Universidad Miguel Hernández de Elche
Programa de Doctorado Medio Ambiente y Sostenibilidad

Estudio de propiedades mecánicas de Eco-hormigones fabricados con áridos reciclados mixtos españoles, provenientes de Residuos de la Construcción y Demolición (RCD) y su potencial uso en Chile

---

Memoria de Tesis Doctoral

Marcos Alfonso Díaz González

Director: Dr. Manuel Jordán Vidal

Co- director: Dr. David Blanco Fernández

2022

UNIVERSITAS
Miguel Hernández

TESIS POR COMPENDIO DE PUBLICACIONES

La Tesis Doctoral, titulada "Estudio de propiedades mecánicas de Eco-hormigones, fabricados con áridos reciclados mixtos españoles, provenientes de Residuos de la Construcción y Demolición (RCD) y su potencial uso en Chile" se presenta baja la modalidad de Tesis por compendio de las siguientes publicaciones:

Marcos Díaz; María Belén Almendro-Candel; David Blanco y Manuel Miguel Jordán (2019). Aggregate Recycling in Construction: Analysis of the Gaps between the Chilean and Spanish Realities. Buildings, 2019, 9, 154. https://doi.org/10.3390/buildings9070154

Indicios de calidad: SJR (Scimago Journal Rank): Q1 Architecture/ Q2 Building and Construction; Q2 Civil and Structural Engineering.

Marcos Díaz González; Pablo Plaza Caballero; David Blanco Fernández; Manuel Miguel Jordán Vidal; Isabel Fuencisla Sáez del Bosque y César Medina Martínez (2021). The Design and Development of Recycled Concretes in a Circular Economy Using Mixed Construction and Demolition Waste. Materials 2021, 14, 4762. https://doi.org/10.3390/ma14164762

Indicios de Calidad: JCR category rank: Q1: Metallurgy & Metallurgical Engineering | Q2: Materials Science, Multidisciplinary | Q2: Chemistry, Physical | Q2: Physics, Applied | Q2: Physics, Condensed Matter. SJR (Scimago Journal Rank): Q2: Material Sciences (miscellaneous)/ Q2: Condensed Matter Physics.

INFORME DIRECTORES

El Dr. D. Manuel Miguel Jordán Vidal, director, y el Dr. D. David Blanco Fernández, codirector de la Tesis doctoral titulada **"Estudio de propiedades mecánicas de Eco-hormigones, fabricados con áridos reciclados mixtos españoles, provenientes de Residuos de la Construcción y Demolición (RCD) y su potencial uso en Chile"**

INFORMAN:

Que D. Marcos Alonso Díaz González ha realizado bajo nuestra supervisión el trabajo titulado "Estudio de propiedades mecánicas de Eco-hormigones, fabricados con áridos reciclados mixtos españoles, provenientes de Residuos de la Construcción y Demolición (RCD) y su potencial uso en Chile" conforme a los términos definidos en su Plan de Investigación y de acuerdo al Código de Buenas Prácticas Científicas de la Universidad Miguel Hernández de Elche, cumpliendo los objetivos previstos de forma satisfactoria para su defensa pública como Tesis Doctoral.

Lo cual firmamos para los efectos oportunos, en Elche a 24 de junio de 2022.

Director de la Tesis
Dr. D. Manuel M. Jordán Vidal

Codirector de la Tesis
Dr. D. David Blanco Fernández

INFORME-CAPD

El Dr. D. José Navarro Pedreño, Coordinador del Programa de Doctorado en Medio Ambiente y Sostenibilidad

INFORMA:

Que D. Marcos Alonso Díaz González ha realizado bajo la supervisión de nuestro Programa de Doctorado el trabajo titulado **"Estudio de propiedades mecánicas de Eco-hormigones, fabricados con áridos reciclados mixtos españoles, provenientes de Residuos de la Construcción y Demolición (RCD) y su potencial uso en Chile"** conforme a los términos definidos en su Plan de Investigación y de acuerdo al Código de Buenas Prácticas de la Universidad Miguel Hernández de Elche, cumpliendo los objetivos previstos de forma satisfactoria para su defensa pública como tesis doctoral.

Lo cual firmamos para los efectos oportunos, en Elche a 24 de junio de 2022.

Prof. Dr. D. José Navarro Pedreño

Coordinador del Programa de Doctorado en Medio Ambiente y Sostenibilidad

Agradecimientos

A Brianna Isabella Díaz Soto y a Velaskan Marión Soto Pizarro, mis dos amores, por motivarme a seguir adelante. Aparecieron justo en el momento indicado en mi vida, para concretar este desafío.

A mis Padres: Silvia González González y Oscar Díaz Santis; mi Hermano Adrián; y Abuelita Mónica González González, por su incondicional cariño y apoyo. Gracias por estar, desde el inicio de este proyecto, en los momentos más difíciles.

A David Blanco Fernández, Co Director de Tesis, por brindarme la oportunidad de cursar este Doctorado. Gracias por creer en mí, estimado Amigo.

A Manuel Jordán Vidal, Director de Tesis, por guiarme y aconsejarme en este Post grado. Siempre tuvo una palabra de aliento con el fin de ayudarme.

A Danny Lobos Calquín, Pedro Naranjo Lamilla y Mauricio Pradena Miquel, por sus consejos y comentarios, basados en su experiencia. Cada uno de ellos me ayudó a complementar esta investigación.

A César Medina Martínez, Académico de la Universidad de Extremadura UNEX, por darme la oportunidad de realizar 2 artículos en conjunto. Gracias por su apoyo y hospitalidad en mi estancia en Cáceres, España.

A José Ignacio Tertre Toran, presidente de la Asociación de RCD en España, por su ayuda y gestión para iniciar esta investigación. Gracias a él, conocí la UNEX.

Y a Rodrigo Quintana Castro, Eduardo Quintana Castro, Juan Carlos Lathrop, César Cabello Pizarro y otros amigos, quienes de una y otra manera me apoyaron en este largo camino.

Índice

Resumen

El concepto de Economía Circular, está creciendo cada vez más en el concierto internacional, específicamente en el sector de la construcción. En base a este tema no es novedad la creación de nuevos materiales sustentables provenientes de Residuos de la Construcción y Demolición (RCD), cuya fabricación ayude a descontaminar el medio ambiente. En este contexto, Chile se halla en un estado incipiente de desarrollo.

El siguiente estudio muestra el análisis de las propiedades mecánicas de los eco hormigones fabricados con áridos reciclados mixtos españoles (fracción fina y gruesa en conjunto) y su potencial uso Chile. Para tales efectos se analizó y comparó la normativa técnica y legal de Chile y España, referente al uso de áridos reciclados. Posteriormente se entrevistó a expertos, pertenecientes a diversos organismos gubernamentales, como también al sector privado. Por último, se compararon varios temas en el marco de estas 3 variables (España, Chile y la opinión de expertos).

Para tener un conocimiento técnico y aplicando la normativa española, se realizaron diversos ensayos a estos eco hormigones, en el Laboratorio de la Escuela Politécnica de la Universidad de Extremadura, relacionados con las propiedades mecánicas (resistencias a la compresión, tracción, flexo tracción, densidad, aire ocluido) y propiedades durables (penetración de agua bajo presión).

Dentro de las diversas opiniones realizadas por los expertos, se conoce que el árido natural se está agotando, debido a la fuerte extracción en las últimas décadas por la alta demanda de este material. Para tales efectos, proponen incentivar el uso de los áridos reciclados, en aquellos proyectos que soliciten cuantificar los RCD.

Dentro de los resultados más importantes obtenidos en laboratorio, se evidenció una igualdad en la consistencia entre las diferentes muestras realizadas con diferentes porcentajes de reemplazo. A la vez se observó un aumento de la resistencia a la compresión, en aquellos hormigones con un 25% de reemplazo en la fracción gruesa, con respecto a la mezcla patrón, como también una disminución en la absorción de agua bajo presión.

A la luz de los resultados, se puede inferir que existe un potencial uso del árido reciclado mixto en Chile. Esto debido a que la actualización de la actual norma chilena “NCh 163: Áridos para Morteros y Hormigones – Requisitos.”, permitiría aceptar, en un principio, 5% de árido reciclado, proveniente de hormigones. Si bien es ínfimo el porcentaje, comparado con las recomendaciones de literatura científica, es, sin duda, un punto de partida para desarrollar materiales reciclados, como el hormigón.

Abstract

The concept of Circular Economy is growing more and more in the international concert, specifically in the construction sector. Based on this theme, the creation of new sustainable materials from Construction and Demolition Waste (RCD), whose manufacture helps to decontaminate the environment, is not new. In this context, Chile is beginning to enter into this issue.

The following study shows the analysis of the mechanical properties of eco-concrete made with recycled Spanish mixed aggregates (fine and coarse fraction together) and its potential use in Chile. For such purposes, the technical and legal regulations of Chile and Spain, referring to the use of recycled aggregates, were analyzed and compared. Subsequently, experts belonging to various government agencies, as well as the private sector, were interviewed. Finally, several topics were compared within the framework of these 3 variables (Spain, Chile and expert opinion).

In order to have a technical parameter with Spain, several tests were carried out on this eco-concrete, in the Polytechnic Laboratory of the University of Extremadura, related to the mechanical properties (resistance to compression, traction, flexural traction, density, occluded air) and other properties (penetration of water under pressure).

Within the various opinions made by the experts, it is known that the natural aggregate is running out, due to the strong extraction of this material in recent times. For such purposes, they propose to encourage the use of recycled aggregates, in those projects that request to quantify CDW.

Among the most important results obtained in the laboratory, they show equality in consistency between the different samples made with different percentages of replacement. At the same time, an increase in compressive strength was observed in those concretes with 25% replacement in the coarse fraction, with respect to the standard mixture, as well as a decrease in the absorption of water under pressure relative to the same. .

In light of the results, it can be inferred that there is a potential use of mixed recycled aggregate in Chile. This is due to the fact that the update of the current Chilean standard "NCh 163: Aggregates for Mortars and Concrete - Requirements", would allow accepting, initially, 5% of recycled aggregate from concrete. Although the percentage is negligible, compared to the scientific literature, it is a start to develop recycled materials such as concrete.

1. Introducción

La industria de la construcción es responsable de un 12% de las emisiones de gases de efecto invernadero y de generar ~25-30% de los residuos sólidos producidos anualmente en la Unión Europea (UE) [1], lo que equivale a una producción media de 800 millones de toneladas anuales. Mientras que, en Estados Unidos y China, la producción de residuos de construcción y demolición (RCD) alcanza una cifra de 534 millones y 200 millones de toneladas anuales respectivamente [2], en Chile, la industria de la construcción genera un alto porcentaje de materiales que resultan de desechos, cuyos residuos se trasladan finalmente a un vertedero autorizado.

De la vasta gama de materiales utilizados en la industria, el hormigón, constituido principalmente por áridos que representan entre un 60-75% de su volumen y en un menor porcentaje por cemento (10-15% del volumen), es el material más utilizado habiendo alcanzado en el 2018 una producción de 165 y 150 millones de metro cúbicos en la UE y EE.UU, respectivamente [3]. Se estima que alrededor del 45% de los áridos extraídos son empleados en la fabricación de hormigones [4], y su proceso de fabricación es el responsable de ~8% del total mundial de CO_2 [5].

Sin duda, Chile es un país caracterizado por su riqueza y diversidad en recursos naturales, especialmente en recursos minerales entre los que se incluyen los áridos. Sin embargo, en la última década se ha puesto de manifiesto la escasez de este recurso pétreo en ciertas regiones, del mismo modo que se incrementan las alertas desde grupos ecologistas acerca de los daños irreparables que la extracción de este material de forma reiterada y descontrolada provoca en los ecosistemas, especialmente en los más sensibles.

Para mitigar los efectos nocivos de la extracción de áridos, problema que no solo afecta a Chile, sino que a varias regiones donde se extraen áridos, la industria de la construcción se ha enfocado en las siguientes acciones:

- Diseño y desarrollo de nuevas formulaciones de materiales de base cemento (morteros y/o hormigones) más sostenibles [6], a través de la incorporación de subproductos industriales (residuos agroforestales o de biomasa, industria ornamental y cerámica [7], construcción y demolición) bien como *supplementary cementitious materials* y/o árido reciclado (residuos de hormigón o mixto procedentes de los RCD).
- Estudios de residuos de construcción y demolición, para ver su aplicabilidad como material de construcción.
- Implementación de leyes y normativas técnicas para considerar al árido reciclado como un material más dentro de los ya existentes.

El uso de áridos reciclados es una de las estrategias más extendidas para alcanzar de forma simultánea el doble objetivo de introducir el concepto de economía circular y la sostenibilidad en la construcción. Estos se obtienen del tratamiento correcto de los RCD en las plantas de gestión, en las cuales se categorizan en fracciones granulométrica (principalmente arena, grueso y grava) dependiendo de su tamaño y composición. Según su composición se clasifican en [8]:

- Áridos reciclados de hormigón (RCA, *recycled concrete aggregates*) un contenido en hormigón (Rc) y áridos desligado (Ru) ≥ 90% y ≤ 10% de materiales cerámicos (Rb)

- Áridos reciclados mixtos (MRA, *mixed recycled aggregates*) con $70\% \leq Rc+Ru < 90\%$ y $Rb \leq 30\%$
- Áridos reciclados cerámicos (RMA, *recycled masonry aggregates*) con $Rc+Ru<70\%$ y $Rb> 30$

En cuanto a los áridos reciclados mixtos (MRA), debido al volumen que representan respecto al total de RCD (~67% del total en España) [8], ha despertado el interés de la comunidad científica, puesto que existe en la actualidad una laguna científico-técnica en la viabilidad de valorizar la fracción gruesa y/o fina en el diseño de hormigones. Recientemente Martínez-Lage et al. [9] registró que la incorporación de un 100% de MRA se traduciría en reducir más del 35% la generación de desechos y un 50% del agotamiento abiótico.

Respecto a las normativas implementadas en países para la utilización de áridos reciclados, estos han sido incorporados de forma desigual en las normativas relacionadas. En general el uso de la fracción gruesa de RCA y MRA en Europa es permitido con un límite máximo de sustitución de un 15 al 100% para hormigones estructurales o no estructurales. Adicionalmente, el MRA fino solamente es contemplado para aplicaciones de uso no estructural.

2. Objetivos

Objetivo General.

- Analizar las propiedades mecánicas de los eco hormigones, fabricados con áridos reciclados mixtos, en conjunto, con materiales españoles, proponiendo su uso en Chile.

Objetivo Específicos.

- Concluir, a través de la comparación de la actualidad chilena, con la actualidad española existente, referente al uso de áridos reciclados en el sector de la construcción, soluciones para incluirlas.
- Obtener el porcentaje de reemplazo óptimo, de acuerdo con cada requerimiento, de áridos reciclados mixtos por áridos naturales.
- Demostrar científica y técnicamente su posible uso, con materiales chilenos, para ser utilizados en obras de edificación e infraestructura, de acuerdo con las diferentes propiedades analizadas.

3. Materiales y Métodos

3.1. Materiales

Se empleó un árido natural (AN) correspondiente a una grauvaca silícea machacada con aristas marcadas y formas laminares que se presenta en dos fracciones granulométricas: i) arena natural 0/6 mm (ANf); y ii) grava natural 6-12 mm (ANc).

Los MRA utilizados proceden de la planta de gestión de RCD de ARAPLASA, situada en el norte de la provincia de Cáceres (España) presentándose al igual que los áridos naturales en dos fracciones: i) arena mixta reciclada 0/6 mm (MRAf); y ii) grava reciclada mixta 6/12 mm (MRAc). Su morfología y composición se encuentran en el artículo 2 de esta memoria. Adicionalmente, la MRAf ha sido obtenida a partir del mismo MRA que el MRAc presentando dicha fracción un color rojizo asociado a la presencia de los finos cerámicos.

El cemento portland utilizado es un CEM I 42.5 R, el cual fue suministrado por la planta del grupo Lafarge Holcim en Villaluengo de la Sagra, en la provincia española de Toledo (España). Finalmente, se utilizó el aditivo superplastificante FUCHS BRYTEN NF, aditivo reductor de agua de policarboxilato modificado a base de agua, de color pardusco, libre de cloruros, utilizado, con contenido de sólidos ~20%, densidad igual a 1.1 g/cm^3 y pH = 8.0, suministrado por FUCHS Lubricantes S.A.U.

3.2. Diseño de las mezclas

Se fabricaron nueve mezclas, una mezcla de hormigón convencional y ocho mezclas con hormigón más diferentes porcentajes de MRAf y/o MRAc. El detalle y la composición de estas mezclas se pueden consultar en el artículo 2 de esta memoria. Para llevar a cabo el diseño y formulación de las mezclas utilizó el *DOE British Method*. Asimismo, en este proceso de dosificación se han considerado los áridos secos, así como la propiedad de absorber agua de estos agregados (como también se les denomina) reciclados durante los primeros 10 minutos (~70% de la absorción total de agua absorbida a las 24 hrs inmersos en agua). Con esta estrategia, se garantiza que todas las mezclas independientemente de su esqueleto granular tengan la misma agua disponible para la hidratación del cemento. Adicionalmente, para conseguir una trabajabilidad adecuada con esta relación a/c se ha añadido una cantidad de aditivo de 5.89 kg/m^3.

Todas las mezclas diseñadas cumplen los requisitos de dosificación (contenido mínimo de cemento – 300 kg/m3 y máxima relación a/c efectiva – 0.55) exigidos por la norma europea EN-206-1 para clase de durabilidad XC2. Las mezclas estudiadas se prepararon en una hormigonera de eje vertical de laboratorio de 85 litros siguiendo el siguiente procedimiento: i) el árido grueso (ANc y MRAc) se mezcló durante 30 s; ii) se agregaron los áridos finos (ANf y MRAf) y se mezclaron los materiales durante 30 s; iii) se agregó el conglomerante (cemento), mezclándose durante 60 s; iv) posteriormente se añadió el 80% del agua de amasado más el aditivo superplastificante, y se dejó mezclar 45 s; y v) se incorporó finalmente el agua restante y se amasó durante 240 s. Finalmente, las muestras se fabricaron y curaron según la norma europea EN 12390-2.

3.3. Comparación de la actualidad chilena con la española

Para realizar esta comparación se empleó la siguiente metodología de trabajo. Se estableció la realidad chilena en cuanto al reciclaje de áridos, para lo cual se revisó diversa bibliografía, incluyendo también documentación técnica y legal (normativa) o tesis anteriores, entre otras. Luego se procedió a determinar la realidad del reciclaje de áridos en España, para esto se revisaron la regulación legal y técnica, incluyendo, proyectos y obras realizadas, entre otras fuentes. Finalmente, se entrevistó a seis expertos chilenos (profesionales pertenecientes al ámbito de la construcción), con el fin de dar a conocer la percepción que existe en el sector.

4. Resultados

4.1. Actualidad chilena

En Chile, no existe normativa técnica que incluya al árido reciclado dentro de sus especificaciones. La normativa legal recopilada hace referencia a ambientes libres de contaminación, gestión de residuos y gestión de residuos de la construcción y demolición, los cuales son posibles profundizar en el artículo 1 que puede consultarse en el anexo de esta memoria.

- Constitución Política de la República de Chile
- Leyes N° 19.300 y N° 20.920
- NCh 3562: Gestión de Residuos
- Política de Gestión Integral de Residuos Sólidos (PGIRS)
- Acuerdo de Producción Limpia (APL)

4.2. Actualidad española

En España, los documentos PG-3 y EHE-08 correspondientes a normativa técnica, incluye dentro de sus especificaciones el uso del árido reciclado. Los diversos documentos que componen la normativa legal también abordan las áreas mencionadas en el punto anterior, es decir, ambientes libres de contaminación, gestión de residuos y gestión de residuos de la construcción y demolición. El detalle de los documentos se encuentra en el artículo 1.

- Constitución española
- Ley 10/1998 y 22/2011
- Orden MAM/304/2002
- I PNRCD (2001-2006) y II PNRCD (2008-2015)
- PEMAR (2016-2020)
- Real Decreto 105/2008 y 1247/2008

4.3. Entrevistas a profesionales

Se entrevistó a los siguientes seis profesionales del campo de la construcción:

- Roberto Tedias de Constructora TVIAL Ltda.
- Jorge Fuentes de Constructora BROTEC
- Francisco Mora de SERVIU Metropolitano
- Gabriela Muñoz de Laboratorio Nacional de Vialidad
- Gabriel Palma de Laboratorio Nacional de Vialidad
- Víctor Reyes de Ministerio de Obras Públicas

Todos los profesionales entrevistados señalan estar en conocimiento de la futura escasez de áridos en la Región Metropolitana (Chile). Sin embargo, comentan que al no existir normativa técnica con respecto de los áridos reciclados, estos no pueden ser utilizados en obras. Además, pareciera no haber interés en la utilización de áridos reciclados sobre los áridos naturales en la industria, siendo una de las posibles razones, el desconocimiento técnico de estos áridos. Adicionalmente, al no existir leyes de gestión de los residuos de la construcción y demolición no se realiza una separación de estos residuos. Los profesionales entrevistados pertenecientes a MOP y SERVIU Metropolitano señalan que existe interés de estas entidades en incluir los áridos reciclados en sus normativas.

4.4. Propiedades de los Eco hormigones estudiados

4.4.1. Propiedades en estado fresco

- Consistencia: Todas las mezclas se encontraron dentro de la trabajabilidad objetivo de diseño.
- Aire Ocluido: La incorporación de MRA fino y/o grueso generó un incremento en esta propiedad. Existe una relación lineal entre esta propiedad y el porcentaje de arena reciclada para distintos porcentajes de sustitución de árido grueso.
- Densidad: Se observó un descenso en esta propiedad de acuerdo con el porcentaje de incorporación de árido reciclado mixto (MRAf y/o MRAc). Las mezclas que incorporan simultáneamente ambas fracciones en un 50% presentaron el mayor descenso en esta propiedad.

4.4.2. Propiedades en estado endurecido

- Densidad: Se obtuvo un descenso de esta propiedad con la incorporación de MRA (MRAf y/o MRAc), debido a la menor densidad que presenta esta nueva tipología de áridos reciclados respecto a los áridos naturales.
- Resistencia a la Compresión: Se observó que independientemente del tipo de hormigón: i) la resistencia a la compresión aumenta a medida que se incrementa el tiempo de curado, siendo esta evolución muy similar a la mostrada por el hormigón de referencia; ii) la resistencia relativa a compresión alcanzada a los 7 días equivale a un 75.7%-83.6% de la obtenida a los 28 días; y iii) la resistencia media obtenida a los 28 días es superior a la resistencia característica de diseño de 25 MPa. La resistencia a la compresión de los hormigones reciclados con respecto al hormigón convencional varía de acuerdo con los distintos tiempos de curado. Para tiempos cortos (t<28 días) la incorporación de MRAf y/o MRAc provocó una pérdida respecto a la mezcla de referencia. Sin embargo, para un t=90 días se observó un aumento de la resistencia. La incorporación de MRAc de forma individual no tiene un efecto nocivo en esta propiedad. En cuanto a la incorporación individual de los MRAf, se observó un ligero incremento de la resistencia a la compresión. Las mezclas que incorporan simultáneamente en su composición MRAc y MRAf tuvieron un mal desempeño a los 28 días. Cabe señalar que, al igual que sucede cuando se incorporan individualmente los MRA, se registró una mejora prestacional de los hormigones a los 90 días de curado.
- Resistencia a tracción indirecta: Las mezclas que solo incorporaron MRAf experimentaron un pequeño incremento de la resistencia a tracción, a diferencia de las mezclas que solo incluyeron MRAc, las que registraron un pequeño descenso en esta característica. En cuanto

a las mezclas que incorporaron simultáneamente ambas fracciones, se observó que la incorporación de la MRAf tuvo un efecto positivo al: i) disminuir el descenso de resistencia de las mezclas respecto a las mezclas que incluyen en su composición solamente MRAc; y ii) incrementar su resistencia respecto a las mezclas que incorporan únicamente MRAc.

