UNIVERSIDAD DE CÓRDOBA

Departamento de Ingeniería Rural
Área de Ingeniería de la Construcción

TÉCNICAS NO DESTRUCTIVAS DE AUSCULTACIÓN APLICADAS A TRAMOS EXPERIMENTALES EJECUTADOS CON ÁRIDOS RECICLADOS DE RCD

NONDESTRUCTIVE TECHNIQUES APPLIED ON EXPERIMENTAL SECTIONS BUILT WITH RECYCLED AGGREGATES OBTAINED FROM CDW

Tesis Doctoral

JAVIER TAVIRA DÍAZ

Córdoba, 2020

TITULO: *Técnicas no destructivas de auscultación aplicadas a tramos experimentales ejecutados con áridos reciclados de RCD*

AUTOR: *Javier Tavira Díaz*

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Campus de Rabanales
Ctra. Nacional IV, Km. 396 A
14071 Córdoba

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Técnicas no destructivas de auscultación aplicadas a tramos experimentales ejecutados con áridos reciclados de RCD

"Nondestructive techniques applied on experimental sections built with Recycled aggregates from CDW"

Tesis doctoral presentada por

Javier Tavira Díaz

Para la obtención del título de

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Programa de Doctorado de Ingeniería Agraria,

Alimentaria, Forestal y del Desarrollo Rural Sostenible

Directores

Dr. José Ramón Jiménez Romero
Dr. Enrique Fernández Ledesma

TÍTULO DE LA TESIS:

TÉCNICAS NO DESTRUCTIVAS DE AUSCULTACIÓN APLICADAS A TRAMOS EXPERIMENTALES EJECUTADOS CON ÁRIDOS RECICLADOS DE RCD

DOCTORANDO: Javier Tavira Díaz

INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS

A pesar de los esfuerzos realizados en los últimos años para aumentar la tasa de reciclado de residuos de construcción y demolición (RCD), actualmente en España se recicla menos del 50%, lo que sigue alejado del 70% prescrito para el año 2020 según la Directiva Marco de Residuos 2008/98/CE del Parlamento Europeo.

Los Árido Reciclados (AR) de RCD pueden sustituir a los Áridos Naturales (AN) en capas no ligadas de pavimentos, evitando así la sobreexplotación de canteras, graveras y el depósito de RCD en vertederos. No obstante, las diferencias entre los AN y los AR de RCD son muy significativas en su composición química y propiedades físico-mecánicas. Esto no debería suponer un problema para su empleo en capas granulares de firmes de carreteras y pavimentos en general, siempre y cuando se garantice que las prestaciones estructurales y funcionales de los firmes ejecutados con estos AR sean las mismas que las que se obtendrían con los AN. Una de las mejores alternativas para el uso de los AR es su uso en carreteras de baja intensidad de tráfico o vías ciclistas. Por otro lado, siempre que sea posible, el reciclado in-sito de los RCD puede ser una alternativa para reducir la huella de carbono y energía embebida de los AR.

La mayor barrera técnica que existe para el empleo de los AR en capas no ligadas de firmes es la escasez de estudios a escala real en pavimentos de carreteras y vías peatonales.

La presente Tesis Doctoral abarca el estudio de distintas aplicaciones de AR mixto y de hormigón en tres tramos experimentales, donde se abarca un espectro de intensidades de tráfico diverso, que va desde un tráfico ligero T4 hasta un nivel medio-alto de tráfico T2. Esto hace que la investigación realizada aporte una valiosa información científico-técnica y avance en el conocimiento del comportamiento de los AR de RCD en aplicaciones constructivas a escala real y a largo plazo.

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

1. Javier Tavira, José Ramón Jiménez, Jesús Ayuso, María José Sierra, Enrique Fernández Ledesma (2018). Functional and structural parameters of a paved road section constructed with mixed recycled aggregates from non-selected construction and demolition waste with excavation soil. *Construction and Building Materials*, *164*, 57-69.
2. Javier Tavira, José Ramón Jiménez, Jesús Ayuso, Antonio López-Uceda, Enrique Fernández Ledesma (2018). Recycling screening waste and recycled mixed aggregates from construction and demolition waste in paved bike lanes. *Journal of Cleaner Production*, *190*, 211-220.
3. Javier Tavira, José Ramón Jiménez, Enrique Fernández Ledesma, Antonio López-Uceda, Jesús Ayuso (2020). Real-scale study of a heavy traffic road built with in situ recycled demolition waste. *Journal of Cleaner Production*, *248*, 119219.

Para la realización del primer estudio se ha contado con la jefa de la Unidad de Control Técnico de Obras de la Agencia de la Obra Pública de la Junta de Andalucía, María José Sierra López.

La investigación llevada a cabo en esta Tesis puede en enmarcarse en el ámbito de los siguientes Proyectos/Contratos de Investigación:

Título: "Reciclaje de los RCD generados en las zonas expropiadas del aeropuerto de Córdoba en las obras de infraestructura derivadas de la ampliación de pista". Empresa: PLODER-UICESA. IP: J.R. Jiménez. Periodo: 2009-2019.

G-GI3000/IDI0. Título: "Aplicaciones de los áridos reciclados de residuos de construcción y demolición (RCD) para la construcción sostenible de infraestructuras viarias en Andalucía central". Entidad financiadora: Consejería de Fomento y Vivienda. Junta de Andalucía. Fondos FEDER. Investigador Principal: J. Ayuso Muñoz. Financiado en 2012-2014.

G-GI3002-IDIE. Título: "Análisis de la percepción - demanda social de los usuarios de las vías ciclistas andaluzas y estudio pre-normativo para reducir los accidentes por deslizamiento/derrape con pavimento mojado y mal tiempo. (CICLOVÍAS)". Entidad financiadora: Consejería de Fomento y Vivienda. Junta de Andalucía. Fondos FEDER. Investigador Principal: J. R. Jiménez. Financiado en 2013-2015.

Por todo ello, se autoriza la presentación de la Tesis Doctoral " Técnicas no destructivas de auscultación aplicadas a tramos experimentales ejecutados con áridos reciclados de RCD".

Córdoba, 16 de junio de 2020

Firma de los directores

JIMENEZ ROMERO JOSE RAMON - 30795058J

Firmado digitalmente por JIMENEZ ROMERO JOSE RAMON - 30795058J
Fecha: 2020.06.26 16:44:17 +02'00'

FERNANDEZ LEDESMA ENRIQUE - 30976712J

Firmado digitalmente por FERNANDEZ LEDESMA ENRIQUE - 30976712J
Nombre de reconocimiento (DN): c=ES, serialNumber=30976712J, sn=FERNANDEZ LEDESMA, givenName=ENRIQUE, cn=FERNANDEZ LEDESMA ENRIQUE - 30976712J
Fecha: 2020.06.26 17:42:07 +02'00'

Fdo.: Prof. Dr. José Ramón Jiménez Romero

Fdo.: Prof. Dr. Enrique Fernández Ledesma

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Abstract

This Thesis studies the use of Recycled Aggregates (RA) obtained from Construction and demolition wastes (CDW) in unbound granular layers of roads and biking lanes. Six different types of RA were used in three different real scale experimental sections.

The first study took place in the service road of the A-376 motorway, two different RA composed the granular layers, Mixed recycle soil (MRS) obtained from the screening wastes of a recycled mixed aggregate with excavation soil (RMAS), unselected CDW mixed with excavation soil was the raw materials of these RA, MRS formed the granular subbase and RMAS composed the granular base, there was a comparison section built with natural aggregates (NA) in its granular layers, 5 cm of hot mix asphalt (HMA) covered the surface of the Experimental Section. Chemical and physical properties were studied in laboratory, densities and moisture content were controlled during the construction of the road, deflections and surface regularity was measured for a period of seven years, results showed that RA and NA had a similar structural and service performance.

The second study materialized in an Experimental Bike Lane (EBL) near the Rabanales Campus, two different RA obtained from CDW composed its granular layers, Recycled mixed aggregates with screening wastes (RMSW) formed the granular subbase, these RMSW were obtained from the wastes of the crushing of a recycled mixed aggregate (RMA) that constituted the granular base. A comparison section was built with NA in the base layer. Chemical and physical properties were studied in laboratory, during the construction of the experimental biking lane densities and moisture content were controlled, 4cm of HMA covered the Surface of the EBL, bearing capacity and elastic moduli of the layers were

evaluated for a period of three years, results proved that RA can substituted NA in pedestrian and bike pavements.

In the third study, two RA were obtained from the demolition of 105 dwellings near to the Cordoba Airport, these RA formed the granular layers of an Experimental section in the road CH-2, RMA composed the granular subbase and RCA constituted the granular base layer. A mobile jaw crusher made from the foundations and concrete of the existing rigid pavements the RCA, while structural parts of the houses, walls and roofs constituted the RMA. A comparison section was built with NA in the base layer. Chemical and physical properties were studied in laboratory, densities and moisture content were controlled during the construction of the road, deflections and Surface regularity was measured for a period of ten years. The number of daily vehicles was above 9000, this road would be classified as a T2 (200-799 heavy traffic vehicles per day and lane). RA obtained a higher bearing capacity than NA.

Structural and functional characteristics of pavements built with RA are similar to those pavements constructed with NA, therefore RA from CDW can replace NA in unbound pavement layers. RA use in pavements can help to avoid landfilling with CDW and mitigate overexploitation of quarries and river gravels, this reuse of materials contributes significantly to the circular economy.

Resumen

La presente Tesis Doctoral estudia el uso de los Áridos reciclados (AR) de los residuos de construcción y demolición (RCD), de diferente naturaleza (hormigón y mixtos) en la formación de capas estructurales granulares no ligadas de capas granulares de pavimentos de carretera y vías ciclistas. Para ello se estudió la evolución de las prestaciones estructurales y funcionales de tres tramos experimentales reales donde se emplearon seis tipos de AR distintos.

El primer estudio se realizó en la vía de servicio de la autovía A-376. Se emplearon dos tipos de AR: un suelo reciclado mixto (SRM), el cual fue obtenido del precribado a partir del rechazo de la fabricación de una zahorra reciclada mixta (ZRM). En la obtención de estos AR se emplearon RCD no seleccionados en origen mezclados con suelos de excavaciones. El SRM se empleó en la capa de formación de explanada, mientras que la ZRM se empleó como capa granular en el firme. Se construyó una sección de referencia con suelo seleccionado y zahorra artificial. Sobre toda la superficie del tramo experimental se extendió una capa de mezcla bituminosa de 5 cm de espesor. En una primera fase, todos los materiales fueron caracterizados, posteriormente en una segunda fase se controló su puesta en obra y una vez abierto al tráfico durante siete años se controló la evolución de las deflexiones y la regularidad superficial, siendo los resultados obtenidos en las secciones construidas con AR similares a las de los AN.

En el segundo estudio se emplearon dos AR de RCD en la construcción de la vía ciclista que une el núcleo urbano de Córdoba con el Campus de Rabanales de la Universidad de Córdoba. Se empleó un suelo reciclado mixto en la explanada, obtenido del precribado en la fabricación de una ZRM en planta de tratamiento, esta zahorra se utilizó en la capa granular del firme. En la capa de rodadura se emplearon 4 cm de mezcla

bituminosa en caliente. Todos los áridos empleados en el tramo experimental se caracterización mecánica, física y químicamente, posteriormente se controló su puesta en obra y una vez fue abierta al tráfico se estudió la evolución de la capacidad portante y módulos de elasticidad del firme durante tres años. Los resultados mostraron que la ZRM y el SRM pueden sustituir al suelo seleccionado y a la zahorra artificial en vías ciclistas y peatonales sin afectar a su funcionalidad.

En el tercer estudio se emplearon dos AR obtenidos de la demolición de 105 viviendas próximas al aeropuerto de Córdoba con los que se construyeron un tramo experimental en la carretera CH-2, en concreto se empleó un AR mixto (ARM) en la formación de la explanada y un AR de hormigón (ARH) en la capa granular del firme. El ARH se obtuvo a partir de la trituración insitu con una machacadora móvil de mandíbulas de los RCD obtenidos de las cimentaciones y de las losas de hormigón de los pavimentos existentes, mientras que los ARM se obtuvieron a partir de las estructuras aéreas de las viviendas, muros y tejados. Como tramo de referencia se construyó una sección con zahorra artificial en la capa de firme. Se realizaron ensayos en laboratorio para caracterizar los tres materiales granulares empleados en el tramo experimental y una vez terminada la ejecución del tramo experimental de la carretera se puso en servicio, la evolución deflexiones y regularidad superficial se estudió durante 10 años, se midió el tráfico determinando que el número de vehículos diarios superaba los 9000, siendo su categoría de tráfico la T2 (200-799 vehículos pesados/día), los AR obtuvieron una mayor capacidad portante y mejor evolución con el paso del tiempo que la zahorra artificial empleada.

Las características estructurales y funcionales de los firmes ejecutados con AR son similares a las de los firmes construidos con AN en carreteras de baja y media intensidad de tráfico, por tanto, los AR de RCD pueden sustituir a los AN en capas no ligadas de pavimentos sin que sus prestaciones mecánicas y funcionales se vean alteradas por el paso del

tiempo. El empleo de los AR en detrimento de los AN reduciría la sobreexplotación de canteras y graveras, así mismo, se evita el depósito de RCD en vertedero o su vertido, con el consiguiente daño al medio ambiente, esta reutilización contribuye significativamente a la economía circular. Esta tesis incluye el cálculo de módulos a través de cálculos directos e inversos para los áridos reciclados, lo cual es un aspecto clave en el diseño de firmes.

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Abreviaturas

RCD	Residuos de la construcción y demolición
ANEFA	Asociación nacional de empresarios fabricantes de Áridos
AR	Áridos reciclados
AN	Áridos naturales
PEMAR	Plan Estatal Marco de Gestión de Residuos
PG-3	Prescripciones Técnicas Generales para Obras de Carreteras y Puentes
AOPJA	Agencia de Obra Pública de la Junta de Andalucía
CDLO	Coeficiente de Desgaste de Los Ángeles ()
ZRH	Zahorras recicladas de hormigón
ZRM	Zahorras recicladas mixtas
ARH	Áridos reciclados de Hormigón
ARC	Áridos reciclados cerámicos
ARA	Áridos reciclados asfálticos
ARM	Áridos reciclados mixtos
IRI	Índice de regularidad internacional
RMS	Raíz del error medio cuadrático
QCS	Quarter Car Simulation
RS	Rectified Slope
CDW	Construction and Demolition Waste
RMAS	Recycled mixed aggregates with excavation soil
MRS	Mixed Recycled soil

FWD	Falling weight deflectometer
IRI	International Roughness Index
NA	Natural Aggregates
RA	Recycled Aggregates
RCA	Recycled Concrete Aggregates
CBR	California Bearing Ratio
ER	Experimental Road
NDT	Nondestructive Testing
CS	Crushed Stone
SS	Selected Soil
SG	Subgrade
GPR	Ground Penetrating Radar
PG3	Spanish general technical specification for road construction.
AASHTO	American Association of State Highway and Transportation Officials
CRA	Catalogue of pavements with Recycled Aggregates
EBL	Experimental Bike Lane
RMA	Recycled Mixed Aggregates
RMSW	Recycled Mixed Aggregates with Screening Wastes
RMCA	Recycled Mixed Ceramic Aggregates;
SW	Screenings wastes.
EU	European Union
ES	Experimental Section
IRI	International Roughness Index

ICP-MS	Inductively Coupled Plasma Mass Spectrometry
LP	Laser Profiler
RL	Right Lane;
LL	Left Lane
SPT	Standard Proctor Test;
MPT	Modified Proctor Test;
M	Mean
SD	Standard Deviation

1. Introducción y Estado del Arte

La población mundial superó los 7200 millones de personas en 2018 [1], y se estima que alcance los 8500 millones de personas en el año 2030 [2]. A principios del siglo XX el consumo de materias primas que no fueran combustibles o comida era de 7000 millones de toneladas con una población de 1650 millones de personas [3], en el año 2017 se llegó a un total de 90.000 millones de toneladas con una población de 7200 personas [4]. El alarmante ritmo de consumo de materias primas unido al crecimiento de la población y la contaminación ambiental hacen insostenible el actual modelo de desarrollo, de ahí la necesidad de introducir medidas que minimicen los daños causados al planeta. El nuevo paradigma de economía circular pretende reducir el consumo de recursos naturales y fomentar el reciclado de materiales, dándole a los residuos una segunda vida. El 50 % de todos los recursos mundiales se destinan al sector de la construcción, es por esto que se están comenzando a implementar procesos que permitan aumentar el ciclo de vida de las materias primas [5].

La generación de residuos de la construcción y demolición (RCD) a nivel europeo supone entre el 25-30% de todos los residuos generados [6], en el año 2016 unas 923 millones de toneladas de RCD fueron generados en Europa [7], mientras que en España se generaron unos 35 millones de toneladas en 2016 [7], el nivel de reciclado de los RCD en España es bajo (en torno 30-40%) lo cual está lejos del objetivo de la directiva marco de residuos [8] que lo fijaba en un 70% para el año 2020 [5], esto hace necesario que se consideren nuevos usos para estos residuos ya que de no ser así, su principal destino es el relleno de grandes superficies del territorio originando graves daños sobre nuestro ecosistema presente y futuro. El reciclado de RCD haría el consumo de áridos naturales producidos se redujera, siendo esta la una alternativa sostenible. El concepto de sostenibilidad se basa en la minimización de los recursos consumidos, la disminución de las actividades que dañen el medio ambiente y la protección de la salud [9,10].

La producción mundial de áridos prácticamente se duplico desde el año 2007 a 2014, pasando de 21.000 millones de toneladas a 40.000 millones de toneladas. En Europa la producción alcanzo las 2.660 millones de toneladas [11], mientras que en España la producción total de áridos alcanzo los 112 millones de toneladas en el año 2017 según la Asociación nacional de empresarios fabricantes de Áridos (ANEFA), de los cuales solo un millón de toneladas era de áridos reciclados (AR) de RCD [12], lo que representa un 0,4% del total de áridos naturales (AN) producidos.

La extracción de áridos daña el medio ambiente, afectando a los paisajes eliminando especies vegetales y animales, así mismo, la propia extracción genera más residuos, aproximadamente por cada metro cúbico de árido extraído se produce unos 2400 kg de residuos [13], esta cantidad tan elevada se alcanza al considerar el rechazo que se genera en la planta de tratamiento durante el proceso de fabricación, dependiendo del uso que vaya a tener el árido se generarán más o menos cantidad de residuos, además los lodos procedentes del lavado del material no son susceptibles de uso, el propio proceso de extracción genera la necesidad de rehabilitar los frentes explotados, con lo que se producen residuos adicionales

El uso eficiente de las materias primas es uno de los mayores retos que tiene el sector de la construcción para conseguir un sector sostenible [14], los mayores problemas que presenta la construcción es el excesivo consumo de recursos no renovables procedente de canteras y graveras fluviales y la gran cantidad de residuos generados, una tercera parte de los residuos generados en la Unión Europea son generados por la construcción [15], La economía circular promueve el uso de los materiales reciclados en sustitución de la explotación de los recursos naturales, como en el caso de Europa estas políticas están siendo promovidas [16]. Esta orientación implica darle diferentes vidas útiles a los recursos con unos estándares altos de calidad en el producto [17,18].

La Figura 1-1 se muestra cómo sería este proceso, los áridos naturales que formen parte de la infraestructura son empleados de manera continua en las posteriores rehabilitaciones. Así mismo, las demoliciones de edificaciones y obras de ingeniería civil están compuestas de una diversidad de materiales como pueden ser: madera, metales, vidrio, asfalto, tierras de excavación, hormigón, cerámicos, plásticos, etc. Una vez que estos residuos son tratados retirando las impurezas y posteriormente machacados y triturados para adquirir una adecuada granulometría pueden ser reutilizados, haciendo que no sea necesario llevar a vertedero estos residuos y logrando una valorización de los mismos, consiguiendo que se inicie un círculo virtuoso que elimine la espiral del consumo sin retorno (economía lineal).

Figura 1-1 Economía circular aplicada al sector de la construcción de obras de infraestructuras

La presente tesis va a estudiar el empleo de materiales procedentes de residuos de construcción y demoliciones en capas de bases y subbases granulares, ya que la reutilización de los materiales procedentes de excavación es un objetivo prioritario dentro del Plan de Residuos de la comunidad autónoma andaluza que a su vez viene impuesto por el legislador europeo. En primer lugar, se estudiará el empleo de áridos mixtos mezclados con tierras procedentes de excavaciones en un tramo experimental de carretera, se controlará su puesta obra, para posteriormente auscultarlo durante un periodo de siete años con equipos de Auscultación de alto rendimiento, como son el deflectómetro de impacto y el perfilómetro laser.

Por otro lado, dado que la fracción fina procedente del rechazo en el machaqueo de los RCD tiene altos contenidos de mortero e impurezas que hacen que no sea recomendable su utilización en capas granulares, se va a ejecutar un estudio en un tramo de carril bici para ver su evolución a lo largo del tiempo, y contrastar si es posible su empleo en vías de baja capacidad. Para ello se controlará la puesta en obra de todas las capas del firme y posteriormente se controlará la evolución de las deflexiones en un periodo de dos años.

Por último, debido a que no se conocen casos previos de demoliciones de edificaciones que son aprovechadas in-situ para construir las capas granulares de una vía de alta capacidad (tráfico T2) se va a estudiar un tramo experimental de carretera construida con áridos reciclados de residuos de demolición de edificaciones reciclados in situ con una planta móvil. Para ello, se hará un estudio de caracterización de materiales, se controlará la puesta en obra de los materiales y se vigilará su evolución a través de la medida de deflexiones y auscultando la regularidad superficial durante siete años a partir de su apertura al tráfico.

1.1. Estado del Arte en el uso de los RCD

Los AR son los productos obtenidos a partir del tratamiento de los RCD. Las propiedades físico-mecánicas y químicas de los AR dependerán de su composición y del proceso de tratamiento realizado en planta [19]. Los AR según su composición se pueden clasificar según se indica en la Tabla 1-1.

Tabla 1-1 Clasificación de AR en función de su composición [20]

Tipo/categoría	ARH	ARM	ARC	ARA
Composición (EN 933-11)	Rc+Ru≥90%	Rc+Ru+Ra≥70%	Rc+Ru+Ra≤70%	Rc+Ru+Ra≥90%
	Rb≤10%	Rb≤30%	Rb≥30%	
	Ra≤5%	Ra≤15%	Ra≤15%	Ra≥50%
	X_o+ X_g≤1%	X_o+ X_g≤1,5%	X_o+ X_g≤1,5%	X_o+ X_g≤1%
	X_g≤0,5%	X_g≤1%	X_g≤1%	X_g≤0,5%
	FL≤0,2%	FL≤0,5%	FL≤0,5%	FL≤0,5%

ARH: Árido reciclado de hormigón; ARM: Árido reciclado mixto; ARC: Árido reciclado cerámico; ARA: Árido reciclado asfáltico.

La nomenclatura utilizada para los componentes es:

- Rc = Hormigón, productos de hormigón, morteros Piezas para fábricas de albañilería de hormigón
- Rb = Piezas para fábrica de albañilería de arcilla (es decir, ladrillos y tejas). Piezas para fábrica de albañilería de silicato de calcio Hormigón celular no flotante.
- Ra = Materiales bituminosos.
- Ru = Áridos no ligados.
- FL = Material flotante en volumen.
- Xo= Madera, vidrio, plásticos, metales y otras impurezas.
- Xg = Yeso

La densidad y la absorción de agua de los AR está íntimamente ligado a su composición [20], Comparando los AR con los AN se tiene que los AR tienen densidades de compactación inferiores a los AN mientras que la absorción de agua es superior como se puede apreciar en varios trabajos experimentales en los que se ha comparado el comportamiento de ambos materiales [21–26], con la salvedad del ARA que presenta absorciones similares a los AN [27].

La granulometría es una propiedad muy importante en los materiales no ligados empleados en capas de base y subbase de caminos, sin embargo no es una propiedad limitante para los AR, el coeficiente de forma y porcentaje de partículas trituradas tampoco son limitantes para su empleo en firmes de carreteras [20,28]. En cuanto a la resistencia a la fragmentación medida mediante el ensayo de Los Ángeles (LA), se tiene que los ARH y los ARA suelen tener un valor inferior al 40%, mientras que los ARC y ARM suelen superar este límite, debido al alto contenido de mortero adherido que tienen los ARM y al mortero de albañilería que normalmente acompaña a los ladrillos cerámicos (ARC).

Los AR suelen ser no plásticos, al carecer los residuos de los que proceden de plasticidad.

Las propiedades químicas de los ARM-ARC difieren de las de los ARH en lo que se refiere a contenido de compuestos de azufre, siendo esta una propiedad limitante en los ARM-ARC ya que puede comprometer la estabilidad volumétrica y estructural. Los yesos y morteros presentes en los ARM aportan gran parte de los sulfatos y compuestos de azufre, no obstante se ha identificado que para porcentajes de hasta un 4% de los sulfatos no se producen problemas de inestabilidades en capas granulares de firmes de caminos agrícolas y carriles bici [22], la realización de un pre-cribado de la fracción fina antes de la trituración de los RCD mixtos reducirá la presencia de sulfatos en los ARM [29].

En cuanto al contenido de materia orgánica, esta suele estar entre 0,42-1% y no es una propiedad limitante para el empleo de los AR en obras de infraestructura lineal [20].

1.2. Definición de los RCD

Los RCD son los residuos generados por la construcción, renovación y demolición de edificios y de infraestructuras de ingeniería civil; puentes, carreteras, canales, conducciones, ferrocarriles, etc. El término RCD identifica lo siguiente:

- Residuos de demoliciones totales o parciales de edificios y obras lineales;
- Escombros producidos durante la renovación o construcción de edificios e infraestructuras civiles;
- Residuos generados en la conservación de carreteras

Los RCD pueden incorporar materiales como hormigón, asfalto, ladrillos, cerámicos, escayola, vidrio, yeso, metales, plásticos, madera, tierras de excavación y rocas naturales. Ejemplos de RCD y sus constituyentes son dados por la Agencia de Protección ambiental de Estados Unidos [29]. El asfalto, hormigón, cerámicos y áridos no ligados son materiales inertes constituyentes de los RCD y con un alto potencial de reciclado, mientras que el yeso, vidrio, metales, plásticos y madera son normalmente consideradas impurezas [30,31]

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, ladrillos, tejas y materiales cerámicos.

17 02 Madera, vidrio y plástico

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

17 04 Metales (incluidas sus aleaciones).

17 05 Tierra (incluida la excavada en zonas contaminada), piedras y lodos de drenaje

17 06 Materiales de aislamiento y materiales de construcción que contienen amianto.

17 08 Materiales de construcción a partir de yeso.

17 09 Otros residuos de construcción y demolición

1.3. Marco legislativo

1.3.1. Marco legal comunitario

La directiva 75/442/EEC del año 1975 fijo una primera definición para los residuos que fue "cualquier sustancia u objeto del cual su poseedor se desprenda o tenga la intención o la obligación de desprenderse" así mismo fija el concepto de que "quien contamina paga". Posteriormente en el año 2008 se aprueba la directiva 2008/98/CE, en la que se fija como objetivo el transformar a la Unión Europea en una "sociedad de reciclado, evitando que trate de evitar la generación de residuos y que utilice los residuos como un recurso", se propone la separación en origen de los residuos antes de someterlos a operaciones de valorización, así mismo se establece una jerarquía descrita por la pirámide de la siguiente figura 1-2:

Figura 1-2 Pirámide de Jerarquía en la gestión de los residuos [33]

La actual directiva europea de residuos, fija para 2020 el objetivo de aumentar a un mínimo del 70% "la reutilización, el reciclado y otra valorización de materiales, incluidas las operaciones de relleno que utilicen residuos sucedáneos de otros materiales, de los residuos como sucedáneos de otros materiales, de los residuos no peligrosos procedentes de la construcción y de las demoliciones, con exclusión de los materiales presentes de modo natural en la categoría 17 05 04 de la lista de residuos", por tanto las tierras procedentes de excavaciones del terreno natural quedan excluidas del concepto de RCD según esta directiva, el objetivo para la reutilización en obras de restauración y de tierra para las tierras y piedras procedentes de la excavación se fija en un 90%, por lo que una línea que investigará la presente tesis es el empleo de mezclas de tierras procedentes de excavaciones con RCD.

1.4. Marco legal estatal

El R.D. 1481/2001 regula la eliminación de residuos mediante depósito en vertedero, básicamente regula la manera en que se deben depositar los residuos según sea la naturaleza de estos; inertes, peligrosos y no peligrosos. El R. D. 105/2008 [34] regula la producción y gestión de los RCD, en ella se define residuo de la construcción como cualquier sustancia del que se quieren deshacer llevándolo a vertedero, así mismo se define residuo inerte como aquel que no experimenta transformaciones físicas, químicas o biológicas no es soluble ni combustible, no es biodegradable, la toxicidad del lixiviado deben ser insignificantes, se fijan una serie de obligaciones para el poseedor de residuos entre las que hay que destacar a que los residuos se deben separar en las siguientes fracciones:

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.

Esta separación es preferible en origen es decir en la obra, de esta manera se facilita la reutilización de estos residuos.

En España las directrices sobre reciclado se fijan en el Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016-2022 [33]. Anteriormente estuvieron en ejecución el I Plan Nacional de RCD del 2001 al 2006 y el II PNRCD desde el año 2007 hasta el 2015. El PEMAR ha sido aprobado por el Ministerio de Agricultura, Alimentación y Medio Ambiente. Con respecto a los RCD se plantea la necesidad de estudiar las siguientes cuestiones:

- Reducción del volumen de RCD destinados a operaciones de relleno y a vertedero

- Integración de costes ambientales en el precio de los materiales naturales, a fin de aumentar el empleo de los materiales reciclados

- Se promoverán nuevas normas que garanticen la calidad y seguridad de los materiales reciclados empleados.

Para conseguir estos objetivos se proponen las siguientes políticas:

- Fomentar la demolición selectiva, para realizar una separación adecuada en origen de manera que se facilite la reutilización de los materiales.

- Promover el uso de materiales de RCD en capas no ligadas de obras lineales, se establece el objetivo de emplear un 5% de AR en obras públicas y privadas.

- Desarrollo de proyectos de I+D+i que favorezcan la transformación de los RCD en materiales reciclados de alta calidad y durabilidad.

Figura 1-3 Economía circular (Plan Estatal de Gestión de residuos) [33]

Con respecto a la normativa técnica vigente, se tiene que en el artículo 510 del Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3), en vigor a partir de la Orden FOM/2523/2014 de 12 de diciembre, se permite el uso de AR como capa de zahorra para las categorías de tráfico T2 a T4 (< 800 vehículos pesados/día), no obstante los límites físicos y químicos no están adaptados de una manera acorde a la naturaleza de los AR, ignorando por tanto que el comportamiento de los AR y los AN es distinto. El artículo 513 se permite el empleo de AR en capas tratadas con cemento, estos AR deben de contar con un documento que justifique su origen, la idoneidad de sus características para el uso propuesto, su correcto tratamiento y que no se encuentran mezclados con otros contaminantes. La normativa estatal presenta problemas para el empleo de los AR en obra, ya que impone límites físico-mecánicos y químicos que entorpecen su empleo siendo recomendable su modificación con objeto de que puedan reutilizarse estos materiales reciclados. Por otro lado, el marco legal estatal se encuentra incompleto al no haberse desarrollado el fin de la condición de residuo (artículo 5 ley 22/2011), no pudiéndose pasar a denominar estos AR como productos para de esta manera ser utilizados sin restricciones en el nuevo paradigma de la economía circular.

1.5. Marco legal autonómico

El Reglamento de Residuos de Andalucía aprobado con el Decreto 73/2012, regula la producción, posesión y gestión de los residuos que se generen en Andalucía, se rige por los principios de jerarquía ya vistos en la directiva europea 2008/98/CE reflejados en la Figura 1-2

Andalucía dispone de un Plan director Territorial de Residuos no peligrosos 2010-2019, fue aprobado el 2 de noviembre mediante el Decreto 397/2010.

El Decreto 397/2010, de 2 noviembre, por la que se aprueba el Plan Director Territorial de residuos no peligrosos de Andalucía 2010-2019, este documento incide nuevamente en el principio de jerarquía, en lo que respecta a los RCD plantea como actividad fundamental la separación en origen de los residuos. La Consejería de Obras Públicas y Vivienda de la Junta de Andalucía a través de la empresa pública Gestión de Infraestructuras de Andalucía, S.A. publicó en el año 2010 el documento "Recomendaciones para la redacción de pliegos de especificaciones técnicas para el uso de materiales reciclados de residuos de la construcción y demolición (RCD)", estas especificaciones son una caracterización de los distintos tipos de AR que se pueden emplear para formar capas no ligadas de firmes, el origen de la necesidad de estas especificaciones que difieren de lo establecido en PG3 con respecto a las propiedades físicas y químicas exigidas para los materiales que forman las capas no ligadas, se fundamenta en el hecho de que si no se modifican los límites fijados por esta norma los AR no podrán ser empleados en obra de pavimentos.

Posteriormente en el año 2012 la Agencia de Obra Pública de la Junta de Andalucía (AOPJA) adjudicó, en la convocatoria de proyectos de I+D+i para los años 2011-2013 de la Consejería de Obras Públicas y Vivienda el proyecto de título "Aplicaciones de los Áridos Reciclados de Residuos de Construcción y Demolición (RCD) para la construcción sostenible de Infraestructuras Viarias en Andalucía Central" a la Universidad de Córdoba y en el que participó el Centro de Estudios de Materiales y Control de Obra (CEMOSA) y la Asociación de Empresas Gestoras de RCD de Andalucía (AGRECA). El objetivo fundamental de este proyecto era el de fomentar el uso de los AR de RCD en obras lineales, como resultado de este, se han redactado los siguientes documentos:

- "Guía de áridos reciclados de residuos de construcción y demolición (RCD) de Andalucía Central"
  Es un estudio de laboratorio sobre distintas muestras de AR en el que se analiza su comportamiento en laboratorio frente a la adición de cemento, cal y yeso, fue publicado en el año 2015.
- Guía de Buenas Prácticas en la Gestión y Tratamiento de Residuos de Construcción y Demolición (RCD)"

Esta guía da a conocer a todos los agentes involucrados en la gestión de los RCD las obligaciones que tienen, Los AR de RCD se fundamentan en una demolición selectiva y una correcta separación, el tratamiento a disponer depende del material de AR que se quiera obtener, para zahorras y suelos mixtos bastará con disponer de pretratamiento con criba y machacadora de mandíbulas, para obtener gravas y arenas se deberá disponer de un molino de impacto para así conseguir un AR con una granulometría más homogéneo.

- "Catálogo de Firmes y unidades de obra con áridos reciclados de Residuos de Construcción y Demolición (RCD)".

  Este catálogo define los distintos tipos de AR que se pueden tener en función de sus características físico-mecánicas y químicas, determinando los espesores necesarios de cada capa de AR a disponer en función del tipo de vía y tráfico que se requiera, facilitando secciones de firme con AR de RCD para vías de tráfico T2-4, caminos Rurales, Acerados y Vías peatonales, vías ciclistas y rellenos zanjas drenantes y urbanas.

Por último en el año 2017 se actualizan las Recomendaciones para la redacción de pliegos para el uso de materiales reciclados de RCD, como variaciones más significativas se modificó el límite del Coeficiente de Desgaste de Los Ángeles (CDLO) desciende a 40 para zahorras recicladas de hormigón (ZRH) y para zahorras recicladas mixtas (ZRM) pasa a 45 en vías ciclistas y 40 para el resto de vías, con respecto a los parámetros químicos en zahorras se pasa de un porcentaje máximo de azufre total del 1%, llegando a 1,3% para zahorras de hormigón y mixtas tipo I, llegando al 1,8% para zahorras mixtas tipo II, así mismo se limita el contenido de sulfatos solubles en agua 0,7% para zahorras que no puedan afectar a hormigones próximos y 0,5% en el resto de casos. El contenido de materia orgánica en zahorras pasa a un 1% para zahorras de hormigón y mixtas tipo I y un 2% para las mixtas tipo II.

Figura 1-4 Guías y Catálogos publicados sobre RCD.

