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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Evaluation of the effects of recycled aggregates on the properties of High Performance Concrete

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Barcelona, June 2016

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This research has received the financial support of the *Ministerio de Economía y Competitividad* by INNPACT project (IPT-2011-1655-370000) and the support of Vías y Construcciones S.A, and Drace Infraestructuras S.L.

Keywords: recycled aggregates, high performance concrete, fly ash, steam curing, shrinkage, prestressed concrete sleepers.

Printed in Barcelona, Catalonia, June 2016

“If you’re not buying recycled products,
you are not really recycling.”
Ed Begley, Jr.

ABSTRACT

In recent decades, the use of High Performance Concrete (HPC) has grown vastly, being used in multiple applications and structures with high requirements. However, the use of recycled aggregates (RA) has been mostly limited to conventional concrete. Many studies have defined limiting properties of RA, replacement ratios of natural aggregates and particular techniques to achieve suitable conventional concrete containing RA. Nonetheless, very few studies have been focused on the use of RA in the production of HPC.

This study examines the behaviour of High Performance Recycled Aggregate Concrete (HPRAC) in physical, mechanical, durability and structural properties according to the RA content and its quality. RA were sourced from Construction and Demolition Waste of several categories: Recycled Concrete Aggregate (RCA) obtained from 40, 60 and 100 MPa concretes, Ceramic Waste Aggregates (CWA) and Recycled Mixed Aggregates (RMA).

In the first experimental phase (Papers I and II), the limiting replacement ratios of RA were established in order to achieve comparable HPRAC to the reference HPC with a design strength of 100 MPa. The physical, mechanical and durability properties were studied for concretes containing 20, 50 and 100% of coarse RCA and RMA, and 15 and 30% of fine CWA. According to the mechanical properties, 100% of coarse RCA can be used, as long as RA is sourced from a 60 MPa minimum-strength concrete waste. Nevertheless, durability behaviour was more influenced by the use of RA and consequently replacement ratios of RCA could only be maintained on those obtained from parent concretes with the same quality as the new HPC. Moreover, significant reductions of the RA quality (RCA sourced from 40MPa - strength concretes or RMA) only permitted 20% replacement ratios. On the other hand, the concretes containing fine CWA (up to 30%) reached higher performances than those from conventional HPC.

On the following experimental phases the study was focused on the use of RCA which have the highest applicability in precast and prestressed HPC elements. On the second experimental phase (Papers III and IV), fly ash was used in replacement of 30% of Portland cement in order to enhance the RCA performance. Keeping in mind prestressed concrete as potential application which requires high early-age strength, the concrete mixtures were also subjected to an initial steam curing cycle. The natural aggregates could be completely replaced by RCA sourced from the same quality HPC, producing improved mechanical properties and pore structures. It was determined that when using lower quality aggregates, the use of steam curing was mandatory to fulfil the standard requirements for prestressed concrete. The steam curing had negative effects on the long-term mechanical properties, however the steam-cured HPRAC had greater improvements on the pore structure and the mechanical properties than conventional HPC.

The third experimental phase (Paper V) assesses the role of RCA in internal curing whose effect is significant in HPC. The effects of RCA were investigated in the plastic, autogenous and drying shrinkage of HPC, being the second of special interest in concretes with low water-cement ratio. The results revealed that the plastic and drying shrinkage became higher as the quality of the RCA decreased and the replacement ratio increased. However, a reduction in the autogenous shrinkage was proved to be possible by the use of a high content of lower quality RCA, since they acted as internal curing agents.

A pilot study of monoblock prestressed concrete sleepers containing RCA was carried out (Paper VI). The suitable behaviour of the HPRAC mixtures containing 50 and 100% of RCA sourced from 100 MPa-strength concretes enabled the production of prestressed concrete sleepers. The structural properties of HPRAC were tested on the conventional HPC and on both HPRAC sleepers. The prestressed concrete sleepers were subjected to static and dynamic load tests at rail-seat and centre sections. The structural requirements for prestressed concrete sleepers were extensively verified by sleepers made with HPRAC. Regardless of the replacement ratio, the HPRAC sleepers’ results barely differed from those of conventional HPC sleepers.

RESUM

En les darreres dècades, l'ús de Formigó d'Altes Prestacions (FAP) ha crescut considerablement en múltiples aplicacions i estructures d'elevat requeriment. Tot i això, l'ús d'àrids reciclats (AR) ha estat bàsicament limitat a formigons convencionals. Diversos articles han definit propietats limitants dels AR, nivells de substitució d'àrids naturals i tècniques específiques per tal d'aconseguir formigons amb àrids reciclats que poguessin ser considerats adequats. No obstant, molt pocs estudis s'han dedicat a la utilització dels AR en la producció de FAP.

Aquest estudi examina el comportament del Formigó Reciclat d'Altes Prestacions (FRAP) en les propietats físiques, mecàniques, de durabilitat i estructurals d'acord al contingut d'AR i la seva qualitat. Els AR es van obtenir de Residus de Construcció i Demolició de diverses categories: Àrids Reciclats de Formigó (ARF) procedents de formigons de 40, 60 i 100 MPa, Àrids de Residus Ceràmics (ARC) i Àrids Reciclats Mixts (ARM).

En la primera fase experimental (Articles I i II), es van establir els percentatges de substitució recomanats per tal de que els FRAP fossin comparables al FAP de referència amb una resistència de 100 MPa. Es van estudiar les propietats físiques, mecàniques i de durabilitat de formigons amb 20, 50 i 100% d'ARF i ARM gruixuts, i 15 i 30 % d'ARC fi. D'acord a les propietats mecàniques, es pot utilitzar el 100% d'ARF, sempre que procedeixi de residus de formigons amb un mínim de 60 MPa de resistència. No obstant, la durabilitat es més susceptible a l'ús d'AR i conseqüentment els nivells de substitució només poden mantenir-se en àrids procedents de residus de formigons de la mateixa qualitat que el nou FAP. També es va detectar que la reducció severa en la qualitat de l'AR (ARF obtingut de formigons de 40 MPa o ARM) només permet la seva utilització en un 20%. D'altra banda, els formigons produïts amb ARC fi (fins a un 30 % de substitució) van assolir prestacions més elevades que aquelles assolides pels FAP convencionals.

En els següents apartats, l'estudi es va centrar en la utilització d'ARF el quals tenen una major aplicabilitat en elements de FAP prefabricats i pretesats. En la segona fase experimental (Articles III i IV), es van utilitzar cendres volants en substitució del 30·% de ciment Portland, per tal de millorar les prestacions dels ARF. Tenint en compte el formigó pretesat com a aplicació potencial, el qual requereix d'altes resistències a edats curtes, les mescles de formigó es van sotmetre a un cicle inicial de curat en vapor. Els ARF obtinguts de residus de FAP de la mateixa qualitat poden ser utilitzats en un 100%, produint millores en les propietats mecàniques i en les estructures poroses. Per als formigons amb ARF de qualitats inferiors, es va determinar que l'ús del curat de vapor era imprescindible per tal de complir amb els requeriments normatius per a formigons pretesats. El curat de vapor presentà efectes negatius sobre les propietats mecàniques a llarg termini, però el FRAP va mostrar evolucions superiors en l'estructura porosa que el FAP de referència.

En la tercera fase experimental (Article V), es va avaluar el rol de l'ARF en el curat intern, la influencia del qual pot ser significativa en FAP. Es van investigar els efectes dels ARF en les retraccions plàstica, autògena i per assecament, essent la segona d'especial interès en formigons amb relacions aigua-ciment baixes. Els resultats van mostrar que la retracció plàstica i per assecament incrementa quan la qualitat dels ARF disminueix i seu nivell de substitució augmenta. No obstant això, la reducció de la retracció autògena es possible amb l'ús d'un alt contingut d'ARF de qualitats inferiors ja que, de fet, actuen com a agents de curat intern.

Degut a l'idoni comportament prèviament observat en les mescles de FRAP amb el 50 i 100% d'ARF procedent de residus de formigons de 100 MPa de resistència, es va portar a terme un estudi pilot de travesses monobloc de formigó pretesat amb ARF (Article VI). Les travesses de formigó pretesat es van sotmetre a assajos estructurals de càrrega estàtica i dinàmica en les seccions sobre carril i central. Les exigències estructurals per a travesses de formigó pretesat van ser àmpliament assolides per les travesses de FRAP. Amb independència al percentatge de substitució, el comportament de les travesses de FRAP no va mostrar diferències significatives respecte al de les travesses de FAP convencional.

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

- *Published papers:*

PAPER I

Gonzalez-Corominas A, Etxeberria M. (2014): Experimental analysis of properties of high performance recycled aggregate concrete. Construction and Building Materials, Vol. 52, pp. 227–35. (2014 Impact factor: 2.3; Q1).

PAPER II

Gonzalez-Corominas A, Etxeberria M. (2014): Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. Construction and Building Materials, Vol. 68, pp. 618-26. (2014 Impact factor: 2.3; Q1).

PAPER V

Gonzalez-Corominas A, Etxeberria M. (2016): Effects of using Recycled Concrete Aggregates on the shrinkage of High Performance Concrete. Construction and Building Materials, Vol. 115, pp. 32-41. (2014 Impact factor: 2.3; Q1).

- *Submitted papers:*

PAPER III

Gonzalez-Corominas A, Etxeberria M, Poon C.S. (submitted second review on May 2016): Influence of steam curing on the pore structures and mechanical properties of fly-ash High Performance Concrete prepared with recycled aggregates. Cement and Concrete Composites. (2014 Impact factor: 3.3; Q1).

PAPER IV

Gonzalez-Corominas A, Etxeberria M, Galindo A. (submitted on January 2016): Steam curing influence on fly-ash High Performance Recycled Concrete. ACI Materials Journal. (2014 Impact factor: 0.9; Q1).

PAPER VI

Gonzalez-Corominas A, Etxeberria M, Fernandez I. (submitted on April 2016) Structural behaviour of prestressed concrete sleepers made with High Performance Recycled Aggregate Concrete. Materials and Structures. (2014 Impact factor: 1.7; Q1).

ACKNOWLEDGMENTS

I would like to thank my PhD director, Prof. Miren Etxeberria, for letting me develop this project and for all the support she has given me since I started working with her as an undergrad student. Prof. Miren Etxeberria has guided me in this journey with passion and commitment in order to go beyond our goals. I also want to thank Prof. C.S. Poon for hosting me during my PhD stage in the Hong Kong Polytechnic University. Prof. C.S. Poon has contributed with wise advises which were kindly appreciated.

I have to mention the essential contribution of the students and technicians from the Department of Construction Engineering who have helped me to develop all the intense experimental phases from this study.

My special thanks Anna and Mati who have been next to me from the beginning of this journey making it more pleasant. During all this years, I met wonderful colleagues, DEC's PhD students and professors, which became friends.

I want to sincerely express my gratitude to my family and friends for encouraging me and for being my best support. Finally, I want to dedicate this thesis to Ivan for his understanding, patience and care.

CONTENTS

APPENDED PAPERS

1. INTRODUCTION

1.1. Background

The construction industry is responsible for a high percentage of raw materials consumption worldwide, and its contribution to environmental impact is clearly significant. In 2012, the global consumption of raw aggregates used in construction exceeded 26 billion tons (Sonawane and Pimplikar, 2013). Likewise, due to the increase demand from developing countries, the consumption rate of aggregates is expected to double within the next two or three decades (Oikonomou, 2005). For this reason, there is a growing interest from the construction field in developing materials and technologies in order to achieve sustainable procedures and products. Particularly in the cement and concrete manufacturing, the use of recycled aggregates is a leading trend towards the sustainable development.

On the other hand, the generation of Construction and Demolition Waste (C&DW) is both an economic and environmental concern which significantly increased during the last two decades. The C&DW is one of the most voluminous and heaviest waste streams generated in the European Union (EU). The C&DW accounts for approximately 33% of all industrial waste generated in the EU (Eurostat, 2012), which represents the highest amount among any other sector. According to the data from 2012, 821 and 26 million tons of C&DW were produced in the European Union and Spain, respectively.

European Union countries encourage reusing and recycling in construction by publishing C&DW recycling targets. According to the Waste framework Directive 2008/98/EC (European Union Parliament, 2008), the minimum recycling percentage of C&DW by the year 2020 should be at least 70% by weight. While some North-western European countries have accomplished or surpassed the required recycling rates, others are still far below the target. Especially in Southern-European countries, the disposal of C&DW on landfills is still an obstacle towards reaching the environmental targets stated by the EU. In Spain the recycled rates of C&DW from 2009 were estimated in 14 % (European Topic Centre on Resource and Waste Management, 2009), while more locally in Catalonia the rate increased to 58 % (Agència de Residus de Catalunya, 2010).

Another key factor affecting the application of recycled C&DW is the variability on its composition. In Spain, approximately 85% of the total C&DW is a mixed material composed by crushed concrete and mortar, natural aggregates, masonry elements, asphalts and other minor inorganic components (GERD. Gremio de Entidades de Reciclaje de Derribos, 2008). The heterogeneous C&DW composition produces a high range of physical and mechanical properties on the recycled aggregates which leads to a lack of confidence on clients and contractors (Silva et al., 2014). Likewise, both excessive transportation distances between construction/demolition sites and treatment plants and little restrictive standards and specifications are not aligned with the conscious C&DW treatment.

In Spain, the C&DW is regulated by the R.D. 105/2008 February 1, which aims to establish the legal framework for their production and management in order to promote the prevention, reuse, recycling and other forms of recovery of C&DW. The disposal of C&DW should ensure proper treatments and contribute to the sustainable development of the activity. The resolution from January 20th of 2009 approved the National Integrated Waste Plan 2008-2015, which represented the beginning of a waste management policy focused on recycling and minimization. The plan also included the first measures to promote the use of recycled products from C&DW.

The relatively low cost of Natural Aggregates (NA) goes against the use of recycled aggregates. However, the cost of processing the recycled aggregates is expected to become lower than the cost of disposing the C&DW waste, due to the increase of both landfilling taxes and purchasing of the natural aggregates (Whyte et al., 2005). The reduction of transportation distance and an on-site C&DW reuse would cease any doubt on the environmental and economic benefits of the recycled aggregates.

1.2. Research significance

Over the past twenty years, many studies have been published on the effects of using recycled coarse aggregates as a replacement of natural aggregates in concrete (Etxeberria et al., 2007; Koenders et al., 2014; Tabsh and Abdelfatah, 2009; Thomas et al., 2013; Xiao et al., 2012). Generally, the recycled aggregates have higher porosity, water absorption capacity and contaminants content and also lower density and abrasion or impact resistance than the natural aggregates (Silva et al., 2014). The use of RCA in the production of low and medium strength concretes (up to 50-60 MPa according to ACI (ACI Committee 363, 1997) and BS EN 206-1) decreases the compressive strength and modulus of elasticity of the concrete. Recycled aggregate concretes show increased shrinkage, creep and water sorptivity in comparison with those of Natural Aggregate Concrete (NAC). Nevertheless, the use of appropriate mix design methods with the addition of mineral admixtures can mitigate the negative influence of recycled aggregates (Kou and Poon, 2015; Tam and Tam, 2007).

On the other hand, relatively few investigations have been published about the use of recycled aggregates in the production of High Performance Concrete (HPC). The term HPC is used for concrete mixtures with high workability, durability and ultimate strength (Mehta and Aitcin, 1990). Even so, HPC is easily related to high-strength concretes which are defined by the ACI as those concretes with a compressive strength in range of 60-100 MPa.

Some studies related to the use of recycled aggregates in HPC (Ajdukiewicz and Kliszczewicz, 2002; Kou and Poon, 2015) revealed that the quality of the parent concrete, from which the recycled aggregates are derived, is a key factor affecting the properties of the resulting HPC produced. It has been reported that the use of RCA, sourced from crushing original HPC, for the production of new HPC can improve mechanical and durability properties even at high replacing ratios. However, other studies concluded that only 30% of coarse RCA could be used to produce HPC (Limbachiya et al., 2000), and even others affirmed that recycled aggregates were not suitable for high strength concrete applications due to compressive strength reduction and poorer long-term durability (Tu et al., 2006).

Up to date, the threshold qualities and compositions of the recycled aggregates for the production of HPC has not been accurately defined. Also the range of replacement ratios extracted from the existing literature is still too wide and unprecise for particular recycled aggregate qualities. This is a field of great interest due to the high quality of structures made in the last decades which are expected to be demolished in the near future, creating a great source of high quality C&DW waste which can be used in the production of new HPC.

On the other hand, most of the studies made about the use of recycled aggregates in HPC were focused on concrete productions using Portland cement exclusively. However, some studies (Kou et al., 2008) on low-strength concrete have stated that fly-ash contributes to the enhancement of Recycled Aggregate Concrete (RAC). The mechanisms causing the enhancement in the RAC's behaviour are: the improvement of the Interfacial Transition Zone (ITZ), the crack filling in old mortar paste attached in the recycled aggregates, and the recycled aggregates' residual binding ability.

The study from Ajdukiewicz and Kliszczewicz (Ajdukiewicz and Kliszczewicz, 2002) showed very optimistic results from using fly ash in High Performance Recycled Aggregate Concrete. Their study deeply discussed the influence of the mineralogy of the raw aggregates contained in the recycled aggregates; however the replacement ratios to achieve similar behaviour to those from conventional fly-ash HPC were not identified. Also the physical and durability properties and the pore structures in fly-ash HPC with recycled aggregates have not been studied.

High Performance Concrete can be used in the production of prestressed concrete elements which require high early compressive strengths. Nonetheless, the replacement of Portland cement by fly ash produces a reduction of the hydration temperature as well as a reduction of the strength gain at early ages. In order to increase early-age concrete strength, steam curing is usually used because it accelerates the cement hydration development (Yazıcı et al., 2005; Zhimin et al., 2012). The high temperature experienced during the first day in the steam curing tank enhances the binder reaction within the concrete. However, it must be said that steam curing modifies the properties of the resulting cement matrix (Ba et al., 2011; Ramezanianpour et al., 2014).

Kou et al. (Kou et al., 2004) studied the influence of steam curing on the mechanical properties of recycled aggregate concrete in low strength concrete. However, steam curing can also be of great interest when applied to High Performance Concrete with recycled aggregates when high early-strength is required. The influence of recycled aggregates on the mechanical properties of steam-cured HPC is still unknown. Also the effect of steam curing on the pore structures and the durability properties of the recycled aggregate concretes needs to be tackled.

Another major concern on the use of recycled aggregates is the shrinkage strain which is particularly interesting in HPC. The shrinkage is made of plastic shrinkage, autogenous shrinkage and drying-shrinkage and it is the consequence of diverse factors such as temperature and relative humidity, size and shape of the concrete piece, components, water/binder ratios and age of concrete (Tam and Tam, 2007). The HPC implies that other factors become more determinant than in traditional concretes, and autogenous shrinkage is one of those to be taken into consideration (Meddah and Sato, 2010; Suzuki et al., 2009). However, most studies of recycled aggregate concretes were only focused on the study of drying shrinkage. Also some studies (Corinaldesi, 2010; Suzuki et al., 2009) mentioned that recycled aggregates could act as internal curing agents reducing the concrete shrinkage similarly to lightweight aggregates.

Likewise the study of the structural properties of the recycled aggregate concretes is still limited and there is also a lack of pilot studies worldwide about the use of recycled aggregates in HPC. The promotion of using recycled aggregates in real HPC applications should transition from experimental studies to pilot tests. In order to reach the industrial level, the knowledge of recycled aggregates' behaviour in real-scale concrete applications is key and would potentially open new markets.

1.3. Scope and objectives

The main objective of this investigation is to assess the influence of recycled aggregates on the physical, mechanical, durability and structural properties of High Performance Concrete. The study analyses the effect of the quality of recycled aggregates and the level of replacement of natural aggregate on the properties of HPC made with recycled aggregates. This study intends to identify and correct the weakest properties triggered by the use of recycled aggregates in HPC.

Within this overall objective and the framework of the thesis, there are a number of specific objectives that relate to different stages of the research project.

- To analyse the influence of the substitution of natural aggregates by recycled aggregates of several qualities in the physical, mechanical and durability of concrete. To define the proper replacement ratio for each recycled aggregate quality in order to achieve similar properties to those from the reference conventional HPC.
- To evaluate the effects of fly ash on the physical, mechanical and durability properties of High Performance Recycled Aggregate Concrete (HPRAC). To assess the need of steam curing in the fly-ash HPC in order to be used in prestressed concrete applications. To analyse the influence of steam curing in the porous structure and mechanical behaviour of HPRAC in comparison with conventional HPC.
- To study of the plastic, autogenous and drying shrinkage of HPRAC as well as to assess the internal curing capacity of recycled aggregates.
- To analyse the structural behaviour of HPRAC in comparison with conventional HPC. To develop the production of prestressed concrete sleepers using HPRAC in order to evaluate the fulfilment of the Spanish technical specifications and to develop a comparative study of stress-strain behaviour between conventional HPC and HPRAC.

The recycled aggregates used in the HPC production were: coarse Recycled Concrete Aggregates (RCA) sourced from parent concretes of medium, high and very high strength (40, 60 and 100

MPa of compressive strength) and coarse Recycled Mixed Aggregates and fine Ceramic Waste Aggregates sourced from a local C&DW treatment plant. The physical, mechanical and durability properties were analysed in HPC and HPRAC containing 20, 50 and 100% of coarse recycled aggregates and 15 and 30% of fine recycled aggregates.

Fly ash and steam curing were the variables set up in the study in order to enhance the HPRAC performance, while reducing the minimum recycled aggregates' quality required and maximizing their replacement ratio. The physical, mechanical and durability properties were verified. The pore structure and the evolution of compressive strength were key factors in the assessment of the fly ash and steam curing influence on HPRAC in comparison with HPC.

Due to the importance of shrinkage in HPC and the influence of recycled aggregates, the study of shrinkage was based on the assessment of plastic, autogenous and drying shrinkage. The shrinkage analysis was developed in order to assess the potential internal-curing effect from the RA. The very different Recycled Aggregate (RA) qualities provided a broad spectrum of water absorptions whose influence on the shrinkage behaviour should be considered. The RA were used with high moisture levels and could act similarly to other proven internal curing agents (Suzuki et al., 2009; Zhutovsky and Kovler, 2012).

The pilot study and the structural behaviour analysis was focused on prestressed concrete sleepers made with two selected HPRAC mixtures. The HPRAC mixtures were selected according to their optimal behaviour in order to meet the Spanish Railway Infrastructure Administrator (ADIF)' requirements for the approval of prestressed concrete sleepers produced. In the structural analysis, the stress-strain behaviour from both HPRAC and conventional HPC were compared. Moreover a comparative study between the experimental results and the values proposed by four methods of assessing the ultimate load was carried out.

1.4. Structure of the thesis

This document introducing the compilation of papers conducted as part of the PhD research has been divided in seven chapters. Their content is summarized below:

In chapter 1, the current situation and the reason which encouraged these investigation are presented. The main and the specific objectives of the research, their scope and the structure followed in this document are stated.

In chapter 2, the materials used to produce HPC and HPRAC in all experimental phases were characterized. The concrete production was detailed, by presenting the concrete proportioning and the casting and curing methods.

Chapter 3 summarizes the research published on Papers I and II. The physical, mechanical and durability properties from HPRAC were analysed according to the quality and amount of recycled aggregates.

Chapter 4 corresponds to the research from Papers III and IV. The influence of fly ash and steam curing was evaluated in conventional HPC and HPRAC, considering prestressed concrete elements as potential applications.

In chapter 5, the investigation published in Paper V was summarized. The shrinkage behaviours of HPRAC were compared with those from HPC in order to determine the internal curing capacity of recycled aggregates.

Chapter 6 correspond to the research from Paper VI which described the structural performance of the prestressed concrete sleepers produced with conventional HPC and two types of HPRAC mixtures.

2. MATERIALS AND CONCRETE PRODUCTION

This chapter details the materials used in the HPC concrete production. The binders, aggregates and admixtures used during the experimental phases were characterized prior to the concrete production. A Portland-cement HPC from an existing precast concrete company was selected as reference HPC. The materials composing the reference HPC were used in the reproduction of the conventional HPC mixture.

In the first experimental phase (Papers I and II), the natural aggregates were replaced by recycled aggregates. In the second experimental phase, fly-ash and steam curing were incorporated. In the third and fourth experimental phases, designated concrete mixtures were selected from the first phase in order to carry out specific tests.

2.1. Binders and admixtures

The cement used in the first experimental phase was an ASTM Type I Portland cement (CEM I 52.5R) for all concrete mixtures. The high strength and rapid hardening cement presented low alkali content and specific surface of 4947.8 cm^2/g. The rapid-hardening Portland cement was used in order to achieve concretes of 1-day compressive strength higher than 50 MPa, thus meeting the requirements for precast and prestressed concrete (ADIF, 2009; Ramezanianpour et al., 2013).

In the second experimental phase, Portland cement was used in combination with fly-ash. In this case, the Portland cement was commercially available CEM I 52.5R and equivalent to ASTM Type I cement. The fly ash used, with a specific surface of 3360.0 cm^2/g and a density of 2.32

g/cm^3, was equivalent to ASTM class F. The chemical compositions of the Portland cements and the FA are given in Table 1.

Table 1. Chemical compositions of binders.

Composition (%)	SiO_2	Al_2O_3	Fe_2O_3	*CaO*	*MgO*	K_2O	TiO_2	P_2O_5	Na_2O	Cl^-	SO_3	*LOI*
Low-alkali Portland Cement	21.75	3.38	4.55	64.65	1.63	0.64				0.01	2.66	1.20
Portland Cement	21.91	3.57	4.67	64.98	1.45	0.57	0.18	0.18	0.12			1.05
Fly Ash	55.46	26.94	5.86	5.70	1.50	1.51	1.41	0.83	0.62			3.70

For all experimental phases, a high performance superplasticizer based on polycarboxylate ether (PCE) with a specific gravity of 1.08 was used for concrete production. The dosage used was at a constant percentage of binder weight (1.5%) following the manufacturer’s recommendations.

2.2. Aggregates

2.2.1.Natural aggregates

The source and type of the natural aggregates used in the production of the concrete were those used in the production of a commercial High Performance Concrete in a Spanish precast concrete company. The natural fine aggregates employed were two river sands mainly composed of silicates and divided into two different particle size fractions (0-2mm and 0-4mm) in order to achieve higher compaction. Two types of coarse natural aggregates were used to improve the workability and the mechanical behaviour of the concrete, rounded river gravel (siliceous composition) and crushed dolomitic coarse aggregate. The particles size distributions of the natural aggregates are shown in Fig. 1.

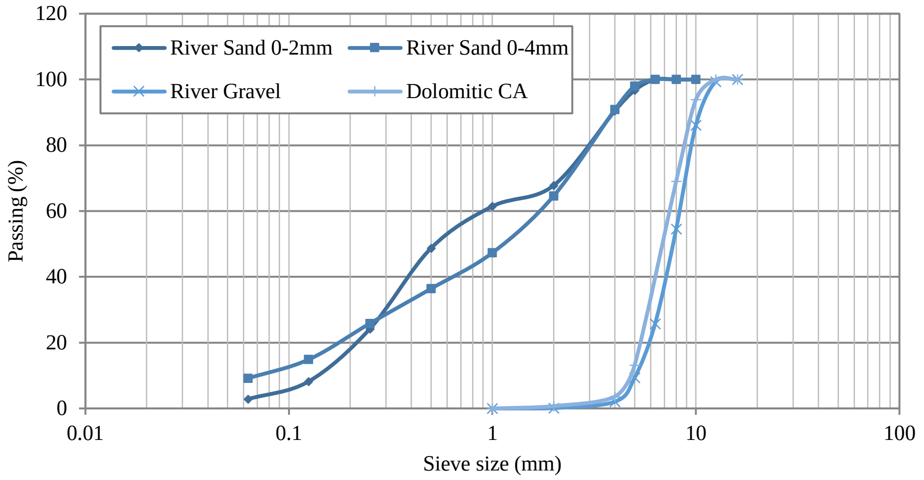

Fig. 1. Particle size distribution of natural aggregates.

The physical and mechanical properties of the natural aggregates are given in Table 2.

Table 2. Physical and mechanical properties of natural aggregates.

Natural aggregates	*Oven-dried particle density (kg/dm^3)*	*Water absorption (%)*	*Sand equivalent (%)*	*Flakiness index (%)*	*Crushing value (%)*	*LA Index (%)*
River Sand 0-2 mm	2.57	1.93	75.00			
River Sand 0-4 mm	2.50	1.02	87.88			
River Gravel	2.61	1.29		17.71	18.92	19.61
Dolomitic CA	2.68	2.13		7.81	20.15	24.77

2.2.2.Recycled aggregates

In the first experimental phase five different types of aggregates were assessed for the production of High Performance Recycled Aggregate Concrete. The Paper I describes the utilization of Recycled Concrete Aggregates (RCA) from three different qualities according to the strength of the parent concrete from which were sourced. In Paper II, the use of fine Ceramic Waste Aggregate (CWA) and coarse Recycled Mixed Aggregate (RMA) were studied. The following experimental phases were focused on RCA due to their higher applicability in prestressed concrete elements.

The RCA with maximum sizes of 10 mm, RCA100, 60 and 40 MPa were obtained from crushing three parent concretes of different qualities (of 100, 60 and 40MPa of characteristic compressive strength). The RCA 100 MPa was sourced from rejected 100 MPa compressive strength concrete specimens or sleepers obtained from the same Spanish prestressed concrete manufacturer which provided the reference HPC mixture. The components of parent 100 MPa concrete were the same components described in the natural aggregates section. The 60 MPa parent concrete was specifically produced in the laboratory to achieve 60 MPa at 28 days, afterwards it was crushed for RCA60 production and stored for a minimum of 180 days before using in concrete manufacture. The RCA 40 MPa was sourced from crushing 3-year old precast beams with a compressive strength of 40MPa at 28 days. The parent concretes of 60 MPa and 40 MPa were composed of crushed fine (0-4 mm) and coarse limestone aggregates (4-10 mm and 10-20 mm) and Ordinary Portland cement (CEM I 42.5). Their particle size distributions are shown in Fig. 2.

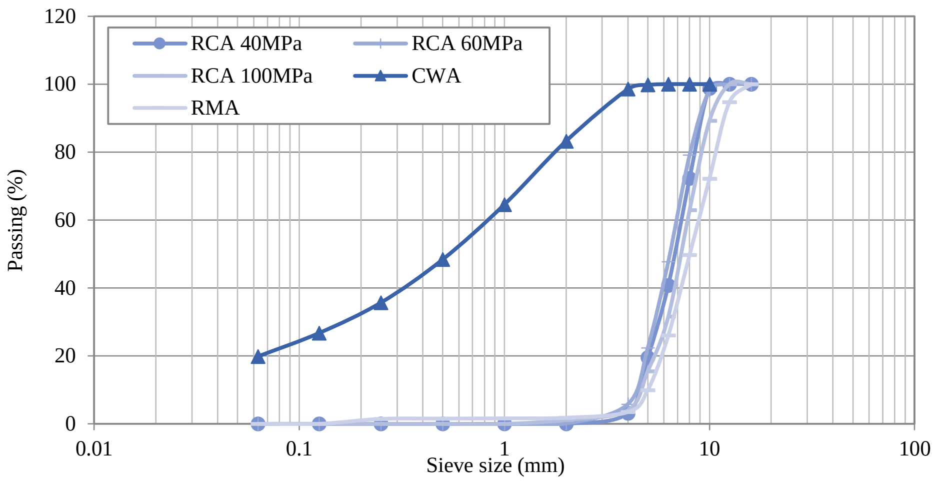

Fig. 2. Particle size distribution of recycled aggregates.

The RMA containing 67% ceramic waste was sourced from a treatment plant located in Catalonia (Spain). The compositions of the RMA are given in Table 3, following the specifications of EN-933-11. The RMA composition did not fulfil the ceramic aggregate classification requirements of the RILEM (Vincke and Rousseau, 1994) and DIN standards (DIN 4226-1:2000, 2000) (>90% or >80% of ceramic content, respectively). The mixed aggregate category was adopted to define the RMA composition, in spite of showing a high proportion of ceramic components (Silva et al., 2014).

Table 3. Composition of the RMA according to the UNE-EN 933-11:2009.

Recycled aggregates	*Composition (%)*					
	Concrete products	*Unbound aggregates*	*Masonry products*	*Bituminous products*	*Glass products*	*Others*
RMA	22.2	9.8	67.3	0	0.1	0.7

The fine Ceramic Waste Aggregate (FCA) was sourced from crushing old rejected bricks. The CWA was used as replacement for both of the natural fine aggregates. As can be seen on Fig. 2, the FCA showed higher ratios of filler and finer particles than the natural aggregates. However, the particle size distributions of the fine aggregates samples combined with 15% and 30% of FCA were acceptable according to Spanish Structural concrete requirements (EHE-08, 2010).

The physical and mechanical properties of the recycled aggregates are shown in Table 3. The physical and mechanical properties of each type of aggregates were determined according to EN specifications. The natural aggregates had higher density and lower absorption capacity than the recycled aggregates. Nonetheless when the parent concrete had higher compressive strength, the RCA achieved better physical properties. The three types of RCA had less than 7% absorption capacity which is the maximum absorption capacity required by the Spanish Structural concrete regulation (EHE-08, 2010). RMA showed a water absorption capacity of 16.45% due to the high proportion of ceramic material.

Table 4. Physical, mechanical and chemical properties of the recycled aggregates.

Recycled aggregates	*Oven-dried particle density (kg/dm^3)*	*Water absorption (%)*	*Flakiness index (%)*	*Crushing value (%)*	*LA Index (%)*	*Soluble sulphate (%SO_3)*	*Chloride content (%Cl^-)*
RCA 100 MPa	2.47	3.74	16.53	22.59	24.01	0.43	0.02
RCA 60 MPa	2.39	4.9	13.57	23.36	25.24	0.52	0.01
RCA 40 MPa	2.3	5.91	9.59	25.55	24.31	0.45	0.02
CWA	2	14.37					
RMA	1.8	16.45	12	34.62	25.2		

The Los Angeles Index of all the aggregates was lower than 30%, which indicated a high resistance to abrasion; moreover, the Los Angeles Index of RMA was similar to the one obtained from dolomitic coarse aggregate. Nevertheless, aggregates crushing value revealed higher differences between recycled and natural aggregates.

2.3. Concrete mixtures

All concrete mixtures from Phase 1 to 3 were prepared and produced in the laboratory. The NAC proportioning was provided by a Spanish HPC manufacturer and followed the Fuller's dosage method (Fuller and Thompson, 1907). All four types of recycled coarse aggregate were used to substitute (by volume) 20, 50 and 100% of the coarse natural aggregates and the fine CWA replaced 15 and 30% of fine natural aggregates (see Table 5). In Phase 2, the fly ash was used as replacement of 30% of Portland cement and the recycled aggregates were used only in 100% replacement ratios (see Table 6). The concrete proportioning parabola correctly fitted the Gessner parabola provided by the Fuller's method in both cases: when using natural and recycled aggregates.

In order to control the concrete production, the recycled aggregates were nearly saturated, at 80-90 % of their water absorption capacity. In general the higher water absorption from recycled aggregates reduces the workability of the concrete mixtures (Martínez-Lage et al., 2012), however in this case the moisture content in the RCAs neutralized such effect. In addition, the high moisture states enabled higher control on the reacting water with the binder and avoided problems derived from water on the RCAs surface or bleeding (Poon et al., 2004b). The fine natural aggregates were over-saturated (3-4% of moisture content).

As shown in Table 4, 380 kg of binder and a constant effective water-binder ratio of 0.285 were used in all concrete productions (considering effective water that outside the aggregates (Neville, 1995)). The volume of mixing water was determined before concrete production, in order to maintain the water amount reacting with the binder constant (effective water). The volume of mixing water was composed of the effective water and the water absorbed by the aggregates at concrete production (effective absorption capacity). The total water amount of the concrete was considered as the total amount of effective water, effective absorption capacity of aggregates and moisture water (water inside the aggregates).

The amount of chemical admixture added was kept constant at 1.5% of the cement weight in all concrete mixtures. The mix proportioning and the admixture amount produced dry consistency of fresh concrete, between 0-20 mm in the concrete slump test (S1 class following the EN 206-1:2000 standard).

Table 5. Concrete mixture proportioning of Portland cement concretes.

Mix notation	*Replace. ratio (%)*	*Cement (kg)*	*River Sand 0-4 mm*	*River Sand 0-2 mm*	*River Gravel*	*Dolomitic Gravel*	*RA*	*Total Water (kg)*	*Effective W/C ratio*
HPC	0	380	711.8	215.2	302.1	784.5	-	135.4	0.285
HPRAC-RCA100	20	380	711.8	215.2	241.6	627.6	202	137.1	0.285
	50	380	711.8	215.2	151	392.2	505.1	146.5	0.285
	100	380	711.8	215.2	-	-	1010.2	162.3	0.285
HPRAC-RCA60	20	380	711.8	215.2	241.6	627.6	195	138.2	0.285
	50	380	711.8	215.2	151	392.2	487.5	149.8	0.285
	100	380	711.8	215.2	-	-	975.1	170.4	0.285
HPRAC-RCA40	20	380	711.8	215.2	241.6	627.6	187.8	139.7	0.285
	50	380	711.8	215.2	151.1	392.3	469.4	153.1	0.285
	100	380	711.8	215.2	-	-	938.8	175.3	0.285
HPRAC-CWA	15	380	605	182.9	302	784.5	108.6	154.1	0.285
	30	380	498.2	150.7	302	784.5	217.2	166.3	0.285
HPRAC-RMA	20	380	711.8	215.2	241.6	627.6	147	160.8	0.285
	50	380	711.8	215.2	151	392.2	367.4	191.3	0.285
	100	380	711.8	215.2	-	-	734.9	244.8	0.285

Table 6. Concrete mixture proportioning of fly ash concretes.

Mix notation	*Replace. ratio (%)*	*Cement (kg)*	*Fly Ash (kg)*	*River Sand 0-2mm (kg)*	*River Sand 0-4mm (kg)*	*River Gravel (kg)*	*Dolomitic Gravel (kg)*	*RA (kg)*	*Total Water (kg)*	*Effective W/B*
HPC-FA	***0***	266	114	182.5	711.8	302.1	784.5	---	133.6	0.29
HPRAC - RCA100-PFA	***100***	266	114	182.5	711.8	-	-	1010.2	160.3	0.29
HPRAC-RCA60-PFA	***100***	266	114	182.5	711.8	-	-	975.1	168.4	0.29
HPRAC-RCA40-PFA	***100***	266	114	182.5	711.8	-	-	938.8	173.8	0.29

2.4. Specimen casting and curing

In each phase, the concrete specimens were prepared following the same procedure which reproduced the casting stage from a precast and prestressed concrete manufacture. The specimens were compacted using a vibrating table during two stages of 30 seconds each.

2.4.1.Curing method

In all experimental phases the concretes underwent a conventional air-curing process with the exception of Phase 2. In Phase 2, the concrete specimens were divided into two series: air-cured and steam-cured.

