UNIVERSIDAD DE CÓRDOBA

DEPARTAMENTO DE INGENIERÍA RURAL. ÁREA DE INGENIERÍA DE LA CONSTRUCCIÓN

APLICACIONES DE LOS ÁRIDOS RECICLADOS PROCEDENTES DE RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN EN LA CONSTRUCCIÓN DE INFRAESTRUCTURAS VIARIAS.

(APPLICATIONS OF RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE IN THE CONSTRUCTION OF ROADS INFRASTRUCTURE)

TESIS DOCTORAL
(Con Mención Internacional)

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Directores:
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Córdoba, Mayo de 2012

TÍTULO: *Aplicaciones de los áridos reciclados procedentes de residuos de construcción y demolición en la construcción de infraestructuras viarias*

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TESIS

para aspirar al grado de Doctor con Mención Internacional por la Universidad de Córdoba presentada por la Ingeniera Dña. Mª Auxiliadora Barbudo Muñoz

La Doctoranda

Fdo.: Mª Auxiliadora Barbudo Muñoz

Vº Bº Los Directores

Fdo.: Prof. Dr. Jesús Ayuso Muñoz. *Prof. Dr. Francisco Agrela Sainz*

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JESÚS AYUSO MUÑOZ, Profesor Titular, y FRANCISCO AGRELA SAINZ, Profesor de Universidad, del Departamento del Área de Ingeniería de la Construcción del Departamento de Ingeniería Rural de la Universidad de Córdoba,

INFORMAN:

Que la Tesis titulada "**APLICACIONES DE LOS ÁRIDOS RECICLADOS PROCEDENTES DE RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN EN LA CONSTRUCCIÓN DE INFRAESTRUCTURAS VIARIAS**", de la que es autora Dña. Mª Auxiliadora Barbudo Muñoz, ha sido realizada bajo nuestra dirección durante los años 2009, 2010, 2011, 2012, y cumple las condiciones académicas exigidas por la Legislación vigente para optar al título de Doctor por la Universidad de Córdoba.

Y para que conste a los efectos oportunos firman el presente informe en Córdoba a 27 de Abril de 2012.

Fdo.: Prof. Dr. Jesús Ayuso Muñoz

Fdo.: Prof. Dr. Francisco Agrela Sainz

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RESUMEN

Los áridos procedentes del reciclaje de residuos de construcción y demolición (RCD) son cada vez más usados en nuevas obras de construcción, debido a diversos factores como el ahorro económico, pero sobre todo, por el beneficio medioambiental que este proceso supone.

Entre las posibles aplicaciones de estos áridos, destacan la construcción de explanaciones, capas de firme de carretera o la fabricación de nuevos hormigones. Los destinos de estos materiales dependerán, pues, de la naturaleza, granulometría y composición cada uno de ellos.

De todas estas aplicaciones, la fabricación de hormigón estructural es el uso más restrictivo, y para ello, es comúnmente utilizado el árido reciclado (AR) procedente de hormigón. Suele tener menor cantidad de impurezas y su comportamiento en nuevas aplicaciones, aunque en bajas proporciones de sustitución, está originando buenos resultados.

Sin embargo, estos suponen una leve porción de la totalidad de áridos reciclados producidos en España, en comparación con otros áridos reciclados, como pueden ser los mixtos o cerámicos, característicos de la mayoría de las construcciones mediterráneas. Además, lo normal es desechar la fracción más fina de estos materiales por ser ésta la que posee mayor cantidad de sulfatos, y por tanto, el hormigón fabricado con él presentaría menor durabilidad y más contaminación potencial por lixiviación.

Por tanto, se debe buscar una salida al mercado a otros tipos de áridos, así como proporcionar una serie de recomendaciones para su aplicación. De esta forma, esta Tesis Doctoral pretende fomentar el reciclaje de los RCD, mediante el estudio de las posibilidades de aplicar los áridos reciclados mixtos y cerámicos, tanto ligados con cemento como no ligados, en la construcción de firmes de carreteras.

Para ello, se han caracterizado diferentes áridos reciclados, de diferente naturaleza y origen, con la intención de obtener correlaciones entre su composición y su comportamiento mecánico en obra. Sin embargo, se llegó a la conclusión que el comportamiento de áridos reciclados depende más del sistema de tratamiento recibido en planta que de su composición.

A partir de esta información, de todas las plantas estudiadas se eligió aquella que realizaba una mejor gestión y tratamiento de los RCD, y se seleccionaron, dos áridos reciclados mixtos de granulometría continua, con diferentes porcentajes de partículas cerámicas. Se ha estudiado el comportamiento de ambos materiales ligados con un 3% de cemento CEM II, tanto en laboratorio, como material de sub-base en un tramo experimental. Los resultados se han comparado con los obtenidos con un árido natural de referencia fabricado de igual forma, obteniendo una resistencia a compresión adecuada, bajas deflexiones bajo carga por impacto, y valores apropiados de rugosidad.

Por último, se han estudiado los efectos que la utilización de estos materiales en obras de infraestructura viaria puede tener sobre el medio ambiente por lixiviación de componentes orgánicos e inorgánicos. De los resultados obtenidos, se puede afirmar que la mayoría de áridos reciclados se tratan de materiales inertes, o en su defecto, no peligrosos, y que el contenido de sulfatos lixiviados en ellos es mucho menor que la cantidad limitada por la normativa española de carreteras (PG-3), a pesar de que este criterio se rige más desde un aspecto mecánico que medioambiental.

De toda la investigación realizada, la conclusión principal que se desprende es la alta importancia de tener una correcta gestión en vertedero, un adecuado proceso de tratamiento en planta y una apropiada selección en origen. Con estos tres pasos, se puede afirmar que los áridos reciclados mixtos se pueden utilizar en carreteras sin riesgo estructural ni medioambiental.

ABSTRACT

Aggregates from recycling construction and demolition waste (CDW) are increasingly used in new construction due to various factors such as economic savings, but, above all, because of the environmental benefit that this process entails.

Possible applications of these aggregates include the construction of earthworks, base or sub-base layers of pavements, or the manufacture of new concrete. These materials have different uses depending on the nature, particle size and composition of each one.

Among all these applications, the fabrication of structural concrete is the most restrictive use, and for this reason, the recycled aggregate (RA) from concrete is commonly used. It usually has fewer impurities and its behaviour in new applications, although in low substitution proportions, is triggering good results.

However, the above represent a minor portion of the total recycled aggregates produced in Spain, compared to other recycled aggregates, such as mixed or ceramic, which are typical of most Mediterranean buildings. Furthermore, particles of less than 4 mm of these materials are usually discarded because this is the fraction with the largest amount of sulphate, and, therefore, the concrete made with it presents a lesser durability and more potential pollution from leaching.

Therefore, new opportunities and recommendations should be sought for the application of other types of aggregates. Thus, this doctoral thesis aims to promote the recycling of the CDW, by studying the possibilities of applying the mixed and ceramic recycled aggregates, both cement-treated and untreated material, in the construction of road pavements.

For this purpose, different recycled aggregates of a different nature and origin have been characterized in order to obtain correlations between their composition and their mechanical behaviour in building work. However, it was concluded that the behaviour of recycled aggregates depends more on the treatment system received in the recycling plant than on their composition.

From this information, among all the plants studied, one plant that performed the best management and treatment of CDW was chosen, and two mixed recycled aggregates from it, with continuous granulometry and with different percentages of ceramic particles, were selected.

The behaviour of both materials treated with 3% CEM II cement has been studied both in the laboratory and as sub-base material in an experimental section. The results were compared with those obtained with a reference natural aggregate manufactured similarly, with an adequate compressive strength, low deflections under impact load, and appropriate roughness values being obtained.

Finally, the potential effects of the use of these materials in road infrastructure on the environment from the leaching of organic and inorganic components have been studied. From the results obtained, it can be affirmed that most of the recycled aggregates are inert materials, or, failing that, non-hazardous, and that the leached sulphate content in them is much lower than the amount limited by the Spanish road normative (PG-3), although this criterion is governed more from a mechanical aspect than an environmental one.

From the research carried out, the main conclusion that emerges is the great importance of the proper management of CDW in the dump, a suitable treatment process in the recycling plant and an appropriate selection in origin. With these three steps, it can be said that the mixed recycled aggregates can be used on roads without any structural or environmental risk.

ÍNDICE

1. INTRODUCCIÓN

La creciente sensibilización en el uso de recursos disponibles lleva a considerar potencialmente a cualquier producto o residuo industrial como un nuevo material secundario.

Cada vez es mayor la concienciación social de la necesidad de llevar a cabo un Desarrollo Sostenible, lo cual se plasma en un, cada vez mayor, uso de residuos de diferente naturaleza en actividades constructivas, a pesar de que, en ocasiones, no se da suficiente difusión a estas actuaciones.

Sin embargo, resulta primordial tener información acerca de las novedades aparecidas en el campo del reciclaje de residuos, ya que ésta es una vía fundamental para incentivar y promover su utilización.

Dar a conocer la experiencia adquirida en aplicaciones de residuos en obras ya ejecutadas es sumamente valioso para mejorar los procesos y reducir los errores en las futuras actuaciones. En este trabajo se expondrán aplicaciones de materiales secundarios en el campo de la ingeniería civil, que si bien han experimentado una evolución creciente en su aplicación durante los últimos años, siguen siendo una asignatura pendiente en nuestro país, a tenor de las grandes cantidades generadas y de las bajas tasas de reciclaje aún conseguidas.

1.1. RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN

Se entiende por Residuo de Construcción y Demolición (**RCD**) cualquier sustancia u objeto que, cumpliendo con la definición de residuo incluida en el artículo 3.A de la ley 10/1998 de 21 de abril, se genera en una obra de excavación, nueva construcción, reparación, remodelación, rehabilitación y demolición, incluyendo el de obra menor y reparación domiciliaria. Estos residuos suelen ser fundamentalmente de naturaleza inerte, y están constituidos básicamente por tierras y áridos mezclados, piedras, restos de hormigón, ladrillos, yesos, maderas, y en general, todos los desechos generados en las actividades propias de la construcción, reforma, demolición y mantenimiento de edificios o infraestructuras en general.

El sector de la construcción provoca un grave impacto en el entorno, desde la extracción de áridos naturales, la fabricación de cementos, hasta la proliferación de escombreras. La construcción es un gran consumidor de recursos no renovables y una importante fuente de residuos y contaminación para el aire, el suelo y el agua.

En la **Comunidad Europea** se producen 461 millones de toneladas anuales de residuos en forma de desechos de construcción y de escombros de demolición (*European Commission DG ENV, 2011*). Hace algunos años, estos residuos se depositaban de forma habitual en escombreras ilegales o eran mal gestionados por personal no especializado. Sin embargo, cada vez más, se suelen extraer de forma separada gran parte de los materiales para poder ser reciclados, como el vidrio, la madera, el hiero, el aluminio, el cobre, el plomo, los plásticos o el cableado eléctrico.

Los niveles de reciclaje y reutilización de RCD varían enormemente entre los Estados Miembros, desde el 14% de España, hasta el 98% de Holanda, 94% de Dinamarca, 92% de Estonia, 86% de Alemania, 80% Irlanda o 75% de Reino Unido, aunque el promedio de la EU-27 está en un 46% (*European Commission DG ENV, 2011*).

Para incrementar su tasa de reciclaje, el Gobierno de España ha regulado la producción y tratamiento de los RCD aprobando el II Plan Nacional Integral de Residuos 2008-2015, estableciendo en él una tasa mínima de reciclaje de 35% para el 2015 (*Ministerio de Medio Ambiente, 2009*). De esta forma, el reciclaje de los RCD ha llegado a convertirse en una realidad en nuestro país durante los últimos años, pues resulta una manera de preservar los yacimientos naturales y de llevar a cabo un mejor control de los vertederos de este tipo de residuos. Los objetivos de este Plan son los de reducir, reutilizar, reciclar y otras formas de valorización de residuos. En concreto, en el anexo 6, se fijan las directrices a desarrollar con respecto a los residuos de construcción y demolición (II PNRCD).

En la actualidad, los áridos reciclados se destinan a aplicaciones que no requieren un alto nivel de calidad, pero la evolución creciente del desarrollo tecnológico de su procesado y de su control de calidad permitirá en un futuro próximo alcanzar un nivel equiparable con los áridos naturales. Por tanto, el reciclado ha de incentivarse tomando medidas adecuadas que canalicen su empleo, regulando y controlando su calidad.

Un aspecto fundamental a tener en cuenta en la recuperación y reciclado de RCD es el hecho de que convergen intereses económicos y medioambientales en el mismo punto. El reto para el futuro es, por tanto, conseguir compatibilizar el desarrollo económico de la humanidad con la preservación del medio ambiente que la sustenta, es decir, lo que se conoce como "crecimiento sostenible". En este sentido, son prioritarias todas las actividades recuperadoras y recicladoras. Aunque no sea posible la sustitución total de la actividad primaria por la secundaria o recicladora, cualquier iniciativa a favor de esta última, es un paso adelante hacia el mencionado crecimiento sostenible, que se impone como la única alternativa posible al futuro desarrollo de las actividades productivas.

Resumiendo, los principales motivos que conducen al reciclaje de RCD son los siguientes:

- Limitación de los recursos naturales. El consumo excesivo de recursos naturales para la construcción, más el impacto ambiental que su continua extracción provoca, así como el elevado coste de gestión de los vertederos controlados, han hecho necesario el reciclaje de los materiales incluidos en estos residuos. Por tanto, el reciclado persigue, principalmente, preservar los recursos naturales.

- Subida continua de los precios de las materias primas y energía, así como dependencia de países productores de petróleo.

- Disminución de la cantidad de residuos a tratar. Con el reciclado se reduce el volumen en el vertedero, además de proteger el medio ambiente, limitando el potencial de descarga a las aguas subterráneas de los constituyentes lixiviados en los vertederos, o de emisiones atmosféricas de los contaminantes que se producen en la combustión.

- Imperativos legales. Cada vez hay más normativa que prohíbe la coevacuación junto con los residuos sólidos urbanos (RSU).

1.2. PROCESO DE RECICLADO

El reciclaje de los RCD es una solución técnicamente viable y muy extendida en otros países europeos, tal y como se ha visto anteriormente, que consiste en la adecuada separación de los materiales que componen los comúnmente denominados "escombros", de forma que se separan los materiales pétreos (hormigón, ladrillo, mampostería y cerámica) de los no pétreos (metales, madera, plásticos, etc). Posteriormente, los primeros son sometidos a una o varias etapas de trituración y clasificación, permitiendo obtener un árido reciclado apto para un nuevo aprovechamiento.

Figura 1. Ejemplos de plantas de tratamiento

Según *Sánchez de Juan, 2004*, el procesamiento de estos RCD puede dividirse en dos fases:

a) ***Demolición selectiva en origen***, para evitar materiales no deseables como pueden ser los escombros de mampostería, vidrio, maderas, tuberías, cables…etc.

Cuando los RCD proceden de obras de ingeniería civil como puentes u otras estructuras, el material no suele contener impurezas, pero la demolición de estructuras de edificación debe incluir una separación previa de los materiales potencialmente reciclables como madera, papel, cartón, y plástico. A pesar del aumento del coste de demolición del edificio, esta selección proporciona una mayor calidad de los materiales de demolición y elimina la necesidad de hacer selección en la planta de reciclaje, y reduciendo los costes de transporte y tasas de vertido.

b) ***Transformación de los escombros de demolición en áridos***. Las plantas de producción de árido reciclado son similares a las plantas de producción de árido natural, a las que se suelen añadir electroimanes para la separación del acero, y otros sistemas de eliminación de impurezas.

Figura 2. Separador magnético (electroimán)

Figura 3. Sopladora de plásticos

Constan principalmente de machacadoras, cribas, mecanismos transportadores y equipos para la eliminación de contaminantes, aunque el sistema dependerá de la aplicación final que se le vaya a dar al árido reciclado y de la cantidad de impurezas que contenga (*Sánchez de Juan, 2004*).

Habitualmente, el proceso de reciclado lleva consigo una selección en la entrada de la planta y también en el proceso de regeneración de áridos. Los RCD recibidos son separados según su volumen, composición y granulometría en diferentes acopios, y más tarde, separados de los metales, maderas, papel y cartón, y otros materiales de gran volumen no aptos. El material restante, pasa por una cribadora donde es separada su fracción más fina, como arenas y arcillas, antes de pasar por una máquina trituradora donde se obtiene el producto final reciclado.

Figura 4. Ejemplos de cribas

Los materiales no aptos del proceso de reciclaje, también llamados "impurezas", son clasificados, separándose los residuos peligrosos, la parte susceptible de valorización y la parte no valorizable. Los residuos peligrosos como los amiantos, disolventes, fibras minerales, etc., son entregados a un gestor autorizado. La parte susceptible de valorización como los metales, maderas, etc. es transportada a la planta de reciclaje. Por último, la parte no valorizable, que no puede ser aprovechada de ninguna forma, se destina al vertedero controlado.

Las plantas de tratamiento pueden ser clasificadas de diferente forma, según dos puntos de vista:

1. De acuerdo a su ***movilidad***, las plantas pueden clasificarse en: móviles, semi-móviles o fijas. Las dos primeras normalmente están destinadas a reciclar directamente en obra, mientras que las plantas fijas necesitan instalaciones propias, que se traducen en una mayor inversión (*Rodríguez-Avello y Lainez*, *2003*).

Las *plantas fijas* de tratamiento gestionan residuos muy heterogéneos, obligando a equipar la planta con máquinas de mayor robustez, y sobredimensionada para la capacidad normal prevista en otras aplicaciones.

Por otro lado, las *plantas móviles* pueden ubicarse temporalmente en los puntos de generación de los RCD, pero resultan más caras que las fijas por unidad de peso procesado, debido, principalmente, a su carácter compacto y sistema de movimiento. Además, las plantas móviles y semi-móviles son más selectivas en cuanto a la tipología y tamaño del escombro tratado.

2. Según las ***operaciones unitarias*** realizadas en el proceso, las plantas de tratamiento de RCD se pueden clasificar en diferentes niveles de tecnología. Se denominan *plantas de Nivel tecnológico 1* a aquellas que comportan un desbrozado inicial con la retirada de elementos indeseables y una posterior clasificación de los productos por tamaño (*Rodríguez-Avello y Lainez, 2003*).

Las *plantas de Nivel 2* se suelen usar para producir materiales reciclados de aplicación probada en las obras públicas y construcción. El machaqueo y la clasificación granulométrica de los áridos, permite su venta inmediata, disminuyendo de forma notable la cantidad de residuo destinada a vertedero.

Las *plantas de Nivel 3* son más apropiadas para el tratamiento de materiales limpios, como los hormigones estructurales, o los escombros cerámicos seleccionados, con un aprovechamiento casi integral de sus componentes. Suelen ser instalaciones de tipo fijo, y son capaces de fragmentar residuos de hormigón con grandes dimensiones. Los productos obtenidos de la trituración secundaria con molino de impactos, pueden cumplir la normativa del árido natural, pues el proceso es similar al de elaboración de un árido machacado y clasificado.

Para las *plantas de Nivel 4*, a base de moliendas selectivas y clasificaciones en húmedo, no se prevé una aplicación inmediata en España, hasta que la reglamentación sobre las tasas de vertido, la obligación de reciclar y los precios de venta de los productos, resulten lo suficientemente atractivos para que el inversor privado vea una igual o mayor rentabilidad que la de cualquier otra industria extractiva.

La calidad del producto de dos plantas, de igual nivel tecnológico, podrá ser muy diferente dependiendo de los sistemas de separación y clasificación que tenga cada una. Los requisitos de granulometría son muy importantes, y dependerán de la regulación de los equipos de trituración y de la eficacia del sistema de cribado.

1.3. ÁRIDOS RECICLADOS

Por **áridos reciclados**, se entienden como aquellos residuos que son de naturaleza fundamentalmente inerte, que proceden del reciclaje de los RCD.

En la actualidad, la elevada generación de residuos procedentes de obras de demolición y de construcción ligada a la incapacidad de dar una salida a los mismos tanto económica como medioambientalmente, está provocando el aumento de estudios relacionados con ciertos materiales para su reutilización y reciclaje. Dichos estudios se basan en la caracterización de la naturaleza de estos materiales y su comportamiento bajo ciertas posibilidades de uso, como en explanaciones, capas granulares de firmes de carreteras y hormigones estructurales y no estructurales, si bien su uso se limita principalmente a rellenos y explanaciones.

Aunque las investigaciones sobre áridos procedentes de construcción y demolición comenzaron en los años 90, no existen en la actualidad normativa técnica específica para el uso de este tipo de árido. Por este motivo, se utiliza en España la Instrucción de Hormigón Estructural (EHE-08) para el uso en hormigones y el Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y puentes (PG-3) para su empleo en carreteras (*Ministerio de Fomento, 2004*).

Según *Alaejos, 2008*, y basándose en las proporciones de sus ***componentes***, los áridos reciclados pueden dividirse en:

- ***Áridos Reciclados Cerámicos***. Áridos que se obtiene por procesamiento de material, predominantemente, cerámico. Se clasifican como tales aquellos áridos con un contenido de hormigón inferior al 70% y con una cantidad de partículas cerámicas superior al 20% (*Agrela et al, 2009*). Tienen una mayor absorción y una menor densidad que el resto de áridos reciclados (*Agrela et al, 2009*) y en España, suelen ser aplicados en sub-bases y explanadas de carreteras y caminos rurales.
- ***Áridos Reciclados Mixtos***. Son los productos obtenidos en el tratamiento de RCD de diferentes naturalezas, con un contenido de partículas cerámicas menor que el 20%, y de hormigón, entre el 70 y el 90% (*Agrela et al, 2009*).

Muchas normativas no permiten el uso de estos dos últimos tipos en hormigón estructural. Otras, como la holandesa, toleran el uso de árido reciclado cerámico en hormigones no estructurales (*Robas, 2011*). Este tipo de árido puede compararse al árido ligero. Su empleo aumenta el contenido de aire y obliga también a una relación agua/cemento (a/c) mayor. Adicionalmente, la resistencia a compresión y el módulo de elasticidad del hormigón pueden verse afectados muy negativamente.

- ***Áridos Reciclados Asfálticos***, con alto contenido de partículas bituminosas. El reciclado de asfaltos para la reparación de firmes dañados, es una técnica viable con resultados contrastados, los cuales no presentan ningún problema de durabilidad si están bien proyectados y ejecutados (*Redacción Ambientum, 2001*).
- ***Áridos Reciclados de Hormigón***, con reducidos porcentajes de materiales cerámicos y bituminosos. Es el material secundario obtenido al reciclar los residuos de hormigón. Se tratan, por tanto, de áridos con un contenido de partículas de hormigón superior al 90%.

Es el único tipo de árido reciclado que puede ser admisible para hormigón estructural, según la EHE'08. Para ello, no debe tener partículas asfálticas, con unos valores límites de impurezas, y siempre y cuando la sustitución del árido grueso convencional sea menor o igual al 20%, en cuyo caso, las propiedades mecánicas permanecen prácticamente constantes. Cuando se empleen porcentajes mayores de sustitución los efectos sobre las mismas pueden representar una limitación en distintos casos.

Figura 5. Árido reciclado cerámico

Figura 6. Árido reciclado mixto

Figura 7. Árido reciclado de hormigón

Figura 8. Árido reciclado bituminoso

En general, la calidad del árido reciclado está claramente influida por su tamaño, presentando las fracciones finas unas peores propiedades (disminución de la densidad, aumento de la absorción, mortero, impurezas, partículas ligeras, terrones de arcilla, así como mayor contenido de cloruros y de sulfatos).

Sin embargo, atendiendo a la ***granulometría***, los áridos reciclados pueden dividirse en:

- ***Zahorras recicladas***. Son el conjunto de áridos de diferentes tamaños. Se tratan de materiales granulares de granulometría continua, normalmente, entre 0 y 40 mm, o 0 y 31.5 mm.
- ***Gravas Recicladas***, con tamaño de partículas superior a 4 mm. En ocasiones, suele denominarse como ***grava*** al árido que queda retenido en el tamiz de 8 mm de apertura, y ***gravilla***, a las partículas comprendidas entre 4 y 8 mm.
- ***Arenas Recicladas***. Son finos reciclados con tamaño inferior a 4 mm. A su vez, pueden ser clasificadas como ***arenas finas***, con tamaño inferior a 2 mm y ***arenas recicladas gruesas***, con tamaño de partículas comprendido entre 2 y 4 mm.
- ***Filler*** (o polvo). Se trata de las partículas que poseen un tamaño inferior a 0.063 mm. Suele encontrarse adherido a otras partículas más gruesas, y no es recomendable para la fabricación de hormigón ya que envuelve a las partículas de cemento, no dejando que el agua las hidrate, ni dejando que el resto de los áridos se adhieran correctamente.

Figura 9. Zahorra reciclada

Figura 10. Grava reciclada

Figura 11. Arena reciclada

Figura 12. Filler reciclado

1.4. APLICACIONES

Las especificaciones que debe cumplir un material para un uso determinado están basadas en años de investigación y experiencia, habiéndose demostrado que los materiales que cumplen las especificaciones han tenido un comportamiento satisfactorio. A continuación se incluye una tabla donde se especifican los posibles usos que pueden tener los diferentes residuos que se producen, relacionados con los procesos de deconstrucción y demolición, y los posibles usos que pueden tener una vez tratados.

Residuo recepcionado	Empleo
Trozos de asfalto	✓ Capas con aglomerados, capas sin aglomerados, capas de cubrición.
Material producido al desempedrar el pavimento	✓ Materiales de relleno, protección contra heladas, capas de grava. ✓ Aditivos para: - Hormigón - Capas con aglomerados hidráulicos - Asfalto - Componentes de hormigón
Escombros de edificios **Ladrillos/materiales ligeros de construcción**	✓ Materiales de relleno, capas de relleno, capas subordinadas, empedrado. ✓ Capas para pistas de deporte, substratos de suelos, piedras para la construcción de edificios, material para basamentos
Hormigón armado y no armado	✓ Materiales de relleno, protección contra heladas, capas de grava. ✓ Áridos para hormigón, componentes de hormigón, material de bases.
Balasto usado de vías férreas	✓ Balasto de vías férreas, gravilla. ✓ Gravillas finas.
Desechos mixtos de obras	✓ Basurero. ✓ Clasificación: - Escombros de edificios (60%) - Otras sustancias útiles, no minerales (20%) - Materias residuales (20 %)

Tabla 1. Posibilidades de empleo de los RCD tratados (Fuente: SADECO, S.A.)

De igual forma, se puede resumir las posibles aplicaciones de las diferentes tipologías de áridos según su procedencia como se muestra en la siguiente tabla:

ÁRIDOS NATURALES (Arenas y Gravas, rocas trituradas)	Construcción	✓ Morteros ✓ Hormigones ✓ Prefabricados ✓ Materiales de relleno ✓ Bases y Subbases de carreteras ✓ Balasto de construcción de vías férreas ✓ Firmes de aglomerados asfálticos ✓ Piedras para escolleras, etc.
	Aplicaciones industriales	✓ Industria cerámica y vidrio ✓ Lechos filtrantes ✓ Revestimientos aislantes y refractarios ✓ Materiales abrasivos ✓ Industria papelera ✓ Industria de los plásticos ✓ Industria de la pintura y detergentes ✓ Fabricación del cemento ✓ Industrias químicas y farmacéuticas ✓ Tratamiento de agua ✓ Cargas ✓ Usos agrícolas ✓ Aditivos para piensos ✓ Corrección de suelos, etc.
ÁRIDOS LIGEROS (Densidad de partícula inferior a 2.000 Kg/m^3)	✓ Morteros puzolánicos ✓ Hormigones ligeros ✓ Prefabricados ligeros ✓ Rellenos especiales ✓ Cerámicas	
ÁRIDOS SECUNDARIOS (Artificiales) **Y ÁRIDOS RECICLADOS**	✓ Materiales de relleno ✓ Bases y subbases para carreteras	

Tabla 2. Aplicación de áridos según procedencia (Fuente: ANEFA)

La utilización de los áridos reciclados es cada vez más habitual en el sector de la construcción. Su uso dependerá de su naturaleza y composición mayoritaria: en explanaciones se suelen usar los áridos procedentes de residuos cerámicos, asfálticos, de hormigón o mezcla de ellos, mientras que en aplicaciones más restrictivas como en la fabricación de hormigón, se suelen usar los áridos reciclados de hormigón, y en ocasiones, su mezcla con material cerámico. Cada una de estas aplicaciones obliga a fijar distintos niveles de exigencias en las propiedades del árido reciclado.

1.4.1. Obras de tierra y terraplenes

En España, las especificaciones técnicas para el uso de materiales como terraplenes y rellenos se recogen en los artículos 330 y 332 del Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3). Concretamente en el apartado 3.2. del artículo 330 (Terraplenes) se indica que "*además de los suelos naturales, se podrán utilizar en terraplenes los productos procedentes de procesos industriales o de manipulación humana, siempre que cumplan con las especificaciones de este artículo y que sus características físico-químicas garanticen la estabilidad presente y futura del conjunto*".

Debido a la homogeneidad de los áridos reciclados de hormigón, y la ausencia de armaduras y otros contaminantes, pueden sustituir sin problema a los áridos naturales, a pesar de desaprovechar las posibilidades de uso de estos materiales. Es por ello que se suelen usar otros áridos reciclados de peor calidad para este tipo de aplicaciones (*CEDEX, 2010*).

Por su parte, los residuos de mampostería con fracción granulométrica 0/20 mm pueden usarse en obras de tierra y terraplenes con las adecuadas condiciones de homogeneidad y limpieza, eliminando el yeso para evitar reacciones expansivas.

Estos últimos materiales presentan una mayor absorción, por lo que se recomienda una humectación previa a su puesta en obra (*Pozo y Pérez, 2007*).

1.4.2. Carreteras o caminos rurales

El firme de una carretera se puede definir como el conjunto de capas de materiales seleccionados colocados sobre la explanada que tienen la finalidad de proporcionar una circulación segura y cómoda. Puede ser de tres tipos:

Flexible: lo constituyen capas granulares no tratadas.

Semirrígido: el formado por bases o sub-bases tratadas con conglomerante hidráulico y pavimento bituminoso.

Rígido: aquel pavimento de hormigón colocado directamente sobre la explanada o sobre una base granular.

La construcción y conservación de carreteras ofrece amplias posibilidades para incorporar cantidades importantes de materiales procedentes de la valorización de residuos (*Sinis, 2002*). Concretamente, en el PG-3 se especifica que los áridos reciclados de hormigón pueden ser usados en firmes de carretera como zahorras (artículo 510), como material tratado con cemento (artículo 513), y como hormigón magro vibrado (artículo 551) siempre y cuando hayan sido tratados adecuadamente para satisfacer las especificaciones técnicas establecidas.