1.6. Proceso de tratamiento de los RCD

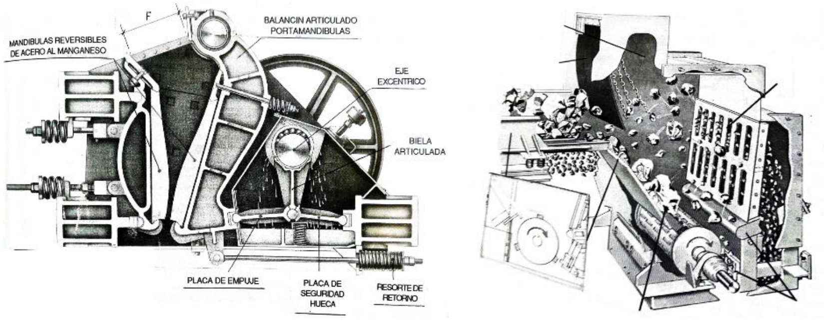
El tipo de RCD y la calidad obtenida depende fundamentalmente del método de demolición empleado. La separación de los residuos en origen tiene un impacto fundamental en la calidad de los AR obtenidos. Habitualmente la demolición de un edificio o una infraestructura entraña el uso de explosivos, excavadoras, bolas de derribo, cizallas hidráulicas y ripadores. Los residuos resultantes son una mezcla de hormigón, plásticos, metales, cerámicos, tejas, escayolas, ladrillos, madera y otros. En las demoliciones selectivas necesariamente se emplean trabajadores que operan con maquinaria ligera, de esta manera se logra la separación de los materiales procedentes de la demolición. Este procedimiento suele ser más caro y de duración más larga que con la demolición convencional, sin embargo, se obtienen RCD con menos impurezas que hacen que tengan una mayor calidad consiguiendo una mayor tasa de recuperación. En ambos casos la retirada de materiales no deseados es previa a la transformación de los RCD.

Los RCD son transformados en AR en plantas de tratamiento. Existen tres niveles de tratamiento según la comisión Europea [6] (Figura 1-6). El nivel 1 consiste en plantas de machaqueo móviles provistas de algún tipo de tamizado, este nivel es el más básico y normalmente es empleado directamente en el lugar donde se ejecutan las obras. El nivel 2 se corresponde con plantas fijas que disponen de una mayor capacidad de producción, disponen de retirada de metales mediante el empleo de electroimanes además del machaqueo y cribado por tamaños, se corresponde con el tratamiento primario recogido en la Guía de Buenas prácticas [28]. En el nivel 3 se incluye el triaje manual para realizar una separación más efectiva que la realizada en el nivel 2, además se emplean supresores de polvo y lavadoras, se correspondería con el tratamiento secundario de la Guía de Buenas Prácticas [29].

Las plantas de tratamiento pueden recibir RCD con una composición más homogénea, es decir con hormigón o fresado de firme limpio de otros elementos, o por el contrario un RCD mixto formado por distintos materiales, en este caso se separan los elementos más grandes mediante el empleo de grúas y excavadoras, para posteriormente reducir el tamaño de los escombros mediante una trituración o machaqueo. Dependiendo del producto que se quiera obtener existen dos tipos de trituradoras que se pueden emplear:

- Machacadora de mandíbulas (Figura 1-5 (a)), se compone de dos placas que comprimen el material reduciendo el tamaño del RCD. Este tipo de trituración genera un árido con un bajo contenido de finos, inferior al 10%.
- Molino de Impacto o trituradora de impacto (Figura 1-5 (b)), este tipo de trituración permite obtener áridos con una granulometría más homogénea y con un porcentaje más elevado de finos.

Durante las operaciones de machaqueo y cribado se producen grandes cantidades de polvo, las plantas de tratamiento de RCD disponen de dos métodos para reducir el polvo, las campanas de succión y los rociadores de agua [36,37].



(a) (b)

Figura 1-5 Tipos de trituraciones de RCD. (a) Machacadora de mandíbulas, (b) Trituradora de impacto. [39]

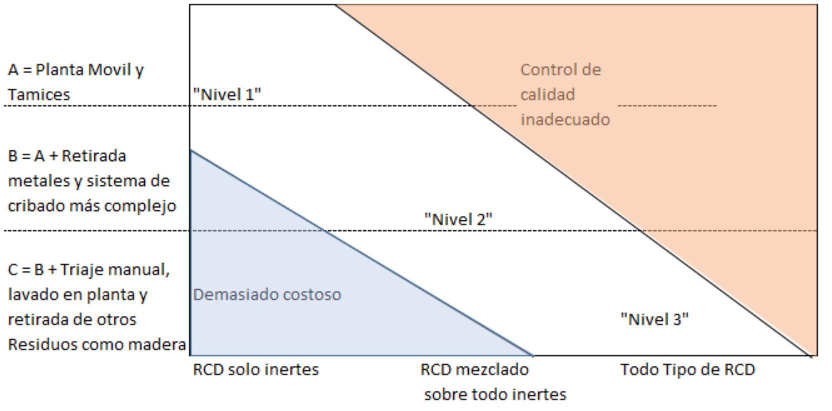


Figura 1-6 Plantas de tratamiento según informe para la comisión Europea [6]

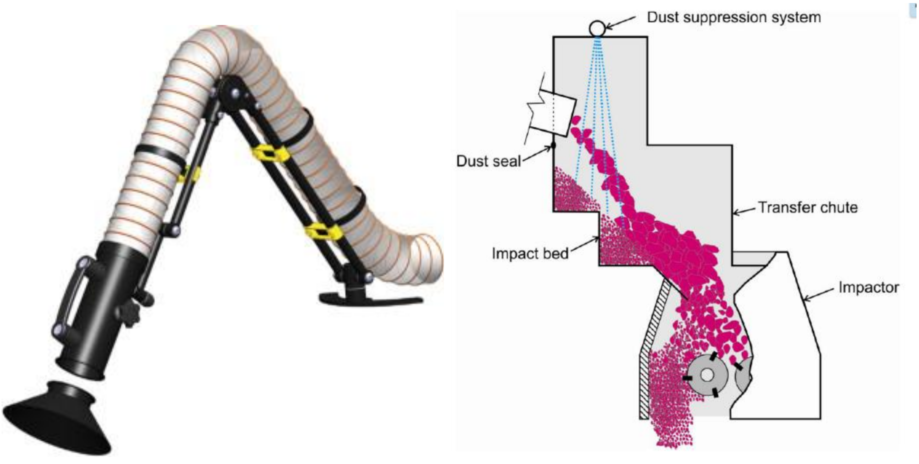


Figura 1-7 Sistemas de tratamiento del polvo, (a) campana de succión [34]**, b rociadores de agua** [35]

Las investigaciones sobre nuevas plantas de tratamiento están centradas en distintos aspectos. Existen estudios específicos sobre eficiencia en plantas de reciclado de RCD, en lo relativo a aspectos técnicos [39–41], viabilidad económica [42–45] e impacto medioambiental [46,47]. Actualmente las investigaciones se están centrando en la manera de obtener unos AR de una calidad superior [48,49].

1.7. Aplicaciones de los Áridos reciclados de RCD.

La reutilización de los RCD entraña beneficios medioambientales, como son la reducción de la explotación de materias primas no renovables y la disminución en el relleno de vertederos.

Aunque el reciclado de los RCD implica una ventaja medioambiental significativa, hay una gran deficiencia en el uso de materiales derivados de los RCD en obras de ingeniería y arquitectura. El coste añadido que necesitan los materiales procedentes de los RCD en comparación con los procedentes de materiales naturales son una barrera para su empleo [50,51], esto se ve agudizado en países en los que el precio de las materias primas es bajo [52], el uso más habitual de los AR de RCD es como capas no ligadas en la construcción de carreteras y caminos [20], no obstante existen otros usos para estos áridos reciclados en rellenos de zanjas y hormigones [11,53,54]. Otro motivo significativo para el no empleo de los AR de RCD es debido a las restricciones existentes en la normativa, en el caso de España el PG-3 limita los contenidos de materia orgánica, compuestos de azufre, sales solubles, desgaste de los Ángeles y granulometrías a unos valores que hace que para la mayor parte de los AR de RCD no se puedan emplear como capas no ligadas de pavimentos. Se viene empleando AR en capas de firme no ligadas desde hace veinte años [52], no obstante, en España su empleo aún no se ha generalizado siendo necesario la realización de un mayor número de investigaciones a escala real que garanticen su estabilidad y durabilidad en condiciones reales de tráfico en la intemperie. Estos tramos, además de generar conocimiento científico-técnico son un demostrativo para ingenieros proyectistas y directores de obra.

1.7.1. Áridos reciclado de RCD en hormigones y morteros

Los AR están muy limitados por sus propiedades físico-mecánicas para su empleo en hormigones según las normativas internacionales. Una adecuada distribución granulométrica contribuye a mejorar la resistencia mecánica del hormigón amasado [55], la fracción gruesa obtenida en la trituración del RCD suele cumplir con las graduaciones que fijan las normas UNE y ASTM [56].

La fracción fina de los AR y la adherencia de estas partículas sobre la parte gruesa puede generar que se necesite más agua de amasado y disminuir la adherencia entre el cemento y el árido. Las recomendaciones RILEM [57] y las especificaciones de Hong Kong [58] fijan un límite del 5% para el contenido de partículas finas de tamaño inferior a 4 mm en el árido grueso total.

Los valores de absorción de los AR son superiores a los de los AN estando estos en el intervalo 10-40% [59], se incumple el límite del 5% que fija la EHE, las recomendaciones RILEM suben este límite hasta el 10%, la norma alemana [60] es del 10% para ARH y el 15% para el ARM. El empleo de AR reduce la trabajabilidad de la amasada, esto se debe a la mayor absorción de agua con respecto a los AN [61,62]. Esta mayor absorción se traduce en decrementos en la resistencia a compresión de un 15% para amasadas de hormigones con un 20% de AR [63]

Las impurezas presentes en los AR producen bajadas en la resistencia mecánica del hormigón, así mismo en función del elemento se pueden producir otras patologías, como son las reacciones álcali-árido en presencia de vidrio, ataque por sulfatos debido al yeso, elevadas retracciones por arenas arcillosas. Generalmente los ARH tienen menos impurezas que los ARM. La EHE [64] limita el contenido de partículas ligeras al 1% del peso total de las muestras, al 0,25% el contenido de restos de arcillas y al 1% los compuestos totales de azufre. Las recomendaciones australianas para el empleo de AR en la producción de hormigón [65] establece que el contenido máximo de impurezas debe ser inferior al 2%, otras normas como las recomendaciones RILEM las de Hong Kong o Belgas establecen un máximo del 1% para los ARH, Las recomendaciones RILEM establece un 5% para los ARM, la norma británica [66] fija un máximo del 1% en impurezas.

Existen diversas investigaciones para el uso de AR en morteros y hormigones, lo habitual es reutilizar las demoliciones de hormigones en nuevos hormigones una vez que han sido procesadas mediante el machaqueo. La resistencia a compresión no se ve afectada si la tasa de reposición del AN por AR no supera el 30% [67–70]. Sagoe-Crentsil y col. [71] realizaron un estudio de laboratorio donde se compararon probetas de hormigón hechas con AR y con AN de origen basáltico y no encontraron diferencias significativas en las resistencias a compresión y a tracción.

La EHE-08 [64] solo permite el empleo de hasta un 20% de AR si el origen de este es de demoliciones de hormigones el AR mixto no está permitido. En el estudio realizado por Rodríguez-Robles y col. [72] se comprobó que los hormigones amasados con ARM tenían unas propiedades similares al del hormigón estructural. El uso de AR en bloques y ladrillos en una tasa de reposición de hasta el 50% no represento mermas en las resistencias a compresión [73]. La resistencia a la abrasión en muestras de mortero realizadas con AR cerámico obtiene mejores resultados que el AN aunque menor resistencia a la compresión [74]. La durabilidad del hormigón se ve comprometida por el empleo de la fracción fina de los AR según el estudio realizado por Bravo y col [75]. Como conclusión se puede decir que la sustitución parcial del árido grueso natural de los hormigones por AR es factible, siendo contraproducente el empleo de la fracción fina cuando su origen es cerámico ya que inhiben el pegado del cemento con las partículas más gruesas del esqueleto mineral del hormigón, favoreciendo el ataque por carbonatación y mermando su resistencia a compresión.

En cuanto a los morteros, se ha determinado el máximo porcentaje de fracción fina de ARH a disponer en su amasado. En el estudio de Ledesma y col. [76] se verifico que las propiedades mecánicas del mortero dosificado con hasta un 50% de fracción fina de ARH no se veían mermadas en relación con el mortero amasado con arenas naturales, la misma proporción del 50% de arena de fracción fina de ARC fue verificada como aceptable en morteros de albañilería [77].

1.7.2. Áridos reciclados en rellenos tipo en terraplén y zanjas

La fracción fina de los AR es únicamente empleada en el relleno de zanjas y como cama de apoyo de tuberías. En estas zonas los requerimientos normativos para los AN son limitados, fijando el art. 510 del PG-3 que el material no sea plástico en capas de zahorras, a nivel internacional en el Reino Unido existen unas recomendaciones para el empleo de AR en rellenos de zanjas y camas de tuberías [78].

Como experiencias en el empleo de AR rellenos en las camas y zanjas de tuberías de saneamiento destaca la de Rahman y col. [79], estos investigadores realizaron un estudio sobre en el que se emplearon tres tipos distintos de rellenos; Áridos reciclados de Hormigón (ARH), Áridos reciclados cerámicos (ARC) y Áridos reciclados asfálticos (ARA). Las propiedades geotécnicas y los resultados de lixiviación permiten emplear los ARH y ARC, el ARA no cumplió el límite de desgaste de Los Ángeles al ser superior a 35.

Los contenidos de sulfatos y cloruros son las propiedades más limitantes para el empleo de los AR en zanjas de tuberías, sin embargo Viera y col. [80,81] realizaron dos investigaciones con la fracción fina (tamaño máximo 10mm) a partir de ARM, los resultados obtenidos en laboratorio y al cabo de un año expuestos a la intemperie, en lo que respecta a resistencia al corte y adherencia son similares a los de los rellenos con AN, el estudio de lixiviados arrojo un contenido en sulfatos de 3200mg/kg, por lo que estos rellenos de ARM puedan emplearse en la proximidad de otros hormigones no sulforresistentes.

Durante los años 2012-2014 se desarrolló el proyecto Arco [82], en el cual, participó: la empresa de abastecimiento de agua Emasesa (Sevilla), la constructora Contrat, el laboratorio de control de materiales Vorsevi, la empresa de reciclado de materiales de la construcción Aristerra y la Universidad de Sevilla con los Grupos de Investigación TEP-107 "Estructuras y Geotecnia" y TEP-172 "Arquitectura: Diseño y Técnica". En este estudio se plantearon 5 tramos experimentales de conducciones de abastecimiento y saneamiento de distintos materiales: Fundición Dúctil, PVC, Polietileno, Hormigón y Gres, los rellenos se harían con una arena reciclada de hormigón (Ru+Rc>90%) y una zahorra reciclada mixta (Rc>50%, Rb<15% y Ra<5%) y se compararían con albero (suelo seleccionado) y arena, se midieron resultados con placa de carga estática y dinámica (deflectómetro manual) para la zahorra reciclada superiores a 100MPa para el Ev2 lo cual hace que consigan una capacidad portante similar e incluso superior a la del suelo seleccionado, sin embargo se detectaron valores elevados en contenido de iones sulfatos, superiores a 4800mg/kg lo que podría dañar otros hormigones próximos como es el caso de cimentaciones y conducciones próximas.

En el año 2016 el catálogo de firmes de RCD [54] establece que los AR empleados en camas de tuberías deben tener una serie de propiedades físicas y químicas, a este respecto se limita el contenido de Cloruros al 0,1% y el de sulfatos al 0,5% en caso proximidad con materiales ligados con cemento, el contenido de finos se limita a 10% (tamiz 0,063 mm), las impurezas máximas se limitan al 1%. Sin embargo, la fracción fina de los ARM suele tener un alto contenido de sulfatos que proviene del propio cemento del mortero lo cual hace que no sea reutilizable en estas aplicaciones, sin embargo, esta fracción fina puede potenciar reacciones puzolánicas [83], y convenientemente activada con soluciones alcalinas [84] se logran resistencias superiores a las obtenidas con conglomerantes hidráulicos.

Debido a la escasez de usos para la fracción fina de los AR más allá de su empleo en el relleno de zanjas, se tiene la necesidad de buscar nuevos usos y empleos para este material, es por esto que la presente tesis proponga el estudio de su uso como capas no ligadas de firme, para ello se estudiará el empleo de la fracción fina de un AR en las capas granulares del firme de un carril bici.

1.7.3. AR en capas no ligadas de firmes

La granulometría de los AR para su empleo como zahorra artificial debe cumplir con los límites fijados por el artículo 510 del PG-3, ZA 0/32, ZA 0/20 o ZAD 0/20. Los ARH suelen cumplir con estos límites mientras que los ARM pueden no cumplir, no obstante, esta propiedad no es limitante como ha quedado constado en varios estudios donde se han empleado ARM en capas de zahorras [21–23], la granulometría de los AR tiene una gradación homogénea lo que facilita la interacción entre las distintas partículas que forman la capa logrando una buena adhesión y un mayor grado de compactación [85]. Para lograr una buena compactación es recomendable el realizar una humectación previa de los AR.

La resistencia al desgaste medido mediante el ensayo de Los Ángeles, para los ARM es una propiedad limitante para su empleo como zahorras según el artículo 510 del PG-3 donde se limita su uso para valores superiores a 35 para tráficos T3 y T4. En los AR la parte que aporta más resistencia al desgaste es la que proviene del árido natural y la que menos aporta son los restos de mortero, en muestras de AR que no superen el 44% de mortero adherido se logra limitar el desgaste de LA al 40% [85], aunque hay autores como Barbudo y col. [86] y Vegas y col. [28] que consideran que la parte cerámica hace que la resistencia a la fragmentación disminuya, según Jiménez [20] esto no es así al ser la fracción cerámica más resistente incluso que la parte de hormigón, estos valores altos en los ARM podrían deberse al mortero adherido al cerámico.

Los AR suelen ser no plásticos al no estar mezclados con tierras de excavación, sus coeficientes de forma, partículas trituradas, equivalentes arena no son propiedades limitantes para su empleo en capas granulares de firmes de carretera [20,83].

A pesar de que los AR no cumplen con los límites en el PG-3 para el contenido de impurezas, de materia orgánica y el equivalente de arena, estas no son propiedades limitantes para el contenido habitual superior al 1% de materia orgánica y su uso como capas no ligadas en firmes de pavimentos [20,28].

El contenido de compuestos que provienen del azufre suele ser una propiedad limitante para el empleo de los AR, normalmente los ARM superan el límite del 1% para contenido de azufre total marcado por el artículo 510 del PG3 para su uso como zahorra. Vegas y col. [83] realizaron una investigación tomando muestras de AR mixto de tres plantas de tratamiento del País Vasco, se determinó que un contenido inferior al 3,74% de sales solubles no generaba problemas de estabilidad en las capas no ligadas. Los límites normativos para suelos naturales según PG-3 art. 330 son 1% para suelos utilizados por debajo de la explanada del firme mientras que en la explanada se limita a 0,2%, no parece lógico usar estos límites para los AR. Tampoco existen artículos científicos o técnicos que abalen este límite del 0,2% para materiales naturales.

La lixiviación que se produce en los AR puede ser un factor determinante para su empleo en capas de firme no ligado, por ejemplo, si hay cimentaciones construidas en zonas próximas del lugar donde se quiere emplear los AR, y además estas contienen hormigones elaborados sin cemento sulforresistente, el lixiviado de los AR podría provocar daños en estas estructuras. Para este caso, según la normativa europea [87] el límite sería de 6000mg/kg para considerarlo como inerte en un test de percolación con una relación de 10 litros de líquido por cada kg de sólido. Según el estudio prenormativo de Vegas y col. [83] se debe limitar el contenido de sulfatos solubles en agua en los AR a 4800mg/kg, el art. 510 del PG-3 establece un 0,5% de SO3 total en caso de capas ligadas con cemento próximas a hormigón no resistente al ataque por sulfatos, la Guía de áridos reciclados de Andalucía Central [88] estudio la estabilidad de AR con un 4-5% de SO3 concluyendo que el límite de compuestos de azufre podía der hasta 1,3% en caso de no existir elementos vulnerables al ataque con sulfatos.

Los AR presentan unas densidades tras la compactación menores a las de los AN, sin embargo, la humedad óptima es mayor. El comportamiento de la densidad de los ARM se ve menos afectada por la variación en la humedad que en los ARH y AN. Para mejorar la trabajabilidad es recomendable saturar los AR con agua al menos una hora antes de la compactación, esto se debe a la mayor absorción de agua que presentan estos materiales reciclados [21,85].

En cuanto a la capacidad portante de los AR de RCD medida en laboratorio con el índice de CBR, Los valores de CBR en áridos suelen cumplir la siguiente relación; AN≤ARH≤ARM [20,83,86], estas ligeras diferencias pueden tener su origen en la distinta resistencia mecánica que tienen los hormigones o partes cerámicas que componen los ARM y los ARH [20]. Vegas y col. [83] observaron incrementos en el CBR de los AR al cabo de 90 días con respecto a 4 días del 30% al 100% parece que la fracción fina cerámica del AR genera una reacción puzolánica con el hidróxido de calcio presente del hormigón.

A continuación, se describen los principales trabajos experimentales llevados a cabo en tramos reales de caminos rurales y carreteras con AR en capas no ligadas.

Arm [89] estudio en laboratorio y en tres tramos de carretera experimentales el empleo de una zahorra reciclada de hormigón (ZRH) comparando la evolución con una zahorra artificial procedente del machaqueo de granito. Los módulos elásticos de la ZRH obtenida en laboratorio fue de 200MPa, en la puesta en obra llegó a valores superiores a 800MPa a los 25 meses, las zahorras naturales no experimentan incrementos de resistencia a lo largo del tiempo.

Poon y col. [90] determinaron en laboratorio que la fracción fina del ARH, en concreto la parte inferior a 0,15mm y la existente entre 0,3-0,6mm son las más activas, obteniendo en probetas compactadas resistencias a compresión a los siete días de 1,54 y 1,32MPa respectivamente. La permeabilidad inicial del AR de hormigón tenía un valor inferior al del AN, sin embargo al cabo de 7 días, la permeabilidad del AR sufrió un descenso que la colocó en valores inferiores al del AN.

Lancieri y col. [26] estudiaron dos tramos de carretera pavimentadas ejecutadas en el año 1998, sus bases y subbases granulares se formaron a partir de AR de RCD. La Figura 1-8 muestra las dos secciones pavimentadas con mezcla bituminosa, se empleó una ZRM como base granular no plástica, la subbase granular 0/70 presentaban plasticidad para la sección de carretera 2. Los módulos de la base granular experimentó un incremento en su media en la carretera 1, pasando de 235MPa en el año 2001 a 379MPa en el año 2005, mientras que en la carretera 2 el valor del módulo de la base granular no se incrementó manteniendo en ambos años un valor medio de 300MPa, este incremento de resistencia en la zahorra del tramo 1 se explicaba por el mayor porcentaje de mortero existente en los constituyentes de este ARM un 17% frente al 13% del ARM de la carretera 2, así mismo la capa de 3cm de rodadura existente en la carretera 1 consiguió limitar el caudal de infiltración de agua y un endurecimiento superior al de la carretera 2.

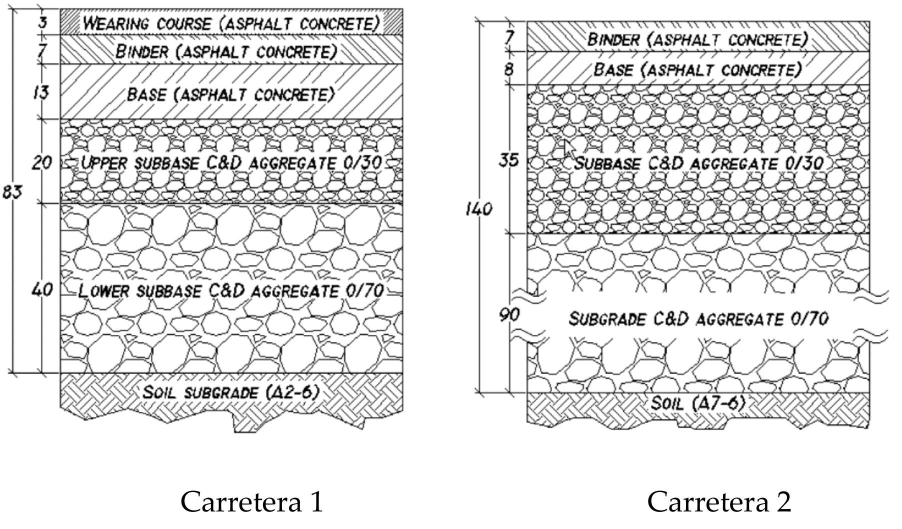


Figura 1-8 Secciones del firme en los dos tramos experimentales de Lancieri y col. [25]

Jiménez y col. [24] realizaron un estudio en un camino rural no pavimentado con mezcla bituminosa en el que se emplearon AR de RCD seleccionados (ver Figura 1-9), se obtuvieron dos AR a partir de los productos procedentes de las demoliciones de edificios, de las cimentaciones se obtuvo una ZRH, por otro lado de la estructura aérea y particiones del edificio se obtuvieron una ZRM. La ZRH y la ZRM superaban los límites de sulfatos 0,3% -0,7% respectivamente, así como el contenido de sales solubles 0,8%-1,3% respectivamente. El estudio de lixiviación obtuvo un total de 1385mg/l iones SO_4 por lo que sería catalogado como residuo no peligrosos según la Directiva 2003/33/ EC [87]. Los valores de capacidad portante fueron similares en ambas secciones, a partir de las deflexiones medias obtenidas, se consiguieron unos módulos equivalentes en el tramo 1 y tramo 2 de 420 y 489MPa respectivamente. En cuanto al índice de regularidad internacional (IRI), se aprecia que el comportamiento fue peor en la capa construida con zahorra artificial caliza (ZAC).

Jiménez y col. [23] realizaron posteriormente otro tramo experimental donde se empleó un AR de RCD no seleccionados como capa base granular (Figura 1-10), su proceso de tratamiento apenas consto de un cribado inicial y un posterior machaqueo de los escombros con tamaño superior a 40mm, por último se retiraban los elementos metálicos mediante el empleo de un electroimán, así mismo las impurezas más evidentes se retiraban manualmente, este material se empleó como base granular con un espesor de 20cm sobre otra de 25cm de AN, la sección de comparación empleaba otro AN como base granular con el mismo espesor de 20 cm. La ZRM empleada superaba los límites de contenido de yesos 2,8%, sales solubles 3,0 % y sulfatos solubles 3,3 % establecidos en el artículo 510 del PG3 para su empleo como zahorras, el estudio de lixiviación obtuvo un total de 1409mg/l iones SO4 por lo que sería catalogado como residuo no peligrosos según la directiva 2003/33/EC [87]. A partir de las deflexiones medias obtenidas se obtuvieron unos módulos equivalentes en el tramo 1 y tramo 2 de 135 y 100MPa respectivamente. En cuanto al IRI se apreció que el comportamiento fue peor en la capa construida con ZAC. Se constata que una buena selección en origen de los RCD mejora sustancialmente los resultados estructurales, se aprecia que el IRI de caminos rurales es mejor en las capas construidas con materiales reciclados, esto podría deberse a una menor resistencia a la fragmentación de los AR y su facilidad para sellar la superficie, lo que también favorece una mejor resistencia a la exposición al agua. Los resultados de lixiviados mostraron valores de residuos inertes con una baja concentración de SO4 incluso con concentraciones de yesos superiores al 1,2%.

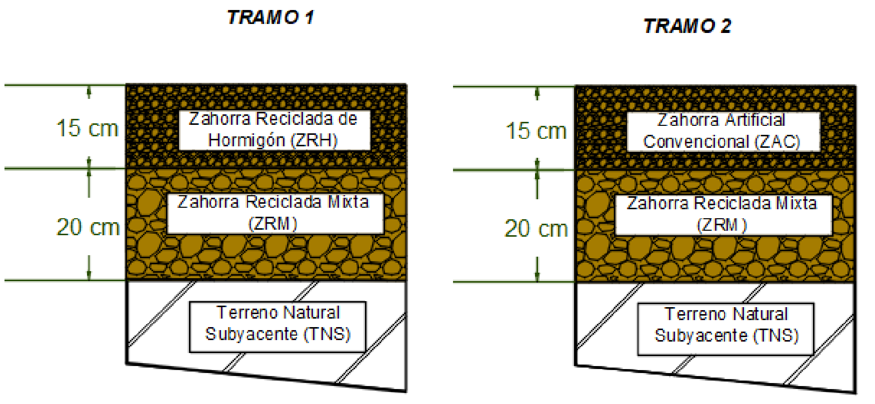


Figura 1-9 Secciones Tipo en tramo experimental con RCD seleccionados [24]

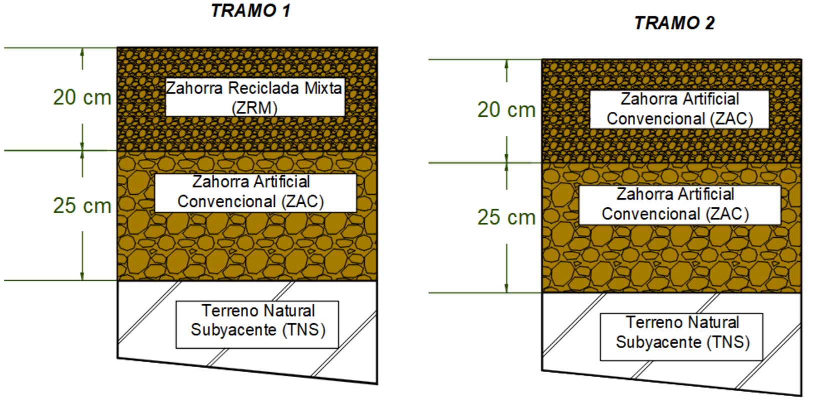


Figura 1-10 Secciones Tipo en tramo experimental con RCD no seleccionados [23]

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2. Objetivos y estructura de la presente tesis doctoral

2.1. Objetivos

El objetivo principal de la presente tesis doctoral es el estudio de tramos experimentales a escala real ejecutados con áridos reciclados de residuos de construcción y demolición (AR de RCD) mediante técnicas no destructivas de auscultación de infraestructuras viarias. De esta manera se podrán conocer tanto las características mecánicas de los materiales reciclados puestos en obras y de su influencia en la evolución de las prestaciones funcionales y estructurales de las vías ensayadas.

Los tipos de residuos empleados y técnicas desarrolladas en su reciclado, incluyendo técnicas de reciclado in-situ, no han sido previamente utilizados en otros trabajos de investigación similares. La determinación de las propiedades mecánicas de materiales puestos en obra y las recomendaciones de uso derivadas de la misma, es uno de los principales motivos por el cual la se justifica el carácter novedoso de la misma.

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

1. Caracterizar física-mecánica y químicamente todos los AR de RCD empleados en las capas no ligadas de los tres tramos experimentales construidos, prestando especial interés a la granulometría, composición de los áridos reciclados, coeficiente de descaste de Los Ángeles, absorción y densidad, índice de lajas, sulfatos solubles en agua y en ácido, compuestos totales de azufre. En uno de los tramos experimentales se estudiará la lixiviación para evaluar el comportamiento de los áridos

reciclados a corto plazo (test de conformidad), con ello se pretende estudiar las posibles afecciones que pueden generar en el medio ambiente el empleo de los RCD.

2. Estudiar en tramo real zahorras mixtas mezcladas con suelos procedentes de excavación. El estudio se realizará en una vía de servicio de una autovía, se auscultará durante siete años para verificar su viabilidad. La mezcla de AR de RCD con productos procedentes de excavación puede ser una alternativa viable para el empleo de ambos materiales en capas no ligadas de carreteras con un nivel de tráfico bajo.

3. Estudiar el comportamiento mecánico del material de rechazo producido en el proceso de fabricación de zahorras recicladas en planta de reciclaje en una vía ciclista, con objeto de demostrar la utilidad de estos materiales de rechazo en vías ciclistas, aumentando así significativamente su valor añadido. Se verificará y contrastaran los resultados de estos materiales reciclados de RCD con capas ejecutadas con suelos y áridos naturales.

4. Estudiar en vías de media-alta capacidad del uso de áridos reciclados de residuos de edificación procesados con planta móvil, tanto en la formación del cimiento del firme (explanada) como en el propio firme de la carretera. Los resultados de las capas ejecutadas con árido reciclado se compararán con zahorras artificiales convencionales con objeto de contrastar la capacidad y estabilidad de los AR de RCD con áridos naturales.

5. 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.

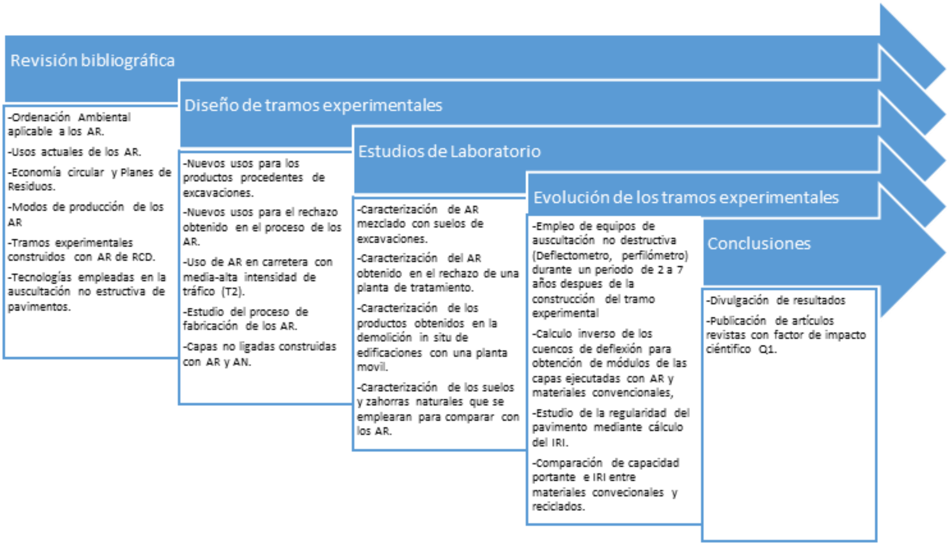

Figura 2-1 Esquema y metodología de la presente tesis doctoral

2.2. 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 y clasificadas en el primer decil dentro de su categoría.

El capítulo tercero corresponde al artículo " FUNCTIONAL AND STRUCTURAL PARAMETERS OF A PAVED ROAD SECTION CONSTRUCTED WITH MIXED RECYCLED AGGREGATES FROM NON-SELECTED CONSTRUCTION AND DEMOLITION WASTE WITH EXCAVATION SOIL", los autores son: Javier Tavira, José Ramón Jiménez, Jesús Ayuso, María José Sierra, Enrique Fernández Ledesma. Publicado en: Construction and Building Materials, en 2018, volumen 164, páginas

57-69. IF: 4.046; 9/132 Engineering, Civil (D1). Esta investigación se realiza la caracterización de dos materiales reciclados mezclados con suelos de excavaciones y de un suelo seleccionado y una zahorra artificial (objetivo 1). Estudio del proceso de obtención de los materiales reciclados (objetivo 2). Durante la construcción de la vía se controlaron densidades de compactación, humedades, se realizaron placas de carga estáticas y dinámicas. Una vez abierto al tráfico, en el tramo se controló la evolución de las deflexiones y la regularidad superficial durante un periodo de siete años, los resultados obtenidos muestran que el comportamiento de los AR mezclados con suelos de excavación es aceptable para una vía de baja intensidad de tráfico (vía de servicio).

El cuarto capítulo corresponde al artículo denominado " RECYCLING SCREENING WASTE AND RECYCLED MIXED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE IN PAVED BIKE LANES" los autores son: Javier Tavira, José Ramón Jiménez, Jesús Ayuso, Antonio López-Uceda, Enrique Fernández Ledesma. Publicado en: Journal of Cleaner Production, en 2018, volumen 190, páginas 211-220. IF: 6.395; 18/251 Environmental Sciences (D1). En este trabajo se estudia la evolución de las capas del firme de una vía ciclista, para ello se empleó la fracción fina obtenida en el rechazo de la producción de una ZRM (objetivo 3), así mismo, se empleó esta ZRM, una zahorra artificial convencional y un suelo seleccionado, los cuales fueron empleados conforme al PG-3como capas de referencia con las ejecutadas con AR de RCD. Los resultados muestran que los materiales reciclados obtenidos a partir del rechazo, así como la ZRM obtienen valores similares a los suelos y zahorras convencionales. Mediante cálculo inverso, se obtuvieron los valores de los módulos de los materiales.