- *Conventional curing*

The concrete specimens were kept in the moulds for a day. The moulds were covered with a wet burlap and a plastic top to ensure that both temperature and wet conditions remained stable between 18º C and 26º C with a high moisture content. Specimens were demoulded 24 hours after casting. Three cubic specimens were immediately tested after demoulding to measure 1-day compressive strength. The rest of the specimens were cured in a humidity room at 23ºC and 95% humidity until the age of testing was reached.

- *Steam curing*

Immediately after casting, the specimens were initially cured in a steam bath for 24 hours, achieving a maximum temperature of 65 ºC during 8 hours. Both the steam curing temperature and duration have important effects on the progress of the hydration reaction and product formation (Neville, 1995). The steam curing cycle used, which followed the recommendations from Poon and Kou (Kou et al., 2004) and Ramezanianpour et al. (Ramezanianpour et al., 2013), is shown in Fig. 3. After the initial steam curing period, all the specimens were demoulded and stored, as the other conventionally cured specimens, in a standard curing room until the testing ages were reached.

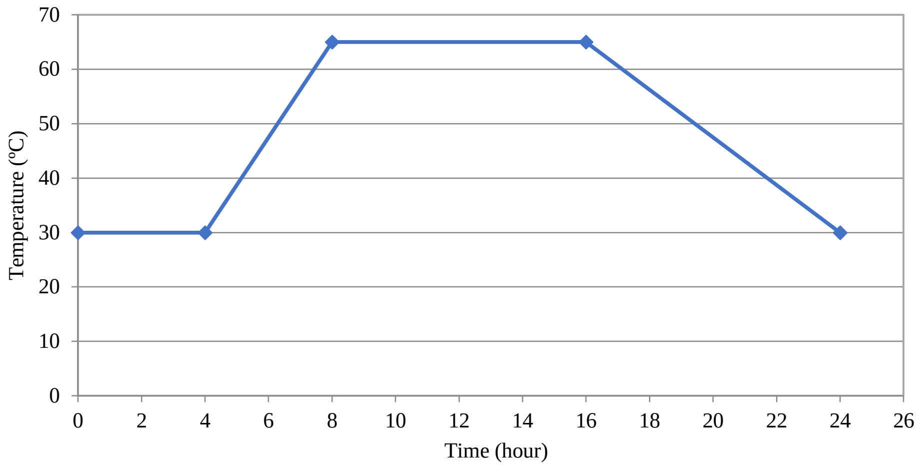

Fig. 3. Heat treatment procedure followed in steam cured concretes during the first 24 hours after casting.

3. PHASE 1: Characterization of HPC containing recycled aggregates

In this experimental phase (Papers I and II), the main objective is to analyse the effect of Recycled Aggregates (RA) sourced from different quality C&DW on the physical, mechanical and durability properties of High Performance Concrete (HPC). Three coarse RA sourced from parent concretes of 100, 60 and 40 MPa, as well as one coarse recycled mixed aggregate and one fine ceramic waste aggregate were used as replacement for natural aggregates. The HPC was designed to achieve 100 MPa compressive strength in order to comply with both the regulations of the Spanish railway sleeper specification (ADIF, 2009) and the technical requirements for its application in precast-concrete factories.

3.1. Methodology

3.1.1.Physical properties

The density, absorption and voids were measured following the ASTM C 642-13 “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete” at 28 days. Three 100 mm cubic specimens were used in this test for each type of concrete produced.

The Ultra-sound Pulse Velocity (UPV) test was carried out in cube specimens of size 100 x 100 x 100 mm. The average UPV values were taken from three cubes obtained from each mixture using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT). The test was done in accordance with the ASTM C 597-09 in a direct transmission state. All the 100 mm cubic specimens were tested at the saturated condition, at the age of 28 days.

3.1.2.Mechanical properties

The compressive strength of concretes was determined using a compression machine with a loading capacity of 3000 kN. The compressive strength was measured at the ages of 1, 7 and 28 days for the 150 mm cubic specimens (in order to verify that they were in accordance with Spanish railway sleeper technical requirements (ADIF, 2009)) and at the ages of 28 and 180 days for the 100∅ x 200 mm cylindrical specimens following UNE-EN 12390-3:2009 standard. Each presented value is the average of three measurements.

The flexural strength was measured following UNE-EN 12390-5:2009 at the age 7 days in accordance with the Spanish railway sleeper technical requirement (ADIF, 2009). The splitting tensile strength and elastic modulus were tested at 28 days in cylindrical specimens of 100∅ x 200 mm following UNE-EN 12390-6:2010 and UNE-EN 12390-13:2014 specifications, respectively. Three specimens were used for each type of concrete produced to determine the mean values.

3.1.3. Durability properties

The concrete capillary water absorption was assessed using 100 mm cubic specimens at 28 days of curing and according to ISO 15148:2002. The cumulative water absorbed was recorded at different time intervals up to 48 hours. Sorptivity is the regression slope described between the amount of water absorbed by a unit surface area and the square root of the elapsed time from initial time to 120 minutes. The results of capillary water absorption as well as the results of sorptivity are the average of three measurements.

The chloride penetrability of concrete was determined in accordance with ASTM C1202 (2012) using a 50 mm thick/100∅ mm concrete sections cut from the middle of 100∅ x 200 mm concrete cylinders. The test was carried out on the concrete specimens at the ages of 28 and 180 days, each result was the average of four measurements.

The Electrical resistivity was measured in the laboratory with a basic electric device. The voltage was measured across a sample of known dimensions and then the resistivity was calculated. The measurement was carried out using electric conductive gel spread on the surface in contact with the copper plates used as cathodes. All specimens were tested at 28 days at the saturated surface-dry conditions and each result was the average of 3 measurements.

3.2. Results and discussion

3.2.1.Physical properties

The results of water absorption and dry-density from Papers I and II revealed that the increase in replacement of coarse recycled aggregates caused the decrease of the dry-density of the concretes and the increase in water absorption, as several authors reported (Silva et al., 2014). The decrease of coarse RA's quality also had negative influences on the physical properties.

However, CWA reduced the accessible pores due to higher filler particles than natural aggregates which led to lower water absorption capacity. A major quantity of filler particles in fine CWA not only led to a better filling, but also the water absorbed in fine ceramic aggregates could produce an internal curing in concretes, improving the cement hydration (Suzuki et al., 2009) and consequently lowering the amount of accessible pores. Similarly in concretes made with lightweight aggregates, Cusson and Margeson (Cusson and Margeson, 2010) found that cement hydration was actually enhanced by internal curing which led to higher C-S-H content.

All UPV concrete values exceeded 4500 m/s and were classified in the range of excellent values, except when 100% of RMA was used, according to the UPV values proposed by Whitehurst (Whitehurst, 1951) whose research determined the quality of concretes with a density of 2400 kg/m^3. The increase of the replacement of natural aggregates for coarse mixed aggregates triggered an increase of pore spaces that affected the transmission of ultrasonic waves. The replacement of 100% of natural coarse aggregates by RMA produced a 20% reduction of UPV, likewise Whitehurst (Whitehurst, 1951) defined this value as good quality concrete. The UPV of the concretes made with RMA showed a direct and linear relationship with compressive strength and permeable pore volumes.

3.2.2.Mechanical properties

The compressive strength from HPRAC mixtures obtained a higher compressive strength than the conventional HPC after 1 day, except for the HPRAC containing 100% of RCA40 and RMA which obtained lower compressive strengths than HPC's.

. The remaining absorption capacity of partially saturated recycled aggregates could reduce the w/c ratio in the ITZ improving its strength at early hydration (Poon et al., 2004a).

Fig. 4a shows the 28-days relative compressive strength of RAC with respect to conventional HPC. HPRAC containing RCA sourced from HPC concrete (RCA 100 and 60) and CWA achieved higher or similar compressive strength than on NAC. The concretes made with 40MPa RCA or RMA, in which more than 50% and 20% of the natural aggregate was respectively replaced, showed lower compressive strengths than NAC's. As some authors (Tabsh and Abdelfatah, 2009) have pointed out, the quality of the old mortar attached in comparison with the new mortar has significant effects on the mechanical behaviour of the RAC.

The compressive strength test was also carried out on cylindrical specimens at 28 and 180 days. RAC showed a higher compressive strength increase from 28 to 180 days than conventional HPC during the same period of time. Increasing recycled aggregate content produced higher developments of compressive strength. At the same time, RMA, which is the most porous recycled aggregate type used, achieved the highest compressive strength increase. The water stored in the recycled aggregates enhanced the cement hydration through internal curing similarly to lightweight aggregates and produced improved mechanical behaviours (Suzuki et al., 2009; Zhutovsky and Kovler, 2012).

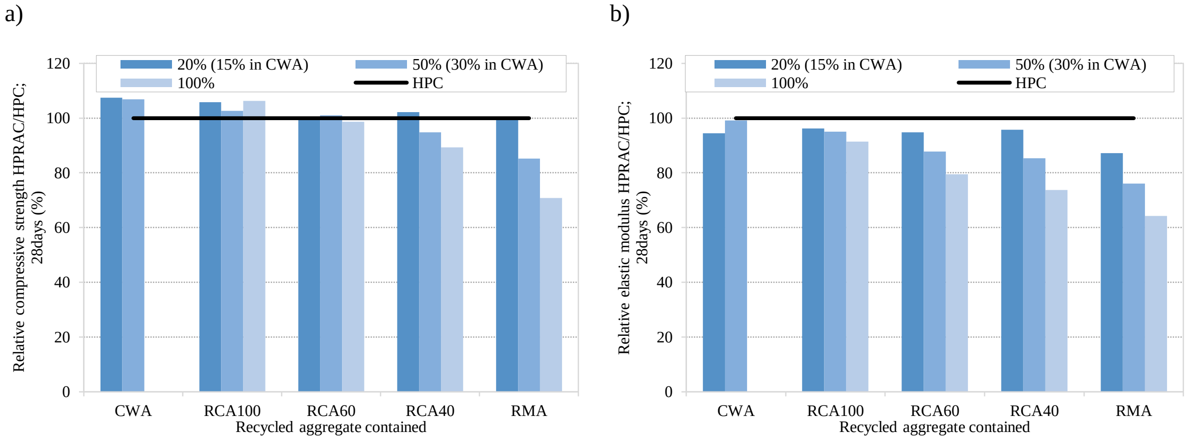

Fig. 4. Relative compressive strength (a) and Relative elastic modulus (b) of HPRAC in comparison with that of reference HPC at 28 days of age.

According to the splitting tensile strength, all concretes mixtures showed suitable performances, excepting concretes made with 100% of RCA-40 and RMA. However, the splitting tensile strength did not seem to be greatly influenced by the RAC replacement level. The ITZ between the cement paste and coarse aggregate has notable influence on this property as reported by Etxeberria et al. (Etxeberria et al., 2007). The elastic modulus seemed to be highly sensible to recycled aggregate replacement (see Fig. 4b). Despite showing lower elastic modulus values, concretes containing CWA and 20% of any RCA quality only suffered 4% reductions. The minimum was found to be 32.4 GPa (HPRAC with 100% of RMA) due to the negative influence of its low particle density (Lydon and Balendran, 1986).

3.2.3.Durability properties

The sorptivity values of concretes produced with coarse RCA and fine CWA were approximately 0.014 ± 0.001 mm/min$^{1/2}$. When the coarse RMA was used for concrete production, sorptivity values increased to 0.021-0.036 mm/min$^{1/2}$. The sorptivity values were significantly lower than those found in other studies for conventional HPC using slightly higher water-cement ratios

(Zhutovsky and Kovler, 2012) which indicates higher influence of the water-cement ratio than that from the aggregate type used.

The results of assessing the chloride-ion penetration of concrete specimens are shown in Fig. 5 (a). The resistance to chloride-ion penetration decreased as the recycled aggregate content increased and as RCA quality decreased. As shown in Fig. 5 (b), at the age of 180 days, the concrete mixtures produced with CWA showed the highest resistances to chloride-ion penetration. The reduction of the total charge passed in the conventional HPC from 28 days to 180 days was that of 35%, however the reduction of total charge in HPRAC with CWA and RMA was that of 52-70% and 35-47%, respectively. In other studies (Zhutovsky and Kovler, 2012), similar improvements of chloride-ion penetration resistance were found in concretes produced with low percentages of fine lightweight aggregates in substitution of natural aggregates due to internal curing.

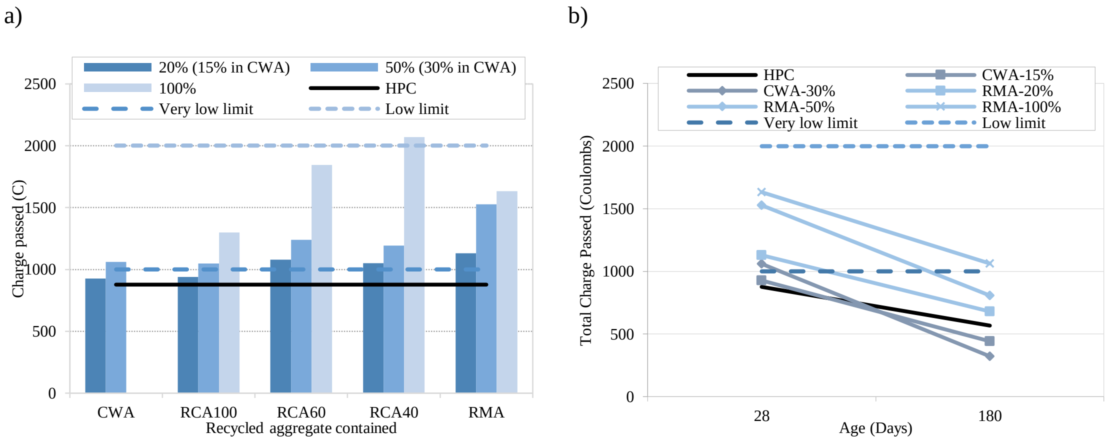

Fig. 5. Chloride-ion penetration at 28 days (a); Chloride-ion penetration evolution over time (28-180 days) of HPC, HPRAC-CWA and RAC-RMA (Very low and low corrosion risks limits according to ASTM C1202) (b).

According to the results of electrical resistivity from Paper I, HPRAC containing RCA generally showed low and moderate risk to corrosion according to the resistivity ranges proposed by Langford and Broomfiel (Langford and Broomfiel, 1987). However, the use of the 100% of recycled aggregates of 40 MPa in concrete production caused a considerable corrosion risk due to the increase of porosity in the concrete.

3.3. Conclusions

According to the results from testing the physical, mechanical and durability properties of conventional HPC and HPRAC with several recycled aggregate types, the following conclusions can be made:

- At 28 days, recycled aggregate concretes achieved the design strength of natural aggregate concrete (100MPa) without any adjustment in cement quantity or effective w-c ratio using: 30% of fine CWA, 100% of coarse RCA of 100 and 60MPa, 50% of RCA of 40 MPa and 20% of RMA.
- The recycled aggregate concretes achieved higher increases of compressive strength from 28 to 180 days than on natural aggregate concrete, especially when replacement ratio increased.
- The physical properties of dry-density, water absorption and UPV were highly influenced by the recycled aggregate quality and replacement level.
- The recycled concretes showed very similar sorptivity values to those from NAC due to very low water-cement ratio used in concrete mixes, except from those made with RMA which showed slightly higher sorptivity.
- After 28 days, the lower quality of coarse recycled aggregates (RCA of 60 and 40 MPa and RMA) showed significantly lower chloride-ion penetration resistance and electrical resistivity than those from conventional HPC.
- CWA and RMA aggregates produced higher improvements of chloride-ion resistance than conventional HPC between 28-180 days which could be due to internal curing effects.

4. PHASE 2: Influence of Recycled Concrete Aggregates on fly-ash High Performance Concrete exposed to conventional and steam curing processes

In this experimental phase (Papers III and IV), the use of recycled aggregates was focused on Recycled Concrete Aggregates (RCA) sourced from 3 different parent concrete wastes. As in Phase 1, the RCA' parent concretes had compressive strength of 100, 60 and 40 MPa. However in Phase 2, all HPRAC contained 100% of RCA. In order to enhance the mechanical and durability behaviour of HPRAC, fly ash was used in 30% replacement (in weight) of the Portland cement intending to achieve HPRACs with higher amounts of RCA which were comparable to the HPC with natural aggregates. According to some studies (Ajdukiewicz and Kliszczewicz, 2002), the binding effects of pozzolanic mineral admixtures can be improved by RCA due providing higher Portlandite amounts, especially those RCAs sourced from HPC. Nonetheless, due to the lower strength gain rate at early ages from fly-ash concretes, the use of steam curing was incorporated in order to fulfil the strength requirements from prestressed concrete elements.

4.1. Methodology

The testing of porosity and pore structure was performed by Mercury Intrusion Porosimetry (MIP) with a 'Micromeritics Poresizer 9320' mercury intrusion porosimeter according to BS 7591-1:1992 on small concrete pieces, weighing approximately 5.5 g at ages of 1, 28 and 90 days. The water absorption was tested according the ASTM C642-13 on 100 mm cubic specimens at the age of 28 and 180 days. The compressive strength was measured at the ages of 1, 28, 90 and 180 days following the UNE-EN 12390-3:2009 using 3 cubic specimens of 100 mm. The splitting tensile strength and modulus of elasticity tests were carried out on three cylindrical specimens of 100Ø x 200 mm at 28 days according to UNE-EN 12390-6:2010 and UNE-EN 12390:2014, respectively. The capillary water absorption was tested at 28 days and 180 days of curing using 100 mm cubic specimens according to ISO 15148:2002. The resistance to chloride-ion penetrability was determined in accordance with ASTM C1202-12 using a 100Ø x 50 mm concrete discs cut from the centre of 100Ø x 200 mm concrete specimens at the ages of 28 and 180 days. In all tests, the final results were the average of three specimens for each concrete mixture.

4.2. Results and discussions

4.2.1.Physical properties

- *Pore structure*

The pore size distributions of fly-ash concrete mixtures from Paper III, obtained from MIP tests, are shown in Fig. 6. The MIP tests provided the cumulative mercury intrusion volume after 1, 28 and 90 days of curing for concrete mixtures cured in conventional air conditions and steam curing. The average pore diameter, the total porosity and threshold pore diameter were also recorded at those testing ages.

After 1 day of curing, the HPRAC with RCA from 100MPa parent concretes (R100 and R100-SC) had significant lower average pore diameters than on the natural aggregates HPC, in both curing methods. Despite the fact that steam curing generally produces larger capillary pores in NAC (Abell et al., 1999), the R100-SC and the R60-SC had finer pore distributions from 1 to 0.05 µm, but the total cumulative intrusions were similar to those of the NAC-SC (Fig. 6a). The recycled aggregate concrete produced using RAC sourced from high quality parent concrete (> 60 MPa) achieved a lower porosity than those from NAC due to the reduction of the water-cement ratio in the ITZ (Poon et al., 2004a) at early hydration. Nevertheless the R40 concretes had the highest pore volume at all pore sizes. After 1 day of curing, the steam-cured concretes obtained lower porosity and average pore diameter than those concretes cured in conventional conditions for a given aggregate type. The steam curing process enhanced the pozzolanic reactions which led to refinements of the pore structure of the RAC (Berry et al., 1990).

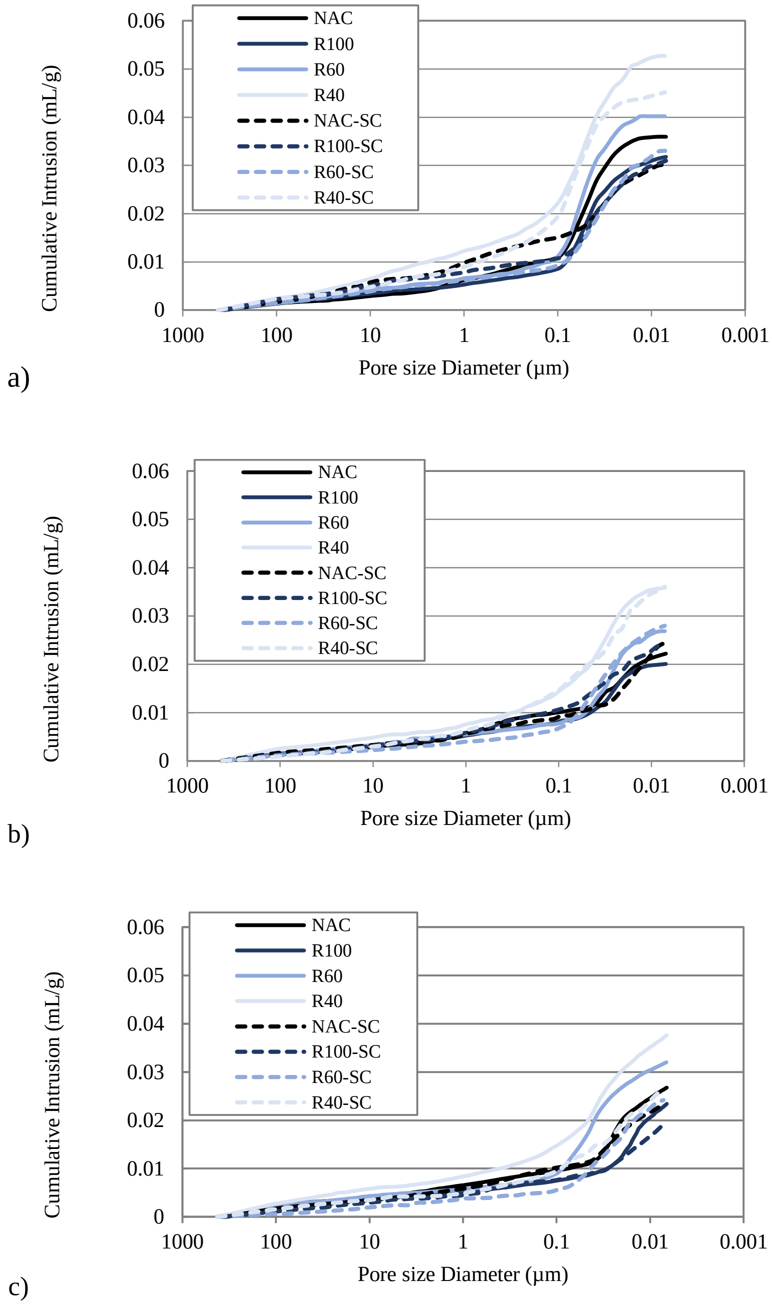

Fig. 6. Pore size cumulative distribution of conventional-cured concretes and steam-cured concretes at the ages of 1 day (a), 28 days (b) and 90 days (c).

At 28 and 90 days of curing, the porosity and the average pore diameter increased with the reduction of the RCA quality, regardless of the curing method used. Fig. 6b and Fig. 6c show finer pore structure and lower pore volumes of the R100 and R100-SC in comparison with those of the NAC and NAC-SC, respectively. The concretes produced employing the lowest quality RCA had a coarser pore size distribution. However, it must be noted that the steam-cured HPRAC showed higher reduction (between 16 and 36%) of the total cumulative intrusion volume from 28 to 90 days in comparison with the NAC (5%). Probably the higher porosity of the RCA permitted a time-extension of hydration and a more effective water transport through the pore structure (Suzuki et al., 2009).

According to the pore size (Mindess and Young, 1981), the HPRACs showed similar or lower macrocapillary pore volumes than those from the NAC-SC but their meso and microcapillary pore size volumes were similar or slightly higher than those from the NAC-SC. Also pore size distributions revealed that steam-cured concretes had similar distributions even when using medium quality RCA (RCA-40) and that the R100 and the R60 kept lower capillary pore volumes than the NAC after 90 days of curing.

- *Water absorption*

In Paper IV, the water absorptions results revealed that the NAC achieved the lowest values. The use of 100% of recycled aggregates significantly increased the water absorption of the recycled aggregates concrete due to a higher water absorption capacity of RCA (see Table 4). Concretes produced with RCA100 and RCA40 increased the water absorption capacity in 16-34% and 82-94%, respectively at 28 days.

The concretes produced with RAC suffered a higher reduction of water absorption capacity from 28 to 180 days of curing than on NAC. In particular, the highest reductions of water absorption capacity and porosity were found in those concretes containing the lowest quality aggregates (RCA60 and RCA 40). The improvement of the long-term physical properties could indicate internal curing effects (Suzuki et al., 2009; Zhutovsky and Kovler, 2012) and beneficial interaction between RCA and fly ash described by several authors (Poon et al., 2000; Yazıcı et al., 2005).

At the age of 28 days, the concretes cured via steam bath achieved slightly lower water absorption capacity than those from conventional-cured concretes. These results are aligned with Ba et al. (Ba et al., 2011), however the conventional-cured concretes had higher improvements which triggered lower values than those from steam curing after 180 days.

4.2.2.Mechanical properties

- *Compressive strength*

The results from compressive strength at the ages of 1, 28 and 90 days are presented in Paper III. According to fly-ash concrete results, only the NAC and R100 conventional air-cured concretes achieved the minimum 1-day compressive strength in order to be used as HPC in prestressed concrete elements, designated as 50 MPa (ADIF, 2009; Ramezanianpour et al., 2013). The steam curing process allowed all concrete mixtures to fulfil that requirement.

The use of RCA100 improved the compressive strength results from NAC at nearly all testing ages for conventional and steam curing processes. The concretes produced with RCA60 had similar or slightly lower compressive strength than NAC which was aligned with the results from Ajdukiewicz & Kliszczewicz (Ajdukiewicz and Kliszczewicz, 2002). A severe decrease on the RCA quality caused notable reductions on compressive strength, the compressive strengths from concretes with RCA40 were, on average, 15 and 16% lower than those from NAC for conventional and steam curing, respectively, due to the low quality of the adhered mortar in comparison to the new cement paste. Nonetheless, it should be noted from Fig. 7 that the RACs had higher compressive strength gain up to 90 days than NAC due to the enhancement of pozzolanic reactivity from fly ash by the RCA content (Kou et al., 2008).

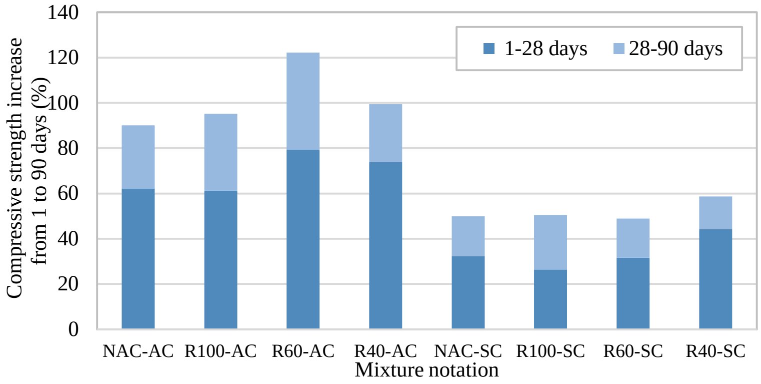

Fig. 7. Compressive strength increase from 1 to 90 days of conventionally air-cured (AC) and steam-cured concrete mixtures (SC).

The steam-cured concretes showed 4-15% higher 1-day compressive strength than their conventional-cured counterparts due to the acceleration of the CSH gel formation. For a given quality of RCA, steam-cured concretes achieved 1-9% and 4-11% lower compressive strength than those from conventional-cured concretes at 28 and 90 days of curing, respectively. A lower gain of compressive strength was also showed by steam-cured concretes in accordance with the results reported by various researchers (Gesoğlu et al., 2013; Kou et al., 2004). However, the highest compressive strength gain was achieved by the RCA-40, which indicates that the use of higher porous RCA could contribute to a better binder hydration (Suzuki et al., 2009).

- *Splitting tensile strength*

All fly-ash concrete mixtures, except R60, R40 and R40-SC, achieved the minimum splitting tensile strength required at 28 days by the Spanish technical specification for prestressed concrete sleepers (4.5 MPa) (ADIF, 2009).

The concretes produced with RCA100 obtained the highest values due to the influence of its high-quality ITZ between the cement paste and the coarse aggregate (Etxeberria et al., 2007). Concretes produced with poorer quality RCA achieved lower strength than NAC (see Fig. 8). The lower quality of the old mortar attached to the RCA and the weaker old ITZ could be responsible for the decrease of splitting tensile strength (Kou et al., 2012).

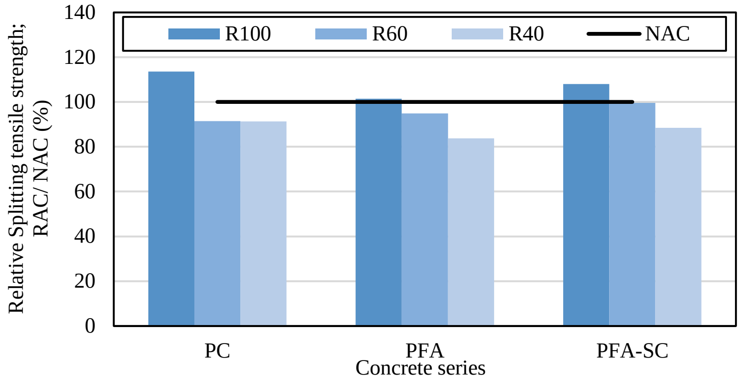

Fig. 8. Relative splitting tensile strength of Portland-cement, fly-ash and steam-cured fly-ash HPRAC mixtures in comparison with the reference natural-aggregate HPC for each series.

The use of steam curing process was beneficial for the splitting tensile strength of recycled aggregate concretes with fly-ash. The RACs exposed to steam curing achieved a 4% higher strength than those concretes exposed to conventional curing process. However, NAC undergoing steam curing achieved lower results than NAC cured on conventional conditions.

- *Modulus of elasticity*

The concrete mixtures designed with RAC obtained lower elastic modulus than on NAC mixtures in both curing methods. As a consequence of the lower dense RCA, the density of RAC decreases which has negative effects on the modulus of elasticity. Concretes with RCA100, RCA60 and RCA40 had on average 5, 13 and 20% lower modulus of elasticity than NAC, respectively. However, the drops of elastic modulus were less severe than those registered on Phase 1. The higher reactivity of fly-ash with RCA and improved ITZ are beneficial factors with respect to binder hydration and cement paste densification in RACs mixtures and certainly influenced the modulus of elasticity results.

The steam curing method had the effect of slightly improving the modulus of elasticity of concrete mixtures. The modulus of elasticity results from steam-cured concretes were up to 7% higher than those from conventional-cured concrete mixtures for the same RCA quality. In line with other studies (Kou et al., 2004), RCA had positive influence on the modulus of elasticity in steam-cured mixtures. It should be noted that the use of lower quality aggregates (RCA40) subjected to steam curing obtained the highest improvements.

4.2.3. Durability properties

In Paper IV, the durability properties of capillary water absorption and chloride-ion penetration resistance were studied for concrete mixtures made with Portland cement and Portland cement with 30 % of fly ash at the ages of 28 and 180 days. The fly-ash concrete mixtures also underwent conventional and steam curing processes.

- *Capillary water absorption*

After 28 and 180 days of curing, the sorptivity of the NAC produced with fly ash was slightly higher than on NAC produced with Portland cement. However, the concrete mixtures with RCA using fly ash showed similar or improved capillary water absorption results to those same concretes produced with Portland cement.

After 28 days of curing, the concrete produced with RCA100 achieved the lowest capillary water absorption results on both curing methods. However, the use of lower quality RCA (RCA60 and RCA40) caused severe increases on the sorptivity due to the high absorption of recycled aggregate and its higher porosity (see Table 4), as also reported others studies (Levy and Helene, 2004; Wirquin et al., 2000). However after 180 days of curing, the concrete containing RCA had similar or lower values to NAC for any concrete series. The development of the ITZ (Etxeberria et al., 2007; Kou et al., 2012) and the effect of internal curing in concretes (Suzuki et al., 2009; Zhutovsky and Kovler, 2012) containing RCA60 and RCA40 aggregates created improvements on the ITZ and binder matrix to balance the higher porosity of the RCAs.

The comparison of the capillary water absorption of conventional-cured concretes and steam curing concretes for a given aggregate type showed that steam curing had negative effects on NAC (Ba et al., 2011). The steam-cured NAC had 46.5% higher sorptivities than those from conventional-cured concrete (NAC-SC). Nevertheless, the sorptivities of steam-cured RACs were 9-34% lower than those undergoing conventional curing. In concretes containing RCA, the porous network after steam curing seemed to be improved by an extended binder hydration.

- *Chloride-ion penetration resistance*

The concretes containing RCA100 had similar or higher resistance to chloride-ion penetration than NAC's (see Fig. 9). However, the RCA quality drop had negative effects on the chloride-ion penetration resistance.

All the fly-ash concrete mixtures could be classified in the corrosion ranges of very low and low corrosion risk (from ASTM C1202-12) according to their charge passed results. It was also found that the concretes produced employing fly ash achieved higher increases of chloride-ion resistance in comparison to those of Portland cement. The use of RCA boosted the chloride-ion penetration resistance of the fly ash concretes. Similarly to the findings of Gesoğlu et al. (Gesoğlu et al., 2013) on lightweight aggregates, the RAC containing fly ash proved to have more similar chloride-ion penetration resistances to those from NAC at longer ages.

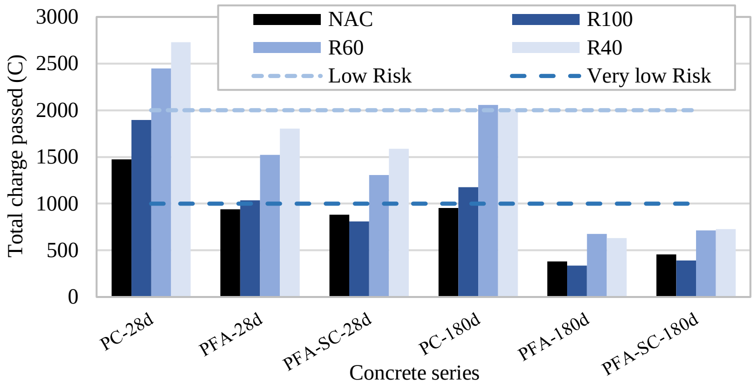

Fig. 9. Results from chloride-ion penetration test for Portland-cement, fly ash and steam-cured fly-ash concrete mixtures at 28 and180 days (Very low and low corrosion risk limits according to ASTM C1202).

The use of steam curing on concretes produced with RCA and fly ash increased significantly the chloride-ions penetration resistance of concrete after 28 days. The steam-cured NAC had 6%

lower total amount of charge passed than conventional-cured NAC; while steam-cured concretes with RCA showed 12.0-21.8% lower charged passed results than conventional-cured RCA concretes. Nevertheless, after 180 days, all the concretes exposed to steam curing showed lower chloride-ion penetration resistance than those concretes exposed to conventional-curing process. However, the negative long-term influence of steam curing was lower in recycled aggregate concretes than in NAC.

4.3. Conclusions

According to the results from testing the HPRAC containing fly ash which underwent conventional and steam curing regimes, the following conclusions can be stated:

- The use of RCA with lower quality caused a reduction of compressive strength and an increase in porosity compared to those from NAC, however such reduction was diminished by the use of fly ash and steam curing.
- After steam curing process, the concretes produced with the lowest quality recycled concrete aggregates (sourced from 40 MPa parent concrete) achieved the highest compressive strength evolution, as well as the highest refinement of porous structure.
- The use of steam curing enabled the fly-ash HPRAC with 100% of RCA of any quality reaching the minimum compressive strength for prestressed concrete sleepers. However, the required splitting tensile strength was only achieved by concrete mixtures containing RCA which were sourced from parent concretes with a minimum strength of 60 MPa.
- The use of lower quality RCA negatively influenced the 28-day capillary water absorption, however they had an important reduction from 28 to 180 days. The steam-cured recycled aggregate concretes had similar sorptivity to those from conventional curing at 180 days, however steam-cured NAC had higher sorptivity than conventional-cured NAC.
- The chloride-ion penetration resistance results indicated low corrosion risk even when using RCA of lower qualities. The steam curing process had low influence on chloride-

ion resistivity of concretes, however it was especially positive when concrete mixtures contained RCA.

5. PHASE 3: Study of the shrinkage behaviour of HPRAC and the internal curing effects of RCA

The HPC when used in prestressed concrete elements requires the study of particular properties which are more determinant in HPC than in conventional concretes. The shrinkage behaviour is a properties of special interest and, particularly in HPC, autogenous shrinkage has to be taken into consideration (Meddah and Sato, 2010; Suzuki et al., 2009). The shrinkage phenomenon is defined as the volume reduction or strain due to the water loss caused by evaporation through the concrete surface or via the reactions of cement hydration (Hewlett, 2004). Total shrinkage is made of plastic shrinkage, autogenous shrinkage and drying-shrinkage. The total shrinkage is the consequence of diverse factors such as temperature and relative humidity, size and shape of the concrete piece, components, water/binder ratios and concrete's age (Tam and Tam, 2007).

In the Phase 3 (Paper V), the HPRAC containing RCA of the three qualities previously tested were subjected to shrinkage tests. The plastic, autogenous and drying shrinkage tests were conducted for conventional HPC and HPRAC containing 20, 50 and 100% of RCA of all three qualities (RCA100, 60 and 40), limiting the binders to Portland cement.

5.1. Methodology

5.1.1. Plastic shrinkage

The setup for the plastic shrinkage test was based on a previous study by Saliba et al. (Saliba et al., 2011). The plastic shrinkage strain was measured with LVDTs which were connected to a data acquisition system. The LVDTs' length change was recorded every minute for 12 hours after concrete casting. The mould used in this experiment was a square prism of 600 x 150 x 150 mm covered with Teflon sheeting to reduce friction. One side of the concrete specimen was embedded in the mould while the other side was left exposed to a free-moving Teflon plate via the use of 4 steel rebars (∅10 mm) in each side (see Fig. 10). The LVDT was setup on the mould's remaining steel plate and it was in direct contact with the free-moving Teflon plate. Two specimens were tested for each concrete mixture.

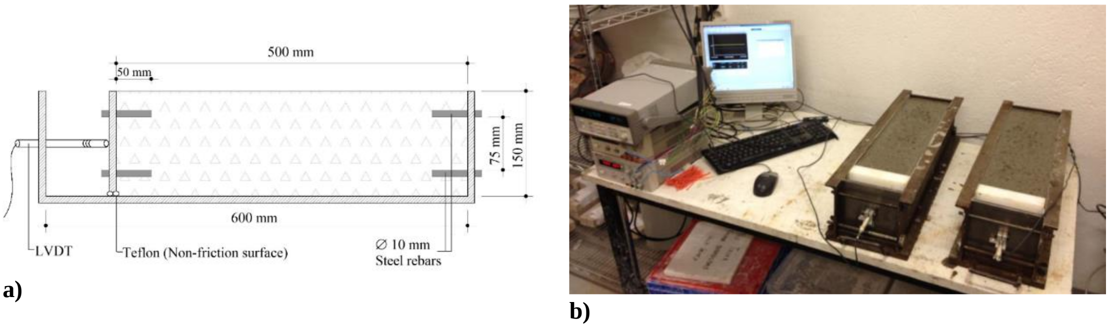

Fig. 10. Plastic shrinkage test setup (a) and specimens (b).