Por el contrario, los áridos reciclados procedentes de materiales cerámicos no cumplen, en general, con las exigencias para su uso en capas de firme como zahorras o materiales tratados con cemento. Es por ello que se recomienda un precribado de los áridos reciclados mixtos para eliminar la fracción más fina, reduciendo el contenido de sulfatos y mejorando su calidad (*CEDEX, 2010*).

La aplicación de áridos reciclados en capas de sub-base o base de carreteras es una práctica habitual en países como Francia, Reino Unido Países Bajos, Alemania, Austria, Suiza y Dinamarca.

En nuestro país, se están usando áridos reciclados de hormigón en capas granulares en polígonos industriales y urbanizaciones, y en carreteras autonómicas estatales. Algunos de ellos son:

- Anillo Verde Ciclista (Madrid) (*Costa, A., 2010*).
- Conexión de la A-367 con la A-357 (Málaga) (*García, 2010*).
- Ramal de acceso a la C-35 en Vidreres (Gerona) (*Ainchil, J., 2010*).
- Tramos de Loja y Santa Fe (*Ramírez y García, 2010*).
- Autovía Murcia-Albacete. Dragado construcción P.O. (*CEDEX, 2010*).

1.4.2.1. Material no ligado (zahorras)

Según el artículo 510 del PG-3, se define "zahorra" como "*aquel material granular, de granulometría continua, utilizado como capa de firme*", siendo la zahorra natural aquella formada por partículas no trituradas y la zahorra artificial la formada por partículas total o parcialmente trituradas.

Concretamente, según el artículo 510.2.1. del PG-3, para las categorías de tráfico T2 a T4 se podrán utilizar materiales reciclados en la formación de firmes, siempre que cumplan las prescripciones técnicas exigidas, y se declare el origen de los materiales (*Ministerio de Obras Públicas, 2004*).

Los áridos reciclados de hormigón son los más usados en capas granulares sin tratar (zahorras), a pesar de que se les exige las mismas especificaciones limitantes que al árido natural (*Vegas y col., 2008*). *Vegas y col. (2011),* propone el uso de los áridos reciclados mixtos con un porcentaje menor del 35% de partículas cerámicas, un contenido de materia orgánica inferior al 0.8% y sulfatos solubles inferior al 0.4%, para la conformación de capas estructurales sin ligar en carreteras.

Tan sólo se limita de forma externa un contenido mínimo de hormigón y un máximo de impurezas, pudiendo incluso igualar o superar la capacidad soporte a largo plazo, con respecto a otros materiales granulares (*CEDEX, 2010*). Es por ello que *Sherwood (2001)* propone que, en carreteras de escaso volumen de tráfico, se podría introducir una cierta relajación en los requisitos que deben cumplir los materiales, lo que facilitaría un mayor uso de los materiales secundarios como los áridos reciclados, y una mayor confianza por parte de los constructores *(Jiménez y col., 2011).*

Así, investigaciones como las de *Vegas y col. (2008)* y *Jiménez y col. (2012)* proponen el uso de áridos reciclados, tanto de hormigón como mixtos, como alternativa a los áridos naturales en caminos rurales sin pavimentar, incrementando la tasa de reciclaje y reduciendo el consumo de recursos naturales, siendo el contenido de sulfatos y la resistencia Los Ángeles sus principales hándicaps.

Ya *Hill y col. (2001)* y *Poon y Chan (2006)* argumentan la viabilidad de estos áridos alternativos para ser usados en la construcción de capas de pavimento o como capas de relleno. *Poon y col. (2006),* por su parte, estudiaron las propiedades auto-cementantes de los áridos reciclados finos de hormigón en capas de sub-base de carreteras sin compactar.

Algunas obras reales con áridos reciclados son un terraplén construido en el acceso del campo de golf de Guadabajaque (Cádiz), o una explanada del Muelle del Prat en el Puerto de Barcelona (*CEDEX, 2010*).

1.4.2.2. Material tratado con cemento

El artículo 513 del PG-3 define "material tratado con cemento" como "la mezcla homogénea, en las proporciones adecuadas, de material granular, cemento, agua y eventualmente aditivos, realizada en central, que, convenientemente compactada, se utiliza como capa estructural en firmes de carretera". Hay dos tipos: suelo-cemento y grava-cemento, y en ambos casos, se permite utilizar materiales reciclados, siempre y cuando cumplan con el resto de las exigencias del PG-3.

Por otro lado, el tratamiento del hormigón reciclado con cemento o ligantes bituminosos aumenta la resistencia del material, reduce la susceptibilidad frente al hielo, la permeabilidad y la posible lixiviación, (*CEDEX, 2010*).

Dongxing y col. (2010) proponen usar estos áridos tratados con cemento como base de carreteras, aunque debe medirse el impacto medioambiental que el uso de estos materiales supone. *Petkovic y col. (2004).*

1.4.3. Hormigones

1.4.3.1. Hormigón estructural

En general, los áridos gruesos reciclados procedentes de hormigón, pueden ser usados en hormigón en masa y en hormigones armados (*Yeung y col., 2006*), siempre manteniendo los criterios de dosificación de los hormigones convencionales (*Etxeberría y col., 2007*). Además, se debe limitar el contenido de cloruros y de sulfatos, al igual que ocurre con los áridos convencionales.

Ya la nueva Instrucción de Hormigón Estructural (EHE-08), en su anejo 15, permite hasta un 20% de sustitución de árido grueso natural por árido reciclado grueso procedente de hormigón, para el caso de hormigones estructurales (*Ministerio de Obras Públicas, 2008*).

Rao y col. (2007) defienden el uso de estos materiales en hormigones de baja exigencia mecánica, incluso en hormigones estructurales, si a éstos se les añade cenizas volantes, humo de sílice...etc. (*Kou y col. 2011*), o superplastificantes para mejorar su trabajabilidad (*Pereira y col. 2012*), siempre teniendo en cuenta la mayor demanda de agua de éstos (*Barra y Vázquez, 1996*). Los áridos reciclados de hormigón de buena calidad pueden ser usados en hormigones estructurales siempre que se seleccionen aquellos que contengan menos de un 44% de partículas de mortero (*Sánchez y Alaejos, 2009*).

Evidentemente, las propiedades de estos nuevos hormigones serán diferentes a los realizados con áridos naturales, aunque *Rahal (2007)* obtuvo resultados muy similares, manteniendo la misma dosificación que en el hormigón de referencia y tomando la precaución de saturar, previamente, los áridos reciclados debido a su alta capacidad de absorción.

Correia y col. (2006) especifican que, en términos de resistencia a compresión y tracción, el uso de áridos reciclados cerámicos para hormigones es completamente adecuado. Sin embargo, su alta porosidad, y por tanto, su alta absorción de agua, los hace menos apropiados desde el punto de vista de durabilidad, ya que elementos no deseables como sales pueden estar disueltos. Así, *Gomes y Brito (2009)* afirman que es posible fabricar hormigón estructural con áridos reciclados, pero no recomiendan una sustitución total de la fracción gruesa (4-32 mm) del árido natural.

También existen numerosas Tesis Doctorales que han investigado la viabilidad del uso de áridos reciclados en la fabricación de hormigón estructural. Un ejemplo es la realizada por *Barra (1996)*, que explica que la utilización de este tipo de áridos afecta principalmente al módulo de elasticidad del hormigón, manteniéndose su resistencia a compresión mediante un aumento de la cantidad de cemento. De igual forma, indica que los áridos reciclados cerámicos en cantidad limitada pueden incluso mejorar la resistencia a hielo-deshielo, sin modificar la resistencia a compresión. Por el contrario, su resistencia a la carbonatación es menor que en hormigones convencionales, aunque puede mejorar con una correcta fabricación de éste.

González (2002) en su Tesis Doctoral explica que, pese a que el árido reciclado de hormigón presenta peores propiedades que el árido convencional, es posible fabricar hormigones estructurales con hasta un 50% de sustitución, manteniendo la resistencia a compresión y frente a cortante, a pesar de producirse una ligera disminución del módulo de elasticidad.

La Tesis Doctoral de *Sánchez (2004)* limita el contenido de árido reciclado, para no repercutir en un peor comportamiento del hormigón, a un 20%, siendo éste procedente de hormigón triturado y en su fracción gruesa (>4 mm). Por otro lado, y para cumplir con las especificaciones impuestas por la EHE'08, el árido reciclado debe poseer una absorción máxima del 7%. El módulo de elasticidad, la retracción, y la fluencia son las propiedades que más se verán afectadas con tal sustitución. Así, la docilidad aumenta progresivamente con el contenido de árido reciclado, y con la relación a/c, el módulo de elasticidad disminuye hasta un 19% de promedio, y la retracción, aumenta hasta un 60% de media, para sustituciones del 100%.

Dada la reducida densidad del árido fundamentalmente cerámico que predomina en los áridos reciclados mixtos, puede utilizarse para la fabricación de hormigones ligeros sin finos (*Katz, 2003)*, aunque también puede usarse en la construcción de estructuras de hormigón en masa y hormigón armado.

Por su parte, la Tesis de *Etxeberria (2004)*, estudia la viabilidad del uso de estos áridos en nuevos hormigones. Concluye que para un 25% de sustitución de árido grueso, y manteniendo la cantidad de cemento y la relación a/c, las propiedades mecánicas no se ven alteradas. De igual forma, aconseja usar cementos con baja alcalinidad o de escorias de alto horno, si se sospecha que el árido puede tener reactividad álcali-sílice. Por otra parte, el incremento de porosidad que supone el uso de áridos reciclados no afecta significativamente a la permeabilidad del hormigón realizado con éstos. En cuanto a lixiviación, indica que los niveles de contaminación potencial de éstos está muy por debajo de los límites holandeses y europeos.

Algunas ***aplicaciones reales*** de estos áridos que se conocen son:

- Puente de Marina Seca del Forum 2004 (Barcelona) (*CEDEX, 2010*).

- Puente atirantado sobre el rio Turia, en la carretera CV-371 (VV-6117) de Manises a Paterna (*Alaejos y col., 2010*).

- Viaductos en la carretera RW 32, cerca de Meppel (Países Bajos) (*CEDEX, 2010*).

- Vivienda unifamiliar en la calle Tato (Madrid) (*Tertre y Navarro, 2010*).

- Compuerta del puerto de Almelo (Países Bajos) (*CEDEX, 2010*).

- Bloque de oficinas (Watford, Reino Unido) (*CEDEX, 2010*).

- Compuerta del puerto de Antwerp (Bélgica) (*CEDEX, 2010*).

- Sede de la Fundación Alemana para el Medioambiente (Deutshe Bundesstiftung Umwelt), en Osnabrück (Alemania) (*CEDEX, 2010*).

- “La casa reciclada”, en Odense (Dinamarca) (*CEDEX, 2010*).

- Viaducto cerca de Helmond (Países Bajos) (*CEDEX, 2010*).

- Compuerta del puerto de Schijndel (Países Bajos) (*CEDEX*, *2010*).

- Muros de carga de hormigón en masa y elementos de hormigón para fachadas y suelos en 272 casas unifamiliares en los Países Bajos (*CEDEX*, *2010*).

- Re-edificación de la zona militar de las afueras de Itzehoe (Alemania) (*CEDEX*, *2010*).

- Losa de la segunda planta de un edificio en Cardington (Reino Unido) (*CEDEX*, *2010*).

1.4.3.2. Hormigón no estructural

Para este uso, el Anejo 18 de la EHE-08 permite el uso de árido reciclado de hormigón, hasta incluso una sustitución del 100%, siempre que cumpla con las especificaciones del Anejo 15 de esta normativa.

Agrela y col. (2011) aconsejan, de igual forma, destinar los áridos reciclados de hormigón para hormigones estructurales, y los reciclados mixtos, para hormigones no estructurales. Investigaciones como la de *Brito y col. (2005)*, *Poon y Chan (2006 b)*, *Poon y Chan (2007)*, *Debieb y Kanai (2008)*, o la de *Mas y col.* (*2012*), también proponen usar este tipo de áridos para hormigones no estructurales, como pueden ser elementos prefabricados de hormigón. Incluso se podrían utilizar hasta un 30% de sustitución de arena natural por áridos reciclados finos, según *Evangelista y Brito (2007)*, o hasta un 50% según *Poon y col. (2009)*.

Al igual que en su aplicación en carreteras, es importante determinar el potencial contaminante de los hormigones realizados con áridos reciclados, y es en este campo en el que han trabajado *Sani y col. (2005)*, demostrando que su uso puede, incluso hasta descender la alcalinidad de este, siempre y cuando su dosificación esté bien diseñada.

Algunas de las ***obras realizadas*** más conocidas con este tipo de áridos en hormigones no estructurales son:

- Elementos decorativos con bloques de hormigón reciclado en el Centro de Exposiciones de Magdeburg (Alemania) (*CEDEX*, *2010*).

- Bloques de hormigón prefabricados (Japón) (*CEDEX*, *2010*).

1.4.4. Morteros

Es una alternativa para la aplicación de la fracción fina de los áridos reciclados (*Álvarez y col., 1997*) (*Sanabria y col., 2005*) (*Silva y col., 2008*), a pesar del aumento de demanda de agua que supone mantener la consistencia (*Vegas y col., 2009*). La resistencia a compresión se reduce, mientras que la resistencia a flexotracción no muestra diferencias apreciables respecto a morteros con arenas naturales (*Corinaldesi y Moriconi, 2009*).

1.4.5. Cementos

Se han fabricado cementos a partir de una mezcla de finos, procedentes de hormigón pulverizado hasta obtener la finura del cemento, escorias de alto horno o lodos con desechos de cemento, 2-3% de yeso, y un acelerador inorgánico de fraguado (*Urcelay, 1997*).

En España no se fabrican estos cementos reciclados, pero en otros países, como China (*Galbenis y Tsimas, 2006*) o Japón, se suelen usar desde hace años en hormigones no estructurales, en cimentaciones, muros de revestimiento o aplicaciones de hormigón en masa (*CEDEX, 2010*).

1.5. CONSIDERACIONES MEDIOAMBIENTALES

La recogida de forma no selectiva de los residuos procedentes de actividades de construcción y demolición provoca la mezcla de distintos tipos de residuos que, en general, no son peligrosos pero que, al mezclarse, pueden dar lugar a residuos contaminados en su conjunto. Esto impide que sean sometidos a un aprovechamiento adecuado o a que sean enviados a vertederos sin las barreras de protección adecuadas (*CEDEX, 2010*).

Entre los materiales y sustancias que pueden encontrarse entre los RCD y que podrían tener alguna característica de peligrosidad destacan (*CEDEX, 2010*):

- Aditivos de hormigón (inflamable).
- Adhesivos, másticos y sellantes (inflamable, tóxico o irritante).
- Emulsiones alquitranadas (tóxico, cancerígeno).

- Materiales a base de amianto, en forma de fibra respirable (tóxico, cancerígeno).
- Madera tratada con fungicidas, pesticidas, etc (tóxico, ecotóxico, inflamable).
- Revestimientos ignífugos halogenados (ecotóxico, tóxico, cancerígeno).
- Equipos con PCB (ecotóxico, cancerígeno).
- Luminarias de mercurio (tóxico, ecotóxico).
- Sistemas con CFCs.
- Envases que hayan contenido sustancias peligrosas (disolventes, pinturas, adhesivos, etc).
- Elementos a base de yeso (fuente posible de sulfhídrico en vertederos, tóxico, inflamable) *(Jang and Townsend, 2001).*

La mayor parte de los RCD se pueden considerar inertes o asimilables a inertes, y por tanto, su poder contaminante es relativamente bajo. Sin embargo, su impacto visual es, con frecuencia, alto, por el gran volumen que ocupan y por el escaso control ambiental ejercido sobre los terrenos que se eligen para su depósito (*CEDEX, 2010*).

Para evaluar el impacto medioambiental de materiales que incorporan subproductos o materiales secundarios, los ensayos de lixiviación son una herramienta indispensable. Cuando los materiales secundarios son aplicados en el exterior, el agua de lluvia, el agua superficial o las aguas subterráneas, pueden ser responsables de que ocurran procesos de lixiviación o procesos de disolución y transporte de componentes de la fase sólida a una fase acuosa. En su interacción con las aguas, los materiales sufren una serie de transformaciones físicas y químicas (*Van der Sloot, 2000*).

Se han identificado más de un centenar de métodos de lixiviación para estudiar la liberación de componentes solubles de una matriz sólida. Así, se puede definir "lixiviación" como el proceso por el cual contaminantes orgánicos o inorgánicos son liberados de una fase sólida a una fase acuosa. En general, el contenido total de un contaminante no es lo decisivo sino su capacidad de ser incorporado a las aguas, es decir, su lixiviación. Cuando el material considerado entra en contacto con el agua, algunos de sus constituyentes se disolverán parcial, o totalmente, en ella creándose un extracto o lixiviado, tanto por difusión, siguiendo un gradiente de concentración, como por advección vertical *(Flyhammar y Bendz, 2006).*

En la *Directiva Europea 2003/33/CE* se establecen los procedimientos, los valores límite y los métodos de prueba para determinar la admisibilidad de los residuos en vertederos. Así, a todos los materiales de los que se sospeche la presencia de elementos contaminantes, se les debe realizar un ensayo de lixiviación. Este estudio consiste, básicamente en la determinación de las concentraciones lixiviables de metales pesados, como Hg, As, Cu, Ba, Cd, Cu, Zn…etc. y de iones como sulfatos, cloruros y fluoruros.

La siguiente tabla, muestra los valores límite para clasificar a un material como (inerte, no peligroso y peligroso):

	Concentración lixiviada (mg/kg)		
	Inerte	**No peligroso**	**Peligroso**
Cr Total	0.5	10	70
Ni	0.4	10	40
Cu	2	50	100
Zn	4	50	200
As	0.5	2	25
Se	0.1	0.5	7
Mo	0.5	10	30
Cd	0.04	1	5
Sb	0.06	0.7	5
Ba	20	100	300
Hg	0.01	0.2	2
Pb	0.5	10	50
Sulfatos	1000	20000	50000
Fluoruros	10	150	500
Cloruros	800	15000	25000

Tabla 3. Clasificación de peligrosidad de residuos en función de la cantidad lixiviada (para L/S=10 l/Kg) para admisión en vertedero

La cantidad disponible de un elemento para ser lixiviado, bajo condiciones extremas, es, una información necesaria para poder predecir las cantidades máximas que se pueden lixiviar a largo plazo. Se habla en este caso del término “*disponibilidad*” o "*concentración potencialmente lixiviable*", para indicar la concentración máxima lixiviable de un elemento (*Galvín y col. (2012 b)* y *Engelsen y col. (2010)*). Se ha diferenciar del concepto de "*concentración total*", que no tiene una relación directa con el impacto medioambiental, y del de "*evolución de la lixiviación con el tiempo*" (*Hidalgo y Alonso, 2005*), que quedan perfectamente explicados en el siguiente gráfico realizado por *Van der Sloot y Kosson (2003):*

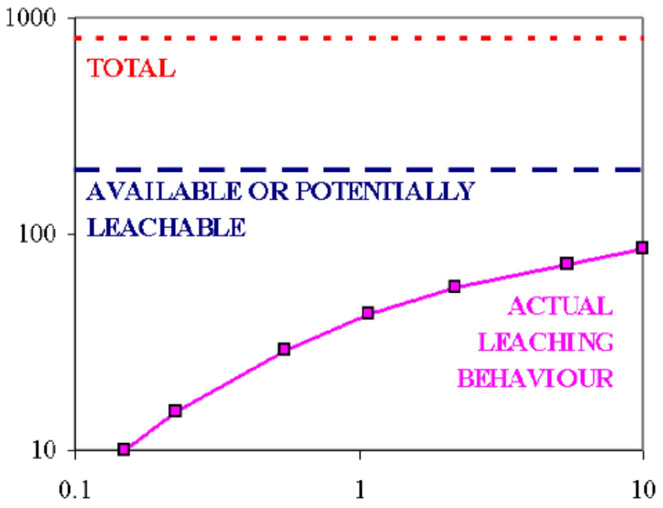

Figura 13. Lixiviación vs. concentración total

Dependiendo de parámetros relevantes de un escenario, como el pH, la cantidad lixiviada puede estar por debajo de la fracción potencialmente lixiviable, particularmente, en los casos en los que se ha realizado un tratamiento para reducir el impacto medioambiental (vitrificación, solidificación-estabilización, etc.). Por tanto, la concentración total, y, en menor extensión la concentración potencialmente lixiviable, no son limitantes necesariamente.

Se puede decir que el comportamiento frente a la lixiviación de todos los tipos de materiales, está relacionado con factores críticos, como la solubilidad de cada elemento (*Lopez Meza y col., 2008*). Ésta está influenciada por el pH, la formación de complejos inorgánicos, la materia orgánica disuelta y por sus propiedades de oxidación-reducción.

La complejidad del proceso de lixiviación hace necesario el uso de simplificaciones. Es por ello que los ensayos para caracterizar el comportamiento de los materiales frente a la lixiviación sean divididos en tres categorías:

a) Ensayos de caracterización básica

Son ensayos utilizados para obtener información del comportamiento a corto y largo plazo, y de propiedades características de los materiales: relaciones líquido/sólido (L/S), composición del medio lixiviante, y factores que controlan la capacidad de lixiviación (pH, potencial redox, capacidad de acomplejamiento, envejecimiento de los materiales, parámetros físicos, etc. (*Galvín y col., 2012*).

b) Ensayos de conformidad

Se usan para determinar si el material produce un lixiviado con concentraciones de elementos por debajo de unos valores de referencia específicos.

c) Ensayos de verificación in situ

Se tratan de ensayos rápidos, y no necesariamente de lixiviación. Se usan para comprobar que el material se comporta del mismo modo que en los ensayos de conformidad.

Los ensayos de lixiviación habrán de elegirse en función de las condiciones en que el material ejerce su función, es decir, su escenario de puesta en obra. Dado que la reproducción exacta de los escenarios reales es muy costosa, se realizan ensayos de laboratorio en condiciones que se aproximen lo más posible a las reales (*Van der Sloot, 1998*).

En la evaluación del impacto para diferentes escenarios, el aspecto fundamental a tratar es la liberación de contaminantes en función del tiempo, durante la fase del ciclo de vida bajo consideración, basados en resultados de ensayos de laboratorio, y verificados con observaciones de campo.

Los ensayos de lixiviación que se usan para evaluar el impacto ambiental, deberían proveer una base para la predicción a largo plazo, siendo conscientes de que una relación 1:1 entre condiciones de laboratorio y condiciones de campo, no puede alcanzarse.

1.6. LÍNEA DE INVESTIGACIÓN PROPUESTA

Resumiendo, los áridos reciclados mixtos (ARM) son el producto obtenido del reciclado de residuos de construcción y demolición (RCD) procedentes, fundamentalmente, de mampostería, con un alto porcentaje en partículas cerámicas, y con un grado de impurezas comúnmente superior al resto. Sin embargo, al ser el tipo de árido reciclado más producido en la geografía española, se hace necesario un estudio más profundo sobre la viabilidad de uso de este material.

De entre todas las aplicaciones indicadas el anterior apartado, esta investigación propone el estudio de la posibilidad de uso de los áridos reciclados mixtos como material tratado con cemento como subbase en tramos reales de carretera, y de su posible impacto ambiental.

2. OBJETIVOS

El objetivo principal que se plantea en esta tesis es el estudio de la viabilidad del uso del árido reciclado producido generalmente en España para su aplicación en carreteras.

Para ello, la investigación se centrará en los siguientes aspectos:

1) Caracterizar las principales propiedades físico-químicas de diferentes tipos de áridos reciclados procedentes de diferentes plantas de tratamiento.

Se pretende hacer un estudio profundo de las principales propiedades físicas y de comportamiento de los áridos reciclados, analizando la influencia de la naturaleza, el material fuente de origen, o el tratamiento recibido de cada uno de los áridos estudiados.

2) Estimar el comportamiento mecánico de los áridos reciclados a partir de sus componentes por medio de un análisis estadístico.

Se persigue encontrar una ecuación matemática a través de la cual poder estimar el comportamiento mecánico de los áridos reciclados, a partir de los resultados obtenidos en el ensayo composición. De esta forma, con un sencillo ensayo, se puede clasificar y vender separadamente según las propiedades esperadas.

3) Estudiar la viabilidad de uso de áridos reciclados con partículas cerámicas como suelo-cemento, en su uso como capa estructural en carreteras.

Los áridos reciclados mixtos son los más abundantes en la geografía española, y por esta razón, se va a evaluar su comportamiento como subbase tratadas con cemento en capas estructurales de carreteras.

4) Estudiar las consecuencias medioambientales del empleo de áridos reciclados en carreteras.

No sólo hay que estudiar el aspecto mecánico, sino que, además, se debe asegurar que la aplicación de áridos reciclados no tiene ningún perjuicio para el medio ambiente. Para ello, se realizarán ensayos de lixiviación con el fin de evaluar el potencial contaminante de éstos.

3. METODOLOGÍA

La investigación que esta Tesis Doctoral incluye, ha intentado abarcar las tres fases normales de estudio:

a) Caracterización de áridos, para determinar la calidad de diferentes tipologías de éstos, y determinar las propiedades más limitantes. Se pretendía asignar unas determinadas características a cada uno de los tipos de áridos reciclados, y poder establecer la aplicación más idónea para cada uno de éstos.

Para ello, 31 zahorras fueron analizadas, 4 de ellas naturales, y 27 áridos reciclados de granulometría continua, de 11 plantas de tratamiento diferentes. Entre estos últimos, se estudiaron 4 áridos reciclados procedentes de hormigón, 15 áridos reciclados mixtos y 8 con alto contenido en partículas cerámicas.

Todos ellos fueron analizados en laboratorio, a través de los ensayos de granulometría, composición, absorción y densidad, índice de lajas, Los Ángeles, Proctor Modificado, CBR inundado, sulfatos solubles en ácido, sulfatos solubles en agua, y materia orgánica.

Se pretendía obtener una ecuación matemática en la que, a través de las diferentes cantidades de elementos obtenidos en el ensayo de composición, se pudiera estimar el comportamiento mecánico que presentarían los áridos estudiados.

Esta fase pretende obtener los objetivos numerados del 1 al 2 del apartado anterior, y los resultados de ésta se muestran en el primer artículo titulado "*Statistical analysis of recycled aggregates derived from different sources for sub-base applications*".

b) Estudio de comportamiento mecánico en su aplicación en obras de infraestructura civil, concretamente como capas de base semirrígida en tramos de carreteras.

De todas las tipologías de áridos reciclados, se eligieron dos materiales mixtos, con diferentes porcentajes de partículas cerámicas, ya que son éstos los más producidos en España. Estos fueron tratados con cemento para su aplicación como suelo-cemento en carreteras, ya que se consideró que iba a ser el uso que poseía un mayor valor añadido. Para ello, se estudiaron su comportamiento tanto en laboratorio como en tramos experimentales como sub-base en la nueva hiperronda de Málaga.

Los objetivos perseguidos en esta fase coinciden con el objetivo número 3, y los resultados se muestran en el artículo denominado "*Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain*", adjuntado en segundo lugar.

c) Estudio de contaminación medioambiental, mediante ensayo de lixiviación, en la que se pretende determinar los metales pesados presentes en los áridos reciclados, y su posible contaminación ambiental, en caso de estar en contacto con agua.

En este estudio, 13 áridos de diferentes plantas de Andalucía fueron estudiados (2 áridos naturales, 2 áridos reciclados de hormigón, 2 áridos reciclados bituminosos, 6 áridos reciclados mixtos, 1 árido procedente de la trituración de ladrillo), más 6 materiales fabricados artificialmente en laboratorio, a partir de un árido reciclado de hormigón y 6 diferentes porcentajes de yeso añadido.

Los valores obtenidos en los ensayos químicos de solubilidad como el de sulfatos solubles en agua y en ácido, fueron comparados con los resultados obtenidos en el test de disponibilidad (ensayo de lixiviación).

El objetivo 4 es el pretendido, y en el tercer artículo adjuntado como "*Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition waste*", se muestran los resultados obtenidos en esta fase.

4. RESULTADOS

Tal y como se ha enunciado anteriormente, los resultados obtenidos se presentan a continuación, en la siguiente cronología:

1º STATISTICAL ANALYSIS OF RECYCLED AGGREGATES DERIVED FROM DIFFERENT SOURCES FOR SUB-BASE APPLICATIONS.

Autores: ***A. Barbudo***, F. Agrela, J. Ayuso, J.R. Jiménez, C.S. Poon

Revista: Construction and Building Materials 28 (2012) 129-138.

Base de Datos en las que está indexada: Journal Citation Reports (JCR)

Índice de impacto de la revista: 1.366

Categoría: Construction and building technology

Lugar que ocupa/Nº de revistas del Área temática: *7/53* (Q1)

2º CONSTRUCTION OF ROAD SECTIONS USING MIXED RECYCLED AGGREGATES TREATED WITH CEMENT IN MALAGA, SPAIN.

Autores: F. Agrela, ***A. Barbudo***, A. Ramírez, J. Ayuso, M.D. Carvajal, J.R. Jiménez

Revista: Resources, Conservation and Recycling 58 (2012) 98-106.

Base de Datos en las que está indexada: Journal Citation Reports (JCR)

Índice de impacto de la revista: 1.974

Categoría: Engineering, environmental

Lugar que ocupa/Nº de revistas del Área temática: 16/45 (Q2)

3º CORRELATION ANALYSIS BETWEEN SULPHATE CONTENT AND LEACHING OF SULPHATES IN RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE.

Autores: ***A. Barbudo***, A.P. Galvín, F. Agrela, J. Ayuso, J.R. Jiménez.

Base de Datos en las que está indexada: Journal Citation Reports (JCR)

Revista: Waste Management 32 (2012) 1229-1235.

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Categoría: Engineering, environmental

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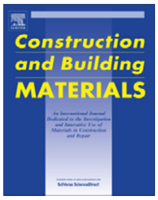

Statistical analysis of recycled aggregates derived from different sources for sub-base applications

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ABSTRACT

One of the main applications of recycled aggregates is the construction of sub-bases for roads as unbound materials, substituting for natural aggregates. For this application, recycled aggregates obtained from crushed concrete are mostly used. Nevertheless, in the Mediterranean area, a large amount of mixed (concrete plus masonry) recycled aggregates is produced, making it advantageous to investigate the possible applications of this type of material, which has a highly variable composition.

This work is focused on studying the possible relationship between different constituents of recycled aggregates and their mechanical behaviour for possible application in roads. To meet this goal, 31 types of aggregates have been studied (four natural and 27 recycled from 11 different treatment plants). Characterisation trials were carried out on all of them, together with mechanical behaviour tests (Los Angeles coefficient, Modified Proctor and C.B.R.). The obtained results were analysed using the standard statistical tests ANOVA and simple and multiple linear correlation analysis.