- Resistencia a flexión: Las mezclas que incorporan solo MRAf experimentaron un pequeño incremento de la resistencia a flexión. Las mezclas solo con MRAc experimentaron un comportamiento desigual. En cuanto a las mezclas que incorporaron simultáneamente ambas fracciones, se observó que la incorporación de la MRAf tuvo un efecto positivo al mejorar el comportamiento de las mezclas con MRAc. Asimismo, todas ellas tienen un comportamiento similar o superior al observado en el hormigón convencional con un 100% de árido natural (ANc y ANf).
- Impermeabilidad al agua: Las mezclas solo con MRAf son las que experimentaron un mayor descenso tanto de penetración máxima (Pmax) como media (Pmed) de agua. En cuanto al uso de MRAc se observó un comportamiento dispar en estas dos propiedades. Respecto al uso simultáneo de MRAc+MRAf, como esqueleto granular de los hormigones, solamente la mezcla M5 (25%MRAc+25%MRAf) permitió obtener un incremento de la impermeabilidad.

4.5. Análisis de coste de fabricación de los hormigones

La mezcla M9 con 50% MRAf + 50%MRAc es la más económicamente rentable, provocando un descenso del coste por metro cúbico (m^3) de hormigón de un 8.03% respecto al hormigón fabricado con árido natural (M1).

5. Discusión

5.1. Comparación actualidad chilena y española

El uso de áridos reciclados procedentes de los RCD es una de las estrategias más extendidas para alcanzar de forma simultánea el doble objetivo de introducir el concepto de economía circular y la sostenibilidad en la construcción. En este contexto, es relevante estudiar el reciclaje de áridos como una alternativa de aplicación de la sustentabilidad en la construcción en Chile, específicamente en las obras viales urbanas e interurbanas, considerando que en este tipo de proyectos se genera gran cantidad de residuos con un alto potencial de reutilización. Sin embargo, mediante la revisión de diversas fuentes bibliografías se determinó que las normativas técnicas de Chile no incluyen el uso de áridos reciclados. Las causas que impiden su uso son variadas, entre ellas se pueden destacar: desconfianza, desconocimiento de sus características, propiedades y potencial rendimiento en las obras de pavimentación. En realidad, no existe tiempo suficiente en las programaciones de obra para poder realizar los ensayos y poder rebatirlo.

Con respecto a la normativa legal, en España existen leyes que obligan al uso de materiales reciclados y también sancionan un tratamiento inadecuado de los RCD, como son las Leyes 10/1998 y 22/2011, como también la Orden MAM/304/2002, entre otros (el detalle se encuentra en el artículo 1 de esta memoria). En Chile, a pesar de existir leyes que regulan y sancionan la disposición de residuos, solo hacen referencia a otros tipos de residuos (domésticos y orgánicos, entre otros), dejando fuera de su alcance los residuos de construcción y demolición. Además, dentro de las bases administrativas tampoco existe la obligación de utilizar materiales reciclados, ni siquiera un cierto porcentaje. Al no haber leyes que obliguen al reciclaje, según los comentarios de los profesionales entrevistados, es difícil crear una cultura sostenible en el sector de la construcción.

Los planes de gestión de RCD españoles están establecidos mediante el Real Decreto 105/2008, mientras que en Chile no existe una ley que ordene el establecimiento de un plan para el manejo de los residuos generados en las obras, solo se exige un certificado que indique que el vertedero de escombros posee la autorización requerida. La norma técnica NCh 3562 trata de solucionar esta situación.

En España, los planes de RCD (PNRCD I, PNRCD II, PEMAR) establecen los objetivos de RCD en cada período de aplicación. Además, el PEMAR (2016-2022), establece el número de plantas y vertederos permanentes, móviles, además de contar con diferentes plantas de tratamiento y vertederos. En Chile solo existen algunas empresas que se dedican al reciclaje de áridos de hormigones.

La aplicación de los áridos reciclados en España es una práctica habitual, fabricándose una alta variedad de productos como: Probetas de hormigón (calidad hasta G-40), Bases granulares, Asiento y recubrimiento de tuberías, Capa Drenante, Suelo cemento y grava cemento, entre otros (toda la información se detalla en artículo 1 de esta memoria). Sin embargo, en Chile únicamente se fabrican tres productos: Probetas de hormigón (Calidad hasta G-30), Base granular y Subbase granular.

5.2. Propiedades en estado fresco

La trabajabilidad de los hormigones reciclados no se ve afectada por la incorporación de árido reciclado mixto independientemente de su porcentaje de sustitución, lo cual permite establecer que la incorporación de la fracción fina y/o gruesa reciclada mixta, no tiene un efecto negativo sobre esta propiedad.

La incorporación de árido reciclado mixto (MRAc y/o MRAf) provoca un incremento lineal del contenido de aire ocluido en estado fresco. Este comportamiento podría estar asociado [10, 11] a: i) mayor absorción de agua de los MRA; ii) menor densidad del mortero adherido presente en el árido reciclado debido a la presencia en su interior de burbujas de aire; iii) textura más rugosa de los MRA que los NA; y iv) presencia de micro o nano fisuras en el interior de los MRA que no están conectadas a los poros permeables del árido.

El descenso en la densidad se encuentra en consonancia con lo indicado por Brito et al. [11] que fijaban disminuciones de hasta un 10% para hormigones que incorporaban hasta un 100% de MRA. Este comportamiento estaría asociado a la menor densidad de los áridos reciclados debido a la presencia de mortero adherido y material cerámico, así como la mayor relación agua/cemento aparente de las nuevas mezclas de hormigones diseñadas [10, 12].

5.3. Propiedades en estado endurecido

La disminución de la densidad de los hormigones reciclados se sitúo entre un 1.4%-5.7% respecto al hormigón de referencia (M1). Dicho descenso está en consonancia con el rango de 3.3-5.0% registrado por otros autores que incorporaban hasta un 100% de MRA [10].

El hecho de que los hormigones reciclados presentan un mejor comportamiento a un tiempo de curado mayor de 28 días podría estar asociado a la actividad puzolánica de la fracción fina (tamaño <0.063 mm) existente en el MRAf, donde se encuentran principalmente los finos cerámicos. Este aspecto, fue registrado previamente por Medina et al. [13, 14] y Asensio et al. [15, 16] que analizaron el comportamiento puzolánico de la fracción fina, observándose que tienen una capacidad de fijar cal a los 28 días entre un 53.3-82.1%. Adicionalmente, este comportamiento estaría también vinculado a: i) la presencia de partículas anhidras de cemento [17, 18, 19] en el mortero adherido en los MRAf que se hidratarán dando lugar a silicatos cálcicos hidratados (gel C-S-H) que contribuirán positivamente al comportamiento mecánico; y ii) las características de las zonas de Interacción Interfacial **(**ITZs, en inglés) existentes entre los componentes Rb del MRA (MRAc y MRAf) /pasta que pueden presentar un espesor igual e inferiores al mostrado habitualmente por los áridos naturales (eITZ=10-50 μm).

La resistencia a compresión de todos los hormigones es superior a la resistencia característica de diseño. Debido a lo anterior, estos nuevos hormigones reciclados pueden ser utilizados como hormigones para uso estructural. Respecto a la mezcla con un 50% MRAf, se visualizó que a los 28 días la resistencia se mantiene constante, mientras que a los 90 días se experimenta un pequeño incremento de un +8.1% respecto a M1. Este comportamiento es mejor que el establecido por Bravo et al. [20] para la sustitución de un 50% de arena de tipo I constituida por Rc+Ru=83.7%, Rb=0.9% y Rg=15.4%. Estos autores registraron una perdida prestacional entre un 6.1/13.3% respecto al hormigón convencional para un porcentaje de sustitución del 50%. Este mejor comportamiento de M3 estaría asociado a la mejor calidad que tiene el MRAf respecto a la arena tipo I estudiado por dichos autores.

La penetración de agua (máxima y media) bajo presión experimentan un descenso para las mezclas M2, M3, M4 y M5, mientras que para el resto de los hormigones se ha registrado un incremento en una (M6, M7 y M8) o en ambas profundidades (M9). Esta mayor impermeabilidad podría estar asociada a la actividad puzolánica de los finos cerámicos (<0.063 mm) de los MRAf, así como a la hidratación del cemento anhidro [21] presente en los finos de morteros de los MRAf que le dotan de una cierta actividad hidráulica, dando lugar a un sistema poroso más cerrado y tortuoso.

Para los porcentajes de MRAc y MRAf > 25% en peso se produce un aumento de la permeabilidad, lo cual podría explicarse debido al efecto beneficioso asociado a su textura superficial más rugosa que le facilita una mejor inclusión (ITZ similares) en la matriz cementante, así como la actividad puzolánica de la fracción <0.063 mm no son capaces de compensar el efecto nocivo que tiene sobre la permeabilidad al agua las propiedades intrínsecas de los mismos (menor densidad, mayor absorción de agua y presencia de microfisuras en su microestructura).

Los valores obtenidos de impermeabilidad al agua se encuentran por debajo de los límites establecidos en el capítulo VII “Durabilidad” apartado 37.3.3 “Impermeabilidad del hormigón” de la Instrucción Española de Hormigón Estructural (EHE-08), donde establece que un hormigón es suficiente impermeable para una clase de exposición (IIIa, IIIb, IIIc, IV, Qa, E, H, F, Qb, Qc); cuando su profundidad de penetración máxima y media es inferior a 50 o 30 mm y 30 o 20 mm respectivamente en función del tipo de ambiente, poniéndose de relieve que los hormigones reciclados tienen una estructura porosa que garantiza la impermeabilidad y una adecuada durabilidad a lo largo de su vida útil frente a este mecanismo de transporte.

6. Conclusiones

Esta investigación ha pretendido abrir cauces, primero de lo cualitativo y después de lo cuantitativo que relacionen los residuos utilizados con las propiedades últimas de los productos. Tras la presentación y discusión de los resultados obtenidos, pasamos a continuación a enunciar las siguientes conclusiones:

De acuerdo con el análisis de la realidad chilena se observa que no existen normativas técnicas que regulen el uso del árido reciclado en el país, resultando en una baja utilización de este en la construcción de obras viales. Esto se puede explicar por i) Desconocimiento de las propiedades de los áridos reciclados y su potencial rendimiento en obras de construcción, ii) Alta calidad de los áridos naturales y su amplia disponibilidad en el mercado, iii) Elevado costo de fabricación, iv) Actitud conservadora en el establecimiento de tecnologías y baja tolerancia en sus rendimientos por parte de organismos gubernamentales y empresas constructoras.

Si bien a la fecha de realización de esta Tesis Doctoral, existe la Nch 3562, la cual establece un plan de gestión y tratamiento de residuos dentro de las obras de construcción, existen muy pocas plantas de tratamiento de este tipo de residuos, lo que hace difícil el inicio de implementación de este sistema. Ante esto, se propone incluir el árido reciclado dentro de las normativas técnicas chilenas, tanto en el Manual de Carreteras, del Ministerio de Obras Públicas del MOP, como en el Manual de Pavimentación y Aguas Lluvias del SERVIU Metropolitano. Paralelamente, se sugiere crear en forma urgente leyes que penalicen la deficiente gestión de los RCD, cuyo fin sea no permitir la extracción de áridos naturales, obligando a las empresas del rubro a reciclar residuos, incentivando además en la inversión en tecnologías, permitiendo el aumento en el desarrollo sustentable dentro la construcción. Adicionalmente, se propone la construcción de infraestructura, que permita recibir y tratar los residuos generados en obra.

En relación con la utilización de árido reciclado mixto grueso (MRAc) y fino (MRAf), ambos poseen las propiedades físicas y mecánicos que exige la normativa vigente de áridos para la fabricación de hormigones. De acuerdo con los resultados obtenidos, el porcentaje óptimo de sustitución, individual o simultáneo, de MRAf y MRAc es de un 25% en peso. Adicionalmente, se recomienda investigar las diferentes tipologías de áridos reciclados mixtos en la fabricación de hormigones.

Finalmente, la presente investigación, contribuirá positivamente a la incorporación de estos áridos reciclados mixtos en los códigos estructurales de hormigón.

7. Bibliografía

1. Comision Europea (EU). No 601/2012 of 21 June 2012 on the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament and of the Council; European Committee: Brussels, Belgium, 2012. data.europa.eu/eli/reg/2012/601/oj

2. Cantero B, Sáez del Bosque IF, Matías A, Sánchez de Rojas MI, Medina C. Effect of recycled aggregate on performance of granular skeleton. Materials Journal. 2020;117(2):113-124. doi.org/10.14359/51720299

3. ERMCO. Ready–Mixed Concrete Industry Statistics. 2018. [Online]. Available online: http://ermco.eu/new/wp-content/uploads/2020/08/ERMCO-Statistics-30.08.2019-R4-1.pdf (accessed on 19 March 2020).

4. European Aggregates Association. Annual Review 2019–2020. European Aggregates Association. A Sustainable Industry for a Sustainable Europe. [Online]. Available online: https://uepg.eu/mediatheque/media/UEPG-AR20192020_V13_(03082020)_spreads.pdf (accessed on 5 May 2021).

5. Monteiro P, Miller S, Horvath A. Towards sustainable concrete. Nature materials. 2017;16: 698–699. doi.org/10.1038/nmat4930

6. Rahla KM, Mateus R, Bragança L. Comparative sustainability assessment of binary blended concretes using Supplementary Cementitious Materials (SCMs) and Ordinary Portland Cement (OPC). Journal of Cleaner Production. 2019;220:445–459. doi.org/10.1016/j.jclepro.2019.02.010

7. Ray S, Haque M, Sakib N, Mita AF, Rahman MM, Tanmoy BB. Use of ceramic wastes as aggregates in concrete production: A review. Journal of Building Engineering. 2021;43: 102567. doi.org/10.1016/j.jobe.2021.102567

8. Velardo P, del Bosque IS, Matías A, de Rojas MS, Medina C. Properties of concretes bearing mixed recycled aggregate with polymer-modified surfaces. Journal of Building Engineering. 2021;38:10221. doi.org/10.1016/j.jobe.2021.102211

9. Martínez-Lage I, Vázquez-Burgo P, Velay-Lizancos M. Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: Technical, economic and environmental analysis. Waste Management. 2020;104:9-19. doi.org/10.1016/j.wasman.2019.12.044

10. Yaprak H, Aruntas HY, Demir I, Simsek O, Durmus G. Effects of the fine recycled concrete aggregates on the concrete properties. International journal of physical sciences. 2011;6(10):2455–2461. doi.org/10.5897/IJPS11.253

11. de Brito J, Agrela F, Silva RV. Construction and demolition waste. In Newtrends in Eco-Efficient and Recycled Concrete. Woodhead Publishing: Amsterdam, The Netherlads. 2019:1–22.

12. Gonzalez-Corominas A, Etxeberria M. Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. Construction and Building Materials. 2014;68:618–626. doi.org/10.1016/j.conbuildmat.2014.07.016

13. Medina C, Banfill P, Sánchez de Rojas MI, Frías M. Rheological and calorimetric behaviour of cements blended with containing ceramic sanitary ware and construction/demolition waste. Construction and Building Materials. 2012;40:822–831. doi.org/10.1016/j.conbuildmat.2012.11.112

14. Medina C, Sáez del Bosque IF, Asensio E, Frías M, De Rojas, M.I.S.; De Rojas, M.I.S. New additions for eco-efficient cement design. Impact on calorimetric behaviour and comparison of test methods. Materials and Structures. 2016;49:4595–4607. doi.org/10.1617/s11527-016-0809-5

15. Asensio E, Medina C, Frías M, Sánchez de Rojas MI. Characterization of Ceramic-Based Construction and Demolition Waste: Use as Pozzolan in Cements. Journal of the American Ceramic Society. 2016;99(12):4121–4127. doi.org/10.1111/jace.14437

16. Asensio E, Medina C, Frías M, Sánchez de Rojas MI. Use of clay-based construction and demolition waste as additions in the design of new low and very low heat of hydration cements. Materials and Structures. 2018;51(4):1-12. doi.org/10.1617/s11527-018-1226-8

17. Chakradhara Rao M. Influence of brick dust, stone dust, and recycled fine aggregate on properties of natural and recycled aggregate concrete. Structural Concret. 2020;22:E105–E120. doi.org/10.1002/suco.202000103

18. European Committe for Standardization. EN 12390-3:2009. Testing Hardened Concrete. Part 3: Compressive Strengh of Test Specimens; European Committee for Standardization: Brussels, Belgium. 2009.

19. Medina C, Sánchez J, Sáez del Bosque IF, Frías M, Sánchez de Rojas MI. Meso-structural modelling in recycled aggregate concrete. In New Trends in Eco-Efficient and Recycled Concrete; Woodhead Publishing: Amsterdam, The Netherlands. 2019:453–476.

20. Bravo M, de Brito J, Pontes J, Evangelista L. Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. Journal of cleaner production. 2015;99:59–74. doi.org/10.1016/j.jclepro.2015.03.012

21. Bordy A, Younsi A, Aggoun S, Fiorio B. Cement substitution by a recycled cement paste fine: Role of the residual anhydrous clinker. Construction and Building Materials. 2017;132:1–8. doi.org/10.1016/j.conbuildmat.2016.11.080

8. Anexos: Publicaciones

8.1. Artículo 1

Marcos Díaz; María Belén Almendro-Candel; David Blanco y Manuel Miguel Jordán (2019). Aggregate Recycling in Construction: Analysis of the Gaps between the Chilean and Spanish Realities. Buildings, 2019, 9, 154. https://doi.org/10.3390/buildings9070154

buildings

MDPI

Article

Aggregate Recycling in Construction: Analysis of the Gaps between the Chilean and Spanish Realities

Marcos Díaz [1], María Belén Almendro-Candel [2], David Blanco [1] and Manuel Miguel Jordan [2,*]

[1] Department of Construction Sciences, Metropolitan Technological University, Dieciocho 390, 8330526 Santiago, Chile

[2] Department of Agrochemistry and Environment, Miguel Hernández University of Elche, Avd. Universidad s/n, 03202 Elche (Alicante), Spain

* Correspondence: manuel.jordan@umh.es

Received: 2 May 2019; Accepted: 20 June 2019; Published: 26 June 2019

check for updates

Abstract: This study conducts a comparative analysis between Chilean and Spanish reality in regard to the recycling of aggregates and their reuse in road works and urban roads. The current situation of both countries was reviewed through different sources of information such as technical and legal regulation, projects and executed works, to then validate them in Chile by way of interviews to various professionals in the field of urban and interurban road construction, as well as others belonging to government bodies. Spain has extensive experience on this issue, as it has a culture of recycling and reusing aggregates that has produced excellent results, a situation which was taken into account to compare it to Chile's reality. The conclusion is that currently, in Chile, although the existence of recycled aggregate use is known, this is not the case on a technical level for professionals in the sector. It lacks a specific government body that is in charge of this issue and does not have appropriate infrastructure for its treatment. The materials with a promising future within the construction sector are the production of crushed granular bases and the creation of low-resistance concretes, which cannot be used, as laws that regulate them are still being drafted.

Keywords: recycled aggregate; sustainability; urban road works

1. Introduction

In Chile, the construction industry (in infrastructure works such as building), has significantly increased its activity. Even though this reflects an increase in the development of the country, bringing greater labour opportunities and leading to numerous social benefits, it implies a high number of demolitions, and therefore, a greater amount of waste and residue that is taken to dumping sites.

On the other hand, although Chile has been characterised by being a country rich with natural resources, especially aggregate, evidence is starting to appear of symptoms of shortage of this stone material in some parts of the country, and there has also been an increase in warnings on behalf of some environmentalist groups on the irreversible damage that can be caused to the ecosystem if this material is continued to be extracted in a persistent and uncontrolled way. It is also important to consider the major negative impact that producing concrete, and specifically its components (such as cement), has on the environment, which directly increases the carbon footprint.

This crisis was already experienced in Spain and numerous European countries several years ago. This is why they have been continuously developing and perfecting aggregate recycling techniques for a significant amount of time. Likewise, they have also focused on creating a suitable framework to be able to promote this activity. As a result, they have developed studies on waste from construction and demolition works (to look into its applicability as a construction material) and have implemented various laws and technical regulations (in order to view recycled aggregate from this type of waste as simply another material, adding it to those that already exist).

In this context, it seems relevant to study the recycling of aggregates as an alternative for applying sustainability to the construction sector in Chile, specifically as it pertains to urban and interurban roads, as large amounts of waste with great reuse potential are generated in these types of projects. To do so, the Chilean reality on this issue must be reviewed, in order to do the same in Spain, then establish a standard for comparison, and finally measure the existing gaps between both countries with regards to the use of recycled aggregates.

Spain was chosen as a reference in this study because it is a country that is very close to the Chilean reality, and it is feasible to determine its context. Its recycling methodology was successful. For these purposes, it is necessary to review the Chilean reality on this issue (regulation, expert opinions), to then do the same with the mentioned European country, in order to establish a standard of comparison and measure the existing gaps among both with regards to the use of recycled aggregates.

2. Research Programme

The research methodology was divided in three phases: The first consists of reviewing Chilean reality regarding the recycling of aggregates by taking an in-depth look at various sources of information, such as technical and legal regulation or previous theses, among others. The second phase entails reviewing the reality of aggregate recycling in Spain. This includes the technical and legal regulation, projects and conducted works, among other sources. The last phase consists of validating the previously conducted review of Chilean reality by interviewing various professionals in the field of construction, specifically those from construction companies with experience in the construction of urban and interurban roads, as well as professionals from the Ministry of Public Works (The Ministry in charge of designing, tendering, overseeing and exploiting infrastructure works (Chile)), the Housing and Town Planning Service (SERVIU in Spanish) (Body that is directly dependant of the Ministry of Housing and Urban Development, born from the merging of 4 bodies: Property, urban improvement, housing and urban works (Chile)) and the National Roads Laboratory (Technical body whose purpose is to technically lead and support quality control work related to the execution of road works (Chile)) with the goal of making the perception that exists in the sector known. With the obtained information, both realities are analysed, showing the existing gaps between both countries regarding the recycling of stone materials, supplemented with the technical opinion of the experts interviewed and the feasibility of implementing their knowledge on this issue (Figure 1).

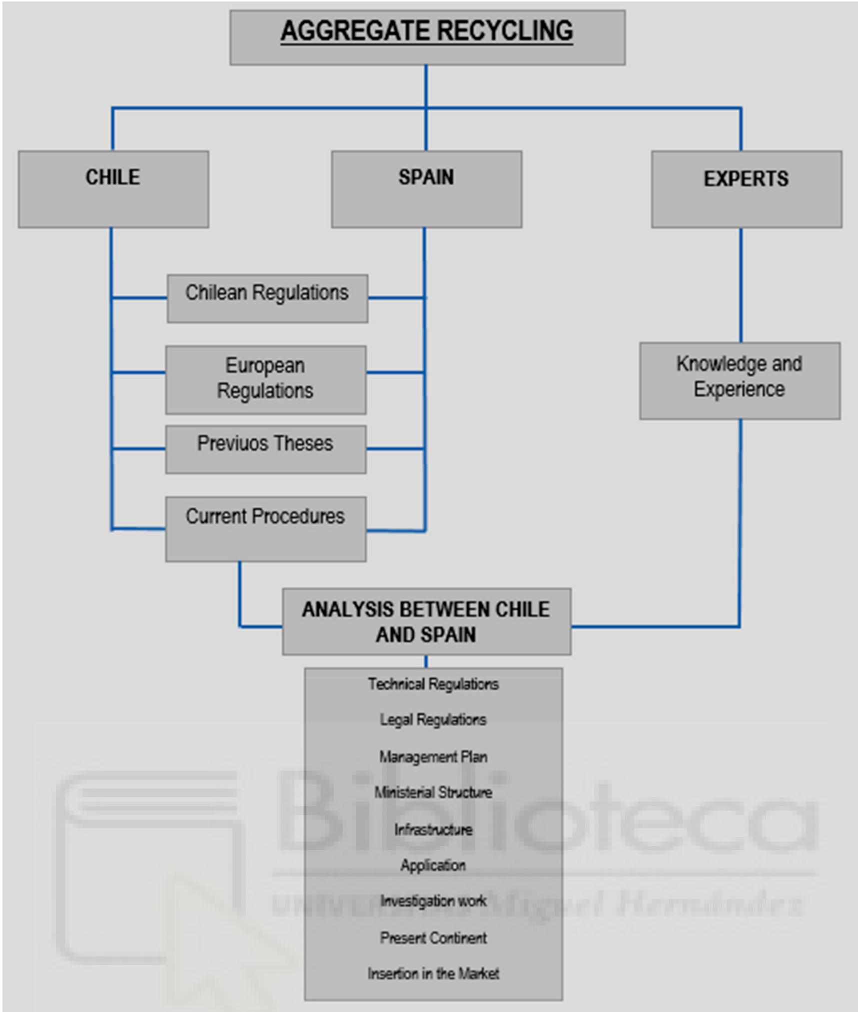

Figure 1. Research methodology.

