path is too deep, driving can be dangerous due to the instability of the surface layer and its rutting will ultimately leave the road with permanent deterioration, which leads to the requirement to reshape the entire cross section [59].

Table 5.10 shows the measurement of the rut depth to the left and right wheel path for each section.

Table 5.10. Rut depth measured by section in millimetres (mm).

Point	**Section I**		**Section II**		**Section III**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
P1	13.5	16.0	16.0	17.0	10.0	11.5
P2	7.5	6.5	6.0	11.0	5.0	8.0
P3	8.5	10.0	9.5	13.0	8.0	9.5
P4	8.5	10.0	9.0	13.5	8.0	9.0
P5	13.5	9.5	9.5	10.5	10.5	10.0
P6	11.0	8.5	10.0	10.0	5.0	13.5
P7	17.5	13.5	11.0	13.5	8.0	14.0
P8	9.0	9.0	10.5	9.5	10.0	11.5
P9	5.0	6.5	12.0	9.0	10.0	6.5
P10	13.5	9.5	10.0	9.5	8.8	16.0
Average by wheel path	10.8 ± 3.7	9.9 ± 2.9	10.4 ± 2.5	11.7 ± 2.5	8.3 ± 2.0	11.0 ± 2.9
Average by section	10.3 ± 3.3		11.0 ± 2.6		9.6 ± 2.8	

The AASHTO Guide for Design of Pavement Structures [61] suggests that the allowable rut depth for unpaved roads is between 25.4 mm and 50.8 mm (1 and 2 inches). As seen in Table 5.10, in any of the positions tested these values have not been exceeded. All values are less than 20 mm, with the average close to 10 mm. With regard to Section I, with an average of 10.3 mm, the rut depth in Section II increased by 6.5% and Section III decreased by 6.6%.

The Guideline of Pavement Surface Condition Rating Manual [62] suggests that there is a low level of severity for a rut depth of less than 10 mm, a medium level of severity for rut depth between 10-20 mm, and high severity level for rut depth greater than 20 mm. Considering that these values are for paved roads, the unpaved road has performed correctly, since Section III was below 10 mm of rut depth and Sections I and II presented rutting close to 10 mm.

To assess the composition effect of sections on rut depth, a similar ANOVA was performed. Table 5.11 presents a summary of these results, finding statistically non-significant differences between those levels that share overlapping bars (Figure 5.18).

Table 5.11. Rut depth results of ANOVA and coefficient of variation.

Properties	**Factor Levels**	**Factor**		
		Composition of Sections		
		Section I	**Section II**	**Section III**
Deflections (mm)	*p*-value		0.3378	
	Average	10.3	11.0	9.6
	c.v.	0.32	0.23	0.29

c.v. = Coefficient of variation (%).

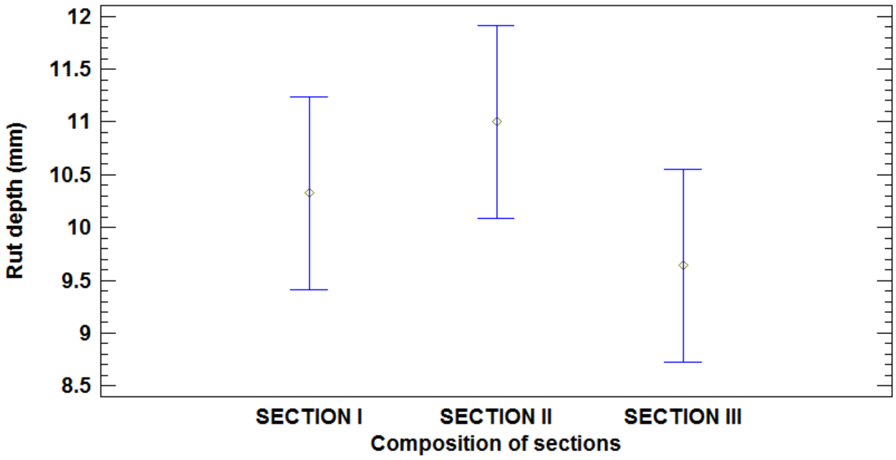


Figure 5.18. Mean values of rut depth and 95% LSD intervals vs. composition of sections.