1. Introduction

The recycling of construction materials has long been recognised as having the potential to conserve natural resources and to reduce the energy used in production [1]. The replacement of natural aggregates by recycled aggregates, totally or partially, has been and is currently being studied in several investigations. The recycled aggregates are used to substitute for natural materials in new concretes [2–5], such as in structural concrete [6,7] or non-structural concrete [8]; in sub-bases as unbound materials [9–13]; in mortars [14,15]; or in seawall foundations [16].

In Spain, the environmental agencies of the different regional governments are mainly responsible for regulating the use of secondary materials in road building and other construction applications [17]. However, there are different technical specifications for materials used in construction. For example, the Spanish Structural Concrete Code EHE-08 sets out the specifications for concrete structures, whereas the general technical requirements specification for road and bridge projects (PG-3) regulates materials for usage in roads.

In all these cases, recycled aggregates are primarily sourced from crushed concrete. However, the architecture of Mediterranean countries commonly utilises large amounts of ceramic materials, which also end up in construction and demolition waste (CDW) [8]. The products obtained are classified as recycled mixed aggregates, which contain crushed concrete, ceramic material and a small quantity of bituminous particles. The main feature of these aggregates is the large variability of their properties due to their different sources and to the different processes in the treatment plants in which they are produced [18].

These recycled aggregates have a lower density than those obtained from crushed concrete and a higher water absorption level [3]. In addition, they also have larger quantities of gypsum particles resulting in an increase in soluble sulphate content, which is usually a limiting factor in recycled aggregates [9]. However, it should be pointed out that recycled aggregates have adequate bearing capacities according to the C.B.R. test [11], in spite of a lower dry density as measured with the Modified Proctor test [10].

Despite the studies mentioned above, a comprehensive study of the characteristics and behaviour of recycled aggregates with a higher content of masonry cannot be found in the literature. It would therefore be very interesting to estimate the mechanical behaviour of recycled aggregate applied in roads using a fast and easy testing methodology, which could be performed *in situ* at the treatment plant. The proposed research aims to determine if the composition test, according to EN 933-11, can predict the mechanical behaviour of recycled aggregate (Los Angeles, Proctor Modified, and C.B.R.) using a correlation model.

For this purpose, 31 materials were studied in this work. They included natural aggregates and recycled aggregates sourced from

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crushed concrete, either mixed or not mixed with ceramic materials. The study aimed to characterise their properties, such as water absorption, density, composition, particle size distribution, and the amount of soluble sulphates. Furthermore, other properties that define material performance, such as compaction using the Modified Proctor test, bearing capacity using the C.B.R. test and resistance to fragmentation using the Los Angeles test, were tested. These obtained data were subjected to statistical analysis to ascertain whether or not there are correlations between these properties. Therefore, analysis of variance (ANOVA) was applied to the obtained results, and an analysis comprising simple and multiple correlation was performed.

In the same way, the presence of a canonical correlation [19] was sought between the composition of the recycled aggregates and the properties defining their mechanical behaviour. This fact would make possible to estimate the behaviour of different types of recycled aggregates based on their different compositions, without performing these tests of mechanical behaviour.

2. Materials

Thirty-one materials were studied in total. Four of the materials were well-graded natural aggregates, applied in actual works as sub-base, while the rest were recycled aggregates with different proportions of bituminous and ceramic components. The recycled aggregates were obtained from 11 CDW treatment plants sited in different provinces of Southern Spanish territory. These recycled aggregates were produced through different recycling processes, as shown in Table 1, but in general, all came from stationary plants, except for B1 and B4, which came from the mobile plant number 5.

In all cases, a pre-treatment was employed in order to remove large impurities, manually or mechanically, and an electromagnetic separator was used to allow the rejection of metal impurities in the material. Only in some cases was there a plastic blower (Table 1). Before the crushing, a pre-screening was often used to reject the fraction of particles with sizes in the range of 0–10 mm. A secondary crushing was only applied in a few cases. The best particle distribution shape is usually achieved by two different crushing processes, but from an economic point of view, a single crushing process is usually the most practical [4].

Once aggregates were stored in stockpiles, the sampling was undertaken in accordance with Standard EN 932-1. In this way, the granular material was homogenised in a laboratory using turning and quartering methods.

The materials studied were non-plastic, which indicated the good behaviour of these materials in relation to water content [9]. The materials studied were classified into four groups, principally allotted according to the proportions of ceramic and concrete particles based on the following criteria:

Group 1. Natural aggregates (N): the materials obtained from massive consolidated rock crushing. In this study, four different natural aggregates were used: silica (N1), limestone (N2) and slate stone (N3 and N4) as reference materials.
Group 2. Recycled concrete aggregates (C): four recycled aggregates with a concrete particle content level of over 90% were used. These were obtained from crushed concrete of different qualities.
Group 3. Mixed recycled aggregates (M): 15 recycled aggregates with a concrete content of between 70% and 90% were used. These materials came from a mixture of concrete and masonry.
Group 4. Mixed ceramic recycled aggregates (B): eight recycled aggregates with a concrete content of below 70% and a ceramic particle content of over 25% were used. These were obtained primarily from crushed masonry.

2.1. Classification test for the constituents of coarse recycled aggregates (UNE-EN 933-11:2009)

Manual separation of the recycled aggregate components was carried out on particles of over 4 mm in size (EN 933-11) to obtain the results shown in Table 2. The values C_m, M_m and B_m correspond to the mean values obtained in C, M and B, respectively.

2.2. Particle size analysis by sieving (UNE 103-101:1998/a1:2006)

The grading particle size distribution of recycled aggregate is required to be the same as that of normal aggregate. In Tables 3–6, it can be observed that all the aggregates had a continuous granulometry that agrees with the results reported by González and Martínez [4]. However, there were large differences between the samples, which may lead to discrepancies in some of the correlations that will be performed.

2.3. Determination of particle density and water absorption (UNE-EN 1097-6:2001)

Table 7 shows the results of the pycnometer test, for particles in the size range of 0.063–4 mm and 4–31.5 mm. For the interpretation of results, a Statgraphic program was used. The program is based on analysis of variance (ANOVA), which is a collection of statistical models and their associated procedures. It provides a test for whether or not the means of several groups are all statistically equal. If the *p*-value resulting from the *F*-test is greater than 0.05, it means that no difference is noted between the groups (corresponding to a significance of less than or equal to 5%) and they form a homogeneous subset of data [20].

Table 1
Recycling processes.

	Plant	CDW selection	Pre-screening #10 mm	Primary crushing	Plastic blower	Screening	Secundary crushing	Screening
C1	1	Yes	–	Impact crusher	–	#30 mm	–	–
C2	8	Yes	–	Impact crusher	–	#30 mm	–	–
C3	3	Yes	Yes	Impact crusher	–	#35 mm	–	–
C4	2	Yes	–	Impact crusher	Yes	#30 mm	–	–
M1	6	Yes	Yes	Jaw crusher	Yes	–	Impact crushing	#35 mm
M2	1	–	–	Impact crusher	–	#30 mm	–	–
M3	6	–	Yes	Jaw crusher	Yes	–	Impact crushing	#25 mm
M4	8	Yes	–	Impact crusher	–	#30 mm	–	–
M5	9	Yes	–	Impact crusher	–	#35 mm	–	–
M6	9	Yes	–	Impact crusher	–	#35 mm	–	–
M7	10	–	Yes	Jaw crusher	–	–	Impact crushing	#40 mm
M8	9	Yes	–	Impact crusher	–	#35 mm	–	–
M9	9	Yes	–	Impact crusher	–	#35 mm	–	–
M10	3	Yes	Yes	Impact crusher	–	#35 mm	–	–
M11	7	–	Yes	Jaw crusher	Yes	–	Impact crushing	#35 mm
M12	4	–	–	Impact crusher	–	#35 mm	–	–
M13	3	Yes	Yes	Impact crusher	–	#35 mm	–	–
M14	9	Yes	–	Impact crusher	–	#35 mm	–	–
M15	9	Yes	–	Impact crusher	–	#35 mm	–	–
B1	5	–	–	Impact crusher	–	#40 mm	–	–
B2	3	Yes	Yes	Impact crusher	–	#30 mm	–	–
B3	9	Yes	–	Impact crusher	–	#35 mm	–	–
B4	5	–	–	Jaw crusher	Yes	–	Impact crushing	#40 mm
B5	9	Yes	–	Impact crusher	–	#35 mm	–	–
B6	4	–	–	Impact crusher	–	#35 mm	–	–
B7	11	–	Yes	Jaw crusher	–	–	Impact crushing	#30 mm
B8	9	Yes	–	Impact crusher	–	#35 mm	–	–

Table 2
Classification test for the constituents of recycled aggregates.

	Concrete and stone[a] (%)	Ceramic particles (%)	Gypsum (%)	Bituminous (%)	Others (%)
C1	98.2	1.6	0.1	0.1	0.0
C2	97.3	2.3	0.0	0.0	0.4
C3	96.7	3.1	0.1	0.0	0.1
C4	96.2	3.5	0.0	0.3	0.0
Cm	97.1	2.6	0.1	0.1	0.1
M1	86.3	5.5	0.1	8.1	0.0
M2	90.3	8.0	0.1	0.7	0.1
M3	78.3	12.5	0.6	6.9	1.7
M4	77.6	14.3	1.1	7.0	0.0
M5	85.7	13.5	0.0	0.4	0.4
M6	84.4	15.1	0.4	0.1	0.2
M7	72.4	16.3	1.6	9.6	0.1
M8	77.2	16.6	0.0	6.2	0.0
M9	73.6	17.2	0.1	0.0	0.4
M10	78.9	19.0	0.9	0.8	0.4
M11	78.3	19.7	0.4	0.9	0.7
M12	67.8	21.0	1.5	9.3	0.4
M13	72.9	21.0	1.0	2.9	2.2
M14	77.5	22.4	0.0	0.0	0.1
M15	74.3	24.5	1.0	0.0	0.2
Mm	78.4	16.4	0.6	3.5	0.5
B1	74.3	25.4	0.2	0.0	0.1
B2	68.2	26.6	0.4	4.4	0.4
B3	69.7	27.2	1.1	2.0	0.0
B4	70.1	29.6	0.2	0.0	0.1
B5	74.3	24.5	1.0	0.0	0.2
B6	56.0	38.2	5.2	0.3	0.3
B7	41.8	46.4	0.5	2.0	9.3
B8	53.0	46.7	0.1	0.0	0.2
Bm	63.4	33.1	1.1	1.1	1.3

[a] Concrete and stone = Rc + Ru.

Table 3
Particle size distribution of Natural aggregates.

Sieve size (mm)	Percentage passing (%)			
	N1	N2	N3	N4
40	100	100	100	100
25	95	95	80	74
20	89	90	70	55
8	69	65	40	26
4	58	47	28	17
2	49	35	21	12
0.5	28	18	10	7
0.25	18	12	8	6
0.063	10	7	6	5

Table 4
Particle size distribution of concrete recycled aggregates.

Sieve size (mm)	Percentage passing (%)			
	C1	C2	C3	C4
40	100	100	100	100
25	85	85	91	76
20	78	74	86	70
8	52	53	56	47
4	36	45	40	31
2	26	38	30	24
0.5	12	26	16	15
0.25	8	20	10	12
0.063	4	13	5	8

For the fine fractions, as the *p*-value for the case of *water absorption* is 0.0056, it can be concluded that significant statistical differences existed between the five groups of aggregates studied. Fisher's least significant difference (LSD) test indicated that there were two subsets of homogeneous data: one formed by the category N samples, which had a lower absorption coefficient and another by the four groups of recycled aggregates (Table 7). This coincided with statements by several authors, such as Collins [21] and Bairagi et al. [2], who indicated that recycled aggregates have very high absorption, and observed that nearly 75% of the 24 h absorption capacity in recycled aggregates is attained in the first 30 min of the soaking period. Nevertheless, for the results of *SSD-density* test, there were no significant statistical differences between the groups because the *p*-value was equal to 0.6921.

For the coarse fractions, four different groups could be identified with respect to water absorption (Table 7). In fact, a higher absorption coefficient was observed with increase in the percentage of masonry, which agreed with the findings of Gomes and Brito [6]. Values obtained were between 3.7% and 12.5% water absorption, which agreed with the statements by Rao et al. [22], indicating that the water absorption in recycled aggregates ranges from 3% to 12% for the coarse fraction. It may be noted that this value was much higher than that of the natural aggregates for which absorption was about 1–3.5%. These values were slightly higher than those presented by Rao et al. [22] (0.5–1%) due to the more porous nature of some of the natural aggregates studied (N3 and N4, mainly).

With respect to the *SSD-density* of this fraction, the analysis showed three homogeneous subgroups, one formed by the M and B, another by C and M, and another by N (Table 7). Despite the slated natural aggregate (N3), which had the lowest average density of natural aggregates group, in most cases (except M3, M8, B1, B4 and B5), fine recycled aggregates had a lower density than the fine natural aggregates. This is due to greater porosity that leads to much higher water absorption.

According to Brito [23], fine fraction of recycled aggregates should have higher absorption and less density. However, lower water absorption and a higher density of the fine fraction were observed in some cases in this study, especially in those with more than 20% of masonry in composition. This may be due to two reasons. First, recycled aggregates studied in other investigations came from crushed concrete and therefore the fine fraction had a higher percentage of mortar, which was the cause of this higher absorption and less density. Second, the fine fraction of recycled aggregates had a composition with more natural aggregate particles than the coarse fraction.

2.4. Chemical analysis

According to Tam and Tam [24], sulphate content may give rise to expansive disruption of concrete. However, some types of sulphates in recycled aggregates, present as cement hydrates in the hardened concrete or residual mortar, may be less likely to participate in any further reaction with the new concrete. According to Vegas et al. [9] and Martín and Morales [7], the solubility of sulphates should be restricted in road materials to guarantee the dimensional stability of the section and to avoid potential adverse effects due to the presence of sulphates in adjacent concrete structures.

Table 5
Particle size distribution of mixed recycled aggregates.

Sieve size (mm)	Percentage passing (%)														
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
40	100	100	100	100	100	100	99	100	100	100	100	100	100	100	100
25	89	84	100	81	99	99	65	92	99	86	87	98	94	86	98
20	85	75	98	69	92	94	55	85	90	77	79	91	92	77	86
8	64	41	64	45	68	68	29	45	56	45	58	58	67	47	51
4	51	29	47	38	53	54	23	31	41	31	39	44	49	34	39
2	40	24	36	34	43	44	19	24	33	24	28	35	40	27	32
0.5	18	18	17	27	23	25	14	11	19	13	15	20	25	17	24
0.25	10	15	11	24	13	15	10	7	12	8	10	14	17	14	20
0.063	5	10	5	21	4	6	6	3	6	4	6	8	3	8	14

Table 6
Particle size distribution of ceramic recycled aggregates.

Sieve size (mm)	Percentage passing (%)							
	B1	B2	B3	B4	B5	B6	B7	B8
40	93	100	100	94	100	100	100	100
25	84	84	95	81	94	92	84	89
20	79	76	87	73	84	88	77	83
8	55	46	45	47	46	70	48	46
4	42	35	31	35	33	56	36	30
2	35	29	24	29	25	46	30	21
0.5	23	21	12	20	14	30	20	12
0.25	17	18	6	15	9	23	14	8
0.063	7	9	0	8	3	14	8	5

Table 8 shows the results obtained for the content of acid-soluble sulphates (UNE-EN 1744-1:1999). A significant difference was observed between the groups formed by N and B. For water-soluble sulphates (UNE-EN 1744-1:1999) and organic matter content (UNE 103204: 1993), the results shown in Table 8 form a homogeneous group of data with no significant statistical differences. On the other hand, Figs. 1 and 2, obtained from the statistical analysis, show two “outliers” or extreme values in the acid-soluble and water-soluble sulphate tests. For this reason, repeated tests were carried out, resulting in values that were very similar to those obtained in the original tests and demonstrating that they were not erroneous values but anomalous ones. In the same way, it was observed that these high percentages correspond to the same samples, M12 and B6, which were taken at the same recycling plant, suggesting an inadequate treatment process.

The mean values obtained in each group show an increase in the soluble sulphate content according to the percentage of masonry in the material. In this way, the N group was the one with the lowest percentage (mean value equal to 0.1% in acid and 0.01% in water) and the B group had the highest mean value (1.8% in acid and 0.87% in water). The presence of sulphates might be due to the presence of mortar [24], crumbs of gypsum or other contaminants in the waste debris. It shows the need for different processing methods at the CDW treatment plants to remove these undesirable materials. On the other hand, organic matter contents obtained in this study were much lower than those obtained by Vegas et al. [9], bearing out the “inert” nature that is typical of CDW.

Table 7
Particle density and water absorption.

	Water absorption (%)				SSD-density (kg/dm^3)			
	0.063–4 mm		4–31.5 mm		0.063–4 mm		4–31.5 mm	
N1	5.7		1.2		2.50		2.83	
N2	4.7		1.6		2.40		2.59	
N3	1.6		2.1		2.25		2.71	
N4	5.0		3.4		2.48		2.64	
Nm	4.3	a*	2.1	a	2.41	a	2.69	a
C1	9.6		5.3		2.06		2.31	
C2	7.1		6.0		2.32		2.43	
C3	8.8		6.4		2.14		2.24	
C4	9.4		3.7		2.37		2.44	
C_m	8.7	b	5.4	b	2.22	a	2.36	b
M1	10.8		5.1		2.30		2.40	
M2	11.7		5.4		2.24		2.43	
M3	8.7		6.5		2.45		2.35	
M4	4.2		8.8		1.31		2.23	
M5	14.1		8.4		2.30		2.36	
M6	15.2		8.8		2.31		2.33	
M7	9.5		8.3		2.37		2.20	
M8	7.7		6.8		2.42		2.46	
M9	9.0		9.2		2.40		2.33	
M10	9.4		8.1		2.14		2.16	
M11	14.2		9.4		2.17		2.20	
M12	8.9		8.0		2.19		2.15	
M13	8.1		8.5		2.20		2.18	
M14	10.0		10.1		2.35		2.30	
M15	7.5		7.6		2.40		2.32	
Mm	9.9	b	7.9	c	2.24	a	2.29	b,c
B1	4.9		7.9		2.48		2.32	
B2	8.5		8.3		2.15		2.12	
B3	10.2		9.2		2.28		2.32	
B4	4.4		9.7		2.59		2.25	
B5	6.0		9.8		2.65		2.25	
B6	7.1		10.2		2.21		2.13	
B7	9.7		11.9		2.34		2.18	
B8	12.0		12.5		2.18		2.27	
B_m	7.9	b	9.9	d	2.36	a	2.23	c

^{*a,b,c,d} classification in homogenous sub-groups.

Table 8
Chemical properties, flakiness index, and crushed and broken surfaces.

	Acid-soluble sulphates (%SO_3)	Water-soluble sulphates (%SO_3)	Organic matter (%)	Flakiness index	Crushed particles (%)
N1	0.26	0.01	0.20	16	81.5
N2	<0.01	<0.01	0.17	8	96.0
N3	0.09	<0.01	0.44	25	73.4
N4	0.06	0.02	0.21	28	100.0
N_m	0.10 [a*]	0.01 [a]	0.26 [a]	19 [a]	87.7 [a]
C1	0.80	0.31	0.56	8	73.0
C2	0.47	0.25	0.66	4	71.2
C3	0.67	0.26	0.30	9	70.0
C4	0.80	0.38	0.15	6	78.0
C_m	0.69 [a b]	0.30 [a]	0.42 [a]	7 [b]	73.1 [b]
M1	0.42	0.12	0.83	10	90.3
M2	0.56	<0.01	0.95	17	96.8
M3	0.87	0.10	0.59	12	92.7
M4	2.67	1.56	0.33	8	96.7
M5	0.96	0.31	0.28	11	97.6
M6	1.02	0.42	0.25	9	97.7
M7	1.62	0.20	0.51	18	87.2
M8	0.35	0.10	0.38	18	97.0
M9	0.69	0.19	0.24	13	97.1
M10	1.23	0.67	0.29	17	69.0
M11	0.54	0.29	0.41	13	92.1
M12	4.56	1.55	0.38	12	69.0
M13	1.40	1.05	0.38	16	94.0
M14	0.32	0.31	0.24	14	97.0
M15	2.34	0.10	0.40	29	100.0
Mm	1.30 [a b]	0.47 [a]	0.43 [a]	15 [a]	91.6 [a]
B1	1.51	0.59	0.89	16	81.0
B2	1.00	0.86	0.48	19	70.0
B3	1.32	0.87	0.26	10	98.9
B4	1.27	0.41	0.73	18	78.0
B5	1.05	0.14	0.26	22	94.7
B6	6.19	3.93	0.47	13	88.0
B7	1.30	0.17	0.32	15	96.3
B8	0.73	0.02	0.21	20	98.2
Bm	1.80 [b]	0.87 [a]	0.45 [a]	17 [a]	88.1 [a]

[*a,b] classification in homogenous sub-groups.

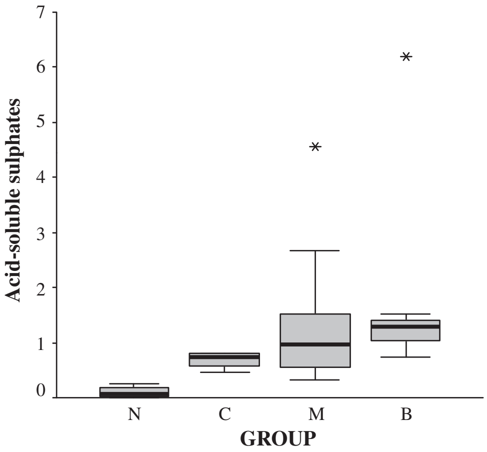

Fig. 1. Boxplots showing acid-soluble sulphates content.

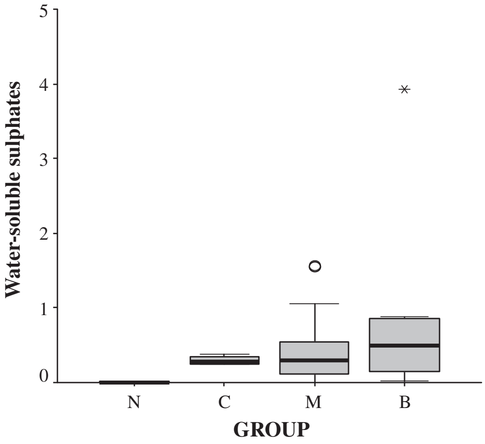

Fig. 2. Boxplots showing water-soluble sulphates content.

2.5. Tests for the geometrical properties of aggregates

Tests were conducted to determine the flakiness index (UNE-EN 933-3:1997/A1:2004) and the percentage of crushed and broken surfaces (UNE-EN 933-5/A1:2005). The results are shown in Table 8. With respect to the flakiness index, two differing groups were observed: one formed exclusively by C with the lowest values, and another formed by the other three types of materials that had a similar mean flakiness index.

In the recycling process, the most common practice in natural aggregates is a primary and secondary crushing. A second crushing typically leads to rounder and less sharp particles. Recycled aggregates, however, are usually produced using only primary crushers; therefore, recycled aggregates are usually flatter and sharper than natural aggregates. In this way, studies by other authors [4] argue that natural aggregates show the highest values. In this case, differing results were obtained mainly because of two reasons: there were two natural aggregates with slate nature that considerably raises the average flakiness index, and some recycled aggregates had undergone two crushing processes.

With respect to the percentage of crushed and broken surfaces, C also had a mean percentage lower than that of the other types of aggregates. On the other hand, N, M and B formed a homogeneous set of data because there was no significant statistical difference between them.

2.6. Resistance to fragmentation (UNE-EN 1097-2:1999/a1:2007)

The results obtained in the tests are shown in Table 9. A lower Los Angeles coefficient was associated with N, with a mean value of 21, which agreed with that reported by Sánchez and Alaejos [14]. The C group had a mean coefficient equal to 33. Nevertheless, there was no significant difference between M and B as both groups displayed a mean value of 38.

Table 9
Results for the tests for mechanical behaviour.

	Los Angeles Coefficient		Modified proctor				C.B.R. index	
			Optimum moisture content (%)		Maximum dry density (Mg/m^3)			
N1	17		5.5		2.20		78	
N2	20		6.3		2.21		152	
N3	19		6.3		2.29		50	
N4	26		6.7		2.21		36	
Nm	21	a*	6.2	a	2.23	a	79	a b
C1	34		12.6		1.87		97	
C2	32		10.5		1.97		55	
C3	34		11.6		1.88		138	
C4	33		11.7		2.00		109	
Cm	33	b	11.6	b c	1.93	b c	100	a b
M1	37		10.5		1.95		40	
M2	35		8.7		2.11		41	
M3	39		12.7		1.92		60	
M4	33		10.3		1.95		78	
M5	38		11.8		2.12		79	
M6	38		12.3		2.09		82	
M7	33		13.5		1.95		48	
M8	41		9.4		1.94		78	
M9	37		11.0		1.88		102	
M10	41		10.3		1.83		71	
M11	38		12.6		1.95		73	
M12	31		13.0		1.83		62	
M13	40		13.3		1.85		94	
M14	40		12.2		1.98		110	
M15	45		11.9		1.96		92	
Mm	38	c	11.6	b	1.95	b	74	a
B1	37		11.5		1.91		155	
B2	36		12.7		1.91		68	
B3	30		11.5		1.92		95	
B4	40		14.6		1.86		157	
B5	40		12.4		1.90		118	
B6	39		15.4		1.67		138	
B7	40		15.2		1.86		45	
B8	43		11.7		1.81		94	
Bm	38	c	13.1	c	1.86	c	109	b

^{*,a,b,c} classification in homogenous sub-groups.

2.7. Compaction test. Modified Proctor (Une 103501:1994)

The data for maximum dry density and optimum moisture are shown in Table 9. For both variables, there are three homogeneous groups. The first, consisting of N, had a lower optimum moisture (6.2%) and a higher dry density value (2.23 kg/dm^3) as compared with that of recycled aggregates [10]. The other two groups were C-M and C-B.

2.8. C.B.R. index (Une 103502:1995)

The test was carried out at the optimum moisture content obtained in the Modified Proctor test after submerging the specimen for 96 h (4 days), and with a load of 4.5 kg. As the UNE 103502 indicates, in cases where the percentage of retained material was between 10% and 30% of the total mass (N4, M4 and M7), this fraction was replaced by an equal proportion of 5–20 mm size. Although the standard does not recommended this test for materials with less than 70% of material which went through the sieve 20 mm, the test was carried out with appropriate substitution of material with particle sizes greater than 20 mm, in order to include these materials in correlations that are studied later.

Table 9 shows the highly dispersed results that were obtained for the four groups, with a minimum value of 36, for the case of N4. The maximum value obtained (157) corresponded to B4. The only conclusion that could be reached with this statistical analysis was that the only groups with significant statistical differences were those formed by B (B_m = 109) and M (M_m = 74).

3. Statistical analysis methods

In order to analyse the influence of the nature of different types of recycled aggregates on their mechanical behaviour, three types of statistical analysis (simple correlation, multiple correlation and canonical correlation) using linear correlations were carried out [25], using the Statgraphics Program as follows.

- *Simple correlation*: refers to any departure of two variables from independence, but most commonly refers to a more specialised type of relationship between mean values. There are several correlation coefficients, but the most common of these is the Pearson correlation coefficient, which is sensitive only to a linear relationship between two variables. In this case, each of the variables for the composition test (mortar and stones, ceramics, gypsum and asphalt) was analysed with each of the variables belonging to the characterisation tests (density and absorption, chemical analysis, flakiness index, and crushed surfaces). The relationship between the composition and mechanical behaviour variables (Los Angeles, Modified Proctor and CBR) was also analysed.
- *Multiple correlation*: In multiple regression analysis, the set of predictor variables ($X_1, X_2, \ldots, X_n$) is used to explain the variability of the criterion variable Y. In this paper, this analysis was used to quantify the relationship between a mechanical behaviour variable and several variables of the composition test.
- *Canonical correlation*: Introduced by Harold Hotelling, is a way of understanding the relationship within cross-covariance matrices. If we have two sets of variables, $X_1, X_2, \ldots, X_n$ and $Y_1, Y_2, \ldots, Y_n$, and there are correlations among the variables, then canonical correlation analysis will enable us to find linear combinations of the Xs and the Ys which have maximum correlation with each other. Therefore, this is a special type of multiple correlation.

In this research, the relationships between two sets of variables were analysed: the mechanical behaviour of a material, as determined using the Los Angeles coefficient, Proctor and C.B.R. tests, and the constituent materials present in the aggregate.

4. Results and discussion

4.1. Simple linear correlations

4.1.1. Correlation between composition and characteristic variables

With regard to the analysis between the composition test and characterisation test variables, it was affirmed that seven statistical significant correlations existed with a p-value < 0.05 (Table 10), corresponding to the values marked in bold. Of these, only four possessed a determination coefficient R^2 approximately equal to or greater than 0.7 as per the following:

- Percentage mortar particles and natural aggregates vs. water absorption of coarse fraction (4–31.5 mm) had a determination coefficient equal to 0.690 (Fig. 3), so the conclusion was that by increasing concrete and stone content, the water absorption of the coarse fraction is reduced.
- Percentage of ceramic particles (masonry) vs. water absorption of coarse fraction (4–31.5 mm) had an R^2 equal to 0.771 (Fig. 4), observing that 95% of the materials had a content of masonry under 30% with a water absorption percentage of less than or equal to 10%.
- Percentage of gypsum vs. acid-soluble sulphates had an R^2 equal to 0.786 (Fig. 5), and the percentage of gypsum with water-soluble sulphates had a coefficient R^2 equal to 0.779 (Fig. 6). In these cases, a positive correlation and an extreme value (B6) were found, which was commented on in Section 2.6. Therefore, in order for this analysis to be considered as being representative, it was necessary for additional tests to be carried out with samples that contained between 2% and 5% gypsum content.

If among the studied materials are selected recycled aggregates less than 0.8% acid-soluble sulphates and a coefficient Los Angeles less than 40, there are nine materials that obey these two requirements. Thus, the two following correlations were found:

- Percentage of mortar particles and natural aggregates vs. Los Angeles coefficient, with a determination coefficient equal to 0.779. In the Fig. 7 it was observed that increasing concrete and stones, the Los Angeles coefficient was decreased.
- Percentage of ceramic particles (masonry) vs. Los Angeles coefficient (Fig. 8). In this case, a determination coefficient equal to 0.787 was observed, such that as the percentage of masonry increases, so does the Los Angeles coefficient.