3. Results and Discussion

This section summarises the contents of some of the laws that comprise the regulatory framework applicable to the Construction and Demolition Waste (CDW) in Spain.

3.1. Spanish Reality

3.1.1. Article 45—Spanish Constitution

The constitution is considered the fundamental law for the organising of any State. This is why it is mentioned in first place on this list. This Article, located in Chapter Three, called "Guiding principles of social and economic policy", referring to the environment and quality of life, establishes the following: That all people have the right to enjoy an environment which is suitable for their development, as well as the duty to preserve it. Furthermore, it establishes the duty that public powers have to monitor the rational use of all natural resources in order to protect and improve quality of life, and to defend and restore the environment, leaning on the essential collective solidarity. Lastly, it decrees the penalties for those who breach this section, which are of a criminal or administrative nature, as well as the obligation to repair any damage caused [1].

3.1.2. Spanish Law 10/1998, of 21 April, on Waste

Its purpose is to prevent the production of waste, establish the legal framework for its production and management, and promote its reduction, reuse, recycling and other forms of recovery, as well as regulating contaminated soils, in order to protect the environment and people's health. It is applicable by extension to, among other issues and the aspects that are expressly regulated in its specific provisions, the management of waste resulting from the prospection, extraction, recovery, disposal and storage of mineral resources, as well as from quarrying [2].

3.1.3. Spanish Law 22/2011, of 28 July, on Waste and Contaminated Soils

One of the purposes of this law is to regulate waste management by advancing measures that prevent its generation and mitigate the negative impacts on human health and the environment that are associated to their generation and management, improving resource use efficiency. Furthermore, its purpose is also to regulate the legal framework of contaminated soils. Waste hierarchy shall be applied by the relevant government bodies for the development of policies and legislation on the issue of waste prevention and management in order to attain the best global environmental result possible. The order of priorities is as follows: Prevention, reuse, recycling, other types of recovery (including energy recovery) and, lastly, disposal. Furthermore, it establishes waste policy resources, such as waste management plans and programmes, measures and economic instruments. It stipulates the obligations of the producer or any other initial owner as regards waste management, storing, mixing, packaging and labelling waste, as well as the obligations of the people responsible for managing the waste. In short, this law establishes the objectives and measures for waste management, specifically the collection, preparation for reuse, recycling, recovery and disposal of waste, the broadened responsibility of the producer and the sanctioning regime in relation to waste [3].

3.1.4. Order MAM/304/2002, of 8 February, which Publishes the Waste Recovery and Disposal Operations and the European List of Wastes

This Order acts under the protection of Spanish Law 10/1998, of 21 April, on waste. The first paragraph of section 2 of the third final provision of Spanish Law 10/1998, of 21 April, on waste, empowers the Ministry of the Environment to publish the European Waste Catalogue (EWC) (approved by Decision 94/3/EC of the Commission of 20 December) and the List of Hazardous Waste (LHW) (approved by Decision 99/404/EC of the Council of 22 December). Both Decisions have been replaced by Decision 2000/532/EC of the Commission of 3 May. Afterwards, Decision 2000/532/EC of the Commission of 3 May was replaced by Commission Decisions 2001/118/EC of 16 January, and by Council Decision 2001/573 of 23 July, which approves the European List of Wastes. The European List of Wastes merges the European Waste Catalogue and the List of Hazardous Waste into a single one. On the other hand, the second paragraph of section 2 of the third final provision of Spanish Law 10/1998, of 21 April, on waste, establishes that the Ministry of the Environment shall publish the list of waste recovery and disposal operations. This list was approved by Decision 96/350/EC, is applicable to all types of waste and allows for the appropriate application of the concepts of recovery and disposal. Two annexes are published at the end of this Order: Annex 1: Waste recovery and disposal operations (Part A: Disposal operations and Part B: Recovery operations) and Annex 2: European List of Wastes (ELW) [4].

3.1.5. National Construction and Demolition Waste Plan (I PNRCD in Spanish) (2001–2006)

The purpose of this Plan is to establish the ecological foundations and objectives for the appropriate environmental management of inert and similar CDW while in effect (2001–2006). Furthermore, it established a series of ecological objectives and suggests the instrumental, funding, monitoring and review measures of the Plan in order to carry them out. The Funding chapter includes both the estimate as well as the total budget for the infrastructures necessary for each Autonomous Community, such as recycling plants, dumping sites for inert materials and transfer plants, based on the amount of waste that each type of treatment will potentially receive. On the other hand, the same chapter also includes the funding methods for the various investments that are to be conducted, such as public and private initiatives in prevention and infrastructure, research, development and innovation (R + D and innovation), as well as citizen awareness actions, statistical control and the training of specialised personnel. Lastly, the Monitoring and Review chapter of the Plan includes a series of tables showing in a quantitative way: The generation and recycling of CDW in different countries of the European Union, an estimate of the construction and demolition waste generation in each Autonomous Community, a forecast of construction and demolition waste management, assuming as a hypothesis a generation of 1000 kg per inhabitant per year; budgets regarding prevention, infrastructure investments, R+D and innovation, raising awareness and training, statistical control and funding by the Ministry of the Environment [5].

3.1.6. National Construction and Demolition Waste Plan (II PNRCD) (2008–2015)

This Plan is included in Annex 6 of the National Integrated Waste Plan (PNIR 2008–2015 in Spanish), which emerges to improve the management of all waste generated in Spain, stimulate the different government bodies and agents involved in achieving ambitious ecological objectives, and comply with legal regulations, such as Spanish Law 10/1998 of waste and European Framework Directive 2006/12/EC (Table 1). This Plan (Table 1) establishes the objective of executing a suitable environmental management of hazardous waste included in the CDW list (an objective of mandatory compliance) as well as other objectives, such as the prevention at source of the generation of CDW, the application of the hierarchy principle, maximising recovery, improving the CDW treatment infrastructure network, closing dumping sites that cannot adapt to the legislation and adapting those that can.

Table 1. Objectives for Construction and Demolition Waste (CDW) for the years 2008, 2012, 2015. [6].

Objective	2008	2012	2015
Collection + appropriate environmental management	80	95	100
Prevention + reuse		10	20
Recycling		25	40
Recovery of waste from construction materials		40	70

Furthermore, it establishes the intended measures for the development of this Plan, includes an estimate of the infrastructure necessary for the management of CDW and analyses the level of deficit in this field in the country. Likewise, it reveals the necessary budget for the application of the intended measures and infrastructure, and assesses the funding needed for the functioning of the Plan, its monitoring and review [6].

3.1.7. Government Framework Plan for Waste Management (PEMAR in Spanish) (2016–2022)

The essential purpose encompassed in this Plan is to replace the current obsolete linear economy with a circular economy, which reintegrates the materials of interest present in waste into the productive process again and again for the production of new products or raw materials, thus seeking that Spanish society progresses towards efficiency in terms of the use of resources.

One of the novelties this new version brings is that the Autonomous Communities must inexcusably meet the national goals for their territory. Waste generated in their territory must comply with the national objectives, except when sector regulation establishes specific criteria, and local entities must make all means available to meet these objectives. In essence, all autonomies are responsible for achieving compliance with the national objectives. Section 13 of this Plan is dedicated to the analysis of CDW, showing records of results of the goals established in the previous Plan, the qualitative and quantitative objectives, and guidelines that make it possible to accomplish said goals.

The objectives established in the PEMAR, in short, are: To apply waste management hierarchy (reuse, recycling, recovery and disposal), to implement the selective collection of waste, boost measures to increase reuse and recycling as well as promoting this market, consider incineration as a recovery operation as long as energetic efficiency is achieved, discontinuing activities (in the case of not having the required authorisations), establishing a single procedure for the electronic registration of waste production and management, implement a deposit, refund and return system, and create a commission of coordination on waste with members from different government bodies [7]. Tables 2 and 3 show the quantitative objectives established by the PEMAR while in effect and number of transfer and treatment installations and dumping sites.

Table 2. CDW objectives for the years 2016, 2018, 2020 [7].

Objective	2016	2018	2020
Non-hazardous CDW (in %) allocated to being prepared for reuse, recycling and other recovery operations (excluding clean soils and stones) (minimum)	60	65	70
Disposal of non-hazardous CDW in dumping sites (in %) (maximum)	40	35	30
% of clean soils and stones (EWL 17 05 04) used in ground and restoration, refurbishing or filling works (minimum)	75	85	90
Disposal of clean soils and stones (EWL 17 05 04) in dumping sites (in %) of the total volume of excavated natural materials (maximum)	25	15	10

Table 3. Number of transfer and treatment installations and dumping sites that received CDW in 2013 [7].

Autonomous Community	Transfer Plants	Permanent Treatment Plants	Mobile Treatment Plants	Dumping Sites
Andalusia	92	119	21	71
Aragon	18	6	1	5
Asturias	3	4	5	1
Balearic Islands	6	2	n/a	1
Canary Islands	0	23	n/a	7
Cantabria	12	4	12	2
Castilla-La Mancha	n/a	28	27	12
Castile and Leon	0	45	0	3
Catalonia	12	50	0	57
Ceuta	n/a	n/a	n/a	n/a
Valencian Community	n/a	n/a	n/a	n/a
Extremadura	16	21	1	0
Galicia	3	43	21	5
La Rioja	n/a	16	0	2
Community of Madrid	10	14	0	4
Melilla	n/a	n/a	n/a	n/a
Region of Murcia	2	4	32	19
Navarre	n/a	7	3	7
Basque Country	n/a	n/a	11	n/a
TOTAL	174	386	134	196

3.1.8. Spanish Royal Decree 105/2008, of 1 February, which Regulates the Production and Management of Construction and Demolition Waste

Its purpose is to establish the legal framework for the production and management of construction and demolition waste, in order to encourage their prevention, reuse, recycling and other ways of recovery, ensuring that those allocated to disposal operations receive an appropriate treatment, and to contribute to a sustainable development of the construction activity. Furthermore, it also establishes the obligations that CDW producers and owners must comply with. The latter includes the minimum amounts of waste generation which, if surpassed, must be divided into fractions. Said fractions are detailed in this Royal Decree. Furthermore, it also establishes the system for the control of production, ownership and management of CDW, general obligations of the manager of these wastes, recovery activities, treatment with mobile plants in permanent waste recovery or disposal plants, disposal activities via depositing them in dumping sites, construction and demolition waste collection, transporting and storage, the use of inert waste in restoration, refurbishing or filling works, planning on CDW, administrative liability and sanctioning regime [8].

3.1.9. Spanish Royal Decree 1247/2008, of 18 July, which Approves the Structural Concrete Standards (EHE-08)

The purpose of this Royal Decree is the approval of the Structural Concrete Standards [9] (EHE-08) (EHE-08: Spanish legislation whose purpose is to regulate the design, execution and monitoring of concrete structures, both in construction and civil engineering works), which include a series of updates that entail the adaptation of this legislation to the prevailing European criteria regarding the demandable requirements for structures, as well as the addition of new construction techniques and materials, including those that have been recycled. Furthermore, these standards establish the requirements to take into account for the design and execution of concrete structures, both for construction as well as civil engineering, with the objective of achieving the security levels that are suitable for their purpose [10].

3.2. Chilean Reality

3.2.1. Political Constitution of the Republic of Chile

Point eight of Article 19 of Chapter III: On constitutional rights and duties, says that the Constitution ensures every person's right to live in a pollution-free environment. It is the State's duty to ensure that this right is not affected and to protect the preservation of nature. Laws may establish specific restrictions to the exercising of certain rights or freedoms to protect the environment [11].

3.2.2. Chilean Law No. 19.300—Law on General Environmental Framework

A law approved by the Ministry of the Presidency in 1994. It establishes the legislative framework that regulates the right to live in a pollution-free environment, the protection of the environment, the preservation of nature and the conservation of environmental heritage. It also regulates the instruments for environmental management such as the Strategic Environmental Assessment, the Environmental Impact Assessment System and the Access to Environmental Information, the Liability for Environmental Damage, the Inspection and Environmental Protection Fund, and Chilean environmental institutionalism [12].

3.2.3. NCh 3562: Waste Management—Construction and Demolition Waste and Excavation Material—Classification and Guidelines for a Management Plan

CDW are inert substances or objects, waste similar to that produced in the household and hazardous waste, which are generated during construction and/or demolition works and whose generator disposes of or has the intention or obligation of disposing of them in accordance with current legislation. The Management of CDW encompasses all the operative actions to which a construction and demolition waste is subjected to, including its gathering, stocking, transportation, pre-treatment, treatment and disposal.

This draft standard, prepared by the National Standards Institute [13] (INN in Spanish) (Non-profit private law foundation created by CORFO in 1973, as a technical body on the issue of infrastructure quality control (Chile)), is currently in a public consultation process. Some of its objectives are:

- Promote the integral management of inert waste and construction work excavation materials, to decrease their environmental, social and economic impact.
- Promote the reduction, reuse, recycling and recovery of waste.
- Ensure an appropriate waste classification and placement for the final disposal of the aforementioned waste.

It establishes basic considerations for the management of inert CDW from excavation, demolition or construction, which the various factors involved, must comply with, such as: Waste and excavation material generator (client and construction company), inert CDW manager (company or organisation that transports, recovers and disposes of it) and carrier of the excavation material for construction and demolition. Furthermore, it decrees the classification of waste from construction and/or demolition works and materials from excavation or roll forming. On the other hand, this standard does not establish basic considerations for the management of hazardous waste similar to that form households, which must be managed in accordance with current legislation.

This standard has **5** annexes, which are the following [14]:

- ANNEX A: List of inert CDW;
- ANNEX B: List of hazardous CDW;
- ANNEX C: List of CDW similar to that from households;
- ANNEX D: List of excavation material;
- ANNEX E: Minimum contents of a Management Plan.

3.2.4. Chilean Law No. 20.920—Framework for the Management of Waste, the Extended Liability of the Producer and the Promotion of Recycling

It was passed on 17 May 2016 and then published on 1 June of the same year. The body responsible for this law is the Ministry of the Environment. The purpose of this law is to decrease the generation of waste and promote its reuse, recycling and other types of recovery, through the implementation of the extended liability of the producer and other waste management instruments, with the goal of protecting the health of the people and the environment.

The execution of this law was inspired by a series of principles, such as gradualism, inclusion, waste management hierarchy, the principle of "he who pollutes, pays", free competition, the liability of the waste generator, transparency, traceability and disclosure.

For the purposes of the use and understanding of this law, it included a list of definitions. These are: Storage, life cycle, marketer, consumer, industrial consumer, distributor, ecodesign, disposal, generator, manager, management, reception and storage installation, handling, environmentally sound handling, best environmental practices, best techniques available, preparation for reuse, pre-treatment, priority product, producer of a priority product or producer, waste picker, recycling, collection, waste, reuse, management system, treatment, recovery and energetic recovery.

Chapter II of this law establishes everything related to waste management, such as prevention and recovery, obligations of waste generators, obligations of waste managers and obligations of waste importers and exporters.

On the other hand, Chapter III, named "of the extended liability of the producer", is comprised of three paragraphs. The first details the general provisions, establishing the concept of "extended liability of the producer", the obligations that priority product producers must comply with and the list of priority products. The second paragraph establishes the collecting and recovery goals and other associated obligations. Lastly, the third deals with everything related to waste management systems.

Chapter IV of this law details the support mechanisms for the extended liability of the producer, and lastly, Chapters V and VI establish the information systems and inspection and sanction regimes [15].

3.2.5. Integral Management of Solid Waste Policy (PGIRS in Spanish)

This policy is born from the instructions provided by the Environmental Policy for Sustainable Development, approved by the Executive Council of the National Environment Commission (CONAMA in Spanish) in January 1998, which offered different tools to improve the deficiencies diagnosed in the current situation regarding waste handling, identifying the actions to develop, both in the short and medium terms.

The purpose of this policy is to guide the implementation of a hierarchical strategy, promoting the prevention of its generation and, if its prevention is not possible, to promote, in this order, its reuse, recycling, energetic recovery, treatment and final disposal, all for the purposes of protecting the health of the people and the environment.

Furthermore, one of the important points included in this policy is the suggestion of the need to have an integral management of waste, whose starting point is the very development of the product. This concept is already successfully implemented in a majority of developed countries and the main objective is to prevent its generation. In the case where this is not possible, minimisation measures are followed in a hierarchical and orderly manner. These are: Reduction, reuse and recycling; with treatment and final disposal as the last and least desirable option.

On the other hand, this management policy includes the different guiding foundations and principles that surround its development, as well as its different lines of action, which are the specific measures that allow compliance with and the success of the objectives proposed by this policy; and the regulatory framework, which establishes the goals to be reached in the short and medium term [16].

3.2.6. Clean Production Agreement (APL in Spanish)

This is a voluntary agreement held between the representative corporate association of a productive sector and public bodies which are competent on several issues, the purpose of which is to improve the productive and environmental conditions in terms of hygiene and labour safety, energetic and hydrological efficiency, emission decrease, waste recovery, good practices, productive encouragement and other issues addressed by the agreement, looking to create synergies and economies of scale, as well as compliance with the environmental laws, which favour an increase in productivity and competitivity among companies.

To strengthen this tool, a key factor is the development of four Official Chilean Standards, which establish the guidelines for the development and implementation of, and accreditation of compliance with, Clean Production Agreements:

- NCh 2797.Of2003 "Clean Production Agreements (APL)—Specifications".
- NCh 2807.Of2003 "Clean Production Agreements (APL)—Diagnosis, Monitoring and Control, Final assessment and Accreditation of compliance".
- NCh 2825, on "Requirements for the final assessment auditors".
- NCh 2796, on "Vocabulary" applied to this Accreditation System.

Since the year 2016, the National council for Clean Production has decided to publicly report the decreases of emissions achieved through Clean Production Agreements in accordance with the Directive of the Ministry of the Environment. Between the years 2012 and 2016, estimated reductions reached 3,242,301 tonnes of CO_2, making the APL the first Chilean mitigation action to report reductions back to the United Nations [17].

3.2.7. Research Programmes Conducted in Chile

First Report on the Handling of Solid Waste in Chile (Based on the "Gathering, Analysis, Generation and Publication of National Information on Solid Waste in Chile" Project, Year 2010)

This report has been developed by CONAMA and summarises the main results of the "Gathering, analysis, generation and publication of national information on solid waste in Chile" project, completed in the year 2010.

In May of that year, Chile became the first full member of the Organisation for Economic Cooperation and Development (OECD) in South America. This status enforces a high standard on their public policies on environmental issues. With this, one of the commitments of Chile is to develop time series mainly associated to the generation, recovery and disposal of waste that facilitates the obtaining of indicators. The information exhibited in this report is part of the objectives of the Integral solid waste management policy. Furthermore, it meets the commitments that Chile has with the OECD regarding disseminating information on the handling of waste to the population. Among other sources, surveys, waste generation factors and diagnostic studies were referred to in order to conduct this report. The Government and the Ministry of the Environment have set as the main goal to continue improving on waste treatment issues. The ideal scenario is to enforce measures to stop seeing waste as rubbish, but instead as a raw material which can be minimised, reused and recycled.

This report is part of the "Gathering, analysis, generation and publication of information on solid waste in Chile" project, conducted in 2009. Its purpose is to deliver a general viewpoint of the amounts and handling of waste in Chile. The idea is to continue examining this information in coming years, in order to improve the national management standards.

As of the year 2005, through agreement No. 265 of the Council of Ministers of CONAMA, the country has:

- Integral Solid Waste Management Policy (PGIRS).
- Action Plan, which lasts until 2010.

The purpose of the Integral Solid Waste Management Policy is to guide the implementation of a hierarchical strategy, promoting the prevention of its generation and, if its prevention is not possible, to promote, in this order, its reuse, recycling, energetic recovery, treatment and final disposal, all for the purposes of protecting the health of the people and the environment. Likewise, among the lines of action until 2010, is to "Merge and complete the regulatory framework". In regard to this there is the Waste Act (Chilean Law No. 20,92), which includes essential concepts such as: Hierarchical strategy, extended liability of the provider and integral management of waste.

Chile, by becoming a member of the OECD, must comply in the established terms, with an information structure associated to solid waste which takes into account a series of requirements regarding definitions, regulations and the cross-border movement of waste, among others. As of 2010, Chile has a new environmental government body comprised of:

- Ministry of the Environment.
- Superintendency of Oversight.
- Environmental Assessment Service.
- Environmental Tribunal.

With the purpose of standardising the requirements, analysis and comparing of information on solid waste on an international level, the OECD suggested a detailed classifying of waste generation sources, which is linked to the classifications used in studies related to solid waste in Chile. Taking into account the main information structure available in the country and the separation of the source of the solid waste, they are classified as industrial solid waste and municipal solid waste [18].

Final "Gathering, Analysis and Generation of Information on Construction Waste" (Solid Waste Group of the Pontificia Catholic University of Valparaíso PUCV) Report

Its purpose is to provide complete information on the generation and handling of construction waste in Chile, in order to meet the requirements enforced by the OECD.

Furthermore, the following points can be established as specific objectives:

- Review the available information on construction and demolition waste.
- Complete and update the information on the generation and handling of construction waste, specifying the amounts and associated characteristics.
- Fill out the information requested on the OECD tables.
- The executing of the following activities was requested in order to conduct this report:
- To review the available information associated to construction waste on a national and international level.
- To modify and update the information associated to construction waste in Chile.
- To complete with the background information obtained from the model, the waste policy information on the OECD tables.
- To study of the "Gathering, analysis, generation and publication of national information on solid waste in Chile" report.

On the other hand, different measures are suggested to be added to the PGIRS. These are born from the results and conclusions obtained during the development of this study and are suggested with the purpose of continuing to improve the development of future research. The first one is a summary table which includes several items, then their current development situation and, lastly, the desired situation or condition to be met. Lastly, different ideas are suggested to enable the obtaining of future information [19].

- Analysis of waste streams.
- Waste generation estimate.
- Assessment of the most favourable scenario for future management.

Third Report on the State of the Environment, 2017 Edition. Chapter 13: Waste

This report corresponds to the third instalment, corresponding to the year 2017, which delivers an update of the country's environmental indicators and statistics, which makes it possible to monitor the evolution of the main components of the environment, as well as some of the problems that affect the country on this issue.

This report corresponds to the continuation of the first and second report on the environment, from the years 2013 and 2015, respectively. Likewise, as recommended by the OECD and as part of the advanced work on the issue of Sustainable Development Goals, as of this report, indicators are added which make it possible to measure the progress registered by the country regarding green growth, one of the great challenges in the medium and long term in order to promote an economic development which ensures the maintenance of the resources and the services they provide for people's quality of life [20].

Construction Waste in Antofagasta, Preliminary Study (by the Studies Unit of the Chilean Construction Chamber (CCHC in Spanish), in Antofagasta)

This study was conducted by the Studies Unit of the Chilean Construction Chamber (CCHC) in Antofagasta together with the work team from the Civil Construction degree of the Catholic University of the North, with the purpose of delivering a tool that helps improve the management of construction and demolition waste in this region.