El quinto capítulo corresponde al artículo " REAL-SCALE STUDY OF A HEAVY TRAFFIC ROAD BUILT WITH IN SITU RECYCLED DEMOLITION WASTE” los autores son: I. Javier Tavira, José Ramón Jiménez, Enrique Fernández Ledesma, Antonio López-Uceda, Jesús

Ayuso. Publicado en: Journal of Cleaner Production, el 1 de marzo de 2020, volumen 248, 119219. IF: 6.395; 18/251 Environmental Sciences (D1). En este artículo se estudia la evolución de las capas de cimiento del firme (explanada) y del propio firme de una carretera con tráfico pesado elevado (T2) (objetivo 4). Los materiales reciclados se obtuvieron de la demolición selectiva de más de 100viviendas unifamiliares afectadas por las obras de ampliación de pista del aeropuerto de Córdoba. Para el reciclado de los RCD se empleó una planta móvil (objetivo 4). En el tramo experimental se utilizaron ZRM, ZRH y una zahorra convencional (objetivo 4), y se estudió el riesgo de contaminación de los AR solo detectándose que el Cromo estaba por encima del límite de inertes, no superando el límite de peligroso. Se estudió la evolución de deflexiones e IRI durante un periodo de siete años, los resultados muestran que los ARM mostraron un mejor comportamiento estructural que la ZRH. La zahorra convencional es la que obtiene valores de módulos más bajos y una pero evolución con el tiempo

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

2.3. Auscultación de tramos experimentales

Se van a describir los tres equipos que se emplearon para determinar la capacidad portante, espesores y regularidad superficial de las capas estructurales de firme con materiales procedentes de RCD en los tres tramos experimentales estudiados.

2.3.1. Medida de deflexión bajo carga por impacto

Los deflectómetros son los equipos que mejor simulan la acción del tráfico sobre el firme, envían una fuerza dinámica al pavimento a través de la elevación y caída de una masa sobre una placa que está en contacto con la superficie del pavimento; esta fuerza puede ser modulada variando la altura y las pesas que se dispongan. Las marcas más habituales para estos equipos son Dynatest, KUAB y Carl Bro, mediante el empleo del deflectómetro de impacto y su posterior análisis del cuenco de deflexiones se puede determinar los módulos elásticos de cada capa que forma parte del firme [1]. El ensayo está regulado en la norma UNE 41250-3 [2].

Simulan de una manera muy realista la acción del tráfico rodado, tanto en magnitud como en tiempo de aplicación de carga, produciendo una deflexión que se aproxima a la que produce un vehículo pesado en movimiento. Así mismo, la magnitud de la precarga es muy pequeña, generalmente 8% a 18%, respecto de la carga de impulso generada antes de la liberación de la masa de impacto. Otras ventajas que hacen que estos equipos sean los preferidos en la actualidad para la evaluación estructural de firmes, es que incluyen la posibilidad de registrar el cuenco de deflexiones y el alto rendimiento en la ejecución de los ensayos pudiendo llegar a realizar más de 100 golpes por hora de trabajo.

El funcionamiento del equipo consiste en un vehículo de arrastre del tipo todo terreno, en cuya cabina se instala un ordenador personal con el software necesario para que el operador ejecute y controle cada uno de los ensayos.

Este vehículo arrastra un tráiler de medida que es el verdadero deflectómetro de impacto, con un sistema de guías capaz de levantar unas pesas a alturas variables reguladas por el operario mediante ordenador desde la cabina, una célula de carga y los geófonos colocados en una viga con situación regulable. Evidentemente en función del número de pesas empleado y de la altura a las que se dejan caer sobre la placa, se podrán obtener distintas presiones en la placa.

Las pesas al caer golpean una serie de tetones de goma unidos a la placa circular de 30 o 45 cm. de diámetro, que transmite la fuerza a la capa analizada y al paquete de firme en su conjunto.

La medida de la deflexión consiste en la evaluación de la deformación producida en la superficie del pavimento, dicha deformación se mide por medio del sensor situado en el centro de la placa, el equipo registra la lectura en micras, aunque lo habitual es dar los resultados en centésimas de milímetro.

El procedimiento operativo para la medida de la deflexión varía en función del tipo de capa que se quiera ensayar, explicándose en detalle a continuación, las directrices que se siguen en cada uno de los casos.

Figura 2-2 vista de lanza con geófonos apoyados sobre capa de zahorra

a) Vía servicio A-376

b) Carril bici Rabanales

c) Carretera CH2

Figura 2-3 Deflectómetros de impacto empleados en los tramos experimentales.

Auscultación sobre capas granulares

Una vez ubicado en el punto de ensayo, se aplican dos golpes con una tensión de contacto de 431kPa en capas de base granular y 246kPa en subbases granulares, ver tabla 2-1 carga de la Agencia de la Obra Pública [3]. El primer golpe se suele desechar, a continuación, como el equipo no genera la tensión exacta se procede a normalizar la deflexión para el valor de carga requerido (ver tabla 2-1).

El plato de carga utilizado en este tipo de capas será de 450mm de diámetro y la configuración de los geófonos a lo largo del eje de simetría del vehículo es la siguiente:

0mm	300mm	450mm	600mm	900mm	1200mm	1500mm

Cuando se detectan puntos con deflexiones superiores a la deflexión teórica esperada, se puede proceder a recompactar la capa evitando que con el extendido de las capas posteriores se produzca un hundimiento parcial del firme, el cual comprometerá la vida útil de la vía.

Auscultación sobre capas de mezcla asfáltica

En cada punto de ensayo se realizan dos golpeos con una presión de contacto de 693 kPa, carga la Agencia de la Obra Pública [3] (ver tabla 2-1). El primer golpe habitualmente no se utiliza, empleándose solo el segundo golpeo. Las deflexiones se normalizan a la presión requerida en la tabla 2-1. El plato de carga utilizado en este tipo de capas es el de 300mm de diámetro y la configuración de los geófonos es la siguiente:

0 (plato) 300 450 600 900 1200 1500 mm

Los resultados obtenidos se presentan en una gráfica de barras en la cual se indican las deflexiones reales obtenidas (barras) y la deflexión teórica, de esta manera si las deflexiones obtenidas quedan por debajo de la teórica se dispone de una capacidad portante superior a la teóricamente esperada.

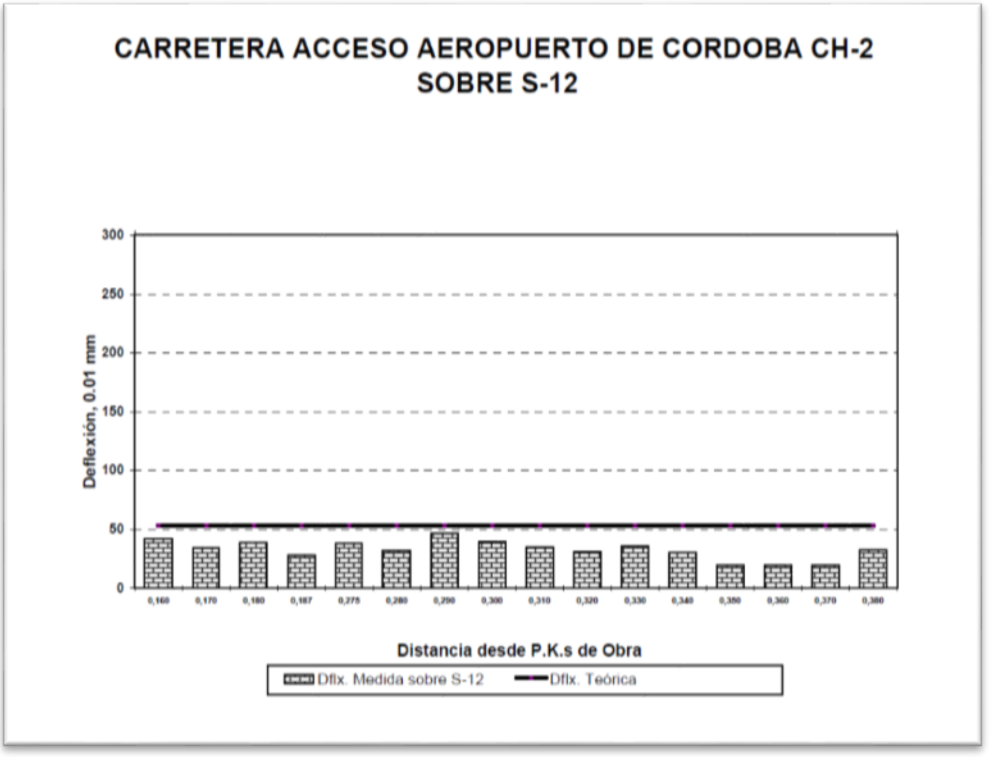

Figura 2-4 Gráfico de deflexiones de tramo de investigación de la CH2.

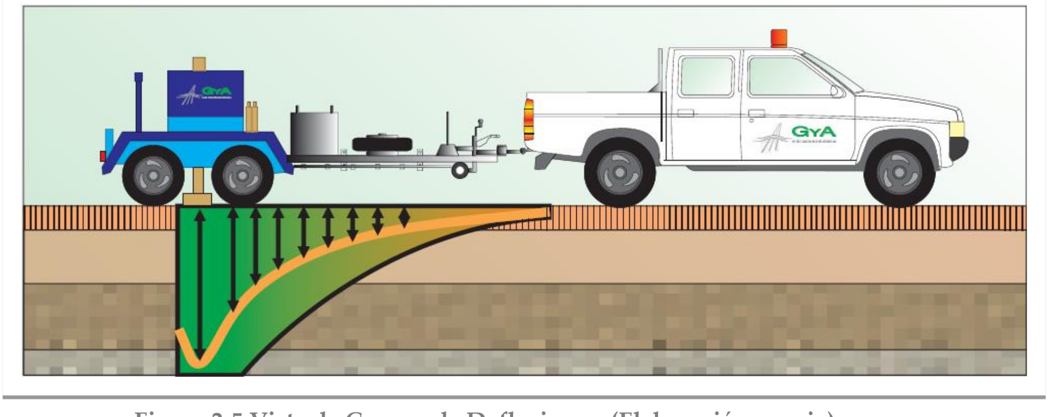

Figura 2-5 Vista de Cuenco de Deflexiones. (Elaboración propia)

2.3.1.1. Magnitud de la carga

Normalmente la carga que se aplica debería de tender a ser equivalente al semieje pesado que se aplica en España (6,5t) o bien (63,7kN), aunque en la normativa andaluza [3] se cambia esta cargas en función de la capa que se esté auscultando como se puede ver en la tabla 2-1.

Capa	Plato (mm)	Presión (kPa)	Carga (t)
Suelo seleccionado	450	246,47	4 (1)
Suelo estabilizado	450	246,47	4 (1)
Zahorra artificial	450	431,33	7
Capas Cementadas	450	431,33	7
Mezclas Bituminosas	300	693,21	5
Hormigón	300	693,21	5

Tabla 2-1 Características del ensayo comparativo según el equipo. [3]

(1) Si sobre el suelo seleccionado no se dispone al menos de una capa base, ya sea de suelo estabilizado o zahorra artificial bajo el aglomerado, la carga pasara a 7t y la presión a 431kPa.

Se auscultarán las deflexiones en los tres tramos experimentales de investigación para el empleo de nuevos usos para los RCD.

2.3.2. Cálculo Inverso

Los resultados de deflexión de los equipos de medida dinámica se pueden emplear para determinar los módulos de las distintas capas que forman la estructura del firme. Los módulos aportan un dato numérico sobre el comportamiento de los RCD que permite contrastarlo con los materiales convencionales para así poder determinar su viabilidad en el empleo como capas de firme no ligados, pudiendo realizar el cálculo a fatiga determinado la vida esperada para la estructura del firme construido. Mediante el empleo del cálculo inverso se puede determinar el valor de los módulos, para ello se requieren los siguientes datos:

- Carga aplicada

- Espesores de las capas consideradas en el cálculo
- Radio de la placa del deflectómetro
- Coeficientes de Poisson

El cuenco de deflexiones obtenido en campo con el deflectómetro solo podrá ser obtenido a partir de un resultado de módulos único. El cálculo inverso es una evaluación mecanicista, a través de la cual se busca la coincidencia, con algún margen de tolerancia, entre el cuenco de deflexión calculado mediante la aplicación de la teoría elástica y el cuenco producido en el firme por el equipo de medida de deflexiones (Figura 2-5). Este proceso normalmente es iterativo y se resuelve con ayuda de software utilizable en ordenadores convencionales.

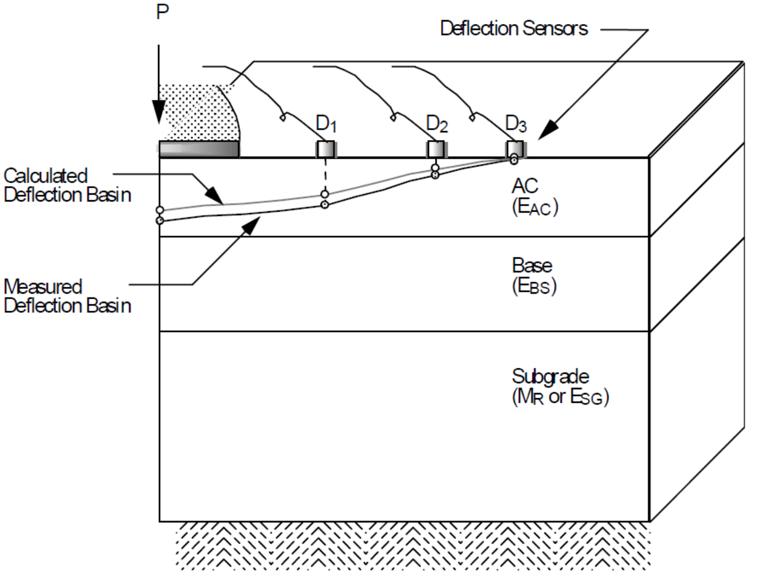

Figura 2-6 Cuenco de deflexión teórico y real [4]

En la Figura 2-7 se muestra el proceso que se lleva a cabo para el cálculo inverso de los módulos de un firme, se requieren los siguientes pasos:

Medida de los cuencos de deflexiones, lo cual consiste en obtener la medida de la deflexión a distintas distancias del punto de aplicación de la carga.

Se necesita disponer del espesor del firme y del valor de la carga aplicada en cada golpeo.

Suministro de los módulos iniciales de las capas del firme, además se puede introducir con un límite superior y otro inferior de esta manera se consigue que no se obtengan resultados incompatibles con el tipo de capa. Por ejemplo, en una capa granular el valor máximo suele ser 1000MPa y el menor 50MPa.

El programa informático empieza a realizar aproximaciones a la solución óptima mediante una subrutina de cálculo, habitualmente se emplean las siguientes: Leaf, Chevron, Weslea, Bisar, Odemark-Bousinesq, Elsym5 etc...

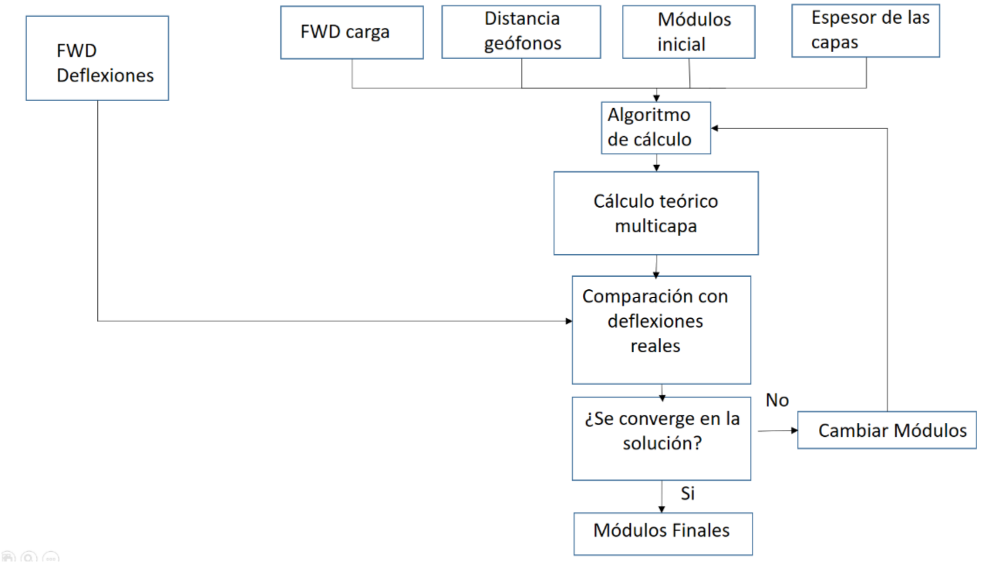

Figura 2-7 Esquema de Cálculo inverso

En esta tesis, se usará el programa Evercalc desarrollado por el departamento de transporte del estado de Washington [4] para el cálculo inverso de los módulos. Este programa emplea la subrutina WESLEA, la cual, fue desarrollada por el "U.S. Army Corps of Engineers "empleando además un algoritmo Gauss-Newton para optimizar la convergencia del cuenco calculado con el medido. Así mismo, se establece si existe o no una adecuada convergencia, para ello se emplea la raíz del error medio cuadrático (RMS). Habitualmente, se considera que la solución obtenida es aceptable si el RMS no supera el 2%.

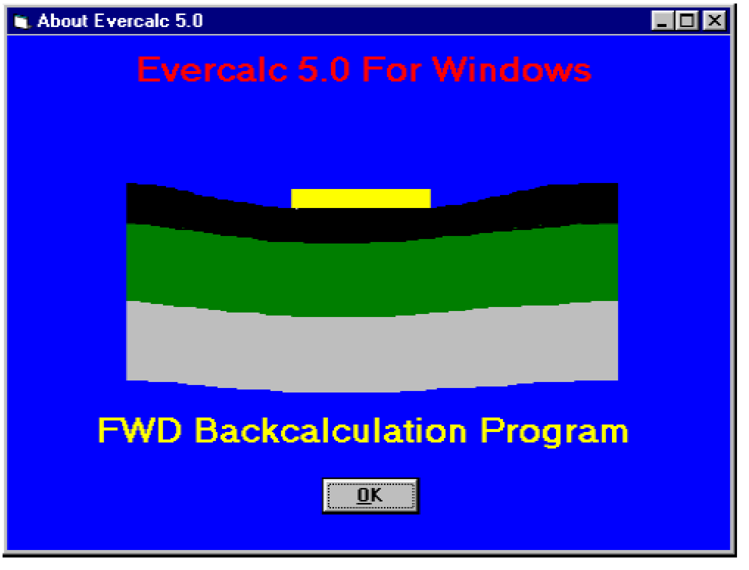

Figura 2-8 Programa Evercalc [4]

La expresión para determinar la RMS es la siguiente [4]:

$$RMS\,(\%) = \left[\sqrt{\frac{1}{n_d} * \sum_{i=1}^{n} \left[\frac{d_{ci} - d_{mi}}{d_{mi}}\right]^2}\,\right] * 100$$

Dónde: RMS: Raíz del error medio cuadrático.

d_{ci}: Deflexión superficial del firme, calculada en el punto del sensor i.

d_{mi}: Deflexión superficial del firme, medida con el sensor i.

n_d: Número de sensores de deflexión usados en el proceso de cálculo inverso

En los tres tramos experimentales estudiados en la presente tesis, se realizaron estudios de cálculo inverso a partir de las deflexiones obtenidas durante la construcción y en los años posteriores a la entrada en servicio de las vías.

2.4. Funcionamiento Georradar

El georradar (Ground Penetrating Radar) es una técnica geofísica no destructiva que proporciona una imagen del subsuelo midiendo diferencias en las propiedades electromagnéticas de los materiales.

Un radar es un dispositivo que emite un pulso corto de energía electromagnética y que es capaz de determinar la presencia o ausencia de un objeto mediante el examen de la energía reflejada de dicho pulso.

En el caso de una estructura de pavimento, la onda electromagnética viaja hasta que se encuentra con una discontinuidad dieléctrica.

Esta discontinuidad puede ser debida a un cambio del material (una nueva capa del pavimento), humedad, presencia de huecos de aire o cualquier otro fenómeno por el que cambie la constante dieléctrica del material.

Dichas propiedades son definidas por una serie de parámetros que, junto con las características de la onda emitida, determinan la propagación de la energía del pulso electromagnético por el medio. El resultado es la generación de una imagen del subsuelo con una altísima resolución vertical y lateral permitiendo caracterizar el entorno.

Una parte de la onda es reflejada por esta discontinuidad y el resto continúa su camino hacia el interior del pavimento.

Controlando con gran exactitud el tiempo de viaje de la onda desde su inicio hasta la recepción de la reflejada, es posible la determinación de los espesores de cada capa de pavimento o la distancia a la que se encuentra alguna incidencia (armaduras, grietas, despegue de capas, huecos, presencia de humedad, etc.).

Es necesario para la determinación de los espesores o distancias, el conocimiento de la constante dieléctrica del material. Según la precisión con que se tenga esta constante, más o menos precisa será la determinación de cualquier espesor o distancia.

Es preciso indicar que para un exacto contraste de los resultados que se obtienen mediante estos ensayos no destructivos, sería conveniente realizar alguna cata o extracción de testigo en algún punto de la carretera auscultada, pudiéndose elegir a posteriori en función del chequeo realizado.

La antena instalada sobre un vehículo todo terreno es de tipo campana TEM de 48”, con un ancho de pulso del transmisor de 1 ns del tipo monociclo. La frecuencia de repetición del pulso es de 5MHz. El receptor tiene una longitud de ventana en tiempo real de 18 ns, con una frecuencia de escaneo de 50Hz y un ancho de banda de 3KHz.

Lleva incorporado un odómetro digital de precisión para asociar la distancia a cada muestra obtenida, así como cualquier incidencia encontrada en la carretera para e introducida por el operador para la mejor ubicación de las medidas realizadas. Su velocidad operativa puede ser hasta de 80Km/h.

La profundidad a que puede penetrar la onda está en función de los materiales que componen la estructura del pavimento ya que la onda va perdiendo energía al atravesar las diferentes capas y dado que unos materiales absorben más energía que otros, la profundidad observable por el georradar depende de éste tipo de materiales, se estima en unos 80 cm aproximadamente.

El operador en todo momento controla el correcto funcionamiento del equipo mediante una pantalla de visualización y su posterior almacenamiento de los datos obtenidos. Los datos auscultados se recogen en ficheros que son tratados posteriormente en gabinete.

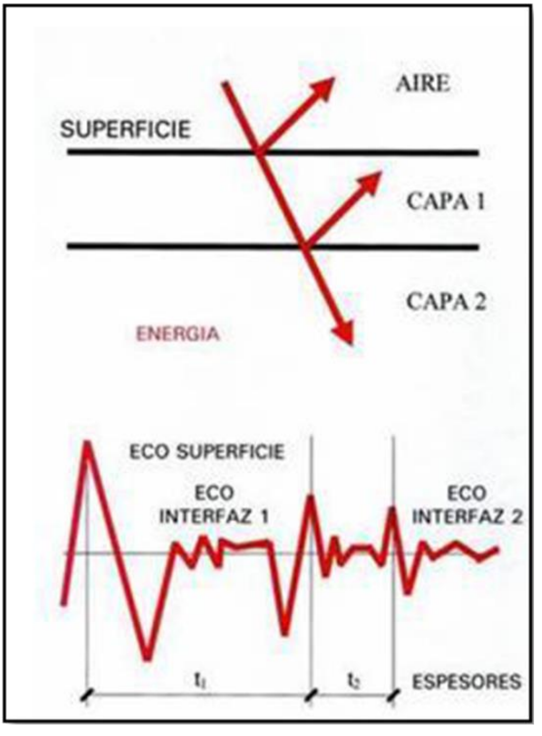

Figura 2-9 Funcionamiento Georradar

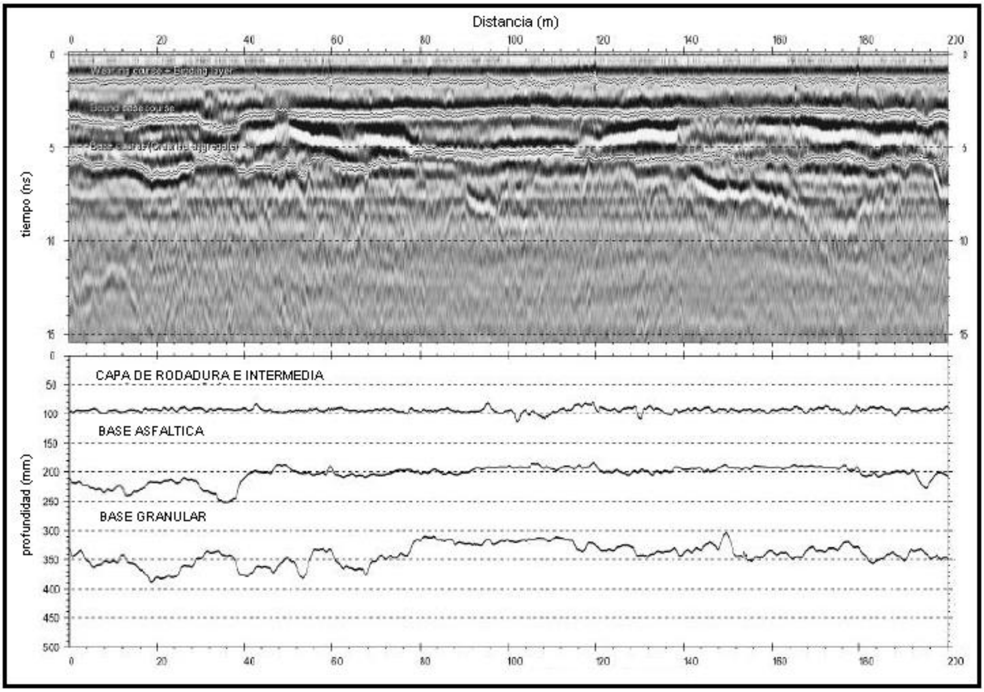

Figura 2-10 Vista de la lectura del georradar [5]

La constante dieléctrica es un buen indicador de la resistencia y de las propiedades de deformación de los materiales granulares de un firme y de la explanada. Cada material tiene una relación única entre su constante dieléctrica y su contenido de agua. Valores de la constante por encima de 9 para estos materiales indican la existencia o problemas potenciales en la capa. Pero, también, valores demasiado bajos pueden indicar dificultades, en el sentido de que la granulometría sea muy abierta y el material sea susceptible a la deformación y a los hundimientos.

En el tramo experimental de la vía de servicio de la A-376 se comprobaron que los espesores de las capas ejecutadas en obra coincidían con los valores teóricos.

2.5. Regularidad superficial del pavimento

El IRI (Figura 2-12) mide las aceleraciones verticales no deseadas, de los vehículos que circulan por las carreteras, es decir los movimientos verticales producidos por irregularidades de las mismas. Se trata, en definitiva, de un índice del confort de rodadura de un vehículo circulando por una carretera. A medida que el IRI medio es menor, mayor es el confort percibido por el usuario.

Se trata de medir las irregularidades máximas admisibles de un tramo de carretera para obtener una buena rodadura, adoptándose como parámetro de medida la regularidad determinada mediante el IRI.

Figura 2-11 Vista perfilómetro Laser.

Los valores límites del IRI definidos en la citada circular 7/95 para cada capa del pavimento, se incluyen en la siguiente tabla:

Tabla 2-2 Límites de IRI según circular 7/95

CAPA	PORCENTAJE MINIMO DELTRAMO		
	50%	**80%**	**100%**
RODADURA	1,5	2,0	2,5
1ª CAPA BAJO RODADURA	2,5	3,5	4,5
2ª CAPA BAJO RODADURA	3,5	5,0	6,5

Para medir la regularidad superficial en los tramos experimentales se empleó el perfilómetro RSP Mk IV de Dynatest. Este modelo de equipo mide y almacena los perfiles del pavimento a una velocidad comprendida entre 30 y 110Km/h. El sistema emplea un acelerómetro de precisión en cada línea de ruedas para medir los movimientos del vehículo y dos sensores láser de infrarrojos para medir los desplazamientos entre el paragolpes delantero, donde éstos están montados, y la superficie del firme.

Un ordenador almacena toda esta información con el fin de calcular los perfiles de la superficie del firme, índices de regularidad. Todas estas medidas son independientes de cualquier variación en el peso y velocidad del vehículo, temperatura, color y textura del pavimento.

Los datos del perfil longitudinal se toman cada 2,5 cm., aunque se realiza un tratamiento matemático de los mismos y se almacenan datos del perfil cada 15cm. Con el fin de tener una perfecta referenciación, cada dato está asociado a una distancia medida con gran exactitud en base a un odómetro digital

Los resultados que se obtienen tras el proceso informático de datos, se presentan en una gráfica que refleja los valores del IRI en tramos de 100 metros para comprobar la aceptación del tramo ensayado (ver Figura 2-13).

Para establecer cierta concordancia a nivel mundial en las medidas de la regularidad superficial, ha sido definido el IRI como unidad de medida universal de la regularidad.

Para definir el IRI se emplea un modelo matemático que simula la suspensión y masas de un vehículo tipo circulando por un tramo de carretera a una velocidad de 80 Km/h. Este modelo se conoce por sus siglas en inglés, QCS (Quarter Car Simulation), dado que representa la cuarta parte de un vehículo de cuatro ruedas o un remolque de una sola rueda.

El IRI en un punto de una carretera se define como la razón del movimiento relativo acumulado por la suspensión del vehículo dividido por la distancia recorrida por dicho vehículo. El modelo matemático de vehículo que se utiliza es el representado en la Figura 2-12. Si se conoce el perfil longitudinal de la carretera, Y(X), y la velocidad a la que circula el automóvil, V, se puede calcular en cada punto el movimiento, z que compone el modelo.

A su vez se puede definir la respuesta del vehículo en término pendiente rectificada, RS (Rectified Slope), en cada uno de los puntos en que se discretiza el perfil longitudinal.

$$RS_i = z_1' - z_2' \qquad (1)$$

Donde z_1' y z_2' representan las pendientes de las masas del vehículo en las distintas posiciones, i, a lo largo del camino de la rueda.

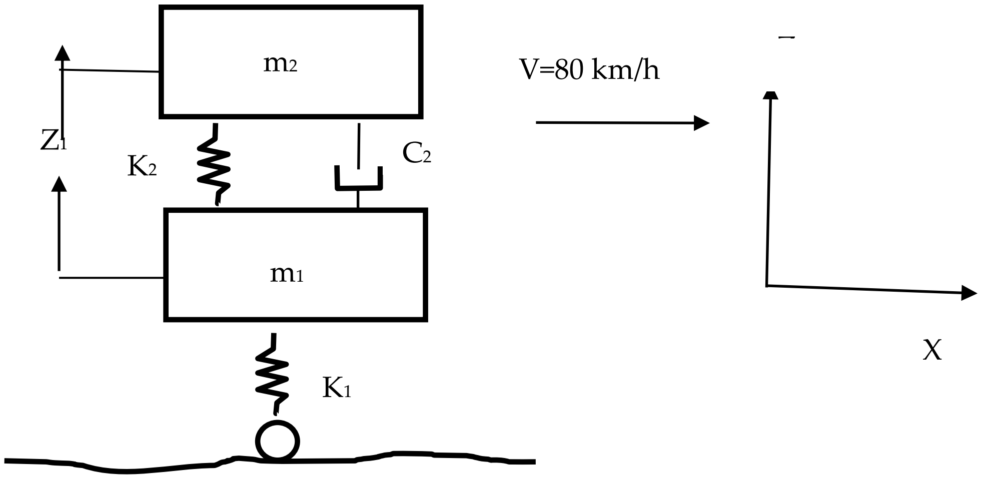

Figura 2-12 Modelo del cuarto de vehículo

Donde:

$$K_1 = \frac{k_1}{m_1} = 653\ \frac{1}{s^2}$$

$$K_2 = \frac{k_2}{m_2} = 63{,}3\ \frac{1}{s^2}$$

$$C = \frac{c_2}{m_2} = 6\ \frac{1}{s}$$

$$U = \frac{m_1}{m_2} = 0{,}15$$

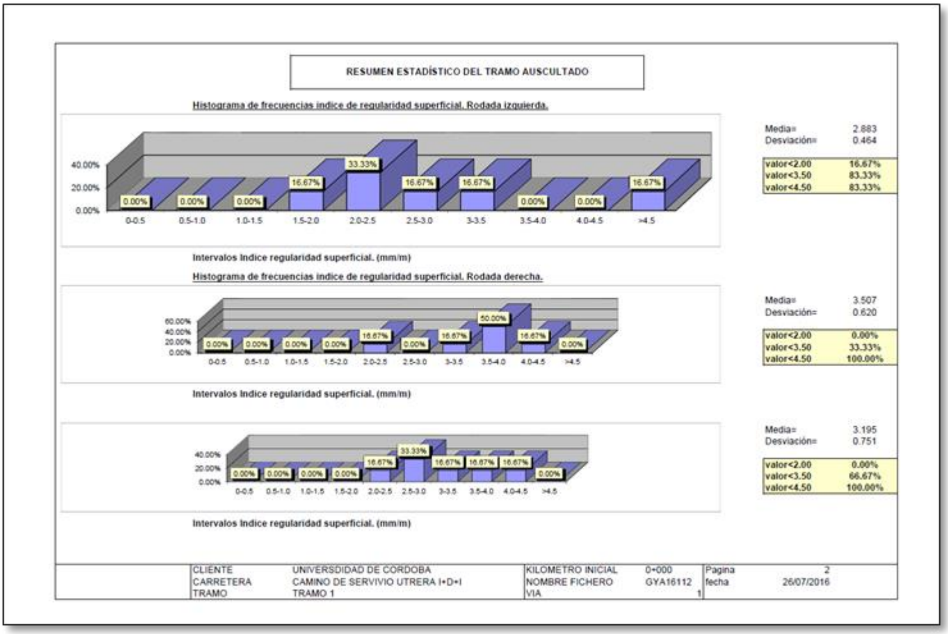

Figura 2-13 .Representación de resultados de IRI el tramo experimental de Utrera

Figura 2-14 Perfilómetro en vía de servicio A-376 y en la CH2

Se tomarán datos de IRI durante y después de su construcción en los tramos experimentales de la vía de servicio de la A-376 y en el de la carretera CH2.

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3. Functional and structural parameters of a paved road section constructed with mixed recycled aggregates from non-selected construction and demolition waste with excavation soil.

This chapter has been published in the journal "Construction and Building Materials" volume 164 (2018) pages 57–69: **Javier Tavira[a], *, José Ramón Jiménez[b], *, Jesús Ayuso[b], María José Sierra[c], Enrique Fernández Ledesma[d]**

[a] JTD Civil Eng., Carretera de Carmona 40 D 1º D 41008 Sevilla, Spain.

[b] Área de Ingeniería de la Construcción, Universidad de Córdoba. Ctra. N-IV, Km 396, 14014 Córdoba, Spain.

[c] Agencia de la Obra Pública. Consejería de Fomento y Vivienda. Junta de Andalucía. Av. Diego Martínez Barrio, 10, 41013 Sevilla, Spain.

[d] Área de Mecánica de Medios Continuos y Teoría de Estructuras, Universidad de Córdoba. Ctra. N-IV, Km 396, 14014 Córdoba, Spain.

*Corresponding authors. Both authors equally contributed to the paper. Address: Construction Engineering Area. University of Córdoba, Ed. Leonardo Da Vinci, Campus de Rabanales, Ctra. N-IV, km-396, CP 14014. Córdoba, Spain. Tel.: +34 667524702; fax: +34 957218550.

E-mail address: jrjimenez@uco.es (JR Jiménez), jtavira@ciccp.es (J. Tavira

Abstract

This paper evaluates the lab and in situ mechanical properties of non-selected mixed recycled aggregates from construction and demolition waste (CDW) used as base and subbase unbound materials. Excavation materials are mixed with CDW to produce recycled mixed aggregates with soil, as well as a finer material referred to as mixed recycled soil. The research was divided into two different stages: a laboratory study characterizing the properties of recycling aggregates and a road test track evaluating the long-term performance of these materials under real traffic and weather conditions. During construction, several density, plate load, and falling weight deflectometer tests were performed to determine the bearing capacity of all layers. A laser profiler was also used to obtained the international roughness index. After the road was opened to traffic, a follow up of deflections and surface roughness was performed during the following seven years.

Two different moduli calculation methods were used: back calculation and forward calculation. Both methods shown acceptable values for these recycled materials. Low quality recycled mixed aggregates can be used as substitutes for natural aggregates as unbound layers. The mechanical performance and surface roughness values obtained from the experimental road shown an acceptable behaviour.