Therefore, if the maximum content of acid-soluble sulphate and the Los Angeles coefficient are limited, which

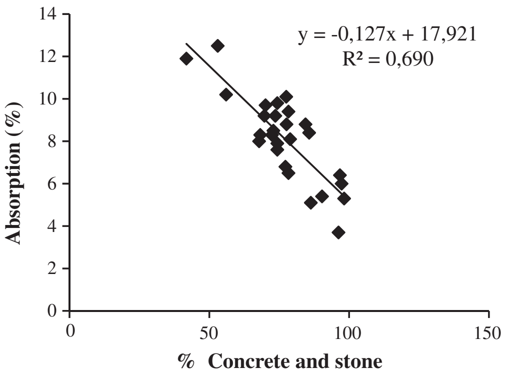

Fig. 3. Correlation between percentage of mortars and stones vs. the water absorption on the coarse fraction (4–31.5 mm).

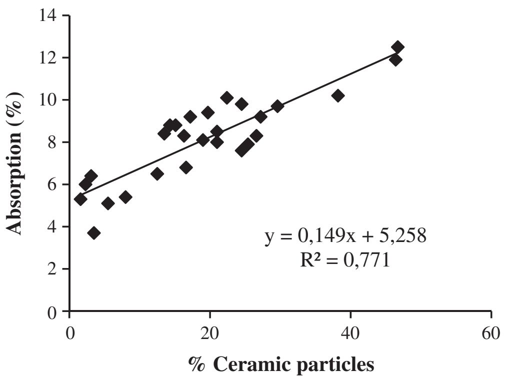

Fig. 4. Correlation between percentage of ceramic particles vs. water absorption on the coarse fraction (4–31.5 mm).

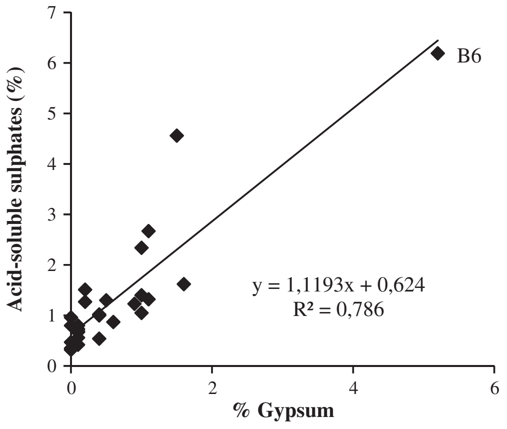

Fig. 5. Correlation between percentage of gypsum vs. acid-soluble sulphates.

Table 10
P-Values and R^2. Simple correlation between composition variables and characterisation variables.

	Concrete and Stone		Ceramic particles		Gypsum		Bituminous	
Water absorption (0.063–4 mm)	0.6693		0.7828		0.2915		0.5244	
Water absorption (4–31.5 mm)	**0.0000**	**R^2 = 0.690**	**0.0000**	**R^2 = 0.771**	0.2630		0.4558	
SSD-density (0.063–4 mm)	0.6318		0.4244		0.3494		0.2095	
SSD-Density (4–31.5 mm)	0.9304		0.9416		0.4182		0.8694	
Flakiness index	**0.0057**	R^2 = 0.244	**0.0018**	R^2 = 0.298	0.1623		0.8068	
Crushed particles	0.0988		0.1062		0.9144		0.8594	
Acid-soluble sulphates	0.1266		0.3339		**0.0000**	**R^2 = 0.786**	**0.0246**	R^2 = 0.041
Water-soluble sulphates	0.5377		0.8259		**0.0045**	**R^2 = 0.779**	0.0645	
Organic matter	0.2908		0.2327		0.3911		0.4195	

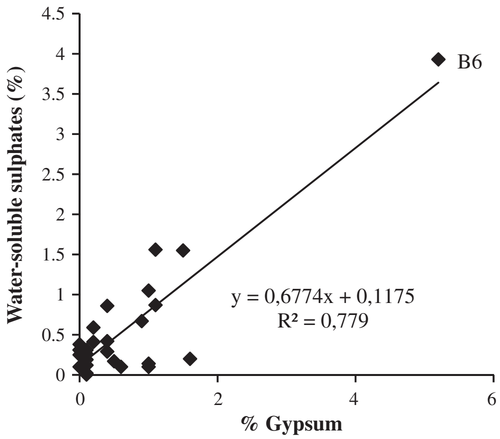

Fig. 6. Correlation between percentage of gypsum vs. water-soluble sulphates.

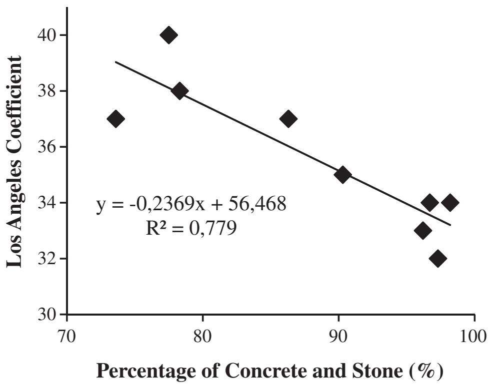

Fig. 7. Correlation between percentage of concrete and stones vs. Los Angeles Coefficient.

are the most limiting properties for use in roads, 33% of recycled aggregates among those studied could be used as road sub-base.

These materials correspond to treatment plants with a good selection at source (Table 1), or for those that did not have this feature, instead had a recycling process that includes a pre-screening and a second crushing (M11). In addition, if a maximum coefficient of Los Angeles equal to 40 is replaced in the equation of the regression line of Fig. 8 and 25% masonry is obtained. Therefore, it can be deduced that recycled aggregates with higher than 25% of masonry must not be applied in road sub-bases.

4.1.2. Correlation between composition and mechanical properties variables

Table 11 shows the results of the statistical analysis of the composition and mechanical properties variables. Although seven statistical significant correlations were observed (p-value < 0.05), none of these correlations had an acceptable correlation coefficient ($R^2 < 0.7$).

Nevertheless, based on the Pearson coefficients shown in Table 12, it can be affirmed that the most influential factor on the Los Angeles coefficient is the percentage of masonry in the recycled aggregates because it has a higher absolute value. The second most influential factor is the percentage of mortar particles and stones, although with a slightly less significant correlation (p-value < 0.05). In this case, the Los Angeles coefficient decreases while the percentage of mortar and stones increases.

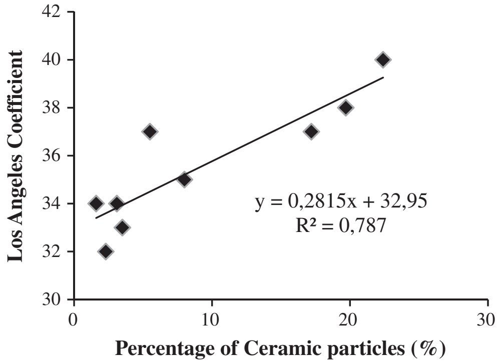

Fig. 8. Correlation between percentage of ceramic particles vs. Los Angeles Coefficient.

For the maximum dry density obtained in the Modified Proctor test, the influence of the content of mortar and stones, masonry and gypsum on the density value was similar. The correlation was, in all three cases, significant at a level of 0.01. Nevertheless, the percentage of asphalt did not have a significant correlation because its p-value was equal to 0.863.With respect to the C.B.R. index, the only factor that affected it significantly was the percentage of asphalt (p-value = 0.003).

4.2. Multiple linear correlations

The following equations show the best fit to a multiple linear correlation model between the Los Angeles coefficient (LA), the Modified Proctor maximum density (MD) or the C.B.R. index (CBR) and the four independent variables that correspond to the four main components of the recycled aggregates: amount of (i) concrete and stone (C&S), (ii) ceramic particles or masonry (CP), (iii) gypsum (G) and (iv) asphalt and other bituminous particles (B).

$LA = 35.0184 + 0.1457\,CP - 0.2824\,B$	(p-value = 0.0128; $R^2 = 0.247$)
$MD = 1.7462 + 0.0026\,C\&S - 0.0386\,G$	(p-value = 0.0008; $R^2 = 0.401$)
$CBR = -412.723 + 5.0429\,C\&S + 5.58781\,CP + 9.1550\,G$	(p-value = 0.0074; $R^2 = 0.322$)

In the above three cases, the p-value was <0.10. Nevertheless, the regression analysis showed low coefficients of determination, R^2, implying that there were no strong correlations between these variables. For that reason, there is no graphical representation.

4.3. Canonical correlations

The results obtained for this analysis are shown in Table 13. It is observed that three canonical correlations (1, 2, 3 in Tables 13–15) existed between the variables obtained in the composition test and the variables obtained through the mechanical behaviour tests. The third correlation is not considered as being significant because it had a p-value of over 0.05. The first one, with a p-value of almost 0, is the one that best explains (with a canonical correlation equal to 0.72) the existing relationship between the two groups of variables:

$$2.55976\,C\&S + 2.33459\,CP - 0.159988\,G - 0.197647\,B = 0.248024\,LA + 0.785859\,MD + 0.907269\,CBR \quad (r = 0.518357)$$

Table 11
P-values and R^2. Simple correlation between composition variables vs. behaviour variables.

	L.A. coefficient		Maximum dry density		C.B.R. index	
Concrete and stone	**0.039**	$R^2 = 0.159$	**0.003**	$R^2 = 0.029$	0.889	
Ceramic particles	**0.009**	$R^2 = 0.246$	**0.006**	$R^2 = 0.024$	0.314	
Gypsum	0.972		**0.001**	$R^2 = 0.000$	0.406	
Bituminous	0.124		0.863		**0.003**	$R^2 = 0.012$

Table 12
Pearson coefficients. Simple correlation between composition variables and behaviour variables.

	L.A. Coefficient	Maximum dry density	C.B.R. Index
Concrete and stone	**−0.399**	**0.551**	−0.028
Ceramic particles	**0.496**	**−0.518**	0.201
Gypsum	0.007	**−0.581**	0.167
Bituminous	−0.303	−0.035	**−0.550**

Table 13
Canonical correlations between composition variables vs. behaviour variables.

Number	Eigenvalue	Canonical correlation	P-Value
1	0.518357	0.71997	**0.0005**
2	0.494925	0.703509	**0.0043**
3	0.162587	0.40322	0.1420

Table 14
Importance of canonical composition variables.

	1	2	3
Concrete and stone	**2.55976**	**0.0389559**	−0.713414
Ceramic particles	**2.33459**	**0.764535**	0.101775
Gypsum	**−0.159988**	**0.379605**	−1.02963
Bituminous	**−0.197647**	**−0.30093**	0.137346

Table 15
Importance of canonical behaviour variables.

	1	2	3
L.A. coefficient	**0.248024**	**0.501699**	0.854752
Max. density	**0.785859**	**−0.669957**	0.313429
C.B.R. index	**0.907269**	**0.215186**	−0.544676

The regression analysis concludes that, even though this correlation is highly significant, the Eigenvalue “r” is very low. Based on the statistical analysis, it can be affirmed that despite the fact that significant statistical correlations exist, the mechanical behaviour of recycled aggregates cannot be estimated from the constituents of the recycled aggregates only. Therefore, the composition of the recycled aggregates obtained according to the norm UNE-EN 933-11, predicts the mechanical behaviour with unreliable values.

However, as the variables are standardised, it can be affirmed that the percentage of mortar and stones and of masonry is of approximately the same importance in relation to the influence of the mechanical behaviour of recycled aggregates because the corresponding coefficients had higher absolute values. Therefore, the percentages of asphalt and gypsum are of lesser importance.

As for the second set of variables, it can be affirmed that on the one hand, the Los Angeles coefficient is the factor that is the least correlated to the results of the composition test. On the other hand, the C.B.R. index is the mechanical test that is most correlated to the components of the recycled aggregates.

5. Conclusions

In this study, a wide range of commercially available aggregates were studied: 13% were natural materials, 13% were recycled concrete aggregates and 74% were mixed recycled aggregates. Although some studies by other authors had already obtained the same conclusions, a statistical analysis confirms and consolidates the following:

1. Recycled aggregates have higher water absorption in the fine fraction than that of natural aggregates. However, in the coarse fraction, water absorption is highly influenced by the relative percentage of mortar and stones and of masonry in recycled aggregates.
2. Higher coarse fraction density corresponds to natural aggregates, followed by recycled concrete aggregate, mixed and ceramic materials.
3. The soluble sulphate content, in both water and acid tests, is strongly influenced by the percentage of gypsum and crushed clay brick in the recycled aggregate. Thus, the soluble sulphate percentage of crushed clay brick is higher than that of natural and other recycled aggregates. The highest values of sulphate were found in some of the materials that were not subjected to a process of selection and removal of large impurities.
4. The recycled concrete aggregates have a lower flakiness index and a lower broken surfaces percentage, in the recycled aggregates.
5. The natural aggregates have a lower Los Angeles coefficient, a lower optimum moisture and a higher Proctor density than the recycled aggregates
6. With increasing content of masonry, the optimum moisture content increases and maximum dry density decreases.

In addition, this study reveals that among recycled aggregates, concrete aggregates have greater resistance to abrasion. Furthermore, although mixed and ceramic recycled aggregates (M and B) are not allowed in Spanish regulations for use in pavement layers, the results obtained in the trial Los Angeles indicated that 14 of the 23 materials studied (61%) meet the requirements imposed by the latter (coefficient less than 40). The remaining materials have slightly higher values, but in no case exceed 45.

In order for recycled aggregates to be used in road sub-bases, it is necessary for the correct selection of the origin of the materials or treatment in a plant with pre-screening and double crushing. From the obtained correlation, it is deduced that recycled aggregates with less than 25% of masonry can be used in road sub-base. Furthermore, mixed recycled aggregates and ceramics have a good mechanical performance for use in low traffic roads, especially because they have a high bearing capacity, as measured by the C.B.R. index.

In conclusion, despite the high expected influence of the components in the mechanical behaviour of recycled aggregate, statistical analysis shows low correlation values. Therefore, the results of each mechanical behaviour trial (Los Angeles, Modified Proctor and CBR) cannot be accurately estimated from the components obtained in the composition test, according to EN 933-11. In addition, there is no relationship between groups of variables formed by the constituents of recycled aggregates and the results of the three tests of behavioural studies. As a result, the constituents of recycled aggregates obtained from the composition test (UNE 933-11) alone do not explain their mechanical behaviour. This fact can be caused by several reasons:

- The high variability in the characteristics of studied recycled aggregates. In order to obtain better results, a deeper classification of the constituents should be carried out, for instance, a subdivision of ceramic materials (crushed brick, glazed ceramic, etc.), a separation of crushed concrete with different resistances, or a classification of natural aggregates by their nature.
- Size distribution. As the aggregates studied come from different treatment plants and different sources nature, they have very different particle sizes, which can affect their mechanical behaviour.
- Different processing systems used by the 11 selected plants. The process of selection and removal of impurities and a pre-screening at the beginning of the process are shown as effective practices to improve the quality of recycled aggregate. Therefore, the treatment plants must support an adequate quality control of CDW at the entrance to the treatment centres, so that the recycled aggregates can be used directly as the sub-base in road pavements.

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Full length Article

Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain

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ABSTRACT

In Spain, the use of recycled aggregates (RA) in the construction of road sub-bases and embankments is growing. Some authors have studied the possibility of using RA in applications with a higher added value, such as the construction of untreated granular sub-bases. However, there is little research on the properties and behaviour of mixed RA treated with cement when used in actual projects as a base for paving roads. This paper includes an investigation of the source of the construction and demolition waste used in RA, the processing plant for the production of RA that manufactures the material treated with cement, and the actual use of RA in a construction project as the sub-base of a motorway access ramp. The results show that the use of some of these aggregates in roads is entirely feasible and that the benefits associated with these aggregates extend beyond the environmental aspects of their use. Some authors have studied the possibility of using these recycled materials in the laboratory, but there are few studies based on real uses of RA from construction and demolition waste (CDW) in roads.

1. Introduction

In recent years, the use of recycled aggregates (RA) made from construction and demolition waste (CDW) has increased considerably in civil engineering (Leite et al., 2011). The reuse of RA is resulting in a significant reduction in the environmental impact caused by this waste. Both the volume of waste that goes into landfills and the consumption of natural resources are reduced with the use of RA (Rodríguez et al., 2007).

In Spain, as in most Mediterranean countries, there are basically two types of RA from CDW. One type is concrete recycled aggregates (CRA), in which more than 90% of the particles come from recycled crushed concrete. The other type is mixed recycled aggregates (MixRA), which contains varying percentages of concrete, masonry, and asphalt (Agrela et al., 2011).

The CRA are in higher demand and can be used in higher value-added applications, as the coarse fraction can be used in the manufacture of structural concrete (Poon et al., 2004; Topcu and Sengel, 2004; Sánchez de Juan and Alaejos, 2004). Consequently, many countries have included within their regulations the possibility of partially replacing the coarse fraction of natural aggregate with CRA in percentages ranging between 20 and 50% (BS 8500-2:2006; EHE, 2008).

Another application of CRA is the construction of roads as either bound or unbound granular layers (Molenaar and Van Niekerk, 2002; Xuan et al., 2010). The principal limitation is the acid-soluble sulphate content, with a maximum of 0.8% allowed by Spanish regulations (PG3, 2004). However, most of the RA produced in Spain is MixRA, and they are usually used in the construction of embankments and compacted layers on sub-grades. Some authors have studied the possibility of using these materials in applications with higher added value, such as the construction of untreated granular sub-bases (Vegas et al., 2008; Jiménez et al., 2011).

Cement treated granular materials have been used as semi-rigid base course for road sections. Their mechanical properties have been studied in order to be applied in structural designs (Lim and Zollinger, 2003). There are a few researches on the properties and mechanical behaviour of MixRA treated with cement when used as road sub-bases or bases in actual civil works. Xuan et al. (2011) studied the influence of the proportion of masonry particles in MixRA, and they determine the relationship between the degree of compaction, the cement content and the masonry content in the compressive strength of the cement treated granular materials.

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Table 1
Constituents of CDW.

Constituents of CDW	Crushed concrete (% by weight)	Crushed masonry (% by weight)
Concrete (natural aggregate mixed with mortar)	98.25	34.28
Masonry (ceramic mixed with mortar)	1.13	63.42
Gypsum	0.31	0.76
Others	0.49	1.54

Therefore, the purpose of this study is to assess the behaviour of two MixRA through laboratory testing and with experimental sections and to compare them with a natural aggregate; all aggregates were treated with cement. We studied the properties of two MixRA and a natural aggregate (NA) in the laboratory to prove their feasibility in a real application, as cement-treated aggregates used as a road sub-base. In September 2009, two sections of an access ramp to a motorway located in Malaga, Spain were constructed. Several tests were conducted to evaluate their performance.

2. CDW processing

To produce the RA used in this research, two types of CDW were used and transformed in an Aristerra treatment plant, Málaga. These residues were characterised by the different proportions of their constituents – crushed concrete (CC) and crushed masonry (CM). The percentages by weight of the residues that comprise each type of CDW are included in Table 1. These percentages were obtained by separating and weighing the different types of residues.

The concrete waste consisted of large concrete blocks of different origins. The masonry waste came from the demolition of a building in Malaga in southern Spain. As can be seen in Fig. 1, the main components of the waste from the demolition of masonry blocks were concrete and other debris such as metal, wood and plastic, which were separated before reaching the processing plant.

Fig. 2 shows a diagram of the CDW treatment that was used to obtain the two recycled aggregates, MixRA-15 and MixRA-22. The first is a mixture of CC and CM at 50% each, and the second is a mixture of 34% CC and 66% CM. A pre-screening size of 25 mm was used, and the coarse fraction was crushed in an impact crusher to obtain both types of RA.

Fig. 1. Demolition of the Ciatesa factory (Málaga).

3. Materials

3.1. Cement

CEM II B-V/32.5 containing 20% silica fly ash was used as cement (UNE-EN 197-1:2000). The properties of the cement are shown in Table 2.

3.2. Natural aggregate (NA)

The natural aggregate was obtained by crushing slate. Its properties are summarised in Table 3. The curve of the sizes of the natural aggregate is close to the lower grading limit, which means that the NA has an excess of coarse particles.

3.3. Recycled aggregates

The properties of MixRA-15 and MixRA-22 are summarised in Table 3. Table 4 presents the constituents of the MixRA-15 and MixRA-22 materials. We obtained results according to UNE-EN-933:11. The grading curves of the RA and the NA are shown in Fig. 3 together with the grading curve range of the material called "soil–cement 40 mm", or SC-40, from the Spanish General Technical Specifications for Road Construction (PG-3). According to PG-3,

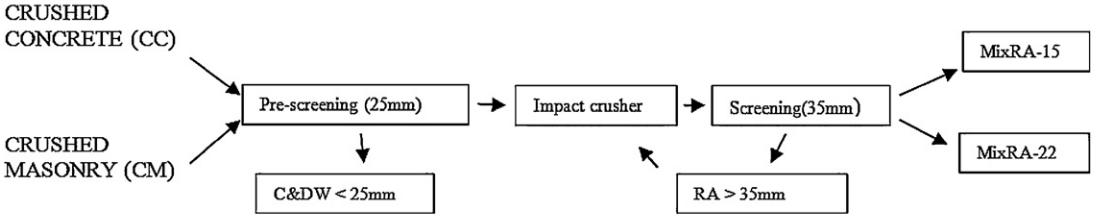

Fig. 2. CDW transformation processing in MixRA.

Table 2
Properties of cement.

SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	LOI (%)	Specific mass (kg $10^3/m^3$)	Specific surface area Blaine (mm^2/g)
26.56	3.89	6.58	58.32	1.12	3.32	1.25	2.96	39.78

Table 3
Properties of natural and recycled aggregates.

Properties	NA	MixRA-15	MixRA-22
Density SSD (0.063–4 mm)	2.48	2.30	2.28
Density SSD (4–31.5 mm)	2.64	2.46	2.32
Water absorption (0.063–4 mm)	4.99	7.7	10.2
Water absorption (4–31.5 mm)	3.38	6.8	9.2
Nominal Size (mm)	40	25	25
Equivalent of the sands	71	67	66
L.A. abrasion value	30	38.6	38.2
Flakiness index	33	11	14
Acid-soluble sulphate (%SO_3)	0.05	0.69	0.72
Organic mater (%)	0.16	0.24	0.26

Table 4
Constituents of recycled aggregates according to UNE EN 933:11.

Constituents of aggregates (UNE 933:11)	MixRA-15	MixRA-22
Natural aggregates	16.08	13.96
Crushed concrete particles	68.20	63.14
Crushed ceramic particles	15.13	22.42
Asphalts	0.11	0
Gypsum	0.35	0.42
Others	0.13	0.06

MixRA-15 and MixRA-22 have values that correspond to SC-40, with a nominal maximum size of 25 mm.

There is no direct relationship between the composition of the CDW before it is processed and the RA because of the pre-screening process that is used to eliminate impurities. This process caused a reduction in some components of the RA; in particular, both types of MixRA contained lower quantities of masonry particles than desired.

3.4. Comparison of individual aggregate properties

The NA had the highest density value, followed by MixRA-15 and MixRA-22. This type of aggregate is lighter than the recycled concrete aggregate, and the NA has reduced water absorption compared with the two recycled materials (Agrela et al., 2011).

The NA has a worse particle size distribution than each type of MixRA, and a better Los Angeles abrasion value. These differences are primarily due to mortar adhesion and to ceramic particles (masonry). The NA has a higher value for the flakiness index than the RA (MixRA-15 and MixRA-22). The equivalent sand value and organic impurities value are similar for all materials.

PG-3 requires a maximum amount of acid-soluble sulphates to be present in aggregates (limit value = 0.8%). In the NA, this content is practically zero. In contrast, in both types of MixRA the acid-soluble sulphate content is close to 0.8% by weight, which is the limit prescribed by the Spanish regulations and other national and international rules (BS 8500:2006; PG3:2004). The results indicate that the incorporation of masonry particles increased the content of acid-soluble sulphates in the MixRA to a limited extent. It is important to control the sulphate content to avoid exceeding the admissible limits by selecting the residue at the source and using an appropriate treatment in the processing plant.

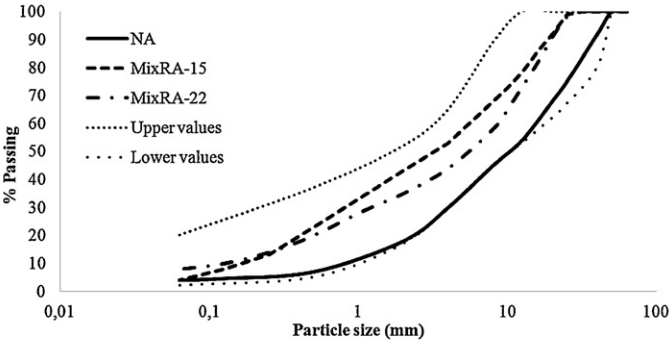

Fig. 3. Particle size distribution compared with the granulometric limits.

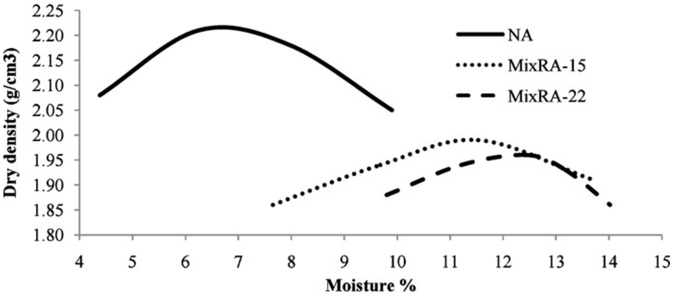

Fig. 4. Modified Proctor curves.

Table 5
Results of experimental tests performed in the laboratory.

	NA	MixRA-15	MixRA-22
Proctor modified test dry density (kg $10^3/m^3$)	2.21	1.99	1.96
% Optimum moisture (Proctor modified)	6.72	11.53	12.45
Vibrating hammer time (s)	40	37	39
Compressive strength after 7 days	3.18	3.43	3.52

The soluble sulphate content, which is caused in part by the mortar-adhered particles, can cause swelling problems associated with the formation of ettringite (Odler and Colan-Subauste, 1999). However, because the three materials meet the requirement set by the Spanish regulations, they were used as granular material in a sub-base layer treated with cement.

4. Laboratory testing

Material samples were extracted from the CDW manufacturing plant. In the laboratory, the materials were homogenised and quartered, and the following tests were performed.

4.1. Modified Proctor

This test was performed according to UNE 103501:1994 as indicated by Spanish regulations (PG3:2004). This indicates it is necessary obtaining “in situ” more than 98% of dry density determinate in laboratory.

Fig. 4 shows the compaction curves obtained for each of the three materials. The values of dry density and optimum moisture are presented in Table 5.

The densities obtained with the Modified Proctor test are lower for the MixRA than for the NA, according to Poon and Chan (2006), because the saturated surface-dry density (SSDS) of the NA (Table 3) is much higher than the value obtained for the two MixRA materials.

It is very important to note that the optimum compaction moisture content is higher in the recycled materials than in the natural materials. This is caused by the higher porosity found in RA, especially in mortar and in masonry materials.

4.2. Vibrating hammer time

The compaction time was calculated using a vibrating Kango hammer with a mass of 10 kg, a ram steel of 3.5 kg, an application frequency of 1900 rpm and an electrical power of 750 W

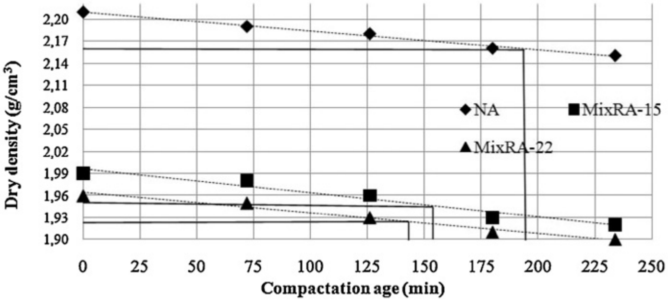

Fig. 5. Period of workability.

(NLT-310:1990). The “cement-treated aggregates” (CTA) specimens were prepared with the different aggregates (MixRA-15, MixRA-22 and NA) by adding both 3% cement to the dry weight and the moisture content found in the Modified Proctor test (Table 5). Different compaction energies were applied by varying the time of application of the load exerted by the vibrating hammer. Compaction was performed in three layers with different compaction times to obtain a density greater than 98% of the Modified Proctor test. The compaction times with the vibrating hammer were similar for each material, as shown in Table 5.

4.3. *Period of workability time*

A study was conducted to determine the period of workability of the materials used when mixed with 3% cement. This test was performed according to UNE 41240:2003. This period refers to the time from the moment when the components are mixed until a drop of 2% points occurs when compared with a reference, which is the maximum density obtained in the Modified Proctor test.

Five specimens of each material were prepared with 3% cement and the optimum moisture content. From the completion of the soil–cement mixture homogenisation until the mixture was compacted with the vibrating hammer into three layers, the workability time was 195 min for the NA, 152 min for MixRA-15, and 145 min for MixRA-22 (Fig. 5). This indicates that the materials should be compacted on-site within 140 min of the time they were mixed at the production plant.

For these test sections, the application of a setting retardant additive was not considered because the materials could be handled (transported, spread and compacted) within the workability time of 140 min. However, the application of a setting retardant is recommended for future projects if the time needed for transportation, spreading and compaction exceeds the period of workability.

4.4. *Compressive strength at seven days*

After the mixture was made with a mechanical mixer, the moulds were filled in three layers, each with a thickness of approximately one-third of the height of the mould. Each of these three layers was compacted with a vibrating hammer for the length of the previously calculated times; the hammer was pressed with a force close to 300 N, and the top layer was filled up to the edge of the mould. After approximately 20 h, the soil–cement specimens were de-moulded and stored in a moist chamber following the standard specifications (NLT 305:1990).

After 7 days of curing, the specimens were subjected to the compressive strength test described in NLT 305/90 standard. The average compressive strength (3 tests) was 3.18 MPa for the NA, 3.43 MPa for MixRA-15 and 3.52 MPa for MixRA-22 (Table 5). These values are between 2.5 and 4.5 MPa, which is required by Spanish regulations (PG3:2004).

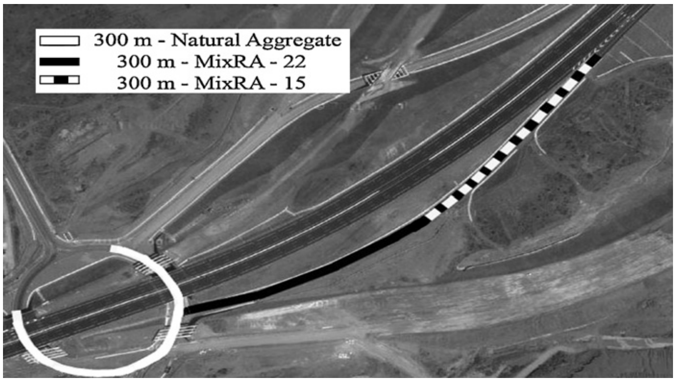

Fig. 6. General view of the test sections.