A diagnosis of the current situation of construction waste management is submitted in this document. This assessment shows monthly generation indexes of these wastes, the role that construction companies must fulfil in the management of construction waste, and analyses potential options of locations to be used as final disposal points. Furthermore, an analysis of construction wastes, their origin, composition and classification are also submitted, as well as their optimal management and the review of an example of waste management both in Chile and abroad.

3.3. Interviews with Experts

Table 4 shows the interviewed experts from the construction sector of Chile.

Table 4. Experts interviewed in Chile.

Professional	Entity
Roberto Tedias A.	TVIAL Ltda. Construction Company
Jorge Fuentes F.	BROTEC Construction Company
Francisco Mora F.	Metropolitan Housing and Town Planning Service (SERVIU)
Gabriela Muñoz R.	National Roads Laboratory
Gabriel Palma P.	National Roads Laboratory
Víctor Reyes G.	Ministry of Public Works

3.3.1. Roberto Tedias Araya (Construction Engineer, General Manager of the TVIAL Ltda. Construction Company), Jorge Fuentes Fuentes (Civil Engineer, Technical Manager of the Brotec Ltda. Construction Company)

They are both aware of the future shortage of aggregates in Santiago de Chile, which is why they see recycling as a solution. They argue that it could be used directly on site without a washing process, which is conducted in a laboratory in order to run tests. Their experience in the use of recycled aggregates has been with crushed granular base and subbase, with structural landfill or embankment.

3.3.2. Francisco Mora Frtiz (Civil Engineer, Metropolitan SERVIU)

He says that recycled aggregate is not considered a construction material in any Chilean regulations, and that adding it would be quite interesting considering the future shortage of natural aggregate in the metropolitan region. Metropolitan SERVIU is interested in including sustainability in its regulations, but the problem is that there is no document which allows its insertion in the institution. Documents that state both technical and environmental specifications on the use of recycled materials are required. His argument is based on the fact that, for now, it is not good business because it cannot compete with natural aggregate. His experience with recycled aggregates is the following: Filler for sewers and crushed granular base and subbase as an aggregate to manufacture concrete for footpaths. At the SERVIU they are aware of the NCh 3562 standard.

3.3.3. Gabriela Muñoz Rojas, Gabriel Palma Papic (National Roads Laboratory)

The National Roads Laboratory has applied the Rubblizing (Technique that consists of fracturing concrete pavement through resonance, in order to intertwine the wastes, turning them into crushed granular base or subbase), making it possible to obtain recycled aggregate to be used as crushed granular base and subbase in the same location. They have used recycled aggregates in embankments and other types of fillers.

3.3.4. Víctor Reyes González (Civil Engineer, Ministry of Public Works)

The Ministry of Public Works is aware that natural aggregate is gradually becoming a less and less available resource, and that there will be greater difficulties to extract it from deposits or quarries. The closest that has been done regarding the use of recycled materials, is the RAP (RAP: Recycled Asphalt Pavement (Asfalto Reciclado para Pavimento)). At the Ministry of Public Works there is an interest to include innovation in regulations, and for this purpose there is a defined protocol which makes it possible to submit technology proposals to a specialised unit, which awards the use of "test sections" through the National Roads Laboratory. The greater the use of recycled materials, the less exploitation of natural aggregates, which will lead to a decrease in the levels of CO_2 released into the environment.

3.4. Technical Analysis

The materials considered in this study are concrete (for manufacturing roads), as well as crushed granular base and subbase (used as the support base in said roads as well as those built with asphalt). With a rising tide of adoption of recycled aggregate (RA) for construction, investigation on ways to improve the quality of RA has been overwhelming. The adoption of RA brings benefits including savings in the limited landfill spaces and the use of natural resources. However, the poorer quality of RA often limits its utilization to low grade applications such as sub-grade activities, filling materials and low grade concrete. The major reason that affects the quality of RA is the large amount of cement mortar remains on the surface of the aggregate, resulting in higher porosity, water absorption rates and thus a weaker interfacial zone between new cement mortar and aggregates, which weakens the strength and mechanical performance of concrete [21]. The results of a recent study [22] indicated that RA affect the resulting mechanical strength of hardened concrete due to the lower specific gravity and higher water absorption as compared to the natural aggregates (NA). Recycled coarse aggregate (RCA) has about 28% higher bonded mortar content (BMC) with porosity of bonded mortar (BM) almost double as that of recycled fine aggregate (RFA). This leads to inferior interface between aggregate and cement paste thereby affecting the overall concrete properties. The presence of mortar has been reported as the main factor causing the lower quality of recycled concrete aggregates (RCA) when compared to natural aggregates (NA). A novel microwave-assisted technique to increase the quality of RCA by partially removing the mortar adhering to RCA particles and breaking up the lumps of mortar present in RCA has been studied [23]. The intrinsic properties of recycled coarse aggregates (RC), associated with bonded mortar, can be modified with two different pre-treatment techniques viz-a-viz HCl pre-treatment and Na_2SO_4 pre-treatment [24]. Other authors report an experimental study to improve the properties of recycled concrete aggregates (RCA) by their impregnation with polyvinyl alcohol [25].

Concrete: The Roads Manual (Document produced for the purpose of establishing policies and unifying procedures and instructions in the various technical areas to which they apply (Chile)) establishes a minimum resistance of 5.0 MPa to the bending tension test. According to this requirement, it would be hard to reach this resistance using 100% recycled aggregate, as its use requires a larger amount of water, and therefore has lower mechanical resistance. It is only possible to do this when using recycled aggregates that have been obtained by demolishing high-performance concretes. It cannot be used in these amounts, as a greater amount of cement has to be used, which would not make it feasible in economic terms. Additionally due to the high likelihood of being affected by shrinking, this would cause cracks. The recommended amount of demolition waste to use according to Spanish literature is up to 20% of the weight. One of the features to consider is the curing based on a superficial film (membrane curing), as well as the superficial saturation [26].

To make it so that concrete with recycled aggregates reaches an ideal resistance, the surface of the stone material must have a minimum amount of adhered mortar. To do so, there are two possible methods to clean the said surface. The first is to wash it, which has the inconvenience of requiring a large amount of water, a resource that is currently scarce in the country and which would therefore noticeably increase costs. The other solution would be to implement a blower system, which makes it possible to clean the surface, but the problem is that doing so increases the levels of pollution, which is an equally critical factor in Santiago and the other regions [27–32].

Crushed granular base: The Roads Manual establishes the need to obtain a CBR bearing ratio of 60%. The values achieved in this field in international literature are of the order of 40% for subbases, conducted with asphalt waste, and of around 60% when conducted with concrete demolition waste. The use of crumb rubber in certain proportions is also considered, in order to not compromise its structural stability. The structural properties increase even more if asphalt waste such as RAP is used [33–36].

3.5. Result Analysis

Taking into account that which has been analysed, the following can be concluded.

3.5.1. Technical Legislation

In Spain there is technical legislation such as documents PG-3 and EHE-08, which consider the use of recycled aggregates, establishing limits, dosage and other aspects. In Chile however, current legislation only considers recycled materials in asphalt mixtures. The Roads Manual has specifications on the use of RAP, for example. However regarding the use of recycled aggregates, there is no legislation that allows its use in road works as of yet.

The interviewees mention that, in general, the construction sector is resisting considering the use of recycled aggregates, as there is distrust about its properties and a lack of knowledge on its benefits when used in road works.

3.5.2. Legal Legislation

In Spain there are laws that mandate the use of recycled materials and as well as penalising an inappropriate processing of CDW. The likely significant effects of projects on the environment must be considered in relation to criteria set out in points 1 and 2 of the Annex, with regard to the impact of the project on the factors specified in Article 3(1), taking into account, among other aspects, the possibility of effectively reducing the impact. [37]. The different environmental assessment systems operating within Member States should contain a set of common procedural requirements necessary to contribute to a high level of protection of the environment. [38]. The Public Administrations will adjust their actions regarding environmental assessment to the principles of institutional loyalty, coordination, mutual information, cooperation, collaboration and coherence [39].

In Chile, despite the existence of laws that regulate and penalise the disposal of waste, they only reference other types of waste (domestic and organic, among others), leaving construction and demolition waste out of their reach. As per the comments made by the interviewed professionals, they say that, as there are no laws that make recycling mandatory, it is hard to create a sustainable culture in the construction sector. Furthermore, within the administrative bases there is also no requirement to use recycled materials, not even a certain percentage.

In Spain,
there is:

- Spanish Law 10/1998;
- Spanish Law 21/2013;
- Spanish Law 22/2011;

- Order MAM/304/2002;
- Spanish Royal Decree 105/2008;
- Spanish Royal Decree 1247/2008;
- I PNRCD (2001–2006);
- II PNRCD (2008–2015);
- PEMAR (2016–2020).

In Chile,
there is:

- Chilean Law No. 19.300;
- Chilean Law No. 20.920;
- NCh 3562: Waste Management;
- Integral Solid Waste Management Policy (PGIRS)
- Clean Production Agreement (APL);
- Research programmes carried out in Chile.

3.5.3. RESCON Management Plan

In Spain, the CDW management plans are set, and have been dealt with since the year 2008 through Spanish Royal Decree 105/2008, whereas in Chile the only requirement is a certificate that states that the dumping site is one that has been authorised. There is no law that mandates the establishment of a plan to manage waste generated in works. Standard NCh 3562 tries to solve this situation.

3.5.4. Ministerial Structure

In Spain,

- There is an entity known as the Ministry of Public Works and Transport, which branches out into several Departments and Administrations. The General Administration of Architecture, Housing and Land, and the General Administration of Roads, are those responsible for Urban Roads and Interurban Roads, respectively (Figure 2).

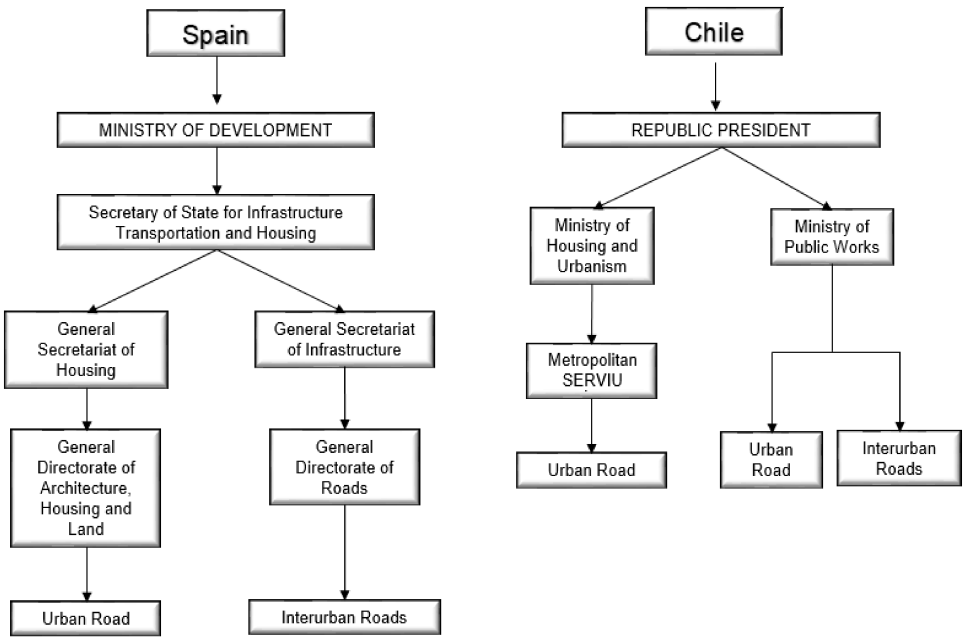

Figure 2. Government reality comparison between Spain and Chile.

In Chile,

- There is no responsible entity such as the mentioned Spanish one (Figure 2). There are only Ministries of Housing and Urban Development (which, through the SERVIU, is responsible for Urban Roads) and the Ministry of Public Works (responsible for Interurban Roads).

3.5.5. Infrastructure

In Spain, the CDW plans (PNRCD I, PNRCD II, PEMAR) establish the objectives for CDW in each respective application period, as mentioned in Tables 1 and 2. Furthermore, the PEMAR (2016–2022), establishes the number of permanent and mobile plants and dumping sites, as can be seen on Table 5.

Table 5. Number of plants and dumping sites in Spain.

PEMAR (2016–2022)	
Transfer Plants	174
Permanent Treatment Plants	396
Mobile Treatment Plants	134
Dumping sites	196

On the other hand, in Chile there are only two companies related to CDW. One of them is RESICO, where recycled aggregates are produced from concrete waste and which are then commercialised in two sizes (3″ and $1\frac{1}{2}$″), and the other is REGEMAC, a company which transfers this construction waste to authorised dumping sites.

In Spain there are different treatment plants and dumping sites.

In Chile there are only a few companies dedicated to recycling concrete aggregates (Table 6).

Table 6. Plants authorised for the disposal of CDW and debris.

No.	Company	Commune
1	REGEMAC	Puente Alto
2	SOCIEDAD BALTIERRA S.A.	Puente Alto
3	SEMOT LTDA.	Puente Alto
4	POZO AEROPUERTO AMB	Pudahuel
5	NEXO RESIDUOS LTDA.	Pudahuel
6	IDEA CORP S.A.	San Bernardo
7	MARGA MARGA S.A.	San Bernardo
8	SOC. PÉTREOS S.A.	Padre Hurtado
9	CERROS DE RENCA	Quilicura
10	RINCONADA S.A.	Maipú
11	SOC. AGRÍCOLA PIZARRO LTDA.	Pirque

3.5.6. Implementation of Recycled Aggregates

In Spain, the use of recycled aggregates has become standard practice, to the extent that this type of material is in the market, and with seals of quality. This situation makes it possible to define a wide variety of implementations, such as granular base and subbase, the manufacturing of test pieces (with a quality of up to G-40) (In accordance with Chilean standard NCh 170, Of. 2016 "Concrete—General Requirements". Mechanical resistance to compression is measured in Degrees, in cylindrical test pieces with a 15 cm diameter and 30 cm height.), concrete prefabs, fillers and embankments, among others.

Meanwhile, in Chile, the interviewed professionals mention a series of implementations such as granular base and subbase. The benefit of this context is that demolition waste can be used immediately, as it can be crushed in situ and then installed right away in the area where the future road project will be executed, aside from the fact that studies back this way of using this type of waste. When dealing with concrete pavement waste, bearing ratios close to 80% can be obtained, whereas asphalt pavement waste can reach a CBR value of 40% at most, which is why its use is limited to granular subbase.

On the other hand, the use of recycled aggregates is not recommended for manufacturing concretes, due to the low resistance levels obtained in tests conducted in their installations, coinciding with the observations made by the construction companies. In practice, the interviewees mention that, despite there being several methods for applying recycled aggregates in works, and the will to apply sustainability in the sector, there are factors that hinder its execution, as in Chile there is still no specific sustainable culture, a process which is currently being developed.

3.5.7. Solutions Proposed by the Experts

The experts offer solutions in accordance with the Chilean reality. All interviews were conducted in October 2018 (Tables 7–11):

Table 7. Opinion by Roberto Tedias Araya—Jorge Fuentes Fuentes.

Existing Problem	Proposed Solution
There are no laws that mandate the creation of a management plan for waste generated during construction.	The creation of NCh 3562 solves this item. The environmental authorities are the ones responsible for implementing these obligations in the sector.
There is a lack of knowledge on standard NCh 3562—Waste management.	When the standard is approved, its use must be facilitated through training on its appropriate implementation
Technical legislation does not include recycled aggregate as a construction material.	Including it in all of the country's technical legislation (Roads Manual, NCh, SERVIU regulations, among others). To this point, only the Roads Manual includes recycled materials (RAP).

Table 8. Opinion by Roberto Francisco Mora Fritz.

Existing Problem	Proposed Solution
There is no procedure that allows the insertion of research or innovation documents.	Create a protocol that streamlines the insertion of research on the use of recycled aggregates in construction. Establish incentives and/or rewards for the most innovative ideas.
There is no great interest in using recycled aggregates in paving works, due to the lack of technical knowledge on behalf of public bodies.	Promote recycled aggregates through research conducted in the sector, showing the benefits compared to its natural counterpart in different implementations in road and interurban works.

Table 9. Opinion by Gabriela Muñoz Rojas—Gabriel Palma Papic.

Existing Problem	Proposed Solution
In tests conducted on concretes with recycled aggregates, the results were critical due to the low resistance of the test pieces, both to compression and bending tension.	The use of concretes manufactured with recycled aggregates is recommended in cases where the resistance is not a critical factor.

Table 10. Opinion by Gabriela Muñoz Rojas—Gabriel Palma Papic.

Existing Problem	Proposed Solution
In the country there are no incentives to make use of recycled aggregates, due to their cost being greater than their natural counterpart.	Establish in the administrative bases of the projects to be tendered, a certain percentage of reuse of demolished materials based on technical criteria.

Table 11. In accordance with the experts': Factors must be considered in order to analyse the use of recycled aggregates.

Situation	Benefits	Disadvantages
Washing and blowing of CDW from concrete pavement demolitions.	Removes the layer of mortar adhered to the Surface of the CDW.	High cost per m^3 of water and high levels of pollution.
Installation of a mobile crushing plant on site.	Makes it possible to crush demolition waste in situ. Decrease of the transport cost of natural aggregate to the site. Decrease of the transport cost of construction waste to the dumping site.Decrease in pollution levels from lorries.	There is no appropriate space to install this machinery. Possible expansion of the project's deadline. Additional cost for the extra on-site use (in the case of communes that apply a tax for the use of a public asset. High machinery rental and purchase cost.
Rubblizing	Makes it possible to demolish the existing pavement and generate a layer of granular base in situ. Decrease of the transport cost of natural aggregates to the site. Decrease of the transport cost of the construction waste to the dumping site. Decrease in pollution levels from lorries.	High machinery rental and purchase cost.

In Spain,
the following products are manufactured for construction:

- Concrete test pieces (with a quality of up to G-40);
- Granular bases;
- Granular subbases;
- Securing and covering of pipes;
- Draining layers;
- Prefabricated pieces of concrete;
- Embankments;
- Fillings;
- Cement floor and cement gravel.

In Chile,

- Manufacturing of concrete test pieces (with a quality of up to G-30);
- Granular base;
- Granular subbase.

3.6. Research Works

In Spain,

- Companies are willing to support research works as a result of the change in mentality of European countries.
- European Union initiatives regarding applying a more sustainable outlook to the different economic sectors (e.g., construction), due to the possible shortage of aggregates endured in the continent.

In Chile,

- There is little willingness by companies to invest knowledge and collaborate with research projects.

3.7. Continental Reality

In Spain,

- Belongs to the European Union.

In Chile,

- Belongs to the Pacific Alliance, MERCOSUR and the Organisation of American States (OAS).

3.8. Insertion into the Market

In Spain,

- Recycled products from CDW are flagged with the "CE"mark. In French this means Conformité Européenne or European Conformity. It corresponds to a European mark for certain products or industrial groups.
- In Catalonia in 2016, 48% of CDW was recovered.
- It is predicted that by 2020, the recycled aggregates market will have developed enough so that its entire production is absorbed in different uses.

In Chile,

- Crushed granular base measuring <3" and $<1\frac{1}{2}$" is manufactured.

4. Conclusions

After analysing the Chilean and Spanish realities regarding waste management, the following is concluded:

1. The addition of recycled aggregate in Chilean technical legislation is suggested, both in the Roads Manual of the Ministry of Public Works as well as in the CNETOP of the SERVIU.

2. The creation of laws that penalise the deficient management of construction works, prohibit the extraction of natural aggregates in a gradual way and force companies to recycle or incentivise them to invest in technologies that enable the development of construction sustainability is suggested.

3. Even though recycled aggregates have been used in the construction of road works, its use is low due to:

- Lack of knowledge of the properties of recycled aggregates and its potential performance in construction works.
- High quality of natural aggregates and their extensive availability on the market.
- High manufacturing cost.
- Conservative attitude in the establishment of technologies and low tolerance of their performance by government bodies and construction companies.
- Investing in projects that encourage the use of recycled aggregates is recommended.

4. In road works and urban roads there is no construction and demolition waste management plan. Proof of this is the inexistence of a hierarchical process for its treatment, as is done in Spain. The only document required by current Chilean legislation is a certificate that proves that the dumping site is authorised. The approval of the NCh 3562 standard project would make it possible to solve both problems.

5. Both the Ministry of Public Works and the SERVIU have the intention of including recycled aggregates in their respective legislations. The difference between them is that the former has a protocol that allows the entrance of innovative proposals (with a prior analysis by the National Roads Laboratory it can make the Roads Manual). The said protocol does not exist in the latter, despite having proved

that recycled aggregates can be used when complying with the required specifications. Establishing a project admission system at the SERVIU (similar to the Ministry of Public Works) is recommended.

6. In Chile there is no ministry that fulfils the same function as the Spanish Ministry of Public Works and Transport. A similar entity is required in order to focus exclusive attention on these types of works and promote the use of recycled materials in them. However, as proposing this approach is not very feasible, boosting the functions of the Ministry of the Environment is recommended, in such a way that recycling and sustainable practices are an equal part of all the economic sectors of the country.

7. In the bidding for tenders phase, establishing measures that make it possible to estimate the amount of waste that will be allocated to recycling is suggested.

8. In Chile there is no infrastructure (treatment, transfer and final disposal plants) that enable the receival and treatment of CDW generated in works. Building them is proposed, thus generating optimal (construction) waste management processes, as is done in Spain.

Author Contributions: Conceptualisation and methodology, M.D.; Writing—original draft preparation, M.D., M.B.A., M.M.J. and D.B.; Writing—review and editing, M.D. and D.B.; Supervising, D.B.

Funding: This research received no external funding.

Acknowledgments: Adrián Díaz González, Civil Engineer of Civil Works, and the Santiago de Chile University, for their support in conducting this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. *Constitución Española*; Agencia Estatal Boletín Oficial del Estado: Madrid, Spain, 1978.
2. *Ley 10/1998, de 21 de abril, de Residuos*; Órgano Jefatura del Estado: Madrid, Spain, 1998.
3. *Ley 22/2011, de 28 de Julio, de Residuos y Suelos Contaminados*; Órgano Jefatura del Estado: Madrid, Spain, 2011.
4. *Orden MAM/304/2002, de 8 de Febrero, por la que se Publican las Operaciones de Valorización y Eliminación de Residuos y la Lista Europea de Residuos*; Agencia Estatal Boletín Oficial del Estado: Madrid, Spain, 2002.
5. *Plan Nacional de Residuos de Construcción y Demolición (I PNRCD) 2001–2006*; Agencia Estatal Boletín Oficial del Estado: Madrid, Spain, 2006.
6. *Plan Nacional Integrado de Residuos (PNIR) 2008–2015*; Anexo 6; Agencia Estatal Boletín Oficial del Estado: Madrid, Spain, 2008.
7. De Galarreta, M.C. Comentario al Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016–2022; Spain, 2016. Available online: http://www.perseaconsultores.es/plan-estatal-marco-de-gestion-de-residuos-pemar-2016-2022/ (accessed on 2 April 2018).
8. Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016–2022; Spain, 2016. Available online: https://www.aprr.eus/wp-content/uploads/2016/11/20151106PEMAR-2016_2022_apartado-13_pag96.pdf (accessed on 2 April 2018).
9. EHE–08 Instrucción de Hormigón Estructural. Available online: https://www.activatie.org/web/publicacion.php?id=380 (accessed on 22 February 2018).
10. Real Decreto 1247/2008, de 18 de julio, por el que se Aprueba la Instrucción de Hormigón Estructural (EHE-08); España, 2008. Available online: https://www.boe.es/eli/es/rd/2008/07/18/1247 (accessed on 3 April 2018).
11. Dirección de Vialidad. *Manual de Carreteras*. Available online: http://www.vialidad.cl/areasdevialidad/manualdecarreteras/Paginas/default.aspx (accessed on 12 April 2018).
12. Ley 19.300. Ley Sobre Bases Generales del Medio Ambiente; Chile, 1994. Available online: http://www.conaf.cl/wp-content/files_mf/1370463346Ley19300.pdf (accessed on 3 April 2018).
13. Constitución Política de la República de Chile; Chile, 1980. Available online: https://www.camara.cl/camara/media/docs/constitucion_politica.pdf (accessed on 23 April 2018).
14. NCh 3562: Gestión de Residuos–Residuos de construcción y demolición (RESCON) y Material de Excavación–Clasificación y Directrices Para Plan de Gestión; Chile. Available online: http://www.inn.cl/desarrollo-programa-normas-chilenas (accessed on 13 April 2018).