5.1.2.Autogenous shrinkage

Autogenous shrinkage strain measurements were conducted following the recommendations of the Japan Concrete Institute (JCI Committee Report. Technical committee on autogenous shrinkage of Concrete, 1999). Strain gauges were vertically embedded in the centre of the specimens using cylindrical moulds of 300 x 150 ∅ mm. The strain gauges were connected to a data acquisition system within the first 10 minutes after the concrete casting. At all time, the concrete specimen was entirely wrapped in two layers of adhesive aluminium foil in order to prevent them from water evaporation (see Fig. 11). The readings were taken at 1 min intervals for 3 days in two replicate specimens per concrete mixture.

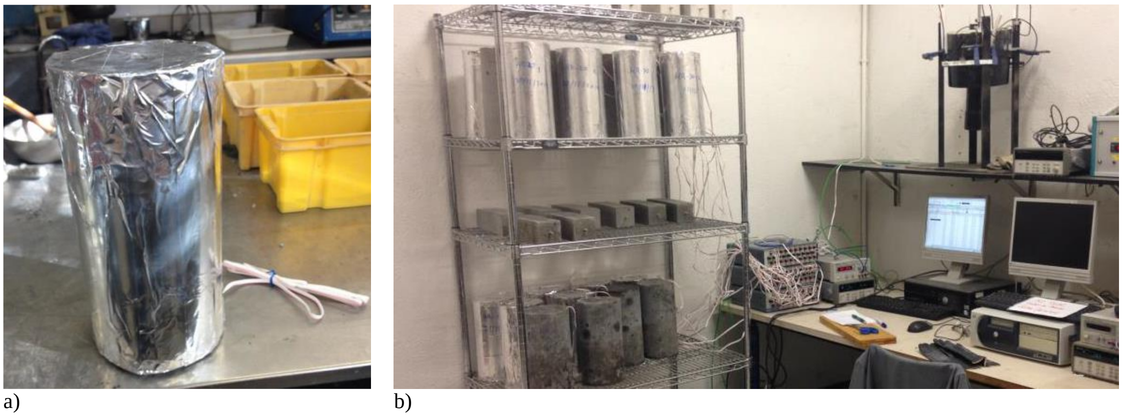
a) b)

Fig. 11. Concrete specimen wrapped with adhesive aluminium (a) and measurement device (b).

5.1.3.Drying shrinkage

The drying shrinkage was determined in accordance to the procedure laid out in ASTM C596 (2009) using 70 x 70 x 285 mm prismatic specimens. Each specimen was fitted with a stainless steel stud at both ends. The prismatic specimens were covered with a wet burlap and a plastic sheet during the initial 24 hours before being removed from the moulds and then cured under water for an additional period of 48 hours. At the age of three days, the specimens were removed from the water tank and wiped with a damp cloth. The initial length reading was immediately recorded using a length comparator (see Fig. 12).

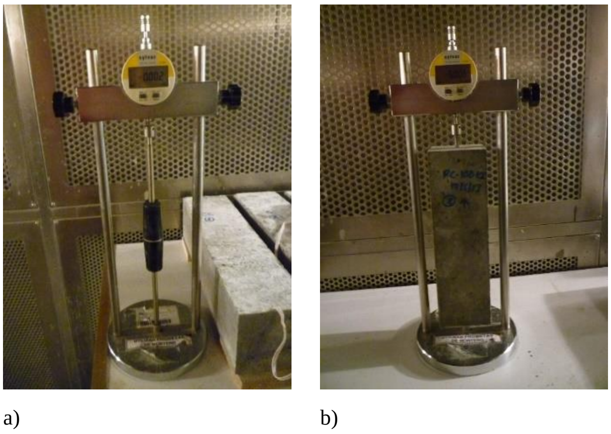
a) b)

Fig. 12. Length change measurement device with control beam (a) and concrete specimen (b).

The specimens were placed in an environmental room for one year at a controlled temperature of 23 ± 2 ºC and 50 ± 5% relative humidity. The drying shrinkage was determined by taking measurements at 1, 4, 7, 14, 21, 28, 56, 90, 180, 360 days and each result was the average obtained from the testing of three specimens per concrete mixture.

5.2. Results and discussion

5.2.1.Plastic shrinkage

The development of plastic shrinkage from Paper V was monitored up to 12 hours and the results from conventional HPC and HPRAC containing 100% of RCA are shown in Fig. 13. The plastic shrinkage of the concrete mixtures produced with any type of RCA was higher than those produced with NAC.

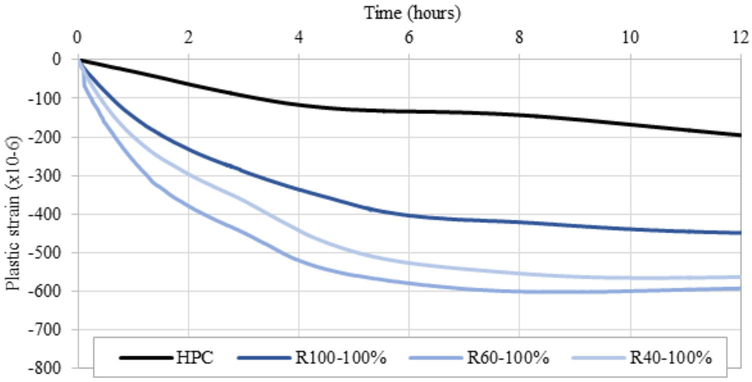

Fig. 13. Plastic shrinkage of conventional HPC and HPRAC with 100 % of RCA.

However, the plastic shrinkage of the concrete mixtures made with RCA derived from original concrete with higher strength values were lower than those of concretes prepared with RCA derived from lower strength parent concretes. In concrete with 100% of RCA replacement, R100, R60 and R40 had a 130%, 210% and 190% higher plastic shrinkage than NAC's after 12 hours, respectively.

Similarly, the amount increase of RCA had a negative influence on the plastic shrinkage. While the concrete mixtures with a 20% RCA replacement ratio showed plastic shrinkage increases of 46-152% in comparison to those of NAC, the 50% and the 100% RCA replacement ratios produced 65-150% and 130-208% increases of plastic shrinkage, respectively.

The rate of plastic shrinkage is highly dependent on the water-to-binder ratio (Saliba et al., 2011). The RAC contain a higher total water-cement ratio which in the initial stages of curing causes higher effective water content. However, the plastic shrinkage strains found in the laboratory proved to be significantly lower than those proposed by Baghabra et al. (Baghabra Al-Amoudi et al., 2004). The threshold value of plastic shrinkage strain was established as -1100 με. There is a high risk of cracking occurring above the threshold strain.

5.2.2.Autogenous shrinkage

Fig. 14 presents the results of testing the autogenous shrinkage up to 72 hours for conventional HPC and HPRAC mixtures containing 100% of RCA.

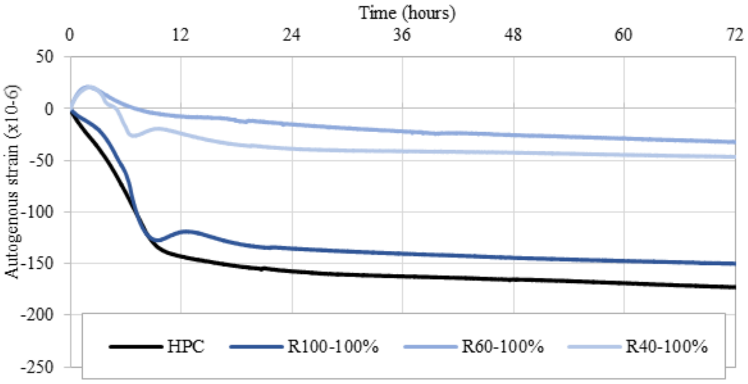

Fig. 14. Autogenous shrinkage of conventional HPC and HPRAC with 100 % of RCA.

The autogenous shrinkage started immediately after casting in the conventional HPC and HPRAC with RCA100. There was a very significant increase in the autogenous shrinkage for the first 10-12 hours, attaining almost total development. The autogenous shrinkage reached the stabilization point after 3 days. The HPRAC with RCA100 (at any replacement ratios) and 20% of RCA60 showed similar or slightly lower autogenous shrinkage than conventional HPC's.

The quality reduction of the RCA and the replacement increase improved the prevention of the autogenous shrinkage. After an initial small expansion, the autogenous shrinkages from the HPRAC with RCA60 and RCA40 (50 and 100% replacement ratios) were considerably lower than conventional HPC's. The lower autogenous shrinkage resulted from the higher amount of water stored within the RCA. Almost all of the autogenous shrinkage had developed within the 8-10 hours after test start. After 72 hours of testing, the HPRAC with 100% of RCA60 and RCA40 achieved reductions of 82% and 73%, respectively, in comparison to the conventional concrete's autogenous shrinkage.

5.2.3. Drying shrinkage

Fig. 15 shows the results of drying shrinkage obtained for 1 year. After 90 days, the strains caused by drying shrinkage ranged from -311 to -717 με. These results are in line with those determined by several other authors employing RCA aggregates (Brand et al., 2015; Corinaldesi and Moriconi, 2009; Kou and Poon, 2015), as well as with the typical drying-shrinkage values described by the ACI (ACI Committee 209, 2005) (-200 to -800 με).

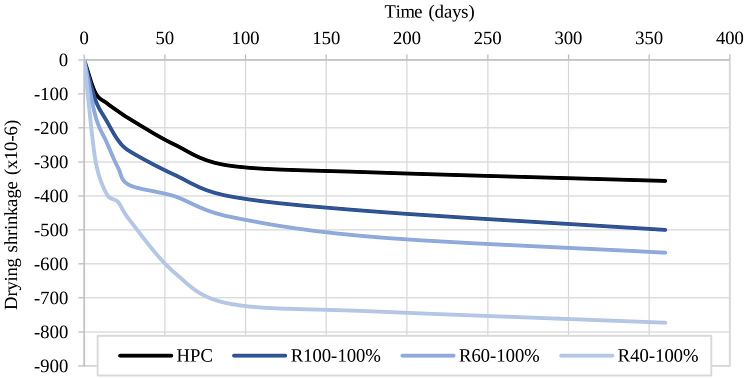

Fig. 15. Drying shrinkage of conventional HPC and HPRAC with 100 % of RCA.

In natural aggregate concrete, the higher the water-cement ratio produced higher shrinkage strain (Zhutovsky and Kovler, 2012). However, in concretes containing highly porous aggregates, the water contained within these aggregates plays an important role in the drying shrinkage increase (Domingo-Cabo et al., 2009; Khatib, 2005).

The relationship between the RCA replacement ratio and drying shrinkage strain showed solid linear correlations for each quality of RCA. The highest drying shrinkages occurred in those concretes containing the highest RCA replacement ratios and the lowest RCA qualities. The concretes produced using RCA100 achieved 54-56% higher shrinkage levels than those of conventional HPC after 28 days. The shrinkage strain increased significantly when the concretes were produced using RCA60 and RCA40. After 28 days, the shrinkage strain of R60 and R40 concrete mixtures were 50-113% and 57-172% higher than those of HPC, respectively.

The higher amount of cement paste (taking into consideration both the old and new paste) contained in the RAC causes higher concrete porosity. Moreover, the use of pre-soaked RCA in the production of RAC, in order to facilitate the proper workability of the fresh concrete, means that there is more water available for evaporation. The concretes containing higher amounts of RCA and lower quality RCA were the concretes that had the highest water mass losses.

The results showed that the RAC's modulus of elasticity, which is dependent on the elastic modulus of the coarse aggregate, has a significant influence on the drying shrinkage. The relationship between the concrete's relative modulus of elasticity and drying shrinkage strain showed a strong linear correlation, in accordance with the findings presented by Silva et al. (Silva et al., 2015).

5.3. Conclusions

The following conclusions can be made based on the results of this study:

- The plastic shrinkage of concretes increased as the employed RCA quality was reduced and the replacement ratio was increased. However, the obtained values for all HPC mixtures were lower than those required for concrete cracking appearance.
- The autogenous shrinkage of concretes decreased at the same time that the quality of RCA reduced and the replacement ratio increased. This was in all probability due to a higher water storage capacity of RCA which acted as internal curing agent.

- The lower quality of the RCA as well as the higher replacement ratios produced higher drying shrinkage values. Drying shrinkage increase showed linear correlation with both decrease of relative modulus of elasticity and increase of replacement ratio.

6. PHASE 4: Pilot study: Effects of RCA on the structural properties of prestressed HPC sleepers

The phase 4 (Paper VI) consisted of a pilot study in which prestressed concrete sleepers made with HPRACs were tested according to the Spanish technical specification (ADIF, 2009). The aim of this study was to compare the HPRAC sleepers' results with those from conventional HPC sleepers and the minimum standard requirements. Also an analysis of the structural properties of HPC and two HPRACs was carried out by assessing the load-strain behaviour of the reinforcement. Two types of HPRAC sleepers were tested using 50 and 100% of RCA as replacement of the coarse natural aggregates. The RCA were sourced from crushing old rejected sleepers (100 MPa concrete) whose successful mechanical and durability performance in HPRAC had been previously verified. The prestressed concrete sleepers were subjected to static load tests at rail-seat and centre sections, and also dynamic load and fatigue tests at the rail-seat section. In the centre section tests, a study was carried out comparing the experimental results and the proposed values obtained from four assessment methods of ultimate capacity.

6.1. Methodology

6.1.1.Prototype of prestressed concrete sleeper

The prototypes of the prestressed HPRAC sleepers and the reference prestressed HPC sleepers were produced in a Spanish precast concrete plant. The manufacturing procedure, the geometrical dimensions of the sleeper, the prestressing rebars and tension were kept constant for all concrete mixtures. The fresh concretes were compacted in the sleeper moulds using a vibrating table in two stages of 30 seconds. Immediately after casting, the sleepers were stored in a standard curing room (23±2° and 95% of humidity) for the first 24 hours. After those 24 hours, the prestressing rebars were released and the sleepers were demoulded. The Fig. 16 shows the schematics of the prestressed concrete sleeper prototypes.

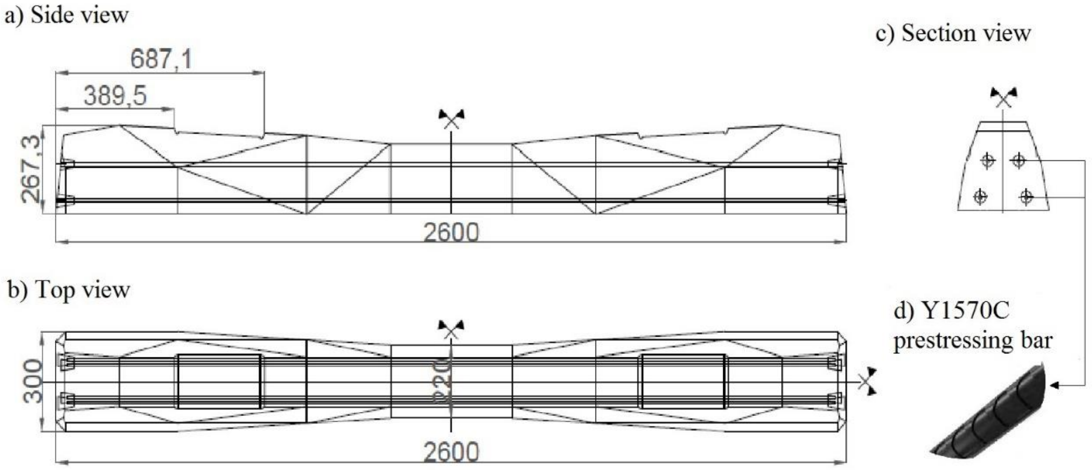

Fig. 16. Schematics of a prestressed sleeper: (a) side view, (b) top view, (c) section view (unit: mm) and (d) detail of the prestressing rebar of Ø10 mm.

6.1.2.Test setups

Five structural tests were carried out in accordance with the European Standards (EN 13230-2:2009) and the Spanish railway technical specification for prestressed concrete sleepers (ADIF, 2009) (see Fig. 17): 1) Static positive load test at the rail-seat section, 2 and 3) Static negative and positive load tests at the centre section, 4) Dynamic test at the rail-seat section, 5) Fatigue test at the rail-seat section. The load-strain behaviours were registered in all tests except from dynamic test using strain gauges installed in the prestressing rebars.

In centre section tests, a comparison between the experimental static test results and the values obtained following different methods for the prediction of ultimate capacity of reinforced or prestressed concrete sections was carried out. Four different stress-strain diagrams for concrete at ultimate state were considered; the bi-linear stress-strain; the quadratic parabola diagram; the parabola rectangle according to Eurocode 2 and a variation of the last one according to SIA262.

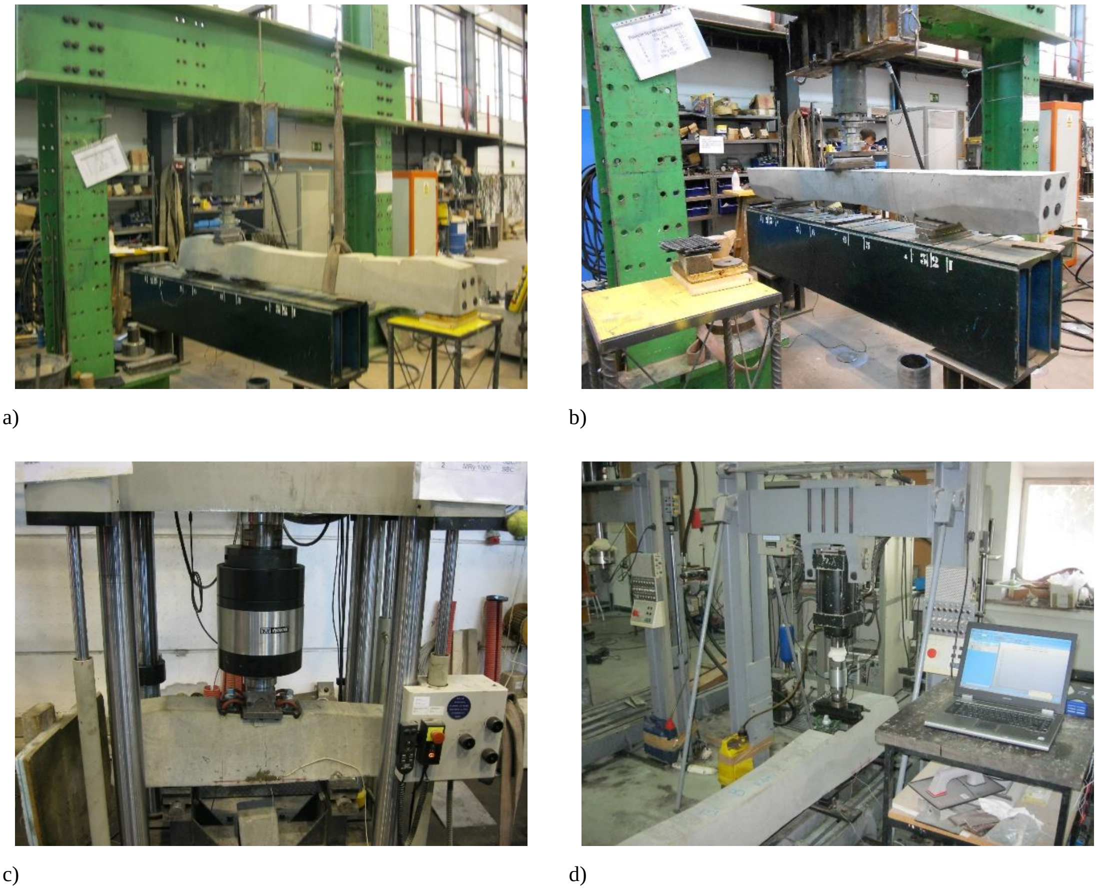

Fig. 17. Pictures of testing setup of the static positive load test at the rail-seat section (a), static negative load at centre section (b), dynamic load test (c) and fatigue test (d).

6.2. Results and discussion

6.2.1.Static positive load test at the rail-seat section

All HPRAC sleepers fulfilled the first crack formation requirements, as well as the conventional HPC sleepers. No cracks appeared under the initial reference load (156 kN). The load producing the first crack was very similar for all sleepers (219-221 kN), however the results from HPRAC had higher variability than those from HPC.

The ultimate load from all sleepers satisfied the minimum requirements (ADIF, 2009). However, the loads which produced 0.05 mm cracks on HPRAC sleepers were 3% lower than those from HPC for both replacement ratios. Moreover, the ultimate loads from HPRAC sleepers with 50% and 100 % of RCA were 5% and 3%, respectively, lower than on conventional HPC sleepers.

Fig. 18 shows the results from the strain gauges installed at the centre of the rail-seat section in the inferior rebar of the sleepers. Both the HPRAC and HPC sleepers showed very similar behaviours, however the HPC sleepers' stiffness was slightly greater than those from HPRAC sleepers.

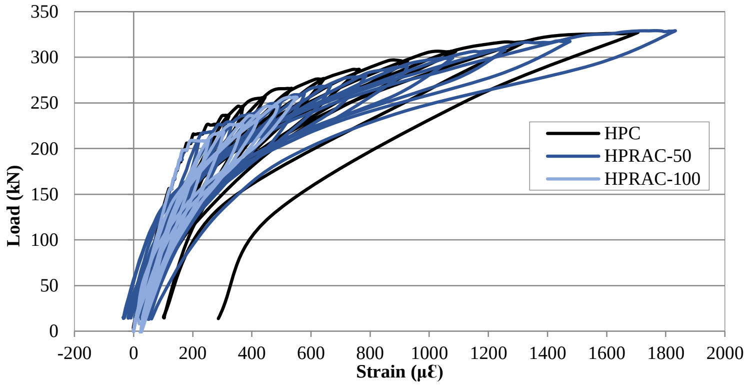

Fig. 18. Load-strain results from static load test at rail-seat section of HPC and HPRAC sleepers.

6.2.2. Static load tests at the centre section

- Negative design

In all the tested HPC and HPRAC sleepers, the first crack formation appeared after exceeding the the initial load reference value. The results from HPRAC sleepers were generally similar to those from HPC sleepers, however HPRAC-50 sleepers reached the highest loads preceding the first crack appearance. Consequently, the results revealed that the use of HPRAC at any replacement ratio had no influence on the static negative load's results.

The load-strain analysis (Fig. 19) revealed similar slopes from all three sleepers on the elastic zone. Both the HPC and HPRAC sleepers with 100% of RCA had also very similar plastic behaviour, showing small yielding at similar loads and very similar strains for each loading step. However the HPRAC sleepers with 50% of RCA showed higher load values on the first crack formation and slightly higher yielding and strain than those found in HPC in the plastic zone.

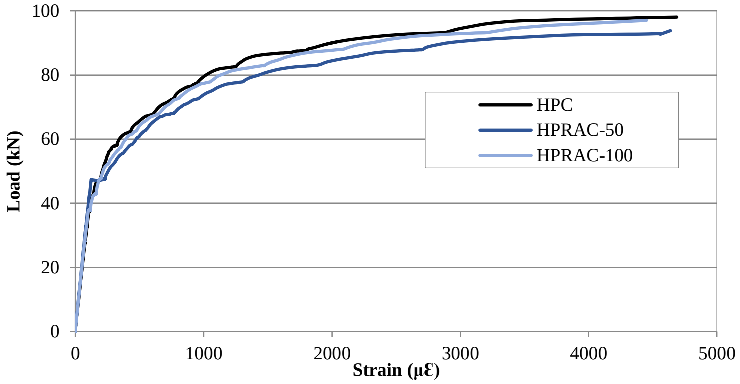

Fig. 19. Load-strain results from static negative load test at centre section of HPC and HPRAC sleepers.

- Positive design

For all sleepers, the positive loads causing the first crack formation at the centre section were much higher than the initial reference load. The test results of HPC and HPRAC sleepers were considered similar, however the HPRAC sleepers' standard deviations were higher than those of the HPC sleepers. Most of the standard deviations represented less than 5% of variability which ensured their wide acceptance according to the requirements given by the Spanish regulation.

The load-strain results of HPC and HPRAC-50 sleepers showed similar elastic slopes, however the HPRAC-50 sleepers showed lower yield points than those obtained by the HPC sleepers. The HPRAC-100 sleepers showed lower slopes on the elastic zone but they achieved a similar yield point to that of the HPC sleepers.

- Prediction of the ultimate capacity of HPC and HPRAC sleepers at centre sections

The differences between the four cross-section diagrams used were minimal. However, in all cases, the Quadratic parabola method was the one which better adjusted to the test data. In addition, it was observed that the prediction of the ultimate capacity was basically the same in all cases, which confirms that the hypothesis made for the ultimate strain was sufficiently accurate.

The ultimate concrete strain used in the analysis showed, in general, good agreement when the positive design section capacity was assessed, however it could be a bit conservative when applied to negative design, due to the higher contribution of the concrete. In all cases, the value proposed in the EC2 achieved good results and always in the safety side for any type of concrete.

6.2.3.Dynamic test at the rail-seat section

The results of the dynamic positive load test at the rail-seat section from HPC and HPRAC sleepers, for both replacement ratios, met all the requirements from the Spanish specifications. The loads creating the first crack formation in HPRAC sleepers were very similar to those found in the static load test. HPC sleepers achieved slightly higher results than HPRAC sleepers, revealing a slight negative influence of the replacement ratio. The average loads from HPRAC sleepers with 50 and 100% of RCA were 8 and 11% lower than that from HPC sleepers, respectively.

The average loads which produced a crack width of 0.05 mm in HPRAC sleepers were higher than the required 234 kN. The loads from HPRAC sleepers were the same for both RCA replacement ratios and slightly lower (1.4%) than that from the HPC sleepers.

The average ultimate loads from all sleepers were higher than the designated minimum requirement (343 kN). HPRAC sleepers with 50 and 100% RCA replacement ratios achieved average ultimate loads which were 2.4 and 1.6% higher than that from HPC sleepers, respectively. The standard deviations found in the HPRAC sleepers were higher than those from HPC sleepers for all load results.

According to Koh et al. (Koh et al., 2016), some factors lowering the strength in dynamic tests are: pronounced micro-cracks, weakened bonding strength due to delamination and severe loading conditions. The conventional HPC sleepers showed 10.9% lower load which created 0.05 mm crack and 17.6% lower ultimate load in the dynamic test in comparison with the static test results. The dynamic results from HPRAC sleepers were only 9.4-9.8% and 9.6-11.1% lower than the static loads, respectively. Therefore, the dynamic behaviours from those sleepers made with HPRAC were improved, showing smaller reduction than those from HPC.

6.2.4.Fatigue test at the rail-seat section.

After the fatigue cycles, the width of the crack was measured in loaded and unloaded conditions. According to the Spanish specification, the crack widths shall not be greater than 0.1 mm and 0.05 mm in loaded and unloaded conditions, respectively. HPC and HPRAC sleepers reported minor cracks which fulfilled both requirements. After the crack measurements, the sleepers were loaded to failure. All maximum loads from HPC and HPRAC sleepers exceeded the required ultimate load of 390 kN. The ultimate load from HPRAC only varied less than ±5% from HPC sleeper's results.

During the 2 million cycles from the fatigue load test, the strain performance was registered by the strain gauges located in the inferior rebars at the rail-seat section. Fig. 20 shows the relationship between strain and loading cycles when the sleepers were loaded with the initial reference load and loaded with the lower load (dashed line). At the initial cycles, the HPC sleeper strain was slightly lower than those from HPRAC sleepers, however it increased up to 400,000 cycles. For the remaining cycles, the strain from HPC and HPRAC sleepers got stabilized between 120 and 150 µƐ, showing similar results in all sleeper types. Overall, it can be concluded that the fatigue behaviour from HPRACs sleepers was similar to that from common HPC sleepers.

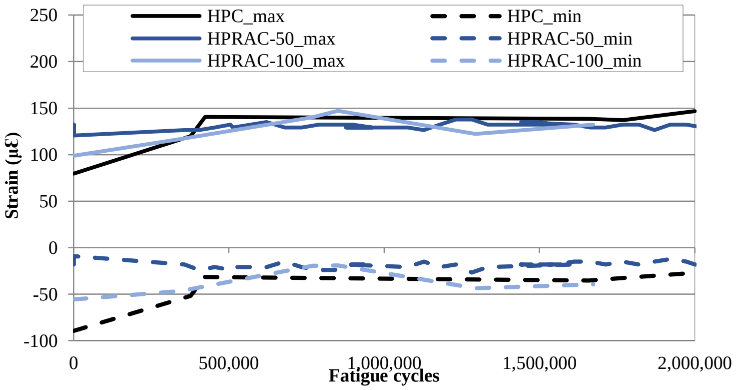

Fig. 20. Strain - cycles results from the fatigue test at the rail-seat section of HPC and HPRAC sleepers (solid line: strain under initial reference load; dash line: strain under minimum load).

6.3. Conclusions

All structural requirements for prestressed concrete sleepers were extensively verified by sleepers made with HPC and HPRAC.

- The HPRAC sleepers' results from static positive load on rail-seat section and centre section, dynamic positive load test and fatigue test were very similar to those from HPC sleepers. However, the standard deviations of the HPRAC sleepers' results were higher than those from HPC sleepers.
- The simplified methods to predict the ultimate capacity at centre section of HPC achieved reasonable values when they were applied to HPRAC. The ultimate concrete strain used in the analysis could be considered slightly conservative when applied to negative design, due to the higher concrete contribution. However, the results obtained according to the proposed method stated in the EC2 were within the safety standards laid down for any type of concrete.
- The load-strain results from HPRAC sleepers revealed very similar behaviour for both replacement ratios. However, HPC sleepers generally showed slightly higher stiffness than HPRAC sleepers.
- The concrete waste from rejected sleepers can be reused as RCA replacing up to 100% the natural aggregates in prestressed concrete sleepers with no significant influence on the structural behaviour.

7. CONCLUSIONS AND FUTURE PERSPECTIVES

7.1. General conclusions

In this investigation, the influence of recycled aggregates has been analysed in High Performance Concrete. Several qualities of recycled aggregates at different replacement ratios of natural aggregates have been selected in order to identify the minimum requirements for the application of High Performance Recycled Aggregate Concrete in the production of prestressed concretes elements. The reference HPC and the HPRAC mixtures were assessed from the mechanical and structural perspective to the physical and the durability performance.

The general conclusions of the investigations are listed below:

- The experimental results revealed that high quality recycled aggregates, sourced from same quality parent HPC, can be used in the production of new HPC replacing 100% of the coarse natural aggregates from the physical, mechanical, durability and structural point of view.
- The HPRAC showed similar mechanical performances to those from conventional HPC at 28 days when replacing the coarse natural aggregate by 100% of RCA of 100 and 60MPa, 50% of RCA of 40 MPa and 20% of RMA or replacing natural fine aggregate by 30% of fine CWA, without any cement adjustment. However, the physical and durability results were more susceptible to the use of recycled aggregates. Considering the durability properties analysed at 28 days, only the 100% replacement ratio could be maintained for coarse RCA obtained from 100MPa concrete in order to keep similar behaviour than conventional HPC.

- The use of fly ash enhanced the HPRAC achieving closer durability properties to those from HPC than in Portland cement concrete series. The steam cured concretes, after reaching improved early-age performance, showed a reduction on the long-term properties. However, these reductions were moderated when the HPRAC were produced using fly ash and cured under a steam curing regime, especially on those HPRAC containing lower-quality RCA. The higher porosity of RCA, containing higher amount of water, could enhance the binder hydration rate of steam cured concretes.

- The higher porosity and water absorption capacity of recycled aggregates in comparison with those from natural aggregates played an essential role in the shrinkage behaviour. The plastic and drying shrinkage of HPRAC mixtures increased as the quality of the RCA decreased. Also higher RCA contents triggered higher plastic and drying shrinkage strains. On the other hand, lower RCA quality and higher replacement ratio of natural aggregates produced lower autogenous shrinkage strains. The autogenous shrinkage reductions were most likely due to a higher water storage capacity of RCA which acted as internal curing agent.

- The prestressed concrete sleepers produced with HPRAC containing 50 and 100% of RCA obtained from 100 MPa parent concrete (which was sourced from sleeper's rejected concrete waste) fulfilled all the structural requirements. Both the conventional HPC and the HPRAC sleepers showed similar structural test results and load-strain behaviours.

7.2. Specific conclusions

- *Characterization of HPC containing recycled aggregates*
  - The HPRAC achieved higher increases of compressive strength than those from conventional HPC, especially when the replacement ratio increased. Also, HPRAC containing CWA and RMA aggregates produced higher improvements of chloride-ion resistance than conventional HPC between 28-180 days. The

higher evolutions on the HPRAC properties suggested an improvement on the cement hydration which could be due to an improvement of the ITZ and the effect of recycled aggregates as internal curing agents.

- The effect of internal curing agents in High Performance Concrete can be more significant than in ordinary strength concretes. The lower density and higher water absorption capacity and porosity, despite producing some negative effects such as the reduction of the modulus of elasticity, could be beneficial for the internal curing of HPC by containing higher water amounts than natural aggregate.

- *Influence of Recycled Concrete Aggregates on fly-ash High Performance Concrete exposed to conventional and steam curing processes.*
  - The increase on the RCA replacement ratio and the RCA quality reduction typically showed negative effects on the physical, mechanical and durability properties, as in the pore structures of HPRAC. However, the use of fly ash and steam curing eased the achievement of the requirements from prestressed concrete elements in HPRAC with higher contents of lower quality RCA.
  - The fly-ash HPRAC containing lower quality RCA and cured in a humidity room did not fulfil the minimum compressive strength requirements to be used in prestressed concrete elements. The use of an initial steam curing regime was needed to reach the minimum 1-day strength for prestressed concrete sleepers. However, the required splitting tensile strength was only achieved by concrete mixtures containing RCA sourced from parent concretes with a minimum strength of 60 MPa.
  - The fly ash concretes with low quality RCAs achieved higher resistance to chloride ion penetration than the Portland-cement conventional HPC at 180 days. The fly ash could improve the ITZ of HPRAC by penetrating into the RCA's

pores and filling the superficial cracks with the new hydration products. Younger RCA could have a residual binding ability which could be activated by fly ash.

- Due to steam curing process, the concretes suffered lower evolutions over time of the mechanical and durability properties. However the evolution of concrete properties were improved by the use of RCA. The HPRAC containing the lowest quality RCA (sourced from 40 MPa parent concrete) achieved the highest compressive strength evolution, as well as the highest refinement of porous structure. The higher porosity of RCA, containing higher amount of water, could enhance the binder hydration rate of steam cured concretes by compensating the barrier effect from the early-age hydration products formed in the steam curing cycle. Overall, the HPRAC reached a more appropriate behaviour by undergoing the steam curing process than the conventional HPC.

- *Study of the shrinkage behaviour of HPRAC and the internal curing effects of RCA*
  - The analysis of shrinkage revealed considerable differences between the conventional HPC and HPRAC behaviours. The higher amount of total water on the concrete mixtures and the lower modulus of elasticity from HPRAC were associated with the plastic and drying shrinkage increase. Despite the shrinkage strains obtained were not considered critical, the use of HPRAC requires a more rigorous control on the curing conditions than conventional HPC.
  - The autogenous shrinkage behaviour revealed opposite tendencies to those from plastic and drying shrinkage. The use of RCA sourced from 60 MPa and 40 MPa concretes reduced significantly the autogenous shrinkage of HPRAC when replacing 50 and 100% of natural coarse aggregates. The recycled aggregates containing high amounts of moisture compensate the internal stress of cement hydration reactions by providing the remaining water similarly to the internal curing effect from lightweight aggregates.

- *Pilot study: Effects of RCA on the structural properties of prestressed HPC sleepers*
    - The comparative study of the HPRAC sleepers with the conventional HPC sleepers showed similar results on those tests required by the Spanish Technical Specification of prestressed concrete sleepers. However the standard deviations from the HPRAC were higher than those found in HPC sleepers.
    - The simplified methods to predict the ultimate capacity of HPC achieved reasonable values when they were applied to HPRAC. The ultimate concrete strain used in the analysis could be a bit conservative when applied to negative design. However, the value proposed in the EC2 achieved good results and always in the safety side for any type of concrete.
    - In general, the analysis of the load-strain behaviour registered on the prestressing rebars revealed very similar behaviour in any type of concrete sleeper. However the HPC sleepers showed slightly higher stiffness than those of HPRAC at the initial stages of the tests.

7.3. Future perspectives

The present study clears up some of the topics about the use of recycled aggregates in the production of High Performance Concrete, however there are still numerous questions which require further investigation. Some of the future investigations are summarized below:

- The ceramic fine aggregates revealed very suitable performances in replacement of fine natural aggregates. Higher replacement ratios should be analysed in order to find the maximum replacement ratios. Also according to the high porosity of the ceramic particles, the ceramic fine aggregates could probably be efficient internal curing agents reducing significantly the autogenous shrinkage.
- The lower quality aggregates produced the higher reductions of the HPRAC properties. The use of previous surface treatments in order to improve their physical and mechanical

properties could ease the use of higher recycled aggregate amounts in structural concrete applications.

- The ITZ plays an essential role in the properties of concrete. Some papers revealed that RCA can reduce the porosity in this area which could be an interesting feature for the use of recycled aggregates. In order to verify the beneficial behaviour of recycled aggregates on HPC, the study of the ITZ microstructure could help to understand the mechanical and structural performances of HPRAC.
- The amount of pilot studies is still limited but of great interest for the complete characterization of recycled aggregates concrete. The scope of the pilot test conducted in this study could be extended to a comparative study of long-term durability between the HPC and the HPRAC sleepers. The study of the HPRAC sleepers’ performance in real railways would be a key factor for their commercialization.

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Paper I

Experimental analysis of properties of high performance recycled aggregate concrete

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Published in *Construction and Building Materials* (2014 Impact factor: 2.3; Q1)

Experimental analysis of properties of high performance recycled aggregate concrete

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Abstract

Due to the increase in the demolition of high strength concrete structures and the interest of precast concrete companies in being more competitive, it is necessary to analyse the use of recycled concrete aggregates (RCA) in high performance concrete (HPC). In this study, HPC were produced using 20%, 50% and 100% of RCA on substitution of natural coarse aggregates. Three types of RCA were used, they were produced crushing original concrete of 100, 60 and 40 MPa of compressive strength. The physical, mechanical and durability properties of the recycled aggregates concretes and conventional concrete were analyzed. The results showed that considering mechanical properties, the 100% natural coarse aggregates' replacement would be possible when RCA were produced from original concrete with a minimum compressive strength of 60MPa. When durability properties were considered concrete produced with up to 50% of RCA could be used in HPC production.

Keywords: *Recycled concrete, High Performance Concrete, Recycled concrete aggregates, Mechanical properties, Durability properties.*

1. Introduction

The high performance concrete (HPC) is designed to have better mechanical properties and higher workability and resistance to aggressive chemicals than traditional concrete [1]. Certain demolition waste materials have been successfully used in the manufacture of conventional concrete, and even in HPC. However, there have only been a few attempts to use recycled concrete aggregates (RCA) in HPC production because of the inherent negative aspects associated to RCA. None the less, the use of this recycled material is important in HPC, since the use of HPC is becoming more extensive worldwide. The use of RCA in the concrete industry could lead to a situation much closer to that of sustainable development.