4. CONCLUSIONS

In this study, the behaviours of two MRA of CDW were evaluated under field conditions. A low-traffic unpaved road was built on an expansive clay subgrade. This material was classified as inappropriate according to PG-3 due to its high free swelling (over 5%). Additionally, it was classified as A-7-6 according to the AASHTO. The following conclusions were drawn from this study:

Section III, which was constructed with MRA, did not exhibit a decrease in the dry density, and there were no significant differences in the densities measured over time. However, sections I and II exhibited significant differences in their dry densities, including decreased density over time. Density loss was mainly due to the base material. Because both sections were made with NA, no significant difference was found between the behaviours of sections I and II, which were differentiated by the subbase material type. Section I was constructed with NA, while the subbase of Section II was constructed with MRA.

Deflections were measured over 18 months. In all of the measurements, the deflections in the section made with NA, both the base and subbase, were lower than those in sections that used MRA in some structural layers. In July 2014 and July 2015, the deflections in Section II, whose subbase was made with MRA, were lower than those in Section III, which was constructed with MRA in the base and subbase. In January, the deflections in Section III were lower than those in Section II. In the base layer made of MRA, a low degree of compaction resulted in smaller deflections. Deflections in sections with MRA in January 2016 were less than 800 (μm) which is considered acceptable for this type of road.

The elasticity modulus of the base layers of the three sections, which were measured using an FWD, satisfied the requirements for unpaved rural road, this value exceeded 100 MPa in the three sections.

Permanent vertical deformations measured in the wheel paths, after more than two years since the opening of the road, were lower or very close to 10 mm. Therefore, the severity level of rut depth was low. The lowest values were obtained by Section three, which was performed only with recycled materials

The results of this study suggest that MRA can be used in structural layers of unpaved roads with low traffic over subgrades of expansive clays. In addition, the L.A. abrasion coefficient and total sulphur content requirements established by the Spanish Technical Specification could be increased for these roads.

Thus, according to the experimental data obtained in this study, we recommend the use of RA in unpaved rural roads with low traffic. The use of RA could reduce the volumes of construction and demolition waste in landfills and increase the recycling rate. Consequently, the commercial values of these recycled materials would increase while achieving environmentally sustainable development in the construction and engineering sectors.

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AUTHOR CONTRIBUTIONS

Jesús Ayuso and José Ramón Jiménez conceived and designed the experiments; Isaac Del Rey, with the collaboration of the company TRAGSA, carried out the experiments; José Ramón Jiménez, Adela P. Galvín, and Isaac Del Rey analysed the data; Isaac Del Rey, Jesús Ayuso, and Adela P. Galvín wrote the paper.

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CAPÍTULO 6. CONCLUSIONES

1. CONCLUSIONES GENERALES

Tras realizar un análisis de los resultados obtenidos en la investigación desarrollada se presentan las siguientes conclusiones:

Relativo a la evaluación ambiental y análisis de los elementos críticos presentes en los lixiviados de los AR, así como el estudio de su procedencia:

1. 14 de los 20 materiales estudiados se clasifican como residuos no peligrosos. Tres ARH y todos los ARA se consideran inertes. Los mayores riesgos ambientales fueron detectados en AR con alto porcentaje de partículas de hormigón, mortero y cerámicas.
2. El estudio inicial identificó el cromo y los sulfatos como los compuestos más limitantes.
3. Se detectaron altos niveles de cromo (Cr) y sulfato en tres de cinco materiales cerámicos. Estos presentaron los mayores contenidos en arcilla (más del 90 %).
4. Los resultados del análisis del estado de oxidación del Cr mostraron que esencialmente todo el Cr total liberado por los materiales cerámicos estaba presente como Cr (III), que es menos nocivo ambientalmente.
5. Ninguno de los tres hormigones estudiados liberó cantidades significativas de Cr o sulfato. Este bajo nivel de Cr podría deberse al bajo contenido de cemento del concreto reciclado probado
6. La prueba de columna caracterizó el comportamiento a largo plazo de los dos compuestos limitantes, y se identificaron los mecanismos principales que rigen la liberación de Cr (lavado de la