15. Ley 20.920. Ley Marco para la Gestión de Residuos, la Responsabilidad Extendida del Productor y Fomento al Reciclaje; Chile, 2016. Available online: https://mma.gob.cl/wp-content/uploads/2015/06/Presentacion-LEY-REP-20920_Junio_2016.pdf (accessed on 6 February 2018).
16. Etxeberria, M.; Vázquez, E.; Marí, A.; Barra, M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cem. Concr. Res.* **2007**, *37*, 735–742. [CrossRef]
17. Li, J.; Saberian, M.; Thach, B.; Nguyen, B. Effect of crumb rubber on the mechanical properties of crushed recycled pavement materials. *J. Environ. Manag.* **2018**, *218*, 291–299. [CrossRef] [PubMed]
18. Domingo-Cabo, A.; Lázaro, C.; López-Gayarre, F.; Serrano-López, M.; Serna, P.; Castaño-Tabares, J. Creep and shrinkage of recycled aggregate concrete. *Constr. Build. Mater.* **2009**, *23*, 2545–2553. [CrossRef]
19. Dilbas, H.; Simsek, M.; Çakır, Ö. An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume. *Constr. Build. Mater.* **2014**, *61*, 50–59. [CrossRef]
20. Silva, R.V.; de Brito, J.; Dhir, R.K. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [CrossRef]
21. Tam, V.W.Y.; Tam, C.M.; Le, K.N. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resour. Conserv. Recycl.* **2007**, *50*, 82–101. [CrossRef]
22. Kim, Y.; Hanif, A.; Usman, M.; Park, W. Influence of bonded mortar of recycled concrete aggregates on interfacial characteristics–Porosity assessment based on pore segmentation from backscattered electron image analysis. *Constr. Build. Mater.* **2019**, *212*, 149–163. [CrossRef]
23. Akbarnezhad, A.; Ong, K.C.G.G.; Zhang, M.H.; Tam, C.T.; Foo, T.W.J.J. Microwave-assisted beneficiation of recycled concrete aggregates. *Constr. Build. Mater.* **2011**, *25*, 3469–3479. [CrossRef]
24. Kim, Y.; Hanif, A.; Kazmi, S.M.S.; Munir, M.J.; Park, C. Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates–Comparative assessment of assorted techniques. *J. Clean. Prod.* **2018**, *191*, 339–349. [CrossRef]
25. Kou, S.C.; Poon, C.S. Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. *Cem. Concr. Compos.* **2010**, *32*, 649–654. [CrossRef]
26. Kou, S.; Poon, C. Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Constr. Build. Mater.* **2015**, *77*, 501–508. [CrossRef]
27. Behera, M.; Bhattacharyya, S.K.; Minocha, A.K.; Deoliya, R.; Maiti, S. Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review. *Constr. Build. Mater.* **2014**, *68*, 501–516.
28. Saberian, M.; Li, J.; Nguyen, B.; Wang, G. Permanent deformation behaviour of pavement base and subbase containing recycle concrete aggregate, coarse and fine crumb rubber. *Constr. Build. Mater.* **2018**, *178*, 51–58. [CrossRef]
29. Abdel-Hay, A.S. Properties of recycled concrete aggregate under different curing conditions. *HBRC J.* **2017**, *13*, 271–276. [CrossRef]
30. Bo, W.; Yong, Y.; Zhao, X.-Y. Residual mechanical properties of compound concrete containing demolished concrete lumps after exposure to high temperatures. *Fire Saf. J.* **2019**, *105*, 62–78.
31. Bo, W.; Hemao, J. Compressive fatigue behavior of compound concrete containing demolished concrete lumps. *Constr. Build. Mater.* **2019**, *210*, 140–156.
32. Hadavand, B.; Imaninasab, R. Assessing the infuence of construction and demolition waste materials on workability and mechanical properties of concrete using statistical analysis. *Innov. Infrastruct. Solut.* **2019**, *4*, 29. [CrossRef]
33. Gupta, N.; Kluge, M.; Chadik, P.; Townsend, T. Recycled concrete aggregate as road base: Leaching constituents and neutralization by soil Interactions and dilution. *Waste Manag.* **2018**, *72*, 354–361. [CrossRef]
34. Arulrajah, A.; Disfani, M.; Horpibulsuk, S.; Suksiripattanapong, C.; Prongmanee, N. Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications. *Constr. Build. Mater.* **2014**, *58*, 245–257. [CrossRef]
35. Arshad, M.; Ahmed, M. Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pavements. *Constr. Build. Mater.* **2017**, *151*, 83–97. [CrossRef]
36. Ahmed, E.; El-Maaty, B. Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. *Ain Shams Eng. J.* **2013**, *4*, 661–673.

37. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0052 (accessed on 3 June 2019).
38. Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programs on the environment (OJ L 197, 21.7.2001, p.30). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32001L0042 (accessed on 3 June 2019).
39. Spanish Law 21/2013 of December 9 of environmental impact assessment. Available online: https://www.boe.es/eli/es/l/2013/12/09/21/con (accessed on 3 June 2019).

8.2. Artículo 2

Marcos Díaz González; Pablo Plaza Caballero; David Blanco Fernández; Manuel Miguel Jordán Vidal; Isabel Fuencisla Sáez del Bosque y César Medina Martínez (2021). The Design and Development of Recycled Concretes in a Circular Economy Using Mixed Construction and Demolition Waste. Materials 2021, 14, 4762. **https://doi.org/10.3390/ma14164762**

materials

Article

The Design and Development of Recycled Concretes in a Circular Economy Using Mixed Construction and Demolition Waste

Marcos Díaz González [1,*], Pablo Plaza Caballero [2], David Blanco Fernández [1], Manuel Miguel Jordán Vidal [3], Isabel Fuencisla Sáez del Bosque [2] and César Medina Martínez [2]

[1] Department of Construction Sciences, Metropolitan Technological University, Dieciocho, Santiago de Chile 161, Chile; dblanco@utem.cl

[2] Department of Construction, Research Institute for Sustainable Territorial Development (INTERRA), University of Extremadura, 10003 Cáceres, Spain; pcaballerop@unex.es (P.P.C.); isaezdelu@unex.es (I.F.S.d.B.); cmedinam@unex.es (C.M.M.)

[3] Department of Agrochemistry and Environment, Miguel Hernández University of Elche, 03202 Elche, Spain; manuel.jordan@umh.es

* Correspondence: mdiaz@utem.cl

Abstract: This research study analysed the effect of adding fine—fMRA (0.25% and 50%)—and coarse—cMRA (0%, 25% and 50%)—mixed recycled aggregate both individually and simultaneously in the development of sustainable recycled concretes that require a lower consumption of natural resources. For this purpose, we first conducted a physical and mechanical characterisation of the new recycled raw materials and then analysed the effect of its addition on fresh and hardened new concretes. The results highlight that the addition of fMRA and/or cMRA does not cause a loss of workability in the new concrete but does increase the amount of entrained air. Regarding compressive strength, we observed that fMRA and/or cMRA cause a maximum increase of +12.4% compared with conventional concrete. Tensile strength increases with the addition of fMRA (between 8.7% and 5.5%) and decreases with the use of either cMRA or fMRA + cMRA (between 4.6% and 7%). The addition of fMRA mitigates the adverse effect that using cMRA has on tensile strength. Regarding watertightness, all designed concretes have a structure that is impermeable to water. Lastly, the results show the feasibility of using these concretes to design elements with a characteristic strength of 25 MPa and that the optimal percentage of fMRA replacement is 25%.

Keywords: recycled concrete; recycled mixed sand; recycled mixed gravel; mechanical properties; strength; watertightness

Citation: González, M.D.; Plaza Caballero, P.; Fernández, D.B.; Jordán Vidal, M.M.; del Bosque, I.F.S.; Medina Martínez, C. The Design and Development of Recycled Concretes in a Circular Economy Using Mixed Construction and Demolition Waste. *Materials* **2021**, *14*, 4762. https://doi.org/10.3390/ma14164762

Academic Editor: Jean-Marc Tulliani

Received: 5 July 2021
Accepted: 4 August 2021
Published: 23 August 2021

1. Introduction

Climate change and global warming have become important issues that directly impact the world economy. This has led to countries developing laws and regulations that control the emission of CO_2 and the appropriate management of waste. In this context, the construction industry is responsible for 12% of all greenhouse gas emissions in the European Union (EU) and for generating ~25–30% of the solid waste produced every year in the EU [1], which equates to an average annual production of 800 million tonnes. In addition, as many as 534 and 200 million tonnes of construction and demolition waste (C&DW) are generated every year in the United States and China, respectively.

Concrete is the most used material in the construction sector worldwide, with the EU and USA producing 165 and 150 million cubic metres, respectively, in 2018 [2]. This industry is characterised by requiring large amounts of natural resources, as this material is mainly composed of aggregates—60–75% of the volume of concrete—and, to a lesser extent, cement—10–15%. Its manufacturing process is responsible for ~8% of the total worldwide amount of CO_2 [3]. Three trillion tonnes of aggregate were used in the field of civil engineering in 2018, ~45% of which were used to manufacture concrete [4].

In this context, the construction industry has tried to mitigate the adverse effects of its activity in recent years by designing and developing new formulations for materials with a cement base (mortars and/or concretes) that are more sustainable [5,6]. This has been done by adding industrial by-products (agroforestry or biomass waste, ornament and ceramics [7] industry and construction and demolition waste [8,9]) as supplementary cementitious materials and/or recycled aggregate (concrete or mixed waste from C&DW). The use of recycled aggregate from C&DW is one of the most widespread strategies for simultaneously achieving the double goal of instituting the concept of circular economy and sustainability in construction.

Recycled aggregates are obtained from the appropriate treatment of C&DW in management plants, where they are classified in granulometric fractions (mainly sand, coarse and gravel) depending on their size and composition. According to this last criterion, they are classified as (i) recycled concrete aggregates (RCA) with amounts of concrete (Rc) and unbound aggregates (Ru) $\geq$90% and $\leq$10% of ceramic materials (Rb), (ii) mixed recycled aggregates (MRA) with 70% $\leq$ Rc + Ru < 90% and Rb $\leq$ 30% and (iii) recycled masonry aggregates (RMA) with Rc + Ru < 70% and Rb > 30.

RCA are recycled aggregates that have been studied in greater depth in the international literature, focusing mainly on the coarse fraction (maximum particle size $\geq$ 4 mm). In this line of work, it is worth highlighting the study conducted by Bravo et al. [10], who found that the density decreased between 4.7% and 7.7% by adding 100% of RCA, while considering that their mechanical strength decreases if their composition includes particles of a ceramic nature. Moreover, Thomas et al. [11] concluded that the density of concretes decreased by 5% with a 20% of RCA replacement due to the high porosity and the presence of adhered mortar. Etxeberría et al. [12] analysed concretes with 100% RCA, a water–cement ratio of 0.5 and 325 kg of cement/m^3, registering a decrease between 20% and 25% decrease in compressive strength compared with the reference concrete. This loss could be offset by increasing the cement content, a strategy which is of no interest economically or from the viewpoint of sustainability. Likewise, these authors observed that concretes with average compressive strength (30–45 MPa) manufactured with 25% recycled coarse aggregate had the same mechanical properties as traditional concrete. McNeil et al. [13], in their literature review, were able to summarise their findings on what concretes with RCA experience: (1) replacing natural aggregate (NA) in concrete with RCA decreases the compressive strength but yields comparable splitting tensile strength; (2) the modulus of rupture for RCA concrete was slightly lower than that of conventional concrete, likely due to the weakened interfacial transition zone (ITZ) from residual mortar; and (3) the elastic modulus is also lower than expected, caused by the more ductile aggregate.

As regards assessing the fine fraction of RCA, there have been fewer studies that have focused on studying the design of structural concretes. Evangelista et al. [14] assessed the feasibility of adding the fine fraction of RCA and observed that the compressive strength was not impacted for percentages $\leq$30% in weight. Minkwan et al. [15] found that the compressive strength of concrete with 100% of fine RCA decreased by approximately 30% and 10% compared with the reference concrete with normal strength and high strength, respectively. Bravo et al. [16] observed that (i) recycled mixes with contents of fine RCA $\leq$25% have properties that are comparable with those of the reference concrete and (ii) contents of RCA >25% cause decreases in the properties, leading to losses of up to 19% compared with traditional concrete.

Regarding the simultaneous use of coarse and fine RCA, Fernández et al. [17] concluded that the properties that are impacted the most due to replacing natural aggregate with recycled aggregate are workability (with 100% coarse aggregate replacement, it more than doubles compared with the reference concrete), the elastic modulus (decreases by 42% with 100% coarse aggregate replacement and also decreases by 7% with 30% fine aggregate replacement), the contractive deformation (obtaining deformations between 40% and 56%

after 360 days with 100% coarse aggregate replacement) and water absorption (between 8.5% and 9%, proportions that are higher than the 5% established by the Spanish Code on Structural Concrete, or Structural Concrete Instruction EHE-08).

Plaza et al. [18] report that the use of small percentages (<25%) of coarse concrete aggregate alone or with recycled concrete sand decreases the total porosity and refines the structure of the pores. The opposite effect was observed for higher percentages. Recycled concretes have less compressive strength after 28 days than the conventional material, although the decrease was less than 17% in all cases studied. The loss of strength is greater in mixes that have recycled mixed fines. Regarding tensile strength, Plaza et al. [18] revealed that it increased by 9.49% with a coarse recycled aggregate replacement rate of 100%. However, in replacement mixes (50% coarse aggregate + 50% fine aggregate) this property decreased by up to 14.13%. Furthermore, there was a 1.74% increase in strength in concretes with no coarse aggregate replacement but with 50% mixed fine aggregate compared with the reference concrete. Corinaldesi et al. [19], Malesev et al. [20] and López et al. [21] noted that the elastic modulus decreased between 15% and 44.8% compared with the reference concrete, where the recycled coarse aggregate had a greater negative influence. Lovato et al. [22] even reveals that for the same level of axial compressive strength, higher than 20 MPa, and despite the greater consumption of cement, the costs are similar to those of the reference concrete and only vary by around 20%. Agrela et al. [23] suggest the following classification for RA: Recycled concrete aggregate, with >90% concrete; Mixed recycled aggregates (MRA), with between 30% and 10% ceramic content; and recycled ceramic aggregates, with >30% ceramic content. Regarding flexural strength [18], it is similar in conventional concrete and recycled concrete with less than 75% replacement. In higher percentages, the use of recycled materials in both fractions causes up to a 15% strength loss. Recycled concretes that have both coarse aggregate recycled concrete and recycled sand are suitable for their use in structural concretes with a characteristic strength of 30 MPa.

Regarding mixed recycled aggregates (MRA), due to the volume they represent of the total amount of C&DW (~67% of the total in Spain), in the past decade they have aroused the interest of the scientific community. There is currently a scientific–technical shortcoming in the feasibility of assessing the coarse and/or fine fractions in the design of concretes. In this regard, Sáez del Bosque et al. [24] revealed that the elastic modulus of the ITZ (Interfacial Transition Zone) varies with the type of materials that are present in the recycled aggregate, with ITZs associated with organic components (such as wood, plastic and asphalt) having a lower minimum elastic modulus value depending on the content of ceramic and concrete particles. Recently, Martínez-Lage et al. [25] recorded that the addition of 100% of MRA entailed saving more than 35% of waste generation and 50% of abiotic depletion. Martínez-Lage et al. [26] revealed that the decrease in compressive strength and the deformation modulus vary from 20% to 30% and 30% to 40%, respectively, in concretes with 100% coarse recycled aggregate replacement rate. Meanwhile, Poisson's ratio, which is independent of the rate of replacement, varied from 0.14 to 0.2. Mas et al. [27] revealed that compressive strengths, 90 days later and with 30% coarse aggregate replacement, decreased by 23.8% for CEM II cements and 13.5% for CEM III/A. The strength increased, with 50% replacement, by +7.5% for CEM V/A cement (Series 1-CEM V). López et al. [28] produced non-structural concretes with 100% coarse aggregate replacement using concretes with low strength (15 MPa), using 200 kg cement/m^3 of concrete. Meanwhile, Medina et al. [29] revealed that the use of MRA in concretes with a 25% coarse aggregate replacement rate has no effect on the absorption capacity. However, at a replacement rate of 50%, the sorptivity of recycled concretes is 10–20% higher than the reference concrete. Cantero et al. [30] concluded that in concretes with coarse MRA, the higher the replacement rate, the lower the density in a fresh state and the higher the air content: in concrete with a 100% rate of replacement, the density was 7% lower and the air content 37% higher than the reference concrete. It also backs its use in concretes, with a characteristic strength of 30 MPa.

As a result of the research conducted, recycled aggregates have been added unevenly in the regulation of concrete in different countries. Table 1 shows the type of recycled aggregate, fraction and maximum percentage (minimum and maximum value) allowed by each continent, as well as the type of concrete (structural or non-structural) that can be crafted using recycled aggregates. It also shows that the common aspect is that all continents allow the use of the coarse fraction of RCA and RMA, whose maximum limit of replacement ranges from 15% to 100% for structural or non-structural concretes. Regarding the fine fraction of RCA, it reveals that, with the exception of the American continent, its use is allowed in the eco-design of new concretes. In addition, fine MRA is only allowed for non-structural uses. In this context, it is worth noting that in South American countries [31], the technical regulation does not yet allow the use of recycled aggregate (RCA/MRA), due to the lack of trust it generates and the absence of authorised managers of C&DW who obtain optimal quality recycled aggregates that are durable.

Table 1. Recycled aggregates in international regulation. Typology and maximum rate of incorporation.

Continent	Material	Fraction	% Allowed		Type of Concrete
			Minimum Value	Maximum Value	
Asia (China, Korea and Japan)	RCA	Coarse	20	100	Structural
		Fine	30	100	Structural
		Coarse	0	100	Non-structura
		Fine	0	30	Non-structural
Australia	RCA	Coarse	-	30	Structural
	MRA	Coarse	-	100	Structural
Europe (Belgium, Germany, Italy, Denmark, Holland, Portugal, Switzerland, United Kingdom, France, Spain)	RCA	Coarse	15	100	Structural
		Coarse/Fine	-	100	Structural
	MRA	Coarse	25	100	Structural
		Fine	-	20	Non-structural
America (Brazil)	RCA	Coarse/Fine	-	100	Non-structural
	MRA	Coarse/Fine	-	100	Non-structural

Note. RCA: recycled concrete aggregate; MRA: mixed recycled aggregate.

In this context, the main novelty of this research study lies in delving into the progress of the knowledge on the joint valorisation of the coarse and fine fraction of mixed recycled aggregate, as research conducted heretofore had focused mainly on the RCA fraction and, to a lesser extent, on the coarse fraction of MRA. There are no prior studies that simultaneously use fine and coarse MRA to produce structural recycled concretes. Likewise, this study contributes to the development of regulation or guides that make it possible to, depending on the quality of the fMRA (their composition and intrinsic properties), establish the applications where they could be used, such as the concrete industry, defining the minimum parameters it must meet to comply with the building code and the areas of environmental exposure where new concretes can be used, as well as other applications in the scope of the construction sector. As stated by Plaza et al. [18], the partial replacement of natural aggregate with coarse recycled aggregate alone or together with fine recycled aggregate (RCF) from concrete wastes has a generally beneficial effect on eco-efficiency (the relation between compression, tensile strength, bending and CO_2 emitted), with values that are similar or greater than those shown by HP (conventional concrete). The use of coarse recycled aggregate concrete and RMF (recycled mixed fine aggregate) has a beneficial effect on eco-efficiency to split tensile strength (strength/CO_2 emission ratio), whereas the eco-efficiency is slightly lower (<3%) than HP in terms of compressive and flexural strength. The benefits of using coarse and/or fine recycled aggregate to partially replace natural aggregate are not only a decrease in the emissions of CO_2 when manufacturing concrete but also the significant mitigation of environmental issues triggered by gathering the necessary waste.

In this line of research, the main goal of this research was to further deepen scientific and technical knowledge on the simultaneous use of the fine and coarse fractions of the mixed fraction of construction and demolition waste as components of the granular skeleton of recycled concretes. Doing so required characterising the physical (density, entrained air and consistency) and mechanical (compressive, tensile and flexural strength) characterisation, as well as the watertightness under pressure, of the new eco-concretes, which include 0%, 25% and 50% of coarse MRA and/or 0%, 25% and 50% of fine MRA, which can be used for applications in the field of civil engineering and construction.

2. Materials and Methods

2.1. Materials

The natural aggregate (NA) used was crushed siliceous greywacke with sharp edges and layered shapes (see Figure 1) which comes in two granulometric fractions: (i) natural 0/6 mm sand (fNA); and (ii) natural 6–12 mm gravel (cNA). This aggregate meets all the requirements of European standard EN 12620 for aggregates used to manufacture concretes. Table 2 shows the physical and mechanical properties of the aggregates used in the study, as well as the requirements stipulated by European standard 12620 [32] and EHE-08 for aggregates used to manufacture concretes [33].

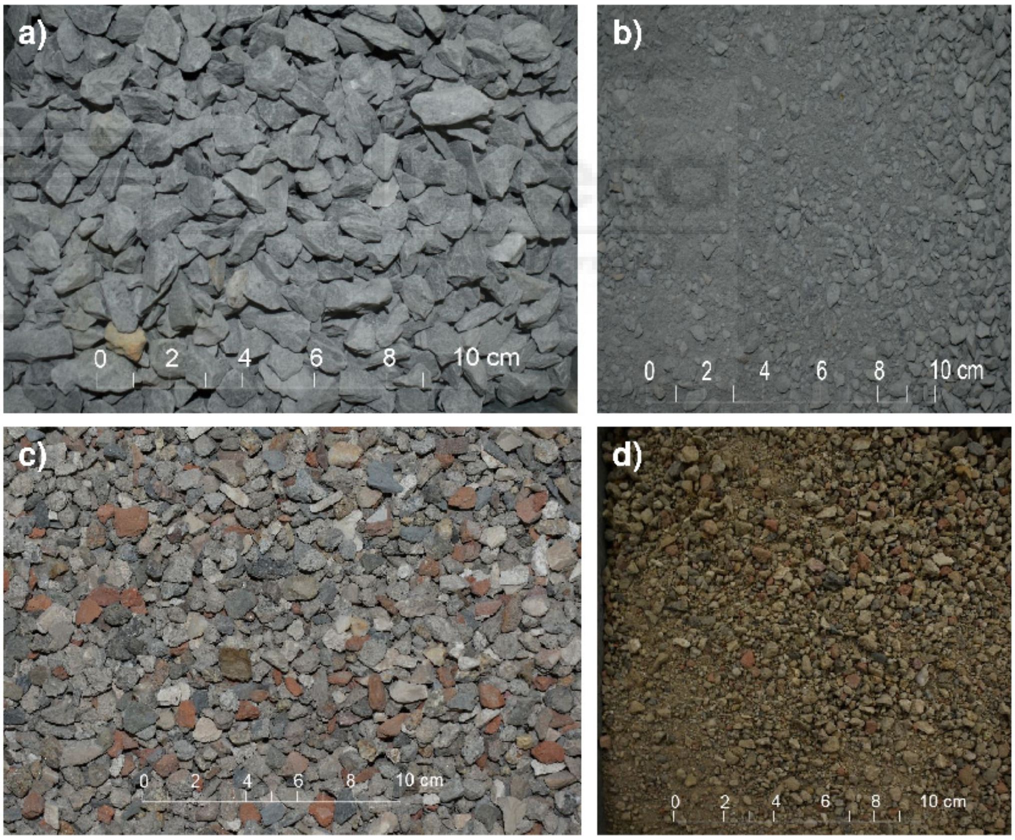

Figure 1. View of the aggregates used to manufacture concretes. Legend: (**a**) View of natural aggregate; (**b**) View of natural aggregate after grinding; (**c**) View of recycled aggregates and (**d**) View of recycled aggregates after grinding.