The suitability of RCA for use in different applications with a low or moderate degree of requirement has been extensively tested and proved by many authors [2-13]. Dosage method and substitution rates of the natural aggregate were established considering the properties of RCA in concrete production to achieve adequate fresh and hardened properties, comparable to those of natural aggregate concrete (NAC). Some authors [4, 5] suggested that the use of coarse RCA could be extended to high performance concrete (HPC), offering additional value to RAC.

Following on from previous research work, Limbachiya [14] examined the influence of coarse RCA in high-strength concrete, 50 MPa or more. The concrete performance was assessed, while practical issues and durability properties were also tackled. The results obtained showed that concrete containing up to 30% of coarse RCA could be used in a wide range of applications in high performance engineering and the durability properties were similar to those of NAC concrete.

Moreover, Ajdukiewicz and Kliszczewicz [15] studied high performance concrete using RCA obtained from medium and high strength demolition concrete and analysed their influence on concrete properties. The properties of the original concrete had significant influence on mechanical properties of the recycled aggregate concrete (RAC); the RAC obtained higher compressive strength than conventional concrete when the RCA was produced with HPC aggregates.

In this research work, three different compressive strength (40MPa, 60MPa and 100 MPa) crushed concretes were used as coarse RCA for high performance concrete production. High performance concretes were made by replacing 20%, 50% and 100% of natural coarse aggregates for one of the three types of RCA employed. The production of the RCA concrete was carried out in the laboratory and the physical (density, absorption, volume of permeable pore space and ultrasonic pulse velocity), mechanical (compressive, splitting tensile, flexural strengths and modulus of elasticity) and durability (capillary water absorption, electrical resistivity and chloride ion penetrability) properties were determined and the obtained results were compared to those of conventional concrete (CC), whose mix proportions was the same as the original concrete of 100 MPa RCA.

2. Experimental details

2.1. Materials

2.1.1.Cement and additive

ASTM Type I Portland cement, CEM I 52.5R, was used in concrete mixtures with the characteristic rapid hardened strength of 52.5 MPa, low alkali content and specific surface of 4947.8 cm^2/gr. The chemical properties of cement are given in Table 1.

Table 1. Chemical composition of cement

Composition	SiO_2	Al_2O_3	Fe_2O_3	***CaO***	***MgO***	K_2O	Cl^-	SO_3	***LOI***
(%)	21.75	3.38	4.55	64.65	1.63	0.64	0.01	2.66	0.91

A high performance additive of a superplasticizer type was used for the concrete production.

2.1.2.Aggregates

Natural and recycled aggregates were used as coarse aggregate in the concrete mixtures. In this study, a mixture of two types of natural coarse aggregates was used, crushed dolomite and river gravel.

Three types of coarse RCA with different characteristic strength were used. Type 1 (coded as RCA 100MPa), using the crushed high strength concrete obtained from a precasting factory of rejected specimens of 100 MPa compressive strength.

Type 2 (coded as RCA 60MPa), using the crushed 60 MPa compressive strength concrete produced in the laboratory and crushed after 28 days of curing; Type 3 (coded as RCA 40MPa) using the crushed rejected 40 MPa compressive strength concrete produced by precast concrete company. These three recycled aggregates were selected for their high strength quality as a lower strength quality aggregate would not achieve the properties required for a high performance concrete. Etxeberria et al. [2] and Tabsh and Abdelfatah [6] found that the weak point of medium-high strength concretes made with coarse recycled aggregates can be determined by the strength of the recycled concrete and its attached mortar.

The nominal sizes of the natural and recycled coarse aggregates were 10 mm and their particle size distributions are shown in Fig. 1. It can be seen that the size grading of the natural and recycled coarse aggregate was similar. Physical and mechanical properties of the coarse aggregate were determined according to EN specifications. As Table 2 shows, the natural aggregate had a higher density and lower absorption capacity than any other RCA. In contrast, when the original concrete had higher compressive strength, the RCA achieved better physical properties. However the three types of RCA had a lower absorption capacity than 7%, which is the maximum absorption capacity required by the Spanish Structural concrete regulation [16]. The Los Angeles Index of all the aggregates was lower than 30%, which indicates high strength to abrasion; moreover the RCA index were similar, or even lower, to that from dolomitic coarse aggregate.

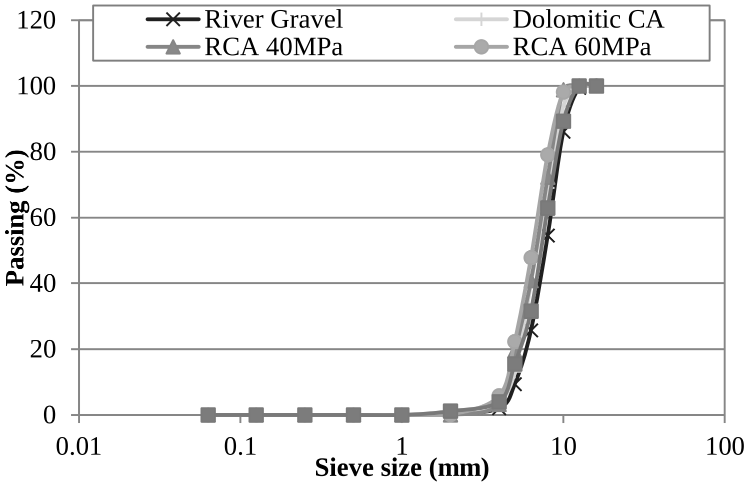

Fig. 1. Particle size distribution of coarse aggregate according to ASTM

Table 2. Physical and mechanical properties of coarse aggregates.

Type of aggregates	*Physical and mechanical properties*			
	Oven dried particle density (kg/dm^3)	*Water absorption (%)*	*Flakiness index (%)*	*LA Index (%)*
River Gravel	2.61	1.29	17.71	19.61
Dolomitic Gravel	2.68	2.13	7.81	24.77
RCA 40MPa	2.3	5.91	9.59	24.31
RCA 60MPa	2.39	4.9	13.57	25.24
RCA 100 MPa	2.47	3.74	16.53	24.01

Two different types of river sand were used as fine natural aggregate in all the concrete mixtures. Their particle size distributions were adequate according to Spanish Structural concrete regulation [16]. The physical properties of the fine aggregate are shown in Table 3.

Table 3. Physical and mechanical properties of fine aggregates

Physical properties	*Oven dried particle density (kg/dm3)*	*Water absorption (%)*
River Sand 1	2.50	1.02
River Sand 2	2.57	1.93

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory (referenced as 100, 60 and 40, according to the original concrete strength of the recycled aggregates). The three types of recycled coarse aggregate that were used on substitution (by volume) were those of 20%, 50% and 100% natural aggregates.

In order to control the concrete production, recycled coarse aggregates were wetted the day before use by means of a sprinkler system and then covered with a plastic sheet until used in the concrete production in order to maintain the level of high humidity. A recommended level of moisture is 80% of their total absorption capacity [2]; however the most important point was that the aggregates employed were wet in order to reduce their absorption capacity [7]. Due to moderate initial moisture content, recycled aggregate absorbed a certain amount of free water and lowered the initial w/c ratio in the ITZ consequently improving the interfacial bond between the aggregates and cement [8]. However, recycled aggregates should not be saturated [17], as that would probably result in the failure of an effective interfacial transition zone between the saturated recycled coarse aggregates and the new cement paste. In line with these recommendations, Poon et al. [18] discovered that the compressive strength of concrete made with saturated aggregate was lower than concrete made with air dried aggregates due to the negative effect of the bleeding of the saturated aggregates.

The same process of wetting used for the RCA was employed on the natural fine aggregate in order to control the results at 1-day compressive strength and avoid dispersions. In order to reduce the amount of added water at the mixing stage the moisture content of the fine aggregates were fixed at 3-4% (oversaturated) as this would achieve higher compressive strength at very early ages.

The concrete mix proportions were defined according to the Fuller’s dosage method [19]. The coarse and fine aggregate percentages of the conventional concrete dosages were adjusted to be within the standard curve that allows for the maximum compaction of granular elements, which is the method that corresponds to the Gessner parabola. This parabola is defined by the aggregate maximum size and the sieve sizes and, it permits one to calculate an ideal (theoretical) passing percentage. The percentage of each type of natural fine and coarse aggregate was corrected to achieve passing percentages similar to the passing percentages defined by the Gessner parabola in all sieve sizes. Despite the fact that RCA aggregate did not have the same size distribution as NCA the theoretical parabola was also similar.

As shown in Table 4, 380 kg of cement and the effective water –cement ratio of 0.285 were used in all concrete productions. The effective water-cement ratio of CC concrete was determined and maintained constant for all concretes (the effective water was the water reacted with the cement). In order to control the effective water –cement ratio in all the other concretes, oversaturated fine aggregates were used (the unabsorbed water was considered as part of effective water), the natural coarse aggregates were used in a dry condition and it was considered that they absorbed 20% of their total water capacity (which was the water absorption capacity of aggregates submerged in water up to 30 minutes), and recycled aggregates were used with approximately 80% of humidity and their effective absorption capacity was that of 70%. The total water amount of the concrete was considered as the amount of effective water weight plus the moisture (or absorbed water) of the aggregates (see Table 4).

Table 4. Proportioning of the concrete mixtures

Concrete reference	*River Sand 1*	*River Sand 2*	*River Gravel*	*Dolomitic Gravel*	*RA*	*Total Water (kg)*	*Cement (kg)*	*Effective W/C ratio*
CC	711.8	215.2	302.1	784.5	---	135.4	380	0.285
RC-20-100	711.8	215.2	241.6	627.6	202.0	137.1	380	0.285
RC-50-100	711.8	215.2	151.0	392.2	505.1	146.5	380	0.285
RC-100-100	711.8	215.2	---	---	1010.2	162.3	380	0.285
RC-20-60	711.8	215.2	241.6	627.6	195.0	138.2	380	0.285
RC-50-60	711.8	215.2	151.0	392.2	487.5	149.8	380	0.285
RC-100-60	711.8	215.2	---	---	975.1	170.4	380	0.285
RC-20-40	711.8	215.2	241.6	627.6	187.8	139.7	380	0.285
RC-50-40	711.8	215.2	151.1	392.3	469.4	153.1	380	0.285
RC-100-40	711.8	215.2	---	---	938.8	175.3	380	0.285

Dry consistency was maintained in all concrete mixtures and the 1.5% respect to cement weight of superplasticizer was used in all mixtures.

The recycled concrete mixtures were coded as RC-x-y (x = percentage of recycled aggregate replacement level; y =type of recycled aggregate used).

2.3. Specimens casting and curing

For each concrete mixture, 100 mm cubes were used to determine the hardened concrete density, absorption, the permeable pore voids, the ultrasound pulse velocity (UPV) and the electrical resistance. 150 mm cubes and 100x100x400 prisms were used to determine the compressive strength and the flexural strength, respectively. The 100∅/200 mm cylinders were used to evaluate elastic modulus, tensile strength and resistance to chloride-ion penetration of concrete.

All the specimens were cast in steel moulds (except the 150mm cubes which were cast in plastic moulds) and compacted using a vibrating table during two steps of 30 seconds each. The concrete specimens were kept for a day in the moulds which were covered with wet burlap and a plastic top to ensure that temperature and wet conditions were stable between 18º C and 26º C and high moisture. Specimens were demolded 24 hours after casting. Three cubes were immediately used after demolding to measure 1-day compressive strength. The rest of the specimens were cured in humidity room at 23ºC and 95% humidity until the age of testing.

2.4. Tests of hardened properties of concrete

2.4.1. Physical properties

- *Density, absorption and volume of permeable pore space*

The density, absorption and voids were measured following the ASTM C 642 – 97 “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete” at 28 days. Three cube specimens were used for each type of concrete produced.

- *Ultra-sound pulse velocity (UPV) test*

The cube specimens of size 100 x 100 x 100 mm were used for the UPV test. The average UPV values were taken from three cubes obtained from each mixture using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT). Two measurements were taken at the middle of each cube, in a perpendicular direction to that of the casting direction of the concrete. The test was done in accordance with the ASTM C 597 in direct transmission state. All of the specimens were tested at the saturated conditions, at the age of 28 days.

2.4.2. Mechanical properties

- *Compressive, flexural, splitting tensile strengths and elastic modulus*

The compressive strength of concrete was determined using a compression machine with a loading capacity of 3000 kN. The compressive strength was measured at the ages of 1, 7 and 28 days following the UNE-EN 12390-3.

The flexural strength was measured at 7 days following the UNE-EN 12390-5. The tensile strength and elastic modulus were tested at 28 days also following the UNE-EN 12390-6 and UNE 83-316-96 specifications, respectively. Three specimens were used for each type of concrete produced.

2.4.3. Durability properties

- *Capillary water absorption*

The capillary water absorption was assessed on concrete at 28 days after mixing and using 100 x 100 x 100 mm cubic specimens according to ISO 15148:2002(E). For sorptivity determination, the bottom face of specimens was submerged in water 5 mm (the lateral surfaces were impregnated with impermeable resin). The cumulative water absorbed was recorded at different time intervals up to 48 h by weighing the specimen after removing the surface water using a dampened tissue. Sorptivity is the slope of the regression curve of the quantity of water absorbed by a unit surface area versus the square root of the elapsed time from initial instant to 120 minutes. The results of capillary water absorption are the average of three measurements.

- *Electrical resistivity*

Corrosion is an electro-chemical process. The rate of flow of the ions between the anode and cathode areas, and therefore the rate at which corrosion can occur, is affected by the resistivity of the concrete [20]. Concrete resistance was measured in the laboratory with a basic electric device. The voltage and current were measured across a sample of known dimensions, and then the resistivity was calculated. Low-resistance contact between the concrete and measurement circuit is critical in obtaining an accurate measurement. The measurement was carried out using electric conductive gel spread on the surface in contact with the copper plates used as cathodes. The strength applied on the cathodes can have significant effects on field resistance measurements, so that the specimens were assessed with a fixed weight at the same position upon the cathodes. All specimens were tested at 28 days at the saturated surface dry conditions and each result was the average of 3 measurements.

- *Chloride ion penetrability*

The chloride penetrability of concrete was determined in accordance with ASTM C1202 (1997) using a 50 mm thick/100∅ mm concrete disc cut from the 100∅/200 mm concrete cylinder. The resistance of concrete to chloride ion penetration is represented by the total charge passed in Coulombs during a test period of 6 h. In this study, the chloride ion penetrability test was carried out on the concrete specimens at the ages of 28 days and each result was the average of four measurements.

3. Results and discussion

3.1. Physical properties

3.1.1.Density, absorption and volume of permeable pore space

The results of absorption, dry-density and volume of permeable space (voids) are shown in Table 5. As was expected, while replacement of RCA was increased the dry-density of concretes decreased. This was due to the increase of RCA that showed lower particle density than natural aggregates. Absorption and volume permeable spaces showed clear tendencies related to natural aggregates replacements. Most of mixtures showed higher absorption and volume of voids than CC concrete due to the physical properties of the RCA. Higher absorption capacity and higher volume of voids of RCA affected the final properties of the concrete which were used.

Table 5. Dry-density, absorption and voids of concrete mixtures at 28 days

Notation	*Dry-density (Kg/dm^3)*	*Absorption (%)*	*Voids (%)*
CC	2.51	1.39	3.49
RC-20-100	2.50	1.24	3.10
RC-50-100	2.48	1.51	3.72
RC-100-100	2.43	1.51	3.67
RC-20-60	2.44	1.76	4.44
RC-50-60	2.40	1.93	4.64
RC-100-60	2.34	2.43	5.69
RC-20-40	2.47	2.08	5.14
RC-50-40	2.43	2.12	5.16
RC-100-40	2.39	2.17	5.20

3.1.2.UPV (Ultrasonic Pulse Velocity)

The UPV results of the conventional concrete and recycled concretes can be seen in Fig. 2. The conventional concrete, CC, was the mixture that showed better quality results. As some research works showed [21, 22], the UPV values decreased as the level of natural aggregates replacement for RCA increased. In spite of that, the concrete produced with 100 MPa-RCA suffered a small drop in UPV results when the RCA replacement was up to 50%, due to similar properties of RCA adhered mortar to concrete new mortar.

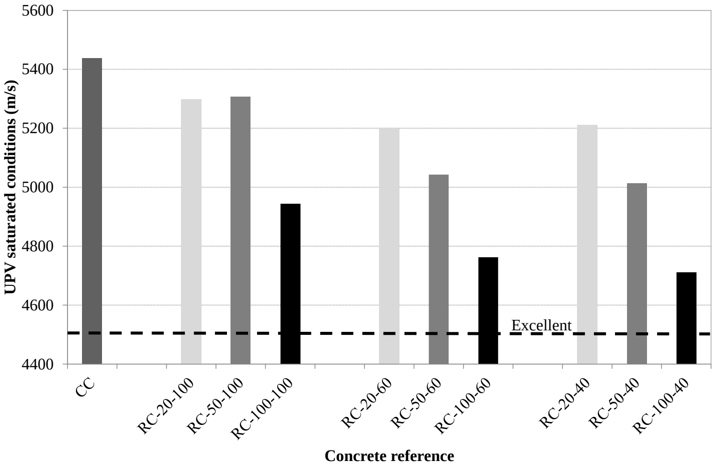

Fig. 2. UPV of concrete at 28 days and Whitehurst excellent range definition [23].

All UPV concrete values exceeded 4500 m/s and they were classified in the range of excellent values according the UPV values proposed by some authors as Whitehurst [23] that determined the quality of concretes with a density of 2400 kg/m3. The increase of replacement of natural aggregates for recycled aggregates and the decrease of recycled concrete quality triggered an increase of pore spaces that affected the transmission of ultrasonic waves.

3.2. Mechanical properties

3.2.1.Compressive strength

The compressive strength results are presented in Table 6 for the concrete mixtures. Recycled aggregate concrete (RAC) mixtures obtained a higher compressive strength than the conventional concrete (CC) after 24 hours, except for HR-100-40 concrete which obtained a similar result (Fig. 3). As Fig. 4 shows, the CC achieved in 24 hours, 56% of its strength at 28 days. Nevertheless RAC obtained, in 24 hours, up 65-80% of their strength at 28 days. The different moisture rate of natural fine aggregates in CC production could be the reason for explaining the lower early-age compressive strength and the higher evolution from 1-28 days of CC. A higher amount of water was added to the mixer in the CC concrete production and consequently CC had more free water which was influential in the obtaining of 24 hours strength. Moreover, remaining absorption capacity of partially saturated RCA could reduce the w/c ratio in the ITZ improving its strength at early hydration [7].

Table 6. Compressive strength of concrete mixtures

Concrete reference	*Compressive strength (MPa)*		
	1- day	*7-days*	*28-days*
CC	57.36	91.19	102.09
RC-20-100	73.79	88.51	108.03
RC-50-100	79.24	94.76	104.80
RC-100-100	78.73	93.43	108.51
RC-20-60	73.55	102.1	102.48
RC-50-60	72.38	98.77	103.10
RC-100-60	79.42	100.1	100.78
RC-20-40	67.06	91.73	104.28
RC-50-40	60.69	84.39	96.84
RC-100-40	56.62	79.88	91.23

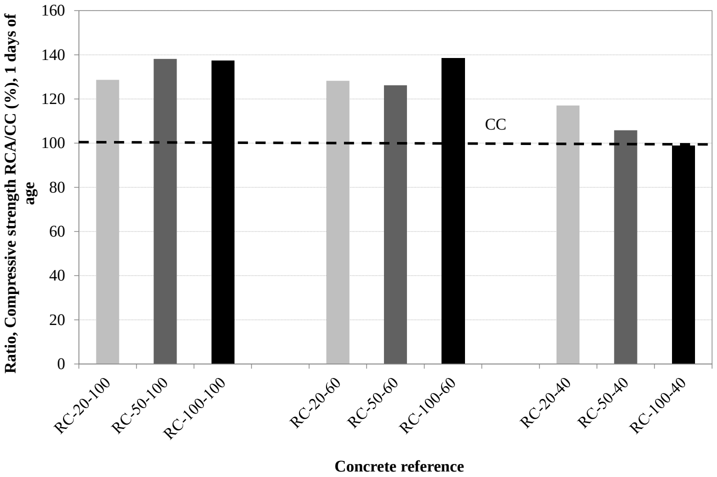

Fig. 3. Compressive strength of recycled concretes in comparison with that of conventional concrete at 1 day of age

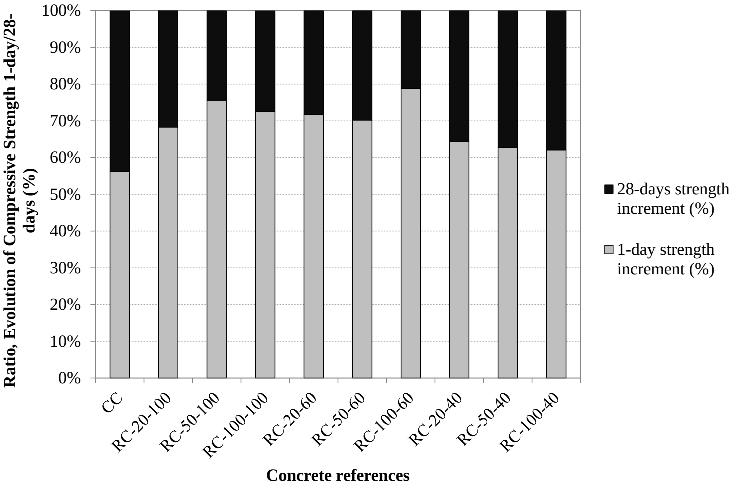

Fig. 4.Evolution of compressive strength from 1-day compressive strength to 28-days compressive strength of concrete series in percentage.

Fig. 5 shows the 28-days relative compressive strength of RAC with respect to CC, all RAC achieved similar strength to that of CC. According to RAC made with 40MPa recycled aggregates, where more than 50% of replacement of the natural aggregate was used, it achieved a lower compressive strength than that of the CC. This negative influence on compressive strength was due to the poorer quality of the attached mortar in the recycled aggregates in comparison with that of the new mortar. This was indicated as well in the study of Etxeberria et al. [2], Tabsh and Abdelfatah [6] and Adjukiewicz & Kliszczewicz [15]. Despite this, in the rest of the RAC concretes the influence of the amount of RCA and their substitution was barely noticeable. The low water-cement ratio and a more adequate bond strength of the recycled aggregates allowed the RAC to show a behaviour comparable to conventional concrete [24].

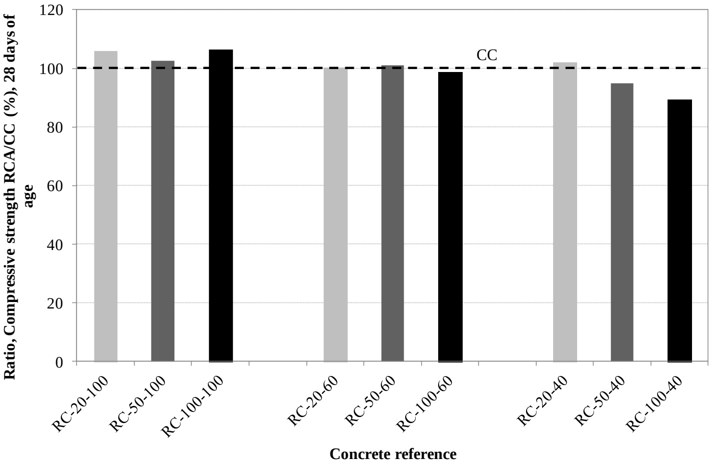

Fig. 5. Compressive strength of recycled concretes in comparison with that of conventional concrete at 28 days of age

The high surface roughness of the recycled aggregates leads to a good bond between cement paste and aggregates, as Hoffman et al. [25] stated. Furthermore, Poon et al. [7] suggested that HPC recycled aggregate achieved comparatively denser ITZ than conventional aggregate concrete and improved the mechanical properties of this region. The microstructure of ITZ using this type of RAC appeared to have similarities to ITZ in lightweight aggregate concrete [26, 27]. Newly formed hydrates gradually fill the ITZ due to the partially saturated aggregates absorbing a certain amount of water and lower the w/c ratio in the ITZ at early hydration. The reduction to 10mm nominal maximum diameter, despite presenting a greater specific surface area, allowed the aggregates to present fewer surface irregularities. High-quality cement paste is capable of more efficiently enveloping the recycled aggregates. Consequently weaker points introduced by recycled aggregates were reduced.

3.2.2.Flexural, Splitting tensile strength and modulus of elasticity

In Table 7, the results of flexural strength at 7 days, splitting tensile strength and modulus of elasticity at 28 days are shown. According to flexural strength results, all the concretes made with RCA achieved higher or similar strength to that of CC. In Fig. 6, the recycled aggregate concrete results are compared with the reference CC. Concretes made with maximum 50% of recycled aggregates on replacement of natural ones improved the conventional concrete result by 10-20%. Even using total replacement of medium strength concrete aggregates (40MPa), RAC flexural strength achieved similar values to that of CC. Relative values from Fig. 6 indicate that the flexural strength seemed to be the mechanical property which was less influenced by RAC quality or replacement. This may be due to the bond between paste and aggregate in RC which is comparable to those of CC as confirmed by several researchers [25, 28].

Table 7. Flexural strength, Tensile strength and modulus of elasticity of concrete mixtures

Concrete reference	*Flexural strength (MPa) 7-days*	*Tensile strength (MPa) 28-days*	*Elastic modulus (GPa) 28-days*
CC	6.47	5.13	50.41
RC-20-100	7.42	5.71	48.54
RC-50-100	7.65	5.64	47.93
RC-100-100	6.84	5.12	46.10
RC-20-60	7.98	6.32	47.79
RC-50-60	6.80	5.10	44.28
RC-100-60	6.33	5.88	40.09
RC-20-40	6.70	5.31	48.29
RC-50-40	6.83	6.21	43.04
RC-100-40	6.53	4.20	37.15

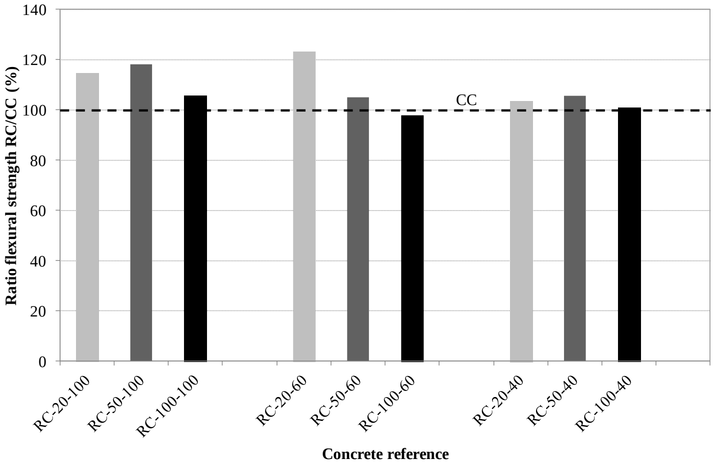

Fig. 6. Flexural strength of recycled concretes in comparison with that of conventional concrete at 7 days of age.

According to the splitting tensile strength (see Table 7), all concretes mixtures showed a good performance, except the concrete made with 100% of 40 MPa RCA. All the other series achieve more than 4.5 MPa of tensile strength, which is the minimum requirement for high performance concrete elements such as railway sleepers [29]. Fig. 7 shows the splitting tensile strength of the recycled concrete in comparison with that of CC. The splitting tensile strength did not seem to be very influenced by the RAC replacement level in each recycled aggregate quality used, probably due to the influence of the ITZ between the cement paste and the coarse aggregate with respect to this property [2]. A visual examination of crushed test specimens was carried out to assess the failure mode of recycled concrete specimens. Fig. 8 shows fracture surface of the CC and 100, 60 and 40 MPa RAC with the total replacement of coarse aggregate in the splitting tensile strength test. Regarding the RCA failure pattern, aggregate splitting was evident in most RAC.

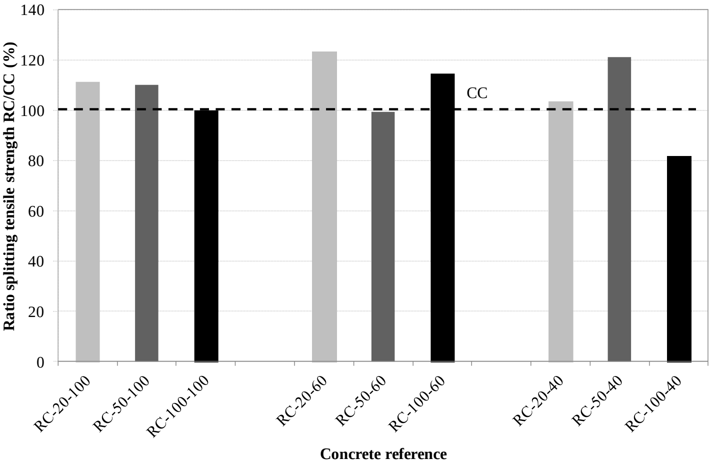

Fig. 7. Splitting tensile strength of recycled concretes in comparison with that of conventional concrete at 28 days of age.

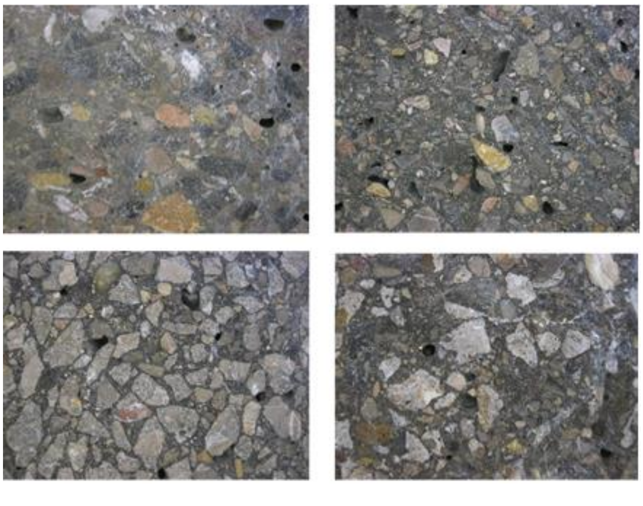

Fig. 8. Conventional concrete (up-left) and recycled aggregate concrete, 100MPa (up-right), 60MPa (down-left) and 40 MPa (down-right), showing failure pattern of aggregates

The results of the modulus of elasticity test are shown in Table 7. This mechanical property seemed to be more sensible to RCA replacement. It is known that the modulus of elasticity of concrete is influenced by the modulus of elasticity of the coarse aggregate [24] and according to Lydon and Balendran [30], the modulus of elasticity of aggregate is proportional to the square of its density. Despite showing lower elastic modulus values, all the RAC mixture showed high results, the minimum was found to be 37 GPa (RC-100-40).

In Fig. 9, recycled concretes modulus of elasticity is compared with that of conventional concrete at 28 days of age. All mixtures showed lower results than the reference CC concrete but the concrete made with 20% of RCA replacement just showed a reduction close to that of 5%. The use of 100% of 100MPa recycled aggregates produced a reduction of modulus of elasticity lower than 10%. The modulus of elasticity of the very strong hardened cement paste and that of the aggregate in high performance concrete have little difference, however the difference is much higher in the medium strength concrete. Moreover, in HPC the strength of the aggregate- matrix interface is higher [24]. The relation between replacement and modulus reduction was more emphasised when RCA of 60 MPa and 40MPa were used. The use of aggregates with poorer mechanical properties accentuated the negative effect of RCA in elastic modulus, as was exposed by Lydon and Balendran [30].

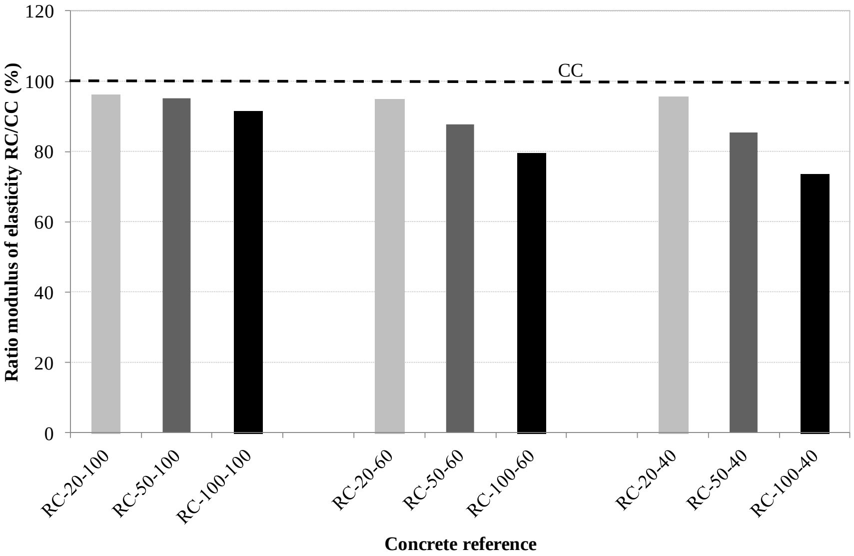

Fig. 9. Modulus of elasticity of recycled concretes in comparison with that of conventional concrete at 28 days of age.

3.3. Durability

3.3.1. Capillary water absorption

The sorptivity values of all concretes were approximately 0.014±0.001 mm/min$^{1/2}$ (see Table 8), they have a low value due to the low water-cement ratio. According to Neville [24], absorptivity values obtained in the first 4 h can be correlated with concrete w/c ratios. The values of 0.09 mm/min$^{1/2}$ and 0.17 mm/min$^{1/2}$ correspond to concretes with w/c of 0.4 and 0.6, respectively. Zhutovsky [31] found sorptivity values between 0.06-0.1 for high performance concrete up to 0.33 w/c ratios. The lower sorptivity values achieved in this research work are probably due to the use of lower effective w/c ratio for concretes production. A high quality ITZ could originate, therefore a more impervious zone was created because the interface area was denser than those of natural aggregates. Moreover, as Etxeberria et.al [8] affirmed the mortar filling the coarse aggregate should be the main cause of capillary water absorption.

The results of assessing capillary water absorption during 48 hours of concrete specimens are shown in Fig. 10. Capillary water absorption of all recycled aggregate concrete was not higher than that of the natural aggregate concrete. The fact that RAC introduces higher capillary absorption is attributed to the higher absorption of recycled aggregate in comparison with natural aggregate; this has also been reported by other researchers [32-34]. In this study due to the very low water-cement ratio in all concretes the increase of the water amount (by weight) in the specimens, in the first 30 minutes, was lower than 0.05% with respect to the dry weight of the specimens. After 48 hours, the weight in all samples increased approximately by 0.11% with respect to the initial weight. Consequently, the behaviour of all concretes could be considered as adequate and similar.

Table 8. Sorptivity of concrete mixtures.

Concrete reference	*Sorptivity (mm/min$^{1/2}$)*
CC	0.014
RC-20-100	0.015
RC-50-100	0.015
RC-100-100	0.013
RC-20-60	0.014
RC-50-60	0.014
RC-100-60	0.013
RC-20-40	0.013
RC-50-40	0.014
RC-100-40	0.014

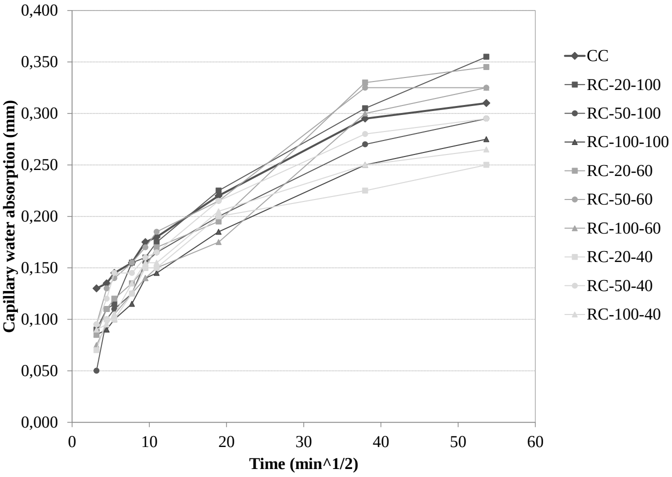

Fig. 10. Capillary water absorption of concrete mixtures

3.3.2. Electrical resistivity

The results of electrical resistance test of all concretes in saturated condition are shown in Fig. 11. All specimens were tested at 28 days and each result was the average of three measurements. The different types of concrete showed (Fig. 11), in general, a low and moderate risk to corrosion when electrical resistivity values were compared with limit ranges proposed by Langford and Broomfiel [35]. However, the use of the 100% of recycled aggregates of 40 MPa in concrete production caused a high corrosion risk, due to the increase of porosity in the concrete.

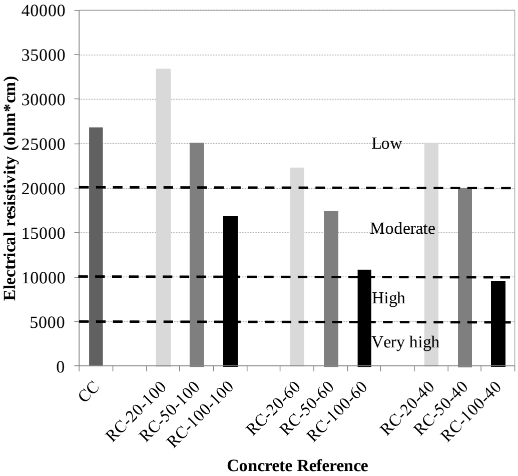

Fig. 11. Electrical resistivity of concrete and range limits of corrosion risks [29].

This property clearly showed an influence due to the replacement level and the quality of recycled aggregates which depend on the quality of the original old concrete's mortar. As the replacement of NA for RCA so too did increased the risk of corrosion because of the higher porosity of the mortar attached to recycled aggregates.

3.3.3. Chloride-ion penetration

The results of assessing the chloride-ion penetration of concrete specimens are shown in Fig. 12. It shows that the resistance to chloride ion penetration decreased as the recycled aggregate content increased. The results could be classified following the ASTM C1202 (1997) corrosion ranges between very low and moderate risk of corrosion. The reference conventional concrete allowed for the lowest passing of chloride ions through the specimens. As was shown in Fig. 12, while the concrete produced with 20% and 50% of coarse RCA obtained results on the limit of very low corrosion range, the total replacement of series 60MPa and 40MPa achieved values of or above the moderate corrosion limit, respectively. The RAC produced in this research work achieved much higher resistance to chloride-ion penetration than those obtained by other researchers in recycled concrete of moderate requirements [36], this was due to low water-cement ratio of the paste. The research works on high performance concrete produced with lightweight aggregate [31,37] revealed that the density of the cement paste, determined by the w/c ratio, was the main factor for the resistance to chloride ion penetration. Despite of showing higher absorption capacity, lightweight aggregates showed similar results to CC and the resistance decrease in the same proportion as that of CC when w/c ratio was increased.