Keywords:

Construction and demolition waste, mixed recycled aggregates, backcalculation, forward calculation, International Roughness Index, experimental road.

Acronyms:

CDW - construction and demolition waste; RMAS - Recycled mixed aggregates with excavation soil; MRS - Mixed Recycled soil; FWD - falling weight deflectometer; IRI - International Roughness Index; NA - natural aggregates; RA - recycled aggregates; RCA - recycled concrete aggregates; CBR - California Bearing Ratio; ER - experimental road; NDT - nondestructive testing; CS - crushed stone; SS - selected soil; SG - subgrade; GPR - ground penetrating radar; PG3 - Spanish general technical specification for road construction.

3.1. Introduction

The construction sector contributes significantly to greenhouse gas emissions because of the use of heavy machinery and because of cement production; these emissions contribute greatly to climate change (UE Directive 2010/31/EC). Additionally, construction activities consume a large quantity of non-renewable natural resources, such as aggregates, which are scarce in many countries. To reduce these negative effects and contribute to the sustainability of the sector, it is necessary to promote the use of recycled aggregates (RA) from construction and demolition waste (CDW). This will provide a second life cycle to raw materials [1].

In 2009 approximately 530 million tonnes of CDW were produced in the European Union [2]. Spain produced 26 million tonnes in 2012 [3]. If the excavation soils from construction activities were included, the total waste would be 1350 to 2900 million tonnes [4]. These data show the importance of CDW and excavated soils to waste generation. According to the European Commission, 25–30% of total generated solid waste comes from construction. The recycling rate in Spain reached 30% in 2011 [5], which is below the EU-27 average (47%) [5] and it much lower than that in other European countries such as Germany (86%) or Denmark (94%) [2]. The waste framework directive of the European Parliament on waste stipulated that by 2020, a minimum recycling level must be achieved of 70% of non-hazardous CDW [6].

The possibility of using RA from CDW in road construction has been studied by many researchers. Vegas et al. [7], Garcia [8], Poon et al. [9] and Jiménez et al. [10-12] assessed the feasibility of using RA as a granular material in the structural layer of pavement. Vegas et al.[7] and Jiménez et al.[10-12] concluded that the most critical properties are sulphur content because it can generate dimensional unstability of the layer and fragmentation resistance which is deeply related with durability. Jiménez et al. [10-12] compared the behaviour of RA from CDW with that of natural aggregates (NA) on unpaved rural roads. They concluded that RA can be used as an alternative to NA on unpaved roads. Few studies on the mechanical capacity of RA have been made on experimental road sections [13].

In a laboratory study, Del Rey et al. [14] found that cement-treated RA in a size range of 0–8 mm can be used as a subbase layer for light-traffic roads. Agrela et al. [15] performed tests on a road section constructed with recycled mixed aggregates (RMA) in Malaga (Spain), and concluded that RMA treated with 3% cement can be used in the subbase layers of roads. Perez et al. [16] used recycled concrete aggregates (RCA) and natural aggregates (NA) treated with cement as sub-base layers in two road test sections. Deflections showed that RCA had a higher bearing capacity although a higher percentage of water was needed.

Cardoso et al. [17] reviewed the use of RA in geotechnical applications, mainly the use of CDW in pavement layers. Several studies were performed on pavements made with NA, RCA, and RMA; these produced several conclusions regarding the bearing capacity, durability, and workability of RA relative to NA. The international roughness index (IRI) and deflections were similar in both materials, with RA performing better. RMA and RCA have a higher optimum water content than NA. The Californian bearing ratio (CBR) of RMA was lower than that of NA, but it could be increased by adding RCA.

There has been some international experience with RMA and RA used in low volume traffic roads. In China [18], RA obtained from concrete and bricks waste was used in bases and sub-bases. Cement was added, and deflection tests were made comparing RMA and RCA stabilized with cement and limestone. The main conclusion was that RA treated with cement are feasible for road pavement construction.

Park [19] used two road sections constructed from variable-quality RCA and compared them with those constructed from NA, obtaining similar deflections. Lancieri et al [20] performed a long-term test using RMA as an unbound layer in two paved sections, obtaining elastic moduli for these recycled unbound layers over a period of eight years. These materials showed an increase in bearing capacity due to self-cementing and further traffic compaction.

The elastic modulus is a basic input needed to calculate stress-strain values for pavement. Mechanical durability is deeply connected with this parameter.

This paper has two main purposes. The first one is to study the short and long-term performance of low quality recycled materials obtained from non-selected CDW mixed with excavated soils. The second one is to calculate the elastic moduli of these materials in an experimental road (ER) using nondestructive testing (NDT) such a FWD. The elastic modulus of each layer can be determined using the deflection basin [21]. This way, the mechanical properties of these materials can be obtained, assuring the bearing capacity of the road.

Because of the high amount of excavated soil obtained from construction sites [4,13], it is quite important to find new applications for these wastes. To the best of the authors' knowledge, there are no previous studies investigating RA mixed with excavated soils and used as unbound layers in roads. RMA with soil (RMAS) could also be a good material for reducing plasticity of the excavated wastes, because RA has no expansive properties [13]. To test the viability of RA used in unbound layers in road pavements, it is critical to reproduce real scale models. It is fundamental to perform middle- and long-term evaluations to verify the consistency of

RA in these uses. Because of the duration of the present study, this target has been achieved. It also fills a gap in the availability of long-term performance studies on recycled materials used in roads open to traffic.

3.2. Materials and methods

3.2.1. Description of test sections

The experimental road (ER) was built on the service road of a four-lane freeway in Seville (south of Spain). The ER consists of three sections, each one 150 m long (total length of 450 m). Fig.3-1 shows a description of the three sections and the thicknesses of the structural layers. The surface course for all sections consists of 5 cm of asphalt concrete. The base course of the first two sections is a crushed limestone (CS-1) used as a reference and a recycled mixed aggregate from non-selected CDW with excavation soil (RMAS-1). In the third section, granular base course materials would be classified as a A1a, according to AASHTO [22]. The subbase course was built with two different materials, a natural selected soil, which would be classified as A3 according to AASHTO [22] (SS-1), and a mixed recycled soil (MRS-1) from preliminary screening in sections I.II and I.III, which would be classified as A4 [22]. Construction of the ER lasted from February to June of 2009.

The two basic characteristics of this road are as follows:

•Traffic intensity is homogeneous for all sections investigated. Traffic counting was performed from the September 5th 2016 (Monday) to September 11th 2016 (Sunday). The mean value for heavy vehicles was 30 per day, from a total of 659. According to Spanish standards [23] this road would be classified as a T41 (25-49 heavy vehicles/day).

• The subgrade has the same composition in the three sections. It is a red silty clay, classified as A6 in accordance with AASHTO [22] (SG-1).

3.2.2. CDW treatment process

Two recycled materials (MRS-1 and RMAS-1) were collected from a recycling plant located 5 km north of the ER (Sevilla, Spain). Fig.3-2 shows a schematic of the process followed to obtain both recycled materials. MRS-1 was obtained from the preliminary screening process (20 mm sieve) of a non-selected CDW mixed with excavation soils. The excavated soil came from construction sites around the recycling plant, basically this material came from foundations and ditches excavations. When excavation soils are not reused in-situ, they must be managed by an authorized recycling plant. In this case, the excavation soils were mixed with the non-selected CDW in the recycling plant.

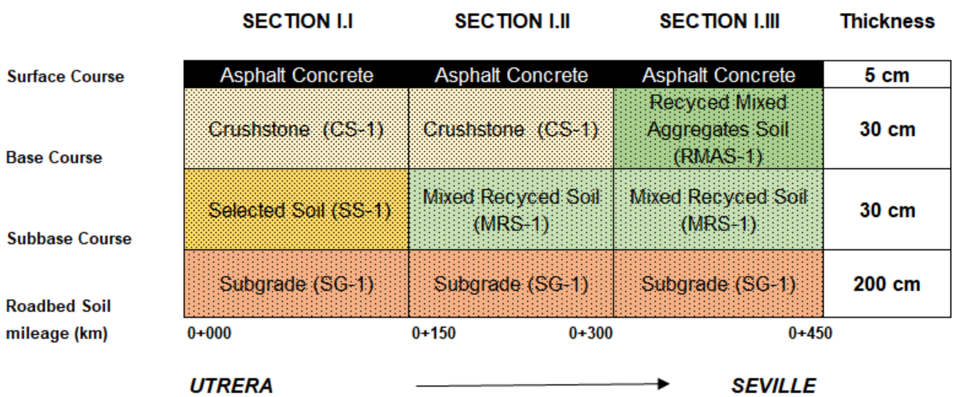

Fig. 3-1 Experimental Road cross sections.

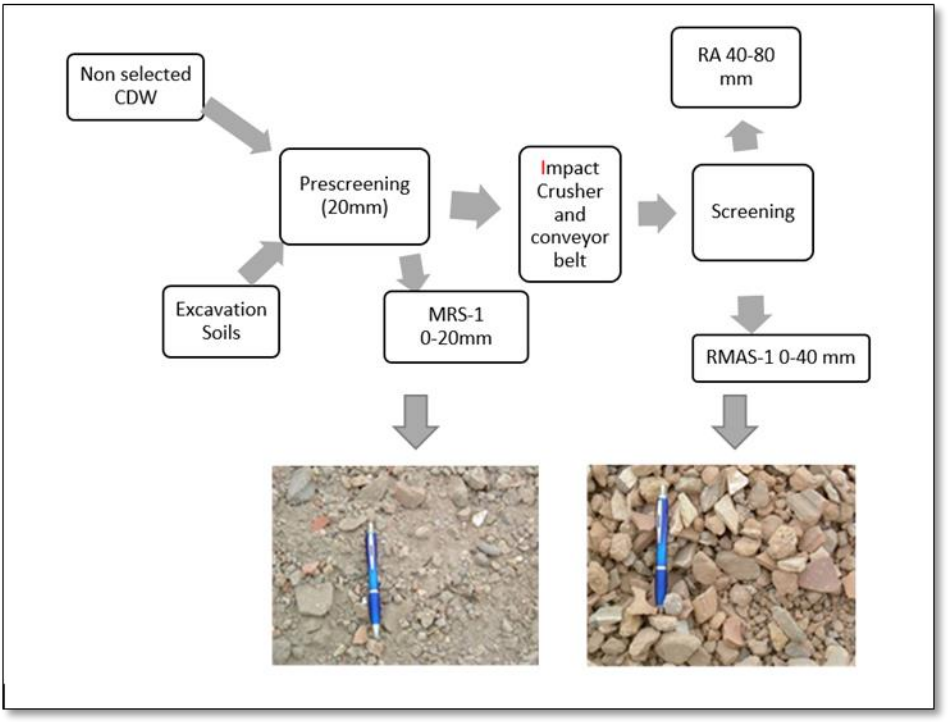

Fig. 3-2 Flow diagram in the recycling plant.

To obtain RMAS-1, the material larger than 20 mm was crushed in an impact crusher and screened with a 40 mm sieve. A magnetic conveyor belt was used to remove metallic elements.

3.2.3. Material characterisation

The samples used to characterise the materials were collected prior to compaction during the construction of the ER, according to UNE-EN 932-1:1997 [24]. Samples were homogenised and reduced in a laboratory using a quartering method, according to UNE-EN 932-2:1999 [25].

Table 3-1 presents the compositions of MRS-1 and RMAS-1, determined according to UNE-EN 933-11:2009 [26]. MRS-1 has a high percentage of natural soil from excavation; no other previous research has been found of a RMA with these characteristics. According to Agrela et al. [27], Jiménez

[13], and Cardoso et al. [17], both MRS-1 and RMAS-1 due its elevated content of natural soil would be unclassified RA.

Both of the natural materials (SS-1 and CS-1) came from limestone quarries. All of the parameters fulfilled the requirements of articles 330 (SS-1) and 510 (CS-1) of the Spanish general technical specification for road construction (PG3) [28]. Table 3-2 shows the primary mechanical, physical, and chemical properties of these materials. The densities and CBRs of NA are higher than those of MRS-1 and RMAS. The CBR value for recycled materials falls between previous values obtained for RMA 69–90 % [13,14]. The optimum moisture is higher for recycled materials than natural materials.

Based on their mechanical properties, all granular materials used in the ER (MRS-1, SS-1, RMAS-1 and CS-1) meet the limits established by PG3 for use as road materials, except for the Los Angeles test of RMA-1, which was not under the 35 % limit (PG3). According to previous literature, most values for RMA fall between 35 and 43% [13,20], local specifications for RMA raise this value to 50% [29].

With respect to chemical properties, PG3 imposes a 0.2 % limit on the content of organic matter and soluble salts for a granular sub-base. This limit decreases to 0.07 % in granular bases. Previous studies [10,12,13] showed that soluble salt content below 3.74% does not create stability problems. Organic matter is not a limiting property in road applications, and has a typical range of 0.42-1.00 % according to Jimenez [13].

The sand equivalent in RMAS-1 does not meet the PG3 minimum value of 35%. Previous studies of recycled materials used as unbound layers did meet these limits [10,12].

Particle size distribution was studied in accordance with standard UNE-EN-933-1:2006 [30]. As shown in Fig. 3-3, both materials have less than

10% of fine fraction (< 0.063 mm), and the coefficients of uniformity and gradation are very similar in both materials.

Table 3-1 Composition of the mixed recycled aggregate. UNE-EN-933-11:2009.

		MRS-1	RMAS-1
Class	Type	Weight (%)	Weight (%)
R_A	Asphalt	0	0
R_B	Ceramics	5.3	2.5
R_C	Concrete and Mortar [a]	16.5	42.56
R_L	Lightweight particles	0	0
R_U	Unbound aggregates [b]	1.9	40.57
X_1	Natural Soil [c]	75.4	13.57
X_2	Others [d]	0.9	0.8
	Total	100	100

[a] Natural aggregates with cement mortar attached from concrete or masonry
[b] Natural aggregates without cement mortar attached
[c] Excavation soil.
[d] Wood, glass, plastic, metals, gypsum.

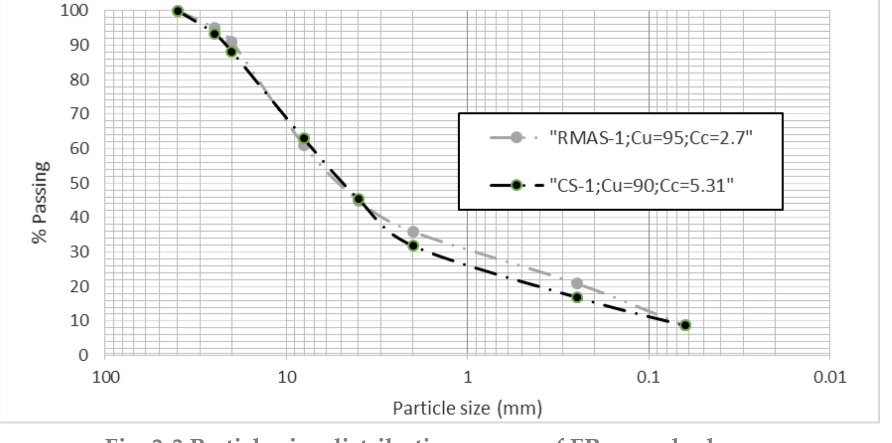

Fig. 3-3 Particle size distribution curves of ER granular bases.

3.2.4. Description of external factors

Climate has a great influence on the behaviour of pavement layers. Precipitation and temperature values were collected from a nearby weather station located in Los Molares (Seville) with UTM coordinates (262696, 4117760).

Fig. 3-4 shows the average monthly maximum and minimum temperatures. From 2009 to 2016, there were no extreme temperatures. Fig. 3-5 shows that the highest observed rainfall (912 mm) occurred in 2010. The driest year was 2012, with only 405 mm. Total rainfall was 460 mm in 2011 and 555 mm in 2009. Major rains occurred from November to March during the period of lowest temperatures, meaning that monthly rain during this period was 49 mm.

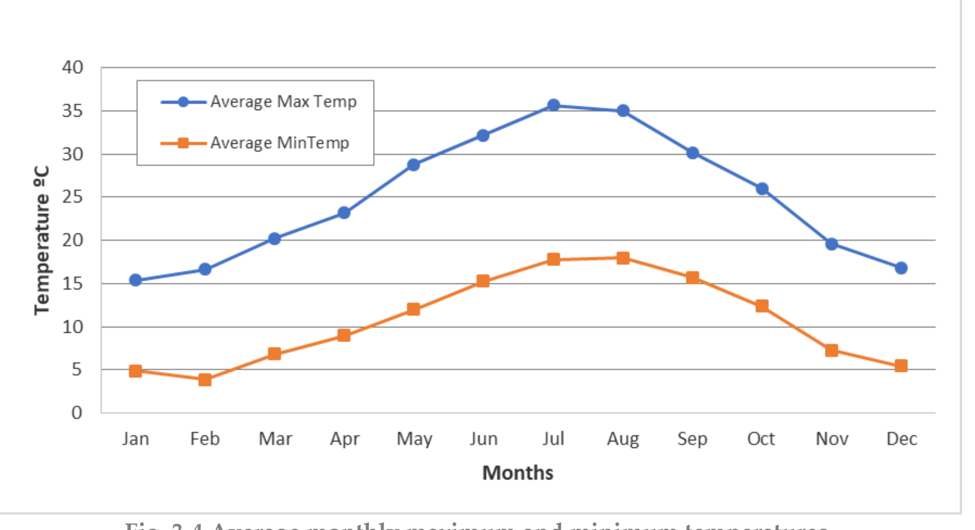

Fig. 3-4 Average monthly maximum and minimum temperatures.

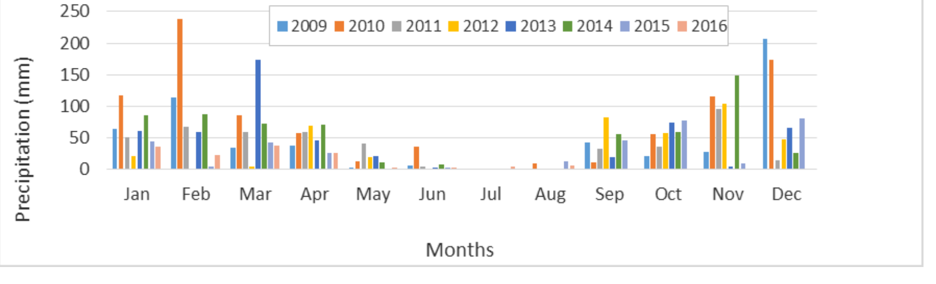

Fig. 3-5 Monthly total precipitation (mm).

3.2.5. Tests in site

3.2.5.1. Control of compaction

Moisture and dry density was measured using a Troxler apparatus during the construction of the road in May 2009. Five measurements were measured on each section of the subbase and base course. The tests were performed according to ASTM-D-6938:15 [31].

3.2.5.2. Plate load tests

Six static plate load tests were performed, one on each of the three sections of the sub-base and base course, in accordance with Spanish standard UNE 103808:2006 [32]. A 200 kN load device and 300 mm diameter steel plate were used. The strain moduli Ev1 and Ev2 (first and second load cycle) were measured. Tests were performed during construction of the road in May 2009.

3.2.5.3. Falling weight deflectometer (FWD)

Pavement deflection is commonly accepted as a state indicator of pavement structural conditions [33]. This test consists of the bearing capacity determination of each layer, starting at the subbase. A Dynatest Heavy Weight Deflectometer 8081 equipped with seven geophones was used. The geophones were located at 0-300-450-600-900-1200-1500 mm. This equipment has been used in previous studies (see Jimenez et al [10,12]).

A 450 mm diameter plate was used for the granular layers (bases and subbases), and a 300 mm diameter was used on surfaced courses. Loads of 39.24 kN were applied with a pressure of 246.47 kPa on subbases, loads of 68.67 kN were applied with a pressure of 431.33 kPa on bases, and loads of 49.05 kN were applied with a pressure of 693.21 kPa on surface courses, the standard that regulates these loads and configurations is the "Technical Specifications for High-Performance Dynamic Monitoring

Tests" [34] from the Civil Works Agency of Regional Government of Andalusia (Spain).

Deflections were obtained every 20 m along the three sections, in accordance with ASTM D4694 (2003). According to Spanish standard, temperature did not influence the measurement of the deflection located under the plate at a distance of 0 mm. This occurred because the asphalt concrete was less than 10 cm thick [33].

Fig. 3-6 shows the theoretical deflection calculated with multilayer software BISAR [35]. This software applies the theories of Burmister [36] and Acum and Fox [37], and is implemented with a solution for determining strain and stress by Shiffmann [38]. The theoretical deflection was obtained for each layer and section according to the elastic moduli and Poisson ratios. Poisson ratio values were adopted of 0.35 (for granular layers and roadbed soil), and 0.33 (for the bituminous layer) [39,40]. Roadbed moduli were determined from CBR tests performed along the section using the correlation described in the pavement instruction of Andalusia (Spain) [39].

	Layer	Thichness		Modulus (MPa)	Poisson´s ratio	Theoretical deflection mm/100
	Base Course	5 cm	E1	**6000**	**0,33**	**149**
	Granular Base	30 cm	E2	**225**	**0,35**	**241**
	Subbase	30 cm	E3	**75**	**0,35**	**238**
	Roadbed Soil CBR=3	200 cm	E4	**30**	**0,35**	**-**

Fig. 3-6 Layer mechanical properties for the three sections (adapted from García-Garrido 2016).

Table 3-2 Physico-mechanical and chemical properties of unbound materials.

		Materials					Standard
Properties		SG-1	SS-1	MRS-1	RMAS-1	CS-1	
Grading	Max. Size (mm)	12.5	80	25	20	25	UNE 103101:1995
	% passing sieve # 0.063	39.9	14.3	18	13	13.8	UNE 103101:1995
Atterberg Limits	Liquid Limit	23.8	-	24.6	23.4	-	UNE 103103:1994 UNE 103104:1993
	Plastic Limit	11.2	-	17.8	18.6	-	UNE 103103:1994 UNE 103104:1993
	Plastic Index	12.6	-	6.8	4.6	-	UNE 103103:1994 UNE 103104:1993
	Sand equivalent (%)				27.4	42.2	UNE-EN 933-8:2000
	Los Angeles (%)				42	28	UNE-EN 1097-2:2010
	Flakiness index (%)				23	8	UNE-EN 933-3:2012
	Crushed particles (%)				100	100	UNE-EN 933-35:1999
Modified Proctor	Max. Density (Mg/m3)	1.6	2.1	1.8	1.94	2.38	UNE 103501:1994
	Optimum Moisture (%)	10	9	14.5	10.5	7	UNE 103501:1994
C.B.R.(*)	100%	5.9	74.4	56	65.5	100.7	UNE 103502:1995
	95%	3	42.3	38.9	35.3	66.6	UNE 103502:1995
	Swelling after 4 days soaking (%)		0.2	0.1	0.1	0	UNE 103502:1995
	Acid-soluble sulphate (%SO3)		0.13	0.92	0.31		UNE 103201:2003
	Organic matter (%)	2.51	0.11	1.04	0.92		UNE 103204:1993

(*) The CBR tests were carried out with laboratory samples compacted at their corresponding maximum dry density of Modified Proctor and 4-day of soaked conditions

3.2.6. Laser profiler (LP)

Road roughness strongly influences operation costs, and is generally related to the regularity of pavement surfaces. Globally, the accepted parameter for establishing the smoothness of roads is the IRI [41], which was calculated according to ASTM E867-06:2012 [42]. There are correlations with the present serviceability index (PSI), another important index [43]. A new road has a PSI value of 4.5, which is equivalent to a 0.285 m/km IRI, while a road at the end of its life has a PSI value of 2, which is equivalent to a 4.45 m/km IRI. Longitudinal profile data was collected in 2009 and 2016 to study IRI evolution over time. The IRI was measured using a RSP MARK-IV device, which was previously used in the studies of Jimenez et al [10,12]. Eight passes were conducted for each IRI mean value. Data were analysed using a one-way analysis of variance (ANOVA).

3.2.7. Elastic modulus calculation

3.2.8. Back calculation using RMS

Back calculation is the main method used to calculate moduli [44]. This method consists of comparing the theoretical deflections in the road with the actual data obtained from a FWD. It is an iterative process in which the error tends to be minimized at each step [45]. The moduli for bases and subbases were obtained from Evercalc [45]. In essence, this software calculates a deflection basin until it matches the measured deflections. The required inputs are layer thickness, Poisson ratio, and the seed moduli for each layer. Tolerable error is calculated using the root mean square (1).

$$\boldsymbol{RMS}\ (\%) = \left[\sqrt{\frac{1}{n_d}\sum_{i=1}^{n}\left[\frac{d_{ci}-d_{mi}}{d_{mi}}\right]^2}\right]\cdot \mathbf{100} \qquad (1)$$

Where:

- RMS = root mean square error,
- dci = calculated pavement surface deflection at sensor i,
- dmi = measured pavement surface defection at sensor i,
- nd = number of deflection sensors used in the back calculation process.

Seed moduli are the initial moduli used in the computer program to calculate surface deflections. Evercalc uses WESLEA [46] as the layered elastic solution to compute theoretical deflections, and uses a modified Augmented Gauss-Newton algorithm for optimization. The process is terminated when the error is tolerable or when the maximum number of iterations is reached.

3.2.8.1. Forward calculation

Another way to determine the mechanical properties of pavement layers is through the use of forward calculation [47]. This is an empirical approach for the calculation of the flexible and rigid pavement layer moduli developed by Stubstad et al. [47]. It involves estimating the modulus of the pavement using the Hogg model [48], whose implementation is described by Wiseman [49]. Three cases are considered. Cases I and II are for subgrades with Poisson ratios of 0.4 and 0.5, respectively. Case III allows any value to be used as the Poisson ratio. The adimensional constants used for the three approaches in the Hogg model are presented in Table 3. The most fittable version for the characteristics of the ER is case number III, which uses a Poisson ratio of 0.35 for roadbed soil.

The following equations are used:

$$\mathbf{E_0} = \mathbf{I} \cdot \frac{(1+\upsilon_0)*(3-4*\upsilon_0)}{2*(1-\upsilon_0)} \cdot \left[\frac{S_0}{S}\right] \cdot \left[\frac{p}{D_0*l}\right] \qquad (2)$$

Where: E0 = subgrade modulus, υ_0 = Poisson ratio, S0 = theoretical point load stiffness, S = pavement stiffness, p = applied load, D0 = deflection from centre plate, l = characteristic length, I = Influence factor, m = characteristic length coefficient, $\overline{m}$ = stiffness ratio coefficient.

$$r_{50} = r \cdot \frac{(1/\alpha)^{1/\beta} - B}{\left[\frac{1}{\alpha} * \left[\frac{D_0}{D_r} - 1\right]\right]^{1/\beta} - B} \qquad (3)$$

Where: Dr = deflection at offset distance r, r = distance from centre of load plate, B = curve fitting coefficient, b = curve fitting coefficient, a = curve fitting coefficient,

$$l = y_0 \cdot \frac{r_{50}}{2} + [(y_0 \cdot r_{50})^2 - 4 \cdot m \cdot \alpha \cdot r_{50}]^{0.5} \qquad (4)$$

Where: y0 = characteristic length coefficient, r50 = offset distance where Dr/D0=0.5.

$$\left[\frac{S}{S_0}\right] = 1 - \overline{m} \cdot \left[\frac{\alpha}{I} - 0.2\right] \qquad (5)$$

If a/I < 0.2 then $\left[\frac{S}{S_0}\right] = 1.0$

The second step is to use the subgrade modulus to determine the moduli for subbases and bases using equation (6) [50].

$$E_i = 0.2 \cdot h_i^{0.45} \cdot E_{i+1} \qquad (6)$$

Where: Ei = modulus of the upper layer, Ei+1 = modulus of the lower layer, hi = thickness of the upper layer.

Dynamic moduli from these granular base and subbase deflections were calculated by the following equation, proposed by Brown [51]:

$$E_0 = \frac{2\sigma_0 a(1-\mu_0^2)}{d_0} \qquad (7)$$

Where: E_0 = equivalent modulus of the entire pavement system beneath the load plate, a = radius of the FWD plate, σ_0 = Pressure of the FWD impact load under the load plate d_0= deflection at 0 mm at the centre of the FWD plate.

Table 3-3 Hogg model coefficients.

CASES		I	II	III
Depth to hard bottom	h/l_0	10	10	Infinite
Poisson´s ratio	μ_0	0.50	0.40	All values
Influence factor	I	0.1614	0.1689	0.1925
Range Δ_r/Δ_0		> 0.70	> 0.426	All values
$r_{50}=f(\Delta_r/\Delta_0)$	α	0.592	0.548	0.584
	β	2.460	2.629	3.115
	B	0	0	0
Range Δ_r/Δ_0		< 0.70	< 0.426	
$r_{50}=f(\Delta_r/\Delta_0)$	α	0.219	0.2004	
	β	371.1	2283.4	
	B	2	3	
$l=f(r_{50}, \alpha)$	y_0	0.620	0.602	0.525
	m	0.183	0.192	0.180
$S_0/S = f(a/l)$	$\bar{m}$	0.52	0.48	0.44

3.3. Results and discussion

3.3.1. Quality control of compaction

Figs. 3-7 and 3-8 show the dry density and moisture content of the subbase and base layers during construction. The compaction values obtained for the base and subbase course layer were above 98% and 95%, respectively, in the modified proctor. This means that the values meet the limits in PG3 articles 330 and 510 [28]. However, the compaction water content was lower than the optimum moisture obtained in the laboratory, possibly because of the lack of experience using RA by the construction companies and supervising engineers.

According to Fig. 3-7, results for the subbases show that the densities for MRS-1 (sections I.II and I.III) are lower than those for conventional soil SS-1 (section I.I). In base layers, densities are also lower for recycled materials (RMAS-1) than for crushed quarry (CS-1), as shown in Fig. 3-8. These results are in line with previous studies carried out by Jiménez et al. [9–12] and Del Rey et al. [14].

Fig. 3-7 shows that moisture content is similar for the three section materials. In MRS-1, there is an important gap between the optimum moisture content and the content obtained on site. Fig. 3-8 shows similar results for the base layers. Materials were placed in work with a moisture content below the optimum value obtained in laboratory tests. This is attributable to the lower dry density and higher water absorption capacity of recycled aggregates relative to NA. Jiménez [13] proposed that in recycled mixed aggregates the water absorption values range from 11 to 15%, while in NA this value range from 0.5 to 1.8%.

This work has shown that the quality control of compaction and moisture of mixed recycled aggregates placed on site has to be higher than for natural aggregates, since recycled aggregates require a greater amount of compaction water and the construction companies have no experience in the use of mixed recycled aggregates.

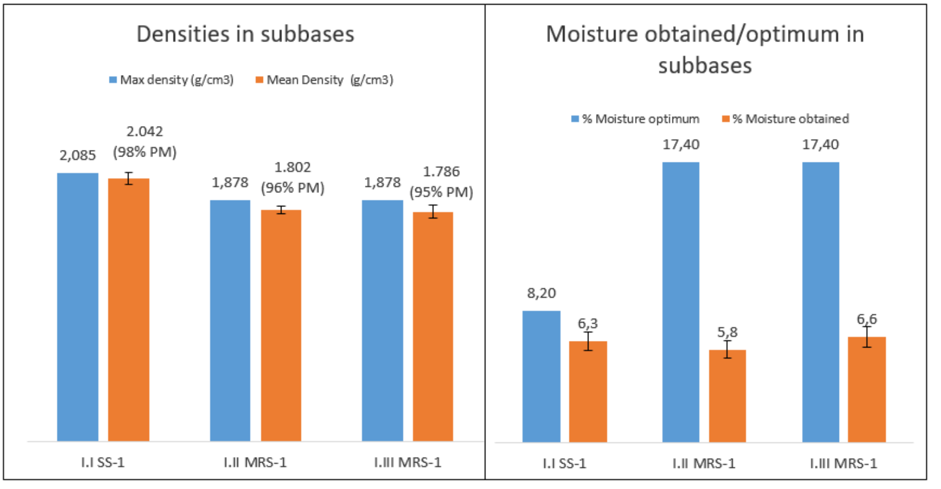

Fig. 3-7 Densities and moistures in subbases.

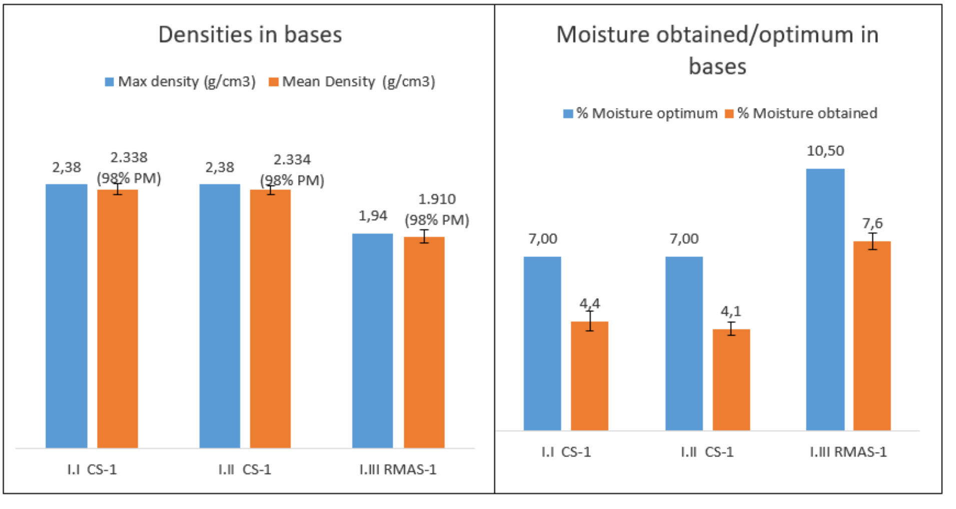

Fig. 3-8 Densities and moistures in bases.

3.3.2. Loading test plate results

The deformation moduli in subbases are similar for recycled materials, while the selected soil of section I.I is higher. As shown in Fig. 3-9, the ratio between both cycles is higher than 2 in MRS-1 and lower than 2 in quarry materials (SS-1), which can be justified by the lower compaction percentage of MRS-1 with respect to SS-1 (Fig. 3-7).

Deformation moduli on granular bases are similar in sections I.I and I.II. The modulus for section I.III is lower, as shown in Fig. 3-10. The ratio between Ev1 and Ev2 seems to be lower than 2 for CS-1 and RMAS-1, which means that high compaction has been obtained during the placement on site (Fig. 3-8).

The plate load test in Fig. 3-9 and Fig. 3-10 shows values over 200 MPa for the Ev2 in bases and subbases. The ratio between Ev2 and Ev1 is below 2.2; these values comply with Spanish standards [28] limits for foundation failure by vertical strain.

Despite the good bearing capacity of the recycled materials used in this study, the moduli obtained in this work are lower than those obtained by Jiménez et al. [10] on an experimental unpaved rural road. These authors tested a selected mixed recycled aggregate, a recycled concrete aggregates and a crushed limestone as reference. The layers built using recycled aggregates showed a high bearing capacity, the Ev2 values oscillated between 270 and 405 MPa for mixed recycled aggregates and 321 and 642 MPa for recycled concrete aggregates, the values oscillated depending on the test point and date. This high bearing capacity was justified by the excellent material of the subgrade. Nevertheless, the Ev2/Ev1 ratios are lower in this ER with respect to those obtained by Jiménez et al. [10].

In a second work, Jiménez et al. [12] evaluated on an experimental rural road the performance of a recycled aggregate from non-selected CDW. The Ev2 values was 132 MPa, a lower value than that obtained in this study. The low bearing capacity of the subgrade and the poor quality of the recycled material justified these results.

This new ER has shown that natural materials used are of a high quality possessing a high bearing capacity, and that recycled materials have obtained similar results, which makes them a viable option for NA replacement.