Table 2. Physical and mechanical properties of the aggregates.

Property	Aggregates				EN-12620/ EHE08
	fNA	cNA	fMRA	cMRA	
Dssd (kg/m^3) [34]	2.76	2.74	2.70	2.42	-
WA_{24} (wt %) [34]	1.18	0.88	5.39	6.28	<5
LC (wt %) [35]	-	16	-	32	<40
FI (wt %) [36]	-	21		10	<35

Note. fNA: natural sand; cNA: natural gravel; fMRA: mixed recycled sand; cMRA: mixed recycled gravel; Dssd: dry saturated surface density; WA_{24}: water absorption coefficient after 24 h; LC: Los Angeles coefficient; and FI: flakiness index.

The MRA used came from the ARAPLASA C&DW management plant, located in the north of the province of Cáceres (Spain), which came, like natural aggregates, in two fractions: (i) recycled mixed 0/6 mm sand (fMRA) and (ii) mixed recycled 6/12 mm gravel (cMRA). Regarding their morphology, they are characterised by preferably having rounded and slightly layered shapes (see Figure 1). Regarding their composition (see Table 3), the gravel is characterised by being comprised by ~88% debris from unbound concrete, mortar and aggregate, as well as ~11% ceramic material (tile, blocks, bathroom fittings, etc.) and other minority components (<1.3%), mainly floating particles (plastic and wood), gypsum and glass, in a percentage that makes up less than 1% of the weight. In addition, it is worth noting that fMRA was obtained from the same MRA as cMRA, with the former having a reddish colour due to the presence of ceramic fines.

Table 3. Components of the mixed recycled gravel (cMRA) (EN 933-11 classification [37]).

Class	Type	Content (% Weight)
Rc	Concrete and mortar	43.98
Ru	Natural stone	43.94
Rc + Ru		87.82
Rb	Baked clay material	10.93
Ra	Asphalt	0.87
FL	Floating particles	0.02
G	Gypsum	0.34
X + Rg	Others and glass	0.02

Figures 1 and 2 shows the granulometric distribution of the natural and recycled aggregates, revealing that they all have a continuous grain size. Likewise, it reveals that regardless of their nature, sands are within the granulometric spectrum recommended by EHE-08 for manufacturing concretes, as is the amount of particles that pass through the 0.063 mm sieve, which is less than 10% of the weight, the maximum limit stipulated by EHE-08 for crushed sands of a siliceous nature.

The Portland cement used was a CEM I 42.5 R that met all the physical, chemical and mechanical requirements established by European standard EN 197-1 [38] and was supplied by the plant of the Lafarge Holcim group located at Villaluengo de la Sagra in the province of Toledo (Spain). Lastly, we used superplasticiser additive FUCHS BRYTEN NF, a water-reducing additive made of modified polycarboxylate with a base of water and a brownish colour. It is free of chloride, has a ~20% content of solids, a density of 1.1 g/cm^3 and pH = 8.0 and was supplied by FUCHS Lubricantes S.A.U.

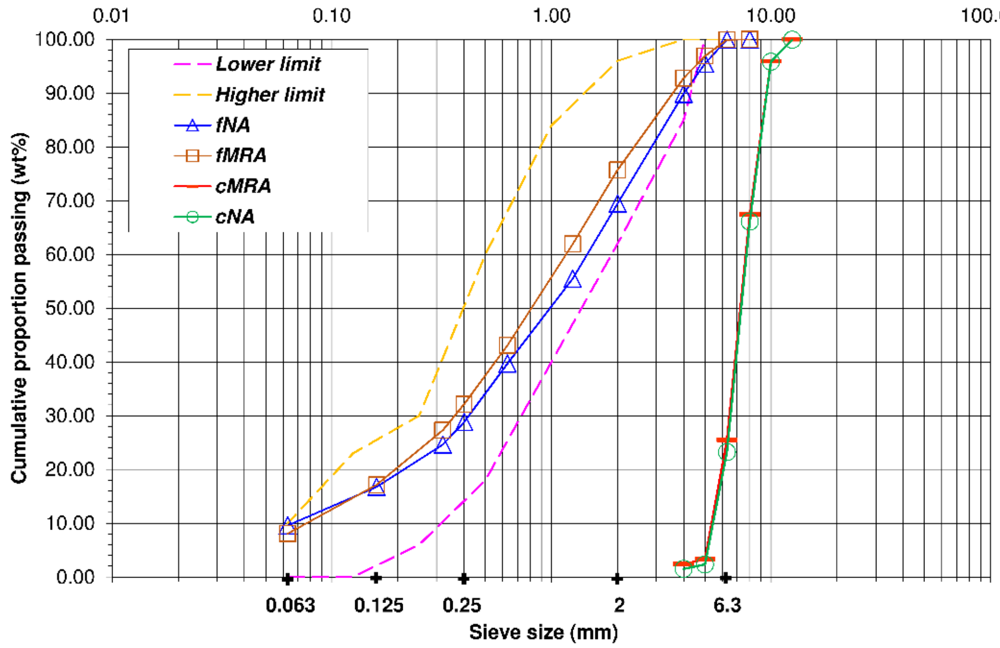

Figure 2. Granulometric distribution of aggregates (NA and MRA).

2.2. Concrete Properties Studied

Table 4 lists the properties analysed in fresh and hardened states, as well as the standard that describes the trial methodology and size of the samples used to assess the property being studied.

Table 4. The concrete properties analysed in fresh and hardened states.

Properties	Trial	Standard	Sample Size (mm)	Trial Duration (days)
Physical	Density	EN 12350-6 [39]	Cubic 150 × 150 × 150	Beginning
	Entrained air	EN 12350-7 [40]	-	Beginning
	Consistency	EN 12350-2 [41]	-	Beginning
Mechanical	Compression	EN 12390-7 [42]	Cubic 150 × 150 × 150	7, 28 and 90
	Traction	EN 12390-6 [43]	Cylindrical 100 ϕ × 200	28
	Bending	EN 12390-5 [44]	Prismatic 100 × 100 × 400	28
Durable	Penetration under pressure	EN 12390-8 [45]	Cylindrical 150 ϕ × 300	28

2.3. Mix Design

Nine mixes were manufactured: (i) Conventional concrete, with 100% NA (M1); (ii) Concrete with 25% fine MRA (M2); (iii) Concrete with 50% fine MRA (M3); (iv) Concrete with 25% coarse MRA (m4); (v) Concrete with 25% fine MRA and 25% coarse MRA (M5); (vi) Concrete with 50% fine MRA and 25% coarse MRA (M6); (vii) Concrete with 50% coarse MRA (M7); (viii) Concrete with 25% fine MRA and 50% coarse MRA (M8); (ix) Concrete with 50% fine MRA and 50% coarse MRA (M9).

In order to design and formulate the mixes we used the mix-design rules [46], taking as baseline data a design characteristic strength (f_{ck}) of 25 MPa (C25/30), a maximum aggregate size of 12.5 mm, a constant effective water–cement ratio (w/c) of 0.45 and an S2 target workability as established in EN 206-1 [47], which is equivalent to a 70 ± 20 mm slump. Likewise, dry aggregates were taken into consideration in this dosage process, as well as the water absorption of the recycled aggregates in the first 10 min of being immersed in water (~70% of the total water absorption after 24 h). With this strategy, we guaranteed that all mixes had the same amount of water available to hydrate the cement, regardless of their granular skeleton. In addition, 5.89 kg/m^3 of additive was added in order to achieve a suitable workability with this w/c ratio.

All the mixes designed met the dosing requirements (minimum cement content: 300 kg/m^3 and maximum effective w/c ratio: 0.55) stipulated by European standard EN-206-1 [47] for durability class XC2. The mixes studied (Table 5) were prepared in an 85-litre laboratory vertical shaft mixer using the following procedure: (i) the coarse aggregate (cNA and cMRA) was mixed for 30 s; (ii) the fine aggregates (fNA and fMRA) were added and the materials were mixed for 30 s; (iii) the binder (cement) was added, mixing it for 60 s; (iv) then 80% of the mixing water was added as well as the superplasticiser additive, mixing it for 45 s and (v) the remaining water was added and mixed for 240 s. Lastly, the samples were manufactured and cured following European standard EN 12390-2 [48].

Table 5. Composition of the concretes designed.

Materials (kg/m^3)	Mix								
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
fNA	916.8	684.0	446.4	902.4	666.0	434.4	888.0	648.0	429.6
fMRA	0.0	228.0	446.4	0.0	222.0	434.4	0.0	216.0	429.6
cNA	993.2	988.0	967.2	733.2	721.50	705.90	481.0	468.0	465.4
cMRA	0.0	0.0	0.0	244.4	240.5	235.3	481.0	468.0	465.4
Cement	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0
Water	224.4	228.9	231.1	232.8	237.4	241.5	243.9	247.5	252.3
Additive	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9

Figure 3 summarizes the manufacturing process and tests carried out on the studied mixtures.

Figure 3. Flow diagram corresponding to the manufacturing process and tests carried out on the studied mixtures.

3. Results and Discussion

3.1. Properties in a Fresh State

3.1.1. Consistency

Table 6 shows the results of consistency, entrained air content and density of the concretes designed. Regarding consistency, all mixes were within the target design workability (50 ≤ S2 ≤ 90 mm), which reveals that adding the mixed recycled fine and/or coarse fraction does not have a negative effect on this property. This result is in line with Plaza et al. [18] who observed that the simultaneous addition of recycled concrete aggregate and concrete or mixed sand does not lead to a decline in the workability of recycled concretes. This behaviour is in line with Agrela et al. [23] and Medina et al. [29] who respectively suggested, as strategies to mitigate the negative effect that the higher water absorption of recycled aggregates has on this property, to pre-saturate them before the mixing process or to add the water initially absorbed by these recycled aggregates to the dosage.

Table 6. Concrete properties in a fresh state.

Mix	Consistency (cm)	Entrained Air (vol %)	Density (kg/m^3)
M1	6.00	1.97	2416.37
M2	6.00	3.00	2380.97
M3	5.17	3.90	2354.57
M4	5.50	2.20	2372.79
M5	5.50	3.60	2322.27
M6	6.50	5.50	2275.41
M7	6.50	2.77	2331.01
M8	5.67	4.20	2286.24
M9	5.17	5.57	2288.47

Figure 4 shows the concrete slump test of conventional concrete (M1) and concrete with a higher content of MRA, highlighting that the individual or simultaneous use of the fractions does not have a negative effect on this property.

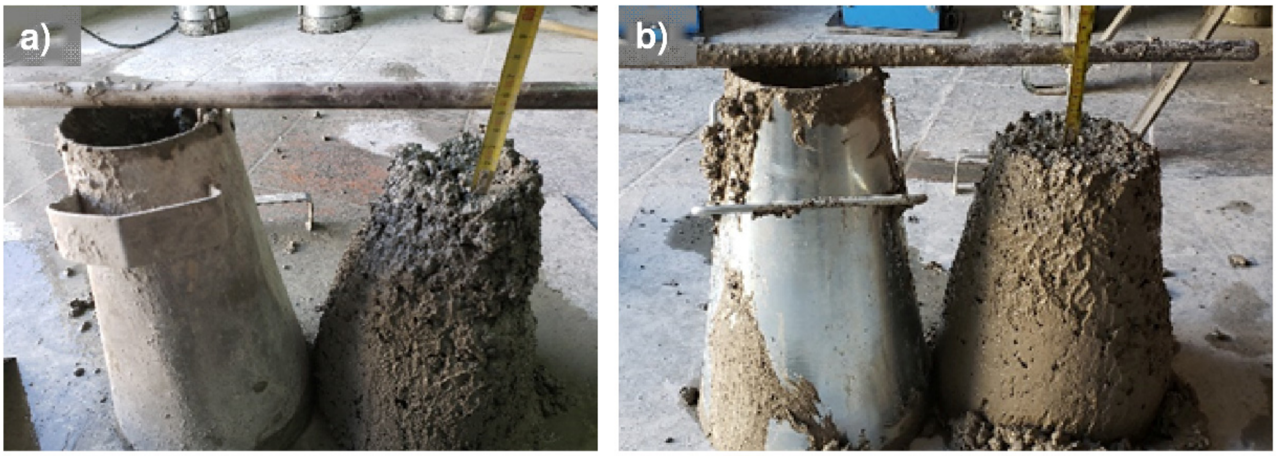

Figure 4. Concrete slump test: (**a**) Concrete with 100% NA (M1) and (**b**) Concrete with 50% fMRA and cMRA (M9).

3.1.2. Entrained Air

Table 6 lists the amount of entrained air in fresh concrete, revealing that the addition of fine and/or coarse MRA caused an increase in this property, with the value for M3 (50% fMRA), M7 (50% cMRA), M8 (25% fMRA + 50% cMRA) and M9 (50% fMRAf 50% cMRA) being 1.9, 1.4, 2.1 and 2.79 times higher than that registered for mix M1 (100% NA), respectively. This performance could be connected with [49,50] (i) higher water absorption by the MRA, (ii) lower density of the adhered mortar present in the recycled aggregate due to the presence of air bubbles within, (iii) the rougher texture of MRA compared with NA and (iv) the presence of microcracks inside the MRA which are not connected to the aggregate's permeable pores. These results are in line with the observations by Cantero et al. [30] and Plaza et al. [18], who registered an increase of this property when adding contents of up to 100% MRA and 100% RCA, respectively.

Figure 5 reveals the linear relationship that exists between this property and the percentage of recycled sand for different percentages of coarse aggregate replacement (0%, 25% and 50%), with all cases having an $R^2 \geq 0.99$. This trend was previously registered by Yaprak et al. [49], who added from 0% to 100% of recycled concrete sand.

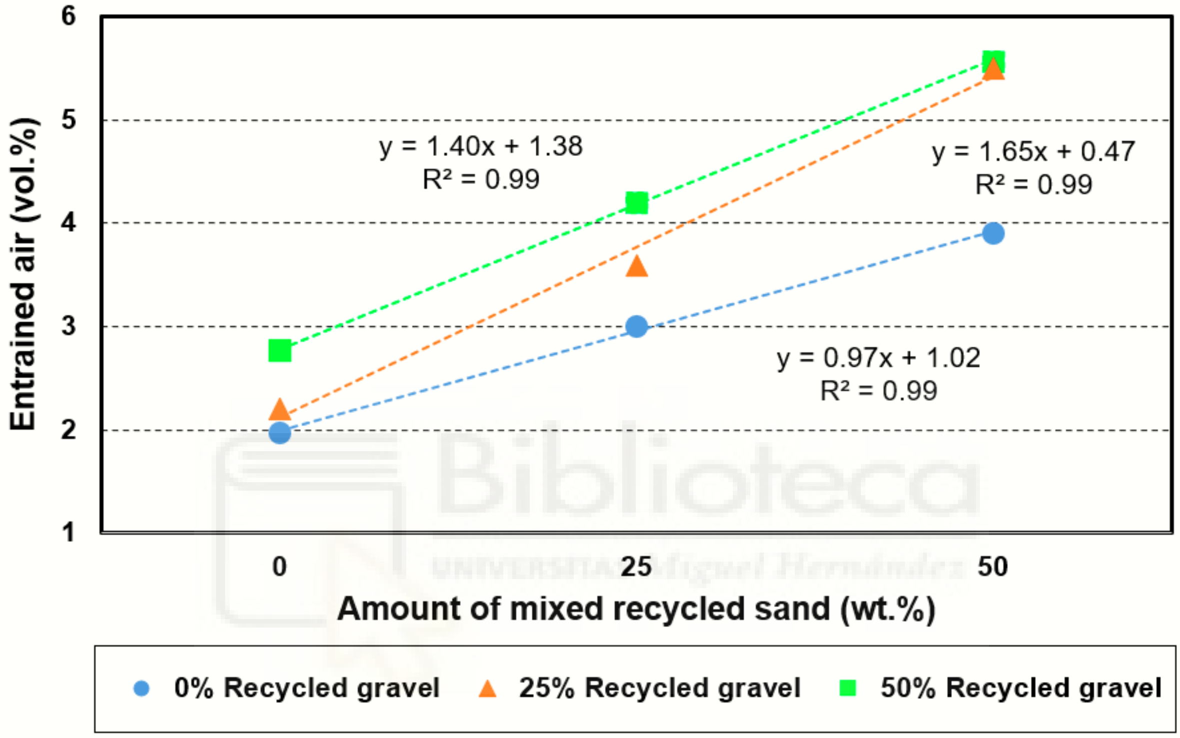

Figure 5. Connection between the percentage of mixed recycled sand and entrained air.

3.1.3. Density

Table 6 lists the density values for fresh concrete. It reveals a decrease of said property in connection with the percentage of addition of mixed recycled aggregate (fMRA and/or cMRA). These decreases reached their maximum value in mixes that had both fractions added at 50% simultaneously; as for mixes M8 and M9, these values were 5.4 and 5.3 compared with mix M1, respectively. This was also the case with the mix that added 25% cMRA + 50% fMRA (M6), with a 5.8% decrease compared with M1. This decrease is in line with Brito et al. [50], who registered decreases of up to 10% for concretes that had up to 100% of MRA. This behaviour would be connected with the lower density of recycled aggregates due to the presence of adhered mortar and ceramic material, as well as the apparent higher water/cement ratio of the new concrete mixes designed [49,51].

Regarding the values obtained, it is worth noting that they were within the 2430–2300 kg/m^3 and 2430–2220 kg/m^3 ranges of values for concretes that have different percentages of recycled concrete aggregate [52,53] and mixed recycled aggregate [51], respectively. Lastly, this observed trend is in line with research previously registered by other authors: Plaza et al. [18] registered densities of 2428.56 kg/m^3 for conventional concretes, 2367.38 kg/m^3 for concretes with a 100% coarse aggregate replacement rate and 2310.51 kg/m^3 for mixes with 100% recycled coarse aggregate replacement and 50% fMRA; César Medina et al. [52] registered a density of 2347 kg/m^3 with 25% of cMRA replacement and densities of 2335 kg/m^3 with 50% cMRA replacement. A. González et al. [51], with high-performance recycled concrete aggregates with 20% and 50% cMRA replacement, obtained densities of 2430 kg/m^3 and 2340 kg/m^3, respectively.

3.2. Properties in a Hardened State

3.2.1. Density

Table 7 lists the values of apparent density in hardened concretes analysed following 28 days of curing, once again revealing a decrease of this property with the percentage of addition of MRA (fMRA and/or cMRA), due to the lower density of this new typology of recycled aggregates compared with natural aggregates (Table 2). This decrease was between 1.4% and 5.7% compared with the reference concrete (M1). In this context, it is worth noting that said decrease is in line with the 3.3–5.0% range registered by other authors who added up to 100% of MRA [49]. Regarding the values obtained, it is worth stressing that they are within the range of values (2450–2270 kg/m^3) registered previously by other authors who added mixed recycled aggregates [10,29,30].

Table 7. Density and compressive strength evolution.

Mix	D_{28d} (kg/m^3)	a_{cs7d}	σ	a_{cs28d}	σ	a_{cs90d}	σ
M1	2412.15	33.45	0.26	40.02	0.22	46.67	0.67
M2	2377.78	31.72	0.38	41.54	1.10	55.58	0.75
M3	2330.17	33.14	0.61	40.00	0.46	50.43	0.72
M4	2368.30	30.92	0.69	38.48	0.33	48.31	0.31
M5	2321.38	31.38	1.04	37.84	0.34	47.85	0.23
M6	2274.07	31.04	0.28	38.02	0.41	47.16	0.94
M7	2319.11	30.85	0.80	37.77	0.49	50.60	0.87
M8	2283.52	30.62	0.90	36.82	0.91	52.12	0.72
M9	2278.12	29.87	0.53	39.46	0.79	52.44	0.83

Note. D_{28d}: density in a hardened state after 28 days; σ: standard deviation; a_{cs7d}: average compressive strength after seven days; a_{cs28d}: average compressive strength after 28 days; a_{cs90d}: average compressive strength after 90 days. a_{cs} average compressive strength with a cubic sample, which must be multiplied by 0.90 to turn it into a cylindrical sample of 150 ϕ × 300 mm.

3.2.2. Compressive Strength

Table 7 shows the evolution of the compressive strength of the various mixes analysed after 7, 28 and 90 days. It shows that regardless of the type of concrete, (i) compressive strength increases with the curing time, an evolution which is very similar to that displayed by the reference concrete, (ii) the relative compressive strength after seven days is 75.7–83.6% of that obtained after 28 days, a similar percentage to the figure obtained (70%) in Portland cement concretes with no additions and a w/c ratio <0.45 [54] and to the 65–93% range of values registered by Bravo et al. [16] for concretes that partially added C&DW, and (iii) the average strength after 28 days is higher than the design strength of 25 MPa. Therefore, these new recycled concretes could be used as concretes for structural use.

Figure 6 shows the compressive strength variation of recycled concretes compared with conventional concrete for the various curing times. It reveals that for short times (t < 28 days), the addition of fMRA and/or cMRA caused a maximum performance loss of 10.7% compared with M1 and was suffered by the mix that had 50% fMRA + 50% cMRA (M9). However, at t = 90 days there was an increase in strength. The maximum increase was +19% over M1, observed in the mix that had 25% fMRA (M2). Likewise, concretes with 50% cMRA and 0%, 25% and 50% fMRA (M7–M9) had a better behaviour, recording increases ranging from 8.4% to 12.4% compared with M1.

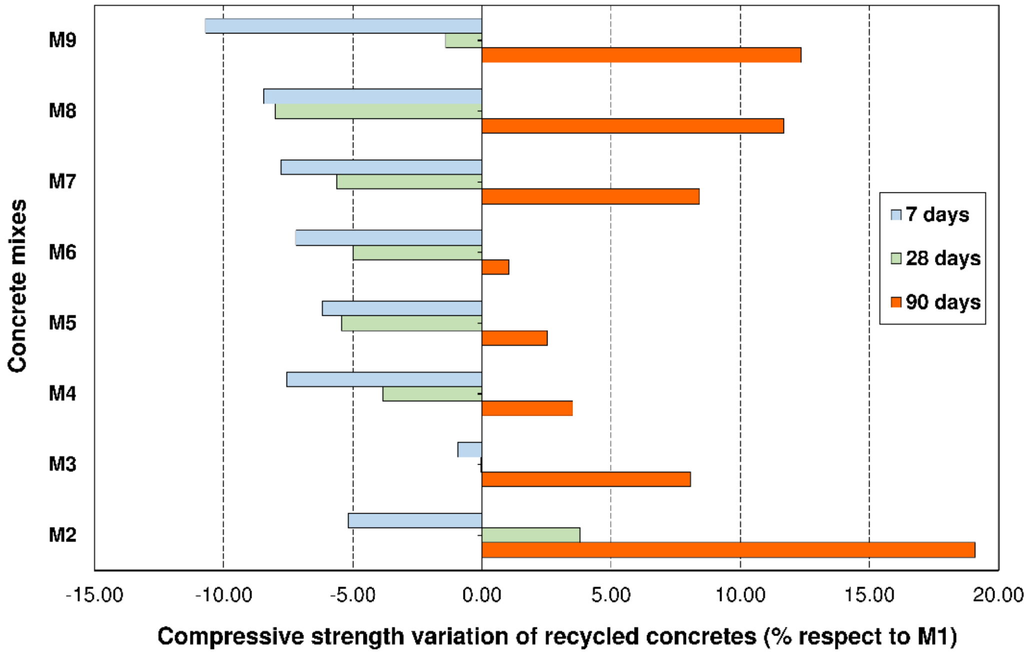

Figure 6. Compressive strength variation of recycled concretes (M2–M9) compared with conventional concrete (M1).