segunda etapa) y sulfato (control de solubilidad al principio y agotamiento en las etapas finales).

7. La determinación de los principales estados de oxidación de Cr en todos los lixiviados obtenidos en la prueba de columna. Los datos mostraron que la mayor parte del Cr total se liberó como Cr (VI), que es más dañino y lixiviable que el Cr (III) debido a la influencia del pH en el estado de oxidación y la lixiviabilidad de Cr. Cuando el pH es menor que 5, la mayoría de Cr se lixivia como Cr (III). Por el contrario, cuando el valor del pH es neutro o ligeramente alcalino, el Cr se lixivia como Cr (VI). Finalmente, la lixiviabilidad del cromo disminuye cuando el pH está por encima de 12.
8. El estudio identificó los componentes clave de los AR que plantean riesgos ambientales después de la aplicación de estos áridos como materiales de construcción. Para prevenir y reducir los riesgos, se recomienda la demolición selectiva para eliminar una porción significativa de materiales cerámicos (ladrillos y baldosas) y yeso ya que se ha demostrado que tienen una relación directa con altos niveles de Cr y sulfato. Del mismo modo, además de la demolición selectiva, la calidad del árido reciclado va a depender además de las buenas prácticas de los gestores del RCD. Así pues, que las plantas gestoras realicen un correcto sistema de tratamiento (tanto primario como secundario) hace que el árido tenga una óptima calidad como producto no sólo a nivel técnico, sino también ambiental y siendo por tanto inocuo para el medioambiente.

En cuanto al estudio de la viabilidad del uso de la fracción fina de los AR (0-8 mm) tratada con cemento en capas estructurales de firmes de carreteras:

1. Todos los AR cumplen con las especificaciones técnicas de la normativa española (PG-3, 2015) en cuanto a la resistencia a compresión con un contenido mínimo de cemento (3%)

2. Un ARM no cumple con el límite de sulfatos solubles en ácido (PG-3, 2015) no mostrando pérdidas significativas en las propiedades mecánicas en relación a los otros AR.
3. No existen diferencias estadísticamente significativas entre ARH y ARM en las propiedades mecánicas (resistencia a compresión y módulo de elasticidad) y durabilidad (cambios dimensionales).
4. No existen diferencias estadísticamente significativas en la resistencia a compresión en los MGTC con diferente granulometría (grava reciclada y arena reciclada)
5. Los MGTC realizados con arena reciclada tienen un módulo de elasticidad mayor que los realizados con grava reciclada. Aunque en ambos grupos los valores del módulo de elasticidad son adecuados para su utilización en capas de bases o subbase de carreteras.
6. Las condiciones ambientales tienen una gran influencia en los cambios dimensionales. En un ambiente con una humedad del 50% ocurren retracciones mientras que en muestras sumergidas en un tanque de agua existen expansiones.
7. La realización de MGTC a partir de arena reciclada de RCD (0-8 mm) es factible para su uso como bases o subbases de caminos rurales. Además, los realizados con arena reciclada tienen mejores propiedades mecánicas y cambios dimensionales que los realizados con grava reciclada.

En relación a la viabilidad de utilizar ARM procedentes de RCD como capa estructural del firme de un camino rural sobre arcillas expansivas:

1. El módulo de elasticidad de las capas base de los tres tramos ensayados estimado a partir de las deflexiones fue superior a los 100 MPa que cumple con los requisitos para caminos rurales sin pavimentar.