Higher strengths were observed in the specimens made with recycled materials. This may be due to various reasons, particularly the poor size distribution of the NA, its higher coefficient of flakiness, and, finally, possible pozzolanic behaviour, which could produce cementitious particles from the waste concrete that were not yet hydrated (Kou et al., 2011).

5. Experimental performance and tests

5.1. *Description of test sections*

Three test sections, each 300 m long, were built as part of an access road to a motorway in Malaga using the NA and both types of MixRA as the cement treated sub-base. This access road corresponds to a road section designed for traffic category T2, 200–799 heavy goods vehicles per day and a sub-grade category E3, modulus greater than 300 MPa (Spanish Instruction of Highway 6.1 IC Pavement Sections, 2003).

This research was conducted in the New Round West of Malaga in September 2009. The location was Connection Road C-3310 with Mediterranean motorway A-7 (Fig. 6). This road was constructed by Sacyr Company and promoted by the State Company for Land Transport Infrastructure.

The pavement structure consists of an improved sub-grade, a sub-base and two asphalt layers with a total thickness of 15 cm (Fig. 7). The improved sub-grade consists of 30 cm of cement stabilised natural soil with 2% cement (CEM II B/V-32.5 N). Above the improved sub-grade, a 20-cm-thick sub-base was applied that was made with the RA treated with 3% of the same cement. This material is known as Soil Cement SC40 (PG3:2004) in the Spanish regulations. The sub-base was compacted to a density greater than 98% of the density obtained in the Modified Proctor laboratory test.

The soil–cement mixture was prepared in a mobile continuous production plant situated 500 m from the test sections, and it was transported in 25-ton trucks. A conventional paver was used, with extrusion plates and vibrant complements for pre-compaction. The compaction was performed with a 15-ton vibratory roller and a 35-ton pneumatic tyre roller until the appropriate density was achieved. It was applied the same compaction procedure in conventional and recycled layers.

To control cracking in the layer of cement treated material has been used a pre-cracking equipment (Fig. 8), in order to avoid reflective cracking in the overlying asphalt layers. The pre-cracking procedure is to open a furrow in the layer of cement treated material at the end of compaction. This furrow was performed applying a cutting element, which carries on its rear injector cationic bitumen emulsion. In this way, a film is formed by coagulation, which prevents the setting of cement treated material on either side of the crack that has formed. The injected product has a dual mission:

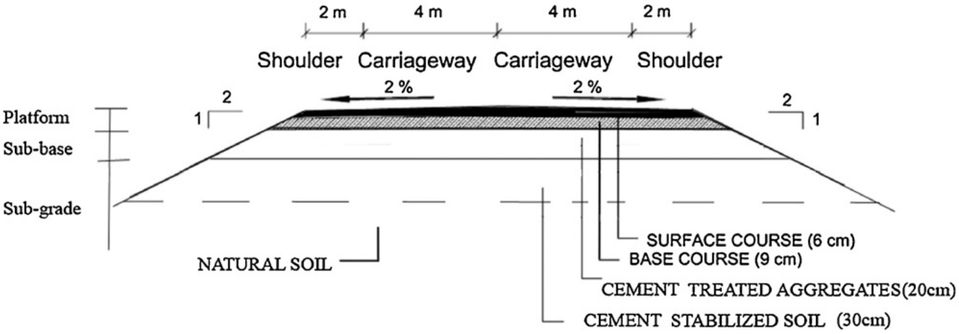

Fig. 7. Cross section of the road.

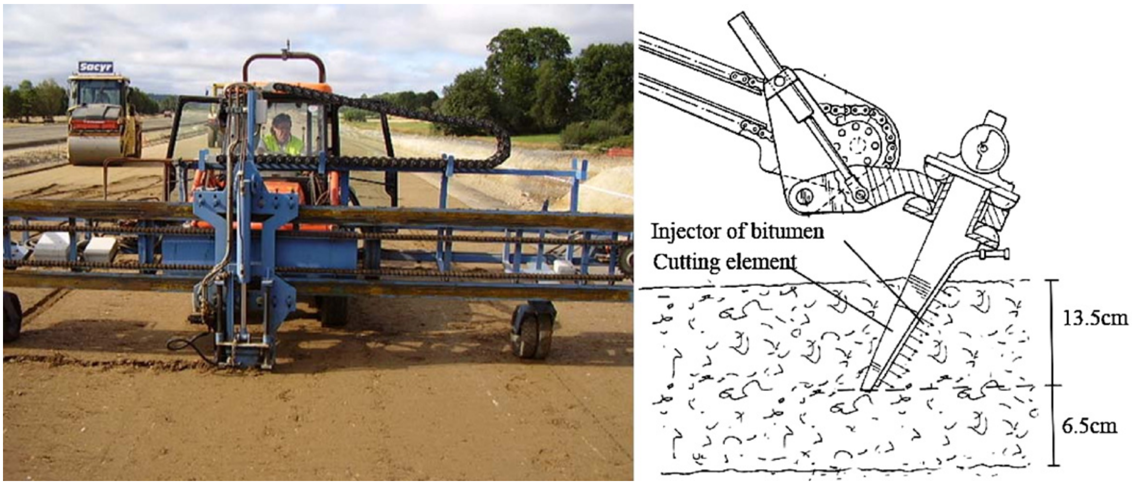

Fig. 8. Pre-cracking equipment.

creates an area of weakest resistance, favorable for the formation of shrinkage cracks, and its discontinuity allows accurate pre-location of the crack. This equipment is patented as utility model ES-2-034-713. These transverse cracks were created every 4 m, and the depth of the furrow was 135 mm.

5.2. Experimental test on real application

A group of experiments was performed on each of the three test sections to control the quality of the application and the mechanical behaviour and durability of the materials applied. Table 6 provides an overview of the experiments. The day of construction of the cement-treated sub-base is referred to as day 0.

Table 6
Overview of experiments using sections of road.

	Standard	Age (days)
Density and humidity “in situ”	ASTM D2922	0
Compressive strength. Evaluation by specimens manufactured in the laboratory	NLT-305/90	3, 7, 28, 90
Compressive strength. Evaluation by testing of cores	EN 13791:2007	28
Deflectometer impact – applied on surface of sub-grade	ASTM D4695-03	−1
Deflectometer impact – applied on surface of sub-base		28
International Roughness Index (IRI) – pavement surface	NLT-330/98	540

5.2.1. Field density and moisture content

The field density and moisture content were determined with nuclear density equipment, model Troxler 3440, according to ASTM D2922. Twenty-five measurements of density and moisture content were taken in each of the three test sections.

The results for each test section are included in Table 7. The average dry density, moisture content and degree of compaction were 2.2 g/cm^3, 6.39%, and 100.4% in the NA, 1.95 g/cm^3, 10.4%, and 98.0% in MixRA-15, and 1.95 g/cm^3, 12.4%, and 99.5% in MixRA-22. In the test section with MixRA-15, a lower degree of compaction was achieved because it was compacted with a moisture content lower than the optimal value.

The standard deviation (SD) of each variable was also calculated. The highest values of SD were observed for MixRA-22. Meanwhile, MixRA-15 and the NA had the lowest values of this statistical function, which indicates that they were applied more evenly.

5.2.2. Compressive strength

Two methods were used on-site to determine the compressive strength of the materials. With the first method, samples were taken immediately prior to compaction when the truck arrived with the material prepared for the sub-base. The material was collected in bags and transported to the laboratory, where specimens were fabricated by achieving the adequate degree of compaction with a vibrating hammer to test compressive strength. The NLT-305/90 standard was applied, and the compressive strength and dry density of each material were determined after 3, 7, 28 and 90 days of curing (Fig. 9).

With the second method, 6 cores were drilled after 28 days, beginning at the moment when the sub-base layer of the road was

Table 7
In situ assessments of density and humidity.

	NA			MixRA-15			MixRA-22		
	Density (kg $10^3/m^3$)	Moisture (%)	Compaction (%)	Density (kg $10^3/m^3$)	Moisture (%)	Compaction (%)	Density (kg $10^3/m^3$)	Moisture (%)	Compaction (%)
1	2.21	6.45	100.0	1.92	10.1	96.7	1.95	14	99.2
2	2.23	6.35	100.9	1.99	10.4	99.7	1.94	13.5	98.7
3	2.23	6.05	100.9	1.93	10	96.9	1.95	12.6	99.2
4	2.20	6.75	99.5	1.98	10.8	99.5	1.93	12.7	98.2
5	2.23	6.35	100.9	1.99	10.7	99.7	1.94	11.2	98.7
6	2.21	6.55	100.0	1.93	10.2	96.9	2.00	10.8	101.7
7	2.23	6.15	100.9	1.99	10.6	100.0	1.97	10.5	100.2
8	2.21	6.65	100.0	1.94	10.1	97.5	1.92	12.5	97.7
9	2.20	6.85	99.5	1.92	10.7	96.5	1.94	11.0	98.7
10	2.21	6.55	100.0	1.97	10.9	99.0	1.95	11.9	99.2
11	2.23	6.25	100.9	1.98	11.2	99.5	1.94	12.4	98.7
12	2.24	5.95	101.3	1.92	10.7	96.5	1.93	14.0	98.2
13	2.21	6.45	100.0	1.99	10.4	99.7	1.94	13.2	98.7
14	2.23	6.35	100.9	1.93	10.3	97.0	1.95	11.8	99.2
15	2.21	6.55	100.0	1.95	10.5	98.0	1.94	12.3	98.7
16	2.23	6.25	100.9	1.93	10.3	97.0	1.95	12.4	99.2
17	2.23	6.15	100.9	1.92	10.2	96.5	1.97	12.6	100.2
18	2.21	6.65	100.0	1.94	10.4	97.5	1.94	12.2	98.7
19	2.23	6.05	100.9	1.98	10.1	99.5	1.96	11.4	99.7
20	2.20	6.75	99.5	1.93	10.9	97.0	1.93	12.5	98.2
21	2.21	6.45	100.0	1.98	11.0	99.5	1.94	13.4	98.7
22	2.23	6.35	100.9	1.93	10.2	97.0	1.91	13.5	97.2
23	2.23	6.05	100.9	1.93	10.3	97.0	1.95	11.6	99.2
24	2.21	6.45	100.0	1.94	10.4	97.5	1.94	13.2	98.7
25	2.23	6.35	100.9	1.95	10.0	98.0	1.96	12.8	99.7
Mean	2.22	6.39	100.4	1.95	10.4	98.0	1.95	12.4	99.5
SD	0.012	0.24	0.55	0.025	0.32	0.01	0.017	0.94	0.89

Table 8
Average density and compressive strength of the test sections.

	Ages (days)	NA		MixRA-15		MixRA-22	
		Density (kg $10^3/m^3$)	Compressive strength (N/mm^2)	Density (kg $10^3/m^3$)	Compressive strength (N/mm^2)	Density (kg $10^3/m^3$)	Compressive strength (N/mm^2)
Specimens compacted in laboratory	3	2.18	1.39	1.93	2.52	1.91	3.18
	7	2.23	2.73	2.05	3.17	1.93	3.41
	28	2.20	3.37	1.93	3.88	1.87	3.99
	90	2.21	4.07	1.98	4.28	1.90	5.05
Cores in situ	28	2.24	4.17	2.04	4.51	2.05	4.25

constructed, according to EN 13791:2007. The average compressive strength values are included in Table 8, and Fig. 9 shows the evolution of the compressive strength of each material with time.

The cores have a somewhat higher compressive strength than the specimens compacted in the laboratory, due to higher dry density values in the real application (Table 8). Therefore, it can be concluded that the application of the cement-treated MixRA materials was adequate and that their mechanical behaviour was satisfactory.

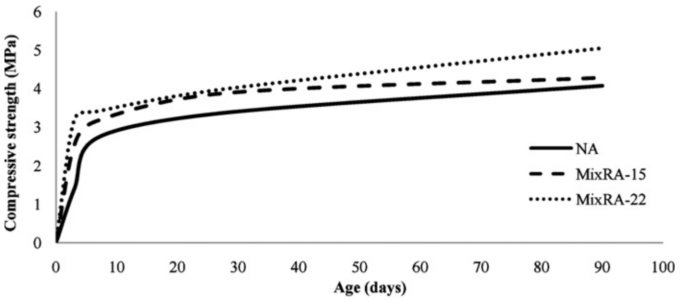

Fig. 9. Compressive strength evolution.

The compressive strength of mixed aggregates treated with cement must be greater than 2.5 MPa, which is the minimum and necessary value to be able to use these materials in roads in Spain. MixRA-22 treated with cement has a somewhat greater strength (3.41 MPa) than cement-treated MixRA-15 (3.17 MPa). These compressive strength results can be considered satisfactory, and they are in accordance with results obtained by Xuan et al. (2012) in their studies of cement-treated recycled aggregates.

The lower density observed for MixRA does not greatly affect the mechanical behaviour of materials treated with cement because the compressive strength achieved was appropriate, as seen in other studies (Xuan et al., 2010).

5.2.3. *Deflections of the sub-base layer*

The determination of the deflections was conducted with an impact deflectometer according to NLT-338/07. The purpose of this test was to determine the vertical deformation under a load of 67.0 kN, which was applied through a circular disk 450 mm in diameter. Impact deflectometer measurements were performed both on cement-stabilised (improved) sub-grade soil and on the cement-treated sub-base with the studied materials at 28 days after their construction.

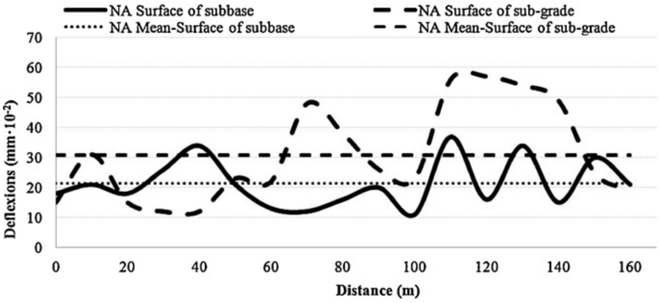

Fig. 10. Deflections of sub-grade surface and sub-base. Test section with NA.

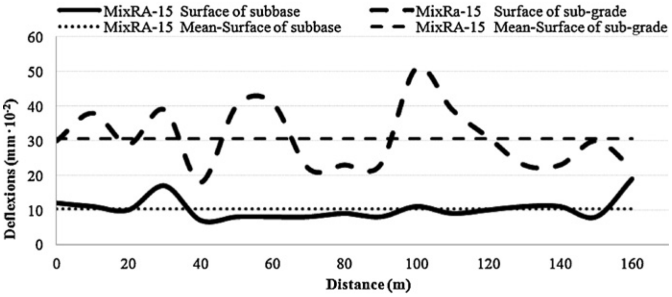

Fig. 11. Deflections sub-grade surface and sub-base. Test section with MixRA-15.

Table 9
Deflections on cement-treated MixRA sub-base and cement stabilised sub-grade soil.

	NA	MixRA-15	MixRA-22
Mean deflection on cement stabilised soil (mm 10^{-2})	30.9	30.7	29
Mean deflection on cement treated layer (mm 10^{-2})	21.8	10.4	9.5
Mean reduction of deflection (%)	29.4	66.1	69.0
SD – cement stabilised soil (mm 10^{-2})	15.6	8.9	5.1
SD – subbase (mm 10^{-2})	7.8	3.12	1.4
Improving the uniformity – ΔU (%)	50	64.9	72.5
Equivalent modulus cement stabilised soil (MPa)	557.9	574.9	608.6
Equivalent modulus cement treated layer (MPa)	865.8	1748.3	1914.0

Seventeen measurements were taken on each of the two layers in the three test sections. The spacing between the measurements was 10 m, and the measurements were taken over a total distance of approximately 160 m to avoid using measurements at the beginning and end of each test section. Figs. 10–12 show the deflections in each test section of the cement-stabilised natural sub-grade soil and of the cement-treated MixRA sub-base layer.

As Table 9 shows, the mean deflection of the cement-stabilised sub-grade soil in the three test sections is very similar: 0.309 mm in section NA, 0.307 mm in section MixRA-15 and 0.290 mm in section MixRA-22. The uniformity is higher in test section MixRA-22 because it has a lower standard deviation (SD). The stabilised soil in section NA has a SD equal to 15.6, well above that for MixRA-22 SD of 5.1, and almost twice that of MixRA-15 SD of 8.9. This indicates that the cement-stabilised sub-grade soil layers of MixRA were more homogeneous.

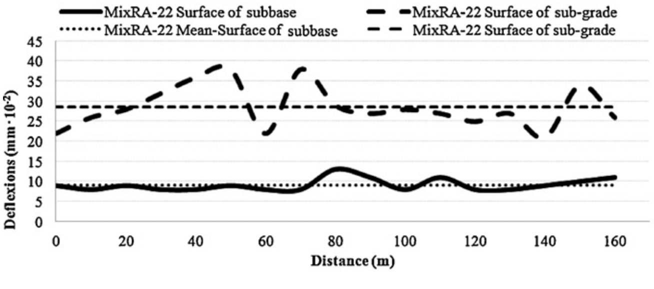

Fig. 12. Deflections of sub-grade surface and sub-base. Test section with MixRA-22.

Equivalent modulus was calculated according to proposal function by Brown (1996):

$$E_{\upsilon} = \frac{2pa(1-\upsilon^2)}{d}$$

where p is the contact pressure bellow the plate (0.421 MPa), a is the plate radius (225 mm), υ is Poisson's ratio (0.30 in cement stabilised soil, and 0.25 in cement treated sub-base), and d is the measured plate deflection in mm. The results of equivalent modulus were included in Table 9

The sub-base layer should improve the resistance to deformation by impact force compared with the resistance of the underlying sub-grade layer. The mean deflection of the cement-treated MixRA sub-base is also similar for both test sections, with a deflection of 0.104 mm in section MixRA-15 and 0.095 mm in section MixRA-22. In contrast, the section with the NA has a mean deflection equal to 0.21 mm on its surface, indicating that this material did not perform as well in its resistance to deformation on impact.

To evaluate the improvement of the SD in the two layers of solid ground, an index (ΔU) was calculated expressing the improvement in the SD associated with the cement-treated MixRA sub-base and the cement-stabilised sub-grade soil. The construction of the sub-base improved the uniformity from 65% to 70%.

5.2.4. *International Roughness Index (IRI)*

Eighteen months after construction of the test sections, NLT-330/98 was applied and the "International Roughness Index" (IRI) was measured. This test was performed on the completed asphalted pavement.

A system consisting of laser sensors and computerised readings was used for the measurements. This system was assembled on a vehicle equipped with an accelerometer on each line of the rear wheels to measure the movements of the vehicle and two laser sensors located at the front to measure the displacements. A computer stored all of the information and calculated the longitudinal profile of the pavement surface. The data were taken every 25 mm of displacement throughout the 300 m of each test section. The IRI measurements were measured three times.

To determine the IRI, a mathematical model proposed by the NLT 330-98 (according to ASTM E867-06) was used, which simulates the suspension and mass of a vehicle travelling along a stretch of highway at a speed of 50 km/h. This model is known as a QCS (quarter car simulation) because it represents one-quarter of a four-wheeled vehicle.

Although the IRI is a dimensionless unit, it is usually expressed in m/km to facilitate its calculation.

Spanish legislation requires that the IRI index of a section of highway be lower than 1.5 m/km for solid subsoil. When values obtained are below this value, a comfortable ride will be experienced at speeds up to 140 km/h.

Table 10 includes the IRI results from each 100-m sub-section. Lower values for the IRI were obtained in the test section where MixRA-22 was used, with a mean IRI value equal to 0.54 m/km. The test section with MixRA-15 had a mean IRI value equal to 0.88 m/km, and the test section with the NA had a mean value equal to 1.00 m/km. Thus, both test sections comply with the Spanish regulations (PG3:2004).

The SD shows that increased dispersion of the results occurred in the section where MixRA-15 was used, with a value of 0.41. In

Table 10
IRI measurements.

	NA			MixRA-15			MixRA-22		
	Laser 1	Laser 2	Mean	Laser 1	Laser 2	Mean	Laser 1	Laser 2	Mean
1st pass									
100	1.39	1.60	1.49	0.40	0.22	0.31	0.93	0.48	0.71
200	0.67	1.38	1.02	1.41	1.00	1.21	0.39	0.30	0.34
300	0.91	0.99	0.95	0.93	0.56	0.75	0.40	0.19	0.29
2nd pass									
100	1.54	1.33	1.43	0.31	0.40	0.36	0.68	0.81	0.75
200	0.81	0.75	0.78	1.12	1.33	1.23	0.15	0.53	0.34
300	0.66	0.82	0.74	1.12	1.00	1.06	0.37	0.40	0.38
3rd pass									
100	1.08	0.78	0.93	0.64	0.30	0.47	1.21	1.11	1.16
200	0.90	0.68	0.79	1.42	1.16	1.29	0.51	0.16	0.33
300	0.89	0.90	0.89	1.21	1.30	1.26	0.72	0.35	0.54
Mean (m/km)	0.98	1.02	1.00	0.95	0.81	0.88	0.60	0.48	0.54
SD	0.29	0.31	0.30	0.39	0.42	0.41	0.31	0.29	0.30

contrast, the results from the sections with MixRA-22 and the NA present a dispersion of 0.30.

MixRA-22 presented the highest dispersion with regards to compaction. This result may be compatible with the compaction results, because the solid ground is made up of three layers, including the foundation of the road.

As can be seen in Table 10, all of the mean values remained below 1.5 m/km. The lower IRI values occurred in the section where MixRA-22 was used. The beginning of the sections constructed with MixRA-22 and the NA showed higher values, resulting in a decrease of the IRI values in the second and third sections.

It can be concluded that the cement-treated MixRA-15 and MixRA-22 sub-base layers exhibit acceptable behaviour because highly satisfactory roughness values were obtained at 18 months after construction.

6. Conclusions

This paper presents the results of an investigation into the use of mixed recycled cement-treated aggregates to build the sub-base and base layers of roads. Prior to the performance evaluation, the aggregate properties were first evaluated. Regarding the materials themselves, the following differences were found between the natural aggregate and the mixed recycled aggregate:

- Natural aggregates have a higher density than mixed recycled aggregates and lower water absorption than recycled aggregates.
- The acid-soluble sulphate content in mixed recycled aggregates must be controlled, and it must be lower than 0.8% (expressed in SO_3) to use these materials in cement-treated pavement layers.
- The mixed recycled aggregates have lower resistance to fragmentation than natural aggregates, but this is not particularly important for soil–cement manufacture.
- The investigated mixed recycled aggregates have an adequate particle size distribution for use in cement-treated pavement layers.
- The particles of the mixed recycled aggregates have an appropriate form coefficient, as measured by the flakiness index.
- The content of ceramic particles (masonry) in the mixed recycled aggregates does not preclude its use as soil–cement.

The following conclusions can be made for cement-treated recycled aggregates used in road sub-bases:

- Mixed recycled aggregates have a low optimal density in the Modified Proctor test because of the increasing percentage of masonry particles.
- Compared with natural aggregates, a greater amount of water is necessary to enable optimal compaction of cement-treated mixed recycled aggregates in road sub-bases.
- Also compared with natural aggregates, cement-treated mixed recycled aggregates have a lower workability time, and thus it may be useful to apply a setting retardant additive.
- Cement-treated mixed recycled aggregates exhibit good mechanical performance in terms of adequate compressive strength, low deflections under impact load and appropriate roughness values.

The results of the roughness test indicate that mixed recycled aggregates show an adequate durability with values below the 1.5 m/km limit specified by PG-3.

Therefore, it can be concluded that it is possible to use cement-treated recycled aggregates in the construction of sub-base layers of roads, even if they contain a proportion of masonry, suitable processing is performed and the quality of the application is strictly controlled. Consequently, from an environmental and an economic point of view, the mixed recycled aggregates are a good alternative to natural materials.

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Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes

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ABSTRACT

In some recycled aggregates applications, such as component of new concrete or roads, the total content of soluble sulphates should be measured and controlled. Restrictions are usually motivated by the resistance or stability of the new structure, and in most cases, structural concerns can be remedied by the use of techniques such as sulphur-resistant cements. However, environmental risk assessment from recycling and reuse construction products is often forgotten. The purpose of this study is to analyse the content of soluble sulphate on eleven recycled aggregates and six samples prepared in laboratory by the addition of different gypsum percentages. As points of reference, two natural aggregates were tested. An analysis of the content of the leachable amount of heavy metals regulated by European regulation was included. As a result, the correlation between solubility and leachability data allow suggest a limiting gypsum amount of 4.4% on recycled aggregates. This limit satisfies EU Landfill Directive criteria, which is currently used as reference by public Spanish Government for recycled aggregates in construction works.

1. Introduction

Construction in Mediterranean countries commonly utilises large amounts of ceramic material. Naturally, this material also ends up in construction and demolition waste (CDW) (de Brito et al., 2005). The products obtained from these CDW recycling are classified as mixed recycled aggregates (MRA), which contain crushed concrete originating from natural aggregates (NA), ceramic material and a small quantity of bituminous particles.

These recycled aggregates (RA) have lower densities and higher water absorption levels than NA (Evangelista and de Brito, 2007; González-Fonteboa and Martínez-Abella, 2008). However, it should be noted that they exhibit adequate bearing capacities (Park, 2003), in spite of achieving a lower dry density in the modified Proctor test (Molenaar and Van Niekerk, 2002). Recent studies have reported that in the Los Angeles abrasion test all of the attached mortar of recycled concrete aggregates is powdered, apart from the abrasion suffered by the NA. Thus, when the attached mortar amount is high, the Los Angeles coefficient increases (Sánchez and Alaejos, 2009). In addition, high variation in properties due to different origins and the different processing systems in the treatment plants (Hendricks and Jansen, 2003) require that their use in construction is carefully designed (Tam and Tam, 2007).

The soluble sulphate content is often a limiting factor in using RA in civil engineering because it may lead to dimensional instability of the section and loss of strength in concretes (Vegas et al. 2008, 2011). Sulphates are known to react with cement components in the presence of moisture causing expansive reactions (Martin-Morales et al., 2011). For this reason, sulphate-resistant cement should be seriously considered in situations where gypsum contamination is suspected. Consequently, the Permanent Commission of Concrete (CPH, 2008) limits the acid-soluble sulphate percentage to 0.8%. However, the focus of the present work is to analyse the sulphate levels according to environmental aspects, not according to structural resistance or stability. The source of the sulphates in RA is predominantly gypsum drywall ($CaSO_4 \cdot 2H_2O$), a very common component of MRA (Jang and Townsend, 2001). Moreover, cement based materials also contain gypsum as setting regulator.

RA from CDW are composed mostly of inert compounds but also contain hazardous materials such as metals and chemical components that can contaminate the environment. When these materials are used in road construction, rainwater, surface water or groundwater may come into contact with them and leach hazardous elements, representing a potential threat to the environment (Van der Sloot et al., 2006; Michelis et al., 2009). Therefore, the content of harmful compounds in RA must be low and the leaching behaviour of these elements should be acceptable for materials used in construction and engineering both during their service life and in subsequent recycling (Wahlström et al., 2000; Roussat et al., 2008).

The environmental impact caused by these materials is not determined by the total amount of pollutants, but by the amount that water can dissolve into the soil reaching the surface and/or underground water. Thus, the potential environmental risk

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depends on the availability of the contaminants for leaching (Kosson and Van der Sloot, 1997; Dijkstra et al., 2002). European authorities require that the environmental risk caused by the recycling of CDW is kept as low as possible. In Program DGXII EC, Program DGXII EC, Van der Sloot et al. (2001) identified CDW as being one of six priority waste streams and the measurement and management of CDW in EU member states was described. Therefore, for civil applications where the material is placed in direct contact with the environment (e.g., outside the landfill) concerns have been raised by regulators regarding the chemical characteristics of the material and the potential environmental risk. To this end, the chemical composition of the RA must be adequately characterised (Jang and Townsend, 2001).

When high gypsum amount is present in the RA, sulphate may leach, resulting in elevated concentrations. Under anaerobic conditions, the sulphate ion SO_4 is reduced to the sulphide ion, which establishes equilibrium with hydrogen ions to form three different sulphide species. Hydrogen sulphide (H_2S) is a weak acid which dissociates to hydrogen bisulphide (a soluble gas that may volatilise from the aqueous solution into the gas phase). Concentrations of a few tenths of a milligram per litre in the aqueous phase cause noticeably objectionable odours and tastes (Pomeroy and Cruse, 1969). Gypsum has a solubility of approximately 2400 mg/L at 25 °C in pure water (Dean, 1973). At equilibrium, this would result in a sulphate concentration of 1170 mg/L (Jang and Townsend, 2001).

In particular, the presence of sulphates in drinking water would have cathartic effect in humans when it is present in excessive amounts (Sawyer et al., 1994). For this reason, many European member states have defined the Ecotox thresholds (ET). An ET establishes the concentration above which there is a sufficient concern regarding adverse ecological effects. This parameter is useful to determine whether a contaminant is present in drinking water in concentrations that may be harmful to any ecological receptor.

Nowadays, limitations on the application of these recycled aggregates are mainly mechanical, but as seen above, the main misgiving in this sector is its potential environmental contamination. With all this in mind, the present study is focused onto relate both concepts, through the relationship between soluble sulphate levels (mechanical matter) of these aggregates and leached sulphates (pollution capacity by EN 124537-3).

For this, thirteen aggregates came from different CDW processing plants distributed across Andalusia (Spain) were studied. In addition, six materials were prepared artificially in the laboratory by adding different percentages of gypsum to a RA.

The solubility and leachability data were correlated with each other allowing the identification of the compounds (EN 933-11) which directly affect to the sulphate levels on the RA. Thus, in order to provide to managers of CDW plants an easy estimation of the pollutant potential of their products according to the composition, the maximum percentage of restrictive constituents such as gypsum and ceramic particles, were determined.

The study also approaches the classification of all the tested materials depending on their potential pollutant release. Due to the nonexistence in Spain of specific legislation about environmental assessment of this sort of residues, currently the threshold values of the EU Landfill Directive are used as reference by the Spanish producers. For that reason, the present study includes the leached concentrations of heavy metals listed by the EU Landfill Directive and the material classification according to this regulation.