These results reveal that the addition of cMRA individually (M4–M7) does not have a negative effect on this attribute, registering a small decrease (Δ_{M4} = −3.8%/Δ_{M7} = −5.6%) and a slight increase (Δ_{M4} = +3.5%/Δ_{M7} = 8.4%) compared with M1 after 28 and 90 days, respectively. This performance is in line with the observations of Cantero et al. [30], Poon et al. [54], Gomes et al. [55] and Lotfy et al. [56], who revealed that for recycled coarse aggregate replacement percentages ≤ 50%, there are no significant differences with conventional concretes.

Regarding the individual addition of fMRA (M2 and M4), we observed that the addition of 25% in weight (M2) led to a slight increase in compressive strength, reaching +3.8% and +19.1% compared with M1 after 28 and 90 days, respectively. This behaviour is in line with the study of Bravo et al. [10], who established that type I recycled fine aggregates (Rc + Ru ≥ 80% and other components ≤20%) caused variations in compressive strength ranging from +3.8 to −12.5 after 28 days and in concretes with a replacement percentage of 25%. Likewise, this result was also obtained by other authors [57–60], who registered 3.7%, 5% and 16% increases compared with conventional concrete for 10%, 30% and 50% additions of RCA, respectively. This increase was connected with the filler effect of fine RCA and their rough texture and shape, which allowed for a better packing of the granular skeleton [61,62].

Regarding the 50% fMRA replacement (M3), the study showed that after 28 days the resistance remained constant, whereas after 90 days, there was a slight increase of +8.1% compared with M1. This behaviour is better than that established by Bravo et al. [63] for a 50% replacement with type-I sand comprised by Rc + Ru = 83.7%, Rb = 0.9% and Rg = 15.4. These authors registered an attribute loss ranging from −6.1% to −13.3% compared with conventional concrete, for a 50% percentage of replacement. This improved behaviour of M3 is linked to the better quality of fMRA (Table 2) compared with the type-I sand studied by said authors.

Likewise, Figure 5 reveals that mixes M5, M6, M8 and M9, which simultaneously incorporated cMRA (25% and 50%) and fMRA (25% and 50%) in their composition, had a worse performance after 28 days, registering a 5.5%, 5.0%, 8.0% and 1.4% decrease compared with M1, respectively. These decreases are lower than the ~7% and ~17% observed by Plaza et al. [18], who added 50% coarse RCA + 50% fine RCA and 50% coarse

RCA + 50% mixed sand, respectively. In addition, it is worth noting that similar to when MRA were added individually, an improved performance was registered for the concretes after 90 days of curing, with mix M9 (cMRA = 50% + fMRA = 50%) reaching a maximum increase of 12.4% compared with M1.

This improved behaviour of the new concretes (M2–M9) at curing times greater than 28 days could be connected with the pozzolanic activity of the fine fraction (sizes < 0.063 mm) present in fMRA, where there are mainly ceramic fines. This aspect was previously registered by Medina et al. [60,61] and Asensio et al. [62,63], who analysed the pozzolanic performance of the fine fraction of C&DW with variable compositions (26.5% $\leq SiO_2 \leq$ 70.5%, 4.4% $\leq$ CaO $\leq$ 24.5%, 5.8% $\leq Al_2O_3 \leq$ 18.5%), observing that they have a lime fixation capacity after 28 days of 53.3–82.1%. These values are lower than silica fume (~90%) and higher than fly ash (~45%).

In addition, this behaviour could also be linked to (i) the presence of anhydride cement particles [64–66] in the mortar adhered to the fMRA that will become hydrated, generating calcium silicate hydrate (C-S-H) which will positively contribute to the mechanical behaviour and (ii) the attributes of existing ITZs among the Rb components of MRA (cMRA and fMRA)/paste that can have a thickness equal to or lower than the one that natural aggregates normally have (e_{ITZ} = 10–50 μm), as shown previously in the studies by Medina et al. [29] and Sáez del Bosque et al. [24] in concretes that had coarse fractions of ceramic aggregate from bathroom fittings and coarse mixed recycled aggregate, respectively.

Figure 7 shows the appearance of concretes M1, M3, M6 and M9 after being subjected to the compression test after 28 days, revealing that the type of failure was similar in all of them and that their morphology can be classified as suitable according to European standard EN 12390-3 [65,67].

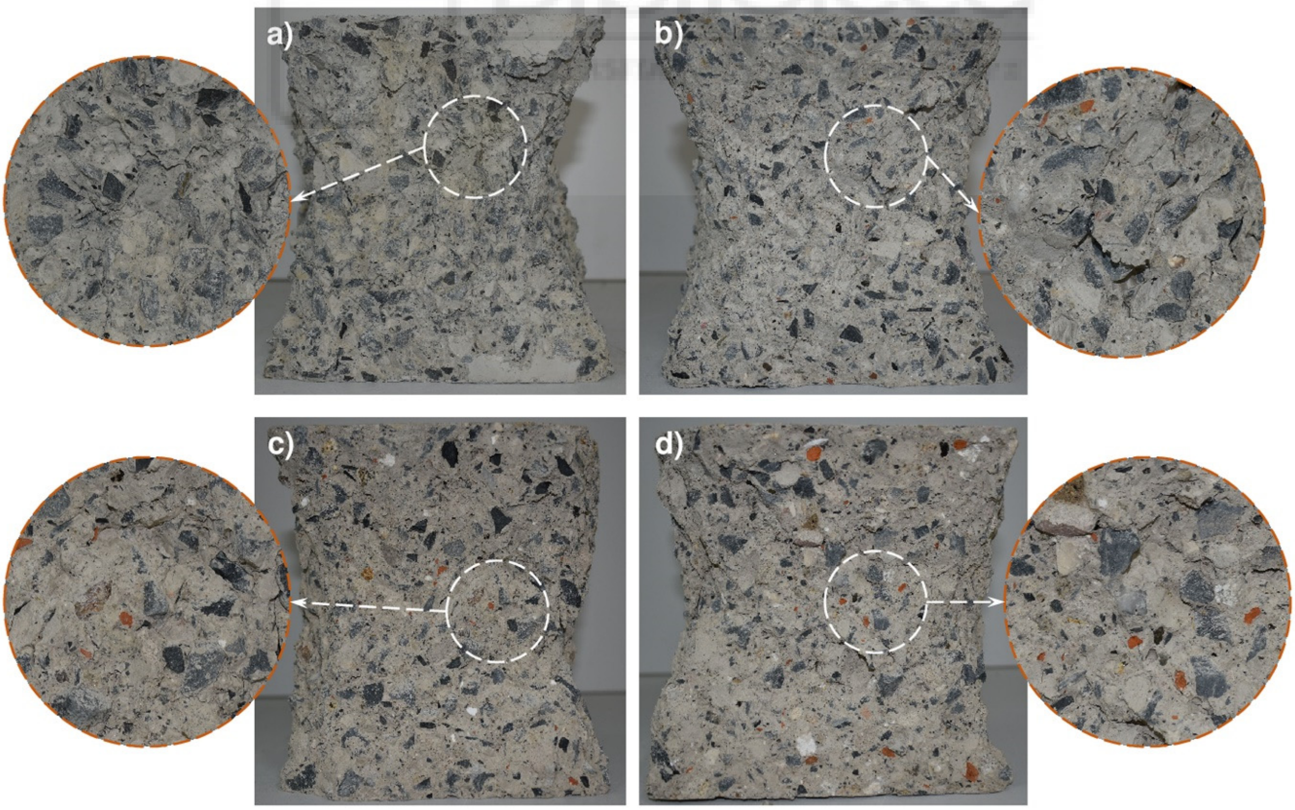

Figure 7. Type of failure of the concretes: (**a**) M1; (**b**) M3; (**c**) M6; and (**d**) M9.

Lastly, Figure 6 verifies that the aggregate/paste ITZ is the area where the cracks preferentially begin and then spread when a concrete item is subjected to an external force that surpasses its operational status limit [68]. This happens because this area is the weakest and the one where the most stress concentrates, as observed by Medina et al. [67] by simulating the stress in the coarse/paste aggregate ITZ subjected to compressive forces [69].

3.2.3. Splitting Tensile Strength

Table 8 shows the tensile strength of concretes tested after 28 days and the variations in strength compared with conventional concrete (M1) and compared with the concretes that exclusively had cMRA (M4 and M7). It reveals that the mixes that only had fMRA (M2 and M3) experienced a slight increase in tensile strength between 8.7% and 5.5% compared with M1, respectively. This behaviour is in line with the observations of Ahmed et al. [68] and Kirthika et al. [69], who revealed that the use of fine MRA in percentages lower than 50% did not lead to a significant loss of performance (<10%) in the new concretes.

Table 8. Tensile and flexural strength of concretes 28 days later.

Mix	fcmt (MPa)	Δfcmt (%) ♣	Δfcmt (%)	fcmf (MPa)	Δfcmf (%) ♣	Δfcmf (%)
M1	3.45 ± 0.09	-	-	3.82 ± 0.12	-	-
M2	3.75 ± 0.07	+8.70	-	4.16 ± 0.11	+8.90	-
M3	3.54 ± 0.13	+5.51	-	4.15 ± 0.23	+8.64	-
M4	3.21 ± 0.05	−6.96	-	4.10 ± 0.02	+7.33	-
M5	3.41 ± 0.06	−1.16	+6.23 ♠	4.28 ± 0.09	+12.04	+4.39 ♠
M6	3.31 ± 0.07	−4.06	+3.12 ♠	4.21 ± 0.06	+10.21	+2.68 ♠
M7	3.29 ± 0.06	−4.64	-	3.69 ± 0.27	−3.40	-
M8	3.40 ± 0.05	−1.45	+3.34 *	3.83 ± 0.21	+0.26	+3.79 *
M9	3.44 ± 0.06	−0.29	+4.56 *	4.06 ± 0.20	+6.28	+10.03 *

Note. fcmt: mean splitting tensile strength; fcmf: mean flexural strength; ♣ strength variation compared with M1; ♠ strength variation compared with M4; and * strength variation compared with M7.

Regarding the mixes whose composition included 25% cMRA (M4) and 50% cMRA (M7), it is worth noting that they registered a small decrease of 7.0% and 4.6% compared with M1, respectively. These losses are similar to those registered by Cantero et al. [30] in concretes with 25% and 50% of mixed recycled aggregate and lower than the 12% and 14% losses registered previously by other authors who [70–75] analysed concretes with 100% of recycled aggregates, which had 10% ≤ Rb ≤ 14%.

Regarding the mixes that include both fractions simultaneously, we observed that the addition of fMRA had a positive effect by (i) lessening the decrease in strength of the mixes (M5, M6, M8 and M9) compared with the mixes that only included cMRA (M4 and M7), with the decrease reaching 1.45% ≤ Δfcmt ≤ 4.06%, and (ii) increasing their strength compared with mixes that only had cMRA (M4 and M7), with this change ultimately being 3.12% ≤ Δfcmt ≤ 6.23%. This behaviour is better than that observed previously by Plaza et al., who registered a 7.3% and 11.0% decrease compared with conventional concrete in concretes with 25% coarse RCA + 50% fine MRA and 50% coarse RCA + 50% fine MRA, respectively. This same tendency was revealed for concretes with 50% coarse RCA + 50% fine RCA, again registering decreases ~11% compared with conventional concrete [76].

Lastly, it is worth noting that the failure mechanism was the same in all tested concretes, causing a brittle failure that led to the tested mixes splitting in half. In addition, we observed that (i) the failure surface obtained is irregular, confirming the existence of intact coarse aggregates (cNA or cMRA) and thus again revealing that the failure emerges from the ITZ of the coarse and/or fine aggregates and the cement paste, and (ii) the granular skeleton (fine and coarse aggregates) is distributed homogeneously, regardless of whether the aggregate is natural or recycled (Figure 8).

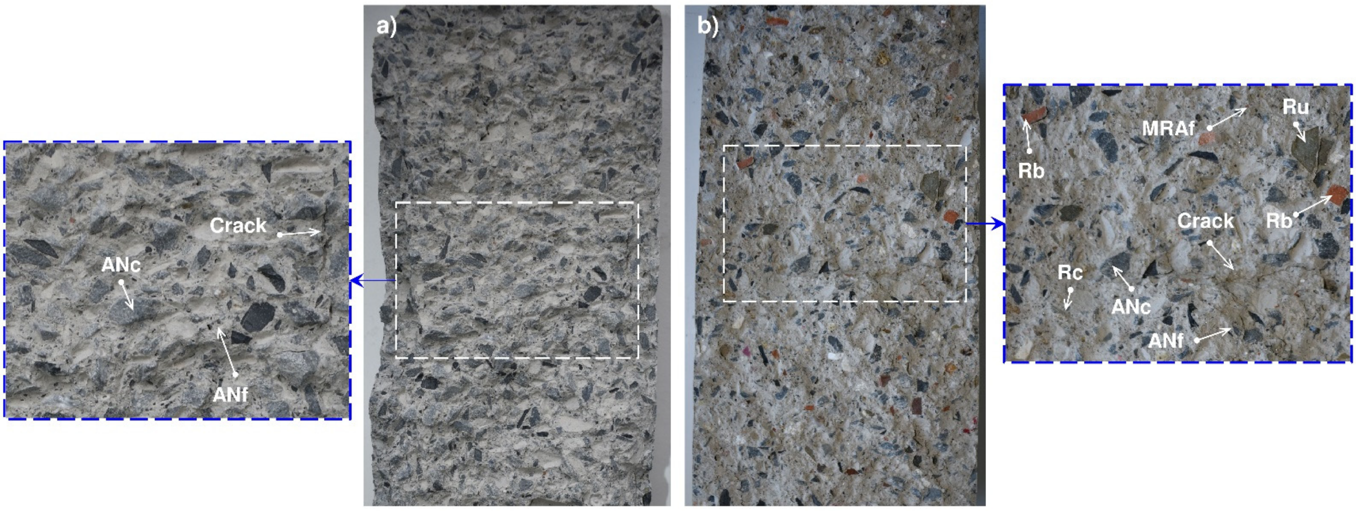

Figure 8. Appearance of the concretes when performing the tensile test 28 days after producing the mortar: (**a**) conventional concrete (M1) and (**b**) concrete with 50% cMRA + 50% fMRA (M9).

3.2.4. Flexural Resistance

Table 8 lists the flexural strength values of the tested concretes after 28 days, and the variations in strength compared both with conventional concrete (M1) and with the concretes that exclusively had cMRA (M4 and M7). It reveals that the mixes that only had fMRA (M2 and M3) experienced a slight increase in flexural strength of +8.9 and +8.6% compared with M1, respectively. This result is in line with the prior observations of Ahmed [76] and Kirthika [77], who registered 6.7% and 3.2% increases compared with conventional concrete for a fine MRA replacement percentage of 50%, respectively.

Regarding mixes with 25% cMRA (M4) and 50% cMRA (M7), it is worth noting that they displayed an uneven behaviour, with mix M4 registering a 7.3% increase compared with M1 and M7 showing a 3.4% decrease compared with M1. This behaviour was similar to that observed by Cantero et al. [30], who established that for replacement percentages lower than or equal to 50% of coarse MRA, there were no significant variations of this mechanical attribute (Δfcmf $\leq$ 10% compared with conventional concrete).

Regarding the mixes that simultaneously incorporate both fractions, we observed that the addition of fMRA had a positive effect by improving the behaviour of mixes with cMRA (M4 and M7). It is worth noting that mixes M5 and M6 registered a 4.4% and 2.7% increase compared with M4, and mixes M8 and M9 showed a 3.8% and 10.0% increase compared with M7. Likewise, all of them had a similar or improved behaviour compared with that observed in conventional concrete with 100% natural aggregate (cNA and fNA).

Lastly, all samples tested, regardless of the composition of their granular skeleton, had failures due to the formation of a crack in the middle part of the span, rising from the part being pulled (the lower part of the sample) to the part being compressed [77] (the highest part where the load is applied). Likewise, observing the cracked area, we once again saw that the failure took place along the aggregate/paste transition area, with the aggregates being detached from the matrix.

3.2.5. Water Penetration Depth under Pressure

Figure 9 shows the results obtained regarding the maximum and mean depth of the mixes analysed.

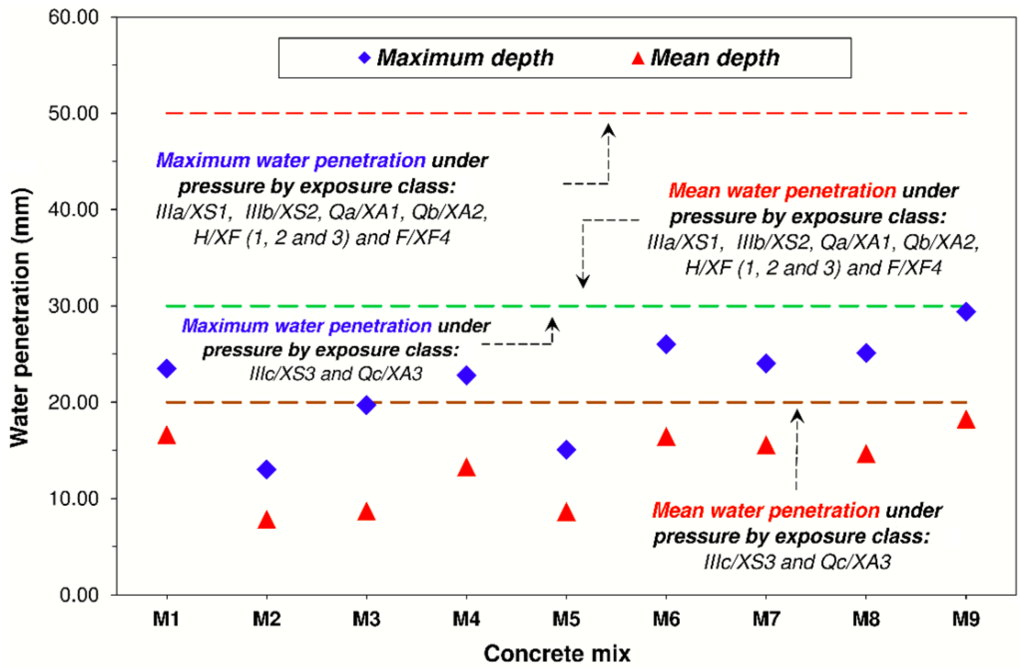

Figure 9. Water penetration of the concretes under pressure. Limits established in EHE-08 and EC-2 (Note. IIIa: marine class—subclass: aerial; IIIb: marine class—subclass: submerged; IIIc: marine class—subclass: tidal and splash zones; Qa: aggressive chemical class—subclass: weak; Qb: aggressive chemical class—subclass: average; Qc: aggressive chemical class—subclass: strong; H: with frost class—subclass: without deicing salts; and F: with frost class—subclass: without deicing salts).

Regarding the individual incorporation of fMRA (M2 and M3), we observed that these mixes experienced a larger decrease both in maximum (Pmax) and mean (Pmed) water penetration, with the decrease ending up being between 16.1% $\leq$ Pmax $\leq$ 44.6% and 47.7% $\leq$ Pmed $\leq$ 52.9% compared with conventional concrete (M1). This greater watertightness could be connected with the pozzolanic activity of ceramic fines (<0.063 mm) of the fMRA, as well as with the hydration of anhydrous cement [78] present in the fines from fMRA mortars that give them a certain hydraulic activity and thus lead to a more sealed and tortuous pore structure.

Regarding the use of cMRA, we observed that an addition of 25% (M4) and 50% (M7) caused an uneven behaviour in these two properties. In the case of M4, the table shows that Pmax and Pmed experienced a slight (2.8%) and small (20.1%) decrease compared with M1, respectively. This behaviour is in line with the prior observations of Mas et al. [77], who observed that the depth remained constant for coarse MRA replacement percentages $\leq$25%. Regarding mix M7, it experienced an increase of Pmax (2.4%) and a slight decrease of Pmed (6.4%). This behaviour could be connected with the fact that the microcracks present in MRA have a greater impact on Pmax than Pmed.

Regarding the simultaneous use of cMRA and fMRA as the granular skeleton of the concretes, the table shows that only the 25% cMRA + 25% fMRA mix (M5) made it possible to obtain an increase in water penetration, causing a 35.8% and 33.9% decrease in Pmax and Pmed compared with M1, respectively. This result, as happened with the other properties studied, makes it possible to say that there is no performance loss for MRA replacement percentages lower than or equal to 25%.

In this context, it is worth noting that for weight percentages of cMRA and fMRA greater than 25%, there was an increase in water penetration, which could be explained by the beneficial effect of its rougher surface texture enabling a better entry (similar ITZs) in the cement matrix, as well as the pozzolanic activity of the <0.063 mm fraction not being able to compensate for the negative effect that its intrinsic properties have on water penetration (lower density, higher water absorption and the presence of microcracks in its microstructure).

The values obtained are under the limits established in chapter VII "Durability" Section 37.3.3 "Resistance to water penetration" of the Spanish Code on Structural Concrete (EHE-08), which establishes that a concrete is watertight enough for a given type of exposure (IIIa, IIIb, IIIc, IV, Qa, E, H, F, Qb, Qc) when its maximum and mean penetration depth is lower than 50 or 30 mm and 30 or 20 mm, respectively, depending on the type of environment (see Figure 9). This highlights that recycled concretes have a porous structure that guarantees watertightness and a suitable durability throughout their useful life against this transport mechanism.

Lastly, Figure 10 shows the penetration front of the samples manufactured for concretes M1, M3, M6 and M9. As can be seen, the water penetration outlines have a similar morphology, and there are no visible differences between the mixes manufactured with NA and cMRA and/or fMRA.

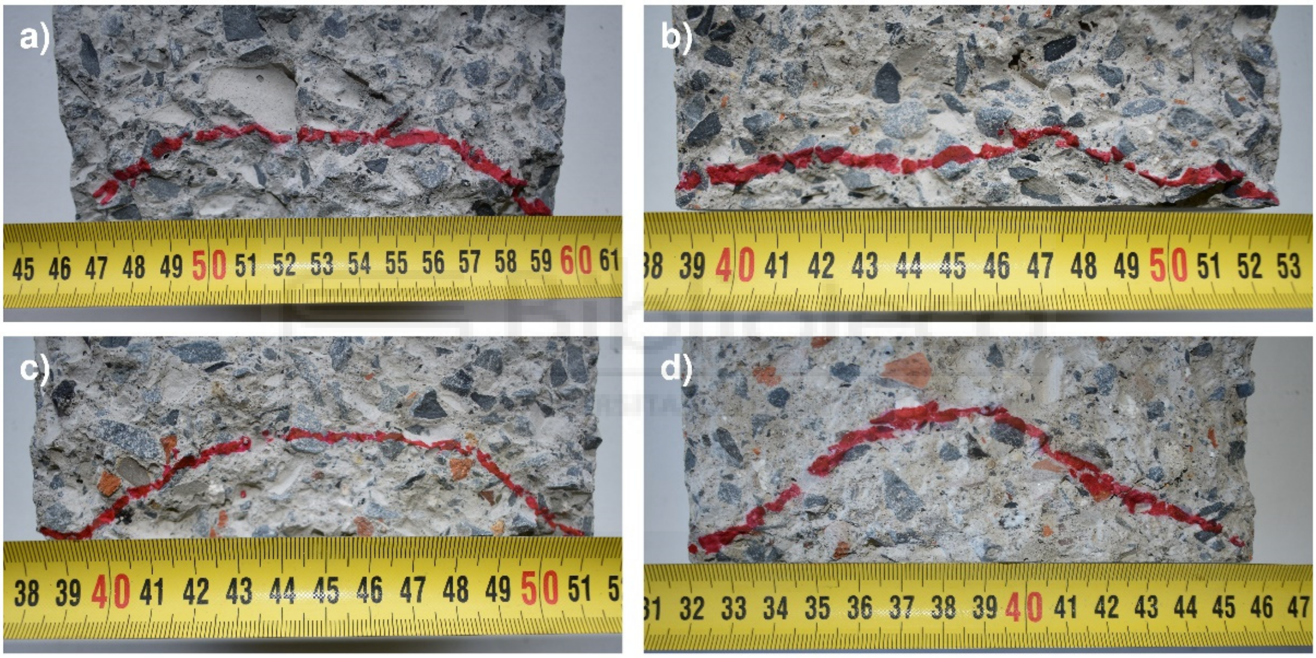

Figure 10. Penetration fronts of the concretes: (**a**) M1; (**b**) M3; (**c**) M6; and (**d**) M9.