2. Las deformaciones verticales permanentes medias medidas en la capa de base, después de más de dos años desde la apertura del camino rural están próximas a 10 mm en los tres tramos, que se consideran aceptables para este tipo de caminos.
3. Los resultados de esta investigación sugieren que las zahorras recicladas mixtas se pueden usar en capas estructurales de caminos rurales no pavimentados construidos sobre explanadas de arcillas expansivas. Además, el coeficiente de desgaste de Los Ángeles, así como el contenido de compuestos totales de azufre establecidos por la normativa técnica española podrían ser aumentados para este tipo de caminos.

2. LÍNEAS DE INVESTIGACIÓN PROPUESTAS

La presente tesis doctoral pone de manifiesto la viabilidad de la utilización de AR en infraestructuras civiles, lo que permite llevar a cabo una construcción más sostenible. Sin embargo, existen aspectos que no han podido ser abordados y que, a la luz de los resultados obtenidos en la misma, sería muy interesante su estudio para mejorar la valorización de los residuos de construcción y demolición. En base a lo anterior, se proponen las siguientes futuras líneas de investigación:

En primer lugar, desde el punto de vista de la construcción sostenible, economía circular y conseguir una buena eficiencia energética y disminución de la emisión de gases de efecto invernadero (principalmente CO2), y así aumentar el uso de materiales reciclados, habría que desarrollar nuevos ensayos de laboratorio para la detección de los elementos contaminantes críticos en materiales granulares, ya que los ensayos actuales de lixiviación en laboratorio dan resultados que no se corresponden con los que se producen a escala real. Los resultados de lixiviación obtenidos en laboratorio son superiores a los obtenidos a escala real, siendo la normativa ambiental, uno de los mayores limitantes a la hora de utilizar este tipo de materiales.

Por otro lado, al ser la arena reciclada la que tiene mayor producción y, por lo tanto, menor valor añadido, se propone estudiar nuevas aplicaciones en materiales ligados con cemento, empleándolas en sustitución de arena natural en hormigón compactado con rodillo.

Finalmente, resultaría interesante la realización de tramos experimentales con arenas recicladas tratadas con cemento como capa estructural en vías de baja intensidad de tráfico, para poder evaluar el comportamiento a largo plazo en condiciones reales.

ANEXO. ASPECTOS ECONÓMICOS DEL TRAMO EXPERIMENTAL REALIZADO CON ARM DE RCD

El factor económico juega un rol muy importante en la utilización de materiales en la construcción. Además de cumplir con las especificaciones técnicas y ambientales, los AR deben de ser económicamente competitivos con los AN.

En España, para impulsar la reutilización y/o reciclaje de los RCD es importante tomar políticas de gestión de residuos de tipo económico (tasas sobre depósito en vertedero) y legales (obligación de demoler selectivamente, planificación y control).

A pesar de que la viabilidad técnica de los AR está demostrada, incluso existen guías para su reciclaje y puesta en obra (Guía de áridos reciclados de construcción y demolición (RCD) de Andalucía Central, 2015, Gestión y tratamiento de residuos de construcción y demolición (RCD). Guía de buenas prácticas, 2015; Catálogo de firmes y unidades de obra con áridos reciclados de Residuos de Construcción y Demolición (RCD), 2016), los agentes que intervienen en una obra (promotor, redactor de proyecto, contratista, etc.) tienen cierta desconfianza en la viabilidad técnica de los AR (Silva y col., 2017).

Pocos son los estudios económicos realizados en cuanto al uso de AR frente a AN. (Tosic y col., 2015) demostraron que el hormigón realizado con AN tenía un precio más bajo que con AR. Por ello, es necesario la implantación de beneficios a la utilización de materiales reciclados: impuestos sobre AN, beneficios fiscales en materiales sostenibles, ayudas en la utilización de materiales reciclados, impuestos al depositar en vertedero los RCD, etc.