2. Materials

Nineteen materials were studied: two natural aggregates N1 and N2 (come from two limestone quarries); two recycled aggregates from crushed concrete (C1 and C2); two aggregates from materials with high bituminous particle percentage (A1 and A2) and six materials with varying ceramic particle content (M1, M2, M3, M4, M5 and M6). In addition, one "pure" material (B) was studied (composed of 100% crushed brick from ceramic industry debris). Prior to the completion of laboratory tests, a sample of 500 kg was collected for each material in accordance with Standard UNE-EN 932-1. They were homogenised and reduced in the laboratory using the quartering method UNE-EN 932-2. Besides the previously described materials collected from treatment plants, six materials (Xi samples) were produced in the laboratory in order to observe the effect of gypsum content on potential contamination. These were prepared by adding different percentages of gypsum type C6 (EN 13279-1) previously hydrated and crushed to the reference material C1 (Table 1). The test for classification of materials according to their composition was carried out by the standard UNE EN 933-11 and the output data are shown in Table 2.

3. Experimental methods for the assessment of contaminant potential

In the following, the potential for pollution due to the dissolution of sulphates from construction products will be discussed taking into account the previous analysis of the solubility of sulphate ions. All tests were performed with the crushed material passed through a 0.125 mm sieve and dried in an oven to a constant mass. All tests were performed with magnetic stirring except for the leaching test, which was conducted with agitation by end over end rotation system.

3.1. Solubility tests: water-soluble sulphates (UNE 103201) and acid-soluble sulphates (EN 1744-1)

To analyse the solubility of sulphates in water, the standard UNE 103201 was performed. It consists of a quantitative analysis by which sulphates are dissolved in an aqueous solution. The solution is shaken and the sulphates are dissolved with a barium chloride solution. For the measurement of acid-soluble sulphates by the EN 1744-1 method, they are extracted by a similar procedure but with a diluted hydrochloric acid solution.

Both methods to measure the solubility are determined gravimetrically and the sulphate content is expressed as percentage of sulphur trioxide by mass of the aggregate (% SO_3).

3.2. Leaching test: compliance batch test EN 12457-3

Once the solubility of the sulphate ion had been analysed, the leaching behaviour was studied, as it is described below. Leaching tests provide the contaminant level of an element that may be released due to the long term effects of natural water (rain, groundwater, rivers, etc.). Batch tests consist of contacting a subsample of material with a liquid phase, in order to establish pseudo-equilibrium conditions. Once equilibrium has been reached, the release of elements is dependent on the geochemistry of the solid phase and chemistry of the liquid phase rather than on the contact time (Van der Sloot et al., 2002; Lopez Meza et al., 2008). Equilibrium-based leaching tests have been discussed extensively elsewhere (Garrabrants et al., 2004; Kim, 2003).

The procedure EN 12457-3 consist of a two-step batch leaching test that uses a solution of 175 g of dry sample of the material, two liquid/solid ratios (an L/S of 2 and an L/S of 10) and deionised water as a leaching fluid. This method involves stirring the solution in two steps. In the first step, the solution is shaken for 6 ± 0.5 h with an L/S of 2, and the second step uses the same fraction with stirring of the solution for an additional 18 ± 0.5 h, after having added

Table 1
Composition of recycled aggregates Xi prepared in laboratory by addition of hydrated gypsum.

Designation	Percentage of gypsum added (% G)	Percentage of concrete recycled aggregate (% C1)
X1	10	90
X2	7.5	92.5
X3	5	95
X4	3	97
X5	2.5	97.5
X6	1	99

Table 3
Soluble sulphates of aggregates.

	Water-soluble sulphates (% SO_3)	Acid-soluble sulphates (% SO_3)		Water-soluble sulphates (% SO_3)	Acid-soluble sulphates (% SO_3)
N1	0.03	0.08	M5	1.13	1.37
N2	0.03	0.05	M6	1.18	1.65
C1	0.15	0.31	B	0.93	1.70
C2	0.06	0.44	X1	3.04	4.61
A1	0.07	0.19	X2	2.34	3.35
A2	0.08	0.14	X3	2.07	2.35
M1	1.56	2.60	X4	1.52	1.78
M2	0.62	0.65	X5	1.09	1.28
M3	0.54	1.32	X6	0.66	0.77
M4	0.33	0.67	–	–	–

water to obtain an L/S ratio of 10. In both stages, the samples were left to decant, and the pH, conductivity and temperature were measured. The solution was filtered using a membrane filter (0.45 μm), and a subsample of the leachate was taken for each material. The test is performed at natural pH. Elemental concentrations were determined in the laboratory using inductively coupled plasma mass spectrometry (ICP-MS) and the sulphate ion concentration was measured by the standard EN-ISO 10304. The analysis of the leaching behaviour of the tested materials is focused on the measurement of the elements regulated by the EU Landfill Directive: ten heavy metals (As, Pb, Cd. Cr, Cu, Hg, Ni, Zn, Ca, Mg, Se and Sb) and sulphate ion. According to that European document (Table 4), a CDW can be classified as an inert, non-hazardous or hazardous material.

4. Analysis of results

This section includes correlations between different properties, such as the solubility of sulphates and the percentage of gypsum and the solubility of sulphates and the leaching of sulphates, in order to establish the relationships between them.

4.1. Soluble sulphates

The results in Table 3 show that the soluble sulphates (UNE 103201 and UNE 1744-1) of the B material (100% composed by crushed clay brick) was much higher than the content of the mixed aggregates with a low amount of gypsum (M2 and M4) and also higher than the amount detected on the concrete and asphaltic recycled aggregates (C1, C2, A1 and A2). It proves the effect of ceramic particles on soluble sulphate, consistent with the results of Poon and Chan (2006). In addition, the effect of high gypsum particle amount on the mixed recycled aggregates was clearly observed (e.g., data of M1, M3 and M5 in Table 3). Thus, the samples with a percentage of gypsum higher than 2% or ceramic particles higher than 30% showed sulphates solubility of at least 0.90% SO_3 water-soluble sulphate (UNE 103201) and 1.3% SO_3 acid-soluble sulphate (UNE 1744-1).

4.2. Analysis of leaching results

According to the data obtained by the compliance test (Table 5), the concentration on leachates of the elements Hg, Pb and Cd were negligible and inferior to the detection limit (20 ppb). For this reason, they are not included in Table 5. In addition, the artificially manufactured aggregates (Xi samples) released the same levels of Sb and Zn as the material without the addition of gypsum. Thus, it can be affirmed that gypsum is not providing these elements to the leachate. From the leaching results it is observed that the highest amounts of sulphates (equal to or greater than 1% of SO_3) were detected in the recycled aggregates with the highest amounts of ceramic particles: M5 and M6 (both samples with a percentage of ceramic particles higher than 50%) and as expected in the B material (100% ceramic particles). Otherwise, high amounts of sulphates were observed in the Xi samples prepared in the laboratory with a high percentage of gypsum particles (X1, X2, X3 and X4). Specifically, this behaviour was observed for gypsum amount higher than 3%. According to this reasoning, the M1 material showed 1.63% SO_3 because it was the recycled material with the highest portion of gypsum.

Table 2
Composition of tested aggregates according to the percentage (%) of different compounds.

	Concrete and mortar	Natural aggregate	Ceramic particles	Gypsum	Bituminous	Others
N1	0	100	0	0	0	0
N2	0	100	0	0	0	0
C1	85.63	13.64	0.16	0.02	0.54	0.01
C2	68.97	28.01	2.99	0	0	0.03
A1	37.01	5.46	1.11	0	56.42	0
A2	2.61	51.37	3.94	0	42.08	0
M1	59.67	18.75	12.67	2.13	6.78	0
M2	37.64	41.49	20.81	0	0	0.06
M3	60.08	8.14	29.67	1.03	1.06	0.02
M4	38.06	17.68	44.16	0.09	0.01	0
M5	32.67	10.83	50.65	1.32	3.91	0.62
M6	25.69	16.54	56.12	0.33	1.28	0.04
B	0	0	100	0	0	0
X1	77.06	12.28	0.14	10.02	0.49	0.01
X2	79.21	12.61	0.15	7.52	0.50	0.01
X3	81.35	12.96	0.15	5.02	0.51	0.01
X4	83.06	13.23	0.16	3.02	0.52	0.01
X5	83.48	13.30	0.16	2.52	0.53	0.01
X6	84.77	13.50	0.16	1.02	0.54	0.01

Table 4
Acceptance criteria (EU Landfill Directive) for L/S = 10 L/kg.

	Leached maximum concentrations (mg/kg) depending on landfill class		
	Inert	Non-hazardous	Hazardous
Cr total	0.5	10	70
Ni	0.4	10	40
Cu	2	50	100
Zn	4	50	200
As	0.5	2	25
Se	0.1	0.5	7
Mo	0.5	10	30
Cd	0.04	1	5
Sb	0.06	0.7	5
Ba	20	100	300
Hg	0.01	0.2	2
Pb	0.5	10	50
Sulphate (mg/L)	100	2000	5000

Table 6
Classification of RA according to the acceptance criteria (EU Landfill Directive).

Classification according to concentration on heavy metals		Classification according to concentration on sulphates	
Material	Classification	Material	Classification
N1	Inert	N1	Inert
N2	Inert	N2	Inert
C1	Inert	C1	Inert
C2	Inert	C2	Inert
A1	Inert	A1	Non-hazardous
A2	Inert	A2	Non-hazardous
M1	Inert	M1	Non-hazardous
M2	Non-hazardous	M2	Non-hazardous
M3	Non-hazardous	M3	Non-hazardous
M4	Non-hazardous	M4	Non-hazardous
M5	Inert	M5	Non-hazardous
M6	Inert	M6	Non-hazardous
B	Non-hazardous	B	Non-hazardous
X1	Non-hazardous	X1	Non-hazardous
X2	Non-hazardous	X2	Non-hazardous
X3	Non-hazardous	X3	Non-hazardous
X4	Non-hazardous	X4	Non-hazardous
X5	Non-hazardous	X5	Non-hazardous
X6	Non-hazardous	X6	Non-hazardous

Given that the results from testing the leaching of sulphate ions corroborates the solubility results, it may be affirmed that the gypsum content and the percentage of ceramic particles are directly related to the sulphate level in RA and that the amount of these compounds must be controlled.

In order to evaluate the pollutant potential according to the European regulation, the concentrations of the leachates from the nineteen tested materials were compared with the legal limits indicated by EU Landfill Directive (Table 4). Thus, Table 6 shows the classification of recycled materials by two schemes: firstly, comparing the legal levels only to the concentrations of heavy metals; and secondly, comparing the sulphate concentrations. In this way, it was observed that all the materials tested were classified as non-hazardous with exception of the natural aggregates (N1 and N2) and the recycled aggregates from crushed concrete (C1 and C2), which were designated as inert materials.

4.3. The relationship between the percentages of acid-soluble sulphates and water-soluble sulphates

Regarding the solubility tests, a strong correlation between the concentrations of the two types of sulphates was obtained with an R2 coefficient of 0.953 (Fig. 1). According to this trend, the concentration of water-soluble sulphates (UNE 103201) grows by 73% in relation to the concentration of acid-soluble sulphates (EN 1744-1). Despite the different behaviours of the tested materials, it can be affirmed that acid-soluble sulphates were higher than that of water-soluble sulphates in all cases. This result is supported by previous reports (Baedecker et al., 1992; Kucera and Fitz, 1995), which affirm that exposure to high acidity conditions for long times may damage concrete structures.

The resulting trend represented in Fig. 1 shows the regression line passing roughly through the origin. This suggests that if a material does not contain water-soluble sulphates, the material will not contain acid-soluble sulphates either, as expected.

4.4. The relationship between the percentages of gypsum and the water-soluble and acid-soluble sulphates

The relationship between the percentage of gypsum in the materials and the water-soluble and acid-soluble sulphates expressed in% SO_3 showed correlation coefficients (R^2) equal to 0.862 and 0.838, respectively (Fig. 2). In both cases, the concentration of

Table 5
Concentrations of metals and sulphate on leachate at L/S = 10 L/kg.

	Metals (mg/kg)									Sulphate	
	Cr	Ni	Cu	Zn	As	Se	Mo	Sb	Ba	SO_4 (mg/L)	SO_3 (%)
N1	n.d.	0.004	0.012	0.058	0.035	0.003	0.022	0.007	1.411	32	0.03
N2	0.014	0.013	0.001	0.003	0.006	n.d.	0.014	0.002	0.021	41	0.04
C1	0.286	0.028	0.147	n.d.	0.002	0.033	0.228	n.d.	2.395	46.5	0.04
C2	0.048	0.007	0.045	0.010	0.001	0.002	0.027	0.023	0.219	92	0.09
A1	0.005	0.039	n.d.	n.d.	0.135	0.040	n.d.	0.023	n.d.	128	0.12
A2	0.273	0.001	0.136	n.d.	0.013	0.016	0.094	0.036	0.059	180.8	0.17
M1	0.162	0.038	0.047	0.022	0.002	0.016	0.057	0.008	0.486	1707	1.63
M2	0.706	0.027	0.106	0.010	0.002	0.007	0.082	0.011	0.437	669	0.64
M3	0.663	0.040	0.078	0.021	0.002	0.042	0.086	0.008	0.384	714	0.68
M4	1.024	0.007	n.d	n.d.	0.003	0.042	0.042	0.007	0.117	353.5	0.34
M5	0.003	0.028	0.013	n.d.	0.017	0.042	0.156	0.020	0.273	1425	1.36
M6	0.007	0.035	0.045	n.d.	0.008	0.064	0.128	0.048	0.336	1675	1.60
B	3.918	0.027	n.d.	n.d.	0.002	0.049	0.262	n.d.	0.272	1039	0.99
X1	1.021	0.136	0.233	n.d.	0.005	0.038	0.381	n.d.	2.130	1450	1.39
X2	1.041	0.145	0.223	n.d.	0.003	0.022	0.375	n.d.	2.042	1525	1.46
X3	0.957	0.142	0.228	n.d.	0.006	0.040	0.406	n.d.	2.046	1431	1.37
X4	0.730	0.108	0.177	n.d.	0.005	0.043	0.275	n.d.	2	960	0.92
X5	0.782	0.031	0.014	n.d.	0.004	0.008	0.098	n.d.	0.928	564	0.54
X6	1.418	0.042	0.064	n.d.	0.004	0.058	0.223	n.d.	1.578	141.5	0.14

Footnote: n.d. Not detectable (amount <20 ppb).

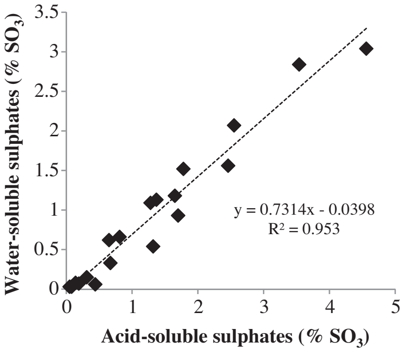

Fig. 1. Correlation between percentages of water-soluble sulphates vs. acid-soluble sulphates.

soluble sulphates increases with increasing gypsum content. However, correlations with the other parameters (concrete and mortar, ceramic particles, etc.) were not apparent. These correlations demonstrate that as calcium sulphate is dissolved in presence of water or acid, sulphate ions are transferred into solution (Jang and Townsend, 2001).

It is also significant that soluble sulphates from a material with 0% gypsum particles (EN 933-11) were not zero. It could indicate that other components as natural aggregates, mortars and ceramic particles are providing a portion of the total sulphate content. This is supported by the high level of sulphate observed from the ceramic material B and from the recycled aggregates M5 and M6. The natural aggregates N1 and N2 also exhibited soluble sulphates, though perhaps not at relevant levels, as shown in Table 3.

4.5. The relationship between the percentages of gypsum and the amount of sulphates leached

The correlation between the percentage of gypsum and the amount of sulphates leached (EN 12457-3) was not relevant ($R^2 = 0.352$ in Fig. 3). Other components contribute to the leaching of sulphates and they must be taken into account. Thus, the sulphates in leaching processes come not only from gypsum but also from other compounds of recycled aggregates such as concrete and mortar, natural aggregates and ceramic particles.

The weak correlation between the gypsum content and the amount of sulphates leached demonstrates that CDW compounds such as concrete and mortars have not been considered in the calculation. The sulphate species from concrete and mortars originate in the additions of gypsum to the clinker. The addition is made in order to retard “fast setting”. Gypsum undergoes rapid reactions with clinker minerals, forming a protective layer of calcium sulpho-aluminates (e.g., ettringite or monosulphate) on the reactive mineral phase (Conner, 1993).

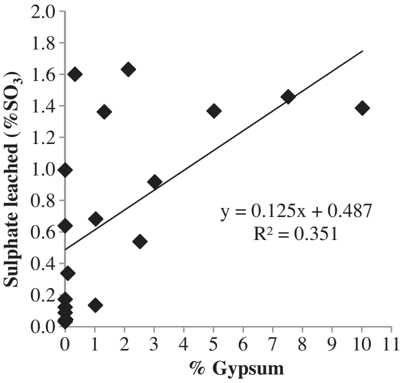

Fig. 3. Correlation between percentages of gypsum vs. sulphates leached.

Moreover, an important chemical phenomenon is limiting the dissolution of gypsum: the solubility equilibrium. When the equilibrium is established, the solution is saturated and according to the results, it occurs for gypsum additions higher than 3%. It is observed in Table 5 for the following materials: X3 (5% gypsum and 1431 mg/L SO_4); X4 (7.5% gypsum and 1525 mg/L SO_4) and X5 (10% gypsum and 1450 mg/L SO_4). The despicable differences proves that after the solubility equilibrium, chemical factors dictates the leaching not the sulphate content.

4.6. The relationship between the solubility and leaching of sulphates

It was observed that the concentration of sulphates in leaching was similar to that of the water-soluble sulphates for most of the tested materials. However, in the artificial samples (Xi), the difference between amount of sulphate leached and the soluble amount was higher when the gypsum amount increased due to incomplete dissolution.

Artificial samples with a gypsum percentage greater than 3% showed marked differences between the solubility and leaching of sulphates and for this reason, these materials are not considered in Fig. 4. The regression line illustrated in this graphic shows a high correlation coefficient ($R^2 = 0.760$) between the sulphate leached and the soluble sulphate.

According to the slope of the regression line, it can be deduced that each unit of leached sulphates is equivalent to 0.843 units of soluble sulphates. The difference is mainly due to the test conditions imposed by the batch testing of the dissolution (Galvín

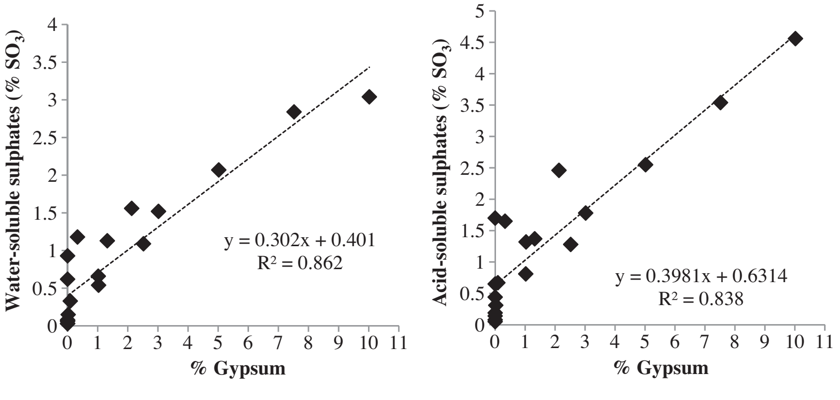

Fig. 2. Correlation between percentages of Gypsum vs. water-soluble sulphates and correlation between percentages of gypsum vs. acid-soluble sulphates.

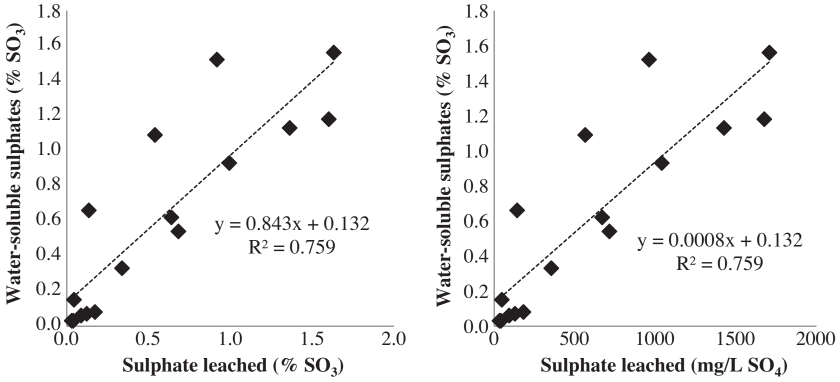

Fig. 4. Correlation between sulphates leached vs. water soluble sulphates.

et al., 2012). These are known to be more aggressive and prolonged than the conditions of a solubility test.

From the European limit, the value of leached sulphate (Table 4) and the correlations obtained, several deductions can be expressed:

- The European limit for a non-hazardous waste is 20000 mg/kg, which is equivalent to 2000 mg/L (at L/S = 10).
- This value corresponds to 1.73% SO_3 (Fig. 4) for water-soluble sulphates (UNE 103201). This differs greatly from the limit suggested by Vegas et al. (2011) (0.4% SO_3). These authors limited the content according to the stability of unbound layers on roads, while the present research was developed according to environmental criteria.
- This limit of water-soluble sulphate, in turn, is equivalent to 2.42% SO_3 (Fig. 1) for acid-soluble sulphates (EN 1744-1).
- Based on the two previous limit values, the percentages of gypsum which would comply with the European restrictions for water-soluble and acid-soluble sulphates are 4.4% and 4.5%, respectively (Fig. 2). These amounts are much higher than those proposed by Vegas et al. (2011) (0.8%) due to the reasons put forth in the previous section.

As the main source of sulphate in the RA is the gypsum, the last statement provides an easy, fast and economical approach for treatment plant managers. It will allow them to identify the approximate potential sulphate levels using only the gypsum amount of the RA produced.

5. Conclusions

The reuse of CDW requires the consideration of the potential environmental impact of recycled aggregates during their second life cycle.

The presence of sulphur compounds could cause not only stability problems, but also the pollution of superficial and/or ground water. High concentrations of these compounds could seriously affect the health of people using such water. Sulphate-based products, such as gypsum, are common in CDW and for this reason this compound amount must be limited.

This limit corresponds to 2000 mg/L of leached sulphates according to EU Landfill Directive used as reference by the Spanish Government. This value, in turn, corresponds to 1.73% SO_3 water-soluble sulphate (UNE 103201) and 2.42% SO_3 acid-soluble sulphate (EN 1744-1), according to the values obtained by this research.

These sulphates can have different sources: natural aggregates, mortar adhering to them and to a greater extent, ceramic particles and gypsum amount (from stucco, plaster, cardboard-plaster panels, etc.) of recycled aggregates. In this way, mixed recycled aggregates with more than 30% of ceramic particles or with more than 2% of gypsum have high soluble sulphate contents. However, limits equal to 4.4% of gypsum particles must be suggested in order satisfy the above limitations of leached sulphates (EN 12457-3) obtained in this study.

The solubility equilibrium was reached for gypsum additions higher than 3%. Thus, despicable differences, were observed in the amount of sulphate leaching from the materials with 5, 7.5 and 10% of gypsum, proving that from that point onwards chemical factors dictated the leaching not the sulphate content. The determination of heavy metals in the aggregates studied indicates that classification according to these values is less restrictive than according to values of leached sulphates. In addition, the metals Cd, Hg and Pb were not released at the aqueous solution by any material, whether natural or recycled.

In conclusion, the usual limits for soluble sulphates are derived more from a structural motivation than an environmental perspective. For this reason, it may be argued that recycled aggregates with less than 4.4% of gypsum and less than 30% of ceramic particles (obtained by 933-11) could be used in non-structural civil applications without potential risk to the environment.

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5. CONCLUSIONES

Las principales conclusiones que se obtienen de la investigación realizada, se muestran a continuación, indicando con P1, P2, o P3, el número de la publicación de la que se desprenden:

1. Existe el concepto generalizado de catalogar los áridos reciclados según su componente predominante, y poder ser adjudicado, de esta forma, a una aplicación determinada. Sin embargo, el estudio estadístico, realizado mediante correlaciones lineales simples, múltiples y canónicas, ha concluido que materiales a priori de menor calidad, han presentado mejores propiedades, posiblemente debido a un mejor sistema de tratamiento en la planta de reciclaje.

Por ello, se puede afirmar que el comportamiento mecánico de los áridos reciclados no sólo depende de su naturaleza y procedencia, sino que existen otros factores, como pueden ser el proceso de tratamiento recibido, la distribución granulométrica, su contenido de finos, o el grado de impurezas del material de origen (P1). Así, un árido reciclado procedente de hormigón triturado, si contiene un elevado porcentaje de yeso, proporcionará peor respuesta que un árido mixto limpio, a pesar de que, por su naturaleza, debería presentar peores características.

2. Sin embargo, y a pesar de que el contenido en yeso sigue siendo la principal fuente de sulfatos solubles, se ha comprobado que las partículas cerámicas aportan sulfatos solubles a los áridos reciclados, y por este motivo, el contenido de estas últimas debería limitarse (P1 y P3).

Así, y siguiendo las limitaciones medioambientales, se puede afirmar que los áridos reciclados con menos de 4,4% de yeso y menos del 30% de partículas cerámicas podrían ser utilizados en aplicaciones de infraestructuras viarias sin riesgo potencial para el medio ambiente (P2 y P3).

3. Para una mejor estimación del comportamiento mecánico, se aconseja realizar una subdivisión de cada uno de los componentes prioritarios de los áridos reciclados

según su naturaleza, resistencia del material de origen, uso anterior, etc (P1). Así, para el caso de las partículas cerámicas, debería diferenciarse si se tratan de partículas esmaltadas o no, y para el grupo de áridos reciclados de hormigón, debería separarse, principalmente, aquellos procedentes de diferentes resistencias. De igual forma, los áridos naturales estudiados fueron de diferente naturaleza, y consecuentemente, sus características y su comportamiento tuvieron diferencias entre los resultados obtenidos dentro de este grupo. Por tanto, también debería clasificarse la naturaleza de estos áridos naturales para una mejor estimación de su futuro comportamiento en obra.

4. En cuanto a su comportamiento mecánico como suelo-cemento, los áridos reciclados mixtos presentan un buen comportamiento frente a resistencia a compresión (P2), ya que tanto en el ensayo en laboratorio como en la puesta en obra, presentaron una resistencia media a compresión superior a la presentada por el árido natural utilizado, debido a la mejor distribución granulométrica de los primeros. Además, las pruebas realizadas en obra proporcionaron resistencias menores a las obtenidas previamente en laboratorio. Sin embargo, en todos los casos, la resistencia media a compresión a 7 días de edad estaba comprendida entre los valores límites impuestos por el PG-3, esto es, 2.5 y 4.5 MPa.

5. Además, los áridos reciclados mixtos estudiados poseen bajas deflexiones bajo carga por impacto (P2): los tramos construidos con los áridos reciclados presentaron una reducción de aproximadamente del 68% en comparación con la deflexión obtenida en el suelo estabilizado, frente al 29% del tramo realizado con árido natural.

6. De igual forma, se han obtenido valores adecuados de IRI (Índice de Rugosidad Internacional) en las secciones fabricadas con árido reciclado mixto (P2): 0.54 m/km para el tramo fabricado con árido reciclado mixto con un 22% de partículas cerámicas, y un IRI de 0.88 m/km para el árido mixto con un 15% de material cerámico, mientras que para el árido natural se obtuvo un valor de 1.00 m/km. En todos los casos, estos valores se encuentran dentro de las exigencias de la normativa española (<1.5 m/km).

7. El tiempo de trabajabilidad disminuye para el caso de los áridos reciclados mixtos, comparados con el árido natural (P2): 140 minutos para los áridos reciclados frente a los 195 minutos del árido natural. Esto se debe, principalmente a la alta porosidad, y mayor absorción de agua propia de los áridos reciclados con partículas cerámicas en su composición.

8. Por tanto, se puede sugerir que los áridos reciclados mixtos que cumplan con las limitaciones del PG-3, pueden ser usados en capas de pavimento tratadas con cemento (P2). Así, los áridos reciclados mixtos, pese a tener mayor absorción y menor densidad que los áridos naturales, y siempre que cumplan con el resto de requisitos exigidos en el PG-3 (una granulometría adecuada y un contenido de sulfatos solubles menor que 0.8%) pueden ser usados, sin perjuicio alguno, en capas de pavimentos como suelo-cemento.

Ahora bien, su puesta en obra requerirá un mayor contenido de agua. Para mantener un tiempo de trabajabilidad similar al de los áridos naturales, es necesario la adición de un retardador de fraguado.

9. Los valores límites de sulfatos solubles impuestos por el PG-3 son más restrictivos que los obtenidos en este estudio para cumplir los límites impuestos por la Directiva Europea para vertederos (P3). Así, la cantidad de sulfatos lixiviados no debe exceder a 2000 mg/l para su depósito en éstos, lo que se corresponde con un 1.73% de sulfatos solubles en agua, y un 2.42% de sulfatos solubles en ácido, valores bastante superiores a los permitidos por el PG-3 (0.8% SO_3).

10. Además, se ha encontrado una solubilidad de las partículas de yeso cercana al 3% en peso de los áridos reciclados estudiados (P3). Así, un contenido de yeso mayor del 3% no aporta, de forma proporcional, mayor contenido de sulfatos solubles ni lixiviados, debido a su dificultad para ser disuelto a tales concentraciones.

11. Por otra parte, la mayoría de los áridos reciclados estudiados son clasificados como no peligrosos, según su concentración en sulfatos lixiviados (P3), y basándonos en la limitación del contenido de sulfatos lixiviados, impuesto por la Directiva Europea

de vertido de residuos. Sin embargo, según la concentración de metales pesados, los áridos estudiados se reparten, de forma similar, entre la clasificación de "inerte", y la de "no peligroso" (P3).

12. La clasificación según los valores obtenidos de sulfatos lixiviados es más restrictiva que la realizada según los valores de metales pesados (P3). Además, los metales Hg, Cd, y Pb no fueron liberados en disolución acuosa por ningún material, ya fuera natural o reciclado.

En resumen, no es posible la estimación del comportamiento mecánico de los áridos reciclados a partir de su composición sino que es necesario tener en cuenta otros factores como el tipo de tratamiento recibido, grado de impurezas, naturaleza de los componentes…etc.

Es factible el empleo de áridos reciclados mixtos en la construcción de sub-bases de carreteras tratadas con cemento, siempre y cuando provengan de un adecuado proceso de tratamiento, y exista un riguroso control en su aplicación, aunque sería necesario un mayor número de tramos experimentales realizados con áridos reciclados para ratificar y confirmar los resultados obtenidos.

Por otra parte, a pesar de que una de las principales limitaciones de la aplicación de áridos reciclados es su mayor contenido de sulfatos solubles, tales restricciones derivan más de una motivación estructural que por aspectos medioambientales.