3.2.6. Analysing the Concrete Manufacturing Costs

Table 9 lists the economic study of the cost of manufacturing the concretes analysed in order to reveal the financial aspects of this study. In this context, it is worth noting that the price of natural aggregates in Spain is lower than in other countries, as this country is characterised by having a high availability of natural resources, which enables the extraction of natural aggregates. These prices (EUR/t) will be much higher in countries with greater legal restrictions on extracting natural resources or with less availability, which would facilitate the recovery of recycled aggregates in the concrete industry from an economic point of view. This table shows that mix M9, with 50% fMRA + 50% cMRA, is the cheapest, leading to a −8.03% decrease compared with natural aggregate (M1). This result is in line with the prior observations of other authors, who registered decreases of under −50% for recycled coarse aggregate replacement percentages between 50% and 100% [78].

Table 9. Manufacturing cost of the mixes studied.

Component	Unit Price (EUR/t)	Concrete Mix								
		M1	M2	M3	M4	M5	M6	M7	M8	M9
fNA	6.79	6.23	4.64	3.03	6.13	4.52	2.95	6.03	4.40	2.92
fMRA	3.60	0.00	0.82	1.61	0.00	0.80	1.56	0.00	0.78	1.55
Can	6.54	6.50	6.46	6.33	4.80	4.72	4.62	3.15	3.06	3.04
cMRA	3.15	0.00	0.00	0.00	0.77	0.76	0.74	1.52	1.47	1.47
Cement	88.60	33.67	33.67	33.67	33.67	33.67	33.67	33.67	33.67	33.67
Water	0.50	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13
Admixture	1.56	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
EUR/m^3 concrete	-	46.51	45.72	44.76	45.49	44.59	43.67	44.49	43.51	42.78

Lastly, in addition to these economic savings, one must consider the positive environmental effect, especially in terms of $kgCO_2eq/kg$, that the correct management of MRA and a decrease in the extraction of natural aggregates entail.

4. Conclusions

The conclusions drawn from this research study are:

- Coarse (cMRA) and fine (fMRA) mixed recycled aggregate meet the physical and mechanical requirements included in the relevant regulation on aggregates for manufacturing concretes.
- The workability of recycled concretes (M2–M9) is not impacted by the addition of mixed recycled aggregate, regardless of its replacement percentage, with all mixes showing an S2 consistency (50–90 mm).
- The addition of mixed recycled aggregate (cMRA and/or fMRA) causes a linear increase in the entrained air content in a fresh state of 1.9, 2.8 and 2.8 times the M1 mix in mixes M3 (50% fMRA), M6 (25% cMRA + 50% fMRA) and M9 (50% cMRA + 50% fMRA), respectively.
- The density of recycled concretes is lower than that of conventional concrete, with the loss of density increasing as the recycled aggregate replacement percentage rises and with greater intensity when using mixed aggregate. This behaviour is similar both in a fresh and hardened state.
- The compressive strength of recycled concretes is lower than that of conventional concrete, with M9 (50% cMRA + 50% fMRA) having the greatest drop (~11%) compared with M1 after 28 days of curing. After 90 days, recycled concretes have a better behaviour than conventional concretes. The addition of fMRA has a positive effect, establishing that the optimal replacement percentage is 25% in weight, regardless of the percentage of cMRA.
- The compressive strength of all concretes is higher than the design strength (f_{ck} = 25 MPa).
- The indirect tensile strength experiences a slight increase with the addition of fMRA, with the maximum increase (~9%) compared with M1 corresponding to the concrete that incorporates 25% of fMRA (M2). The addition of cMRA causes a slight loss (~7%) compared with conventional concrete (M1). This loss is softened with the simultaneous addition of fMRA, obtaining a −0.3% decrease compared with M1 for mix M9 (50% cMRA + 50% fMRA).
- The flexural strength of the new concretes is greater than conventional concrete, with the highest increases (6.3–12.0% compared with M1) belonging to mixes M2, M5 and M9. The addition of 50% of cMRA (M7) causes a −3.4% decrease compared with M1.
- All the concretes designed have a watertight structure under pressure, meeting the maximum and mean depth requirements of the relevant regulation.
- The (maximum and mean) water penetration under pressure decreases slightly for mixes M2, M3, M4 and M5, whereas an increase was registered in one (M6, M7 and M8) or both depths (M9) for all remaining concretes.

- The optimal individual or simultaneous replacement percentage of fMRA and cMRA is 25% in weight, in light of the results obtained in this research study.
- These results reveal the need for future research that addresses the behaviour of these concretes from the viewpoint of their durability properties, as well as investigating different types of mixed recycled aggregates with which to manufacture concretes.
- Lastly, this research will positively contribute to the addition of these mixed recycled aggregates to the concrete-related stipulations of structural codes.

Author Contributions: Conceptualisation, M.D.G., P.P.C., D.B.F., M.M.J.V., I.F.S.d.B. and C.M.M.; methodology, M.D.G., I.F.S.d.B. and C.M.M.; formal analysis, M.D.G., P.P.C. and I.F.S.d.B.; investigation, M.D.G., P.P.C., D.B.F., M.M.J.V., I.F.S.d.B. and C.M.M.; writing—original draft preparation, M.D.G., P.P.C. and D.B.F.; writing—review and editing, M.D.G., M.M.J.V., I.F.S.d.B. and C.M.M.; supervision, D.B.F., I.F.S.d.B. and C.M.M.; project administration, D.B.F. and C.M.M.; funding acquisition, C.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Spanish Ministry for Science and Innovation under coordinated research project PID2019-107238RB-C21/AEI/10.13039/501100011033 and in conjunction with the Government of Extremadura under grant GR 18122 awarded to the MATERIA research group. The authors are grateful to the "Programa de Formación de Capital Académico Avanzado", Universidad Tecnológica Metropolitana Grant: PM-VRAC2020 UTEM, for the financial support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Comision Europea (EU). *No 601/2012 of 21 June 2012 on the Monitoring and Reporting of Greenhouse Gas Emissions Pursuant to Directive 2003/87/EC of the European Parliament and of the Council*; European Committee: Brussels, Belgium, 2012.
2. ERMCO. Ready–Mixed Concrete Industry Statistics. 2018. [Online]. Available online: http://ermco.eu/new/wp-content/uploads/2020/08/ERMCO-Statistics-30.08.2019-R4-1.pdf (accessed on 19 March 2020).
3. Monteiro, P.J.M.; Miller, S.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef]
4. European Aggregates Association. Annual Review 2019–2020. European Aggregates Association. A Sustainable Industry for a Sustainable Europe. [Online]. Available online: https://uepg.eu/mediatheque/media/UEPG-AR20192020_V13_(03082020)_spreads.pdf (accessed on 5 May 2021).
5. Tang, Y.; Feng, W.; Feng, W.; Chen, J.; Bao, D.; Li, L. Compressive properties of rubber-modified recycled aggregate concrete subjected to elevated temperatures. *Constr. Build. Mater.* **2020**, *268*, 121181. [CrossRef]
6. Rahla, K.M.; Mateus, R.; Bragança, L. Comparative sustainability assessment of binary blended concretes using Supplementary Cementitious Materials (SCMs) and Ordinary Portland Cement (OPC). *J. Clean. Prod.* **2019**, *220*, 445–459. [CrossRef]
7. Ray, S.; Haque, M.; Sakib, N.; Mita, A.F.; Rahman, M.M.; Tanmoy, B.B. Use of ceramic wastes as aggregates in concrete production: A review. *J. Build. Eng.* **2021**, *43*, 102567. [CrossRef]
8. Aghayan, I.; Khafajeh, R.; Shamsaei, M. Life cycle assessment, mechanical properties, and durability of roller compacted concrete pavement containing recycled waste materials. *Int. J. Pavement Res. Technol.* **2020**, *14*, 595–606. [CrossRef]
9. Horňáková, M.; Lehner, P. Relationship of Surface and Bulk Resistivity in the Case of Mechanically Damaged Fibre Reinforced Red Ceramic Waste Aggregate Concrete. *Materials* **2020**, *13*, 5501. [CrossRef] [PubMed]
10. Bravo, M.; de Brito, J.; Pontes, J.; Evangelista, L. Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. *J. Clean. Prod.* **2015**, *99*, 59–74. [CrossRef]
11. Thomas, C.; Setién, J.; Polanco, J.A.; Alaejos, P.; De Juan, M.S. Durability of recycled aggregate concrete. *Constr. Build. Mater.* **2013**, *40*, 1054–1065. [CrossRef]
12. Etxeberria, M.; Vázquez, E.; Mari, A.; Barra, M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cem. Concr. Res.* **2007**, *37*, 735–742. [CrossRef]
13. McNeil, K.; Kang, T.H.-K. Recycled Concrete Aggregates: A Review. *Int. J. Concr. Struct. Mater.* **2013**, *7*, 61–69. [CrossRef]
14. Evangelista, L.; de Brito, J. Durability performance of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2010**, *32*, 9–14. [CrossRef]
15. Ju, M.; Park, K.; Park, W.-J. Mechanical Behavior of Recycled Fine Aggregate Concrete with High Slump Property in Normal- and High-Strength. *Int. J. Concr. Struct. Mater.* **2019**, *13*, 61. [CrossRef]

16. Bravo, M.; Duarte, A.P.C.; De Brito, J.; Evangelista, L.; Pedro, D. On the Development of a Technical Specification for the Use of Fine Recycled Aggregates from Construction and Demolition Waste in Concrete Production. *Materials* **2020**, *13*, 4228. [CrossRef]
17. Fernández, S.V. Physical-mechanical characterization of the structural concrete made with recycled aggregates: Experimental comparative with substitution of fine and coarse aggregates. *An. Edif.* **2017**, *3*, 24–31.
18. Plaza, P.; del Bosque, I.S.; Frías, M.; de Rojas, M.S.; Medina, C. Use of recycled coarse and fine aggregates in structural eco-concretes. Physical and mechanical properties and CO_2 emissions. *Constr. Build. Mater.* **2021**, *285*, 122926. [CrossRef]
19. Corinaldesi, V. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Constr. Build. Mater.* **2010**, *24*, 1616–1620. [CrossRef]
20. Malešev, M.; Radonjanin, V.; Marinković, S. Recycled Concrete as Aggregate for Structural Concrete Production. *Sustainability* **2010**, *2*, 1204–1225. [CrossRef]
21. López-Gayarre, F.; Serna, P.; Domingo-Cabo, A.; Serrano-López, M.; López-Colina, C. Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties. *Waste Manag.* **2009**, *29*, 3022–3028. [CrossRef]
22. Lovato, P.S.; Possan, E.; Molin, D.C.C.D.; Masuero, B.; Ribeiro, J.L. Modeling of mechanical properties and durability of recycled aggregate concretes. *Constr. Build. Mater.* **2012**, *26*, 437–447. [CrossRef]
23. Agrela, F.; de Juan, M.S.; Ayuso, J.; Geraldes, V.; Jiménez, J.R. Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete. *Constr. Build. Mater.* **2011**, *25*, 3950–3955. [CrossRef]
24. del Bosque, I.S.; Zhu, W.; Howind, T.; Matías, A.; de Rojas, M.S.; Medina, C. Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate. *Cem. Concr. Compos.* **2017**, *81*, 25–34. [CrossRef]
25. Martínez-Lage, I.; Vázquez-Burgo, P.; Velay-Lizancos, M. Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: Technical, economic and environmental analysis. *Waste Manag.* **2020**, *104*, 9–19. [CrossRef] [PubMed]
26. Martínez-Lage, I.; Martínez-Abella, F.; Vázquez-Herrero, C.; Ordóñez, J.L.P. Properties of plain concrete made with mixed recycled coarse aggregate. *Constr. Build. Mater.* **2012**, *37*, 171–176. [CrossRef]
27. Mas, B.; Cladera, A.; Bestard, J.; Muntaner, D.; López, C.E.; Piña, S.; Prades, J. Concrete with mixed recycled aggregates: Influence of the type of cement. *Constr. Build. Mater.* **2012**, *34*, 430–441. [CrossRef]
28. López-Uceda, A.; Ayuso, J.; Lopez, M.; Jiménez, J.R.; Agrela, F.; Sierra, M.J. Properties of Non-Structural Concrete Made with Mixed Recycled Aggregates and Low Cement Content. *Materials* **2016**, *9*, 74. [CrossRef]
29. Medina, C.; Zhu, W.; Howind, T.; De Rojas, M.I.S.; Frías, M. Influence of mixed recycled aggregate on the physical–mechanical properties of recycled concrete. *J. Clean. Prod.* **2014**, *68*, 216–225. [CrossRef]
30. Cantero, B.; del Bosque, I.S.; Matías, A.; Medina, C. Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes. *Constr. Build. Mater.* **2018**, *185*, 93–101. [CrossRef]
31. Díaz, M.; Almendro-Candel, M.B.; Blanco, D.; Jordan, M.M. Aggregate Recycling in Construction: Analysis of the Gaps between the Chilean and Spanish Realities. *Buildings* **2019**, *9*, 154. [CrossRef]
32. European Committee for Standardization. *EN 12620. Aggregates for Concrete*; European Committee for Standardization: Brussels, Belgium, 2009.
33. Ministry of Public Works. *Code on Structural Concrete (EHE-08)*; Ministry of Public Works: Madrid, Spain, 2008; p. 704.
34. European Committee for Standardization. *EN 197. Cement. Part 1: Composition, Specifications and Conformity Criteria for Common Cements*; European Committee for Standardization: Brussels, Belgium, 2011.
35. Spanish Committee for Standardization. *UNE 83966. Concrete Durability. Test Methods. Conditioning of Concrete Test Pieces for the Purpose of Gas Permeability and Capilar Suction Tests*; Spanish Committee for Standardization: Madrid, Spain, 2008.
36. Teychenné, D.C.; Franklin, R.E. *Design of Normal Concrete Mixes*; Spanish Committee for Standardization: Madrid, Spain, 2010; p. 42.
37. European Committee for Standardization. *EN 933. Tests for Geometrical Properties of Aggregates–Part 11: Classification Test for the Constituents of Coarse Recycled Aggregate*; European Committee for Standardization: Brussels, Belgium, 2010.
38. European Committee for Standardization. *EN 12350-6. Testing Fresh Concrete–Part 6: Density*; European Committee for Standardization: Brussels, Belgium, 2020.
39. European Committee for Standardization. *EN 12350-7. Testing Fresh Concrte–Part 7: Air Content–Pressure Methods. 2020. Link: BS EN 12350-7:2019 Testing Fresh Concrete Air Content. Pressure Methods–European Standards (en-standard.eu)*; European Committee for Standardization: Brussels, Belgium, 2020.
40. European Committee for Standardization. *EN 12350-2. Testing Fresh Concrete–Part 2: Slump Test. 2020. Link: BS EN 12350-2:2019 Testing Fresh Concrete Slump Test–European Standards (en-standard.eu)*; European Committee for Standardization: Brussels, Belgium, 2020.
41. European Committee for Standardization. *EN 12390-7. Testing Hardened Concrete–Part 7: Density of Hardened Concrete*; European Committee for Standardization: Brussels, Belgium, 2020.
42. European Committee for Standardization. *EN 12390-6. Testing Hardened Concrete–Part 6: Tensile Splitting Strength of Test Specimens*; European Committee for Standardization: Brussels, Belgium, 2020.
43. European Committee for Standardization. *EN 12390-5. Testing Hardened Concrete–Part 5: Flexural Strength of Test Specimens*; European Committee for Standardization: Brussels, Belgium, 2020.
44. European Committee for Standardization. *EN 12390-8. Testing Hardened Concrete–Part 8: Depth of Penetration of Water under Pressure*; European Committee for Standardization: Brussels, Belgium, 2020.

45. European Committee for Standardization. *EN-206. Concrete–Specification, Performance, Production and Conformity*; European Committee for Standardization: Brussels, Belgium, 2018.
46. European Committee for Standardization. *EN 1239-2. Testing Hardened Concrete–Part 2: Making and Curing Specimens for Strength Tests*; European Committee for Standardization: Brussels, Belgium, 2020.
47. Kurda, R.; de Brito, J.; Silvestre, J.D. Influence of recycled aggregates and high contents of fly ash on concrete fresh properties. *Cem. Concr. Compos.* **2017**, *84*, 198–213. [CrossRef]
48. Masood, B.; Elahi, A.; Barbhuiya, S.; Ali, B. Mechanical and durability performance of recycled aggregate concrete incorporating low calcium bentonite. *Constr. Build. Mater.* **2019**, *237*, 117760. [CrossRef]
49. Yaprak, H.; Aruntas, H.Y.; Demir, I.; Simsek, O.; Durmus, G. Effects of the fine recycled concrete aggregates on the concrete properties. *Int. J. Phys. Sci.* **2011**, *6*, 2455–2461.
50. de Brito, J.; Agrela, F.; Silva, R.V. Construction and demolition waste. In *Newtrends in Eco-Efficient and Recycled Concrete*; De Brito, J., Agrela, F., Eds.; Woodhead Publishing: Amsterdam, The Netherlads, 2019; Volume 1, pp. 1–22.
51. Gonzalez-Corominas, A.; Etxeberria, M. Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. *Constr. Build. Mater.* **2014**, *68*, 618–626. [CrossRef]
52. Nepomuceno, M.; Isidoro, R.A.; Catarino, J.P. Mechanical performance evaluation of concrete made with recycled ceramic coarse aggregates from industrial brick waste. *Constr. Build. Mater.* **2018**, *165*, 284–294. [CrossRef]
53. Mehta, P.D.P.K.; Paulo, P.D.; Monteiro, J.M. Proportioning Concrete Mixtures. In *Concrete: Microstructure, Properties, and Materials*, 4th ed.; McGraw Hill Professional: Toronto, ON, Canada, 2014.
54. Poon, C.; Shui, Z.; Lam, L.; Fok, H.; Kou, S. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cem. Concr. Res.* **2004**, *34*, 31–36. [CrossRef]
55. Gomes, M.; De Brito, J.; Bravo, M. Mechanical Performance of Structural Concrete with the Incorporation of Coarse Recycled Concrete and Ceramic Aggregates. *J. Mater. Civ. Eng.* **2014**, *26*, 04014076. [CrossRef]
56. Lotfy, A.; Al-Fayez, M. Performance evaluation of structural concrete using controlled quality coarse and fine recycled concrete aggregate. *Cem. Concr. Compos.* **2015**, *61*, 36–43. [CrossRef]
57. Evangelista, L.; de Brito, J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2007**, *29*, 397–401. [CrossRef]
58. Khatib, J. Properties of concrete incorporating fine recycled aggregate. *Cem. Concr. Res.* **2005**, *35*, 763–769. [CrossRef]
59. Nedeljković, M.; Visser, J.; Šavija, B.; Valcke, S.; Schlangen, E. Use of fine recycled concrete aggregates in concrete: A critical review. *J. Build. Eng.* **2021**, *38*, 102196. [CrossRef]
60. Medina, C.; Banfill, P.; de Rojas, M.I.S.; Frías, M. Rheological and calorimetric behaviour of cements blended with containing ceramic sanitary ware and construction/demolition waste. *Constr. Build. Mater.* **2012**, *40*, 822–831. [CrossRef]
61. Medina, C.; Del Bosque, I.F.S.; Asensio, E.; Frías, M.; De Rojas, M.I.S.; De Rojas, M.I.S. New additions for eco-efficient cement design. Impact on calorimetric behaviour and comparison of test methods. *Mater. Struct.* **2016**, *49*, 4595–4607. [CrossRef]
62. Asensio, E.; Medina, C.; Frías, M.; De Rojas, M.I.S. Characterization of Ceramic-Based Construction and Demolition Waste: Use as Pozzolan in Cements. *J. Am. Ceram. Soc.* **2016**, *99*, 4121–4127. [CrossRef]
63. Asensio, E.; Medina, C.; Frías, M.; De Rojas, M.I.S. Use of clay-based construction and demolition waste as additions in the design of new low and very low heat of hydration cements. *Mater. Struct.* **2018**, *51*, 101. [CrossRef]
64. Rao, M.C. Influence of brick dust, stone dust, and recycled fine aggregate on properties of natural and recycled aggregate concrete. *Struct. Concr.* **2020**, *22*, E105–E120. [CrossRef]
65. European Committe for Standardization. *EN 12390-3:2009. Testing Hardened Concrete. Part 3: Compressive Strengh of Test Specimens*; European Committee for Standardization: Brussels, Belgium, 2009.
66. Medina, C.; Sánchez, J.; Del Bosque, I.S.; Frías, M.; De Rojas, M.S. Meso-structural modelling in recycled aggregate concrete. In *New Trends in Eco-Efficient and Recycled Concrete*; Woodhead Publishing: Amsterdam, The Netherlands, 2019; pp. 453–476. [CrossRef]
67. Medina, C.; Sánchez, J.; del Bosque, I.S.; Frías, M.; de Rojas, M.S. Modeling the interfacial transition zone between recycled aggregates and industrial waste in cementitious matrix. In *Waste and Byproducts in Cement-Based Materials*; Woodhead Publishing: Amsterdam, The Netherlands, 2021; pp. 3–27. [CrossRef]
68. Ahmed, S. Properties of Concrete Containing Recycled Fine Aggregate and Fly Ash. *J. Solid Waste Technol. Manag.* **2014**, *40*, 70–78. [CrossRef]
69. Kirthika, S.K.; Singh, S.K.; Chourasia, A. Performance of Recycled Fine-Aggregate Concrete Using Novel Mix-Proportioning Method. *J. Mater. Civ. Eng.* **2020**, *32*, 04020216. [CrossRef]
70. Kou, S.-C.; Poon, C.S.; Wan, H.-W. Properties of concrete prepared with low-grade recycled aggregates. *Constr. Build. Mater.* **2012**, *36*, 881–889. [CrossRef]
71. Yang, J.; Du, Q.; Bao, Y. Concrete with recycled concrete aggregate and crushed clay bricks. *Constr. Build. Mater.* **2011**, *25*, 1935–1945. [CrossRef]
72. Kou, S.C.; Poon, C.S.; Chan, D. Influence of Fly Ash as Cement Replacement on the Properties of Recycled Aggregate Concrete. *J. Mater. Civ. Eng.* **2007**, *19*, 709–717. [CrossRef]
73. Elhakam, A.A.; Mohamed, A.E.; Awad, E. Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete. *Constr. Build. Mater.* **2012**, *35*, 421–427. [CrossRef]

74. Wang, Y.; Zhang, H.; Geng, Y.; Wang, Q.; Zhang, S. Prediction of the elastic modulus and the splitting tensile strength of concrete incorporating both fine and coarse recycled aggregate. *Constr. Build. Mater.* **2019**, *215*, 332–346. [CrossRef]
75. Kumar, R.; Gurram, S.C.B.; Minocha, A.K. Influence of recycled fine aggregate on microstructure and hardened properties of concrete. *Mag. Concr. Res.* **2017**, *69*, 1288–1295. [CrossRef]
76. Bordy, A.; Younsi, A.; Aggoun, S.; Fiorio, B. Cement substitution by a recycled cement paste fine: Role of the residual anhydrous clinker. *Constr. Build. Mater.* **2017**, *132*, 1–8. [CrossRef]
77. Mas, B.; Cladera, A.; del Olmo, T.; Pitarch, F. Influence of the amount of mixed recycled aggregates on the properties of concrete for non-structural use. *Constr. Build. Mater.* **2012**, *27*, 612–622. [CrossRef]
78. Velardo, P.; del Bosque, I.S.; Matías, A.; de Rojas, M.S.; Medina, C. Properties of concretes bearing mixed recycled aggregate with polymer-modified surfaces. *J. Build. Eng.* **2021**, *38*, 102211. [CrossRef]