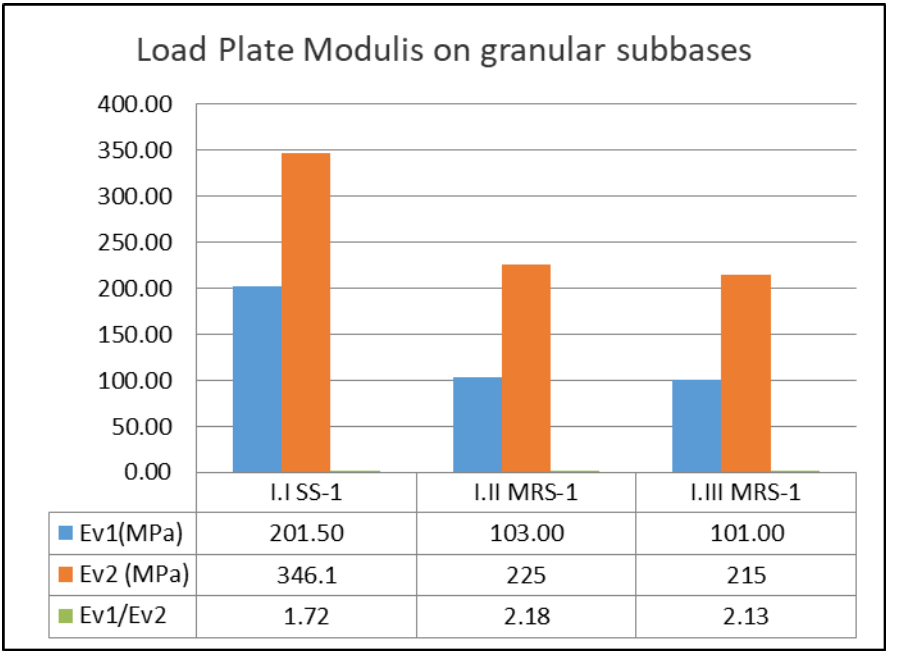

Fig. 3-9 Plate tests results on granular subbases.

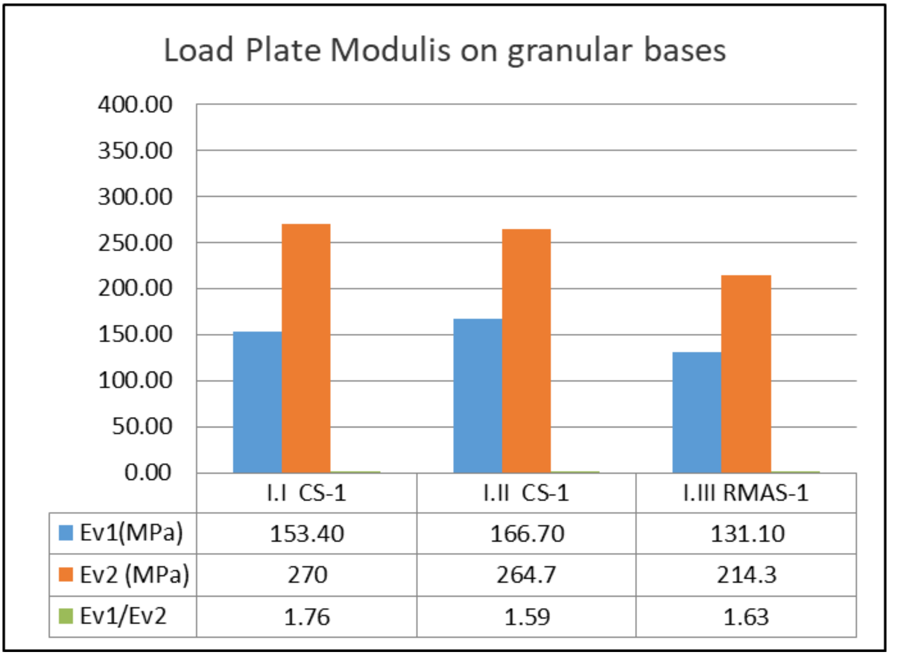

Fig. 3-10 Plate tests results on bases.

3.3.3. Deflection results obtained by FWD

In 2009, the road was opened to traffic. From 2009 to 2013, deflection tests were conducted every six months to investigate the evolution of the bearing capacity of these recycled material layers in comparison with NA layers. During this time a total of eight controls were made. FWD represents a more realistic test than loading test plate because it simulates the dynamic load that real traffic generates.

Deflections are shown for subbases (Fig. 3-11) and bases (Fig. 3-12) along the investigated road. All deflections are lower than their theoretical values, which means that the structural capacity of the layers is higher than expected.

On subbase layers, deflections and moduli are similar in the three sections, as shown on Fig. 3-13. On base layers, the mean value of deflections and moduli are close for sections I.I and I.II as shown in Fig. 3-14. Section I.III has slightly higher deflections and lower moduli values. Table 4 shows the evolution of deflections from June 2009 until January 2013. The deflections obtained are lower than the theoretical values (Fig. 3-6); this means that the structural capacity of the road is higher than expected. Because the road is coated with an asphalt concrete, and because concrete ditches are located along the road, seasonal variations do not affect the value of the deflections for the three sections.

Three one-way ANOVA tests were performed to determine whether seasonal moisture conditions during deflection measurements had a statistically significant effect on the mean deflections obtained with the FWD for each section. As presented in Table 3-4, the p-value of the F-test was over 0.05 for the three sections. This means that there was no significant difference in the mean deflections of the sections during wet or dry seasons. Therefore, climate conditions did not affect deflection values. In contrast, as presented in Table 3-4, there were significant differences in the deflections of the three sections.

Deflection values for section I.II (CS-1+MRS-1) tended to be higher than those for section I.I (CS-1+SS-1). Deflection tended to be minimized in final tests. With respect to section I.III (RMAS-1+MRS-1), the values seem stable, and are higher than those obtained in the two other sections. Values are higher than those obtained by Perez et al. [16] and Agrela et al. [15]. In this Malaga road test, CDW was treated with cement and RC was used for the aggregate, which makes them of better quality than those used in the present research. Deflections showed lower values in section I.I, this was motivated by the higher bearing capacity of SS-1 and CS-1, nevertheless sections build with MRS-1 and RMAS-1 had a suitable performance in the ER. Due to its durability and bearing capacity it can be assure that RMAS-1 and MRS-1 are valid materials for NA substitution as unbound layers.

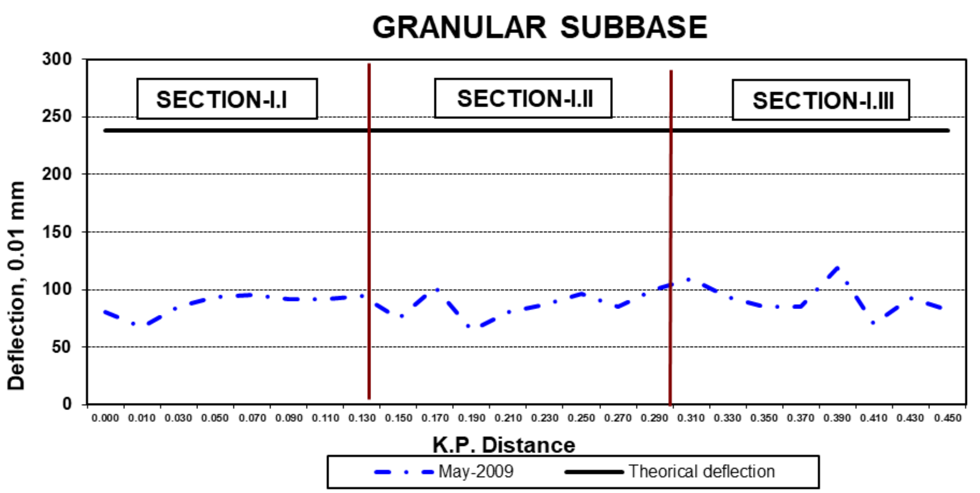

Fig. 3-11 Bearing capacity in granular subbase (12th May 2009). Adapted from García-Garrido [8].

Table 3-4 Deflection results of ANOVA.

Properties	Factor Levels	Factor: Composition of Sections: Section I.I	Section I.II	Section I.III	Date	Section I.I		Section I.II		Section I.III	
Deflections (0.01 mm)	p-value	<0.0001				0.7115		0.2529		0.8125	
	M	45.98	58.06	70.50	Factor Levels	M	SD	M	SD	M	SD
	SD	6.41	11.63	14.60	jun-09	49.11	8.05	64.34	5.95	66.81	9.55
					dic-09	44.49	7.41	59.42	8.47	67.40	21.50
					jun-10	46.99	8.67	57.10	14.98	65.54	12.84
					dic-10	46.15	7.18	61.77	12.50	74.99	18.21
					jul-11	46.20	6.04	62.03	12.36	71.32	16.44
					dic-11	45.98	6.90	55.86	16.37	75.16	16.05
					jun-12	46.25	3.20	51.20	8.25	69.02	12.42
					ene-13	42.63	1.60	52.74	8.19	73.78	8.41

M=Mean
SD=Standard deviation

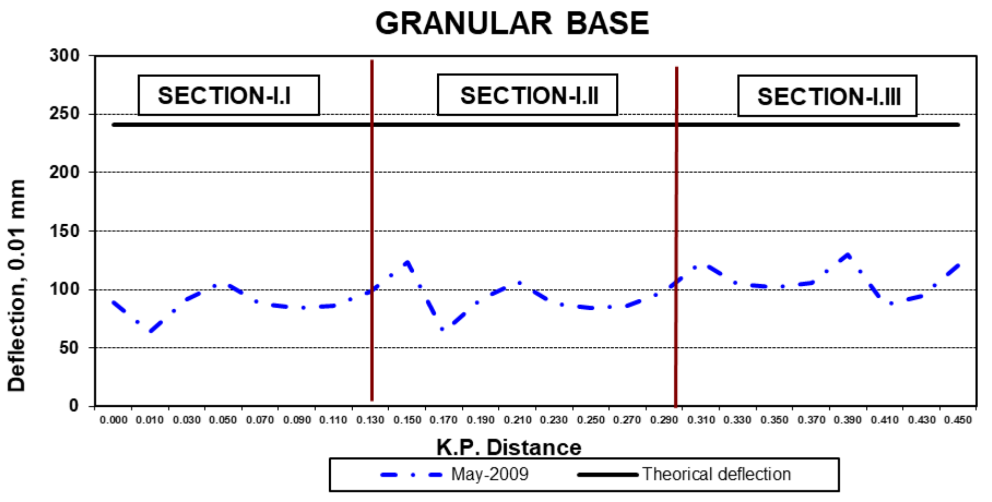

Fig. 3-12 Bearing capacity in granular base (19th and 21th May 2009). Adapted from García-Garrido [8].

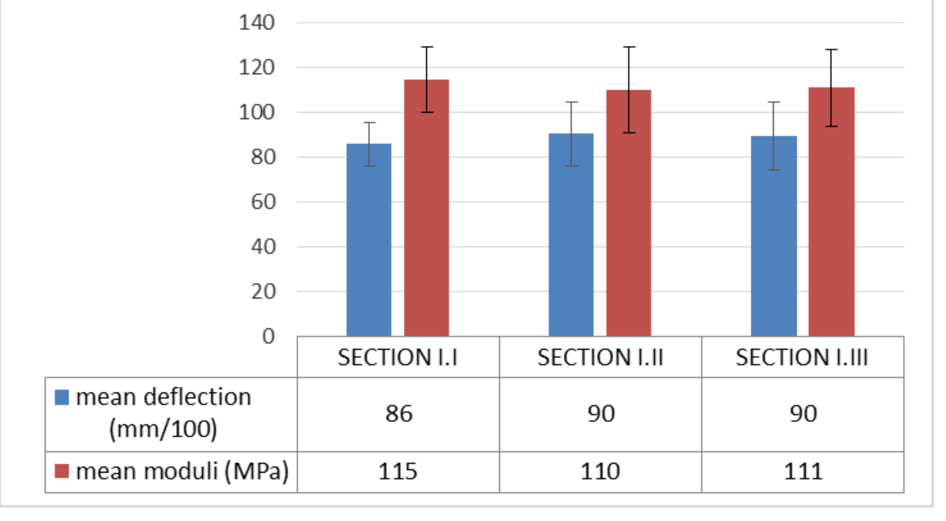

Fig. 3-13 Deflections over granular subbase (May, 2009).

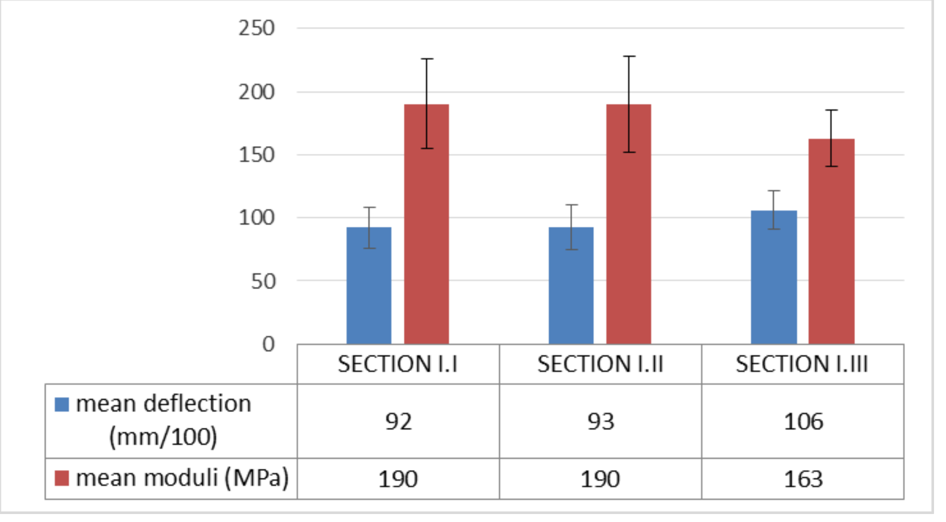

Fig. 3-14 Deflections over granular base course (May, 2009).

3.3.4. Moduli calculations for subbases

Moduli calculations have been made from the deflection basins of the FWD-measured tests from June 2009 to January 2013. To obtain the moduli values, two different methods were used. The first method used back calculation, as described in section 2.6.1 using EVERCAL software [45]. The second method used forward calculation, which is also described in section 2.6.2. GPR and topographic controls were used to determine real thickness of each layer, because moduli obtained through backcalculation are very sensitive to layer thickness.

Moduli for granular subbases SS-1 and MRS-1 are calculated and compared using these two methods. The p-values of both ANOVAs were over 0.05; therefore, there are no significant statistical differences between the mean moduli calculations for each method. Table 5 shows the means and standard deviations for the moduli of SS-1 and MRS-1 using both methods, respectively. It can be concluded that both methods are valid for this calculation. The moduli values obtain in MRS-1 are similar to those back calculated by Lanceri et al. [20] (122–200 MPa). Moduli values obtained are shown on table 5, MRS-1 modulus is between 160.8-156.5

MPa and SS-1 value is between 220.0-223.2 MPa, thus MRS-1 can replace SS-1 with a ratio of 1.4, therefore to obtain the equivalent thickness of a 30 cm layer of SS, 42 cm of MRS-1 are needed. MRS-1 showed an acceptable modulus as a subbase layer in this low bearing traffic road. MRS-1 had a stable mechanical performance during the time that this experiment took place. Therefore, it can be said that it is possible to replace natural soils with MRS on low traffic roads.

Table 3-5 Moduli of SS-1, MRS-1, CS-1 and RMAS-1 (MPa). Summary of comparison between forward and backcalculation.

Method	SS-1		MRS-1		CS-1		RMAS-1	
	M	SD	M	SD	M	SD	M	SD
Back moduli	223.2	21.3	160.8	29.4	484.8	96.4	351.2	57.1
Forward moduli	220.0	32.7	156.5	31.3	477.9	97.9	347.0	68.9
p-value	0.5136		0.2613		0.5671		0.7073	

M (Mean), SD (Standard Deviation).

3.3.5. Moduli calculations for bases

The moduli of the granular bases for CS-1 and RMAS-1 are calculated by forward and back calculation, as in the previous section. An ANOVA was performed to evaluate whether or not there was a significant difference between the methods for these two materials. Table 5 presents the means and standard deviations for the moduli of CS-1 and RMAS-1, respectively, using both methods. The ratio of the mean moduli determined from forward-back calculation in CS-1 equals 1.014. For RMAS-1, this ratio equals 1.012, as shown in Table 5 9. This implies that both methods are valid for this calculation. The moduli values obtain in RMAS-1 are similar to those back calculated by Lanceri et al. [20] (235−379 MPa).

Similar results (160−550 MPa) were obtained by Leite et al. [52] for RMA in a laboratory using a repeated load triaxial test. In Table 6, the moduli for granular bases and subbases are reported, according to AASHTO [43]. RMAS-1 would be classified as a natural aggregate because of its modulus, MRS-1 would be classified as a selected soil (S2), SS-1 would be classified as a selected soil (S3), and CS-1 would be classified as a crushed quarry stone.

RA had lower modulus values than NA. Despite this fact, the mechanical performance of RMAS-1 and MRS-1 makes those materials suitable for low volume traffic roads such as the one used in ER.

Moduli results for granular bases are shown on table 5, RMAS-1 modulus is between 351.2-347.0 MPa while CS-1 modulus is between 484.8-477.9 MPa, thus RMAS-1 can replace CS-1 with a ratio of 1.37, therefore to obtain the equivalent thickness of 30 cm of CS-1, 41 cm of RMAS-1 are needed. Moduli of RMAS-1 showed steady values on each FWD test carried out along 5 years, therefore crushed stone can be replaced by RMAS-1 obtaining an acceptable performance. In the same way the MRS-1 can replace the SS-1 with a ratio of 1.40, therefore to obtain the equivalent thickness of 30 cm of SS-1, 42 cm of MRS-1 are needed

Table 3-6 Maximum values for granular bases and subbases according to ICAFIR [122]**.**

Material	Maximum Moduli (MPa)
A-4 (AASHTO)	150
A-3 (AASHTO)	200
A-1-b (AASHTO)	250
A-1-a (AASHTO)	350

3.3.6. International Roughness Index (IRI)

Two IRI measurements were made on the ER (December 2009 and July 2016). IRI values were obtained as averages of eight passes for each section. In order to detect the effects of the date and the composition of each section on variations in the mean IRI values, a one-way ANOVA was performed. Six different levels were defined, corresponding to the three sections (SI.I, SI.II2 and SI.III) and two measurement dates (2009 and 2016).

The results obtained are presented in Table 7; the results indicate that there were no statistically significant differences between the IRI values for the three sections studied ($p > 0.05$). Likewise, the date has no statistically significant influence on any of the three sections studied ($p > 0.05$). According to the World Bank [41], the values obtained after seven years correspond to a new pavement, and the results are similar for the three sections. There were no significant differences in the behaviour of Section I.I (constructed only with NA) and Section I.III (constructed with CDW aggregates). IRI values obtained after seven years showed the viability of NA substitution by RMAS-1 and MRS-1. This long term period results justifies the use of RMAS-1 and MRS-1 as unbound layers in low volume traffic roads.

Table 3-7 International Roughness Index results of ANOVA.

		Factor									
		Composition of Sections			Date						
Properties	Factor Levels	Section I	Section II	Section III		Section I		Section II		Section III	
IRI (mm/m)	p-value	0.3405				0.4947		0.7138		0.1913	
					Factor Levels	M	SD	M	SD	M	SD
	M	2.28	2.60	2.48	dic-09	2.17	0.90	2.56	0.65	2.33	0.67
	SD	0.80	0.52	0.59	jul-16	2.38	0.70	2.64	0.36	2.63	0.48

M=Mean
SD=Standard deviation

3.4. Conclusions

This research focuses on the mechanical and functional behaviour of an ER built with recycled materials from non-selected construction and demolitions waste mixed with excavation soils (RMAS-1 and MRS-1). The following partial conclusions can be extracted:

RMAS-1 and crushed stone granulometries were very similar. Compaction controls showed that materials were correctly set in place. Dry density was higher and optimum moisture was lower than in natural soils and aggregates; this occurred because of the higher porosity of recycled aggregates.

A high bearing capacity was obtained in sections built with recycled materials, which meet the mechanical requirements of the Spanish regulations for road construction for of any category of traffic. The ratio between Ev1 and Ev2 was under 2.2, which is the Spanish limit; this shows that the materials were correctly set in place. Deflections obtained over three years in the experimental road are lower than the theoretical values; this means that the structural capacity of the three sections is higher than expected.

Section I.I built with natural selected soil and crushed limestone exhibited lower deflection values than sections I.II built with mixed recycled soil (MRS-1) and I.III built with mixed recycled soil and recycled mixed aggregates soil (RMAS-1). Section I.II had lower deflection values than Section I.III. Deflections were stable over time and they were under the theoretical limits required for these type of materials.

The determination of moduli through forward and back calculation for the granular bases and subbases showed no statistically significant differences in mean values for the three sections tested. Both methods used were shown to be valid. Because of the simplicity of forward calculation, it is advisable to use that method to determine the moduli of granular bases and subbases for pavements. Crushed limestone had a mean value (between both methods) of 481 MPa, while the value for RMAS-1 averaged 349 MPa. Selected soil had a mean value of 22 MPa, while MRS-1 averaged 158 MPa. Recycled layers had lower moduli values than natural material layers but still had a higher mechanical performance than expected theoretically, thus it can be used as granular bases and subbases in low volume traffic roads. From a practical point of view, 30 cm of selected soil can be replace by 42 cm of MRS-1, and 30 cm of crushed limestone can be replace by 41 cm of RMAS-1.

After seven years during which the ER was open to traffic, IRI performance was shown to be similar in the three sections. According to its value, it could be catalogued by the World Bank as if it was a new pavement. It can be assured that sections built with recycled materials perform similarly to the section made with natural materials, and that its roughness over time is stable.

The long term results obtained by the present work proof the use of RMAS-1 and MRS-1 as viable replacement materials for natural soils and aggregates in low-traffic roads construction (fewer than 50 heavy vehicles/day). Additionally, the technical specification limits for Los Angeles abrasion and sand equivalents in the Spanish code (PG-3) could be raised to 45 for low-traffic roads and mixed recycled aggregates. Finally this research shows new uses for non-selected construction and demolition wastes and prevents its illegal or legal deposit in landfills. Ecological footprint can be reduced by avoiding natural aggregate extraction from rivers and quarries.

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4. Recycling screening waste and recycled mixed aggregates from construction and demolition waste in paved bike lanes.

This chapter has been published in the journal "Journal of Cleaner Production" volume 190 (2018) pages 211–220: **Javier Tavira[a], *, José Ramón Jiménez[b], *, Jesús Ayuso[b], Antonio López-Uceda[b], Enrique Fernández Ledesma[c]**

[a] JTD Civil Eng., Carretera de Carmona 40 D 1º D 41008 Sevilla, Spain.

[b] Área de Ingeniería de la Construcción, Universidad de Córdoba. Ctra. N-IV, Km 396, 14014 Córdoba, Spain.

[c] Área de Mecánica de Medios Continuos y Teoría de Estructuras, Universidad de Córdoba. Ctra. N-IV, Km 396, 14014 Córdoba, Spain.

*Corresponding authors. Both authors equally contributed to the paper. Address: Construction Engineering Area. University of Córdoba, Ed. Leonardo Da Vinci, Campus de Rabanales, Ctra. N-IV, km-396, CP 14014. Córdoba, Spain. Tel.: +34 667524702; fax: +34 957218550.

E-mail address: jrjimenez@uco.es (JR Jiménez), jtavira@ciccp.es (J. Tavira

Abstract

This research conducts a full-scale study on the use of recycled mixed aggregates from construction and demolition waste and its screening waste in an experimental bike lane. The subgrade and the natural and recycled materials used as the base and subbase courses were characterized in a laboratory. During the construction of the experimental section, densities and deflections were measured to evaluate the

mechanical behaviour of the structural layers and to determine the Young's modulus of the natural and recycled materials. After the lane was open to traffic for two years, the moduli evolution of the materials were studied. For the first time, the results obtained have shown the feasibility of using screening waste that does not meet the physical-mechanical and chemical requirements for use on paved roads as structural layers in bike lanes.

Keywords:

Bike lane, backcalculation, recycled mixed aggregates, screening waste, construction and demolition waste.

Acronyms:

AASHTO - American Association of State Highway and Transportation Officials; CBR – California Bearing Ratio; CDW - construction and demolition waste; CRA - Catalogue of pavements with Recycled Aggregates; CS-1 – Crushed Limestone; EBL – Experimental Bike Lane; FWD – falling weight deflectometer; NA – Natural aggregates; PG-3 – Spanish general technical specification for road construction; RA - recycled aggregates; RCA – Recycled concrete aggregates; RMA – recycled mixed aggregates; RMSW - Recycled mixed aggregates with screening wastes; RMCA – Recycled Mixed Ceramic Aggregates; SG-1 – Subgrade; SS-1 – Selected Soil; SW – Screenings wastes.

4.1. Introduction

Quarries in Europe produced a total of 1000 million tons per year of stone in 2010 [1]. In Spain, the total amount of natural aggregates (NA) produced in 2012 was 208 million tons [2]. An alternative to NA could be the use of recycled aggregates (RA) from construction and demolition waste (CDW). In 2012, CDW production was roughly 821 million tons in the European Union, and in Spain alone, the amount was 20 million tons in 2014 [3]. The amount of waste from the construction industry used as filling material or illegally dumped on empty lots has been increasing over time [4]. CDW is mainly composed of 80% inert materials such as concrete, ceramics, tiles and bricks [5], which have high recycling potential.

Recycling plants can be stationary or mobile, and a mobile plant typically consists of a crusher as well as sorting and sieving devices. The quality of RA obtained in these plants is lower than in stationary plants where several crushers work in conjunction with sieving devices [6].

A “good practice guide” regarding the production and utilization of CDW was recently in published Andalusia, Spain [7]. Public administration, waste management companies and other agents involved in RA production needed a document that explained the technical and legal matters of this recycling process.

In 2015, Spanish recycling plants generated 1.6 million tons of screenings waste (SW), which were sent to landfills [8], which caused clogging and wasted a material that could be recycled. At present, no other use is provided for these materials because SW does not meet road specifications to be used as a filler or in other structural layers. High sulphate, soluble salts and gypsum contents are among the reasons why SW cannot be used as road structural layers [9]. High content of impurities in the fine fraction is typically expected in RA, as well [9]. Lack of landfill areas and the high environmental impact of mining natural aggregates increases the need to conduct experimental studies on SW recycling. Finding viable alternatives for the use of SW favours the development of environmentally friendly construction.

To promote the use of recycled materials from CDW, a catalogue of pavement made with recycled aggregates (CRA) [10] was issued on 2017. This catalogue is a pre-normative draft published by the Public Works Agency of the Regional Government of Andalusia (Spain), but its use and implementation are not mandatory right now. This document regulates new uses for RA from CDW, such as cycling pavements, back fill and bedding material in pipes, unpaved rural roads, and structural road layers, establishing the physical-mechanical and chemical properties required for RA for each of these uses. There is no reference to the use of SW in civil engineering applications in this catalogue. The technical specifications included in the CRA for bike lanes construction materials have been obtained from laboratory tests, so the construction of experimental sections is a key aspect to improve the technical specifications of this catalogue. The Spanish General Technical Specification for Road Construction (PG-3) [11] is the active regulation in Spain. The problem with the application of PG-3 is that the proposed limits have been established for natural aggregates and not for recycled aggregates, thus limiting the use of recycled aggregates [12].

To determine if SW and RA are adequate as granular unbound layers in low bearing capacity roads and if the limits of this catalogue [10] are valid, a real scale experiment is needed to verify its performance and evolution over time.

According to Jimenez [12] there are three types of RA that can be used on roads, including recycled concrete aggregates (RCA), recycled mixed aggregates (RMA) and recycled mixed ceramic aggregates (RMCA). The difference between RCA, RMA and RMCA are its composition. RCA have more than a 90 % of Rc (concrete) + Ru (unbound aggregates without mortar attached) and a less than a 10 % of Rb (ceramic) , RMA have more than a 70% of Rc + Ru + Ra (asphalt) and a less than a 30 % of Rb. Finally RMCA has less than a 70 % of Rc + Ru + Ra and more than a 30% of Rb. Lancieri et al. [13] completed a test with RMA as the unbound layer in two 200-metres long paved sections over two different subgrades classified as A-2-6 and A-7-8, respectively, in accordance with the American Association of State Highway and Transportation Officials (AASHTO) [14]. The elastic moduli for these recycled unbound layers over a period of eight years was calculated, and these materials had an increase in bearing capacity due to self-cementing and further traffic compaction.

Jiménez et al. [15] studied an experimental unpaved road with two different sections of 100 metres long each, with RMA as the granular subbase and RCA and NA as the granular base. The subgrade was classified as A-6 in accordance with AASHTO. Both recycled materials met all specifications required by PG-3 for use in structural layers, except the soluble salt content. Jimenez et al. [16] studied a second experimental road with non-selected RMA obtained with low embodied energy as the granular bases; NA was placed as the granular subbase and compared with RMA. The subgrade was classified as A-1-B according to AASHTO. The RA did not meet the limits for sulphur compounds and soluble salt content. Tavira et al. [17] studied a paved experimental road with three sections that was built with RMA mixed with natural excavation soil in the subbases and RMA in the base; NA was used in the bases and subbases. In all previous studies, the performance of NA was similar to that of RMA. SW was not used in these experimental roads due to its impurities; furthermore, according to previous studies, SW should be removed at the beginning of the recycling process [18].

The main purpose of this research is to study the feasibility of using low quality recycled mixed aggregates from CDW and the SW obtained in its processes as structural layer materials of a paved bike lane where the mechanical requirements are lower than for roads. Construction of an experimental bike lane could validate the use of these recycled materials, which do not satisfy the chemical and physical specifications to be used in roads [13]. Otherwise, these materials would end up in landfills. The elastic moduli of recycled materials are a basic parameter used to estimate pavement longevity in this research, obtained through backcalculation. With this RA moduli input, the equivalent thicknesses of pavement sections built with recycled materials or natural aggregates can be calculated. Full or partial replacement of natural materials by recycled materials can contribute significantly to reduce ecological footprints in road infrastructures [19]. To the best of our knowledge, there are no previous studies regarding the use of SW obtained from CDW as unbound layers materials in the construction of roads or bike lanes.

4.2. Materials and methods

4.2.1. CDW recycling procedure

The experimental bike lane (EBL) was built using two recycled materials from CDW: a recycled mixed aggregate (RMA-1) and a recycled mixed material from screening waste (RMSW-1). Fig. 1 shows the CDW process and collection points of the recycled materials. The first step after arrival of CDW was to reduce bigger fragments that could not be crushed, then primary screening (0/20 mm) removed the finest particles with more impurities and improved the quality of the recycled aggregates subsequently obtained. Then, RMSW-1 was collected. An impact crusher ground particles greater than 20 mm. The ground materials were screened by a 40-mm sieve. At this point, materials larger than 40 mm were returned to the impact crusher to reduce their size. After passing through the sieve, a magnetic belt conveyor was used to remove metallic elements. Finally, a blower removed light particles to obtain RMA-1.

Table 1 shows the composition of the recycled materials in accordance with UNE-EN 933-11 [20]. RMA-1 would be classified as a recycled mixed aggregate according to the catalogue of pavement and work units with RA from CDW (CRA) [10]. Based on its composition, RMA-1 could be used as the base course materials in paved bike lanes.

In accordance with the proposal of CRA use for the construction of paved bike lanes, materials used in subbase layers must contain a percentage of impurities less than 3% (X1 + X2), a quantity of floating particles less than 2 cm3/kg, and a percentage of gypsum particles less than 1%. Due to the high content of impurities in the screening waste, RMSW-1 could not be used as subbase course materials in paved bike lanes.

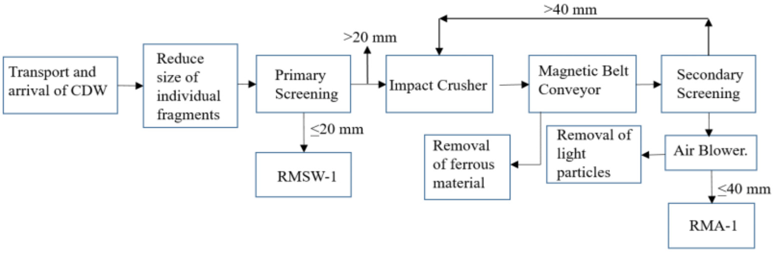

Fig. 4-1 Recycling process of CDW

Table 4-1 Composition of the mixed recycled aggregates [20]

Compositions	RMSW-1	RMA-1
% RA (Asphalt)	2.3	1
% RB (Ceramics)	17.3	24
% RC (Concrete and Mortar)	67	60
FL (Floating particles) (cm3/kg)	2.7	0
% RU (Unbound aggregates)	8	14
% X1 (Gypsum)	1.5	0.8
% X2 (Wood, plastic and metals)	1.2	0.2

4.2.2. Description of the test sections

The EBL was built on a section of a cyclist route that connects the urban area of the city of Córdoba (Spain) with the University Campus (Andalusia, Spain). It was not built beside any common roads as shown on Fig 2. The EBL had three sections of 100 m, 100 m, and 200 m for sections I, II and III, respectively. The structural layers were designed according to the design recommendations for bicycle lanes proposed in the catalogue of pavement and work units made with RA from CDW published by the Public Works Agency of the Regional Government of Andalusia (Spain) [10]. Fig. 3 shows the description of the three sections and the thicknesses of the structural layers. The surface course of all sections was made of 4 cm of asphalt concrete BBTM8B [11], it is a non-continuous bituminous mixture with a maximum aggregate size of 8mm .

The base course of the second section was crushed limestone (CS-1). The recycled mixed aggregate (RMA-1) was used in the first and third sections. The subbase course was built with two different materials. Section I was made of a natural selected soil (SS-1). Material obtained from primary screening of CDW (RMSW-1) was used in sections II and III. Construction of the EBL lasted from October 2014 until February 2015.

4.2.3. Materials characterization

Materials used in the EBL were characterized according to the Spanish General Technical Specification for Road Construction (PG-3) [11] and the catalogue of pavement and work units with RA from CDW (CRA) [10]. Granular layers and the subgrade materials were collected according to UNE-EN 932-1 [21]. Test procedures met specifications of UNE-EN 932-2 [22].

Fig. 4-2 Images of the Experimental Bike Lane

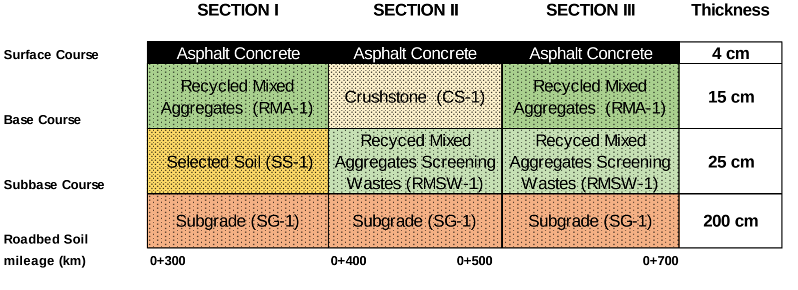

Fig. 4-3 Cross sections of the Experimental Bike Lane

4.2.3.1. Subgrade material

This material was tested to determine the following properties: plasticity index (UNE 103104:1993 and UNE 103103:1994) [23,24], sulphates content (UNE 103201:1996) [25], standard Proctor test (SPT) (UNE 103500:1994) [26], California Bearing Ratio (CBR) (UNE 103502:1995) [27], and free swelling and particle size distribution (UNE 103601:1996) [28].

4.2.3.2. Subbase and base materials

The following properties were tested: plasticity index according to UNE 103104:1993 and UNE 103103:1994 [23,24], the particle size distribution (UNE 103102:1995) [29], modified Proctor test (MPT) (UNE 103501:1994) [30], CBR index (UNE 103502:1995) [27], Los Angeles abrasion coefficient (UNE-EN 1097-2:2010) [31], the total Sulphur content and soluble salt (UNE-EN 1744-1:2010) [25], percentage of crushed particles (UNE-EN 933-35:1999) [32], and flakiness index (UNE-EN 933-3:2012) [33].

4.2.4. Field Testing during construction

4.2.4.1. Field density and moisture content

After setting every granular layer in place, field densities and moisture content were determined using a Trolex model 3440 surface moisture-density gauge according to ASTM D6938 [34]. This test is a quick and non-destructive technique for measuring water content and dry densities of unbound layers. A test was performed every 20 m. The maximum dry density and optimum moisture content of the modified proctor test was used to compare with the results obtained in the field.