Por todo ello, se puede concluir que los áridos reciclados mixtos pueden ser una buena alternativa a los áridos naturales en la construcción de capas de suelo-cemento para sub-base de carreteras.

CONCLUSIONS

The main conclusions obtained from this research are shown below, indicating, with P1, P2, or P3, the number of the publication from which they originate:

1. There is a generalized concept of cataloguing recycled aggregates according to their predominant component, in order to thus be allocated to a particular application. However, the statistical study, performed by simple linear, multiple and canonical correlations, has concluded that material a priori of inferior quality, has presented better properties, possibly due to a better system of treatment received at the recycling plant.

For this reason, it can be affirmed that mechanical behaviour of recycled aggregates depends not only on their nature and source, but also on the recycling process received, size distribution, fine content, or degree of contamination of the initial material (P1). Thus, if it contains a high percentage of gypsum, a recycled aggregate from crushed concrete will lead to a poorer response than a clean mixed recycled aggregate, although, due to its nature, it should present worse characteristics.

2. Despite the fact that gypsum remain the main source of soluble sulphates, it has been found that ceramic particles also contribute soluble sulphates to recycled aggregates, and, for that reason, the content of the latter should be limited (P1 and P3).

Thus, following the environmental restrictions, it can be argued that recycled aggregates with less than 4.4% gypsum and less than 30% of ceramic particles could be used in road infrastructure applications without any potential risk to the environment (P2 and P3).

3. For a better estimate of the mechanical behaviour, a subdivision of each of the priority components of recycled aggregates should be made per type, resistance of the source material, prior use, etc. (P1)

Thus, for the case of the ceramic particles, these should be differentiated if they are glazed or unglazed particles, and for that of the group of recycled concrete aggregates, those from different resistances should, mainly, be separated.

Similarly, the natural aggregates studied were of a different nature, and, consequently, their characteristics and behaviour showed differences between the results obtained in this group. Therefore, the nature of these natural aggregates should qualify for a better estimation of their future behaviour in building work.

4. Regarding mechanical behaviour as cement treated aggregates, mixed recycled aggregates show good behaviour in compressive strength (P2), because both in laboratory testing and in their setting up, the mixed recycled aggregates studied had a higher mean compressive strength than that presented by the natural aggregate used, due to the better particle size distribution of the former. In addition, in site tests, all materials provided a lower resistance than those obtained previously in the laboratory. However, in all cases, the mean compressive strength at 7 days was between the limits given by the PG-3, i.e., 2.5 and 4.5 MPa.

5. Besides, mixed recycled aggregates studied have low deflection under impact loading (P2): the sections built with recycled aggregates showed a reduction of approximately 68% compared with the deflection obtained in the stabilized soil, versus 29% of the section made with natural aggregate.

6. Similarly, appropriate values of IRI (International Roughness Index) have been obtained in sections made from mixed recycled aggregate (P2): 0.54 m/km for the section made with mixed recycled aggregate with 22% of ceramic particles, and an IRI of 0.88 m/km for the mixed aggregate with 15% of ceramic material, while for the natural aggregate a value of 1.00 m / km was obtained. In all cases, these values are within the requirements of Spanish law (<1.5 m/km).

7. Workability period decreases for Mixed recycled aggregates compared to natural aggregate (P2): 140 minutes for recycled aggregates compared with 195 minutes of the natural aggregate. This is mainly due to the high porosity and greater water absorption, typical of recycled aggregates with ceramic particles in their composition.

8. Therefore, it can be suggested that mixed recycled aggregates, which obey PG-3 limitations, can be used in cement-treated pavement layers (P2). Thus, mixed recycled aggregates, despite having a greater absorption and a lower density than natural aggregates, whenever mixed recycled aggregates meet all the requirements in the PG-3 (an appropriate particle size and a content of soluble sulphates lower than 0.8%) they can be used, without prejudice, in layers of flooring and soil-cement.

However, their setting-up will require higher water content. To maintain a workability time similar to natural aggregates, the addition of a setting retarder is required.

9. Limit values of soluble sulphates imposed by the PG-3 are more restrictive than those obtained in this study to comply with the limits imposed by the European Directive on landfills (P3). Thus, the amount of leached sulphates should not exceed 2000 mg/l for its deposit in them, which corresponds to 1.73% water-soluble sulphates, and 2.42% acid-soluble sulphates, values well above those permitted by the PG-3 for use on roads.

10. In addition, a solubility of gypsum particles has been found close to 3% in weight of the recycled aggregates studied (P3). Thus, a gypsum content of over 3% does not contribute, in proportion, to a higher content of soluble or leached sulphates, due to its difficulty in being dissolved at such concentrations.

11. On the other hand, most recycled aggregates studied are classified as non-hazardous, according to their leached sulphate concentration (P3), based on the limitation of the leached sulphates imposed by the European Directive on waste dumping. However, depending on the concentration of heavy metals, the aggregates studied are divided, similarly, between the classification of "inert" and "non hazardous" (P3).

12. That classification according to leached sulphate values is more restrictive than according to heavy metals values (P3). In addition, the metals Cd, Hg and Pb were not released in an aqueous solution by any material, whether natural or recycled.

In short, the estimation of the mechanical behavior of recycled aggregates from its components is not possible, but it is necessary to take into account other factors such as type of treatment received, level of impurities, and nature of the components…etc.

The use of recycled aggregate mixed in the construction of road sub-base treated with cement is feasible, provided a suitable processing is performed and the quality of the application is strictly controlled, but a larger number of experimental sections made with recycled aggregates would required to ratify and confirm the results.

On the other hand, although one of the main limitations of the application of recycled aggregates is their higher content of soluble sulphates, such limits are derived more for a structural motivation than from an environmental standpoint.

Therefore, it can be concluded that mixed recycled aggregates can be a good alternative to natural aggregates in construction of cement treated layers for roads sub-base.

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7. ANEXOS

En este apartado se incluyen otras aportaciones derivadas directamente de la tesis doctoral. Se trata, en primer lugar, de un artículo publicado en una revista internacional, indexada en la JCR, con un estudio más profundo de las condiciones y procedimientos utilizados en el ensayo de lixiviación de material suelto, para la determinación de su contenido potencial contaminante. En segundo lugar, una comunicación en un congreso internacional sobre la utilización de la fracción más fina de los áridos reciclados, como cama para tuberías en la construcción de carreteras.

7.1. ANALYSIS OF LEACHING PROCEDURES FOR ENVIRONMENTAL RISK ASSESSMENT OF RECYCLED AGGREGATE USE IN UNPAVED ROADS

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Analysis of leaching procedures for environmental risk assessment of recycled aggregate use in unpaved roads

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ABSTRACT

The leaching behaviour of recycled materials from construction and demolition projects needs to be deemed acceptable before they are used for civil infrastructure. The study examines three leaching procedures for characterisation of the potential release of heavy metals and anions regulated by the EU Landfill Directive on seven recycled aggregates and two natural materials. The goal of the study is to relate the complex procedures designed for analysis of material leaching behaviour to quick leaching tests used for regulatory purposes. To integrate the data, results of the compliance test, availability test and percolation test were related to each other.

The results revealed that two recycled aggregates (the asphaltic and a concrete material) could be classified as inert material and the remainder were categorised as non-hazardous. Finally, the statistical analysis conducted permitted the identification of the group of heavy metals which are close to their acceptance thresholds. Thus, the noticeable amounts of Ni, Cr, Sb, Zn and Cu warrant their consideration as relevant from an environmental point of view.

1. Introduction

Many previous studies [1–3] have shown that the engineering properties of recycled aggregates (RA) from construction and demolition waste (C&DW) make them suitable for use as granular material in embankments and subbases for paved roads. Other studies have reported the possibility of using recycled aggregate from C&DW as a substitute for natural aggregate for concrete production [4,5].

C&DW is generated from the construction, renovation, repair, and demolition of structures, such as residential and commercial buildings, roads, and bridges. The composition of these materials varies depending on their related activities and structures. Because of this variation, C&DW may also contain materials that are hazardous or otherwise unsuitable for use in construction, such as organic compounds, plaster and metals [6]. A detailed selective demolition plan is required to ensure that hazardous and unsuitable materials in C&DW are separated out [7].

When a recycled material is exposed to the elements, rainwater can leach toxic substances out of the material. These toxic substances can contaminate surface and subsurface water and may cause serious environmental problems [8,9]. Previous research in this area has focused on assessment of the leaching process by which constituents of a solid material (such as contaminated soil, sediment, waste or a construction material) are released into the environment as a result of contact with water. Specifically, the underlying mechanisms of contaminant release and the chemical and physical factors that control leaching behaviour from construction materials under a wide range of environmental conditions have been analysed in several previous studies [10–14].

C&DW treatment plants (i.e., producers) use simple and quick procedures to assess the environmental risk of applying their recycled products in real scenarios. However, in-depth analysis and research of the release behaviour of C&DW constituents requires thorough study of the relevant factors (chemical, physical-transport and external) that must be conducted using leaching tests in the laboratory and subsequent data studies.

Therefore, clearly defined procedures are needed to integrate laboratory test results to construction projects, i.e., field results. Uncertainty in measurements and field conditions must be controlled. In addition, comparison with generally accepted norms such as the EU Landfill Directive [15] permits assessment of whether the application of the recycled product will be innocuous to the environment. In essence, this approach must be followed by the range of professionals (e.g., regulators, design engineers, and environmental consultants) involved with implementation of leaching procedures [16,17].

Recycling of demolition waste began in Spain at the end of the 1990s. The recent adoption of this technology in Spain suggests that the management of C&DW by treatment plants from an environmental point of view may not yet be completely adequate. The

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main consequence of inadequate management is wide variability in the quality of the RA produced. As a result, wastes that contain residues with high pollution loads may transfer their toxicity to the environment. Hence, it is important to characterise the quality of a wide variety of recycled aggregates and to verify their compliance with acceptance criteria for waste management. For this reason, the following types of RA from CD&W composed of different compounds were examined in this study: three recycled concrete aggregates (AR-1, AR-2 and HR-1); three mixed recycled aggregates (AR-3, MR-1 and CR-1 with varying percentages of bitumen, ceramic and concrete fractions) and an asphaltic aggregate (BR-1). In addition, two natural materials (AN-1 and AN-2 both limestones, from two quarries in Cordoba) were used as controls.

In this study, the environmental assessment of RA (for use as unbound subbase material in unpaved road construction) has been approached at two analysis levels. At the characterisation level (more useful from a research perspective than from a practical perspective), the maximum expected release was measured using the availability test NEN 7341 developed by the Dutch procedure [18] and the cumulative release for different exposure conditions was measured using the percolation test NEN 7343 [19]. However, for verification and quality control purposes, the compliance test EN 12457-3 [20] was used to determine whether the RA complied with the acceptance criteria imposed by the EU Landfill Directive. The analysis of the integration of results from these leaching procedures is focused on the behaviour of the heavy metals and anions identified in the cited regulations as being of concern.

In addition, to provide a basis for decisions in management of recycled aggregates, a list of potentially harmful pollutant elements is proposed based on the statistical analysis of the results.

2. Materials

The compositions of the seven RAs were determined according to the UNE-EN 933-11 [21] test (Table 1). RAs from different sources were chosen to provide a representative characterisation of the productive framework that is the object of this study. To characterise the materials, samples for each material were collected in accordance with standard UNE-EN 932-1 (1997) [22]. They were homogenised and reduced in the laboratory using a quartering method (UNE-EN 932-2, 1999) [23]. The main physical properties of the RAs are summarised in Table 2.

For AR-1, AR-2 and HR-1, the dominant compounds were crushed concrete and natural aggregates (representing more than 90% of each material), with a small amount of bitumen. These materials were classified as concrete recycled aggregates. AR-3, MR-1 and CR-1 were composed of concrete particles (more than 70%) and ceramic particles (more than 10%). These materials were classified as mixed recycled aggregates. BR-1 was a material that was composed primarily of bitumen (60.01%) and concrete (35.75%). As Table 2 shows, the natural aggregates exhibited greater densities and lower water absorptivity than the recycled aggregates. The mixed recycled aggregates exhibited higher water absorptivity and lower abrasion resistance than natural aggregates and a higher content of water-soluble sulphate.

3. Experimental methods

3.1. Characterisation procedure and conceptual framework

This study is focussed on analysing three different leaching procedures to assess the pollutant potential of heavy metals and anions present in recycled construction products. Anion concentrations were measured by the standard UNE-EN-ISO 10304-2 and heavy metal content was determined by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin Elmer ELAN DRC-e spectrometer. The device was equipped with a sample introduction system with a dilutor, an Argon plasma ioniser and a quadruple ion detector.

Previous studies have demonstrated that the potential risk of environmental contamination from leaching is determined not by the total content of pollutants (including ions as sulphate or heavy metals), but by the amount of water that can dissolve into the soil and reach surface water and/or subsurface water [10]. Thus, the risk depends on the availability of the contaminants for leaching [24,25]. For the materials examined in this study, the total mass potentially available for leaching was determined according to the Dutch standard NEN 7341. This test method allowed detection of the release threshold of each constituent. This approach has been analysed by other researchers who have proven that at low pH, the leaching curves for metals approach a plateau that corresponds to the level measured using the availability test [26].

Use of an RA in an unbound granular layer implies that percolation of water through the material plays a relevant role in the layer's behaviour. The transport rate of a constituent through the granular material depends on physical factors of the granular material such as porosity, grain size, and permeability. The manner by which the material is placed in the column of the percolation test apparatus (NEN 7343) allows simulation of the physical conditions of the RA in a specific scenario. Different liquid to solid ratios (L/S) represent different amounts of water in contact with the product during the test and can simulate short-, medium-, and long-term exposure situations in practice [16]. To be precise, percolation data can be converted to a time scale according to the following equation from Hjelmar [27]:

$$t = (L/S) \times d \times (H/I) \tag{1}$$

where d is the bulk density in kg/m^3, H is the layer thickness in m, and I is the infiltration rate in mm/y.

The following parameters were estimated for the most unfavourable case (from an environmental point of view) of using the RA as unbound subbase material in an unpaved road: a bulk density of 1900 kg/m^3; a subbase layer thickness of 0.25 m and an infiltration rate of 120 mm/y. As a result, the translation from an L/S scale to a time scale can be assumed (Fig. 1) and the implications for the future in terms of release of metal constituents into the soil over time can be deduced.

Apart from leaching procedures for detailed behaviour assessment, quick and simple tests need to be applied daily by C&DW producers. The compliance test chosen for examination in this study was EN 12457-3 because it is suggested for use in "Section 3. Sampling and test methods" of the EU Landfill Directive for the purpose of classifying a waste material as inert, non-hazardous or hazardous material.

Fig. 1 illustrates the three leaching procedures used to examine the main points of interest: maximum availability, long-term behaviour and release at compliance points.

3.2. Compliance test EN 12457-3

Compliance testing was conducted to check whether the seven recycled construction materials satisfy European regulations. To classify those materials according to the EU Landfill Directive, not only heavy metals but also inorganic anions were measured. The procedure EN 12457-3 consists of a two-step batch leaching test that uses a solution of 175 g of a dry sample of the material, two liquid/solid ratios (an L/S of 2 and an L/S of 10) and deionised water as a leaching liquid. This method involves stirring the solution in two steps. In the first step, the solution is shaken for 6 ± 0.5 h with an L/S of 2, and the second step uses the same fraction with stirring of the solution for an additional 18 ± 0.5 h, after adding water to obtain an L/S ratio of 10. In both stages, the samples are left to decant, and the pH, conductivity and temperature are measured. The solution is filtered using a membrane filter (0.45 μm), and a subsample of the leachate was taken for each material.

Table 1
Composition of the recycled material.

Type of material (% in weight)	Recycled aggregates						
	AR-1	AR-2	HR-1	AR-3	MR-1	CR-1	BR-1
Bitumen	6.75	3.14	0	1.97	7	0	60.01
Ceramic	1.23	0.94	4.85	26.21	14.34	22.45	0.34
Concrete crushed	70.17	74.16	68.84	59.82	55.85	38.12	35.75
Natural aggregates	20.69	21.19	26.30	11.02	21.71	39.36	3.87
Others (gypsum)	1.16	0.57	0	0.96	1.13	0.06	0.03

Table 2
Properties of the natural and recycled aggregates.

Properties	Recycled and natural aggregates								
	AR-1	AR-2	HR-1	AR-3	MR-1	CR-1	BR-1	AN-1	AN-2
Density-SSD (kg/m^3)	2.47	2.35	2.36	2.32	2.23	2.34	2.25	2.61	2.42
Water absorption (%)	4.75	8.01	6.04	9.16	9.88	9.95	4.40	1.22	1.98
L.A. coefficient	31.66	33.78	41.39	36.26	31.34	35.18	32.36	21	20.02
Water-soluble sulphate (%SO_3)	0.67	0.73	0.25	0.78	1.56	0.87	0.17	<0.01	<0.01
Total sulphur (%S)	0.32	0.41	0.47	0.92	2.52	1.15	0.16	<0.01	0.17
Particle size distribution (mm)	Percent passing (%)								
31.5	90.3	89.9	100	100	100	100	100	100	99.5
16	62.9	64.0	68.2	73.7	60.9	82.1	83.3	94.1	83.8
8	25.8	29.6	53.0	45.3	45.2	58.0	60.0	25.5	69.2
4	6.8	5.6	45.2	31.4	38.2	44.3	44.1	3.5	58.5
2	5.6	3.6	40.1	23.9	34.2	35.2	33.1	2.4	49.7

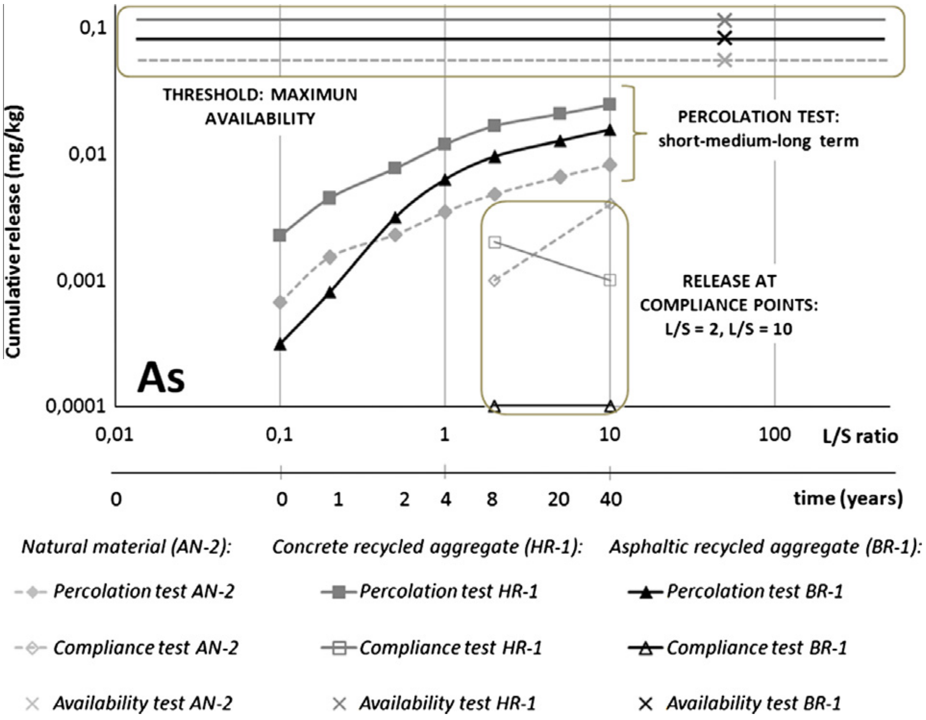

Fig. 1. Cumulative release, leached data (mg/kg) and theoretical concepts deduced from leaching procedures (as on materials AN-2, HR-1, BR-1).

3.3. Availability test NEN 7341

The Dutch test for granular materials is a characterisation test used to assess the fraction of the total mass potentially available for leaching. The NEN 7341 method estimates the maximum potential for leaching of inorganic components from granular materials and is often referred to as the maximum availability test. It is a two-step batch- and pH-controlled leaching test that is conducted using deionised water at an *L*/*S* ratio of 50 L/kg. The sample particle size is reduced to 125 μm, and the pH is kept constant (using HNO_3) for 3 h (the duration of agitation) at 7.0 and 4.0 for the first and second stages, respectively. These test conditions represent a worst-case leaching scenario rather than the conditions that would be expected in a landfill. As a result, the test provides an upper limit of the leaching potential in a landfill environment.

3.4. Percolation test NEN 7343

The column test described by the standard NEN 7343 is thought to simulate the leaching behaviour of a waste material by relating the accumulated released amount of a contaminant, expressed as mg/kg leached, to the liquid/solid ratio. In each column, the leachates were collected at *L*/*S* ratios of 0.1, 0.2, 0.5, 1, 2, 5, and 10 L/kg. The translation of the time scale illustrated in Fig. 1 makes it possible to quantify the retention in the matrix, simulating the release progress of a contaminant during the second life-cycle of the material [26]. However, laboratory results do not translate directly to field conditions because of factors such as temperature, channelling, degree and duration of contact with water, ageing effects (carbonation) and others [10,11].

The columns were designed with an inner diameter of 5 cm and a length of 20 cm. The columns were closed with flanges that were sealed. Depending on the material, between 0.5 and 0.7 L were needed to fill the volume of the column. The leachant was deionised water acidified with nitric acid of analytically pure quality to pH = 4 ± 0.1. The pH is not controlled during the test. Therefore, the waste dictates the chemical conditions in the pore-solution. All of the columns were operated concurrently using multi-channel peristaltic pumps.

4. Results

4.1. Impact assessment of tested RA according to acceptance criteria

This study is focussed on the leaching behaviour of the following heavy metals and anions regulated by the EU Landfill Directive: arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), zinc (Zn), barium (Ba), molybdenum (Mo), selenium (Se),antimony (Sb), chloride (Cl^-), fluoride (F^-) and sulphate (SO_4^{2-}).

C&DW may contain potential pollutants in compounds such as paper, plastic and metal. Another common component of C&DW is gypsum drywall, which is the predominant source of sulphate in RA [28].

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Table 3
Leached concentrations on concrete, mixed and asphaltic recycled aggregates by EN 12457-3 (mg/kg).

	AR-1		AR-2		HR-1		AR-3		MR-1		CR-1		BR-1	
	L/S 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10
Cr	0.011	0.122	0.031	0.026	0.094	0.048	0.565	0.706	0.160	0.162	0.563	0.663	0.027	0.254
Ni	0.034	0.125	0.211	0.130	0.005	0.007	0.016	0.027	0.010	0.033	0.018	0.040	0.004	0.016
Cu	0.160	0.093	0.013	0.079	0.029	0.045	0.081	0.106	0.021	0.047	0.053	0.078	0.042	0.072
Zn	0	0.006	0.007	0.407	0.002	0.010	0.004	0.010	0.007	0.022	0.007	0.021	0.008	0.030
As	0.008	0.008	0.019	0.016	0.002	0.001	0	0.002	0.003	0.002	0.002	0.002	0	0
Se	0.005	0.025	0.005	0.012	0.001	0.002	0.010	0.007	0.002	0.016	0.010	0.042	0.006	0.014
Mo	0.088	0.020	0.131	0.072	0.020	0.027	0.056	0.082	0.037	0.057	0.069	0.086	0.019	0.073
Sb	0.085	0.038	0.043	0.026	0.007	0.023	0	0.011	0	0.008	0	0.008	0.001	0.013
Ba	0.218	0.326	0.321	0.515	0.047	0.219	0.130	0.437	0.113	0.486	0.105	0.384	0.139	0.867
Chloride	30.5	24.5	55	44.5	31	25	44	49	17.5	20	59.5	68.5	89	186
Flouride	1.5	8.5	2	9	1.5	8.5	1.5	9.5	1.5	9	1.5	9	1.5	9.5
Sulphate	351	950.5	202.5	468	382	925	2754	5390	2637	4410	2556	3735	311.5	985

Table 4
Leached concentrations on natural materials by EN 12457-3 (mg/kg).

	AN-1		AN-2	
	L/S 2	*L/S* 10	*L/S* 2	*L/S* 10
Cr	0	0	0.030	0.040
Ni	0.002	0.004	0.002	0.001
Cu	0.007	0.012	0.017	0.023
Zn	0.028	0.058	0	0
As	0.004	0.035	0.001	0.004
Se	0	0.003	0.002	0.000
Mo	0.011	0.022	0.020	0.032
Sb	0.003	0.007	0.004	0.008
Ba	0.177	1.411	0.053	0.317
Chloride	14.5	16	9.5	59
Flouride	2	9.5	1.5	8.5
Sulphate	45	310	35	80

To classify the tested materials according to their pollutant behaviour, the compliance test EN 12457-3 was conducted. This test included the measurement of the aforementioned elements (Tables 3 and 4). Test results (mg of leached element per litre of leachate, mg/L) were transformed into accumulated emissions (mg of leached element per kg of aggregate, mg/kg) to compare these values with the limit values established according to the following expression [29]:

$$C_x(\text{mg X/kg aggregate}) = C_x(\text{mg X/L extracting solution}) \times (\text{L extracting solution/kg aggregate}) \tag{2}$$

where C_x is the concentration of constituent X.

The release of Cd, Hg and Pb are not included in Tables 3 and 4 because the detected amounts were negligible. According to the limit values (Table 5), each RA can be classified as inert, non-hazardous or hazardous waste.

After the acceptance criteria were applied to the results (Tables 3 and 4), the three mixed recycled aggregates AR-3, MR-1 and CR-1 were classified as non-hazardous rather than inert waste due to the high amount of sulphate ion detected on the leachates. This was due to the high contents of ceramic and gypsum particles. In addition, two mixed aggregates (AR-3 and CR-1) exhibited a high release of Cr which exceeded the limit for inert materials. Previous studies [30] have analysed the interaction processes between gypsum crystals and aqueous solution that causes progressive release of Cr.

The concrete recycled aggregates, AR-1 and AR-2 were also classified as non-hazardous rather than inert waste due to their Sb and Ni contents. Ni uptake by blended cement has been attributed to the formation of a 4:1 Ca:Ni phase, which was thought to replace $Ni(OH)_2$ as the solubility limiting phase in cement systems [31]. The remaining recycled materials (HR-1 and BR-1) and the natural materials were classified as inert debris. Although C&DW are generally classified as inert materials and are generally harmless [6,32], the recycled product can be potentially toxic if the management by treatment plants is inadequate. This inadequate treatment could cause construction debris to contain problematic wastes such as adhesives, caulk, paint, formaldehyde resins or PCBs (polychlorinated biphenyls) [33,34]. This highlights the importance of appropriate treatment plant operations to separate out any dangerous constituents of the waste [7].

Table 5
Acceptance criteria (EU Landfill Directive 2003/33/EC).

Parameter	Leached concentrations (mg/kg) depending on landfill class					
	Inert		Non-hazardous		Hazardous	
	L/S 2	*L/S* 10	*L/S* 2	*L/S* 10	*L/S* 2	*L/S* 10
Cr total	0.2	0.5	4	10	25	70
Ni	0.2	0.4	5	10	20	40
Cu	0.9	2	25	50	50	100
Zn	2	4	25	50	90	200
As	0.1	0.5	0.4	2	6	25
Se	0.06	0.1	0.3	0.5	4	7
Mo	0.3	0.5	5	10	20	30
Cd	0.03	0.04	0.6	1	3	5
Sb	0.02	0.06	0.2	0.7	2	5
Ba	7	20	30	100	100	300
Hg	0.003	0.01	0.05	0.2	0.5	2
Pb	0.2	0.5	5	10	25	50
Chloride	550	800	10,000	15,000	17,000	25,000
Fluoride	4	10	60	150	200	500
Sulphate	560	1000	10,000	20,000	25,000	50,000

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Concise protocols for testing granular materials (as EN 12457-3) and comparison with regulatory values allows a qualitative and compliant approach to assessing potential environmental risks posed by contaminants in C&DW but does not take into account the underlying basis for the release phenomena that occur [11,13,14,35]. Below, more elaborate characterisation of leaching procedures for determining the maximum availability of heavy metals and describing short-, medium-, and long-term leaching behaviour is discussed.

4.2. Relationship between leaching tests for granular materials

Comparison of the compliance test results with the characterisation test results (Fig. 2) allows predictions of contaminant release under field conditions and verification of such predictions in the field. Contaminant release predictions can also be related to decisions on utilisation and disposal [17,36,37].

Compliance leaching results may sometimes be useless for other purposes because crucial parameters may not have been measured. When those data are compared with characterisation results, deviations from normal behaviour are more easily identified [17]. This analysis was conducted for the heavy metals regulated by the EU Landfill Directive. According to the control charts (Fig. 2), the predicted behaviour over the long term by the column follows a consistent tendency in leaching metal behaviour regardless of the composition of the RA. These results are consistent with those of other authors who have affirmed that, in spite of the widely different natures of the materials, the leaching trends show similar characteristics [26].