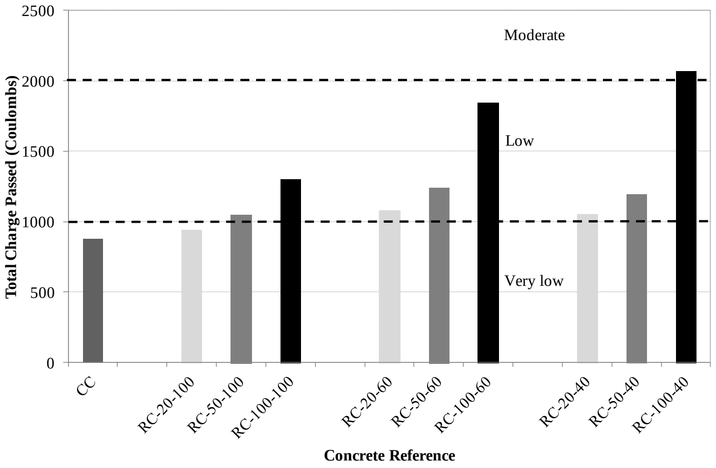

Fig. 12. Chloride-ion penetration of concrete mixtures and ASTM corrosion ranges.

4. Conclusions

The following conclusions can be made based on the results of this study:

- *Physical properties*

The concretes produced using up to 100% of recycled concrete aggregates (RCA) achieved similar properties to conventional concrete, when the RCA were obtained by crushing concrete with similar strength (100MPa) to that of conventional ones. The lower quality of RCA, which had a higher absorption capacity and volume of voids, affected the final properties of the concrete.

- *Mechanical properties*

The compressive strength at early age (24 hours) is more dependent on free water (water added to the mixer) content at mixing time, than the replacement level or the quality of recycled concrete aggregate. At 28 days, the RAC achieved 100MPa strength of conventional concrete without any adjustment in cement quantity or effective w / c ratio when the natural coarse aggregates (with 10mm of maximum nominal diameter) were substituted for:

100% of recycled concrete aggregate, which were obtained by crushing original concrete with a minimum strength of 60MPa strength.

50% of recycled concrete aggregate, which were obtained by crushing original concrete with minimum strength of 40 MPa.

The RAC showed a comparable behaviour to conventional concrete due to the low water-cement ratio and a more adequate bond strength of the recycled aggregates.

The amount of use and quality of recycled concrete aggregate had little influence on the tensile and flexural strength of the recycled aggregate concrete when comparing it to those of high performance conventional concrete.

The use of recycled aggregates with higher porosity than raw aggregates accentuated its negative effect on elastic modulus

- *Durability properties*

The recycled concretes showed very similar sorptivity values to those of conventional concrete due to very low water-cement ratio used in concrete mixes.

According to the resistance of chloride-ion penetration, the concrete produced using up to 50% of recycled aggregates (obtained from crushing concrete with minimum 40 MPa) achieved similar durability properties to those of high performance conventional concrete. The total replacement of natural coarse aggregates for those of lower properties aggregates produced a reduction on the durability properties.

It would be highly recommendable to employ mineral admixtures to recycled concretes mixes in order to produce durable High Performance concrete.

Recycled aggregates sourced from original medium- high strength concrete can be successfully used in HPC. Engineers and producers should be encouraged to maximize the recycled concrete aggregates use and avoid underestimated applications of high quality recycled aggregates.

Acknowledge

The authors wish to acknowledge the financial support of The Ministry of Economy and Competitiveness by INNPACT project (IPT-2011-1655-370000).

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Paper II

Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates

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Published in *Construction and Building Materials* (2014 Impact factor: 2.3; Q1)

Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates

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Abstract

There are various means of obtaining waste for the production of recycled aggregates. In this study the waste material has been obtained from building demolition and also from the ceramic industry (known for the production of large amounts of rejected ceramic wastes). High performance concretes (HPC) was produced using fine ceramic aggregates (FCA) in substitution of 15% and 30% of natural sand, and using 20%, 50% and 100% of coarse mixed aggregates (CMA) on substitution of natural coarse aggregates. The physical, mechanical and durability properties of the recycled aggregate concretes were determined and compared to those of the results of conventional concrete. The results showed that concrete produced with up to 30% of FCA achieved similar or improved mechanical and durability properties to those of conventional concrete. Concrete made with up to 20% of CMA achieved similar compressive strength to High Performance conventional Concrete of 100 MPa. At 180 days of curing the concretes produced with up to 50% CMA obtained low corrosion risk.

Keywords: *Recycled high performance concrete, Fine ceramic and coarse mixed aggregates, Mechanical properties, Durability properties.*

1. Introduction

Southern European countries have maintained a long tradition of using ceramic materials, such as tiles, bricks and blocks, in the construction industry. Ceramic waste is produced by the ceramic manufactures during production as well as in the demolition of existing buildings [1]. Ceramic waste represent an important amount of the construction and demolition waste that reaches recycling and treatment plants. Nevertheless, the combination of this ceramic waste together with other inorganic materials has a negative effect on their properties as it results in mixed recycled aggregates with lower technical properties. In this case selective demolition may represent a more appropriate recycling method of achieving a more efficient and sustainable reuse of ceramic materials [2].

High performance concrete (HPC) is designed to have better mechanical properties and a higher resistance to aggressive chemicals than traditional concrete [3]. Some wastes have been successfully used in the manufacture of conventional concrete and even in HPC[4–6]. The use of recycled ceramic aggregates in High Perfomance Concrete have been examined in relatively few studies [7, 8] and experimental data are limited. De Brito et al. [1] stated that the disparity in water absorption between ceramic and natural aggregates points towards the main difficulty of the use of ceramic aggregates in the production of concrete without losing in strength, workability or durability. However, pre-saturation is a way of minimizing these consequences [1] or even improving mechanical properties when internal stress is required such as in HPC [7]. The use of ceramic waste as clay and fine admixtures has positive values as an additional binder that could be very useful in HPC. If ceramic minerals are mixed with calcium hydroxide and water, pozzolanic reactions can form new compounds thus increasing the strength and durability properties of the concrete [8].

The suitability of ceramic recycled aggregates for use in different applications with a low or moderate degree of requirement (lower compressive strength than that defining HPC, 62MPa according to ACI [9]), has been extensively tested and proved by many authors [10–19]. In most cases the ceramic materials were used as aggregates, however their use as cementitious materials has also been studied [8, 18]. According to some research works the recycled concrete could achieve the properties of conventional concrete when the replacement of natural aggregates by ceramic aggregates are: up to 50 % for fine aggregate [16, 19] and up to 40 % for coarse aggregate [7, 12]. A few authors [7, 8] suggested that the use of recycled ceramic materials could enhance HPC, offering an additional value to the ceramic waste.

Suzuki et al. [7] used porous coarse ceramic waste aggregates for the internal curing of high performance concrete. Their research exposed that there was a high effectiveness of the ceramic aggregates in reduction and even complete elimination of autogenous shrinkage. The incorporation of 40% of coarse mixed aggregate led to a non-shrinking HPC that was accompanied by a significant increase of compressive strength.

Torkittikul and Chaipanich [16] and Khatib [19] studied the mechanical properties of concrete made with fine ceramic aggregates (FCA). Torkittikul [16] established 50% of FCA as the optimum replacement ratio in order to maintain similar workability and compressive strength to those of conventional concrete. Khatib [19] extended the statement to long-term compressive strength, recommending the use of 50% of FCA in the substitution of natural sand for concrete production. However, Khatib [19] affirmed that even at 100% of fine aggregate replacement the reduction in strength was only 10% and indicated that this could be due to cementing action in the presence of FCA. Pacheco and Jalali [13] found that concrete mixtures employing ceramic aggregates achieved durable concrete.

Heidari and Tavakoli [18] studied the mechanical properties of ceramic powder as an addition in concrete production. Their results showed that by replacing 20% of cement for ceramic powder did not have a significantly negative effect on the compressive strength of concrete. Similarly, the experimental results of Vejmelkova et al. [8] showed that 20% of ceramic powder substitution for cement was satisfactory for mechanical properties, and 40% was adequate for chemical resistance.

In this research work high performance recycled aggregate concretes were produced and their properties were compared to the properties of conventional concrete which was defined by a precast and prestressed High Performance Concrete sleepers ‘manufacturer. The production of high performance concrete was carried out using a coarse mixed recycled aggregate (CMA) obtained from a Spanish Construction and demolition treatment plant. A substitution ratio of 20, 50 and 100% of natural coarse aggregates for recycled aggregates was employed. Fine ceramic aggregate (FCA) obtained from crushing rejected bricks from the ceramic industry, in substitution of 15% and 30% of natural fine aggregate, was also used in order to verify its applicability in HPC. High performance concretes were produced in the laboratory and the physical (density, absorption, volume of permeable pore space and ultrasonic pulse velocity), mechanical (compressive, splitting tensile, flexural strengths and modulus of elasticity) and durability (capillary water absorption, electrical resistivity and chloride ion penetrability) properties were assessed. The obtained results were compared to those of conventional concrete (CC) and the minimum requirements specified by Spanish sleepers technical specification [20].

2. Experimental details

2.1. Materials

2.1.1. Cement and additive

ASTM Type I Portland cement (CEM I 52.5R) was used in all concrete mixtures. The high strength and rapid hardening cement presented low alkali content and specific surface of 4947.8 cm^2/g. Rapid hardened cement was used in order to achieve 1-day compressive strength higher than 46 MPa was the required compressive strength for formwork demolding and bars stress transmission in sleepers' production [20]. The chemical properties of the cement are given in Table 1.

Table 1. Chemical composition of cement

Cement Composition	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*CaO*	*MgO*	*K_2O*	*Cl^-*	*SO_3*	*LOI*
(%)	21.75	3.38	4.55	64.65	1.63	0.64	0.01	2.66	0.91

A high performance admixture (superplasticizer type) was used for concrete production in a constant percentage of the cement weight (1.5%) following the manufacturer's recommendations. The super plasticizer was a high range water reducer based on polycarboxylate ether (PCE) with a specific gravity of 1.08. It is indicated for the production of concrete with high early strength and high workability requirement.

2.1.2.Aggregates

Two types of coarse natural aggregates (NA) and two types of river sands were used for production of conventional concrete following mixture proportioning used in HPC for sleepers manufacture.

The two types of coarse natural aggregates (NA) were, crushed dolomite and river gravel. Moreover, one type of coarse mixed recycled aggregate (CMA) was used as a replacement for the natural coarse aggregates. The CMA containing 67% ceramic waste was sourced from a treatment plant located in Catalonia (Spain). The composition of the CMA is given in Table 2 following the specification EN-933-11. CMA composition did not fulfil the requirements of the RILEM [21] and DIN standards [22] to be classified as ceramic aggregate (>90% or >80% of ceramic content, respectively). Mixed aggregate category was adopted to define the CMA composition in spite of showing a high proportion of ceramic components.

Table 2. Composition of recycled aggregates following UNE-EN 933-11:2009.

Composition (%)	*Concrete products*	*Unbound aggregates*	*Masonry products*	*Bituminous products*	*Glass products*	*Others (Wood, plastics and gypsum)*
CMA	22.2	9.8	67.3	0	0.1	0.7
FCA	0	0	100	0	0	0

The nominal sizes of the coarse natural aggregate and the CMA were 10 and 12.5 mm, respectively, and their particle size distributions are shown in Fig. 1. Similar size grading of the NA and CMA were found. Therefore no grading adjustments were carried out before NA replacement. Physical and mechanical properties of the coarse aggregate were determined according to EN specifications. As Table 3 shows, the natural aggregate had a higher density and lower absorption capacity than CMA. CMA showed a water absorption capacity of 16.45% due to the high proportion of 67% of ceramic material (see Table 2). CMA had much lower percentages of natural and concrete aggregates with 9.8% and 22.2% respectively.

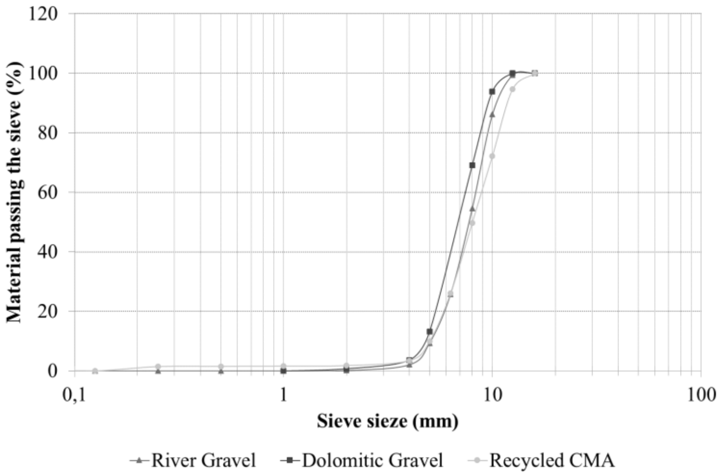

Fig. 1. Particle size distribution of coarse aggregate according to ASTM.

Table 3. Physical and mechanical properties of coarse aggregates.

Physical and mechanical properties	*Oven dried particle density (kg/dm3)*	*Water absorption (%)*	*Flakiness index (%)*	*LA Index (%)*	*Crushing value (%)*
River Gravel	2.61	1.29	17.71	19.61	18.94
Dolomitic Gravel	2.68	2.13	7.81	24.77	20.15
CMA	1.80	16.45	12.00	25.20	34.62

Actually, CMA had a much higher absorption capacity than 7%, the maximum absorption capacity according to Spanish Structural concrete requirements [23]. The Los Angeles Index of all the aggregates was lower than 30%, which indicated a high strength to abrasion; moreover, the Los Angeles' Index of CMA was similar to that obtained from dolomitic coarse aggregate.

Nevertheless, aggregates crushing value revealed higher differences between recycled and natural aggregates. CMA showed lower toughness (34.62%) than dolomitic aggregates (20.15%).

Two different types of natural river sand (River Sand 1 and 2) were used as fine natural aggregate in all the concrete mixtures. Both river sands showed essentially siliceous particles (quartz and felspars). Fine aggregates particle size distributions are shown in Fig. 2. River sand 1 had higher amount of particles between 0.25-2mm than River sand 2 in order to improve compactness of whole fine aggregates fraction grading size distribution. Fine ceramic aggregate (FCA) was used as replacement for both of the natural fine aggregates mentioned. As can be seen, the FCA showed higher ratios of filler and finer particles than the natural aggregates. However, the particle size distributions of the fine aggregates samples combined with 15% and 30% of FCA were adequate according to Spanish Structural concrete requirements [23].

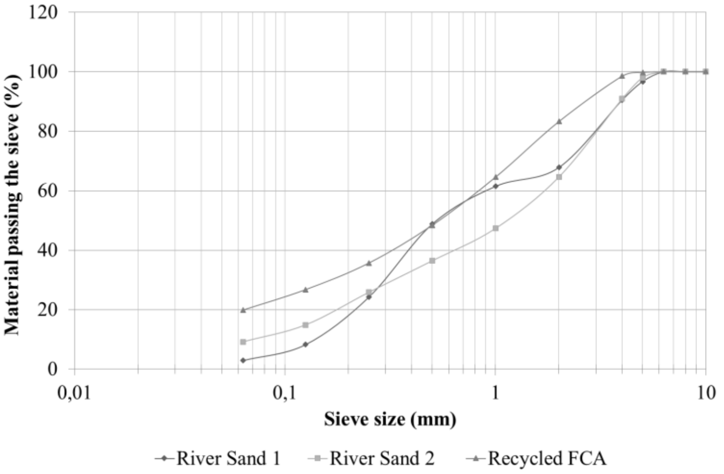

Fig. 2. Particle size distribution of fine aggregate according to ASTM.

The physical properties of the fine aggregates are shown in Table 4. The FCA showed a lower density and a higher absorption capacity than NA. FCA showed a water absorption capacity of 14.37% due to 100% ceramic material content (see Table 2). Table 4 also shows the assessment of fines results and the mechanical tests of Los Angeles and crushing value tests.

Table 4. Physical and mechanical properties of fine aggregates

Physical properties	*Oven dried particle density (Kg/dm^3)*	*Water absorption (%)*	*Absorption capacity after 10min inmersed in water (%)*	*Absorption capacity after 20min inmersed in water (%)*
River Sand 1	2.50	1.02	-	
River Sand 2	2.57	1.93	-	
FCA	2.00	14.37	86.53	100,00

In order to control the results at 1-day compressive strength and avoid its dispersions the fine natural aggregates were wetted the day before use by means of a sprinkler system. Then the fine NA were covered with a plastic sheet in order to maintain a high humidity level until their use in concrete production. The moisture content of the fine natural aggregates was fixed at 3.5-4% (oversaturated) as this would achieve a higher compressive strength at very early ages. Coarse mixed aggregates were also wetted the day before use in order to reduce their absorption capacity [24, 25]. According to Poon et al. [26] and previous research [6, 24], CMA was not saturated as that would probably result in the failure of an effective interfacial transition zone between the saturated coarse mixed aggregates and the new cement paste. CMA moisture was that corresponding to 80% of its total absorption capacity. The ceramic fine aggregate was used in dried conditions, due to its quick absorption capacity (in 20 minutes absorbed 100% of its capacity). Coarse natural aggregates were also used in dried conditions.

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. A Conventional high performance concrete (CC) was produced with natural aggregates. Coarse mixed recycled aggregate (CMA) was used in substitution of 20%, 50% and 100% (by volume) of natural coarse aggregate for the production of high performance concretes RC-20-CMA, RC-50-CMA and RC-100-CMA, respectively. Ceramic fine aggregate (FCA) was used in substitution of 15% and 30% (in volume) of natural river sands for production of RC-15-FCA and RC-30-FCA high performance concretes, respectively. Due to low density of recycled aggregates, the replacement of natural aggregates (both fine and coarse aggregates) was carried out by volume. Following previous research [6] and other authors 'procedure [7, 24], the ratio between aggregates and concrete volumes was kept constant and no modifications on cement amount were conducted.

The concrete mix proportions were defined according to the Fuller's method [27] as followed the prestressed concrete sleepers' manufacturer in the reference CC concrete production. The Fuller method is based on defining conventional concrete dosages by selecting coarse and fine aggregate proportions according to the adjustment within the standard curve that allows for the maximum compaction of granular elements, which is the method that corresponds to the Gessner parabola. This parabola is defined by the aggregate maximum size and the sieve sizes and, it permits one to calculate an ideal (theoretical) passing percentage. The percentage of each type of natural fine and coarse aggregate was corrected to achieve passing percentages similar to the passing percentages defined by the Gessner parabola in all sieve sizes. Despite the fact that FCA and CMA aggregates did not have the same size distribution as the natural aggregates, the theoretical parabola was also similar.

As shown in Table 5, 380 kg of cement and an effective water –cement ratio of 0.285 were used in all concrete productions. The effective water-cement ratio of the conventional concrete was determined (it is the ratio between the water weight, which would react with cement, and cement weight used for concrete production) and it was fixed a constant value for all concretes. The water considered which would react with cement was named effective water. In order to control the same effective water in all concretes, the moisture conditions of the aggregates were intensively controlled. The fine natural aggregates were used in oversaturation conditions (the unabsorbed water was considered as part of the effective water). The natural coarse aggregates were used in a dry condition and it was considered that they absorbed 20% of their total water capacity (which was the water absorption capacity of aggregates submerged in water up to 30 minutes). The coarse mixed aggregate was used with approximately 80% of humidity and their effective absorption capacity was that of 70%. Fine ceramic aggregate was used in dried conditions and its effective absorption capacity was that of 100%. The total water amount of the concrete was considered as the amount of effective water weight plus the moisture (or absorbed water) of the aggregates (see Table 5).

Table 5. Proportioning of the concrete mixtures. (Coded: Conventional concrete: CC; Recycled concrete mixtures, RC-x-y (x = percentage of recycled aggregate replacement level; y =type of recycled aggregate used: Fine ceramic aggregate, FCA; Coarse mixed aggregate, CMA).

Concrete reference	*River Sand 1 (kg)*	*River Sand 2 (kg)*	*River Gravel (kg)*	*Dolomitic Gravel (kg)*	*RA (kg)*	*Total Water (kg)*	*Cement (kg)*	*Effective W/C*	*Admixture (kg)*	*Slump test (mm)*
CC	711.8	215.2	302.0	784.5	---	135.4	380	0.285	5.7	0
RC-15-FCA	605.0	182.9	302.0	784.5	108.6	154.1	380	0.285	5.7	16
RC-30-FCA	498.2	150.7	302.0	784.5	217.2	166.3	380	0.285	5.7	20
RC-20-CMA	711.8	215.2	241.6	627.6	147.0	160.8	380	0.285	5.7	10
RC-50-CMA	711.8	215.2	151.0	392.2	367.4	191.3	380	0.285	5.7	14
RC-100-CMA	711.8	215.2	0.0	0.0	734.9	244.8	380	0.285	5.7	0

Dry consistency was maintained in all concrete mixtures (slump test results were between 0-20mm) and the 1.5% respect to cement weight of superplasticizer was used in all mixtures following manufacturer’s recommendations (see Table 5).

2.3. Specimens casting and curing

For each concrete mixture, 100 mm cubes were used to test the hardened concrete density, absorption, the permeable pore voids, the ultrasound pulse velocity (UPV) and capillary water absorption. Compressive strength and flexural strength tests were conducted using 150 mm cubes and 100x100x400 prisms, respectively, following the requirements of the Spanish sleepers’ technical specification [20]. Moreover, 100∅/200 mm cylinders were used to evaluate compressive strength (in order to establish correlation between different specimen dimensions), elastic modulus, splitting tensile strength and resistance to chloride-ion penetration of the concrete.

All the specimens were cast in steel moulds (except for the 150mm cubes which were cast in plastic moulds) and compacted using a vibrating table during two stages of 30 seconds duration. The concrete specimens were kept for a day in the moulds. The moulds were covered with a wet burlap and a plastic top to ensure that the temperature and wet conditions would remain stable between 18º C and 26º C with a high moisture content. Specimens were demolded 24 hours after casting. Three cubes were immediately tested after demolding to measure 1-day compressive strength. The rest of the specimens were cured in a humidity room at 23ºC and 95% humidity until the age of testing.

2.4. Tests of hardened properties of concrete

2.4.1. Physical properties

- *Density, absorption and volume of permeable pore space*

The density, absorption and voids were measured following the ASTM C 642 – 97 “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete” at 28 days. Three cube specimens were used in this test for each type of concrete produced.

2.4.2.Mechanical properties

- *Compressive, flexural, splitting tensile strengths and elastic modulus*

The compressive strength of concretes was determined using a compression machine with a loading capacity of 3000 kN. The compressive strength was measured at the ages of 1, 7 and 28 days for the cube specimens (in order to verify Spanish sleepers’ technical requirements [20]) and at the ages of 28 and 180 days for the cylinder specimens following UNE-EN 12390-3 standards. Each presented value is the average of three measurements.

The flexural strength was measured following UNE-EN 12390-5 at the age 7 days according to the Spanish sleepers’ technical requirement [20]. The splitting tensile strength and elastic modulus were tested at 28 days also following UNE-EN 12390-6 and UNE 83-316-96 specifications, respectively. Three specimens were used for each type of concrete produced.

2.4.3.Durability properties

- *Ultra-sound pulse velocity (UPV) test*

The cube specimens of size 100 x 100 x 100 mm were used for the UPV test. The average UPV values were taken from three cubes obtained from each mixture using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT). Two measurements were taken at the middle of each cube, in a perpendicular direction to that of the casting direction of the concrete. The test was done in accordance with the ASTM C 597 in a direct transmission state. All of the specimens were tested at the saturated condition, at the age of 28 days.

- *Capillary water absorption*

The concrete's capillary water absorption was assessed using 100 x 100 x 100 mm cubic specimens at 28 days after mixing and according to ISO 15148:2002(E). For sorptivity determination, the specimens were previously oven-dried at 40ºC until constant weight. Then the bottom face of the specimens was submerged in water to a depth of 5 mm (the lateral surfaces were impregnated with impermeable resin). The cumulative water absorbed was recorded at different time intervals up to 120 min by weighing the specimen after removing the surface water using a dampened tissue. Sorptivity is the slope of the regression curve of the amount of water absorbed by a unit surface area versus the square root of the elapsed time from initial instant to 120 minutes. The results of capillary water absorption are the average of three measurements.

- *Chloride ion penetrability*

The chloride penetrability of concrete was determined in accordance with ASTM C1202 (1997) using a 50 mm thick/100∅ mm concrete section cut from the middle of 100∅/200 mm concrete cylinder. The two middle sections obtained from one cylinder were tested at different ages. The external 5 mm sections of the cylindrical were rejected. The resistance of concrete to chloride ion penetration is represented by the total charge passed, in Coulombs, through a water-saturated concrete section during a test period of 6 h. In this study, the chloride ion penetrability test was carried out on the concrete specimens at the ages of 28 and 180 days, each result was the average of four measurements. Each middle section tested sourced from a different 100∅/200 mm concrete cylinders.

3. Results and discussion

3.1. Physical properties

3.1.1. Density, absorption and volume of permeable pore space

The results of absorption, dry-density and volume of permeable space (voids) are shown in Table 6. In considering the concretes made with CMA, dry-density decreased in accordance with the increase in NA substitution for CMA. The absorption and permeable pore volume of concrete made with 20% of CMA increased by 30% with respect to those of CC concrete and they increased by more than 100%when the total volume of the natural coarse aggregates were replaced by CMA. The higher absorption capacity and the higher volume of voids of CMA affected the final properties of the concretes in which they were used.

Table 6. Dry-density, absorption and voids of concrete mixtures at 28 days

Concrete reference	*Dry-density (Kg/dm^3)*	*Absorption (%)*	*Voids (%)*
CC	2.51	1.39	3.49
RC-15-FCA	2.50	1.30	3.24
RC-30-FCA	2.48	1.31	3.26
RC-20-CMA	2.43	1.88	4.55
RC-50-CMA	2.35	2.48	5.83
RC-100-CMA	2.19	3.97	8.70

However, the concrete made with FCA had slightly lower density than that of CC. The absorption and permeable pore volume of concretes made with FCA were lower than those of CC. A major quantity of filler particles in FCA leads to a better filling of pore space than conventional fine aggregate and an improvement of the durability properties [18]. The water absorbed in fine ceramic aggregates could also produce an internal curing in concretes, improving the cement hydration [28] and consequently lowering the amount of accessible pores. Similarly in light weight aggregates concrete, Cusson and Margeson [29] found that cement hydration was actually enhanced by internal curing which lead to higher C-S-H content and Elsharief et al. [30] found lower water absorption of hardened concrete when using pre-soaked light weight aggregates at 7 days of age and similar absorption at 180 days.

3.2. Mechanical properties

3.2.1. Compressive strength

The compressive strength results for the concrete mixtures are presented in Table 7. All recycled concrete mixtures obtained a higher compressive strength than that of the conventional concrete (CC) after 24 hours, except for concrete made with total replacement of coarse mixed aggregate which obtained 10% lower strength. There was a higher amount of free water within CC mixture during the first 24 hours. This was influential in the obtaining of early-age compressive strength. Nevertheless, when CMA replacement was increased to 100%, the cause of the low early-age compressive strength was found to be in the poorer quality of the aggregate. At 24 hours, the concrete produced with CMA and FCA achieved 72-74% and 61-66%, respectively, of their strength at 28 days. In contrast CC concrete achieved 56% of its 28 days strength within 24 hours. FCA concrete was able to achieve higher early-compressive strength because of its higher early absorption capacity as well as the higher specific surface of the fine aggregate. However, the remaining absorption capacity of partially saturated CMA could reduce the w/c ratio in the ITZ improving its strength at early hydration [24, 25]. The weakness and higher porosity of the aggregates was balanced by the high quality cement paste.

Table 7. Compressive strength of concrete mixtures. (*Increase (%) of compressive strength from 28 to 180 days).

Concrete reference	*Compressive strength (MPa)*				
	Cubic specimens			*Cylindrical specimens*	
	1- day	*7-days*	*28-days*	*28-days*	*180-days(*)*
CC	57.36	91.19	102.09	90.70	100.07 (10)
RC-15-FCA	72,05	89.97	109.70	97.01	108.84 (12)
RC-30-FCA	67.60	93.40	109.06	97.41	118.62 (22)
RC-20-CMA	73.85	97.39	101.60	79.61	95.61 (20)
RC-50-CMA	64.02	84.23	87.02	66.40	79.67 (20)
RC-100-CMA	52.07	66.88	72.28	53.03	69.24 (31)

Fig. 3 shows the relative compressive strength of RC with respect to CC at 28-days. It was determined that concrete made with more than 20% of CMA achieved a lower compressive strength to that of CC. This was due to the lower toughness of CMA when compared to that of the natural aggregates (CMA showed significant higher crushing aggregates value, see Table 3) as well as the influence of a higher nominal size [31] Concrete made with FCA achieved a higher compressive strength to that of CC concrete, because of the adequate compaction of the finer particles [32]. The low water-cement ratio and adequate bond strength of the FCA allowed this concrete type to show a comparable behaviour to that of conventional concrete [33]. The presence of water in the FCA allowed for the adequate hydration of the cement through internal curing a fact which could improve the cement hydration and consequently the concretes` properties [7, 9]. Poon et al. [25] suggested that recycled aggregates achieved comparatively denser ITZ than conventional aggregate concrete and improved mechanical properties. The microstructure of the improved ITZ appeared to have similarities to ITZ in lightweight aggregates concrete. Moreover, several authors found higher compressive strength results when using light weight aggregates [34–36] as internal curing agents due to better hydration of the cementitious system.

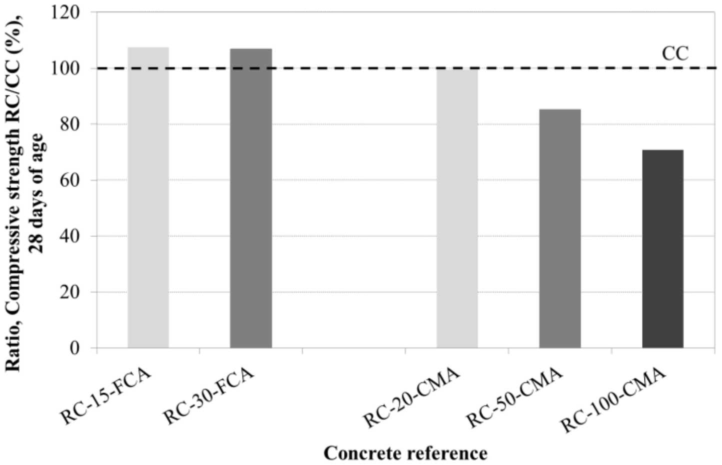

Fig. 3. Compressive strength of recycled concretes in comparison with that of conventional concrete at 28 days of age (cube specimens).

A compressive strength test was also carried out on the cylindrical specimens at 28 and 180 days (Table 7). At 28 days, concretes produced with FCA achieved almost 10% higher strength values than CC. Compressive strength results of concretes made with 15% and 30% of FCA at 180 days showed 9% and 18% higher values than that of CC, respectively. The concrete made with CMA achieved lower compressive strength than CC concrete at 28 and 180 days. However all the concretes produced with recycled aggregates showed a higher compressive strength increase from 28 to 180 days to those of CC concrete during the same period of time.

A thermogravimetric analysis was carried out on CC and FCA concrete (30% substitution for fine ceramic aggregates) at 180 days in order to assess the pozzolanic activity of fine ceramic aggregates. Thermogravimetric analysis (TGA) was conducted between temperatures of 30-1000 °C in a controlled atmosphere of N_2. Mass loss curves and the derivative in function of time were determined to assess the amounts of calcium hydroxide consumed by pozzolanic reactions. Fig. 4 shows the derivative of the mass loss as a function of time by TGA for both samples at 180 days. Physisorbed water and portlandite were assigned to those peaks located at 85 °C and 450 °C respectively. The peak at 800 °C was indicative of the presence of dolomite sourced from the natural coarse aggregates used in these concretes. The partial consumption of portlandite by pozzolanic reaction was confirmed for the fine ceramic aggregates. The small ratio variations of this compound between concretes with or without FCA replacement were indicative of the presence, although to a small extent of pozzolanic reactions. The conventional concrete showed a higher peak with a maximum of around 450 °C. It is possible to assign this higher peak to the presence of more calcium hydroxide and its none reaction to form C-S-H gel [38, 39]. The reduction in portlandite presence in FCA concretes could be due to the formation of new C-S-H gel. The FCA concrete showed a slightly denser and more resistant cement paste than that of CC, probably because the newly formed C-S-H gel filled the voids which were created during the primary cement paste hydration [39].

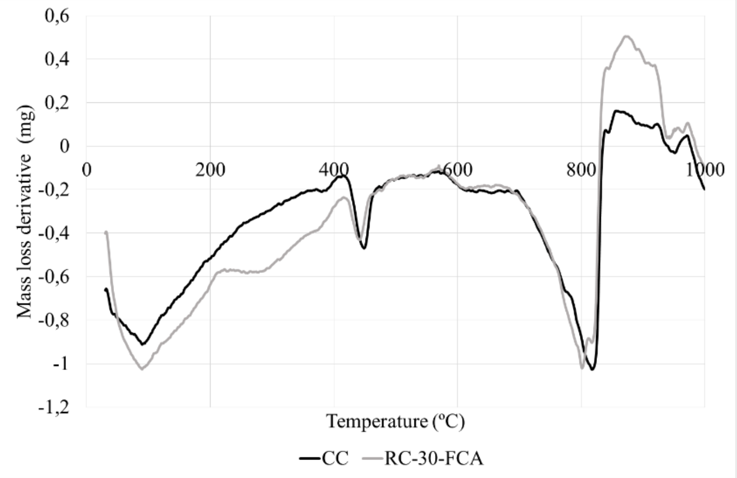

Fig. 4. Time derivative of the mass loss as a function of the increasing temperature obtained by TGA analysis of samples at 180 days.

Despite the positive effect of the pozzolanic properties of FCA, the replacement increase of CMA in concrete also meant an increase of the compressive strength evolution from 28 to 180 days of age. This relation suggests that the positive effect on the compressive strength of recycled aggregates was primary caused because of the internal curing. As these high-performance concretes require low water-cement ratios, the water storage that was created by the ceramic particles became a crucial element in achieving a proper cement hydration and lowering internal stress due to water demand which increased the compressive strength as well as reduced shrinkage effects [7].

3.2.2.Flexural, Splitting tensile strength and modulus of elasticity

Table 8 shows the flexural and splitting tensile strengths and modulus of elasticity of all the concretes. The concretes made with FCA achieved a similar or higher flexural and splitting strength to those of the CC concrete. The use of CMA on substitution of natural coarse aggregates for concrete production had a negative influence on those properties. Only the concrete made with 20% of CMA obtained similar flexural strength to that of CC. As Table 8 shows in splitting tensile strength test, the concrete made with 100% of CMA (4.23MPa) did not reach 4.5 MPa which is the minimum requirement for precast high performance concrete elements such as railway sleepers [20]. The modulus of elasticity seemed to be more influenced by recycled aggregates replacement than the other two properties. This influence is known [32]. According to Lydon and Balendran [40], the modulus of elasticity of aggregate is proportional to the square of its density. CC and FCA concrete achieved nearly 50000MPa. Despite showing lower elastic modulus values to those found in CC, all the CMA concrete mixtures showed high values, the minimum was found to be 32000 MPa corresponding to concrete produced with 100% replacement.

Table 8. Flexural strength, Tensile strength and modulus of elasticity of concrete mixtures

Concrete reference	*Flexural strength (MPa)*	*Splitting tensile strength (MPa)*	*Modulus of elasticity (MPa)*
	7-days	**28-days**	**28-days**
CC	6.47	5.13	50414
RC-15-FCA	8.31	5.14	47605
RC-30-FCA	6.55	5.25	49967
RC-20-CMA	6.94	4.61	43932
RC-50-CMA	5.50	4.50	38368
RC-100-CMA	5.25	4.23	32383

In Fig. 5, the recycled aggregate concrete results are compared with the reference CC. The concretes produced with FCA achieved similar properties to those of the CC, however as mentioned above, the coarse mixed aggregates had a negative influence on those properties. A higher replacement ratio of more than 20% of natural coarse aggregates by CMA meant a drop of up to 20% in flexural strength. The splitting tensile strength of the CMA concrete was found to drop from 10% to 20%. The use of coarse mixed aggregates with poorer physical properties accentuated the negative effect in elastic modulus, as exposed by Lydon and Balendran [40]. The concrete made with 100% of CMA suffered a decrease of 35% with respect to that of CC.

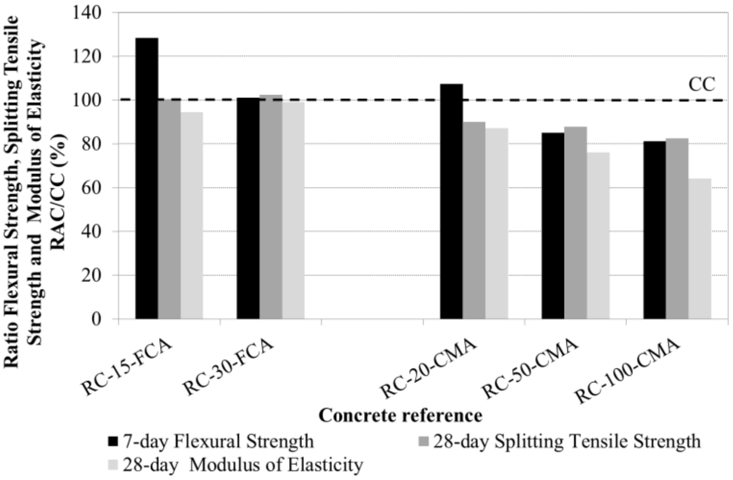

Fig. 5. Flexural strength (7 days of age), Splitting tensile strength and Modulus of elasticity (28 days of age) of recycled concretes mixtures compared to that of conventional concrete.

3.3. Durability properties

3.3.1. Ultrasonic Pulse Velocity (UPV) test

The UPV results of the conventional concrete and recycled concretes can be seen in Table 9. The conventional concrete mixture showed the highest UPV results. Some research works [41, 42] showed that UPV values decreased as the level of natural aggregates replacement for RA increased.

Table 9. UPV and sorptivity results of concrete mixtures

	UPV (m/s)	*Sorptivity (mm/min$^{1/2}$)*	
Concrete reference	**28 days**	**28 days**	**180 days**
CC	5438	0.014	0.008
RC-15-FCA	5293	0.015	0.009
RC-30-FCA	5205	0.016	0.011
RC-20-CMA	5116	0.021	0.011
RC-50-CMA	4754	0.026	0.023
RC-100-CMA	4417	0.036	0.025

All UPV concrete values exceeded 4500 m/s and were classified in the range of excellent values, excepting when 100% of NA was replaced by coarse mixed aggregate, according to the UPV values proposed by some authors such as Whitehurst [43] whose research determined the quality of concretes with a density of 2400 kg/m^3. The increase of the replacement of natural aggregates for coarse mixed aggregates triggered off an increase of pore spaces that affected the transmission of ultrasonic waves. The replacement of 100% of natural coarse aggregates by CMA produced 20% reduction of UPV, even so, Whitehurst [43] defined that value as good quality concrete.

The relation of the UPV with the permeable pore volume and the compressive strength of all specimens were analysed. The UPV of the concretes made with CMA showed a direct and linear relationship with compressive strength and permeable pore volumes (see Fig. 6). The low density of CMA and the percentage used of CMA in concrete production affected the strength and permeable pore volume of CMA concretes. The lower amount of CMA used, the higher the UPV and the higher the strength achieved. These results are consistent with other several studies conducted on recycled aggregate concretes [41, 44, 45].