4.2.4.2. Falling weight deflectometer (FWD)

Pavement deflections are commonly accepted as a state indicator of pavement structural condition [35]. A Dynatest Heavy Weight Deflectometer 8081 equipped with seven geophones was used. The geophones were located at 0, 300, 450, 600, 900, 1200, and 1500 mm from the loading plate. This equipment has been used in previous studies by Jimenez et al. [15,17,36,37], Tavira et al. [17] and Del Rey et al. [37]. A 450-mm diameter plate was used on the granular layers (bases and subbases), and a plate with 300 mm of diameter was used on the surfaced courses. Loads applied were 39.24 kN with a pressure of 246.47 kPa on the unbound layers and 49.05 kN with a pressure of 693.21 kPa on the asphalt concrete layer; these loads and configurations are regulated by the Technical Specifications for High-Performance Dynamic Monitoring Tests [38] from the Civil Works Agency of Regional Government of Andalusia. Deflections were obtained every ten metres along the three sections in accordance with ASTM D4694 [39]. According to the Spanish standard, temperature did not influence the measurement of the deflection located under the plate at a distance of 0 mm because asphalt concrete was below 10 cm of the thickness [35]. Deflections were measured after the completion of each layer and at the completion of the experimental section (February 2015). Twenty six months later, a new test was performed (April 2017).

4.2.5. Elastic modulus calculation

The moduli of the EBL pavement were obtained using Evercalc [40]. This software calculates the pavement structure moduli of the pavement layers through an iterative process that reproduces the mechanical performance under FWD loading, the method is described in detail by Tavira et al. [17]. Basically It compares the calculated deflections with the deflections measured on field, through an iterative process error is minimized after each step. A previous study made by Tarefner et al. [41] proved that Evercalc produced more consistent and accurate modulus values than Backfaa and Modulus software.

4.2.6. Description of external factors

Climate has a great influence in pavement layer behaviour. A local weather station collected precipitation and temperature values at coordinates in the Universal Transverse Mercator (341399, 4191480).

Fig. 4-4 shows the average monthly maximum and minimum temperatures from October 2014 to March 2017, indicating that there were no extreme temperatures. Fig. 4-5 shows that the highest rainfall collected was in November 2014 for a total of 153.6 mm.

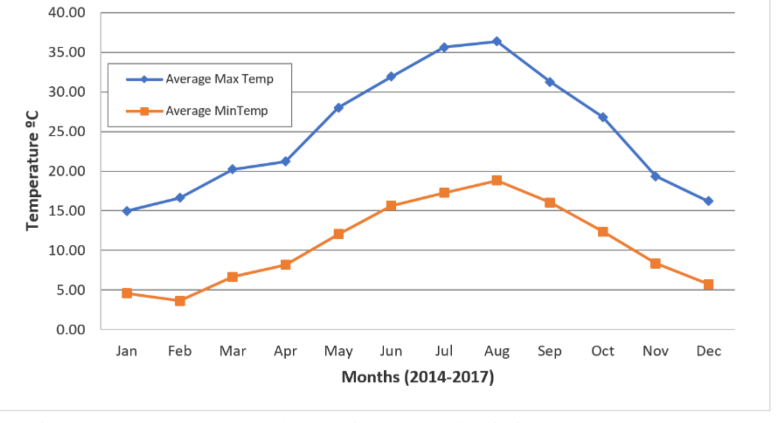

Fig. 4-4 Average monthly maximum and minimum temperatures

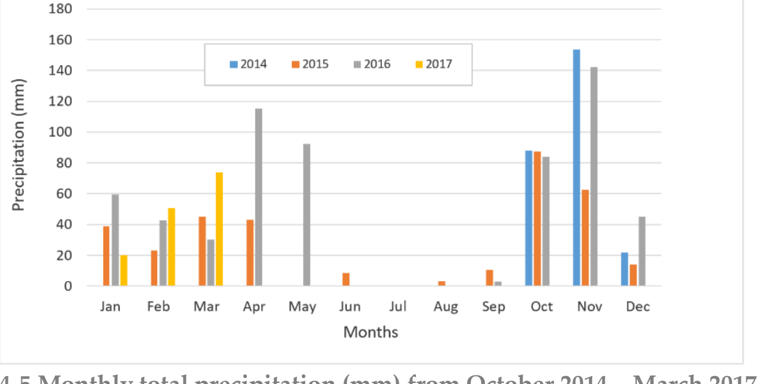

Fig. 4-5 Monthly total precipitation (mm) from October 2014 – March 2017.

Table 4-2 Physical, mechanical and chemical properties of EBL's unbound materials and PG-3 and CRA requirements for mixed recycled aggregates

Properties		SG-1	SS-1	RMSW-1	RMA-1	CS-1	PG3 limits		CRA limits		Standards
							Subbase (SS)	Base (CS)	Subbase (RSS)	Base (RMA-I)	
Water absorption (%)	>4 mm	-	-	8.9	8.0	-	-	-	-	< 9	UNE-EN 1097-6:2014
	<4 mm	-	-	11.2	9.6	-	-	-	-	< 12	UNE-EN 1097-6:2014
Density-SSD (g/cm³)	>4 mm	-	-	2.02	2.13	-	-	-	-	-	UNE-EN 1097-6:2014
	<4 mm	-	-	2.34	2.32	-	-	-	-	-	UNE-EN 1097-6:2014
Max. Size (mm)		12.5	25	20	32	25	100	32	100	40	UNE 103101:1995
% passing sieve # 0.08		67.9	4.6	18.7	5.2	4.6	< 25	-	< 25	0-11	UNE 103101:1995
Liquid Limit		30.7	-	-	-	-	< 30	-	< 30	-	UNE 103103:1994
Plastic Limit		19.2	-	-	-	-	-	-	-	-	UNE 103104:1994
Plastic Index		11.5	-	NP	NP	NP	< 10	NP	< 10	NP	UNE 103104:1993
Sand equivalent (%)		-	-	-	27	42.2	-	> 30	-	> 30	UNE-EN 933-8:2000
Los Angeles (%)		-	-	-	39	28	-	< 35	-	< 40	UNE-EN 1097-2:2010
Flakiness index (%)		-	-	-	13	8	-	< 35	-	< 35	UNE-EN 933-3:2012
Crushed particles (%)		-	-	-	100	100	-	≥ 50	-	≥ 50	UNE-EN 933-35:1999
Max. Dry Density (Mg/m³)		1.85	2.06	1.87	1.84	2.11	-	-	-	-	UNE 103501:1994
Optimum Moisture (%)		12.7	9.1	12.6	14.7	7.4	-	-	-	-	UNE 103501:1994
C.B.R. (%)		5.9	26.4	24	65.5	78.7	≥ 20	-	≥ 20	> 40	UNE 103502:1995
Free swelling (%)		0.6	-	-	-	-	-	-	-	-	UNE 103502:1995
Organic matter (%)		0.27	0.20	1.10	0.92	-	< 0.2	-	< 1	< 1	UNE 103204:1993
Gypsum - $CaSO_4*H_20$ (%)		0.30	0.47	1.5	0.84	-	< 0.2	-	< 2	-	UNE-EN 1744-1:2010
Total Sulphur content SO_3 (%)		-	-	-	0.9	-	-	< 0.7	-	< 1.3	UNE-EN 1744-1:2010
Soluble salt content (%)		0.30	0.0	4.0	3.0	-	< 0.2	-	< 2	-	UNE-EN 1744-1:2010
Water soluble sulphates SO_4 (%)		-	0.13	2.02	1.36	-	-		-	< 0.7	UNE 103201:2003

The CBR tests were carried out with laboratory samples compacted at their corresponding maximum dry density of Modified Proctor and 4-day soaked conditions.
SS: selected soils, CS: crushed stone, RSS: recycled selected soils, RMA-1: recycled mixed aggregates
NP: No Plastic

4.3. Results and discussion

4.3.1. Physical and chemical properties of the materials

Table 4-2 shows the physical and mechanical properties of the unbound materials placed in the EBL as well as the requirements established by the Spanish specifications PG-3 and CRA [10]. Fig. 4-6 shows the particle size distribution of the unbound layer materials. The fine percentage of SG-1 is 67.9%, and it would be classified as an A-6 according to AASHTO [14]. SS-1 would be classified according to AASHTO as an A3 [14] and RMSW-1 would be classified as an A4 [14]. RMA-1 and CS-1 would be classified as A-1-a [14].

Both natural materials (SS-1 and CS-1) came from limestone quarries, and all the physico-chemical properties fulfil the requirements of PG-3 [11] for use as subbase and base materials. Densities and CBR of SS-1 and CS-1 are higher than those of RMA-1 and RMSW-1. CBR of RMA-1 and RMSW-1 are 65.5% and 24%, respectively. The CBR value of RMA-1 is according to the values obtained by Jiménez et al. [12] and Del Rey et al. [37] for mixed recycled aggregates (40-90%), which meet the values of 40% specified for granular bases in CRA [10]. RMSW-1 showed similar values of CBR to those obtained in Tavira et al. [17], and RMSW-1 would be classified by its value as A-3 according to AASHTO [10,11] (CBR >5%).

Optimum moisture is higher in recycled materials than in natural materials, as shown in previous studies [15–17,42], due to the higher water absorption of recycled materials. RMA-1 had a Los Angeles coefficient of 39, which does not meet the limit of 35 required in the PG-3 for base materials, although this limit could be increased up to 40% in accordance with CRA [10]; RA from CDW, due to its origin, has higher abrasion values. According to previous literature, most RMA values should be under 45% [12,13]. In Los Angeles coefficient test all the attached mortar of recycled aggregate is powdered, apart from the abrasion suffered by the natural aggregate. For this reason, both properties are related, when attached mortar content is high, Los Angeles coefficient increases too [12].

Regarding chemical properties, the organic matter, soluble salt and gypsum content in subgrade (SG-1) was under 0.3%. The PG-3 limit was up to 0.2% content of the organic matter; RMA-1 and RMSW-1 have 0.92% and 1.10% organic matter content values, respectively. Organic matter is not a limiting property in road applications and has a typical range of 0.42-1.00% according to Jimenez [12], and on CRA [10], the organic matter is limited to 1% content for granular bases and subbases.

PG-3 limits soluble salt content to 0.2%. RMA-1 had a content of 3%, and RMSW-1 had a 4% soluble salt content. CRA [10] increases this limit to 2% content in subbases. Previous studies [12,15,16,18] showed that a soluble salt content of approximately 4% does not generate dimensional instability in unpaved rural roads, but further studies were needed to assure it with outdoor and traffic conditions. RMA-1 and RMWS-1 content of water soluble sulphates (SO4) does not meet the CRA [10] limit of 0.7% for bases. These limits should be increased for bike lanes up to 1.3% for bases and 2% for subbases. The sand equivalent (27%) and particle size distribution (Fig. 4-6) in RMA-1 do not meet the PG-3 [11] and CRA [10] requirements due to its fine content. Previous studies of recycled materials used as unbound layers did not meet these limits either [15–17].

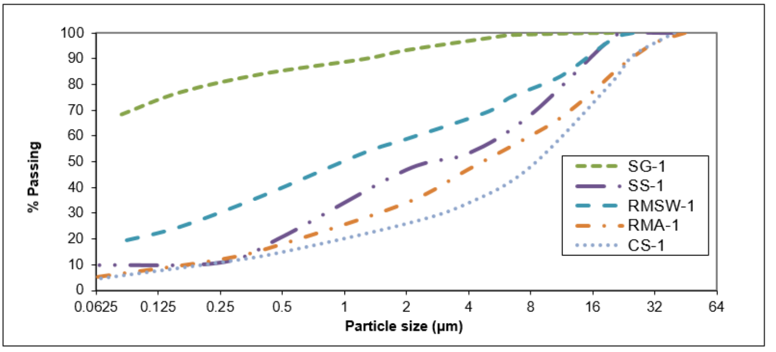

Fig. 4-6 Particle size distribution.

4.3.2. Quality control of compaction

Compaction is the main factor that influences the bearing capacity of unbound layers [43]. Moisture and water content were measured on each granular layer as well as on the subgrade. The degree of compaction was compared with the results of the reference proctor test. On the subgrade, the standard proctor test was used; on granular bases and subbases, the modified proctor test was considered. The limits for the degree of compaction are taken from PG-3 [11]. The Standard Proctor Test results must be over 100% on subgrades, while the Modified Proctor Test results must be over 95% on subbases and 98% on bases. Table 3 shows the average values and standard deviation values obtained on site.

Compaction meets in most cases with PG-3 [11] specifications; therefore, the construction of EBL was acceptable. Average values on subgrade were 104.5%, 103.2% and 102.8% for sections I, II and III, respectively. Regarding to subbases, SS-1 had a 96.2% degree of compaction on section I, while section II and section III were 104.3% and 99.0%, respectively, which meet the limits of PG-3 [11] (95%). All values for the bases were over 98% of the Modified Proctor Test, and the average values were 101.3%, 103.7% and 102.5% for sections I, II and III, respectively.

According to Table 3, the densities for RMSW-1 (sections II and III) are lower than in natural soil SS-1 (section I). In base layers, densities are also lower in recycled materials (RMA-1) than in crushed stone from the quarry (CS-1), as shown in Table 3. These results are in line with previous studies conducted by Jiménez et al. [12,15,16,36], Del Rey et al. [37] and Tavira et al. [17]. The moisture content values for RA are higher than in NA, and the densities are lower because the water absorption in RA is greater than in NA, as shown in previous studies [12,15–17,36,37]. The porosity of RA and its fine portion increase the exposed surface and water absorption, causing these results.

4.3.3. Falling weight deflectometer during construction

Table 4-4 shows the mean (M) and standard deviation (SD) of the deflections and elastic equivalent moduli for every section and layer. The following equation proposed by Brown was used [44]:

$$\boldsymbol{E_0} = \frac{\boldsymbol{2\sigma_0 a(1-\mu_0^2)}}{\boldsymbol{d_0}}$$

E_0 = Elastic Equivalent modulus of the entire pavement system beneath the load plate.

a = Radius of the FWD plate.

σ_0= Pressure of the FWD impact load under the load plate.

d_0 =Deflection at 0 mm from the centre of the FWD plate.

μ_0= Poisson's ratio, value considered was 0.35.

The deflection and equivalent moduli values on the surface course, base and subbase have approximate values among the three sections. Tavira et al. [17] researched a road open to heavy vehicles in which recycled mixed aggregates were mixed with soil and used as the base and subbase granular layers. The results showed lower deflections and higher equivalent moduli because of the lower mechanical requirements in the EBL. Jiménez et al. [15] tested a selected mixed recycled aggregate on an experimental unpaved rural road. Using recycled concrete aggregates and crushed limestone as a reference, the deflections are lower in the rural road than those obtained in EBL. Jiménez et al. [16] also evaluated an experimental rural road by examining the performance of a recycled aggregate from non-selected CDW. Deflection results on granular bases were similar to those obtained in the EBL.

4.3.4. Field control of the evolution of the deflection and equivalent moduli

An analysis of variance (Anova) was conducted with the statistical software Statgraphics Centurion XVI (Version 16.1.18) to assess the significance of the effect of the two factors (section and date) on the surface course deflection. The results presented in Fig. 7 and Table 5 show that there are not significant differences in the mean deflections experienced on each of the sections (p-value >0.05). However, dates had significant influence on sections I and III but did not influence section II. On three sections, the deflection values decreased after two years; this good behaviour occurred because of the light traffic supported by the EBL and the drainage provided by the asphalt layer that helped avoid loss of the granular layers.

Fig. 8 and Table 6 show the Anova of the equivalent modulus evolution between February 2015 and April 2017. Equivalent moduli consider the stiffness of all layers that compose the pavement. The results indicate that there is no significant influence on any section for any date on their equivalent moduli (p-value >0.05). The p-values are under 0.05, so there is a statistically significant difference among dates for sections I and III but not for section II. The moduli values increased after 26 months by 36%, 13% and 34%, respectively, for sections I, II and III. Jiménez [12] describes that the bearing capacity of recycled mixed aggregates from CDW increases over time (demonstrated under laboratory conditions). This author attributes this improvement over time to the pozzolanic reactions occurring between the silica and alumina of the ceramic fines and the hydrated portlandite of the cement, or to certain hydraulic properties that remain in the cement of the concrete and attached mortar. This finding has been tested on a real scale in this research. The equivalent moduli are higher than those obtained by Del Rey et al. [37]; these authors studied a three section experimental road in which non-selected and selected mixed aggregates were compared with natural aggregates. The results showed a mean of 116.9 MPa for the elastic equivalent moduli in the non-selected aggregates, 135.2 MPa in selected CDW, and 160.4 MPa in the NA section.

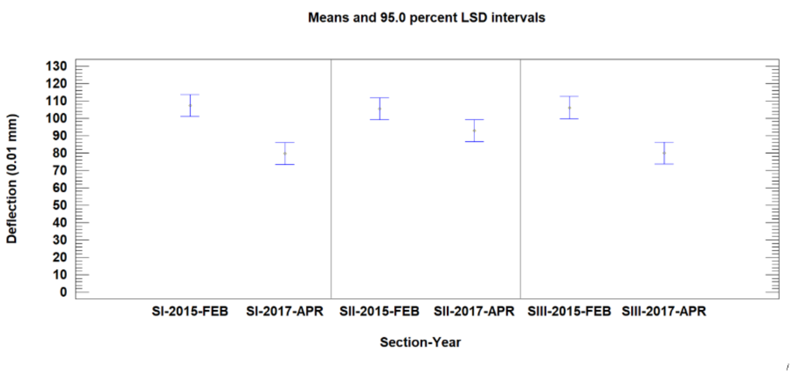

Fig. 4-7 Deflection Evolution on surface course

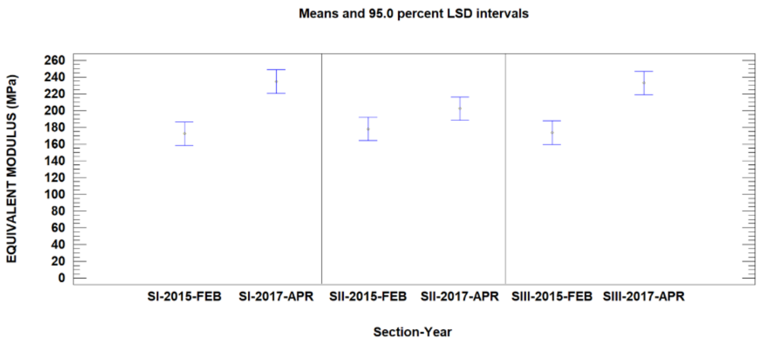

Fig. 4-8 Equivalent moduli on paved EBL

4.3.5. Young moduli calculation of bases and subbases

The deflection basins were analysed with Evercalc [40]; this software back-calculates the moduli through an iterative process, where the measured data are compared with the theoretical data. The process will run until it finds convergence with limited error. As shown in Fig. 9 and Table 7, the evolution of the selected soil SS-1 and RMSW-1 is not statistically significant among materials studied with the ANOVA analysis (p-value >0.05). RMSW-1 had a mean value of 201 MPa, while SS-1 had a mean value of 220 MPa. Moduli values obtained for RMSW-1 indicate that this material may be used as a selected soil (PG-3) [11], and its modulus should be catalogued as A-3 according to AASHTO [14]. Previous studies [13,17] showed similar values of RMSW-1 (122-200 MPa), but subbases in a previous study [17] indicated soluble sulphates content below 1%. Table 7 shows an increased moduli over time of both materials. The moduli increased after 26 months to 9.58% versus 6.1% for SS-1. This moduli value increase for the mixed recycled materials can be explained by certain latent hydraulicity of the cement particles or by various pozzolanic activities of the ceramic particles [12].

Fig. 10 and Table 8 show moduli for granular bases, and there is no statistically significant difference of moduli between CS-1 and RMA-1 (p-value >0.05). The mean moduli of RMA-1 and CS-1 are 424 MPa and 421 MPa, respectively. Moduli values obtained for RMA indicate that this material is acceptable to use as a granular base (PG-3) [11] and can be catalogued as A-1-a according to AASHTO [14]. Previous studies [13,17] showed lower values (235-379 MPa) of RMA than for RMA-1. Other experimental roads [13,37] showed that RA with a content of a 40% mortar and cement can gain resistance due to re-cementation [12]. After 26 months, moduli increased on both materials as follows: RMA-1 had an increase of a 5.55%, and CS-1 had an increase of 2.7%.

Moduli for these recycled materials are used to help calculate the equivalent thickness needed to replace NA. One centimetre of RMSW-1 can replace 1 cm of selected soil, and 1 cm of RMA-1 can replace 1 cm of crushed stone.

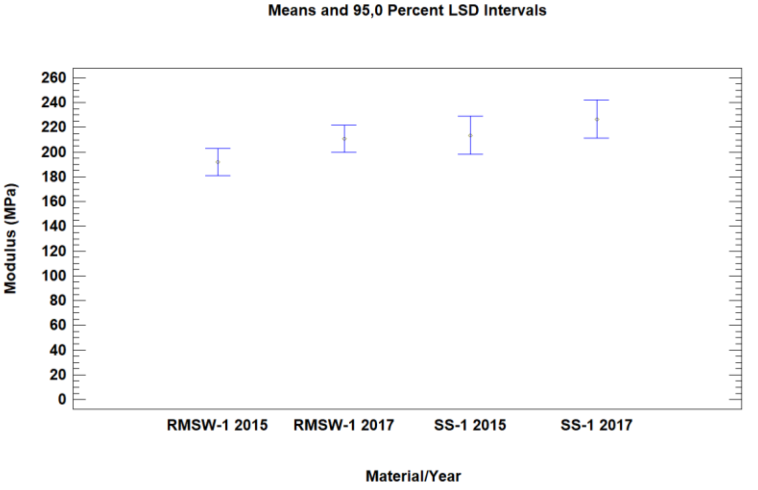

Fig. 4-9 Moduli of granular subbases

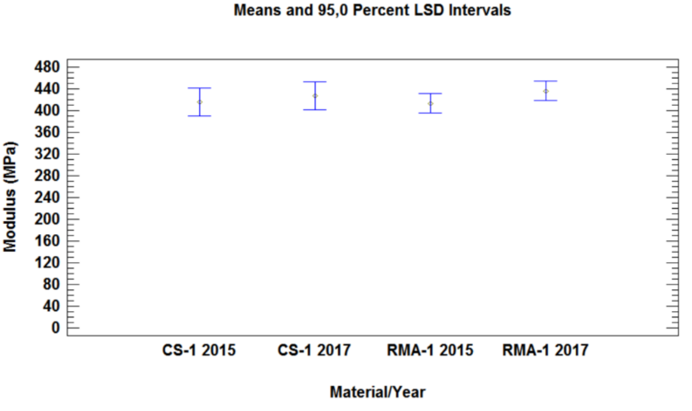

Fig. 4-10 Moduli of granular bases

Table 4-3 % Moisture content and density

Average	Subgrade			Subbase			Base		
	Dry Density (Mg/m3)	Moisture (%)	Compaction (%SPT)	Dry Density (g/cm3)	Moisture (%)	Compaction (%MPT)	Dry Density (Mg/m3)	Moisture (%)	Compaction (%MPT)
Section I	1.93 ± 0.05	7.36 ± 1.28	104.54 ± 2.47	1.98 ± 0.02	4.32 ± 0.87	96.2 ± 0.96	1.86 ± 0.03	9.84 ± 1.57	101.29 ± 1.66
Section II	1.91 ± 0.05	6.72 ± 0.91	103.24 ± 2.88	1.95 ± 0.08	10.86 ± 1.21	104.26 ± 4.29	2.19 ± 0.02	4.06 ± 0.17	103.7 ± 0.82
Section III	1.9 ± 0.06	8.99 ± 2.65	102.75 ± 3.08	1.85 ± 0.06	10.04 ± 0.57	99.02 ± 3.15	1.89 ± 0.04	11.41 ± 0.91	102.49 ± 2.38

Table 4-4 Deflections and equivalent moduli during construction

	Date	Section I				Section II				Section III			
		Deflections (0.01 mm)		Equivalent moduli (MPa)		Deflections (0.01 mm)		Equivalent moduli (MPa)		Deflections (0.01 mm)		Equivalent moduli (MPa)	
		Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
Surface course	06/02/2015	107.26	12.66	172.41	21.34	105.41	19.11	178.05	30.29	106.12	10.63	173.60	18.05
Base	14/12/2014	147.94	34.27	69.21	16.16	153.31	35.10	66.95	16.58	144.63	24.69	69.06	11.22
Subbase	24/11/2014	180.88	37.76	55.55	9.96	196.85	26.18	50.01	6.16	172.10	24.37	57.82	9.81

Table 4-5 Anova analysis of defections on surface course

Properties	Factor Levels	Factor										
		Composition of Sections			**Date**							
		Section I	**Section II**	**Section III**		**Section I**		**Section II**		**Section III**		
Deflections (0.01 mm)	p-value	0.4937				0.0001		0.1372		0.0000		
	M	93.44	99.17	93,02	Factor Levels	M	SD	M	SD	M	SD	p-value
	SD	18.84	18.58	17.07	feb-15	107.26	12.66	105.4	19.11	106.12	10.63	0.9598
					apr-17	79.62	12.81	92.94	16.66	79.92	10.99	0.0623

M=Mean

SD=Standard deviation

Table 4-6 Anova analysis of equivalent moduli on paved EBL

Properties	Factor Levels	Factor: Composition of Sections: Section I	Section II	Section III		Date: Section I		Section II		Section III		
Equivalent Modulus (MPa)	p-value	0.4937				0.0002		0.1270		0.0002		
	M	203.5	190.19	203.21	Factor Levels	M	SD	M	SD	M	SD	p-value
	SD	43.54	35.29	41.38	feb-15	172.41	21.34	178.05	30.29	173.61	18.05	0.8562
					apr-17	234.59	37.39	202.33	37.21	232.81	36.64	0.1106

M=Mean

SD=Standard deviation

Table 4-7 **Anova analysis of granular subbases moduli**

		Factor						
		Composition of Sections						
Properties	**Factor Levels**	**RMSW-1**	**SS-1**		**RMSW-1**		**SS-1**	
Modulus (MPa)	p-value	0.0552			0.094		0.4287	
	M	201.38	220.19	Factor Levels	M	SD	M	SD
	SD	34.70	35.84	feb-15	192.19	36.87	213.64	48.86
				apr-17	210.58	30.56	226.73	15.12

M=Mean
SD=Standard deviation

Table 4-8 **Anova analysis of granular bases moduli**

		Factor						
		Composition of Sections						
Properties	**Factor Levels**	**RMA-1**	**CS-1**		**RMA-1**		**CS-1**	
Modulus (MPa)	p-value	0.8449			0.2542		0.5455	
	M	424.22	421.19	Factor Levels	M	SD	M	SD
	SD	62.58	40.68	feb-15	412.81	71.68	415.48	52.18
				apr-17	435.62	51.24	426.88	26.41

M=Mean
SD=Standard deviation

4.4. Conclusions

This research focus on the mechanical behaviour of an experimental bike lane made with recycled mixed aggregates obtained from CDW (RMA-1) and its screening wastes (RMSW-1). In accordance with AASHTO, the RMA-1 can be classified as A-1-a, and RMSW-1 can be classified as A-4 because of its fine fraction.

According to the behaviour of the recycled materials used on this experimental bike lane, the following limits established in the technical specifications could be modified for granular bases in bike lane construction: organic matter content could be increased to 2%; sulphate content could be increased to a 2.5%; soluble salts content could be increased to 4%; Los Angeles Abrasion could be increased to 40%; and equivalent sand could be decreased to 25%.

Bearing capacity and its evolution over time is more than acceptable for the type of road studied. It exceeds the limits established by regulations for the construction of bike lanes. Moreover, its bearing capacity increased after two years to ensure the use of these two recycled materials as granular layers in bike lanes.

Young's moduli of recycled materials placed on site were calculated, which is a key aspect for pavement design. Subbase layers made with screenings wastes obtained a mean modulus of 200 MPa, while granular bases made with recycled aggregates obtained a mean modulus of 420 MPa. Both recycled materials performed as well as natural aggregates and soils used in the experimental bike lane. RMA and RMSW can replace crushed stone (A1-a) and selected soil (A-3), respectively. Recycled aggregates obtained an equivalent thickness with crushed stone at a ratio of 1:1; therefore, recycled aggregates can replace natural aggregates with the same volume of material. Selected soil (A-3) and screening wastes also have an equivalent structural thickness.

This study promotes new uses for recycled materials from CDW demonstrating the feasibility of using mixed recycled aggregates and its screening wastes as granular bases and subbases in paved bike lane construction. The low mechanical requirements of this type of infrastructure would increase the limit of various limiting properties, such as organic matter content, total sulphur content, soluble salt content and water soluble sulphates.

The findings of this study can reduce natural aggregate extraction from rivers and quarries, significantly minimize the ecological footprint, prevent illegal and landfill deposits of the fine fraction of CDW, and meet the limits of the European Waste Framework Directive. This demonstrates the practical relevance of this study to promote new uses for recycling aggregates and its screening wastes in the construction sector.

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5. Real-scale study of a heavy traffic road built with in situ recycled demolition waste

This chapter has been published in the journal "Journal of Cleaner Production", Volume 248, 1 March 2020, 119219: **Javier Tavira[a], *, José Ramón Jiménez[b], *, Enrique Fernández Ledesma[c], Antonio López-Uceda[d], Jesús Ayuso[b]**

[a] Empresa Metropolitana de Abastecimiento y Saneamiento de Aguas de Sevilla S.A., Sevilla, Spain.

[b] Área de Ingeniería de la Construcción, Universidad de Córdoba, Córdoba, Spain.

[c] Área de Mecánica de Medios Continuos y Teoría de Estructuras, Universidad de Córdoba. Córdoba, Spain.

[d] Área de Ciencia de los Materiales e Ingeniería Metalúrgica, Universidad de Córdoba. Córdoba, Spain.

*Corresponding authors. Both authors equally contributed to the paper. Address: Construction Engineering Area. University of Córdoba, Ed. Leonardo Da Vinci, Campus de Rabanales, Ctra. N-IV, km-396, CP 14014. Córdoba, Spain. Tel.: +34 667524702; fax: +34 957218550.

E-mail address: jrjimenez@uco.es (JR Jiménez), jtavira@ciccp.es (J. Tavira)

Abstract

This real-scale study carries out a research of the behaviour of building demolition wastes in a road with high intensity traffic. A mobile recycling plant treated in situ the demolition wastes from 105 single-family homes. Recycled aggregates were made from two different sources: one aggregate came from concrete taken out of slabs and foundations (recycled concrete aggregate) and the second aggregate came from the remaining reinforced concrete structures, walls and roofs (recycled mixed aggregate). Both recycled materials and a crushed stone formed the granular base and subbase of the experimental paved section. A leaching test analysed the potential pollutant emissions of the recycled aggregates. Different tests were performed during construction of the experimental section, such as densities, loading plates and falling weight deflectometry. This research evaluated deflections and surface roughness for a period of seven years to study the behaviour of these recycled materials long term. The recycled aggregates used did not satisfy all the stipulations of the Spanish standards for granular material as road subbases/bases, such as size distribution, Los Angeles test limit, soluble salt and organic matter content in subbases. Despite this lack of compliance, the results of on-site tests over time compared the mixed recycled aggregate as subbase and the recycled concrete aggregate as the base with natural aggregates; the recycled aggregates presented a better structural behaviour and less surface deterioration than natural aggregates under a mean daily heavy vehicle flow of 371 vehicles per lane and an average daily traffic of 4469 vehicles per lane on average. The article includes the calculation of moduli through forward and back calculations for the recycled aggregates, which is a key aspect in pavement design The bearing capacity of recycled materials increased with time in the structural layer, which is unlike the trend in bearing capacity of the natural aggregates.

Keywords:

Experimental section; back calculation modulus; recycled aggregates; mobile recycling plant; surface roughness; deflections.

Acronyms:

EU – European Union; CDW - Construction Demolition Waste; RA - Recycled Aggregates; NA – Natural Aggregates; RMA – Recycled Mixed Aggregates; RCA – Recycled Concrete Aggregates; PG3 – Spanish general technical specification for road construction; Mixed Recycled Soil (MRS);

Recycled Mixed Screening Wastes (RMSW); ES – Experimental Section; IRI (International Roughness Index); CS-1 – Crushed Limestone; AASHTO - American Association of State Highway and Transportation Officials; - ICP-MS - Inductively Coupled Plasma Mass Spectrometry; FWD – Falling Weight Deflectometer; LP – Laser Profiler; RL – Right Lane; LL – Left Lane; SPT – Standard Proctor Test; CBR – California Bearing Ratio; SG-1 – Subgrade; MPT – Modified Proctor Test; M –Mean; SD – Standard Deviation

5.1. Introduction

World aggregate production came from 21 billion tons in 2007 to 40 billion tons in 2014 [1]. Natural aggregate extraction harms the environment, and the mineral resource depletion and waste generated per cubic metre of natural aggregate obtained were over 2400 kg and 2500 kg, respectively [2]. Total aggregate production on the European Union (EU) was 2660 million tons, and the total waste generation from construction was 868 million tons in 2014 [3]. According to the Waste Framework Directive (2008/98/EC) of the European Union and the EU Parliament, by 2020, a minimum of 70% of construction and demolition wastes (CDW) should be recovered [4]. There are countries where the percentage of recovery, including backfilling operations, reached 70% in 2014; these countries included Belgium 91.8%, Germany 80.8% and Denmark 78.3% [3]. However, there were several countries that did not meet this objective in 2014 [3]. In these countries with low recovery rates, the main destination of CDW is the landfills. In 2014, in Spain, 5 million of tons were backfilled, and 6 million tons were recycled into various outlets from 20 million tons of CDW, while 9 million tons were landfilled [5].

Recycled aggregates (RA) production can play an important role in this objective because it can help to reduce the production of natural aggregates (NA) and avoid CDW from filling lands. According to the European National Aggregates Association, Spain produced 96 million tons of NA in 2015, while only one million tons of RA were produced and sold in commercial plants [6] from the 20 million tons of CDW. Recycled mixed aggregates (RMA) and recycled concrete aggregates (RCA) production were 80% and 12%, respectively, of the total amount of CDW generated in Spain [7]. The substitution of NA by RMA and RCA in road construction as unbound material layers is a plausible solution to meet the 70% recovery rate for CDW [4].

In order to increase the quality of RA, Barbudo et al. [8] published handling recommendations for CDW treatment plants. RA must cover longer distances to the recycling plant, whereas there is little to no transport from the quarry to the processing plant for NA; therefore, according to Bostanci et al. [9], the processing of RA generates 51% higher CO_2 emissions than NA. This fact can be compensated, if NA need to cover a longer distance to the site or if mobile recycling plants are used. According to Rossi and Sales [10], consumption of diesel was 3.4 km/L for a truck carrying 14-15 tons; when NA have an additional distance of 20 km, CO_2 emissions exceed the emissions that are generated by RA, according to Marinković et al. [2].

Another way to reduce CO_2 emissions during RA production is with the use of mobile recycling plants, since transportation distances are shorter than stationary plants [11]. The cost of mobile plants is less than that of stationary plants when the distance of transport is higher than 2.6 km [12]. CO_2 mitigation has been previously studied in the commercial building sector [13] and in the residential building sector [14,15], in order to reduce the CO_2 emission, enviromental policies should recommend the use of recycled aggregates from CDW due to the fact of the longer distances that natural aggregates need to cover and because of the global shortage of natural aggregates [16].

The viability of RMA and RCA in road construction was previously researched in laboratories, such as Poon et al. [17], Poon and Chan [18] and Vegas et al. [19]. Bassani et al. [20] proved in a laboratory study that an alkali-activating solution mixed with CDW obtained a more suitable option than the RA that were stabilized with cement in other previous studies, such as those by del Rey et al. [21], Bassani et al. [22] and Kien [23], or through the construction of experimental road sections of low traffic intensity by researchers, such as Jiménez et al. [24], Jiménez et al. [25], Pérez et al. [26] , del Rey et al. [21] and Tavira et al. [27,28] . Most of these studies, with the exception of Tavira et al. [27] and Lancieri et al. [29], show short-term results and conclusions. All RA tested in these works came from stationary plants.

For eight years, Lancieri et al. [29] studied two paved road sections that were 200 metres long and used RMA used as unbound base layers. An elastic modulus of RMA showed increments due to the low voids percentage in the asphalt layers that prevented incoming moisture and the cement hydration of the RMA fine fraction. Laboratory tests conducted with a gyratory compactor showed that small variations in the dry density induced significant increments in the California bearing ratio (CBR).