La presente tesis se centra en los pilares fundamentales del desarrollo sostenible (económico, social y ecológico), es por ello que se ha realizado una comparación económica de la utilización de AR frente a AN en el tramo experimental realizado (Capítulo 5).

1. EVALUACIÓN ECONÓMICA

Como criterio se implementará el modelo lineal para conocer el impacto económico que tiene la utilización de ARM en capas estructurales de un camino rural. Para ello, se tendrá en cuenta el precio de los AR y AN, gastos de transporte, tiempo de carga y descarga, tiempo de viaje, distancia, etc.

Los datos para la realización de la evaluación económica han sido facilitados por la empresa que ha suministrado los AR (GECORSA) y la encargada de realizar la obra (TRAGSA). En la Tabla I, se puede observar el precio definitivo de la zahorra reciclada mixta seleccionada (ZARM I), zahorra reciclada mixta no seleccionada (ZARM II), Zahorra natural seleccionada (ZN I) y la zahorra natural no seleccionada (ZN II).

La zahorra reciclada proviene de la planta de reciclado de GECORSA, la cual se encuentra en el T. M. de Córdoba, a 67 km del lugar donde se ejecutó el tramo experimental. La zahorra natural fue suministrada por la Cantera de Áridos El Peñón, la cual se encuentra a 17 km del tramo experimental.

Tabla 1. Resumen Económico

	ZARM I	**ZARM II**	**ZN I**	**ZN II**
Tiempo de carga y descarga (m)	20	20	20	20
Velocidad media del camión (km/h)	70	70	70	70
Distancia áridos (km)	67	67	17	17
Tiempo de viaje ida y vuelta (h)	1.91	1.91	0.49	0.49
Coste Camión 24 T. (€/h)	42.00	42.00	42.00	42.00
Coste 24 T (€)	80.40	80.40	20.40	20.40
Coste transporte (€/t)	3.35	3.35	0.85	0.85
Coste del árido (€/t)	*4.55*	*4.15*	*5.15*	*4.90*
Coste total (€/t)	*7.90*	*7.50*	*6.00*	*5.75*

La Tabla 1 muestra que el coste final de los materiales reciclados, a pesar de ser más económicos, es superior al de los AN. Esto se debe a que la empresa suministradora de AR se encuentra a una distancia superior que la cantera de AN. El coste de transporte de los AR (3.35 €/T) es muy superior al coste de transporte de los AN (0.85€/T).

Sin embargo, a medida que se reduce la diferencia entre las distancias de la planta de tratamiento de RCD y la cantera de AN a la obra, la diferencia de precio va disminuyendo. La Tabla 2 muestra como el menor precio de los materiales reciclados puede compensar hasta 12 km de exceso de distancia en la zahorra seleccionada y 15 km en la zahorra no seleccionada.

Tabla 2. Evaluación del precio final de los materiales

Diferencia de distancia (km)	**Diferencia Precio Final (€/T)**	
	ZARM I - ZN I	**ZARM II - ZN II**
70	2,90	2,75
65	2,65	2,50
60	2,40	2,25
55	2,15	2,00
50	1,90	1,75
45	1,65	1,50
40	1,40	1,25
35	1,15	1,00
30	0,90	0,75
25	0,65	0,50
20	0,40	0,25
15	0,15	0,00
12	0,00	-0,10
10	-0,10	-0,25
5	-0,35	-0,50
0	-0,60	-0,75

Una vez analizados los costes de los materiales reciclados frente a los naturales, se puede concluir que los AR son competitivos en precio frente a los AN, siendo los AR más económicos. El menor precio de los AR puede compensar hasta en 15 km una mayor distancia de las plantas de tratamiento.

La utilización de materiales reciclados en la construcción, contribuye a una mejora ambiental, reducción de consumo de recursos naturales y emisiones de gases de efecto invernadero, y una mejora social y económica, cambiando la actual economía lineal por una economía circular, basada en el reciclaje.