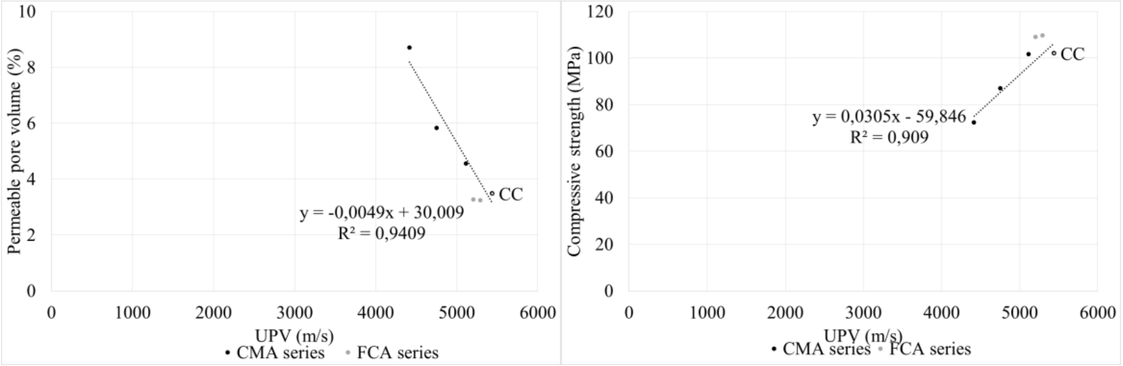

Fig. 6. UPV relationship with Permeable pore volumes and Compressive strength.

However FCA concretes did not follow the correlation established by CMA and conventional concrete. The UPV of concretes made with FCA was lower than that of CC concrete, although the FCA concretes showed lower permeable pore spaces (see Table 6), a higher presence of non-accessible pores could explain the lower ultrasonic pulse velocity, as a result of a better sealing of the particles due to an adequate ITZ surrounding the FCA [24, 25] and internal curing producing denser cement paste [9, 28]. The FCA aggregates showed similar behaviour to those from lightweight aggregates (LWA) found by other authors [34–36]. According to Espinoza and Lopez [35], concretes produced with saturated LWA improve the cement hydration by internal curing resulting in higher C-S-H content which lead to higher compressive strength at 28 days. Elsharief et al. [30] found similar or lower water absorption of hardened concrete when pre-soaked porous light weight aggregates were used than that to CC.

3.3.2.Capillary water absorption

The results of assessing the concrete specimens' capillary water absorption over a period of 2 hours are shown in Fig. 7. Conventional concrete and concrete made with FCA showed similar behaviour during the test. In this study, as a result of a very low water-cement ratio, the increased water amount (by weight) on the CC and FCA concrete specimens was lower than 0.06% for the first 30 minutes (with respect to the dry weight of the specimens). After 2 hours, the weight of the CC and FCA concrete specimens increased approximately by 0.05% of the initial weight, the behaviour of those concretes could be considered similar and adequate. Nevertheless, the capillary absorption of concretes made with CMA showed much higher values than those of FCA or CC concretes, this was probably due to connectivity of the porous in each grain of the coarse mixed aggregate; this has also been reported by other researchers [46–48].

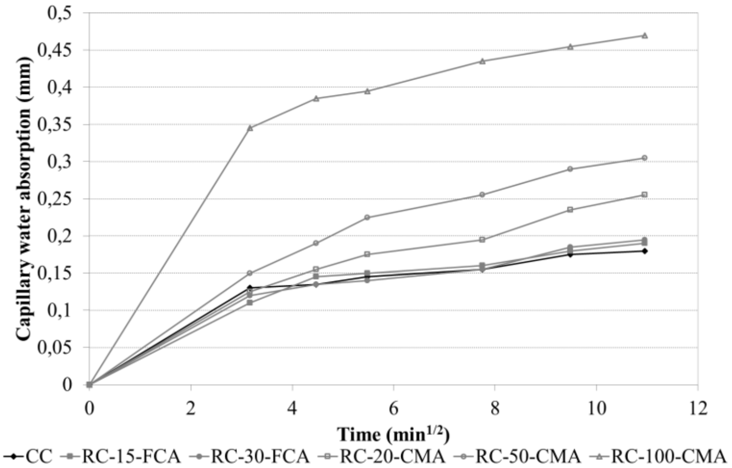

Fig. 7. Capillary water absorption of concrete mixtures at 28 days.

The sorptivity values of CC and concrete made with FCA were approximately 0.015±0.001 (see Table 9), very low values due to the low water-cement ratio. These values were very similar to those found in a previous research on High Performance Concrete using high quality recycled coarse concrete aggregates [6]. When the CMA aggregate was used for concrete production, sorptivity values increased to 0,021-0.036 mm/min$^{1/2}$. Higher values were obtained through a higher replacement of natural aggregates for CMA. Sorptivity values obtained in the first 2 h can be correlated with concrete w/c ratios. According to Neville [33], values of 0.09 mm/min$^{1/2}$ and 0.17 mm/min$^{1/2}$ correspond to concretes with w/c of 0.4 and 0.6, respectively. Zhutovsky [28] found sorptivity values between 0.06-0.1 for high performance concrete up to 0.33 w/c ratios. It could be affirmed that the quality of the cement paste and the water/cement ratio had more influence on the sorptivity values than the replacement of the recycled aggregates. The concrete made with FCA achieved similar sorptivity values to CC probably because FCA finer particles filled pore spaces which the natural sand was not physically capable of sealing. The discontinuity of the porous, due to homogeneous distribution of sand grains through cement paste had little influence on this property.

3.3.3.Chloride-ion penetration

The results of assessing the chloride-ion penetration of concrete specimens are shown in Fig. 8. It shows that the resistance to chloride ion penetration, at the age of 28days, decreased as the recycled aggregate content increased. The results could be classified according to the ASTM C1202 (1997) corrosion ranges between very low and low risk of corrosion.

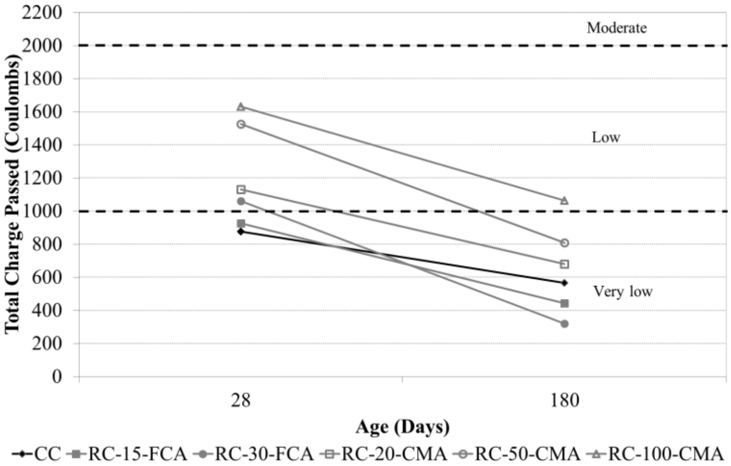

Fig. 8. Chloride-ion penetration of concrete mixtures and ASTM corrosion ranges.

As shown in Fig. 8, at the age of 28 days, the conventional concrete achieved the highest resistance to chloride penetration and it was classified as having a very low risk to corrosion. A similar level of risk was obtained from concrete made with 15 % of FCA. The concrete made with 30% of FCA and all the concretes produced with CMA achieved low risk to corrosion levels.

At the age of 180 days, the concrete mixtures produced with FCA showed the highest resistances to chloride penetration. The reduction of the total charge passed in the CC concrete from 28 days to 180 days was that of 35% (with respect to the data at 28 days), however the reduction of total charge in concrete RC-15-FCA and RC-30-FCA was that of 52% and 70% respectively. The RC-20-CMA, RC-50-CMA, RC-100-CMA was that of 40, 47 and 35%, respectively.

All concretes, except concrete made with 100% of CMA, achieved very low corrosion risk level after 180 days of curing. The concrete produced with FCA achieved the highest increase of resistance to chloride penetration. This was probably due to an adequate internal curing process and some pozzolanic effect. Highly hydrated cement paste produced a dense mortar, which was quite impermeable. Zhutovsky [28] obtained improvement of chloride penetration resistance in concretes when the concretes were produced with low percentages of fine lightweight aggregates in substitution for those of natural aggregates. The lightweight aggregates produced an internal curing which improved the cement hydration. That effect did not appear in the capillary water absorption test, as also confirmed in this research work.

However the effect was also seen to be present in concretes made with CMA, the concrete made with 50% of CMA achieved a considerable increase in its resistance to chloride penetration, probably through an adequate internal curing process.

4. Conclusions

The following conclusions can be made based on the results of this study:

- *According to High Performance Concrete produced with Fine Ceramic Aggregates in substitution of natural fine aggregates:*

The ceramic fine aggregates are more porous than natural aggregates and consequently the density of concrete decreases when 30% of ceramic fine aggregates are used. Nevertheless, the permeable pore volume and water absorption of concretes made with ceramic aggregates also decrease.

The mechanical properties of these recycled concretes were similar to those of the high performance conventional concrete. The mechanical properties of concrete made with 30% of fine ceramic aggregates can also be higher than those of conventional concrete. In the case of FCA concrete, the increase of compressive strength from 28 to 180 days is also higher to that of conventional concrete. This is due to a more adequate cement hydration which is caused by both the ceramic particle effect, pozzolanic reactions and internal curing.

The FCA concretes showed very similar durability properties to those found in conventional concrete. The capillary absorption capacity of concrete made with higher percentages of ceramic fine aggregates is a little higher than that of high performance conventional concrete. However, the chloride-ion penetration, after 180 days, was lower in concretes made with ceramic fine aggregates. UPV test should be carefully used because non-direct relationship with permeable pores and compressive strength was found when using FCA.

One can affirm that concrete produced with up to 30% of fine ceramic aggregates achieved similar or improved properties to those of High Performance conventional Concrete, from the mechanical and durability point of view.

- *According to High Performance Concrete produced with Coarse Mixed Aggregates in substitution of natural coarse aggregates:*

The coarse mixed aggregates had a higher absorption capacity and volume of voids, which significantly affected the final physical properties of the concrete.

The mechanical properties of the recycled concretes were lower than those of the High Performance conventional concrete. Concrete made with up to 20% of recycled coarse mixed aggregates achieved similar compressive strength to that of High Performance conventional Concrete of 100 MPa.

The capillary absorption capacity is the most affected durability property of CMA concretes, the reason being the high percentages of accessible pores within the coarse mixed aggregates.

However the concretes made with up to 50% of coarse mixed recycled aggregates achieved adequate durability properties.

Acknowledge

The authors wish to acknowledge the financial support of The Ministry of Economy and Competitiveness by INNPACT project (IPT-2011-1655-370000) and the support of Vias y Construcciones S.A, and Drace Infraestructuras enterprises.

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Paper III

Influence of steam curing on the pore structures and mechanical properties of fly-ash High Performance Concrete prepared with recycled aggregates

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Submitted to *Cement and concrete Composites* (2014 Impact factor: 3.3; Q1)

Influence of steam curing on the pore structures and mechanical properties of fly-ash High Performance Concrete prepared with recycled aggregates

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Abstract

In this research work, High Performance Concrete (HPC) was produced employing 30% of fly ash and 70% of Portland cement as binder materials. Three types of coarse recycled concrete aggregates (RCA) sourced from medium to high strength concretes were employed as 100% replacement of natural aggregates for recycled aggregate concrete (RAC) production. The specimens of four types of concretes (natural aggregate concrete (NAC) and three RACs) were subjected to initial steam curing besides the conventional curing process. The use of high quality RCA (>100MPa) in HPC produced RAC with similar or improved pore structures, compressive and splitting tensile strengths, and modulus of elasticity to those of NAC. It was determined that the mechanical and physical behaviour of HPC decreased with the reduction of RCA quality. Nonetheless steam-cured RACs had greater reductions of porosity up to 90 days than NAC, which led to lower capillary pore volume.

Keywords: *Recycled aggregate concrete; high performance concrete; steam curing; compressive strength; porosity; MIP.*

1. Introduction

Construction and demolition waste (C&DW) is one of the most voluminous and heaviest waste streams generated in the European Union. C&DW accounts for approximately 33% of all waste generated in the EU [1] and it consists of several materials, including concrete, bricks, gypsum or metals, many of which can be recycled. European Union countries encourage reusing and recycling in construction by publishing C&DW recycling targets. According to the Waste framework Directive 2008/98/EC [2], the minimum recycling percentage of C&DW by the year 2020 should be at least 70% by weight. In spite of the variability on recycled aggregate properties, proper treatment and categorization of the C&DW allow recycled aggregates to be more efficiently employed [3].

Over the past twenty years, many studies concerning the effects of using recycled coarse aggregates as a replacement of natural aggregates in concrete have been published [3–8]. Generally, recycled aggregates have higher porosity, water absorption capacity and contaminant content and also lower density and abrasion or impact resistance than natural aggregates. The use of RCA for the production of low and medium strength concretes (up to 50-60 MPa according to ACI [9] and BS EN 206-1) decreases the compressive strength and modulus of elasticity of the concrete. Recycled aggregate concretes show increased shrinkage, creep and water sorptivity in comparison with those of natural aggregate concrete (NAC). Nevertheless, the use of appropriate mix design methods with the addition of mineral admixtures can mitigate the negative influence of recycled aggregates [10,11].

But relatively few investigations [11–18] have been published about using recycled aggregates for High Performance Concrete (HPC) production. Some studies [11,14,18] revealed that the quality of the parent concrete, from which source the recycled aggregates are derived, is a crucial factor affecting the properties of the resulting HPC produced. It has been reported that the use of RCA, sourced from crushing original HPC, for the production of new HPC can improve mechanical and durability properties even at high replacing ratios [14]. Limbachiya [13] concluded that only 30% of coarse RCA could be used to produce HPC. Tu et al. [16] and Pacheco-Torgal et al. [17] affirmed that recycled aggregates were not suitable for high strength concrete applications due to compressive strength reduction and poorer long-term durability.

Recycled concrete aggregates have a residual binding ability which is apparently activated by using Fly-Ash (FA). Especially, the RCA sourced from HPC, which is normally prepared with a higher amount of cement, enhance binding effects of pozzolanic mineral admixtures by providing higher Portlandite content [14]. Fly ash represents a beneficial mineral admixture for concrete due to the formation of a denser cementitious matrix due to the formation of new CSH gel by the pozzolanic reaction. The use of fly ash has been widely accepted in recent years and its influence on many properties of concrete in both fresh and hardened states have been studied [19–22]. Equally, fly ash ensures economic benefits through saving cement, environmental benefits by using industrial wastes, and technical improvements because of the higher concrete durability [20]. Certain authors [19,22] attempted to produce concrete with high volumes of fly ash, but the most common replacement ratios used in low water/binder ratio concretes are 25-30% [23,24]. On the whole, the long term mechanical and durability properties of fly ash concretes are higher than those of ordinary Portland cement concretes. However, the extended hydration period required for fly ash concrete intensifies dependence on curing conditions. Moreover, for fly ash concrete, at early ages, the heat generation is reduced but the setting and hardening time are increased.

Steam curing at ambient pressure is the most common technique among the accelerated curing methods of concrete. In applications, such as pre-cast concretes and pre-stressed reinforced concretes, which require high mechanical performances at very early ages, the steam curing enables concretes which normally have slower strength gain, such as fly ash concretes, to achieve faster strength gain at the required levels [19]. A typical steam curing cycle consists of a pre-curing treatment of up to 4 hours and a heating and cooling rate of 10-45ºC/h. The maximum temperature reached in steam curing is usually limited to 60±5ºC and this temperature is kept constant at the maximum value for 6-18h [19–21,24,25].

When concrete is subjected to steam curing, the hydration of cement proceeds quickly, the speed of CSH gel formation also increases and the gel wraps round the cement or fly ash particles [20]. The acceleration of compressive strength gain eases the production of pre-cast and pre-stressed concrete elements in the pre-casting plants. The required early compressive strength for formworks demolding and bar stress transmission is in general at more than 30 and 50 MPa respectively [25,26]. Nevertheless, heat and moisture treatment of the concrete also increases the proportion of large pores in the cement paste [27]. Inadequate steam curing regimes can lead to detrimental changes in porosity and pore size distribution of concrete which can significantly reduce mechanical and durability properties, especially over the long term [24].

The total pore volume, pore size distribution and pore interconnection are the main properties influencing the mechanical and durability behaviour of concretes. Several investigations [28,29] have inferred that the mechanical properties and permeability of concrete are principally dependent on the meso and macrocapillary pores. Porous structures in cementitious materials have been widely investigated by using the Mercury Intrusion Porosimetry (MIP) technique [24,30–32]. Nevertheless, this technique has been criticized due to the fact that the pore structures characterized by the MIP method are based on improper assumptions. These assumptions on pore connectivity and pore dimensions can produce differences in the measured MIP values to those of the real pore network [32]. Besides these limitations, MIP is still considered as an appropriate technique used to compare the pore structures of cementitious systems.

This paper details research on the influence of initial steam curing on the pore structures and mechanical properties (compressive strength, splitting tensile strength and modulus of elasticity) of Portland-Fly Ash HPCs containing recycled concrete aggregates. Three different qualities of original concretes (40, 60 and 100MPa of characteristic compressive strength) were crushed to obtain coarse recycled aggregates which were used to replace 100% of the natural coarse aggregates. After concrete casting, the specimens of each type of concrete were exposed for the first 24 hours to two different initial curing regimes, air curing and steam curing, in order to assess the influence of steam curing on the pore structures and the mechanical behaviour.

2. Experimental details

2.1. Materials

2.1.1.Binders and admixture

The cement used was a commercially available Portland cement (CEM I 52.5R) equivalent to ASTM Type I cement. The Portland cement had a specific surface of 4947.8 cm^2/g and a density of 3.15 g/cm^3. A rapid-hardening Portland cement was used in order to achieve concretes of 1-day compressive strength higher than 50 MPa, thus meeting the requirements for precast and prestressed concrete [25,26]. The FA used, with a specific surface of 3360.0 cm^2/g and a density of 2.32 g/cm^3, was equivalent to ASTM class F. The chemical compositions of the Portland cement and the FA are given in Table 1.

Table 1. Chemical compositions of binders.

Composition (%)	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*CaO*	*MgO*	*K_2O*	*TiO_2*	*P_2O_5*	*Na_2O*	*LOI*
Cement	21.91	3.57	4.67	64.98	1.45	0.57	0.18	0.18	0.12	1.05
Fly Ash	55.46	26.94	5.86	5.70	1.50	1.51	1.41	0.83	0.62	3.70

A high performance superplasticizer based on polycarboxylate ether (PCE) with a specific gravity of 1.08 was used for concrete production. The dosage used was at a constant percentage of binder weight (1.5%) following the manufacturer's recommendations.

2.1.2.Aggregates

Two types of 4-10 mm coarse natural aggregates (rounded siliceous and crushed dolomitic) and two siliceous river sands (size fractions of 0-2 mm and 0-4 mm) were used for the production of the natural aggregate concrete (NAC). The natural aggregates were those used in previous research [18] and selected for being those used in HPC to produce commercially-available prestressed concrete elements from a Spanish factory.

The recycled aggregates, RCA100, RCA60 and RCA40, which were used in complete replacement by volume of the natural coarse aggregates, were obtained from crushing three parent concretes of different qualities (of 100, 60 and 40MPa of characteristic compressive strength). The three recycled aggregates mentioned were employed in a previous research [18] with maximum sizes of 10 mm. The RCA100 were sourced from rejected 100 MPa compressive strength concrete specimens obtained from the same Spanish prestressed concrete manufacturer. The parent concrete used to produce RCA100 was the same as the NAC of this study. The 60 MPa parent concrete was especially produced in the laboratory to achieve 60 MPa at 28 days, after which it was crushed for RCA60 production and stored for a minimum of 180 days before using in concrete fabrication. The RCA40 were sourced from crushing 3-year old precast beams with a compressive strength of 40MPa at 28 days. The parent concretes of 60 MPa and 40 MPa were composed of crushed fine (0-4 mm) and coarse limestone aggregates (4-10 mm and 10-20 mm) and Ordinary Portland cement (CEM I 42.5, type I according to ASTM specifications).

The particle size distributions are shown in Fig. 1 and their physical properties are shown in Table 2. The natural aggregate had better physical properties than those of the recycled concrete aggregates. Nonetheless, the physical and mechanical properties of the RCA improve as the original concrete quality increases.

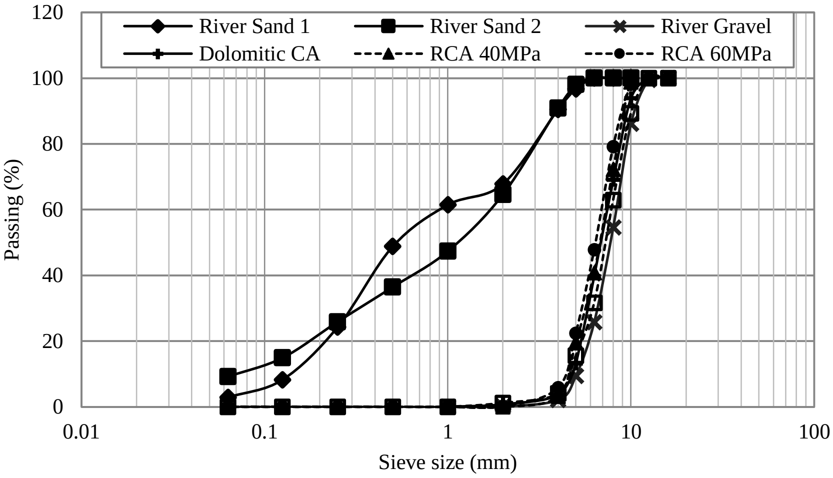

Fig. 1. Particle size distributions of fine and coarse aggregates.

Table 2. Physical and mechanical properties of coarse and fine aggregates.

Physical and mechanical properties	*Dried particle density (kg/dm^3)*	*Water absorption (%)*	*Flakiness index (%)*	*Crushing value (%)*	*LA Index (%)*	*Sand equivalent test (%)*	*MIP Porosity (%)*
River Gravel	2.61	1.29	17.71	18.92	19.61	-	-
Dolomitic Coarse Aggregate	2.68	2.13	7.81	20.15	24.77	-	-
RCA100	2.47	3.74	16.53	22.59	24.01	-	4.88
RCA60	2.39	4.90	13.57	23.36	25.24	-	5.73
RCA40	2.30	5.91	9.59	25.55	24.31	-	8.63
River Sand 1	2.50	1.02	-	-	-	87.88	-
River Sand 2	2.57	1.93	-	-	-	75.00	-

According to Jennings [29], pore structure is the most important feature which may act as flaws in cement based materials. The porosity of recycled aggregates was determined by Mecury Intrusion Porosimetry (MIP) using a ‘Micromeritics Poresizer 9320’ in samples taken from the RCAs of approximately a total weight of 5.5 g. Each mean value was calculated from testing three RCA samples and each sample was composed by three Ø 1 cm RCA particles. The pore size diameter can be divided into four pore size ranges, following Mindess [33] classification; >10μm (air), 10-0.05 μm (macropores), 0.05-0.01μm (mesopores) and <0.01μm (micropores). As can be seen in Fig. 2, some differences in the range of 0.01 to 10 μm were found, RCA-60 showed the lowest percentage of pore volumes in the range of 0.05-10 μm, while RCA-100 contained the lowest percentage of pore volumes of smaller than 0.05 μm. RCA-40 showed significantly higher pore volumes than those RCA-100 and RCA-60 at all the pore size ranges. The total porosity results from MIP of RCA were 4.88-8.63% (see Table 2), detailing standard deviations of 0.25-0.40%. The reduction on the quality of the parent concrete led to higher total porosity of the RCAs.

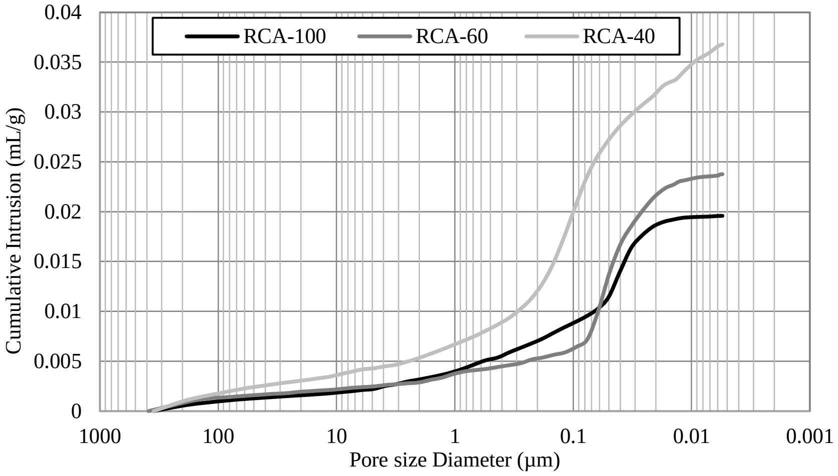

Fig. 2. Distribution of pore diameters of recycled concrete aggregates.

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. The NAC proportioning was provided by a Spanish HPC manufacturer and followed the Fuller's dosage method [34]. Following previous research [12,18], the three types of recycled coarse aggregate were used to substitute (by volume) 100% of the natural aggregates in each RAC series (RAC were referenced as 100, 60 and 40, according to the strength of the parent concrete). The concrete proportioning parabola correctly fitted the Gessner parabola provided by the Fuller's method in both cases, when using NA and RCA.

The moisture content of the fine and coarse aggregates was reproduced following the moisture conditions defined in previous studies [12,18]. The fine aggregates were over-saturated (3-4% of moisture content). In order to control the concrete production, the recycled coarse aggregates were nearly saturated, at 80-90 % of their water absorption capacity. In general the higher water absorption of the RCAs reduces the workability of the concrete mixtures, however in this case the moisture content in the RCAs neutralized such effect. In addition, the high moisture states enabled higher control on the reacting water with the binder and avoided problems derived from water on the RCAs surface or bleeding [35].

As shown in Table 3, 380 kg of binder (266 kg of cement and 114 kg of fly ash) and a constant effective water - binder ratio of 0.285 were used in all concrete productions (considering as being effective water that water which reacted with the binder). The volume of mixing water was determined before concrete production, in order to maintain the water amount reacting with the binders constant (effective water). The volume of mixing water was compose of the effective water and the water absorbed by the aggregates at concrete production (effective absorption capacity). The effective absorption capacity of aggregates was determined by submerging the aggregates in water for 20 minutes.

Table 3. Proportioning of the concrete mixtures (Coded: Natural Aggregate Concrete: NAC; Recycled Aggregate Concrete mixtures, RAC-x-y (x = compressive strength of original concretes reused as aggregates, 100, 60 or 40MPa; y =: initial curing method, air curing (AC) or steam curing (SC)) and the results from the slump cone test.

Concrete reference	*Cement (kg)*	*Fly Ash (kg)*	*Admixture (kg)*	*River Sand 1 (kg)*	*River Sand 2 (kg)*	*River Gravel (kg)*	*Dolomitic Coarse Aggregate (kg)*	*Recycled Concrete Aggregate (kg)*	*Total Water (kg)*	*Effective W/B*	*Slump (mm)*
NAC-(AC/SC)	266	114	5.7	711.8	182.5	302.1	784.5	---	135.4	0.285	16
RAC-100-(AC/SC)	266	114	5.7	711.8	182.5	---	---	1010.2	162.3	0.285	10
RAC-60-(AC/SC)	266	114	5.7	711.8	182.5	---	---	975.1	170.4	0.285	11
RAC-40-(AC/SC)	266	114	5.7	711.8	182.5	---	---	938.8	175.3	0.285	20

The total water amount of the concrete was considered as the total amount of effective water, effective absorption capacity of aggregates and moisture water (water inside the aggregates) [36]. The total water amount in the RAC studied was found to be higher as a result of its higher absorption capacity which initially provided the same cement paste conditions to NAC and RAC.

The amount of chemical admixture added was kept constant at 1.5% of the cement weight in all concrete mixtures. The mix proportioning and the admixture amount produced dry consistencies of fresh concrete, between 0-20 mm in the concrete slump test (S1 class following the EN 206-1:2000 standard).

2.3. Specimens casting and curing

For each concrete mixture, 100 mm cubic specimens were used to determine the compressive strength at the age of 1, 28 and 90 days and 200 x Ø100 mm cylindrical specimens were used for the splitting tensile strength and the modulus of elasticity tested at 28 days. Samples extracted from 100mm concrete cubic specimens were used for the Mercury Intrusion Porosimetry (MIP) test. The specimens were compacted using a vibrating table during two stages of 30 seconds each.

The concrete specimens were divided into two series, air-cured (AC) and steam-cured (SC). The air-cured specimens were stored in the laboratory at ambient conditions for 24 hours. A wet burlap and a plastic sheet being used to cover the specimens to ensure a reduction in water evaporation. The other concrete series was cured in a steam bath 4 hrs after casting (without demolding). Both the steam curing temperature and its duration have important effects on the progress of the hydration reaction and product formation [36]. The steam curing cycle used, which followed the method of Poon and Kou [37] and Ramezanianpour et al. [25], is shown in Fig. 3. After the initial curing stage of 24 hours, the specimens from both series were demolded and three cubes of each series were tested for the 1-day compressive strength. The rest of the specimens were further cured in a curing chamber at constant conditions of 23ºC and 95% humidity until the other test ages were reached.

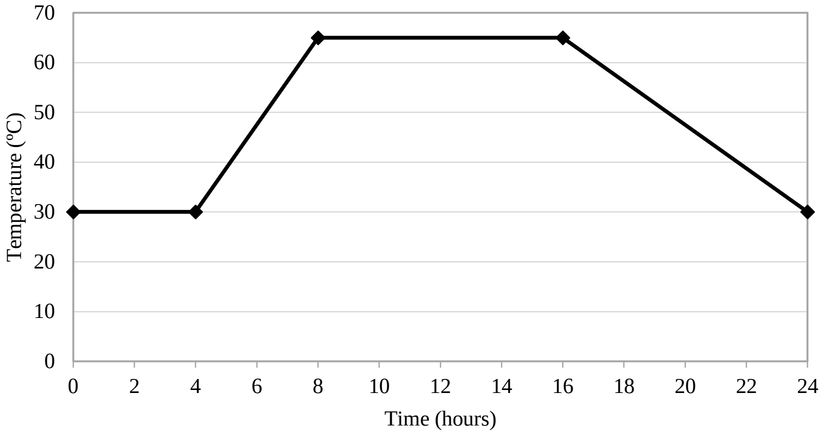

Fig. 3. One-day steam curing cycle.

2.4. Tests of hardened properties of concrete

The compressive strength and the porosity and pore size distribution analysis were determined at the ages 1, 28 and 90 days after the concrete casting. The splitting tensile strength and the modulus of elasticity were tested at the age of 28 days.

2.4.1.Pore structure

The testing of porosity and pore structure was performed by Mercury Intrusion Porosimetry (MIP) with a 'Micromeritics Poresizer 9320' mercury intrusion porosimeter according to BS7591 Part 1. This test was carried out on small concrete pieces, weighing approximately 5.5 g. The crushed samples were obtained from the 100 x 100 x 100 mm cubic specimens. The samples were first immersed in acetone for 4 days to stop the cement hydration and then introduced in a vacuum drier for 2 hours to extract the remaining acetone. Before testing, the samples were dried in an oven at 50ºC for 4 days. Using the MIP technique, a measure of the total porosity of the sample as well as the surface area of the pore network was also obtained. The MIP test was conducted on the concrete samples cured at ages 1, 28 and 90 days and each result represents the average of three tested samples.

2.4.2.Compressive strength, splitting tensile strength and modulus of elasticity

The mechanical properties of concretes were determined using a compression machine with a loading capacity of 3000 kN. The compressive strength was measured using 100 mm cubic specimens following the UNE-EN 12390-3. The splitting tensile strength and the modulus of elasticity were tested at 28 days employing 200 x Ø100 mm cylindrical specimens in accordance with UNE-EN 12390-6 and UNE 83-316-96 specifications, respectively. Each presented value is the average value taken from 3 specimens.

3. Results and discussion

3.1. Pore structure

The porosity, average pore diameter and threshold diameter obtained by the MIP test at the ages of 1, 28 and 90 days are presented in Table 4. The standard deviations were lower than 5% in most of the concretes mixtures. The variability of results between NAC and RACs was similar, however the steam cured concretes' results showed slightly higher variability than those of conventional air curing.

Table 4. Mercury Intrusion Porosimetry tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Mix notation		***Air cured mixtures***				***Steam cured mixtures***			
		NAC-AC	**RAC-100-AC**	**RAC-60-AC**	**RAC-40-AC**	**NAC-SC**	**RAC-100-SC**	**RAC-60-SC**	**RAC-40-SC**
Total Porosity (%)	**1 day**	8.58	7.54	9.36	11.81	7.27	7.36	7.74	10.45
		(0.11)	(0.10)	(0.08)	(0.07)	(0.13)	(0.54)	(0.32)	(0.24)
	28 days	4.88	4.85	6.270	8.170	5.810	6.02	6.63	8.85
		(0.38)	(0.22)	(0.15)	(0.2)	(0.56)	(0.55)	(0.53)	(0.45)
	90 days	6.46	5.60	7.540	8.690	5.160	4.71	5.69	6.24
		(0.09)	(0.11)	(0.01)	(0.43)	(0.46)	(0.19)	(0.24)	(0.36)
Average pore diameter (µm)	**1 day**	0.05	0.04	0.054	0.063	0.046	0.04	0.04	0.06
		(0.004)	(0.004)	(0.002)	(0.001)	(0.001)	(0.003)	(0.003)	(0.002)
	28 days	0.04	0.04	0.040	0.044	0.028	0.03	0.03	0.04
		(0.002)	(0.003)	(0.002)	(0.001)	(0.002)	(0.003)	(0.002)	(0.000)
	90 days	0.028	0.022	0.035	0.034	0.026	0.023	0.027	0.029
		(0.000)	(0.000)	(0.001)	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)
Threshold pore diameter (µm)	**1 day**	111.78	116.98	113.65	218.01	103.95	109.65	113.66	180.04
		(2.17)	(5.80)	(4.69)	(8.35)	(1.32)	(5.06)	(1.96)	(4.45)
	28 days	54.48	74.51	91.88	180.13	62.46	68.57	93.62	113.65
		(2.39)	(4.78)	(6.89)	(10.75)	(0.89)	(1.08)	(1.26)	(7.43)
	90 days	48.01	36.58	86.53	104.89	38.35	36.7	83.18	91.9
		(0.55)	(2.85)	(1.50)	(9.56)	(3.02)	(2.76)	(8.06)	(7.37)

Fig. 4 shows the cumulative mercury intrusion volume after 1, 28 and 90 days of curing employing both curing methods (AC and SC). The pore size distributions of all the samples followed a similar pattern, each curve having three distinct regions: one with a gentle increase of pore volume of pore sizes of up to 0.1 µm; the second within the pore size range between 0.1-0.01 with a significant increase in pore volume; and the last being between pore size of 0.01–0.005 µm with a gentle slope. The majority of the intrusion volume in the first range is due to macropores and macrocracks and the filling of the non-wetting liquid (mercury) into the rough texture of the exterior surface of the crushed sample [30,38]. The majority of the intrusion in the second range is due to capillary pores and the last one due to some parts of gel pores [33].

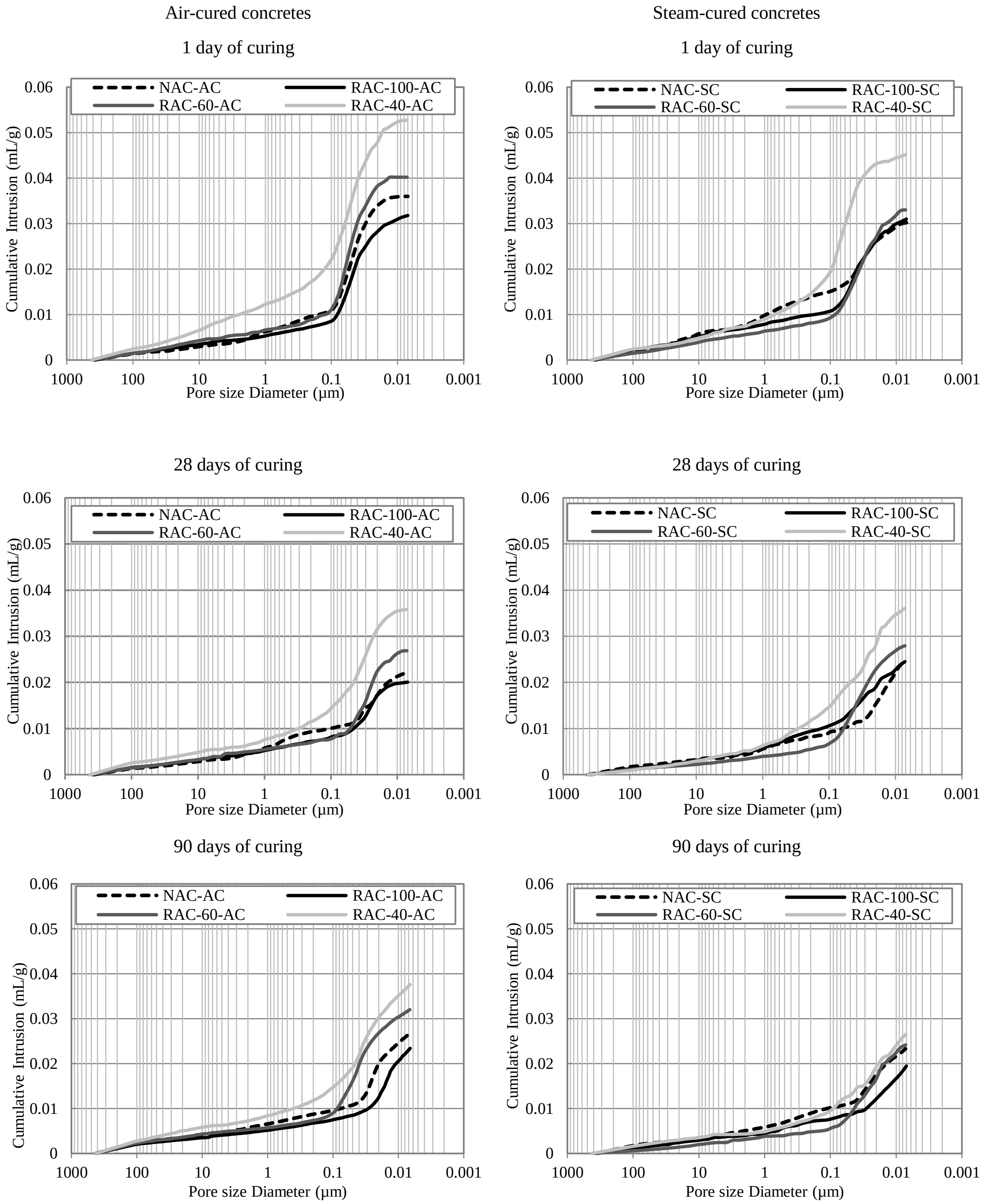

Fig. 4. Pore size cumulative distribution of initially air-cured concretes (left) and initially steam-cured concretes (right) at the ages of 1, 28 and 90 days.