Jiménez et al. [24] investigate a rural road with no asphalt layers, it had two different sections with a hundred metres each; the materials that were used were obtained from selected CDW, as the surface course RCA and NA were used and, as a base course, RMA extended in both sections were used as the granular base. These authors concluded that during a period of two years open to traffic the bearing capacity of both sections kept steady and was slightly higher in sections built with RCA. The surface roughness was similar in both sections after construction, although in sections constructed with NA smoothness dropped more quickly. According to this research content limit of soluble salt in RA might be raised to 1.3% having no affection on the performance of the road layers. Jiménez et al. [25] studied two unpaved sections of 100 metres each; RMA or NA were used as surface courses on the different sections, natural soils formed the underneath layers. The RMA used had sulphur compounds and soluble salts contents higher than those values specified by the road construction Spanish standards (PG3). Both sections showed that the bearing capacity was slightly lower in the section built using RMA, although both sections presented acceptable structural performance. The Young modulus values increased by 27% after 3 years of traffic flow in the section built with RMA and decreased by 23% in the NA section. The surface roughness had more irregularities in the section built using RMA. This study concluded that the technical specification limits for the total sulphur compound and soluble salts can move up to a 6% and 3.3%, respectively, for this type of unpaved agrarian road. Tavira et al. [27] studied an experimental three section paved road, of which each section was 150 metres long. NA were used in bases and subbases in the first section; section three was built with mixed recycled soil (MRS) in the subbases and an RMA mixed with excavation soil; the second section had NA in the granular base and MRS in the subbase. The Los Angeles abrasion test and sand equivalent percentage of the RMA did not meet the limits of the Spanish standards, and RMAS and MRS showed average moduli of 349 MPa and 158 MPa, respectively, which proved that for low volume traffic roads, these limits should be modified.

Tavira et al. [28] studied three experimental sections of a paved bike lane made with recycled mixed screening wastes (RMSW). Moduli evolution of RMA and NA were obtained and compared, and the RA had high organic matter content (2%), a high Los Angeles abrasion test (40%) and low sand equivalent content (27%) compared with the limits allowed by PG3. RA showed their suitability as unbound layers instead of NA in these previous cases.

CBR, deformations and settlements were studied by Li et al. [30] in an experimental road section built with a recycled construction waste as a subgrade filler, RA showed higher bearing capacity than NA.

This study is a long-time performance study of an experimental road that was built with RA from remove of the 105 dwellings. The demolition of the houses was caused by the work on the extension of the runway of the airport of Córdoba (Spain). The main goal of this research is to evaluate in the long term the structural and functional parameters of a high traffic road built with recycled concrete aggregates (RCA) and mixed recycled aggregates (RMA) from demolition waste recycled in-situ. This study includes the calculation of moduli through forward and back calculations for the recycled aggregates, which is a key aspect in pavements design. This paper includes three new aspects: i) the in situ recycling of RMA and RCA obtained with a mobile plant used as the unbound layers; ii) the construction of an experimental heavy traffic road classified as T2 according with the Spanish standard (799-200 heavy vehicles/day per lane); and iii) a long-term study – 7 years – of structural and functional parameters, such as deflections and the International Roughness Index (IRI), which made it possible to evaluate recycled materials under traffic and weather conditions.

The favourable results obtained in this experimental section are a key aspect to increase the recycling rate of CDWs in Mediterranean countries, such as Spain, and to meet the objectives set by the European Directive for 2020.

No previous studies were found related with the use of RMA and RCA made with a mobile plant as unbound layers in an experimental road with heavy traffic for such a long period of time.

5.2. Materials and methods

5.2.1. Airport enlargement works and demolition waste treatment

As a consequence of the enlargement of the runway of the airport of Córdoba (Spain), a total of 105 single-family houses had to be expropriated and demolished in 2009. Fig. 5-1 shows two aerial photographs of Cordoba´s airport runaway in the year 2009, before the enlargement construction (Fig. 5-1-a) and after the enlargement works in the year 2017 (Fig. 5-1-b).

Fig. 5-2 shows the type of single family homes and the machinery that was used in its demolition. Construction of these homes dates from the decade of the nineties. The building process is quite similar in all dwellings; reinforced concrete was the material used in structures and foundations, and the homes had shallow foundations composed of a slab over footings. Beams and columns formed the structure, and one-way spanning slabs made with concrete or ceramic composed the floors and roofs. External enclosures were made of bricks or concrete blocks plastered with coloured cement mortar. Brick tiles topped the roofs. Bricks with plastered gypsum formed the interior walls. These constructions also used ceramic tiles and plasterboards on the walls and floors.

To avoid landfilling the demolition waste from those houses, the debris was recycled in situ with a mobile plant. Because of the shorter travel distances, the economic and environmental costs and the CO_2 emissions were reduced.

The process began with a selective demolition. Workers manually removed doors, window frames, glass and gypsum plasterboard. As shown in Fig. 5-2, the demolition efforts were conducted with an excavator equipped with a crushing jaw; when the concrete was reinforced, the steel was removed.

A mobile jaw crusher plant Parker model 1165 (Fig. 5-3) was used to crush the demolition waste, and all the material passed through the 40 mm sieve.

The CDW of foundations and rigid pavements were processed separately to obtain a recycled concrete aggregate (RCA-1). CDW from walls, structures and roofs were processed by obtaining recycled mixed aggregates (RMA-1). CH-2 Road was constructed as an experimental section (Fig. 5-1).

a) 2009

b) 2017

Fig. 5-1 Orthophoto of the ES (left image year 2009, right image year 2017)

Fig. 5-2. Selective Demolition of single family homes

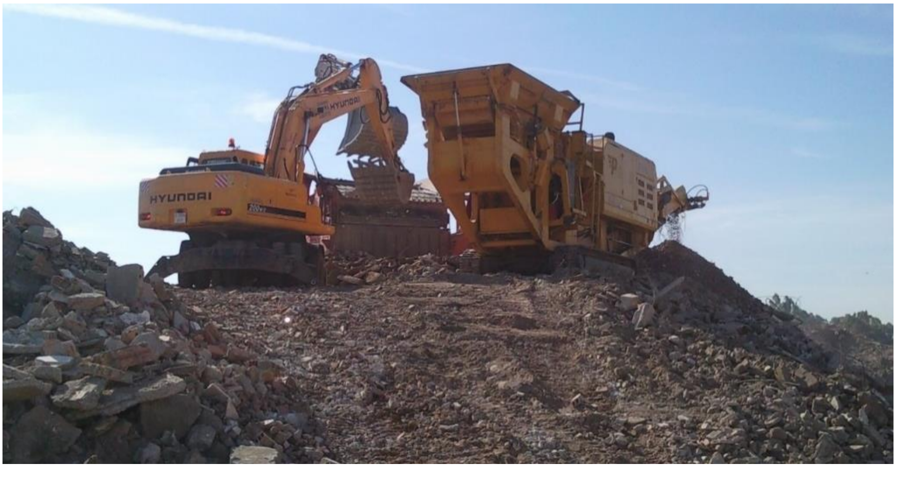


Fig. 5-3. Mobile Plant: Aggregate Screen and Jaw crusher.

5.2.2. Description of test sections

The ES has two sections of 180 m and 170 m. The total width of the road is 8 m; it has two 3.50 m lanes and a 1.00 m shoulder. Fig. 5-4 shows thickness and composition of the layers of the road. Two hot mix asphalt layers were set in the road; the wearing course was made of 4 cm asphalt concrete with an upper sieve size of 16 mm surface course type S according to article 542 of the PG3 [31], and the binder course was 6 cm asphalt concrete with an upper sieve size of 22 mm. The base course was type S according to article 542 of PG3 [31]. The base course of section I was built with a crushed Siliceous rock (CS-1), an RCA-1 was used in section II, both granular layers were identified as A1a according to the American Association of State Highway and Transportation Officials (AASHTO) [32]. The subbase course was built with RMA-1 with a thickness of one metre for both sections, and it was catalogued as A1a according to AASHTO [32]. The subgrade that was present in the ES is a clayey soil that would be classified as A6 [32]. The construction of the ES started in February of 2010 and ended in May of 2010.

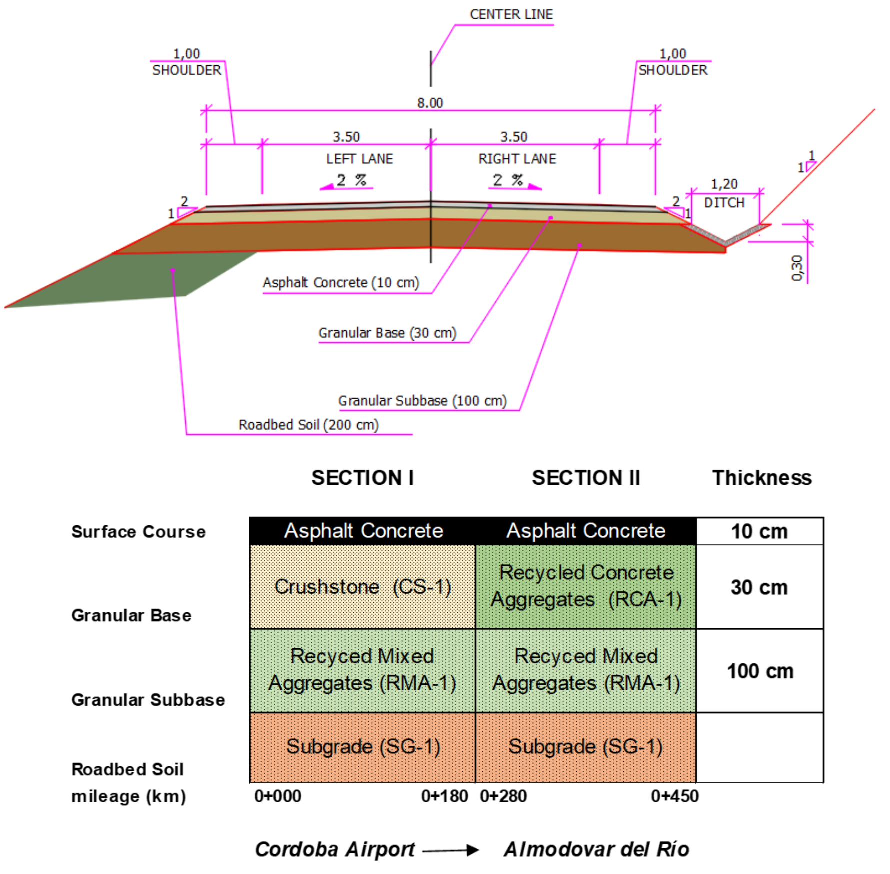


Fig. 5-4 Cross sections of the Experimental Section

5.2.3. Materials identification.

UNE-EN 932-1 [33] were followed to collect the samples of the granular materials employed in the ES. Laboratory tests were conducted on all granular materials and on subgrade to determine its chemical and physical properties.

5.2.4. Compliance test for leaching of granular waste materials

Both materials, RCA-1 and RMA-1, were tested according to UNE-EN 12457-3:2004 [34] to be classified according to the Landfill Directive [4] as inert, non-hazardous or hazardous materials. A total of five samples were studied for RCA-1 (C-1 and C-2) and RMA-1 (M-1, M-2 and M-3). There are two steps in this test. To start, the solution with a liquid-to-solid ratio of 2 was agitated during a total time of 6 + 0.5 h. In the second step, a liquid-to-solid ratio of 10 was needed, therefore extra water was poured and then stirring continued for an additional 18 + 0.5 h. The mixed was passed through a filter (0.45 μm) and an operating a spectrometer PerkinElmer (PerkinElmer Inc., MA, USA) evaluated the solutions by inductively coupled plasma mass spectrometry (ICP-MS).

5.2.5. On-site tests of the ES

5.2.5.1. Control of densities and moisture of granular layers

At the end of compaction of each unbound layer, a nuclear density equipment following ASTM D6938 [35] determined field densities and moisture content. The distance between each test was 25 m. These tests determined the percentage of compaction of the granular layers.

5.2.5.2. Static plate bearing tests

On each of the two sections and on the two unbound layers two plate stations were conducted therefore eight tests were accomplished during the construction of the ES (May 2010). Spanish standard UNE 103808:2006 [35] was followed.

5.2.5.3. Dynamic plate bearing tests

A Dynatest Falling weight deflectometer (FWD) 8012 (Dynatest Denmark A/S, Glostrup, Denmark) equipped with seven geophones measured the deflections and basins (Fig. 5-5-a). The geophones were displayed as in previous experimental study [27].

Every ten metres along the ES deflections were measured following the ASTM D4694 [37]. The Spanish standard [38] does not correct deflections as in this case because the asphalt concrete is not thicker than 10 cm. The FWD tested every layer set on the ES during construction and at the end of the works (June 2010). On September 2011, June 2014 and April 2017, the deflections were controlled. FWD represents the effect of moving loads in a very precise way. FWD allows several times of testing along the road in a short time. FWD can detect deep failures in the pavement structure.

To obtain the dynamic moduli, the following equation proposed by Brown [39], it can be found in the preceding research [27]. In the complete section a 0.35 Poisson ratio was adopted [40-41].

5.2.5.4. Road regularity measurement

The life of the roads is intimated ligated to its conservation and is determined by the smoothness of its profile. The International Roughness Index (IRI) [42] is the most accepted parameter to determine the profile condition of the road. Road profiler followed standard ASTM E867-06:2012 [43]. Laser profiler (LP) RSP MARK-IV device (Dynatest Denmark A/S, Glostrup, Denmark) (Fig. 5-5b) measured IRI during a period of seven years from 2010 until 2017; the right lane (RL) and left lane (LL) of the two sections were measured. This device was used in a preceding investigation of Jiménez et al. [24] and Jiménez et al. [25]. Five IRI evaluations of the ER were completed (years 2010, 2011, 2014, 2016 and 2017).

a). Dynatest FWD 8012 – Testing Deflections on ER on 2017

b). RSP MARK-IV equipment – Testing Roughness on ER on 2017

Fig. 5-5. Falling Weight Deflectometer and laser profiler

5.2.6. Moduli Backcalculation

Evercalc (WASDOT, WA, USA) [44] was the software used for calculating moduli. Using a recursive process, this software reproduce mechanical performance under falling weight deflectometer loading, obtaining moduli of the layers that form the pavement structure. This process was previously described by Tavira et al. [27]. The process compares the deformations obtained on field with the theoretical deflections calculated, in the first step, it uses a root moduli for each layer. Convergence is met when the difference of surface deflection is close to a 2% difference [43].

Tarefder and Ahmed [44] showed that Backfaa and Modulus software produced less precise modulus values than those of Evercalc.

5.2.7. Climatic records

Roads are deeply affected by moisture and temperature. A weather station close to the ES measured rain and temperature data; it was located in the Cordoba´s Airport with UTM coordinates (337196, 4189963).

Fig. 5-6 displays the mean extreme temperatures and rainfall from 2010 to 2017. The months of June, July and August had an average precipitation under 30 mm. Pavement tests were used to study the evolution that took place during dry periods.

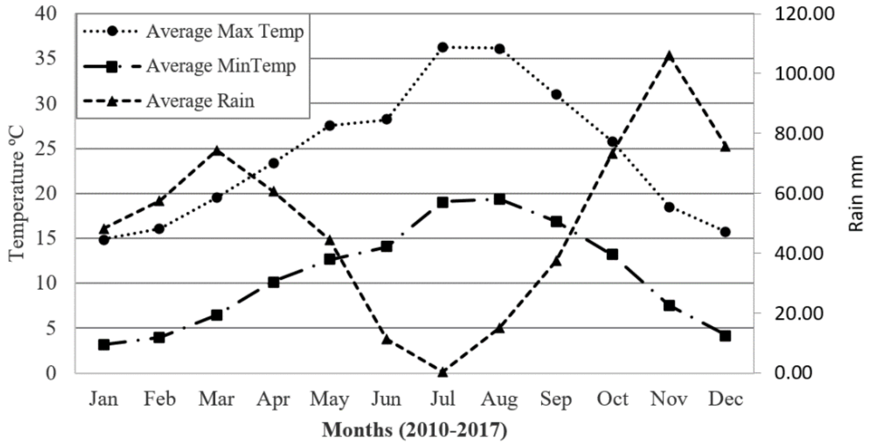


Fig. 5-6 Average monthly maximum, minimum temperatures and rainfall

5.2.8. Automatic traffic counting

A station type TraficompIII (Streeter Richardson, Mangood Corporation, IL, USA) equipped with two pneumatic tubes was set on the kilometre point 0+225 of the Road CH-2. The electronic counters can classify vehicles attending to their standard axle-pattern. The station measured traffic for a week during the month of October for the years 2011, 2013 and 2016. As shown in Table 1, the mean value of daily heavy vehicles was 381 (RL) - 361 (LL) vehicles per day with an average daily traffic flow of 8937 vehicles, according to the Spanish standard [46]. Both lanes would be classified as a T2 (200 – 799 heavy vehicles/day).

Table 5-1 Average Traffic 2011-2013-2016

Date	ADT	RL HTD	LL HTD
10/2011	9595	407	392
10/2013	7600	271	261
10/2016	9616	465	429
Mean	8937	369	373

Average Daily Traffic (ADT)
Traffic Heavy Daily (HTD)
Right Lane (RL)
Left Lane (LL)

5.2.9. Statistical análisis

Analyses of variance (ANOVA) were carried out with the statistical software Statgraphics Centurion XVI (Version 16.1.18, StatPoint Technologies, Inc., Warrenton, VA, USA). The F-test in the ANOVA determine the influence of each factor on the results. The non-overlapping bars indicates that there was no influence on the factor levels studied.

5.3. Results and discussion

5.3.1. Composition of the recycled aggregates

Basis elements of the RA were studied following UNE-EN 933-11 [47], Table 2 displays its composition. RMA-1 and RCA-1 had high contents of concrete and unbound aggregates at 88 and 97%, respectively. According to Jiménez [48], RMA-1 can be categorized as recycled mixed aggregates because its ceramic content is over 10%, and RCA-1 would be classified as recycled concrete aggregates. Ceramic particles were detected in both RA, 3.1% in RCA-1 and 11.3% in RMA-1, whereas gypsum contents were negligible (0.1%).

Table 5-2 Composition of recycled aggregates

Compositions (UNE-EN 933-11)	RCA-1	RMA-1
% RA (Asphalt)	0	0.2
% RB (Ceramics)	3.1	11.3
% RC (Concrete and Mortar) (a)	76	60.2
FL (Floating particles) (cm3/kg)	0	0.0
% RU (Unbound aggregates) (b)	20.8	28.0
% X1 (Natural ground)	0	0.1
% X2 (Other) (c)	0	0.1
% X3 (Gypsum)	0.1	0.1
Total	100	100.0

(a) Natural aggregates with cement mortar attached.
(b) Natural aggregates without cement mortar attached.
(c) Wood, glass, plastic, metals

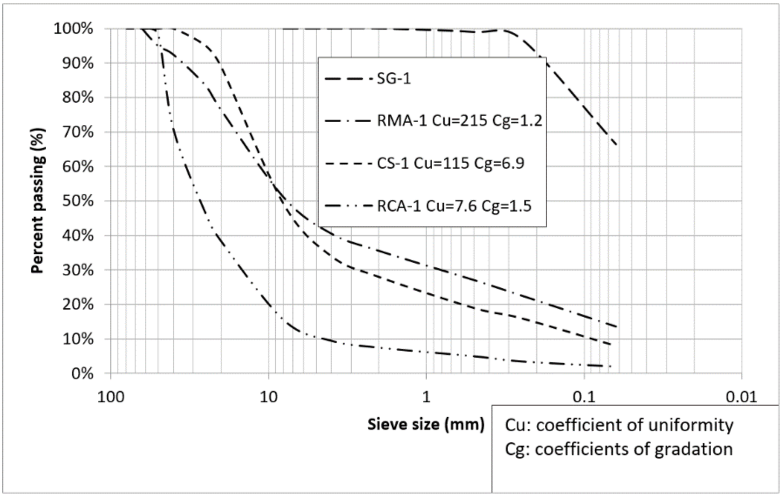


Fig. 5-7 Particle size distribution curves of materials used in ES

5.3.2. Material characterizations

The subgrade, subbase and base material were tested according to Spanish Standards UNE [33], and Table 3 displays physical and chemical properties of the different materials employed as unbound layers and the PG-3 limits for their classification. Additionally, to know the material behaviour, the following tests were carried out: the standard proctor test (SPT), CBR, free swelling in odometer device and collapse.

Fig. 5-7 shows the particle size distribution curves. SG-1 had a passing fraction of 66.50% over the 0.063 mm sieve. RCA-1 is a coarse material, as shown in Fig. 5-7, and less than 10% passes the 4 mm sieve. RCA-1 did not meet the particle size distribution limits prescribed for NA as base layers in article 510 of the PG3 [31], RA were over the fine limit and maximum size, and both materials were classified as selected soils according to article 330 of the PG3 [31] and could only be used as granular subbases. On the other hand, CS-1 meets these limits, and it was classified as a base layer according to article 510 of PG3 [31]. RA were less uniform in their gradation than NA.

SG-1 would be classified as a tolerable soil according to PG-3 [31] and as A6 according to AASHTO [32]. Subgrades of previous experimental sections had similar particle size distributions and CBR, according to Tavira et al. [27] and Tavira et al. [28], and were classified as tolerable soil and marginal soil, respectively.

The materials used in the ES were non-plastic and had no swelling, with the exception of SG-1, which had a very low shrinkage potential. CS-1 fulfilled the requirements of article 510 of PG3 [31]. The densities of recycled materials were lower and the optimum moisture was higher than those obtained in CS-1, which can be explained because of the higher porosity of RA caused by the presence of ceramics and cement mortar; this finding is concordant with the preceding studies of RA [21,24-25,27-28]. RA and RCA-1 did not meet the limit prescribed for abrasion by the PG3 of 30% for T2 traffic. CBR in RMA-1 and RCA-1 was higher than in CS-1. Table 3 showed that RMA-1 manifested stiffer CBR than those presented in other researches [21,24-25,27-28,30]. Past researches abrasion is not expected to surpass a 44% in RMA [25,29]. Regarding the chemical properties, PG3 limits for organic matter and soluble salts are surpass. Past researches [24-25, 48] proved that soluble salt content over 3.9% does not represent expansive behaviour. Jiménez [48] stated that organic content in unbound layers can rise to one percent.

Table 5-3 Properties of the different materials in the unbound layers

Properties	Fraction	SG-1	RMA-1	RCA-1	CS-1	PG3 limits	Standards used (AENOR, 2018)
Particle density ρr (g/cm3)	0.063/4	--	2.154	2.138	2.399		UNE-EN 1097-6: 2000
	4/31.5	--	2.116	2.243	2.590		UNE-EN 1097-6: 2000
Water absorption (%)	0.063/4	--	8.5	8.8	4.7		UNE-EN 1097-6: 2000
	4/31.5	--	8.3	6.7	1.6		UNE-EN 1097-6: 2000
Plasticity (IP)		NP	NP	NP	NP	S.S. <10, A.S.<4, TS>0.73(LL-20) IF LL>40	UNE 103103 :1994 & UNE 103104 :1993
Clean coefficient (%)		--	0.84	0.34	0.86	NA<1	UNE 146130 :2000
Sand equivalent (%)		--	39	51	41	NA>40 (T00-T1) >35 (T2-T4)	UNE EN 933-8 :2000
Los Angeles Abrasion (%)		--	36	34	20	NA<30 (T00-T2) <35 (T3-T4)	UNE EN 1097-2:1999
Flakiness index		--	19	8	8	NA<35	UNE EN 933-3 :1997
Crushed particles (%)		--	70	70	95		UNE EN 933-5:1999
Maximum dry density PM (g/cm3)		1.88	1.92	1.99	2.26		UNE 103501:1994
Optimum moisture content PM (%)		13.7	12.7	11.6	6.3		UNE 103501:1994
CBR (%)		6.61	119	96	87	S.S. >20, A.S.>5, T.S.>3,	UNE 103502:1995
Swelling after 4 day's soaking (%)		0.004	0.05	0.01	0.03		UNE 103502:1995
Free swelling in odometer (%)		0					UNE 103601:1996
Collapse (%)		0.04					NLT 254
Organic matter (%)		0.3	0.5	0.3	0.2	S.S. <0.2, A.S. <1, T.S.<1.0, M.S. <5.0	UNE 103204:1993
Soluble salts (%)		0.05	1.3	0.8	0.1	NA<0.07, S.S. <0.2, A.S. <0.2	NLT 114:1999
Water soluble sulfates (% SO4)		< 0.01	0.7	0.3	< 0.01	T.S.<1.0	UNE 103201:1996
Gypsum content (%)		< 0.01	1.2	0.5	< 0.01	T.S.<5.0	NLT 115:1999
Total sulfur content (% S)		< 0.01	1	0.6	< 0.01	NA<1	UNE EN 1744-1:1998

NP: non plastic; PM: Modified Proctor; HVDL (Heavy Vehicles per Day and Lane)

S.S. Selected Soils, A.S. Appropriate Soils, T.S. Tolerable Soils, Marginal Soils, R.S.S. Recycled Selected Soils, R.T.S. Recycled Tolerable Soils.

T00 (>4000 HVDL), T0 (3999-2000 HVDL) T1 (1999-800 HVDL) T2 (799-200 HVDL) T3 (199-50 HVD) T4 (<50 HVDL)

Samples for the CBR tests were compacted at their corresponding maximum dry density of Modified Proctor and 4-day soaked conditions

Table 5-4. Leachate concentrations (mg/kg) for RCA and RMA according to UNE EN 12457-3 [34]

Element (mg/kg)	RCA-1				RMA-1					
	C-1		C-2		M-1		M-2		M-3	
	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
Ba	0.114	0.242	0.01	0.495	0.083	0.312	0.104	0.368	0.098	0.328
Ni	0.021	0.023	0.003	0.023	0.013	0.001	0.018	0.014	0.013	0.005
Cd	0	0	0	0	0	0	0	0	0	0
Cu	0.147	0.247	0.043	0.227	0.037	0.078	0.136	0.216	0.046	0.089
As	0.005	0.007	0.001	0.009	0.004	0.009	0.002	0.006	0.005	0.011
Zn	0	0	0	0	0	0	0	0	0	0
Pb	0.003	0.002	0	0.005	0.001	0	0	0	0	0
Se	0.001	0	0.001	0	0.01	0	0.016	0.011	0.01	0.027
Hg	0	0	0	0	0	0	0	0	0	0
Mo	0.077	0.088	0.031	0.136	0.04	0.067	0.067	0.099	0.072	0.102
Sb	0.003	0.021	0.001	0.019	0.003	0.016	0	0.005	0.002	0.016
Cr Total	0.131	0.223	0.03	0.164	***0.32***	0.45	***0.623***	***0.825***	***0.355***	***0.549***
classification	I	I	I	I	NH	I	NH	NH	NH	NH

Notes: I: inert; NH: non-hazardous; Value limit exceeded are given in bold and italics

Table 5-5 Limit levels regulated by the Landfill Directive [4]

	Compliance test UNE EN 12457-3 [34]					
	I≤	NH	H	I≤	NH	H
	L/S = 2 (mg/kg)			L/S = 10 (mg/kg)		
As	≤0.1	0.1-0.4	0.4-6	0.5≤	0.5-2	2-25
Ba	≤7	7-30	30-100	≤20	20-100	100-300
Cd	≤0.03	0.03-0.6	0.6-3	≤0.04	0.04-1	1-5
Cr	≤0.2	0.2-4	4-25	≤0.5	0.5-10	10-70
Cu	≤0.9	0.9-25	25-50	≤2	2-50	50-100
Hg	≤0.003	0.003-0.05	0.05-0.5	≤0.01	0.01-0.2	0.2-2
Mo	≤0.3	0.3-5	5-20	≤0.5	0.5-10	10-30
Ni	≤0.2	0.2-5	5-20	≤0.4	0.4-10	10-70
Pb	≤0.2	0.2-5	5-25	≤0.5	0.5-10	10-50
Sb	≤0.02	0.02-0.2	0.2-2	≤0.06	0.06-0.7	0.7-5
Se	≤0.06	0.06-0.3	0.3-4	≤0.1	0.1-0.5	0.5-7
Zn	≤2	2-25	25-90	≤4	4-50	50-200

Inert (I); Non-Hazardous (NH); Hazardous (H)

Table 5-6. Moisture content and density

Average	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)
Section I	1.82 ± 0.06	13.56 ± 0.6	96.66 ± 3.11	1.93 ± 0.02	10.26 ± 0.85	100.59 ± 1.18	2.23 ± 0.02	4.14 ± 0.64	98.67 ± 1.08
Section II	1.83 ± 0.03	13.29 ± 0.92	97.34 ± 1.74	1.95 ± 0.01	10,13 ± 0.53	101.41 ± 0.58	2.02 ± 0.04	8.48 ± 0.93	101.26 ± 1.82

5.3.3. Results of the compliance test

The Landfill Directive 2003/33/EC regulates the limit values for leachate concentrations, and it was used for the comparison of heavy metals, since the anion data were not available. The results of the five samples that were analysed are shown in Table 4. The C-1 and C-2 samples came from RCA, and M1, M2 and M3 came from RMA. The samples extracted from the RCA-1 material comply with the inert limits (IL), and the RMA-1 samples comply with the IL. The only element that was detected in a concentration such that it should not be considered as inert was chromium (Cr) in the samples M2 and M3. Thus, analysing the values that were obtained for the fraction L/S = 10, which was the most unfavourable of the two studied, a Cr concentration of 0.825 mg/kg was obtained for M2 and 0.549 mg/kg was obtained for M3, which classify these samples as non-hazardous. A previous study detected high levels of Cr in RA [48]. Therefore, all RCA-1 and RMA-1 samples meet the requirements of being classified as non-hazardous; their use as unbound layers in roads do not represent a risk to the environment.

5.3.4. Quality control of the on-site works

The aspect that influenced most on the layer stiffness of an unbound material is the compaction obtained [49]. Tests of moisture took place on each granular layer. SPT was used on the subgrade, the MPT was used on bases and subbases. As stayed on the PG-3 [31] degree of compaction has to be over 95% in subbases and 98% in base. Compaction met specifications, as shown in Table 6. On the subgrade this percentage went up to a 96.66% and 97.34% for sections II and I, respectively (Table 6). These results are above 95%. Regarding to subbases, RMA-1 had a 100.59% and 101.41% degree of compaction on sections I and II, respectively, so the limit of 98% for MPT required by PG3 [31] was met.

All values were over 98% of the MPT in granular bases, obtaining a mean value of 98.67% on section II and a 101.2% on section I.

Optimum moisture values were higher in recycled materials (RCA-1 and RMA-1), because of the higher specific surface than conventional aggregates, this explains why densities of standard aggregates are higher than RA, as displayed in Table 3. These results are consistent with those of preceding researches [21,24-25,27-28,48,51].

5.3.4.1. Plate load tests

On the granular subbases, Ev2 was similar in both sections, as shown in Table 7, with values between 194-219 MPa. The plate load tests that were obtained on the granular bases were 25% higher in section II 307-269 MPa (RCA) than in section I (CS) 248-214 MPa, which was due to the cement fraction present in RCA. According to the Spanish Pavement instruction [45], the subbase would be classified as an E2 (Ev2>120 MPa). The results obtained in this experimental section are higher than those that were obtained by [27], who obtained a value for Ev2 of 190-163 MPa for RA mixed with excavation soil. These authors also found lower CBR values (65.5%) than RCA-1 values (138%). The RMA from non-selected CDW were used by Jiménez et al. [25] in an unpaved rural track, its Ev2 showed lower values (145-168 MPa) than the RMA-1 used in this ES due to the lower quality of RA. In the same way, RMA was used by Del Rey et al. [21], who showed lower values 159-144 MPa, due to the lower bearing capacity shown on the CBR of the selected RMA (67.3%) and the non-selected RMA (63.7%) used for the experimental unpaved rural road. Nevertheless, the RMA from selected CDW used by Jiménez et al. [24] for another unpaved rural road were higher 270-405 MPa, which can be explained because of the high bearing capacity of the subgrade 312-453 MPa. Regarding the RCA used for these rural roads Ev2 values are between 321-642 MPa.

Table 5-7 Strain moduli and ratios

KP	Subbase			Base		
	EV1 (MPa)	EV2 (MPa)	EV2/EV1	EV1 (MPa)	EV2 (MPa)	EV2/EV1
0+070 (Section I)	86	194	2.26	107	248	2.32
0+170 (Section I)	131	218	1.66	98	214	2.18
0+300 (Section II)	123	201	1.63	127	269	2.12
0+390 (Section II)	87	219	2.52	149	307	2.06

Table 5-8 Deflections and equivalent moduli during construction on granular layers

		Section I				Section II			
		Deflections (0.01 mm)		Equivalent moduli (MPa)		Deflections (0.01 mm)		Equivalent moduli (MPa)	
	Date	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
Base	12/05/2010	117.52	15.28	147.27	18.85	95.30	14.42	182.31	25.24
Subbase	04/05/2010	69.06	8.68	142.94	17.18	68.50	9.65	144.90	21.63

Table 5-9 ANOVA of defections and moduli test results for factor section

		Factor Section	
	Factor levels	I	II
	D. of f.[a]	(1;286)	
Deflections (0.01 mm)	F-test	179.68	
	p-value	<0.001	
	Mean	38.2	27.7
	s.d.[b]	7.5	6.9
Equivalent Moduli (MPa)	F-test	140.83	
	p-value	<0.001	
	Mean	495	710
	s.d.[b]	100	193

D. of f.[a]*= Degrees of freedom (n1;n2); s.d.*[b] *= standard deviation.*

Table 5-10 ANOVA of defections and moduli test results for factor date

	Factor date								
		Section I				Section II			
	Factor levels	Jun-2010	Sep-2011	Jun-2014	Apr-2017	Jun-2010	Sep-2011	Jun-2014	Apr-2017
	D. of f.[a]		(3;140)				(3;140)		
	F-test		1.33				2.79		
Deflections	*p*-value		0.268				0.042		
(0.01 mm)	Mean	39.5	38.9	38.3	36.4	29.3	28.1	27.1	25.0
	s.d.[b]	6.9	6.7	5.9	8.4	6.7	6.4	7.0	6.2
Equivalent	F-test		1.81				3.14		
moduli	*p*-value		0.148				0.028		
(MPa)	Mean	479	485	487	528	653	683	722	782
	s.d.[b]	102	97	76	118	147	158	207	230

D. of f.[a]= *Degrees of freedom (n1; n2); s.d.*[b] = *standard deviation.*

Table 5-11 ANOVA of moduli in granular sub-base (RMA-1) for factor section

		Factor Section	
	Factor levels	I	II
Moduli of granular sub-base (MPa)	*D. of f.*[a]	(1;142)	
	F-test	1.34	
	p-value	0.234	
	Mean	646	648
	s.d.[b]	107	110

D. of f.[a]*= Degrees of freedom (n1; n2); s.d.*[b] *= standard deviation.*

Table 5-12 . Results of the Anova of modulus (EVERCALC) for year factor on RMA subbase.