The percolation test graph data indicate that the cumulative release of the tested heavy metals can be expected to remain constant for *L*/*S* ratios greater than 0.5 L/kg. This finding implies that for RA to be used in unpaved road construction, the expected release should not increase after 2–4 years from the time of the construction of the

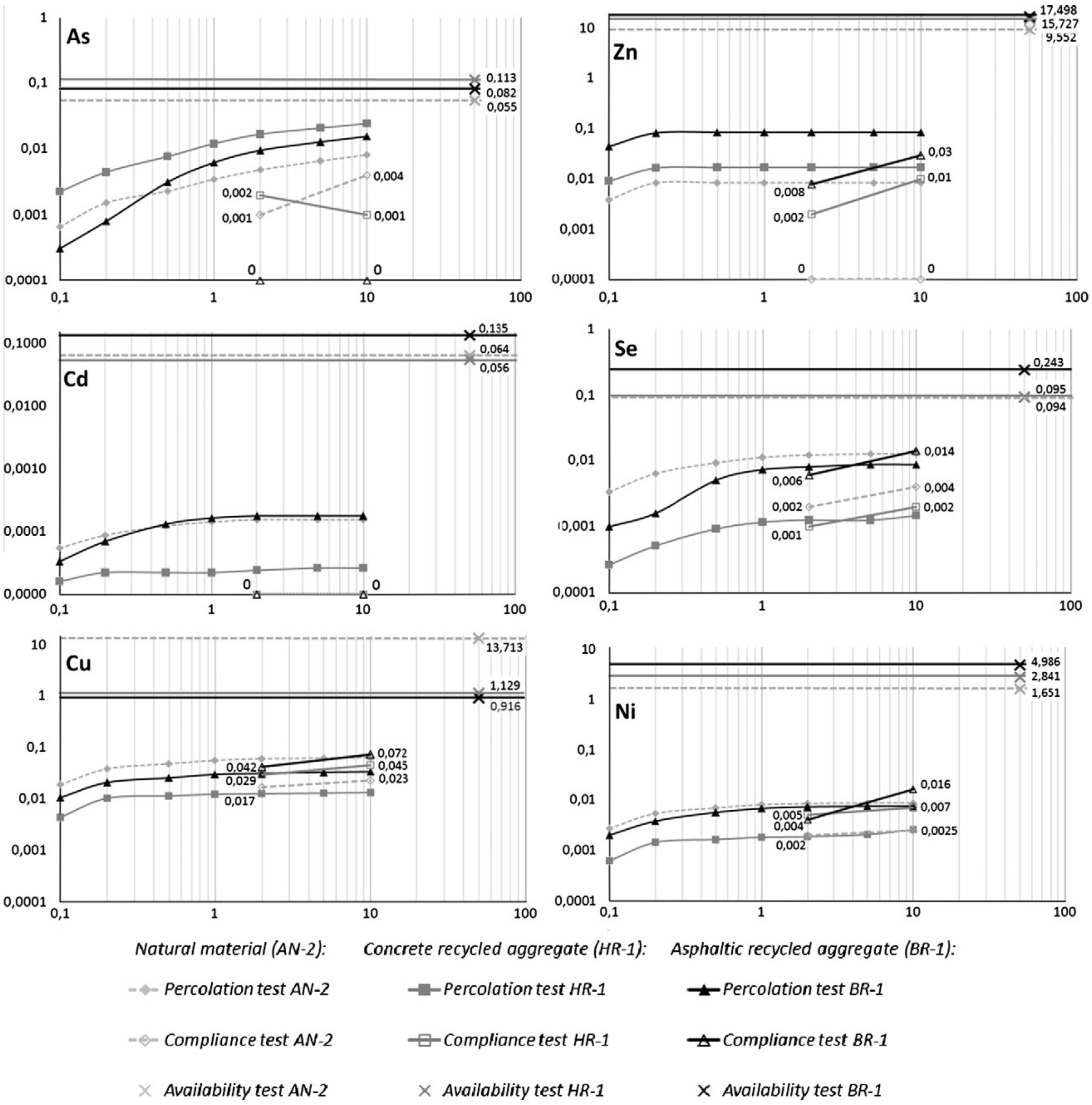

Fig. 2. Cumulative release and leached data (mg/kg) from three leaching procedures performed for three different types of recycled aggregates.

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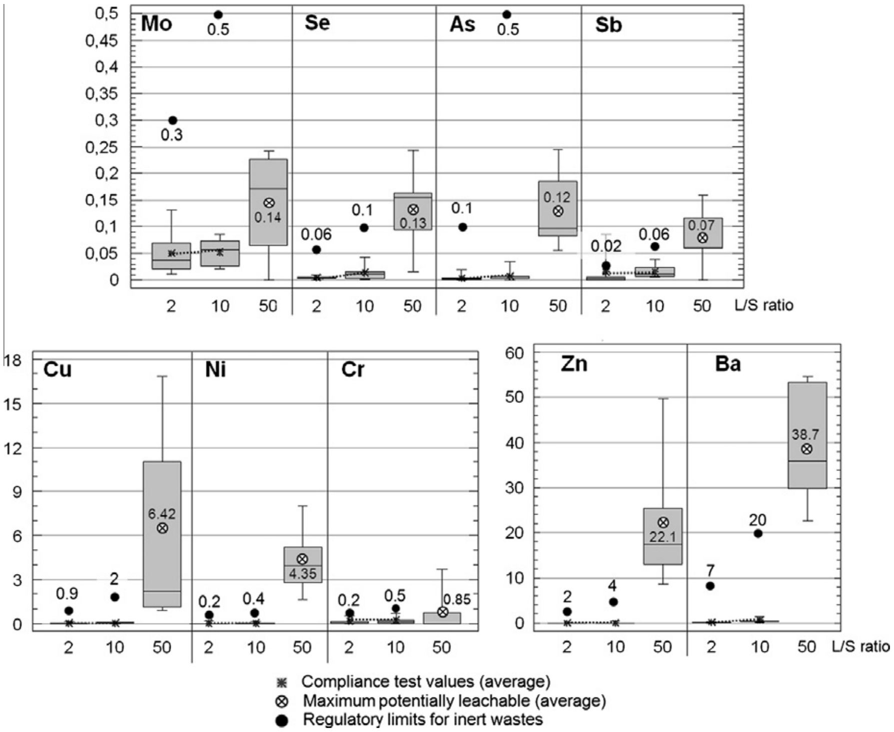

Fig. 3. The whisker plot of the cumulative release (mg/kg) of metals versus *L*/*S* ratios of 2, 10 (compliance points) and *LS* ratio of 50 (availability).

Table 6
Statistical data according to laboratory leaching results.

		Average	Standard deviation	Minimum	Maximum
Mo	*L*/*S* 2	0.050	0.040	0.011	0.131
	L/*S* 10	0.052	0.027	0.02	0.086
	L/*S* 50	0.144	0.089	0.0	0.242
Se	*L*/*S* 2	0.004	0.003	0.0	0.01
	L/*S* 10	0.013	0.013	0.001	0.042
	L/*S* 50	0.134	0.068	0.015	0.243
As	*L*/*S* 2	0.004	0.006	0.0	0.019
	L/*S* 10	0.007	0.011	0.0	0.035
	L/*S* 50	0.127	0.067	0.055	0.246
Zn	*L*/*S* 2	0.007	0.008	0.0	0.028
	L/*S* 10	0.062	0.130	0.0	0.407
	L/*S* 50	22.111	13.815	8.52	49.709
Cu	*L*/*S* 2	0.047	0.048	0.007	0.16
	L/*S* 10	0.061		0.012	0.106
	L/*S* 50	6.429	6.274	0.916	16.821
Ni	*L*/*S* 2	0.033	0.067	0.002	0.211
	L/*S* 10	0.042	0.049	0.0025	0.13
	L/*S* 50	4.357	2.164	1.651	7.968
Cr	*L*/*S* 2	0.164	0.231	0.0	0.565
	L/*S* 10	0.224	0.272	0.0	0.706
	L/*S* 50	0.850	1.462	0.0	3.72
Sb	*L*/*S* 2	0.015	0.029	0.0	0.085
	L/*S* 10	0.015	0.010	0.007	0.038
	L/*S* 50	0.077	0.056	0.0	0.16
Ba	*L*/*S* 2	0.144	0.085	0.047	0.321
	L/*S* 10	0.553	0.371	0.219	1.411
	L/*S* 50	38.759	12.667	22.637	54.709

road. However, a different pattern is observed for As, for which the cumulative release increases throughout the *L*/*S* range (with a maximum at *L*/*S* of 10). This behaviour is consistent with the fact that the regulatory limit for As at *L*/*S* of 2 (0.1 mg/kg) is much lower than the limit value at *L*/*S* of 10 (0.5 mg/kg), due to the pattern of increasing release of this metal.

The availability test results (Fig. 2) represent the threshold available or potentially leachable for each metal. Availability data at a pH of 4 were chosen for the graphic representation of the test results to facilitate comparison of these test results with the expected long-term behaviour (percolation tests performed with deionised acidified water). Therefore, it can be deduced that the

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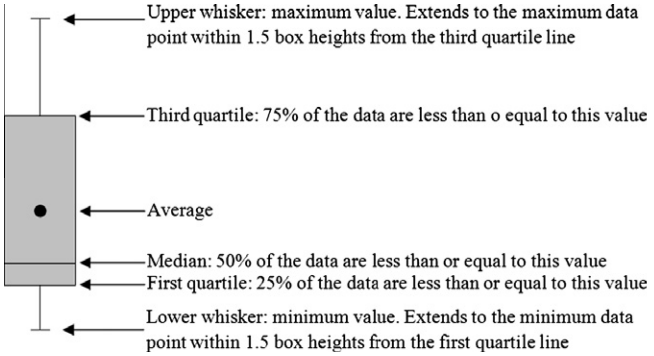

Fig. 4. The structure of the whisker plot and its interpretation [39].

distance from the imaginary asymptote of column data to the threshold varies as a function of the chemical mechanisms that control the release, i.e., dissolution of a mineral (solubility control), absorption processes (sorption control), or availability in the product. Other chemical factors that affect pollutant release are the pH (which is crucial in the release of many constituents), total composition of the product, redox potential, and complexation. At a low pH, leaching curves for metals approach a plateau that corresponds to the level obtained by the availability test [26].

The compliance test, which is conducted over a much shorter duration, is aimed at a direct comparison with threshold values (regulatory limits given in the EU Landfill Directive or availability level). From Fig. 2, it can be seen that agreement between the column test results and the compliance test results existed for most of the metals when the data at $L/S = 2$ L/kg and 10 L/kg are shown in the same chart.

In general, it has been demonstrated that agreement between results from laboratory tests and quick and simple compliance test results is good. The only exception to this was As, for which the leached amount of constituent was quite different from that indicated by the column data.

However, regulatory leaching tests are all simple step tests, and they are inadequate for providing a detailed characterisation of the leaching behaviour [17]. Due to this fact, for ensuring an optimal leaching behaviour of the RA at the long term, it is necessary to perform combination characterisation–compliance tests.

4.3. Statistical analysis of leaching results

Fig. 3 shows the results of a statistical analysis of the test results for all of the tested aggregates. The analysis is focused on the heavy metals regulated by the UE Landfill Directive. However, Cd, Hg and Pb were not included in the analysis because their detected amounts were negligible. The results of the availability and compliance tests are shown by means of whisker plots. The data from the statistical analysis are summarised in Table 6.

Fig. 4 illustrates the structure of the whisker plot. The lower and upper whiskers represent the minimum and maximum data points, respectively, of the particular group of data. They can extend up to 1.5 times the box height from the first quartile line for the lower whisker and the third quartile line for the upper whisker. If the minimum and maximum values exceed that these limits, they may be considered as outliers. The first quartile indicates the lowest 25% of the data set, the median separates the lower and upper 50% of the data set, and the lowest 75% represent the fourth quartile [38].

Fig. 3 and Table 6 show that higher standard deviations are observed in the release values obtained by the NEN 7341 standard for most of the metals. However, the data from the compliance test (for both points: L/S 2 and L/S 10) exhibit a much lower standard deviation.

From the results of the statistical analysis (Fig. 3 and Table 6) and the average values of the results for the compliance test, the metals that are commonly close to their acceptance limits can be identified. This identification makes it possible to examine (and to identify in future studies) the groups of metals of greatest interest from an environmental perspective in the particular case of RA from C&DW used as a subbase in unpaved roads.

The metals that were closest to their limits were Ni, Cr and Sb. This is consistent with the test results that confirmed that the materials AR-3, CR-1, AR-1 and AR-2 can be classified as non-hazardous on the basis of their content of these pollutant metals. In addition, the proximity of the Zn and Cu contents to their limits warrants a thorough study of these metals.

However, a larger distance to the regulatory points (green dot) was observed for Mo, Se, As and Ba. As a result, and according to the results for the tested RAs, these metals would present a lower environmental potential risk, due to their lower contents observed in this study. This result is true also for Cd, Hg, and Pb, due to the negligible amounts of these metals that were detected.

5. Conclusions

Due to the wide variability of the quality of RA produced in Spain, it was important to focus this study on the environmental risk assessment of recycled construction materials of different compositions (concrete, mixed and asphaltic recycled aggregates).

According to the acceptance criteria of the EU Landfill Directive, all of the mixed RAs tested (AR-3, MR-1 and CR-1) were classified as non-hazardous waste, due to the high amount of sulphate ion detected on the leachates, caused mainly by the high percentage of gypsum in the C&DW. In addition, two of these materials (AR-3 and CR-1) showed a high release of Cr that exceeded the inert limit. Due to the high content of Sb and Ni, the concrete materials (AR-1 and AR-2) were also classified as non-hazardous waste. As a result, only the remaining recycled materials (HR-1 and BR-1) and the natural ones could be classified as inert debris.

This study made use of the compliance test and characterisation procedures related the data from the two. The percolation results indicate that the cumulative release of the tested heavy metals remained constant for L/S ratios higher than 0.5 L/kg (with the exception of the increasing pattern observed for As). For an RA used in unpaved road construction, the expected release is not expected to increase within 2–4 years following the construction of the road (calculations according to Eq. (1)).

Representation in the same graph of availability and column test results showed that the availability results on metals can be interpreted as an imaginary asymptote of the percolation data. Finally, the results for leached levels at the compliance points (L/S 2 and 10 L/kg) and for leached values in the percolation test for the same L/S ratios showed good agreement (with the sole exception of As).

The statistical analysis showed higher standard deviations for the release values obtained by the NEN 7341 for all the metals. However, compliance test results (for both points: L/S 2 and L/S 10) had a much lower standard deviation. The statistical analysis identified (by their average values) the metals that are commonly close to their acceptance limits. This finding makes it possible to identify the metals of greater concern from an environmental perspective for the particular case of an RA used as subbase material in an unpaved road. Two groups of metals were identified. The first group (very close to regulatory limits) consists of the following metals that must to be considered relevant for further study: Ni, Cr and Sb, as well as Zn and Cu. The second group consists of the following metals considered of lower environmental risk due to the lower amounts of them that were detected: Mo, Se, As and

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Ba. The negligible amounts of Cd, Hg and Pb detected in all of the RAs tested allow them to be included in this second group.

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7.2. THE USE OF AN OEDOMETER TEST IN RECYCLED AGGREGATES TO EVALUATE BEARING CAPACITY IN PIPE BEDS.

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THE USE OF AN OEDOMETER TEST IN RECYCLED AGGREGATES TO EVALUATE BEARING CAPACITY IN PIPE BEDS

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ABSTRACT

The objective in this work is the analysis of the possibilities of reusing fine recycled aggregates (FRA) as unbound material, in pipe beds, where compactness is not allowed, and the settlement must be uniform. In certain applications, fine recycled aggregates are difficult to reuse in civil engineering, since they contain a high soluble sulphate concentration, a high level of water absorption, and a more low bearing capacity than natural washed sand (NS) for their application as pipe beds. The objective of this study is to find an alternative for the use of these recycled aggregates with a particle measuring reading less than 8mm and for this the quality of these recycled aggregates has been studied in comparison with washed natural sands that are habitually used in pipeline beds. We have compared two FRA from construction and demolition wastes with ceramic and concrete particles, with a NS, to measure the behaviour and mechanical properties, studying their behaviour in oedometer consolidation press testing. The results suggest that the FRA has similar properties in comparison with NS.

KEYWORDS

Fine recycled aggregates, pipeline beds, consolidation, oedometer test

INTRODUCTION

Recycled aggregates which come from the processing of “construction and demolition wastes” (C&D-W) have been used for many years, as much at a national level as international, in different applications such as structural and non-structural concrete. (R.S. Ravidrarajah and T.C. Tam, 1985), highways (T.Park, 2003), pipeline beds, mortars (I. Vegas et al., 2009), etc.

Normally, two kinds of recycled aggregates are used in civil works. On the one hand, large or coarse aggregates that come from ground-up concrete, which are applied in the production of new concrete. (A. Rao et al., 2006) (J.C.R. Aquilar et.al. 2007). On the other hand, recycled aggregates come as much from ground-up concrete, as from construction and demolitions with mixtures of different origins, such as left-overs from construction walling, masonry, etc. These materials are normally processed, obtaining grain reading analysis results from mixtures of coarse and fine particles, which are applied in structural layers for highways. (C.S. Poon and D. Chan, 2006)

The recycled aggregates with fine particle reading measurements tend to have a high water absorption level, low density and elevated quantities of sulphates that are soluble in water, which makes it a material with worse qualities in the applications of civil works (P.J. Wainright et al., 1993). This is the reason why recycled aggregates from fine sizes of grains are rejected.

Several studies exist for the application of recycled aggregates in the production of non-structural concrete (J. Brito et al., 2005), including the finest fractional kind (L. Evangelista and J. Brito, 2007) (J.M. Khatib, 2005). In general, fine recycled aggregates from the grinding up of concrete have been used for the production of new concrete in which their mechanical behaviour is known as well as their durability.

In this present article, fine grain recycled aggregates and their compression resistance that come from a mixture of C&D-W of concrete and construction walling have been studied. Their deformability under pressure is measured by an oedometer, applying these tests in different “Fine Recycled Aggregates” (FRA). The objective is to evaluate the possibilities of reutilizing these recycled materials in pipeline beds for channelling water or air, taking into account that owing to these it is possible that there may be vibrations. The material used under pipelines should present little seating under stress, including when it is submitted to conditions of water saturation.

MATERIALS

In this study, three aggregates with fine particle reading measurements were used: a natural washed sand (NS), and two recycled aggregates the size of grain similar to natural sand, whose characteristics are summarized in Table 1.

Natural Sand (NS)

The natural washed sand that was tested comes from a ground-up granite rock, used in works as a support base for pneumatic tubes or pipes for collecting urban residues (UR), and its covering later on.

This material has a nominal size of between 0 and 4 mm, and has been used as a material of reference in the properties of recycled sands that were tested in this study.

Fine Recycled Aggregates (FRA)

This deals with two recycled fine aggregates, from a size comprised between 0 and 4 mm, produced in the process plant for C&D-W in the Sadeco Environmental Centre (Córdoba, Spain). In this treatment centre, the C&D-W come from walls, concretes, masonries, excavations, etc., or in other words, non-classified residues at their source of origin.

These C&D-W are introduced into an input hopper where a sieve initially separates the material with a size smaller than 8 mm, labelled Fine Recycled Aggregate 1 (FRA 1), which has not been subjected to any kind of crushing. On the other hand, the material retained in this sieve is subjected to a later crushing and sieving, separating the particles that are inferior in size to 8 mm, giving us the Fine Recycled Aggregate 2 (FRA 2)

Table 1. Properties of aggregates

Properties		NS	FRA 1	FRA 2
Particle size distribution (% passing)	8 mm	99	100	100
	4 mm	97	97	96
	1 mm	47	74	77
	0,25 mm	13	43	44
	0,063 mm	6	21	24
Water absorption (%)		1,461	9,397	7,204
Real Density (g/cm^3)		2,63	2,45	2,48
Friability of the Sands (%)		26,01	32,23	29
Sand Equivalent		61,5	34,5	17,5
Acid Soluble Sulfate (% SO_3)		---	1,217	1,094

It should be pointed out that both of the recycled aggregates have not been washed, not like the natural sand, so that the content of the smallest particle size is much greater in these cases, such as we can see in Table 1 and in Figure 1.

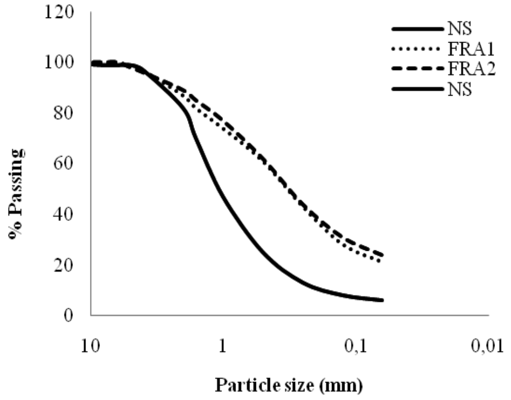

Figure 1.Particle size distribution of aggregates

MIXED MATERIALS

Once each of the materials were identified individually, the same were then mixed together, obtaining eight combinations that have been studied and detailed in Table 2, changing the percentages of natural sand and the degree of compactness. The three materials were tested in the study (NS, FRA1 and FRA2) with as much as a density of 1,4 gr/cm3, as with a density near that which was obtained in the “Standard Proctor” test labeled S.P. and equal to 1,8 gr/cm3. In the same way, two samples were analysied which resulted from each one of the mixed recycled aggregates at 50% with natural sand, with a density equal to 1,4 gr/cm3.

Table 2. Mixing materials

	% NS	FRA1-100%	% FRA2-100%	Density (gr/cm^3)	Humedad (%)
NS	**100**	**0**	**0**	**1,4**	**3,13**
FRA1-100%	**0**	**100**	**0**	**1,4**	**3,13**
FRA2-100%	**0**	**0**	**100**	**1,4**	**3,13**
FRA1-50%	**50**	**50**	**0**	**1,4**	**5**
FRA2-50%	**50**	**0**	**50**	**1,4**	**5**
NS-S.P.	**100**	**0**	**0**	**1,8**	**14,50**
FRA1-S.P.	**0**	**0**	**98**	**1,8**	**16,35**
FRA2-S.P.	**0**	**95**	**0**	**1,8**	**16,44**

EXPERIMENTAL METHODS

Moisture-density relationship

These compaction tests are devised to establish dry unit weight-water content relationships for a soil under controlled conditions, such as comparative effort, water content, etc. (A. Sridharan and P.V. Sivapullaiah, 2005) and presented a mini-compaction apparatus primarily for use in fine grained soils, which requires less volume of soil needed for the standard and modified Proctor test and so the time and effort involved in carrying out the compaction test is much less.

This method consists in the preparation of, at least, five molds with different contents of humidity applying a specific energy of 0,583 J/cm3, or in other words, 16 energy shocks in three layers. It is for this reason that the factors that influence in the final results will be the content of the initial humidity, the specific energy of compaction (energy applied per unit of volume) and the type of soil.

Soil compression tests

Oedometer tests were performed on the soil to measure its mechanical parameters as described in Saffih-Hdadi et al..(2009). It consists of a cylindrical probe confined laterally, which is subjected to different vertical pressures, permitting drainage on its upper and lower sides and measuring the corresponding seats or settlings. For this, a large sample of air dried soil was wetted to reach the desired water content.

It should be pointed out that this test is used on homogeneous soils, on those where the maximum particle size is not greater than the fifth part of the height of the probe. The elements used in the oedometer equipment are the following:

(1) Oedometer cell in which the probe can be covered with water and subjected to the corresponding pressures.
(2) A vertical probe measuring device for deformations.
(3) A bench that permits the application of the charges to the probe, maintaining them constantly for a determined period of time.

Charges were applied in corresponding cycles of 1, 5, 15, 30, 50, 100, 200 and 400 KPa. With each charge, there was a waiting time of 30 minutes, with the object of obtaining stability in accordance with the deformation that was produced.

RESULTS AND DISCUSSIONS

Moisture-density relationship

In Figure 2, the different S. P. curves for the three materials studied are observed.

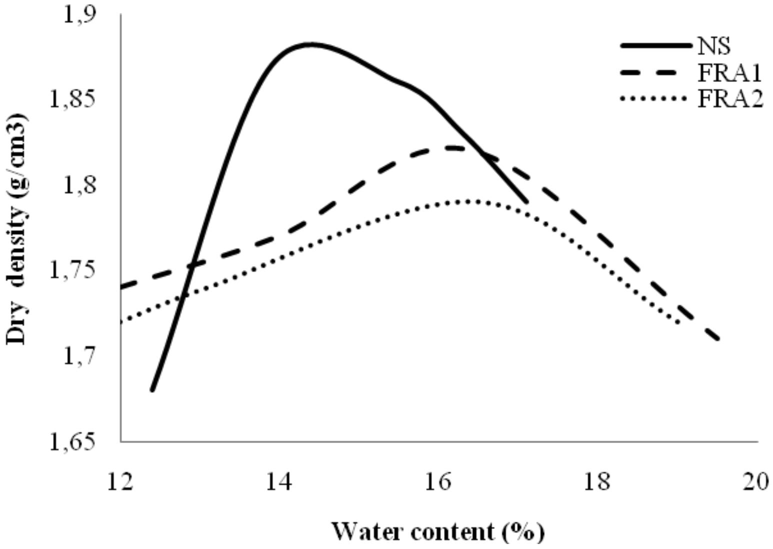

Figure 2: Comparison graph for dry Density-Humidity

Natural sand presents a greater density and less optimum humidity than the recycled materials.

Consolidation test

In Figure 3 and Figure 4, the different results of the oedometer tests are shown and in Table 3, the compression index (Cc), obtained for the distinct values of density-humidity.

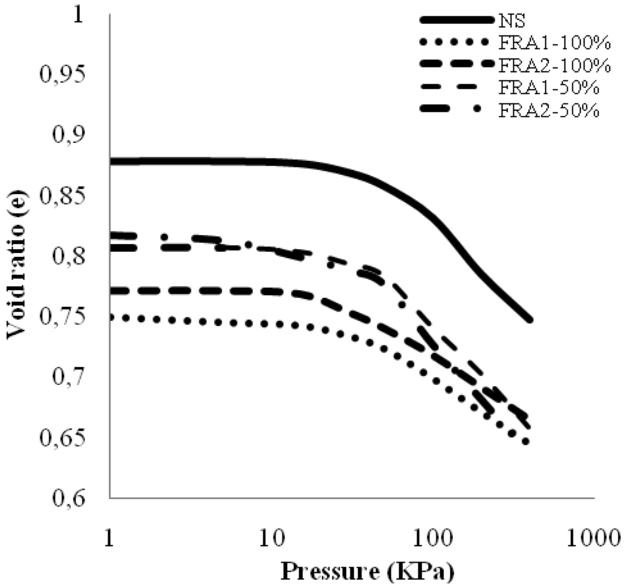

Figure 3. Results using dry density 1,4 gr/cm^3

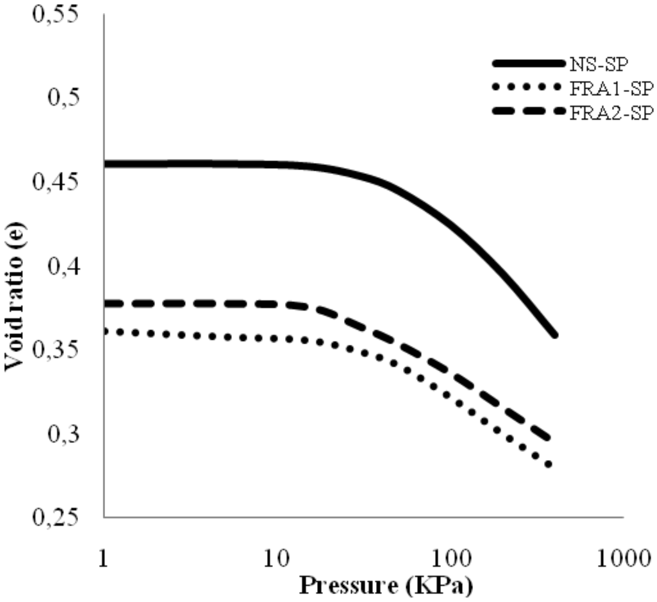

Figure 4. Results using dry density 1,8 gr/cm^3

Table 3: Compression indexes for each sample

Specimen	Dry Density (g/cm^3)	Compression Index (Cc)
NS	**1,4**	**0,140**
FRA1-100%	**1,4**	**0,090**
FRA2-100%	**1,4**	**0,088**
FRA1-50%	**1,4**	**0,138**
FRA2-50%	**1,4**	**0,151**
NS-S.P.	**1,8**	**0,109**
FRA1-S.P.	**1,8**	**0,070**
FRA2-S.P.	**1,8**	**0,069**

It should be pointed out that the compression indexes indicated in Table 3, have been calculated in a straight line from between 100 and 400 KPa. It is observed that the lesser compression indexes are obtained with recycled compacted aggregates with greater density, so that it can be estimated that it is these that present lesser seating

In figure 3, it is observed that natural sand presents a larger Void Ratio than recycled aggregates, owing principally to the fact that this does not present particles with a lesser size than 0,1 mm. On the other hand, recycled aggregates present lesser Void Ratio at the beginning owing to the fact that they constitute nearly 10% of the total weight of the sample and that they would partially fill the existing pores among the larger sized particles.

On the other hand, in the same graph, it can be observed that the mixture that is utilized with each one of the recycled aggregates and the natural sand present a larger initial Void Ratio than the materials that are not mixed, such as was expected, but, nevertheless, the consolidation line has a larger decline (Table 3), in other words, a compression index approximately 60% upper.

As much as in Figure 4 as in Table 3, it is observed that natural sand, for both densities studied presents a Compression Index, greater than recycled aggregates, so that the seating that was hoped for in an increase in vertical pressure will be greater.

CONCLUSIONS

The following conclusions are drawn from results of this investigation:

1. Although, in actuality, recycled aggregates with a size between 0-8 mm have little market outlet, owing to their high absorption, it is possible that they can be used in civil engineering works, such as fill in pipeline beds.

2. Without being washed, recycled fine aggregates present a compression index less than that of natural sand, having therefore a lesser deformation when subjected to vertical load action.

3. The mixtures that are carried out with recycled aggregates and natural sand have behaved worse than recycled aggregates that are not mixed.

4. The best results are exhibited with fine recycled aggregates that are compacted with a dry maximum density obtained in the S. P. test, with which, if possible, it is advised to carry out this operation applying adequate humidity.

In Summary, fine recycled aggregates present a good alternative to natural sands for their use as fill in pipeline beds.

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TÍTULO DE LA TESIS: APLICACIONES DE LOS ÁRIDOS RECICLADOS PROCEDENTES DE RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN EN LA CONSTRUCCIÓN DE INFRAESTRUCTURAS VIARIAS.

DOCTORANDO/A: Mª AUXILIADORA BARBUDO MUÑOZ

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La doctoranda, ha realizado la tesis doctoral en tres cursos académicos. El objetivo principal de la misma es evaluar las posibilidades de uso de los áridos reciclados procedentes de residuos de construcción y demolición en infraestructuras viarias tanto como materiales ligados con conglomerantes hidráulicos como no ligados. Para la consecución de este objetivo, la doctoranda ha realizado una correcta planificación del trabajo de investigación y aplicado las metodologías y técnicas de ensayo adecuadas. Así mismo, conviene destacar que la doctorando obtuvo una beca para realizar una estancia de tres meses en el IST de la Universidad de Lisboa donde realizó parte del trabajo experimental y que le va a servir para la obtención de la Mención Internacional de su tesis.

Por último, el doctorando ha cumplido los objetivos propuestos en la tesis, y una muestra de la calidad de la misma es la publicación de tres artículos en revistas indexadas en el JCR cuyas referencias son:

1. Barbudo A., Agrela F., Ayuso J., Jiménez J.R., Poon C.S., 2012. *Statistical analysis of recycled aggregates derived from different sources for sub-base applications.* Construction and building materials, 28: 129-138.

2. Agrela, F., Sánchez de Juan, M., Ayuso, J., Geraldes, V.L., Jiménez, J.R., 2011. *Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete*. Construction and building materials, 25, 3950-3955.

3.- Barbudo A., Galvin A.P., Agrela F., Ayuso J., Jiménez J.R., 2012. *Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes*. Waste Management 32, 1229-1235.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 25 de ABRIL de 2012

Firma del/de los director/es

Fdo.: JESÚS M. AYUSO MUÑOZ

Fdo.: FRANCISCO AGRELA SAINZ

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