3.1.1. Effect of original quality of RCA on pore structure

After 1 day of curing, the RAC-100 had significant lower average pore diameters than those of the NAC, in both curing methods. Likewise Fig. 4a show that the RAC-100-AC had slightly lower cumulative intrusion (pore volume) at any pore size than the NAC-AC. In steam curing concretes (Fig. 4b), the RAC-100-SC and the RAC-60-SC had finer pore distributions from 1 to 0.05 µm, but the total cumulative intrusions were similar to those of the NAC-SC.

The porosity reduction observed in RAC, containing recycled aggregates sourced from high quality parent concrete (> 60 MPa), when compared to the results of the NAC can be explained by an ITZ improvement. Such early-age improvements in recycled aggregate concretes were attributed by Poon et al. [39] to the reduction of the water-cement ratio in the ITZ at early hydration, a similar behaviour pattern also observed in lightweight aggregates[40,41]. The partially saturated aggregates absorb a certain amount of water, lowering the w-c ratio in the ITZ at early age, and the newly formed hydrates gradually fill the pores in the ITZ.

Nevertheless the RAC-40 concretes had the highest pore volume at all pore sizes. The RAC-40-AC and the RAC-40-SC had total intrusions of 0.053 and 0.048 mL/g, respectively and capillary pore intrusions (between 10-0.01 µm) of 0.046 and 0.042 mL/g, respectively. Park et al. [42] and Igarashi et al. [28] measured the total pore intrusion of cement pastes and capillary pore intrusion of concretes, respectively, using OPC also at early ages (1 day) by the MIP method. According to their results, the total porosity of OPC mixtures with a low water/cement ratio was approximately 0.080 mL/g [42] and the capillary pore volume was in the region of 0.100 mL/g at 24 h [28]. The early-age total pore volume and the capillary pore volume of all the concretes produced in this study, even those RAC containing the RCA-40MPa, were lower than those reported by Park et al. [42] and Igarashi et al. [28] due to the refinement of the porous structure on account of the 30% fly ash replacement of rapid-hardening Portland cement [43,44].

At 28 and 90 days of curing, the RAC-100 generally had similar or lower average pore diameters and threshold pore diameters to those of the NAC at 28 and 90 days of curing (for both curing methods). The pore size distributions of the RAC-100 at 28 days of curing were lower than those of the NAC in all pore sizes (see Fig. 4c) for air-cured concretes. The NAC-SC and the RAC-100-SC also showed similar pore volumes (0.025 mL/g) in the steam curing concretes (see Fig. 4d). Fig. 4e and 4f show the results of the 90-day cured samples in which the RAC-100 showed a finer pore structure and lower pore volumes to those of the NAC. The RCA100 had similar pore size distribution (see Fig. 2) to that of NAC due to the similar quality of the mortar paste. The finer pore structures of the RAC-100 could be explained by an improvement of the ITZ and the new mortar paste through internal curing [15,45].

The total porosities and threshold values of the RAC-60 were higher than those of the NAC, whose average pore diameters were generally very similar at the ages of 28 and 90 days. The RAC-60-AC had slightly lower large macrocapillary pores (10-0.1 µm) than the NAC-AC, but the amount of mesocapillary pores (0.05-0.01 µm) rapidly increased (Fig. 4c and 4e). The RAC-60-SC had slightly higher pore volume (0.028 mL/g) despite showing lower macrocapillary pore (10-0.05 µm) volume than that of NAC-SC (Fig. 4d and 4f).

The porosity, the average pore diameter and the threshold diameter at 28 and 90 day were increased with the reduction of the RCA quality, irrespective of the curing method used (see Table 4), due to the influence of the aggregate type used. Also the concretes produced employing the lowest quality RCA had a coarser pore size distribution (Fig. 4d and 4f).

It must be noted that the steam-cured RAC showed higher reduction (between 16 and 36%) of the total cumulative intrusion volume from 28 to 90 days in comparison with the NAC (5%). Such higher reductions are more than likely caused by the original higher porosity of the RCA which permitted a time-extension of hydration and a more effective water transport through the pore structure in steam curing concretes [15,46]. The RAC showed similar or lower macrocapillary pore volumes to those of the NAC-SC but their meso and microcapillary pore size volumes were similar or slightly higher than those of the NAC-SC.

3.1.2.Effect of steam curing on pore structure

Despite the fact that steam curing generally produces larger capillary pores in NAC [47], the pore structure of the steam-cured concretes with 1 day of curing (Fig. 4b) was improved by the use of recycled aggregates due to a denser ITZ [39]. The use of RCA mitigated the increase of macrocapillary pores due to steam curing, which had been typically observed in steam-cured natural aggregate concretes [27]. After 1 day of curing, the steam-cured concretes obtained lower porosity, average pore diameter and threshold pore diameter than those concretes cured in air for a given aggregate type (Table 4 and Fig. 5). The influence of steam curing was especially positive in the reduction of the average pore size, which was between 12-34% lower in comparison to those of the air-cured concretes.

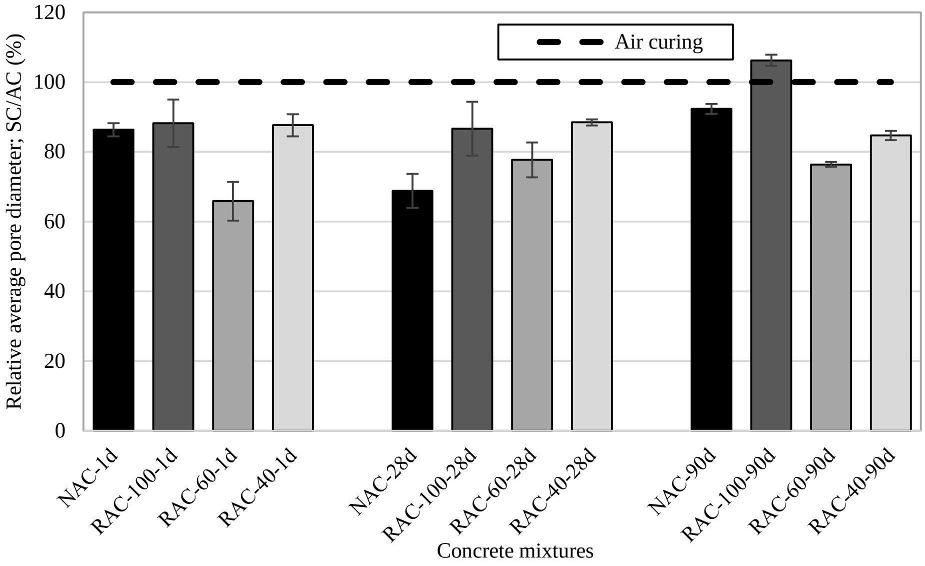

Fig. 5. Relative average pore diameter of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

The steam curing process enhanced the pozzolanic reactions which led to refinements of the pore structure of the RAC [48]. This reaction was clearly observed in the higher reduction of the average pore diameter of the RAC-60-SC when compared with the same concrete subjected to air curing. Several studies [14,37] have confirmed that the use of RAC can improve the binder's hydration by containing higher amount of portlandite and unreacted cement particles. The parent concrete from RCA60 was the youngest concrete used in recycled aggregates production, consequently having more portlandite, due to a lower carbonation ratio, reacting with the pozzolans from FA and increasing CSH formation.

The MIP results at 28 and 90 days still showed lower average pore diameter for steam-cured concretes (Fig. 5). In addition it must be noted that the RAC-60 and the RAC-40 had lower relative average pore diameters, when comparing steam-cured and air-cured concretes, than NAC after 90 days of curing. Moreover the porosity increase, which was due to the use of lower quality aggregates, was lower when they were exposed to steam curing than when they were air-cured. The porosities of the RAC-60-SC and the RAC-40-SC were 10 and 21% higher, respectively, than that of the NAC-SC; while the porosity of the RAC-60-AC and the RAC-40-AC was 17 and 34% higher, respectively, than that of the NAC-AC after 90 days of curing. Also pore size distributions revealed that steam cured concretes had similar distributions even when using medium quality RCA (RCA-40) and that the RAC-100 and the RAC-60 kept lower capillary pore volumes than the NAC after 90 days of curing (Fig. 4f).

3.1.3. Effect of concrete's age on pore structures

Fig. 6 shows the porosity reduction according to three pore size ranges from ages 1 to 90 days of the concretes. When using steam curing, the RAC experienced higher reductions of pore volumes than the NAC from 1 to 90 days age, with respect to all the pore size ranges. Typically, steam-curing produces diminished hydrations of binders due to the isolation of the unreacted binder particles and disruption of the water circulation [20]. The use of porous RCA may permit an enlarged and continuous hydration of binders which led to higher refinement of the pore structure. The highest reductions, especially with respect to the capillary pores (10-0.01µm) were observed in the RAC-40-SC. The RCA40 had the highest porosity which could act as internal curing reservoir and enlarge the binder hydration. A fact that has been reported in other studies using recycled aggregates and lightweight aggregates [15,45,49].

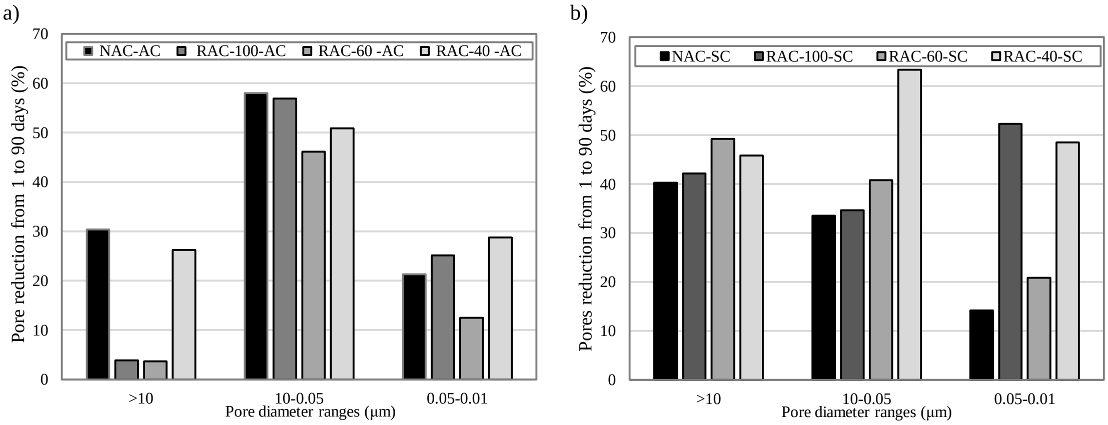

Fig. 6. Pores volume reduction of concretes produced with 30% FA from 1 to 90 days according to three different pore size ranges; (a) initially air-cured concretes and (b) initially steam-cured concretes.

3.2. Compressive strength

The compressive strength test results at the ages of 1, 28 and 90 days are presented in Table 5. The employment of steam curing proved to be essential in the production of concrete for prestressed concrete elements. The use of fly ash diminished the early-age compressive strength, which was detrimental for concrete mixtures containing RCA60 and RCA40. However, the concrete mixtures containing these two lower-quality aggregates could only reach the minimum of compressive strength at 1 day of curing (50 MPa [25,26]) by undergoing the steam curing regime. The standard deviation indicated on Table 5 were in general lower than 5% which were not significant for their acceptability for prestressed concrete applications. The only concrete mixture showing higher standard deviations than NAC was RAC60. RAC60 had been prepared with the youngest parent concrete which appeared to be more influential on the variability of compressive strength due to the remaining reactivity of the RCAs [14,50].

Table 5. Mechanical properties tests results of concrete mixtures at the ages of 1, 28 and 90 days (in brackets, standard deviations).

Mix notation		*Air cured mixtures*				*Steam cured mixtures*			
		NAC-AC	*RAC-100-AC*	*RAC-60-AC*	*RAC-40-AC*	*NAC-SC*	*RAC-100-SC*	*RAC-60-SC*	*RAC-40-SC*
Compressive strength (MPa)	*1 day*	54.11	56.81	46.88	44.23	65.42	66.18	63.03	52.44
		(0.80)	(1.12)	(0.77)	(1.06)	(3.48)	(3.00)	(2.52)	(1.66)
	28 days	87.75	91.61	84.06	76.90	86.59	83.69	82.98	75.63
		(5.38)	(3.93)	(4.85)	(1.07)	(5.67)	(2.25)	(7.42)	(1.71)
	90 days	102.84	110.88	104.16	88.18	98.05	99.62	93.87	83.18
		(4.31)	(3.91)	(5.89)	(4.64)	(4.63)	(2.76)	(4.75)	(1.64)
Splitting tensile strength (MPa)	*28 days*	4.71	4.78	4.47	3.95	4.60	4.97	4.58	4.07
		(0.31)	(0.39)	(0.43)	(0.35)	(0.13)	(0.37)	(0.10)	(0.10)
Modulus of elasticity (GPa)	*28 days*	44.43	42.55	39.49	35.34	46.58	43.90	39.80	37.70
		(2.43)	(0.26)	(1.94)	(1.49)	(0.38)	(1.51)	(1.31)	(0.11)

3.2.1.Effect of original quality of RCA on compressive strength

The compressive strength results show that the use of lower quality RCA reduced the compressive strength of the RAC when compared with the NAC. However, with respect to the high quality RCA, after 1 day of curing, the study determined that the RAC-100-SC produced with RCA sourced from 100MPa recycled concrete and steam-cured, obtained the highest compressive strength. These values being similar to that of the NAC-SC, steam-cured concrete prepared with natural aggregates. Furthermore, with respect to air-cured concretes, the RAC-100-AC attained a higher 1-day compressive strength than the NAC-AC.

After 28 and 90 days of curing, the RAC-100-AC achieved the highest compressive strengths which were slightly higher than those of the NAC for both ages (see Table 5). The results revealed that the use of the RCA-100 increased the mechanical behaviour. The improvement of the compressive strength of HPC by using high quality have been previously reported by other studies [11,14,18].

Despite the fact that the 28-day compressive strength of the RAC-60 was slightly lower than that of the NAC, this small decrease was in line with the values determined in other studies [14]. However, it should be noted that the RAC-60-AC achieved similar compressive strengths to those of the NAC-AC at 90 days, highlighting the higher potential of the recycled aggregates in reacting with fly ash due to the higher pozzolanic enhancement [51].

A severe decrease on the RCA quality caused notable reductions on compressive strength, the RAC-40 compressive strengths were, on average, 13 and 15% lower in comparison with the NAC-AC at the ages of 28 and 90 days respectively. In line with those findings from Etxeberria et al [8] and Tabsh and Abdelfatah [6], the compressive strengths from RAC60 and RAC40 were lower than NAC due to the poorer mechanical properties of RCAs than those of natural aggregates. In all probability the mechanical properties of RCAs were due to the lower quality of the old adhered mortar in comparison to the new mortar paste [52]. The old ITZ between the aged mortar paste and the raw aggregates (existing in recycled aggregates), which typically is the weakest region in concretes, probably is the principal surface in crack developing [8,52].

3.2.2. Effect of steam curing on compressive strength

The steam-cured concretes showed 4 to 15% higher 1-day compressive strength than their air-cured counterparts due to the acceleration of the CSH gel formation (Fig. 7). The obtained compressive strength was higher than that required in pre-cast and pre-stressed reinforced concrete [25,26], even using the lowest RCA quality (aggregates sourced from 40MPa concretes). Concrete mixtures subjected to steam curing suffered an acceleration of binder hydration and CSH gel formation [20,24,27] a fact which is in accordance with the porosity reduction at very early age mentioned previously. But amongst the air-cured concretes, the RAC-40-AC could not be used in pre-stressed concrete due to the negative influence on compressive strength of the poorer quality RCA.

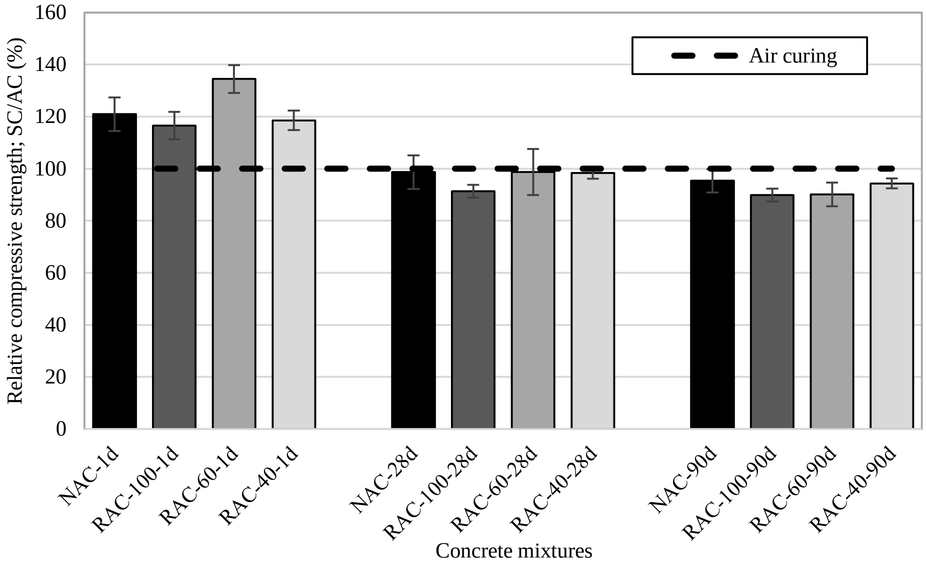

Fig. 7. Relative compressive strength of steam-cured concretes in comparison with air-cured concretes at the ages of 1, 28 and 90 days.

The 28 and 90-day compressive strengths of the steam-cured concretes were similar to those of air-cured concretes when using the same type of aggregate (Fig. 7). For a given quality of RCA, steam-cured concretes achieved 1-9% and 4-11% lower compressive strength to those of the air-cured concretes at 28 and 90 days of curing, respectively. The negative influence of steam curing was increased at long term, in accord with the results reported by various researchers [37,53].

In this research work, the reduction of compressive strength due to the use of steam-curing for recycled aggregate concrete was lower than that reported by Kou et al. [37] in all probability to the high-medium quality of the RCA used in this study. However Kou et al. [37] found slight improvements in compressive strength when using RCA in steam curing as opposed to standard curing. In this study such improvements were not observed as a consequence of the different cement type used, as in this case, a rapid hardening cement was used and Kou et al. [37] employed a normal hardening cement.

3.2.3. *Effect of concrete's age on compressive strength*

Fig. 8 shows the increase of compressive strength (in percentage) with respect to the 1-day compressive strength for each concrete mixture produced. It must be noted that the RAC-60-AC and the RAC-40-AC showed the lowest compressive strength at 1 day (see Table 5) but they attained the highest evolutions at 28 and 90 days. The compressive strength increase revealed the positive influence of using FA in RAC as pointed out by other studies [37,54].

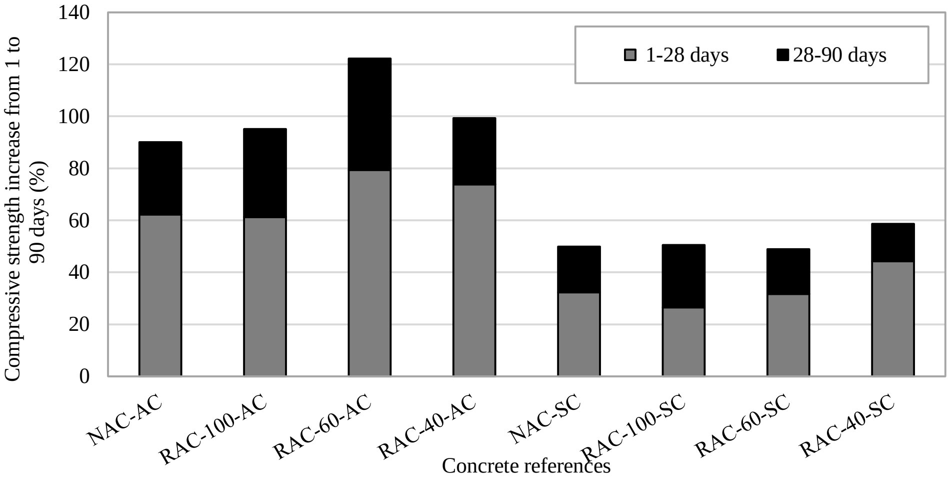

Fig. 8. Compressive strength increase from 1 to 90 days, highlighting gain ranges from 1 to 28 days and from 28 to 90 days.

A comparison between the steam cured concretes and the air cured concretes revealed that the steam curing regime reduced the long term compressive strength gain. These detrimental effects of steam curing on the long term concrete properties had been reported for natural aggregates concretes [37,53]. Nevertheless for steam-cured concretes, the highest compressive strength gain was achieved by the RCA-40, which signifies that the use of higher porous RCA could contribute to a better binder hydration [15,46]. The compressive strength evolution is in correlation with the pore structure improvements from ages 28-90 days, and also the higher average pore diameter reduction of RCA40 compared to all other steam-cured concrete prepared with the higher quality recycled aggregates. The higher reduction of RAC pore volume compared to that of the NAC could confirm the improvement of the ITZ between the cement matrix and the recycled aggregates, as well as the densification of the binder matrix by internal curing.

3.3. Splitting tensile strength

Table 5 shows the results of the splitting tensile strength of all the concretes at 28 days. The concrete mixtures produced with RCA100 aggregates obtained the highest splitting tensile strength results. This was due to the influence of the high-quality ITZ between the cement paste and the coarse RCA which is especially influential on this property [8]. Certain researchers found that when compared with NAC, the RCAs in fact improved the ITZ quality. This found improvement was due to both the surface irregularities of the recycled aggregates and a certain amount of remaining water absorption which had the effect of reducing the water-cement ration of the ITZ [8,52].

A comparative study between NAC concretes and those of lower quality RCA, revealed that there was a drop in the splitting tensile strength of 0.5-5% in RCA60 and 12-16% in RCA40 with respect to NAC concretes. In these cases, the effect of the lower quality of the old mortar attached to the RCA could be responsible for the splitting tensile strength decrease [52]. Moreover, the standard deviations were proportionally higher than those found in other mechanical tests. The reason could be the higher influence of the old ITZ in the splitting tensile strength results [55].

The steam curing process proved to be beneficial with respect to concrete produced with RCAs. The splitting tensile strengths of steam-cured RACs were approximately 7-5% higher than those concretes which were exposed to conventional curing. However, steam-cured NAC achieved lower results than those of the same concrete cured under conventional conditions. Consequently, it was observed that the RAC concrete proved to have better performance than the NAC concrete when submitted to the steam curing process.

According to Spanish technical specification for prestressed concrete sleepers, the concrete needs to have a minimum of 4.5MPa splitting tensile strength [26]. The air cured concrete had to be produced with RCA100 in order to obtain that value. However, the beneficial effects of using steam curing signify that the quality of RCA could be reduced to RCA60, thus keeping the satisfactory results of splitting tensile strength.

3.4. Modulus of elasticity

The modulus of elasticity test results at the age of 28 days are presented in Table 5. The concrete mixtures designed with RAC obtained lower elastic modulus than that of the NAC mixtures for both curing methods. As certain studies pointed out [12,18], the loss of elastic modulus is especially significant in RAC with replacement levels of 100%. According to Lydon and Balendran [56], the modulus of elasticity of aggregate is proportional to the square of its density. Since RCA have lower density, the density of RAC particles is reduced and its modulus of elasticity is reduced. Concretes with RCA100, RCA60 and RCA40 had on average 5, 13 and 20%, respectively lower modulus of elasticity than that of NAC. However, the drops of elastic modulus as a result of using lower RCA quality were less severe than those registered from studies of Portland cement HPCs [18]. The higher reactivity of fly-ash with RCA and improved ITZ are beneficial factors with respect to binder hydration and cement paste densification in RACs mixtures and certainly influenced the modulus of elasticity results.

The steam curing method had the effect of slightly improving the modulus of elasticity of concrete mixtures. The modulus of elasticity results from steam-cured concretes were up to 7% higher than those of conventional-cured concrete mixtures for the same RCA quality. Kou et al. [37] observed that the use of RCA had a positive influences on the modulus of elasticity in steam-cured mixtures. It should be noted that the use of lower quality aggregates (RCA40) subjected to steam curing obatined the highest improvements (7%).

The modulus of elasticity from all the concrete mixtures proved to be within the range considered by the ACI as the typical values of elastic modulus for HPCs [9]. Nonetheless, the maximum modulus of elasticity were those from NAC (44 – 47 GPa), while the RAC mixtures achieved moduli of elasticity between 35 – 44 GPa. The standard deviations (between 0.1 – 2.5 GPa) did not reveal any relation between the use of RCA and the variability on the modulus of elasticity.

4. Conclusions

The following conclusions can be made based on the results of this study:

1. The total porosity of RAC is higher than that of the NAC concretes due to the porosity of the RCA. However RAC exhibited a greater refinement of the porous structure after the steam curing process. The difference of porosity between RAC and NAC in steam-cured concrete mixtures is lower than that employing air curing.

2. The use of RCA mitigated the macrocapillary pore increase generated by the use of steam curing, which is typically observed in steam-cured conventional concretes. The influence of steam curing was especially beneficial in the reduction of the average pore size of RAC in comparison to those concrete mixtures which only underwent air curing. This reduction was higher in concretes produced with lower quality RCA (RCA40 and RCA60).

3. The RCA prepared from lower original concrete quality (up to 40 MPa) resulted in significant losses on the mechanical properties of RAC. However, the concrete mixtures with RCA, especially those sourced from medium-low quality RCA, were less affected by the long-term compressive strength reduction due to steam curing in comparison with NAC mixtures. It must be noted that compressive strength evolution usually diminishes by the use of steam curing.

4. The steam curing process improved the splitting tensile strength of RAC with respect to that of air curing, though in NAC mixtures the steam curing had negative effects on splitting tensile strength.

5. The modulus of elasticity of the RAC mixtures was considerably lower than that from NAC. However, the modulus of elasticity results from steam-cured RCA mixtures were up to 7% higher than those from conventional-cured concrete mixtures for the same RCA quality.

According to the results, it is observed that RAC mixtures have a more suitable behaviour when undergoing the steam curing process than that of NAC mixtures.

Acknowledgements

The authors wish to acknowledge the financial support of The Ministry of Economy and Competitiveness by INNPACT Project (IPT-2011-1655-370000) and the Hong Kong Polytechnic University.

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Paper IV

Steam curing influence on fly-ash High Performance Recycled Concrete

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Submitted to *ACI Materials Journal* (2014 Impact factor: 0.9; Q1)

Steam curing influence on fly-ash high performance recycled concrete

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Abstract

High Performance Concrete (HPC) mixtures were produced using 100% coarse Recycled Concrete Aggregates (RCA) from three different qualities. The concretes were produced using two binders, Portland cement and Portland cement with 30% of fly ash. Moreover, the fly ash mixtures underwent two different curing methods, conventional and steam curing. The effects of RCA on the physical, mechanical and durability properties of HPC were studied for the production of prestressed elements. The natural aggregates could be completely replaced by RCA sourced from the same quality HPC. It was determined that when using lower quality aggregates, the use of fly ash produced low 1-day compressive strength, with the consequent necessity to use steam curing to fulfil the standard requirements to be used in the production of prestressed elements. The steam curing had negative effects on the long-term mechanical properties, however these effects were attenuated by using RCAs which maintained their great durability.

Keywords: *Recycled Concrete Aggregates, High Performance Concrete, prestressed concrete, steam curing, fly ash, compressive strength, durability.*

1. Introduction

Concrete, is a well-known indispensable building material which is extensively used in construction engineering. However, concrete production requires a high consumption of natural resources which in the main have to be quarried, the cause of which creates an important negative impact on the environment. Moreover the construction industry represents one of the economic activities which produces the heaviest and most voluminous amount of waste[1]. It is also estimated that the cement industry is responsible for 5% of CO_2 total emissions[2], without including the energy expense of cement production. The primordial objective of this study is to encourage and propagate the use of Recycled Concrete Aggregates (RCA) in structural concretes with high performance properties in order to reduce natural aggregates quarrying and Construction and Demolition Waste (CD&W) disposal via landfills. This study also deals with the use of fly ash (FA) as cement replacement, the consequent effect of which would be a reduction in CO_2 emissions.

Up to present, few studies have been published on the use of recycled aggregates in HPC production. Limbachiya[3] studied the influence of coarse RCA in high strength concrete, finding that concrete containing up to 30% of coarse RCA could be used in a wide range of high performance engineering applications. Ajdukiewicz and Kliszczewicz[4] and Gonzalez-Corominas and Etxeberria[5] studied HPC using moderate and high strength concretes as recycled aggregates. Both stated that the quality of the original concrete had significant influence on the mechanical properties of recycled aggregate concrete; concluding that it is possible to achieve mechanical property improvement using high-quality recycled concrete aggregates. In fact, certain studies[6] concluded that when compared with natural aggregates, the higher absorption capacity and the lower mechanical strength of the low-grade recycled concrete aggregates resulted in a drop in the quality of the HPC's properties.

This study is based on a previous study of the use of recycled concrete aggregates in the production of HPC[5]. However, in difference to the prior study, this study deals with the extension of the binder being fly ash (FA) as a partial replacement of the Portland cement. The use of fly ash in concrete production has been widely accepted in recent years and its influence on many properties of concrete in both fresh and hardened state have been studied[7–12]. In particular the pozzolanic reactivity of the fly ash represents a beneficial mineral admixture for concrete. In addition, the use of fly ash ensures economical profits through the savings on cement, as well as environmental benefits by using industrial wastes and technical improvements in the production of durable materials[10]. The most common replacement rates of FA used in low water/binder ratio concretes being 25-30%[8,13]. The long term mechanical and durability properties of fly ash concretes are higher than those of Portland cement concretes due to the effect of a continuous hardening system. However, the setting and hardening time of fly ash concretes are longer, although heat generation is reduced.

Pre-stressed concrete elements usually require high early compressive strength thus minimizing inventory levels in the lines from the precast concrete plants. In order to increase early-age concrete strength, steam curing is usually employed as this accelerates the cement hydration development[9,14,15]. The high temperature experienced during the first day in the steam curing tank not only enhanced the binder reaction within the concrete but also had the effect of diminishing the initial lower strengths of the fly ash. The latter being a major concern with respect to its use in concrete production. However, one must mention that steam curing modifies the properties of the resulting cement matrix[13,16]. Ba et al.[13] confirmed that compared with standard curing, the use of steam curing at low pressure could improve the quality of high performance concrete incorporating mineral admixtures. The volume of fly ash particles decreases during the steam curing cycle while the fraction of C–S–H gel increases. Certain studies[16,17] reported that the peak-temperature of steam curing should be 60 – 70 ºC (140 – 158 ºF) and the duration of steam curing at maximum temperature should be between 8-12 hours according to the mechanical and durability properties of the concrete.

In this research work, the influence of the quality RCA aggregates on High Performance Concrete (HPC) was analysed. Three different qualities of crushed recycled concrete aggregates, whose characteristic compressive strengths of the original concrete were 40, 60 and 100MPa (5,802, 8,702 and 14,504 psi), were used as coarse natural aggregates replacement in 100% ratio. Two different binder composites (Portland cement and Portland cement with 30% of fly ash) were used in the HPC concrete production using conventional curing. Moreover curing processes were divided into two phases, conventional curing (Phase 1) and steam curing (Phase 2). In Phase 1 the concretes made with Portland cement and Portland cement-fly ash were submitted to a conventional curing method (exposing the concrete specimens to a 100% of humidity).In the second phase, Phase 2, only the concrete specimens produced using fly ash underwent steam curing in a steam tank for the first 24 hours, in order to increase their early-age compressive strength. After that initial period, all the specimens were cured in a humidity room, under the same conditions, until testing.

2. Research significance

The use of RCAs, sourced from lower quality parent concretes than HPC, decreased the properties of new HPC. Partial replacement of Portland cement by fly ash has been found to be positive for recycled aggregate concretes. Nonetheless, high early-age strength was needed in order to produce prestressed concrete elements. In order to achieve high early-strength in fly-ash concretes, steam curing was required. The authors believe that the use of RCA in fly-ash concretes could reduce the long-term negative effects of steam-curing. At same time, the minimum requirements of prestressed concrete elements could be achieved by fly-ash HPC containing lower-quality RCAs.

3. Experimental investigation

3.1. Materials

In concrete mixtures, a rapid-hardening Portland cement with a characteristic strength of 52.5 MPa (7,614psi) (CEM I 52.5R) was used. The Portland cement had a density of 3150 kg/m^3 (196.6 lb/ft^3) and a specific surface of 4947.8 cm^2/g (2415.7 ft^2/lb). Fly ash (FA) was used as a supplementary material for Portland cement at 30% by weight. The FA was obtained from a local plant and had a density of 2320 kg/m^3 (144.8 lb/ft^3) and a specific surface area of 3360.0 cm^2/g (1640.5 ft^2/lb). The chemical compositions of both binders are shown in Table 1. The admixture added to the concrete mixture was a high performance superplasticizer based on polycarboxylate ethers (PCE) which had a specific gravity of 1.08. This admixture, was used in a proportion of 1% of the binder weight and the slump cone test results were found to be between 0-20 mm (0-0.79 in).

Table 1 - Chemical composition of binders.

	SiO_2,%	*Fe_2O_3,%*	*Al_2O_3,%*	*CaO,%*	*MgO,%*	*K_2O,%*	*Na_2O,%*	*MnO,%*	*TiO_2,%*	*LOI,%*
Portland Cement	21.91	3.57	4.67	64.98	1.45	0.57	0.18	0.18	0.12	1.05
Fly ash	55.46	26.94	5.86	5.70	1.50	1.51	1.41	0.83	0.62	3.70

Crushed dolomite and river gravel were used as natural coarse aggregates. The river gravel had higher particle toughness which improved the concrete’s workability. Two different type of river sand were used as fine natural aggregate in all concrete mixtures. A river sand of 0-2 mm (0-0.08 in) was used in order to improve the grain packing because of its higher content of 0.25-2 mm (0.01-0.08 in) particles. The physical properties of the coarse and fine natural aggregates are given in Table 2.

Table 2 - Physical and mechanical properties of fine and coarse aggregate.

Natural and recycled aggregates	*Oven-dried particle density, kg/m^3 (lb/ft^3)*	*Water absorption, %*	*Flakiness index, %*	*Crushing value, %*	*LA Index, %*	*Assessment of fines. Sand equivalent test, %*
River Sand 0-2 mm (0-0.08 in)	2,570 (160.4)	1.93	-	-	-	75
River Sand 0-4 mm (0-0.16 in)	2,500 (156.0)	1.02	-	-	-	87.88
River Gravel	2,610 (162.9)	1.29	17.71	18.92	19.61	-
Dolomitic CA	2,680 (167.2)	2.13	7.81	20.15	24.77	-
RCA 100MPa (14,504 psi)	2,470 (154.1)	3.74	16.53	22.59	24.01	-
RCA 60MPa (8,702 psi)	2,390 (149.1)	4.9	13.57	23.36	25.24	-
RCA 40MPa (5,802 psi)	2,300 (143.5)	5.91	9.59	25.55	24.31	-

The recycled coarse aggregates employed were sourced from three different parent qualities which had different characteristic compressive strengths, ranging from high to medium strength, 100, 60 and 40 MPa (14,504, 8,702 and 5,802 psi). Type 1 (coded as RCA100) sourced from crushing rejected specimens and concrete waste from HPC pre-stressed elements of 100 MPa (14,504 psi). This HPC concrete was used as a reference in the production of the NAC concrete for this study. Type 2 (coded as RCA60) was obtained by the crushing of 300 x 150 Ø mm (11.8 x 5.9 Ø in) cylindrical concrete specimens of 60 MPa (8,702 psi) compressive strength. The RCA60 concrete was previously produced in the laboratory and crushed after 90 days of curing. Type 3 (coded as RCA40) sourced from crushing three years-old, out of service beams. These beams were produced with concrete of 40 MPa (5,802 psi) compressive strength and their demolition was carefully carried out so as to avoid any presence of other components. Table 2 shows the physical properties of the recycled coarse aggregates.

The physical and mechanical properties of the coarse aggregate were determined according to EN specifications. As shown in Table 2, the natural aggregates had a higher density and lower absorption capacity than any other RCA. Nevertheless, the three types of RCA employed in this study proved to have a lower absorption capacity than that of 7%, which is the maximum absorption capacity permitted by the Spanish Structural concrete regulation [18]. The crushing value of RCA was higher than those obtained from the natural coarse aggregates, showing lower toughness due to the old mortar attached to the aggregates. The abrasion index of all the aggregates was lower than 30%, which is indicative of high strength to abrasion; moreover the RCA abrasion indexes were similar, or even lower, than those obtained from the dolomitic coarse aggregates.

3.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. The three types of RCA were used on substitution (by volume) of 100% of natural aggregates. The concretes' proportioning is detailed in Table 3. The concretes mixtures were referenced as NAC for natural aggregates concrete and R100, R60 and R40 for recycled aggregates concrete (according to the compressive strength of the parent concrete). -PFA is used to designate the use of Portland cement with 30% of fly ash. -SC indicates that the concretes underwent the steam curing regime.

Table 3 - Proportioning of concrete mixtures.

Mix notation	***Cement, kg/m^3 (lb/yd^3)***	***Fly Ash, kg/m^3 (lb/yd^3)***	***River Sand 0-2 mm (0-0.08 in), kg/m^3 (lb/yd^3)***	***River Sand 0-4 mm (0-0.16 in), kg/m^3 (lb/yd^3)***	***River Gravel, kg/m^3 (lb/yd^3)***	***Dolomitic Gravel, kg/m3 (lb/yd^3)***	***RA, kg/m^3 (lb/yd^3)***	***Effective W/B***
NAC	380 (640.7)	-	215.2 (362.8)	711.8 (1,200.1)	302.1 (509.3)	784.5 (1,322.7)	-	0.29
R100	380 (640.7)	-	215.2 (362.8)	711.8 (1,200.1)	-	-	1010.2 (1,703.2)	0.29
R60	380 (640.7)	-	215.2 (362.8)	711.8 (1,200.1)	-	-	975.1 (1,644.0)	0.29
R40	380 (640.7)	-	215.2 (362.8)	711.8 (1,200.1)	-	-	938.8 (1,582.8)	0.29
NAC-PFA	266 (448.5)	114 (192.2)	182.5 (307.7)	711.8 (1,200.1)	302.1 (509.3)	784.5 (1,322.7)	-	0.29
R100-PFA	266 (448.5)	114 (192.2)	182.5 (307.7)	711.8 (1,200.1)	-	-	1010.2 (1,703.2)	0.29
R60-PFA	266 (448.5)	114 (192.2)	182.5 (307.7)	711.8 (1,200.1)	-	-	975.1 (1,644.0)	0.29
R40-PFA	266 (448.5)	114 (192.2)	182.5 (307.7)	711.8 (1,200.1)	-	-	938.8 (1,582.8)	0.29

The proportioning of an existing HPC for the pre-stressed elements produced by a Spanish precast concrete company was taken as a reference for the NAC production. The proportioning followed the Fuller's dosage method[19] which consists of adjusting to the Gessner parabola. A parabola which is obtained by combining the particle size distributions of the fine and coarse aggregates in different percentages. The percentages of coarse and fine aggregates were selected to be within the standard curve that allows for the maximum compaction of granular elements. The binder amount and the total water-binder ratio were previously fixed at 380 kg/m^3 (640.7 lb/yd^3) and 0.36, respectively. As Neville [20] defined, the effective water is the amount of water in concrete which is contained outside the aggregates. Considering the natural aggregates humidity, the effective water-binder ratio was found as 0.29.