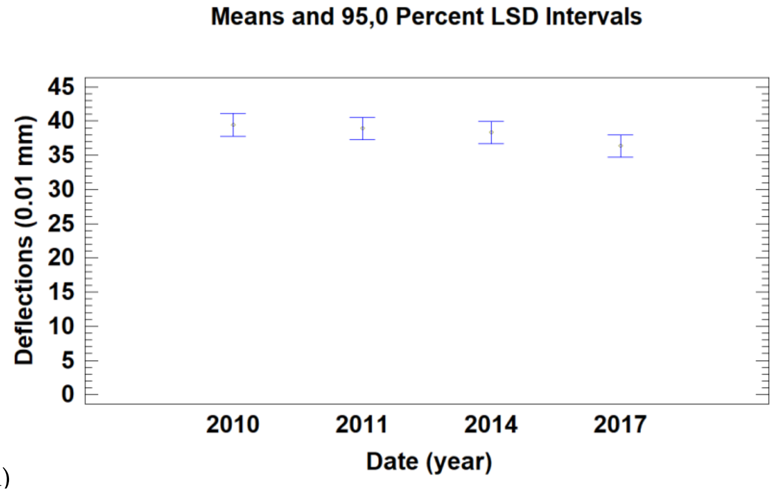
		Factor: Year			
	Factor levels	Jun-2010	Sep-2011	Jun-2014	Apr-2017
Modulus by EVERCALC (MPa)	*D. of f.*[a]	(3,140)			
	F-test	3.2			
	p-value	0.025			
	Mean	622	631	642	693
	s.d.[b]	111	103	111	98

D. of f.[a]*= Degrees of freedom; s.d.b = standard deviation*

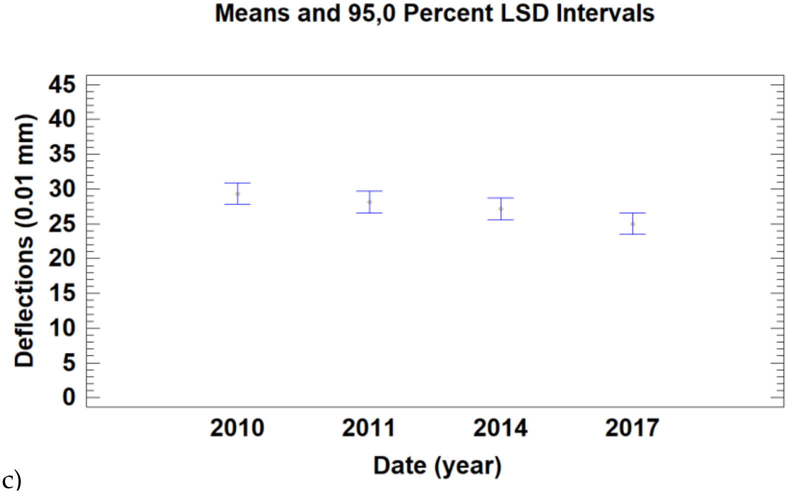
Table 5-13 ANOVA of moduli in granular base for factor section

		Factor Section	
	Factor levels	I	II
Moduli of granular base (MPa)	*D. of f.*[a]	(1;142)	
	F-test	12.55	
	p-value	< 0.001	
	Mean	424	476
	s.d.[b]	70	103

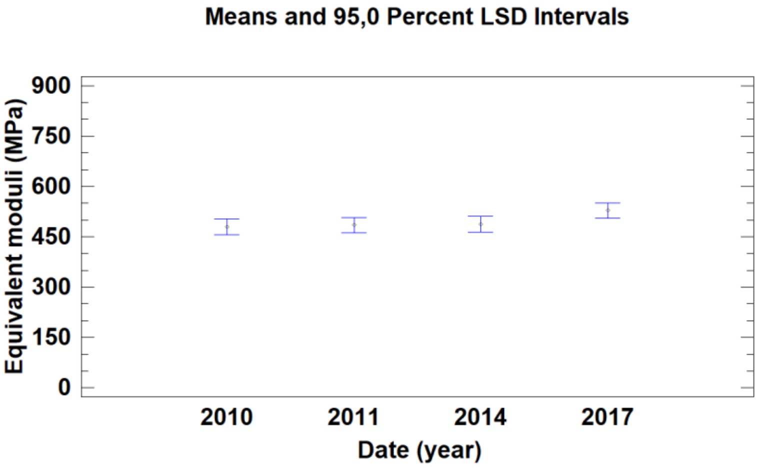
D. of f.[a]*= Degrees of freedom (n1; n2); s.d.*[b] *= standard deviation.*


Means and 95,0 Percent LSD Intervals
Deflections (0.01 mm)
0
5
10
15
20
25
30
35
40
45
2010
2011
2014
2017
Date (year)

a) b)


Means and 95,0 Percent LSD Intervals
Deflections (0.01 mm)
0
5
10
15
20
25
30
35
40
45
2010
2011
2014
2017
Date (year)

c) d)



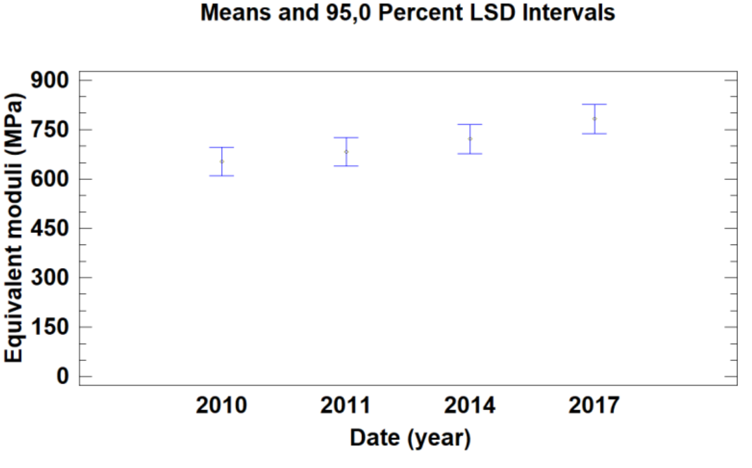


Fig. 5-8 Mean values of: deflection for section I (a) and section II (b), and equivalent moduli for section I (c) and section II (d), and 95% LSD intervals vs. date

 c)

5.3.4.2. Deflection tests with FWD

Table 8 shows that section I and II had similar deflections and equivalent moduli for the subbases of both sections. On granular bases, section II (RCA-1) showed an 18-20% higher modulus than that of section I (CS), the CBR values shown in Table 3 for CS-1 (68%) and RCA-1 (138%) are compatible with these results. Ev2 values (Table 7) are in sequence with the FWD results that were obtained in Table 8. Deflections were lower than those that were obtained in a paved road section made with RA mixed with excavation soil by Tavira et al. [27] and were higher than those that were obtained for an experimental paved road of Malaga made with RCA stabilized with cement, according to Pérez et al. [26].

5.3.4.3. Field control of deflection and equivalent moduli over time

The F-test in the ANOVA that was conducted (Table 9) showed that the section factor influenced the deflections and equivalent moduli results.

One-way ANOVA detected that the date factor was critical for section II, but it did not have influence on the equivalent moduli of section I (Table 5-10).

No statistical differences between the date factor levels were found after calculating the least significant difference (LSD) test. This result can be seen in Fig. 5-8, where the 2010 and 2011 LSD intervals did not overlap the 2017 interval. The increment in the equivalent modulus between 2010 and 2017 was 10% in section I, whereas in section II, this gain was 20%. Conversely, comparing the deflection that occurs in the two sections, section I experienced a decrease of 7.86%, whereas in Section II, a reduction of 14.75% was obtained. The decrease could be attributed by the self-cementing effect that takes place in rehydrated cementitious particles in RCA. Del Rey et al. [21] investigated the cause of this effect and concluded that particles below 0.6 mm in size have a key role, which means that deflection is limited by the proportion of the particles.

Comparing the data with those of other authors, the deflections of ES are lower to those obtained in previous studies with mixed recycled aggregates, such as RMA-MRS (52-73 0.01 mm) [27] and RMA-RMSW (79-92 0.01 mm). The Ev2 values are above those published for RMA in an unpaved rural road (148.2 MPa) [21] and 235 MPa with RMA-RMSW in [28]. This result is explained because of the higher CBR of the RA that were used in this research and the cement mortar content of the RA of this ES.

Table 11 shows that the section factor in the F-Test of ANOVA did not have a significant effect on the structural stiffness of RMA-1 calculated by EVERCALC. Both sections presented very similar values, which means that the RMA layer had a similar performance, which were executed well on-site, independently of the section.

In this long-term study, the date factor had significant effect (p-value <0.05) on the modulus of the granular sub-base RMA-1 calculated by EVERCALC with a 95% of confidence (Table 5-12).

It was evaluated if the date factor was a critical issue for the modulus value of the granular sub-base (RMA-1). The non-overlapping bar corresponding to the year 2017 (Fig. 5-9) indicates that an important gain in the load bearing capacity takes place in the sub-base. There was an increase of 11.4% between 2010 and 2017 in the modulus of the subbase. This trend is congruent with the research produced by [52], through the CBR test in mixed recycled aggregates.

One-way ANOVA was performed with the variable granular base modulus calculated by EVERCALC and the section factor Table 5-13. There was statistical significance in the two section sections.

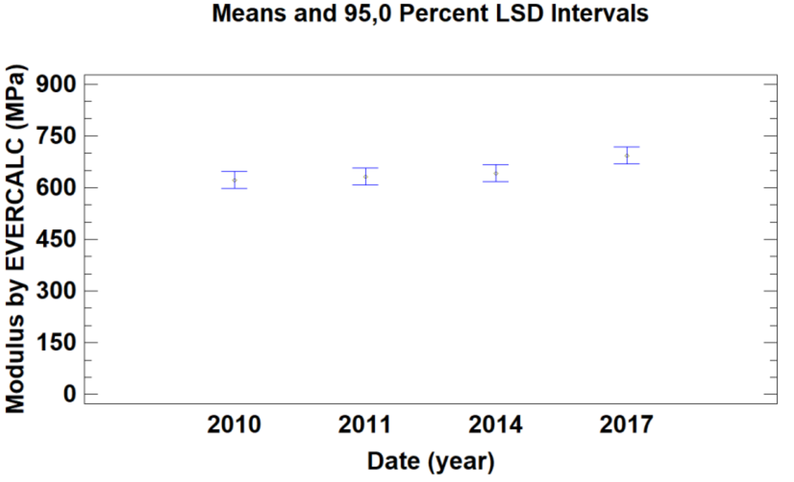


Fig. 5-9 Mean values of moduli in RMA-1 subbase and 95% LSD intervals vs. date

As it has been previously researched, the effect of the date factor on the modulus in the granular base calculated by EVERCALC was studied for each section. According to the statistically analysis modulus obtained in the granular base by EVERCALC were similar in both sections. The moduli of section I with RCA-1 increased 14%, while the CS-1 moduli decreased 5% between 2010 and 2017. RCA moduli were similar to those obtained with RCA treated with cement (558-955 MPa) processed in static plants [26]. This result shows that mobile plants can obtain similar results in terms of load bearing capacity without cement stabilization. RCA obtained lower moduli than RMA due to the lower finer fraction proportion in RCA, in accordance with the aforementioned conclusion of Poon and Chan [18]. [53] López-Uceda obtained a significant load bearing capacity increase over time in the RCA samples, measured by an increase of 80% in the CBR test between 7 days and one year.

5.3.5. International roughness index

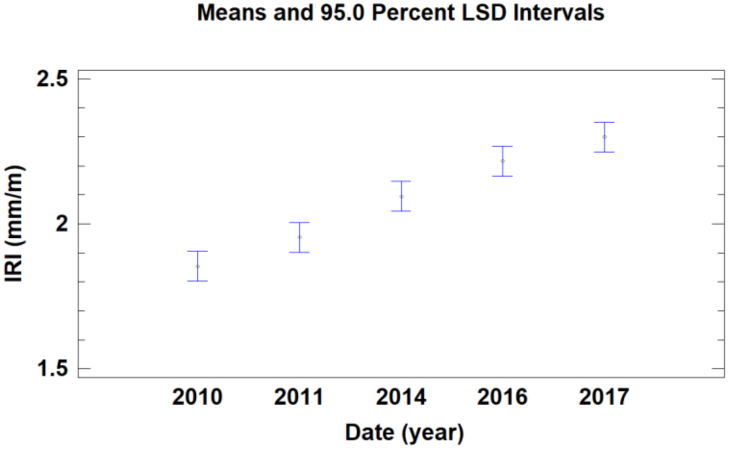
To detect the effect of each section on the IRI test results, the F-test in ANOVA was conducted. The P-value was higher than 0.05, so there was no statistically difference in the IRI performance of Section I built with a standard aggregate layer and RMA and Section II built entirely with RA from CDW.

Two one-way ANOVAs were performed to inquire if the date factor was critical for IRI results on sections I and II. The date factor was decisive on the test results obtained, with a 95% confidence level, for both sections.

Then, the non-overlapping bars among the level factors 2010-2011, 2014 and 2016-2017 indicated that the date factor is predominant in the IRI test results (Figs. 5-10 a and 5-10 b). The increase in the IRI over time is reasonable because, as traffic drives across the road, the surface of the road deteriorates [54].

The mean values for each date met the criteria that were established by the American Department of Transportation [55] to classify general standards as acceptable in terms of the road quality for the experimental section. According to the World Bank [42], the values obtained after 82 months correspond to an acceptable level. A previous study on a paved road made with RMA and MRS showed also acceptable values [27], by 2017 IRI mean values where between 2.38 and 2.64 exposed to a low volume traffic of under 50 heavy vehicles per day and lane. The threshold established by the PG-3 [31] for the IRI in new road constructions were below the IRI corresponding to the three percentiles imposed, which were 50%, 80% and 100% for both sections (Fig. 5-11). [56] analysed the different specifications of the IRI around the world. In the EU, Sweden stablished the most detailed specification corresponding to this case study. The IRI limit is 2.9 m/km for in-service roads. In Fig. 5-11, the mean IRI linear regression is plotted for both sections. For section I, the number of years that the service-roads reached the Sweden limit was 16.2 years, whereas for section II, it was 16.7 years. This result means that the RCA application as a base layer in comparison to the section constructed with NA did not diminish the service life of the road. The IRI mean regression over time was greater in terms of slope and initial IRI in accordance with

[57], who collected different data, including the IRI, from different high-speed and high-quality roads to perform pavement deterioration models.



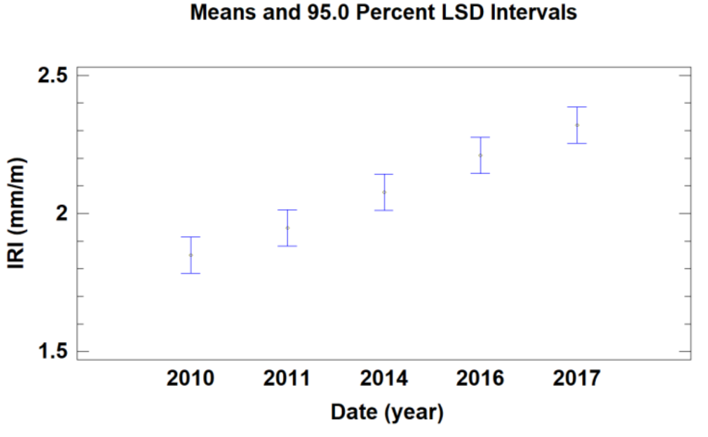


Fig. 5-10. Mean values of IRI section I (a) and section II (b), and 95% LSD intervals vs. date.

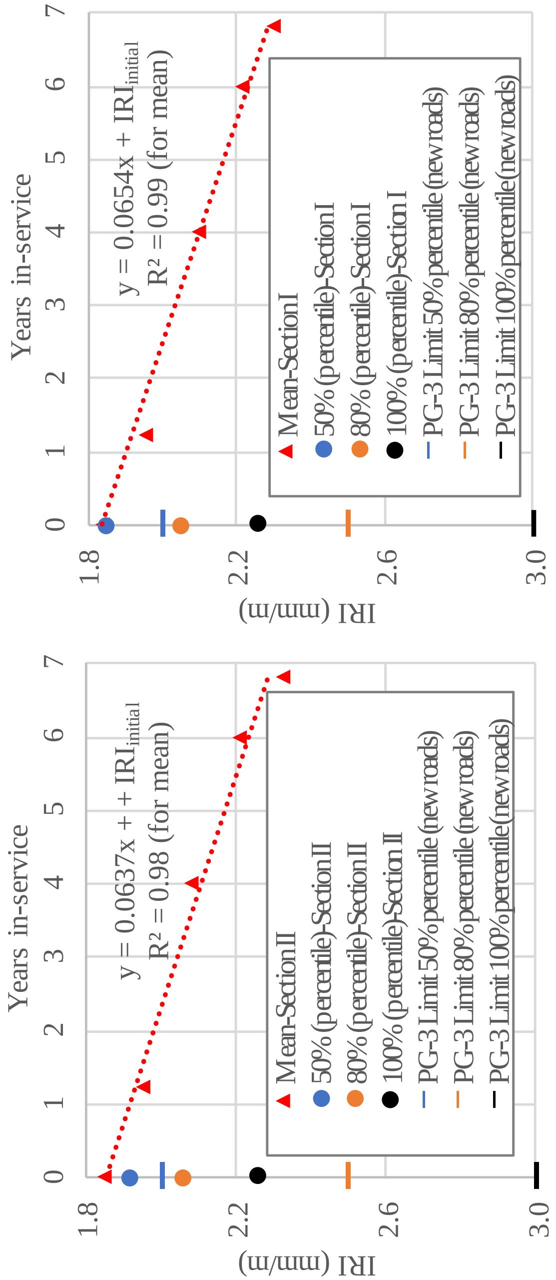


Fig. 5-11. Mean values of IRI over time and IRI of the 80% percentile and the mean, and three percentiles (50%, 80% and 100%) and PG-3 IRI limits for new roads for section I (a) and II (b)

5.4. Conclusions

This research focuses on the evolution of the structural and functional parameters of an experimental section with a high amount of daily traffic (200-799 heavy vehicles per day on each lane). Two unbound RA from the demolition of single family homes with a mobile plant were used as the base and subbase layers. Long-term evaluations of the experimental section were conducted, and the deflections and roughness were measured during a period of seven years from its implementation into service.

Partial conclusions extracted from this research were as follows:

- Recycled aggregates used in this study met the non-hazardous requirements of the European Landfill directive; their use as unbound layers in roads did not represent a risk to the environment.
- The construction and demolition waste after treatment in a mobile plant was proven to be a viable option as new raw material for unbound base/subbase layers in traffic roads with a T2 traffic intensity (200-799 heavy vehicles/day and lane). The recycled aggregate produced did not meet the requirements of the Spanish national standard (PG3) for use as granular base or subbase layers because of their size distribution, Los Angeles abrasion test percentage, soluble salt and organic matter content.
- The experimental section had an adequate structural performance for a T2 traffic intensity road. The recycled aggregates used in this research had a higher bearing capacity than conventional aggregates. The mixed recycled aggregates mean moduli (674 MPa) were greater than those of recycled concrete aggregates (476 MPa) due to the higher percentage of finer fraction. The evolution along the seven years of the study showed an increment in the values of the equivalent and mechanical moduli of the recycled aggregates.

- Recycled concrete aggregates obtained a mean modulus of 476 MPa, which was higher than the mean value of the natural aggregates of 424 MPa. Recycled mixed aggregates had the higher mean modulus of all granular layers obtaining 674 MPa.

- Deflections and moduli test results had different contrasted results depending on the section tested, as well as on the moduli of the granular base calculated by EVERCALC, but not on the moduli of the granular sub-base RMA-1 calculated by EVERCALC or on the IRI results. This finding suggests that: (i) the base layer affected the deflections and moduli test results; (ii) the back-calculate software EVERCALC estimation was in accordance with the results obtained previously; (iii) the granular subbase RMA-1 was properly executed and did not interfere with the other results obtained; and (iv) the roughness surface performance was not affected by the road base layers underneath. The date had a significant effect on section II in deflections and moduli test results. This effect, along with the greater reduction in deflections and an increase in moduli with respect to section I, implies better performance of the granular base made by RCA than the granular base built with NA.

- The asphalt concrete surface met the PG-3 requirements at its implementation and presented an acceptable International Roughness Index throughout the study period of seven years. The service-life estimation in the section with an RCA granular base was not less than the one built with NA.

As shown in this research, the in situ recycling of building debris from mobile plant was proven to be a suitable second raw material as base/subbase layer in road construction with a daily heavy vehicle flow of approximately 400 per lane. The test results that were carried out from putting this material into service up to seven years earlier showed that the recycled aggregates that were used provided good structural behaviour and stability over time, in terms of surface roughness evolution. This study contributes to the sustainability of the construction sector given the fact that transport distances from stationary plants to sites are reduced with the use of mobile plants, thus providing economic and environmental advantages. The reuse of building debris instead of Natural aggregates prevents from landfilling with rests of demolitions and quarry and riverbanks overexploitation and mitigates the effect of the building sector on the planet, this helps to build a new circular model where materials have more than one use enlarging its life cycle.

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6. Conclusiones

6.1. Conclusiones generales

Se presentan a continuación las principales conclusiones obtenidas en las investigaciones planteadas en la presente tesis doctoral:

6.1.1. Tramo experimental en vía de servicio de autovía A-376 construida con áridos reciclados de RCD no seleccionados mezclados con tierras procedentes de excavación.

6.1.1.1. Descripción de las secciones del firme del tramo experimental.

El tramo experimental se construyó en la vía de servicio de la A-376. La longitud total es de 450 m, se dividió el tramo en tres secciones de comparación. La sección I sirvió de referencia, esta fue construida con unos espesores de 30 cm de suelo seleccionado y 30 cm de zahorra artificial. En las secciones II y III se emplearon dos tipos de materiales reciclados: un suelo reciclado mixto (SRM), el cual fue obtenido del precribado a partir del rechazo de la fabricación de una zahorra reciclada mixta (ZRM) y la propia zahorra reciclada. En la obtención de estos materiales reciclados (AR) se emplearon RCD no seleccionados en origen mezclados con suelos de excavaciones, el espesor de estas capas fue de 30 cm. El SRM se empleó en la capa de formación de explanada, mientras que la ZRM se empleó como capa granular en el firme de la sección III, en la sección II se empleó zahorra artificial como base granular del firme.

Sobre toda la superficie del tramo experimental se extendió una capa de mezcla bituminosa continua (MBC) tipo D-20 de 5 cm de espesor.

	SECCIÓN I	SECCIÓN II	SECCIÓN III	Espesor
Rodadura asfáltica	MBC D-20	MBC D-20	MBC D-20	5 cm
Capa granular firme	Zahorra Artificial (ZA)	Zahorra Artificial (ZA)	Zahorra Reciclada Mixta (ZRM)	30 cm
Subbase granular	Suelo Seleccionado (SS)	Suelo Reciclado Mixto (SRM)	Suelo Reciclado Mixto (SRM)	30 cm
Terreno Natural subyacente	TNS	TNS	TNS	200 cm
distancia(km)	0+000	0+150	0+300	0+450

UTRERA → ***SEVILLA***

Figura 6-1 Secciones en tramo experimental vía de servicio A-376.

6.1.1.2. Caracterización de los materiales.

La zahorra artificial y el suelo seleccionado empleados en el tramo experimental cumplían con todos los límites establecidos por los artículos 510 y 330 del PG-3 respectivamente. La ZRM superaba el límite del desgaste de abrasión de los Ángeles de 35 (T3-T4) que fija el artículo 510 del PG-3, tampoco cumplía con el equivalente arena mínimo de 35 (T3-T4). Los contenidos límites de materia orgánica fijados por los artículos 330 y 510 fueron superados tanto para la ZRM como por el SRM. Los valores de CBR de la zahorra artificial y del suelo seleccionado fueron superiores a los valores obtenidos por los AR empleados en el tramo.

6.1.1.3. Principales conclusiones.

1. La granulometría de la zahorra artificial empleada y de la zahorra reciclada mixta son muy similares, siendo la densidad del material

convencional superior al reciclado debido a la mayor porosidad de las partículas que constituyen la zahorra mixta.

2. Las tres secciones construidas en el tramo de experimental alcanzaron una alta capacidad portante. Las deflexiones obtenidas durante un periodo de tres años fueron inferiores a la deflexión teórica, esto implica que la capacidad estructural de las tres secciones fue mayor de la esperada. La sección de referencia mostro valores de deflexión inferiores a las secciones ejecutadas con AR. Las deflexiones fueron estables a lo largo del periodo que duro la auscultación del tramo.
3. No se detectaron diferencias estadísticamente significativas en los valores medios obtenidos para los módulos de elasticidad calculados a través del método directo y del cálculo inverso, por lo que ambos métodos de cálculo son recomendables para la obtención de los módulos de las capas del firme. El valor medio del módulo de la zahorra artificial caliza fue de 481MPa, el valor medio de la zahorra reciclada mixta fue de 349MPa, en cuanto a los suelos empleados como subbase (cimiento del firme), el suelo seleccionado tuvo un valor medio de 221MPa, siendo 158MPa el valor medio para el suelo reciclado mezclado con productos de excavación. Las capas recicladas obtuvieron módulos elásticos más bajos que los materiales naturales, no obstante, tuvieron un comportamiento mecánico superior al esperado, por lo que pueden ser usados como materiales en capas granulares de firme y explanada. Tras los cálculos de los módulos, se puede afirmar que 30 cm de suelo seleccionado son equivalentes a 42 cm de suelo reciclado mixto de las características del material ensayado, mientras que 30 cm de zahorra artificial pueden ser sustituidos por 41 cm de zahorra reciclada mixta de las características de la ensayada.
4. A lo largo de un periodo de siete años se midieron los índices de regularidad internacional en el tramo experimental, no se

detectaron diferencias de la regularidad superficial medida en los tramos formados por materiales reciclados y materiales convencionales. Siendo estos valores aceptables para el tránsito de vehículos en las tres secciones estudiadas.

5. El límite de los Ángeles para zahorras recogido en el artículo 510 del PG3, podría subirse a 45 para vías con un tráfico T4 sin riesgo.

6.1.2. Vía ciclista construida con una zahorra reciclada mixta y el material de rechazo obtenido en su fabricación

6.1.2.1. Descripción de las secciones del firme del tramo experimental.

El tramo experimental se construyó en la vía ciclista que une el Campus de la Universidad de Córdoba en Rabanales con la ciudad de Córdoba. Este se compone de tres secciones midiendo un total de 400 m, las secciones I y II miden 100 m y la sección III mide 200 m. La subbase granular se construyó con un espesor de 25 cm, en la sección I se empleó un suelo seleccionado como referencia de un suelo reciclado mixto (SRM) que se dispuso en las secciones II y III. El SRM fue obtenido del precribado en la fabricación de una zahorra reciclada mixta (ZRM) en planta de tratamiento fija. La base granular del tramo experimental se ejecutó con un espesor de 15 cm. La ZRM se utilizó en la capa granular del firme en las secciones I y III, mientras que en la sección II se empleó una zahorra artificial. En la capa de rodadura se emplearon 4 cm de mezcla bituminosa discontinua (MBD) tipo 8B.

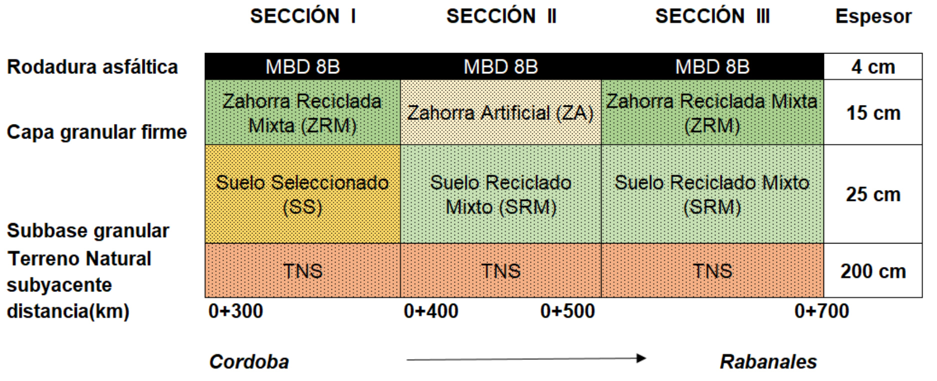

Figura 6-2 Secciones en tramo experimental carril bici Rabanales.

6.1.2.2. Caracterización de los materiales.

Todos los áridos empleados en el tramo experimental se caracterizaron mecánica, física y químicamente, posteriormente se controló su puesta en obra y una vez fue abierta al tráfico se estudió la evolución de la capacidad portante y módulos de elasticidad del firme durante tres años.

La zahorra artificial y el suelo seleccionado empleados en el tramo experimental cumplían con todos los límites establecidos por los artículos 510 y 330 del PG-3 respectivamente. La ZRM superaba el límite del desgaste de abrasión de los Ángeles de 35 (T3-T4) que fija el artículo 510 del PG-3 pero si cumplía el límite del Catálogo de firmes y unidades de obra con AR de RCD (CAR). No cumplía con el equivalente de arena mínimo de 35 (T3-T4) de PG-3 y CAR. Los contenidos límites de materia orgánica fijados por los artículos 330 y 510 fueron superados tanto para la ZRM como para el SRM. La ZRM cumplió el límite de 1% fijado para la materia orgánica por el CAR, mientras que el SRM lo supero. Los contenidos de sales solubles en SRM y ZRM superaron los límites fijados por PG-3 y por CAR. La ZRM no cumplió el límite de contenido de compuestos de azufre según PG-3 pero si cumplió el tope máximo fijado por el CAR. El contenido de yeso de los SRM y ZRM sobrepaso el límite del 0,2% del PG-3 pero no supero el límite del 2% del CAR. Los valores de CBR de la zahorra artificial y del suelo seleccionado fueron similares a los valores obtenidos por los AR empleados en el tramo.

6.1.2.3. Principales conclusiones.

1. A partir del comportamiento de los materiales empleados en el tramo experimental, se pueden modificar las siguientes limitaciones para materiales granulares en vías ciclistas: el límite de materia orgánica puede ascender a un 2%, mientras que el contenido de sulfatos puede modificarse hasta un 2,5%, el contenido de sales solubles podría incrementarse al 4% y el equivalente de arena puede descender a un 25%.
2. La capacidad portante de la vía y su evolución a lo largo del tiempo del estudio (tres años) fue aceptable produciéndose incrementos en los valores de los módulos de los materiales reciclados.
3. El módulo elástico medio del material procedente del rechazo obtenido en la producción de la zahorra reciclada mixta empleada en el tramo experimental, obtuvo un valor medio de 200 MPa, mientras que la zahorra reciclada mixta llegó a 420 MPa. Ambos materiales reciclados obtuvieron resultados equivalentes al suelo seleccionado y zahorra artificial, capas con los que fueron comparados en el tramo experimental construido, demostrando por tanto un comportamiento similar al de los materiales granulares con los que normalmente se construyen vías ciclistas.

6.1.3. Construcción de carretera CH-2 (Córdoba-Aeropuerto) con los áridos reciclados de los RCD de viviendas unifamiliares demolidas como consecuencia de las obras de ampliación de pista del aeropuerto de Córdoba

6.1.3.1. Descripción de las secciones del firme del tramo experimental.

Se empleó una zahorra reciclada mixta (ZRM) en la formación de la explanada con 1m de espesor, en la capa granular del firme se empleó una zahorra reciclada de Hormigón (ZRH) con 30 cm de espesor. En la sección I se dispuso una zahorra artificial caliza con este mismo espesor para que sirviera como tramo de comparación. La ZRH se obtuvo a partir de la trituración insitu con una machacadora móvil de mandíbulas de los RCD obtenidos de las cimentaciones y de las losas de hormigón de los pavimentos existentes, mientras que la ZRM se obtuvo a partir de las estructuras aéreas de las viviendas, muros y tejados.

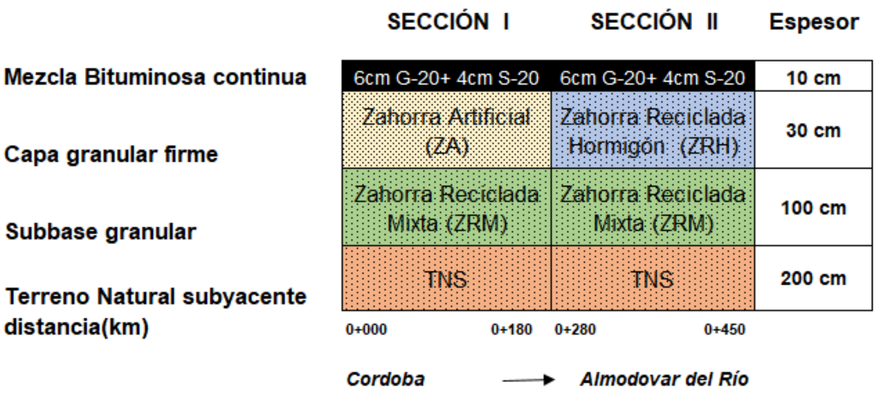

Figura 6-3 Secciones en tramo experimental carretera CH-2.

6.1.3.2. Caracterización de los materiales.

La zahorra artificial empleada en el tramo experimental cumplía con todos los límites establecidos por el artículo 510 del PG-3. La ZRH y la ZRM superaban el límite del desgaste de abrasión de los Ángeles de 30 (T0-T2) que fija el artículo 510 del PG-3, no cumplían con el equivalente de arena mínimo de 35 (T2-T4) de PG-3. Los contenidos límites de materia orgánica fijados por el artículo 330 fueron superados tanto para la ZRM como por la ZRH. Los contenidos de sales solubles en ZRM y ZRH superaron los límites fijados por PG-3. La ZRM y la ZRH no cumplieron con el límite de contenido de sulfatos solubles en agua del PG-3. El contenido de yeso de la ZRM y ZRH sobrepaso el límite del 0,2% del artículo 330 del PG-3. Los valores de CBR de las ZRH y ZRM fueron superiores a los de la zahorra artificial empleada en el tramo experimental.

6.1.3.3. Principales conclusiones.

1. Las dos capas compuestas de materiales reciclados empleadas en la construcción del tramo se les realizo un estudio de lixiviación, el cual concluyo que no eran materiales peligrosos para el medio ambiente.
2. El empleo de maquinaria de reciclado móvil es una opción válida para la producción de materiales reciclados que pueden ser empleados in-situ en carreteras con tráfico T2 (200-799 vehículos pesados al día por carril).
3. El límite de desgaste fijado por el PG-3 para tráfico T2 se sobrepasó, así mismo, se superaron el contenido de materia orgánica, sales solubles y la curva granulométrica de la zahorra reciclada de hormigón no se ajustaba a la de las zahorras del artículo 510 del PG3. El comportamiento de las capas recicladas ha sido mejor que el de la zahorra convencional con el que se ha

comparado, por lo que sería recomendable modificar estos límites para los AR de RCD. Elevando a 35 el desgaste de los Ángeles para tráfico T2, la materia orgánica se limitaría a 1% y el contenido de sales solubles subiría a 1,5%,

4. La capa de subbase ejecutada con la zahorra reciclada mixta ha obtenido un módulo elástico medio de 674 MPa, mientras que la zahorra reciclada de hormigón llego a 476 MPa, esta diferencia de comportamiento se puede explicar por el mayor compactabilidad en la zahorra reciclada mixta y su óptima proporción de partículas cerámicas y derivadas de materiales base cemento. La evolución de la capacidad portante y de los módulos de los materiales reciclados se incrementó a lo largo de los siete años que duro el experimento. La capa de zahorra artificial obtuvo un valor medio de 424 MPa, presentado un decremento desde el inicio del estudio.
5. Los resultados de regularidad superficial obtenidos justifican que las capas granulares naturales o recicladas no afectaron en su evolución. El IRI final obtenido es aceptable para una carretera de alta intensidad de tráfico.
6. Se ha demostrado que los RCD procedentes de edificaciones pueden ser reutilizados en capas no ligadas de carreteras con un tráfico de vehículos pesados elevado (400 vehículos/día/carril) in -situ. Se consigue reducir de esta manera el gasto energético del transporte de materiales, la huella de carbono y la sobreexplotación de canteras y graveras naturales.

6.2. Líneas de investigación propuestas

En esta tesis se ha abordado el uso y empleo de nuevos productos procedentes del tratamiento de RCD en capas no ligadas de pavimentos para tres niveles de tráfico distintos: T2 en una carretera, T4 en una vía de servicio de una autovía y un carril bici. Para verificar el comportamiento de estos nuevos materiales reciclados se han empleado técnicas de auscultación no destructiva que a lo largo de un periodo de entre 3 años para el carril bici y 7 años para la carretera y la vía de servicio han constatado su buen comportamiento en relación a los materiales naturales con los que han sido comparados en cada tramo experimental. No obstante, han quedado aspectos que no han sido tratados por el presente estudio y que serían de un gran interés para optimizar el proceso de reciclado y empleo de estos nuevos residuos que previamente no han sido empleados en otras investigaciones. Por todo lo comentado, se procede a mencionar las posibles líneas de investigación futuras:

En las infraestructuras viales en el ámbito urbano suelen abundar cimentaciones y canalizaciones ejecutadas con hormigones no sulforresistentes, con objeto de poder emplear residuos de la construcción en capas no ligadas de firme en estas zonas, se propone realizar un estudio a escala real donde se verifique si los lixiviados que producen estas capas ejecutadas con residuos generan ataques por sulfatos en los hormigones próximos, así se podría determinar el porcentaje a partir del cual los sulfatos existentes en los residuos pueden generar un ataque en los hormigones no sulforresistentes próximos.

En segundo lugar, se podría realizar un estudio sobre la posibilidad de emplear conglomerantes hidráulicos o mediante el añadido de algún activador alcalino que en conjunción con la fracción fina del residuo favorezca el endurecimiento de estas capas de firme no ligadas, se realizaría un estudio a escala real en la que se estudiaría los lixiviados en estas capas tratadas. Hay estudios de laboratorio, pero son escasos los tramos experimentales con auscultación a largo plazo.

Con objeto de ampliar y mejorar el cálculo de módulos de las capas ejecutadas con AR de RCD se plantea la construcción de nuevos tramos experimentales, de esta manera se conseguirá una mayor experiencia en el cálculo analítico de estos firmes. Así mismo, estos tramos experimentales son demostrativos muy valiosos para Ingenieros Proyectistas, Directores de Obras y Administraciones. Lo cual favorecería el uso de estos materiales reciclados en las obras de ingeniería civil.