The concretes containing supplementary cementitious material were produced by the replacement of Portland cement at 30% by weight for fly ash. The fly ash series proportioning was corrected by reducing the sand content, type 0-2 mm (0-0.08 in), in the same portion as the extra volume introduced by the FA addition.

The RCA aggregates were used in high moisture state due to their high and rapid water absorption capacity. RCA in dry conditions would absorb water from the paste, thus losing workability in fresh state as well as control over the effective w/c ratio in the mix [21]. In this study, recycled coarse aggregate were wetted via a sprinkler system the day before they were used and covered with a plastic sheet in order to maintain their high humidity. They were used with a humidity of 80-90% of their water absorption capacity [22,23]. The effective water-cement ratio obtained from NAC (0.29) was kept constant in all RAC mixes.

3.3. Specimens casting and curing

For each mixture, 100 mm (3.94 in) cubes were used to determine compressive strength, dry-density, water absorption, permeable porosity and capillary water absorption. Cylindrical specimens of 200 x 100Ø mm (7.87 x 3.94 Ø in) were used to test splitting tensile strength. The cylinders were also cut into 5 mm (0.2 in) thick disks in order to test resistance to chloride-ion penetration. All the specimens were compacted in two 30 second stages via the use of a vibrating table. The concretes were submitted to two curing processes. Whilst all the concrete mixes underwent exposure to the humidity room (Phase 1) the fly-ash concrete also underwent an additional exposure in the steam curing tank (Phase 2).

- *Phase 1: Conventional curing*

The concrete specimens produced with Portland cement and those with Portland-fly ash were exposed to conventional curing. All the specimens, which were covered with wet burlaps and plastic sheeting to keep the high humidity conditions, normally underwent air-curing in the laboratory environment, 18-24 ºC (64-75 ºF), for a period of 24 hours. After the initial 24-hour period, all the specimens were demoulded and stored in a standard curing room (25 ºC (77 ºF) and 95% of humidity) until the testing ages were reached.

- *Phase 2: Steam curing*

The four different concretes produced using fly ash, not only underwent curing in the humidity room but also an additional steam curing process because of their low initial compressive strength, in order to enhance their early properties [9]. Immediately after casting, the specimens were initially cured in a steam bath for 24 hours, achieving a maximum temperature of 65 ºC (149 ºF) during 8 hours. The steam curing cycle was defined according to the recommendations of Poon and Kou[15] and Ramezanianpour et al.[17] as shown in Fig. 1. After the initial steam curing period, all the specimens were demoulded and stored, as were the other specimens from Phase 1, in a standard curing room (25 ºC (77 ºF) and 95% of humidity) until the testing ages were reached.

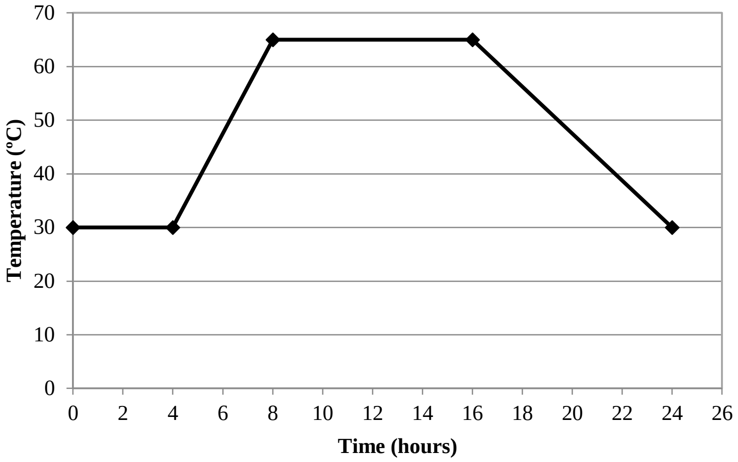

Fig. 1- Heat treatment procedure followed in steam cured concretes during the first 24 hours after casting. (Note: °F=1.8*°C+32.)

3.4. Test of hardened properties of concrete

The density, absorption and voids were measured following the ASTM C 642-97 "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete" at the ages of 28 and 180 days. Three cube specimens were used for each type of concrete.

The compressive strength of concrete was determined using a compression machine with a loading capacity of 3000 kN (674 kips). The compressive strength was measured at the ages of 1, 28 and 180 days according to UNE-EN 12390-3:2009 stipulations, using 3 cube specimens of 100 mm (3.94 in). The splitting tensile strength test was carried out according to UNE-EN 12390-6:2010. The splitting tensile-strength test was performed on three cylindrical specimens of 200 x 100Ø mm (7.87 x 3.94 Ø in) at 28 days of curing.

The capillary water absorption was tested at 28 days and 180 days of curing using 100 mm (3.94 in) cubic specimens according to ISO 15148:2002. The bottom face of the specimens was submerged in 5 mm (0.2 in) of water (the lateral surfaces were impregnated with impermeable resin) and the cumulative water absorbed was recorded at various time intervals up to 2 h via the weighing of the specimens. The water having been previously removed from the test samples' surface employing a dampened tissue. Sorptivity was calculated as the slope of the regression curve of the quantity of water absorbed by the unit of surface versus the square root of the elapsed time. The results of capillary water absorption are the average of three measurements.

The chloride penetrability of the concrete produced was determined in accordance with ASTM C1202 (2012) using 50 x 100 Ø mm (1.97 x 3.94 Ø in) concrete disks cut from the middle of 200 x 100 Ø mm (7.87 x 3.94 Ø in) concrete specimens. The resistance of concrete to chloride ion penetration is represented by the total charge passed in coulombs during a test period of 6 hours.

In this study, the chloride ion penetrability test was carried out on three concrete disks at the ages of 28 and 180 days.

4. Results and discussions

Physical, mechanical and durability properties of concretes were analysed according to the influence of the quality of RCA and fly ash replacement. The influence of the curing process on the properties of the concretes produced employing fly ash was also analysed, and comparisons were drawn from the data obtained in Phase 1 and Phase 2.

4.1. Dry-density, water absorption and volume of permeable pores

Table 4 shows the results obtained by all the concretes produced in Phase 1 and Phase 2.

Table 4 - Results of testing the physical properties at 28 and 180 days.

Mix notation	*Dry-Density, kg/m^3 (lb/ft^3)*		*Absorption (%)*		*Accessible pores volume (%)*	
	28 days	**180 days**	**28 days**	**180 days**	**28 days**	**180 days**
	PHASE 1 - Conventional curing					
NAC	2,460 (153.5)	2,490 (155.4)	2.14	1.73	5.28	4.26
R100	2,390 (149.1)	2,390 (149.1)	2.72	2.25	6.26	5.33
R60	2,330 (145.4)	2,380 (148.5)	3.21	2.23	7.50	5.24
R40	2,270 (141.6)	2,330 (145.4)	3.67	2.75	8.33	6.42
NAC-PFA	2,450 (152.9)	2,460 (153.5)	1.96	1.49	4.80	3.69
R100-PFA	2,360 (147.3)	2,370 (147.9)	2.63	1.66	5.92	4.13
R60-PFA	2,290 (142.9)	2,340 (146.0)	3.17	1.80	7.24	4.29
R40-PFA	2,220 (138.5)	2,290 (142.9)	3.56	2.38	7.90	5.46
	PHASE 2 - Steam curing					
NAC-PFA-SC	2,460 (153.5)	2,470 (154.1)	1.79	1.64	4.43	3.90
R100-PFA-SC	2,370 (147.9)	2,410 (150.4)	2.08	2.00	5.52	4.73
R60-PFA-SC	2,290 (142.9)	2,340 (146.0)	3.07	2.02	7.03	4.96
R40-PFA-SC	2,200 (137.3)	2,290 (142.9)	3.48	2.45	7.66	5.60

- *Influence of the quality of RCA*

The NAC concrete achieved the highest densities, 2,450-2,460 kg/m^3 (152.9 – 153.5 lb/ft^3), at 28 days and the lowest water absorption and porosity values (1.79-2.14% and 4.43-5.28%, respectively at 28 days).

The use of recycled aggregates caused a decrease on the dry-density of concrete, which was more evident when the employed recycled aggregates had a lower quality. The concretes produced using R100, R60 and R40 suffered a dry-density reduction of 3.4%, 6.2% and 9.2% with respect to that of NAC concrete.

Recycled aggregates have a lower density than those of natural aggregates (see Table 4) due to the old mortar still attached to the previously used raw aggregates [24], a condition which leads to lower dry-densities in recycle aggregate concretes.

However, the increase in the evolution of the dry-density from 28 to 180 days was found to be higher in those concretes containing lower quality RCA, and more noticeable in those concretes employing fly ash due to the extended hydration of the incorporated fly ash [7–12].

The use of 100% RAC aggregates significantly increased the water absorption and the porosity of the recycled aggregates concrete (see Table 4). Comparative studies between the natural aggregates and the RCA aggregates proved that the latter had substantially higher water absorption (see Table 2). This differing factor led to an increase of 30% in the water absorptions of concretes containing the highest quality recycled aggregates (RCA100) and an increase of 77% in the concretes produced with RCA40 (see Fig. 2). The porosity of concretes produced using RCA100 and RCA40 increased on average by 21% and 62%, respectively, in comparison with NAC concrete.

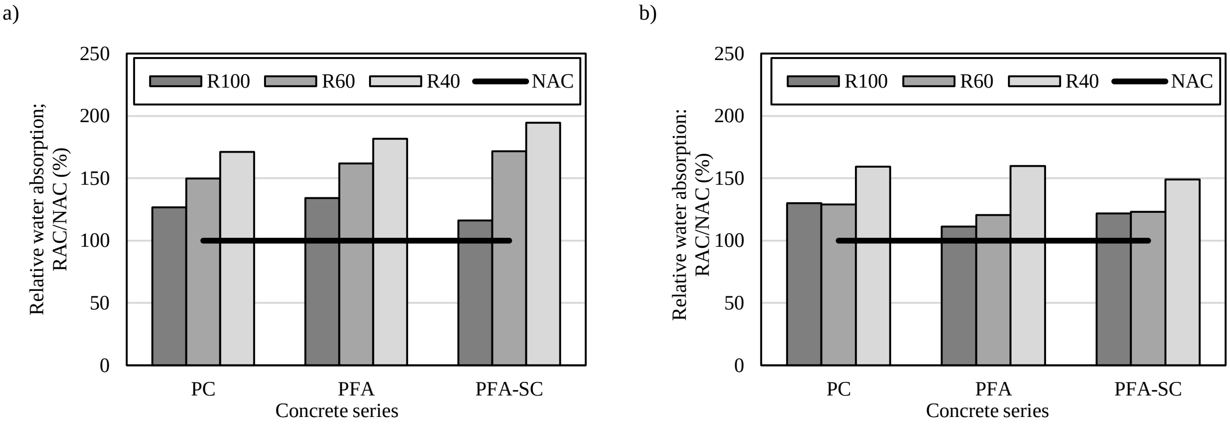

Fig. 2- Relative water absorption of recycled aggregate concrete in comparison with that from natural aggregate concrete at 28 days (a) and 180 days (b) for a given series of concrete.

However, the reduction of water absorption capacity and porosity of concretes produced with RAC were higher than those of NAC concrete from 28 to 180 days of curing. In particular, the highest reductions of water absorption capacity and porosity were found in those concretes containing the lowest quality aggregates (RCA60 and RCA 40). The improvement of the long-term physical properties could indicate internal curing effects[25,26] as well as a beneficial interaction between the RCA aggregates and the fly ash, properties described by several authors[7–12] which extend the pozzolanic reactivity and create a denser cement matrix and ITZ.

- *Influence of fly ash replacement*

An analysis of the test results in Table 4 clearly indicates that the binder type had a minor influence on the dry-densities of the concretes. As Martinez-Lage et al.[27] states, the mix dosage, when compared with the influence of the recycled aggregates replacement, has a very low influence on the density of concretes. The use of Portland-fly ash binder in the mixtures caused dry-density reductions at 28 days of 0.4 – 2.2% for the same aggregates mixtures. The lower density of the fly ash in comparison with the Portland cement was the cause of the concrete dry-density reduction, however this reduction became even less after 180 days and the maximum decrease was 1.7%.

Nevertheless, the use of fly ash improved the water absorption and porosity of both the natural and recycled concrete mixtures. According to the results from Table 4, in comparison with those correspondent mixtures containing only Portland cement, the water absorption and the porosity of the fly ash concretes at 28 days were reduced on average by 4.0 and 5.8%, respectively, and by 18.3 and 17.3%, respectively, after 180 days.

- *Influence of the steam curing regime. Comparing Phase 1 and Phase 2 concretes.*

For a given aggregate type, the use of steam curing had hardly any effect on the density of the concrete mixtures at both testing ages (see Table 4). At the age of 28 days, the use of steam curing caused slightly lower water absorption and porosities in comparison with that of conventional cured fly ash concretes. The enhancement of binder hydration even permitted the obtaining of lower water absorption results in concrete mixtures with RCA100 from Phase 2 (Fly ash + Steam curing) than those of NAC of Phase 1 (Portland cement). These results agree with Ba et al.[13], in which the concretes produced using fly ash subjected to steam curing achieved slightly lower total porosities and lower coarse capillary porous than those of concretes cured in a humidity room. However, after 180 days, the conventional cured fly ash concretes had higher water absorption and porosity improvements which produced lower values than those obtained from steam-curing.

4.2. Compressive strength

The results from the tests taken on compressive strength at the ages of 1, 28 and 180 days are presented in Table 5. In compliance with the Spanish Technical specifications concerning prestressed concrete monoblock sleepers[28] and the taking into account of certain studies recommendations on the matter[16,17], the minimum 1-day compressive strength for HPC to be used in the production of prestressed concrete elements was designated as 50 MPa (7,252 psi). Consequently all Portland cement concrete mixtures produced in this study, 63.1 - 68.3 MPa

(9,152 - 9,906 psi), fulfilled the technical specification requirement. However it must be mentioned that only the NAC and R100 concrete produced with fly ash (undergoing conventional curing) achieved a higher 1-day compressive strength than the 50 MPa (7,252 psi) previously mentioned. In the Phase 2 curing process the combining of the initial steam curing with the use of fly ash, 52.4 - 65.4 MPa (7,600 – 9,485 psi), enabled all the concrete mixtures to fulfil the stipulated requirement for their employment in precast and prestressed HPC elements.

Table 5 - Results from the mechanical properties of concrete mixtures.

Mix notation	*Compressive strength, Mpa (psi)*						*Splitting Tensile Strength, Mpa (psi)*	
	1 day		**28 days**		**180 days**		**28 days**	
			PHASE 1 - Conventional curing					
NAC	68.30	(9,906)	96.60	(14,011)	104.53	(15,161)	5.13	(744)
R100	66.86	(9,697)	102.98	(14,936)	113.94	(16,526)	5.82	(844)
R60	66.26	(9,610)	91.22	(13,231)	98.69	(14,314)	4.69	(680)
R40	63.06	(9,146)	85.82	(12,447)	93.02	(13,492)	4.68	(679)
NAC-PFA	54.10	(7,847)	90.75	(13,162)	98.44	(14,278)	4.71	(683)
R100-PFA	56.80	(8,238)	94.07	(13,644)	104.50	(15,157)	4.78	(693)
R60-PFA	46.87	(6,798)	79.92	(11,592)	93.49	(13,560)	4.47	(648)
R40-PFA	44.23	(6,415)	76.90	(11,154)	89.99	(13,052)	3.95	(573)
			PHASE 2 - Steam curing					
NAC-PFA-SC	65.42	(9,489)	84.14	(12,204)	86.29	(12,516)	4.60	(667)
R100-PFA-SC	66.18	(9,599)	84.72	(12,288)	92.99	(13,487)	4.97	(721)
R60-PFA-SC	63.03	(9,142)	78.27	(11,352)	83.17	(12,063)	4.58	(664)
R40-PFA-SC	52.44	(7,606)	75.63	(10,969)	80.97	(11,744)	4.07	(590)

- *Influence of the quality of RCA*

After 1 day of curing, the recycled aggregate concretes produced using RCA100 achieved similar or higher compressive strength to those of NAC (See Fig. 3). However, the reduction of the quality of recycled aggregates caused lower 1 day compressive strengths of 3.0-13.4% in RCA60 and 7.7-19.8% in RCA40 concretes, with respect to the NAC concretes. At very early ages, the humidity conditions of recycled aggregates, as well as those of natural fine aggregates, have significant influence on compressive strength. In other studies [5,29], the compressive strength drop proved to be less due to higher humidity conditions of the aggregates.

After 28 and 180 days of curing, the recycled concretes containing RCA100 achieved the highest compressive strength results, which, as Fig. 3 indicates, proved to be 0.7-9.0% higher than those of NAC concrete. In accord with the findings of Ajdukiewicz and Kliszczewicz[4] and Gonzalez-Corominas and Etxeberria[5], concrete produced using recycled aggregates sourced from parent HPC concrete achieved higher compressive strength than that of NAC. The reduction in the quality of the RCA had negative effects on the compressive strength at the ages of 28 and 180 days. A comparison study of the lower compressive strength results between NAC concrete and those concretes produced using RCA60 and RCA40 proved that the RCA60 and RCA40 were

3.6-11.9% and 6.2-15.3% respectively, less than NAC. These decreases of long-term compressive strength were in line with the values determined in other studies[4]. In comparison with the new cement paste, the low quality of the adhered mortar attached to the recycled aggregates was in all probability responsible for such reductions.

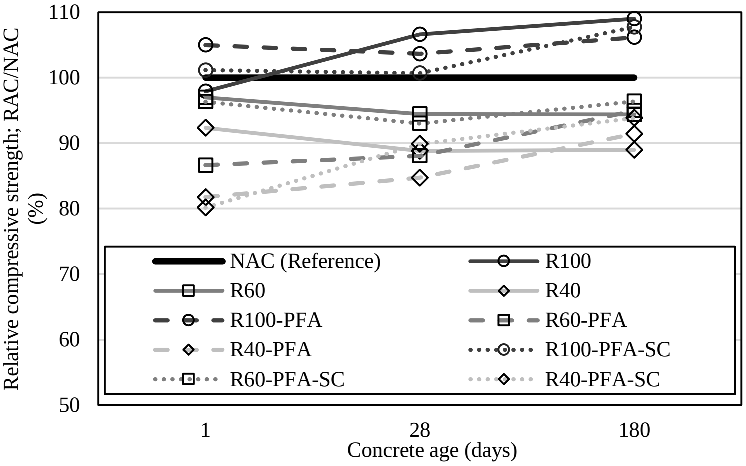

Fig. 3- Relative compressive strength of recycled aggregate concretes in comparison with that from natural aggregate concrete at 1, 28 and 180 days for a given concrete series.

- *Influence of fly ash replacement*

A comparative study of the results of conventional curing revealed that at 1 day of curing, the concretes produced with 30% of fly ash achieved a 15-30% lower compressive strength to those of the concrete produced using only Portland cement. At 28 and 180 days of age, the reduction of compressive strength due to the use of FA was 6-12%. A study of the properties in the concretes produced employing lower quality recycled aggregates and fly ash revealed that those concretes, at 180 days, obtained a greater quantity of similar properties to NAC than the concretes produced using Portland cement.

These results highlighted that the higher pozzolanic enhancement of the recycled aggregates had the effect of causing a greater potential of these aggregates reacting with fly ash than would be obtained with natural aggregates[30]. In all the cases studied, those were the concretes that showed a higher increase of compressive strength from 1 to 28 days and from 28 to 180 days. The compressive strength increase reveals the positive influence of using FA in RAC concrete, a fact pointed out in the studies on the matter by Kou and Poon[15,31].

- *Influence of the steam curing regime. Comparing Phase 1 and Phase 2 concretes.*

The steam-cured concretes showed 16-34% higher 1-day compressive strength than those of conventional-cured fly ash concretes. The obtained compressive strength was higher than that required in pre-cast and pre-stressed reinforced concrete[17,28], even when using the lowest RCA quality (RCA-40) for concrete production.

It was determined that at 28 and 180 days, the compressive strengths of the steam-cured concretes employing the same type of aggregate were lower than those of conventional-cured concretes. In accordance with the results reported by various researchers[15,32,33] a lower increase of compressive strength was achieved by steam cured concretes, thus counteracting acceleration on the early hydration of cement which produces a negative effect on the development of compressive strength in the long term. In recycled aggregate concretes, the gain of compressive strength was higher than that of concrete produced using natural aggregates, which means that the use of higher porous RCA could contribute to a better binder hydration[25,34]. The compressive strength results of steam-cured NAC obtained at 28 and 180 days dropped by 7.5% and 12.5% in comparison with those obtained from conventional-cured NAC. The compressive strength from steam-cured concrete with RCA40 only dropped 1.5% and 10% in comparison with that of conventional-cured concrete with RCA40 at 28 and 180 days, respectively. It was also observed that the differences between RAC and NAC concretes were less in steam-cured concretes than in conventional-cured concretes. In the same manner that Kou et al.[15] even found slight improvements in compressive strength when using RCA in steam curing as opposed to conventional curing.

4.3. Splitting tensile strength

Table 5 shows the results of the splitting tensile strength of all the concretes at 28 days. All the concrete mixtures, with the exception of R60-PFA, R40-PFA and R40-PFA-SC, achieved the minimum splitting tensile strength required at 28 days laid down in the Spanish technical specification for prestressed concrete sleepers, 4.5 MPa (653 psi)[28].

- *Influence of the quality of RCA*

The concretes produced with RCA100 aggregates obtained the highest values (see Fig. 4). This was due to the influence of the high-quality ITZ between the cement paste and the coarse aggregate which can be especially influential on this property[22]. Certain researchers found that in comparison with NAC, the RCA aggregates in fact improved the ITZ. This found improvement was due to both the surface irregularities of the recycled aggregates and a certain amount of remaining water absorption that had the effect of reducing the water-cement ration of the ITZ[22]. A comparative study of NAC concretes with those of lower quality RCA, revealed that the splitting tensile strength dropped by 0.5-8.5% in RCA60 and 8.7-16.3% in RCA40 with respect to NAC concretes. In these cases, the effect of the lower quality of the old mortar attached to the RCA together with that of the weaker old ITZ could be responsible for the splitting tensile strength decrease[35].

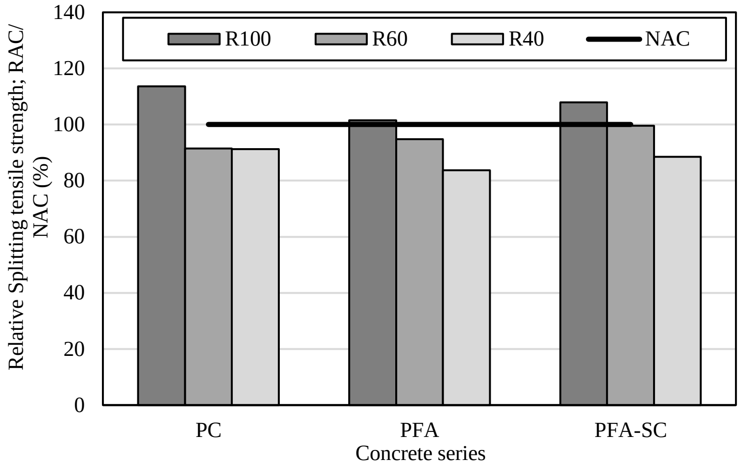

Fig. 4- Relative splitting tensile strength of recycled aggregate concrete in comparison with that from natural aggregate concrete at 28 days for a given concrete series.

- *Influence of the fly ash replacement*

In accordance with the findings of other studies[36–38], it was determined that the use of fly ash in natural and recycled aggregates concrete reduced the splitting tensile strength. However, the resulting drops in the splitting tensile results of the fly ash concretes were not consistent with the quality of the recycled aggregates employed. The drops in the splitting tensile strength were, with respect to concretes produced with Portland cement, of 8% in NAC and between 5-18% in RAC. As Kou et al.[30] determined, it is difficult to establish direct relationships in concrete containing FA and RCA due to the influence of the old and new ITZ.

- *Influence of the steam curing regime. Comparing Phase 1 and Phase 2 concretes.*

The steam curing process appeared to prove beneficial with respect to concrete produced with RCAs. Firstly, the RAC concrete proved to have better performance than the NAC concrete when submitted to the steam curing process. Secondly, a comparative study of test results proved that while the R60-PFA-SC concrete suffered only 0.5% decrease of splitting tensile strength with respect to the NAC-PFA-SC, in contrast, the R100-PFA-SC concrete proved to have 8.0% higher splitting tensile strength than the same NAC-PFA-SC. The splitting tensile strength of steam-cured RACs (Phase 2) was 2.5-3.8% higher than those concretes (produced with fly ash) which were exposed to conventional curing (Phase 1). However, NAC produced at Phase 2 (fly ash and steam curing) achieved lower results than those of the same concrete cured under conventional conditions.

4.4. Capillary water absorption

Table 6 shows the results of the sorptivity of the natural and recycled aggregate concretes after 28 and 180 days. After 28 days of undergoing a conventional curing process, the NAC concrete produced employing Portland cement obtained the lowest sorptivity values. However when employing fly ash, the concrete produced with RCA100 achieved the lowest values for both the Phase 1 and Phase 2 curing methods.

Table 6 - Results from the capillary water absorption test of the concrete mixtures.

Mix notation	*Sorptivity, mm/min$^{1/2}$ (in/min$^{1/2}$)*	
	28 days	**180 days**
PHASE 1 – Conventional curing		
NAC	0.008 (0.31*10^{-3})	0.005 (0.21*10^{-3})
R100	0.008 (0.31*10^{-3})	0.006 (0.23*10^{-3})
R60	0.033 (1.30*10^{-3})	0.006 (0.24*10^{-3})
R40	0.044 (1.75*10^{-3})	0.006 (0.24*10^{-3})
NAC-PFA	0.011 (0.44*10^{-3})	0.008 (0.32*10^{-3})
R100-PFA	0.009 (0.35*10^{-3})	0.008 (0.30*10^{-3})
R60-PFA	0.031 (1.23*10^{-3})	0.007 (0.28*10^{-3})
R40-PFA	0.038 (1.49*10^{-3})	0.007 (0.28*10^{-3})
PHASE 2 - Steam curing		
NAC-PFA-SC	0.016 (0.64*10^{-3})	0.010 (0.41*10^{-3})
R100-PFA-SC	0.008 (0.31*10^{-3})	0.007 (0.28*10^{-3})
R60-PFA-SC	0.028 (1.12*10^{-3})	0.007 (0.27*10^{-3})
R40-PFA-SC	0.025 (0.98*10^{-3})	0.008 (0.31*10^{-3})

- *Influence of the quality of RCA*

An analysis of the test results with respect to the influence of the recycled coarse aggregates on the concrete produced confirmed the following. The RCA100 concretes, which were produced employing the highest quality recycled aggregates, achieved the lowest capillary water absorption results after 28 days of curing. In contrast, the use a lower quality recycled aggregates in the production of both the RCA60 and RCA 40 concretes, caused severe increases in the sorptivity of those concretes (see Table 6). This mentioned negative influence in increased sorpivity is due to the lower quality recycled aggregates' higher porosity and high water absorption capacity (See Table 2). A total replacement of natural aggregates for recycled coarse aggregates with poorer physical properties than those of new concrete, had detrimental influence on the sorptivity. This fact has also been reported in other studies[39–41].

After 180 days of curing, the concrete containing RCA had similar or lower values to NAC for any concrete series (See Table 6). Particularly, the lower RCA qualities (RCA60 and RCA40) produced highly significant reductions of sorptivity values (68-86% from 28 to 180 days). The development of the ITZ[22,31,35] and the effect of internal curing in concretes[25,26,42] containing RCA60 and RCA40 created sufficient improvements on the ITZ and binder matrix to counter balance the higher porosity of the RCAs.

- *Influence of the fly ash replacement*

After 28 and 180 days of curing, the sorptivity of the NAC produced using fly ash was slightly higher than that of the NAC produced using Portland cement. However, the concretes produced with RCA using fly ash showed similar or improved capillary water absorption results to those produced with Portland cement. The highest improvement of this property was found not only in the concretes produced using fly ash but also in the RCA40 concrete, which was produced employing the lowest quality recycled coarse aggregates. It is well known that the higher amount of capillary pores inherent in the old mortar attached to the RCA has a significant negative role on the increase of the RACs’ capillary water absorption capacity. The addition of fly ash can improve the RACs’ ITZ via the filling of the rough and porous surface of the RCA and the closing of the microcracks caused in the RCA´s production[31,36].

- *Influence of the steam curing regime. Comparing Phase 1 and Phase 2 concretes.*

The comparison of the capillary water absorption of the conventional-cured concretes and the steam cured concretes (for a given aggregate type) showed that steam curing had negative effects on NAC concrete. The conventional-cured NAC-PFA had 46.5% lower sorptivities than those that underwent steam-curing (NAC-PFA-SC). It was found that with respect to natural aggregates, the process of steam curing had a negative effect on the porous network of cement matrix that produces higher porosity and higher pore sizes [13,14,43]. In concretes containing RCA, the porous network after steam curing appeared to improve via the resulting action of an extended binder hydration. The sorptivities of steam-cured RACs with fly ash were 9-34% lower than those which only underwent the conventional Phase 1 curing.

4.5. Chloride-ion penetration

The results of the resistance to chloride ion penetration for all concretes at the ages 28 days and 180 days are given in Fig.5. According to their charged passed results, the majority of the concrete mixtures analysed could be classified to be within the corrosion ranges of very low and low corrosion risk (from ASTM C1202-12). Only Portland cement concretes with RCA60 and RCA40 obtained moderate corrosion risks.

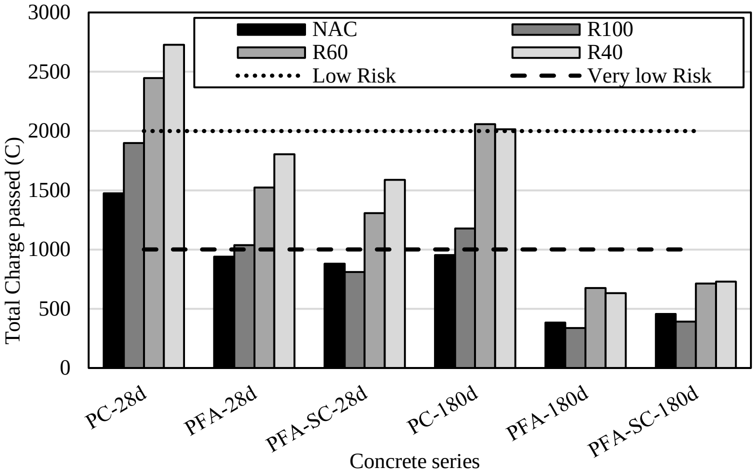

Fig. 5- Chloride-ion penetrability (Charged passed) of concrete mixtures at 28 and 180 days.

- *Influence of the quality of RCA*

The recycled concrete aggregates had lower resistance to chloride-ion penetration than those of NAC at any ages. With respect to the Portland cement concretes, the reduction in the quality of the RCA employed in the concrete mixes resulted in the decrease in resistance to chloride-ion penetration at 28 days (see Fig. 5). The mentioned drop in chloride-ion penetration resistance caused by RCA quality reduction in concretes produced using Portland cement were consistent with the results of Gonzalez and Etxeberria[5]. With respect to the other concrete series, which was produced with fly ash, the R100 achieved similar or lower results than those of the NAC concrete, However, the tests on R60 and R40 showed that they both accumulated higher charge passed, proving that they had lower resistance to the penetration of the chloride-ion.

- *Influence of the fly ash replacement*

The use of fly ash for concrete production had a higher influence on the chloride-ion penetration resistance than the RCA quality reduction or the curing method used. A comparative study between the Portland cement concretes and their corresponding fly ash concretes demonstrated that there was an improvement of chloride-ion penetration resistance in the fly ash concretes of

33.8-45.3% at 28 days and 59.8-71.3 after 180 days. Fly ash reduces the average pore sizes of the cement paste and improves the interfacial transition zone[44].

It was found that the concretes produced employing FA not only achieved higher increases of chloride-ion resistance in comparison to those of Portland cement, but also the use of RCA boosted the chloride-ion penetration resistance of those fly ash concretes. Similarly to the findings of Gesoglu et al.[45] on lightweight aggregates, the RAC containing fly ash proved to have a more similar chloride-ion penetration resistance to those of the reference concrete (NAC) at longer ages.

- *Influence of the steam curing regime. Comparing Phase 1 and Phase 2 concretes.*

The use of steam curing for concretes produced using RCA and fly ash significantly increased the chloride-ions penetration resistance of concrete after 28 days. The tests carried out proved firstly, that the steam-cured NAC concrete proved to have 6% lower total amount of charge passed than the conventional-cured NAC and secondly that the steam-cured concretes produced with RCA showed 12.0-21.8% lower charged passed results than the conventional-cured RCA concretes. In accordance with the findings of Kou et al [15], the use of steam curing in concretes with recycled aggregates was found to enhance and accelerate the pozzolanic reaction of the fly ash addition.

After 180 days, all the concretes that were exposed to steam curing (Phase 2) showed lower chloride-ion penetration resistance than those concretes exposed to just the conventional-curing process (Phase 1). As certain authors have stated [14,43], the steam curing process reduces the improvement on the long term porous structure which can ease the chloride-ion passage. However, the negative long term influence of the steam curing process proved to be lower in the recycled aggregate concretes than in the NAC concrete. The steam-cured NAC concrete had 19.4% higher charge passed than the conventional-cured NAC. The recycled aggregate concretes that underwent steam curing showed 5.5-15.8% higher charge passed than their respective counterpart concretes, which underwent the conventional curing process.

5. Conclusions

In this study, the effects of RCA aggregate quality on the properties of HPC concrete designated for the production of prestressed and precast concrete elements have been investigated. According to the results previously presented, the major conclusions are as follows:

- The physical properties of concretes are strongly influenced by recycled aggregates' quality rather than the type of binder and curing process used, which in contrast seem to have little influence. However, the employment of fly ash and steam curing improved the physical properties of recycled aggregate concretes in the long term.
- According to compressive strength:
    - It was necessary to employ recycled aggregate sourced from HPC of 100 MPa (14,504 psi) in order to achieve similar values to those of the natural aggregates used in HPC of 100 MPa (14,504 psi). The concretes produced using recycled aggregates obtained from 60MPa and 40MPa (8,702 and 5,802 psi) parent concretes suffered a reduction of up to 20%. However, this effect was reduced in the long term when those recycled aggregate concretes were produced employing fly ash.
    - The recycled aggregate concretes produced using fly ash were steam cured in order to achieve the minimum compressive strength required for prestressed and precast elements. Although, the steam curing process proved to have a negative influence on the long term compressive strength of the concrete, it was found to be lower in the recycled aggregate concretes.
- The steam curing process was found to be indispensable in achieving the adequate splitting tensile strength in high performance recycled aggregate concretes produced using fly ash.
- The high performance recycled aggregate concrete obtained higher capillary absorption capacity than the natural aggregates HPC at 28 days. However at 180 days, the recycled aggregate concretes achieved similar values to NAC when the conventional curing process was applied. In contrast, the steam cured recycled aggregate concretes achieved lower capillary absorption capacity than the NAC.
- The addition of fly ash had a higher influence on the chloride-ion penetration resistance than the RCA quality or the curing method. Fly ash concretes with low quality RCAs achieved higher resistance than the Portland-cement NAC at 180 days. However, steam curing had an especially positive influence on the concrete which was produced using RCA.

It was found that the fly ash introduced important benefits on the durability of the HPCs, especially in RACs. However, steam curing was necessary in fly ash HPCs to achieve the mechanical requirements necessary in those concretes produced using lower quality RCAs. From the physical, mechanical and durability point of view the long term negative effects of steam curing were diminished by the employment of RCAs.

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Paper V

Effects of using Recycled Concrete Aggregates on the shrinkage of High Performance Concrete

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Published in *Construction and Building Materials* (2014 Impact factor: 2.3; Q1)

Effects of using Recycled Concrete Aggregates on the shrinkage of High Performance Concrete

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Abstract

Over the past twenty years the use of Recycled Concrete Aggregate (RCA) has been mostly limited to normal-strength concretes. However, satisfactory properties have been found in previous studies dealing with the use of RCA sourced from medium to high strength concrete in the production of High Performance Concrete (HPC). In this study the effects of RCA were investigated in the plastic, autogenous and drying shrinkage of HPC. The quality of the RCA (sourced from concretes of 100, 60 and 40 MPa) and the replacement ratio (20, 50 and 100%) were assessed. The results revealed that the plastic and drying shrinkage became higher as the quality of the RCA decreased and the replacement ratio increased. However, a reduction in the autogenous shrinkage was proved to be possible by the employment of a higher content of lower quality RCA, as this, in fact, acted as internal curing agent. The effects of the internal curing explained the similar or higher compressive strength results of concretes containing RCA when compared to those obtained from the reference concrete.

Keywords: *recycled aggregate, high performance concrete, plastic shrinkage, autogenous shrinkage, drying shrinkage.*

1. Introduction

Over the last twenty years Recycling Construction and Demolition Waste (C&DW) has become a main economic and environmental concern for governments and public institutions. According to the Eurostat [1], C&DW represents the most voluminous waste stream in Europe. Consequently, standards and directive frameworks have been published in order to bring about the control and reduction of C&DW disposal in landfills, decrease the disposal site growth and promote the conservation of natural resources.

In general, when compared to natural aggregates, Recycled Concrete Aggregates (RCA) sourced from C&DW have the following differences in properties, lower density, crushing resistance and fragmentation resistance, and higher water absorption and porosity (the latter due to the old mortar attached to the aggregates) [2,3]. Many studies have focused on the physical, mechanical and durability properties of concrete employing recycled aggregates [4–15] and their findings have concluded that when compared with natural aggregates the lower properties of the recycled aggregates have a detrimental effect on the physical, mechanical and durability properties of the Recycled Aggregate Concrete (RAC). However, the use of RCA has successfully developed since its initial use via the strict following of minimum qualities, maximum replacement ratios, particular mixing methods or mixing designs using mineral admixtures [2,10,14,16–20].

Nevertheless, only a few studies have focused on the effects of using recycled aggregates in High Performance Concrete (HPC) [21–26]. HPC is designed to have more desired workability, higher compressive strength and improved durability properties than those of traditional concrete [27]. Gonzalez-Corominas and Etxeberria [25], Ajdukiewicz and Kliszczewicz [21] and Kou and Poon [23] found that coarse RCA sourced from parent HPC (> 60 MPa) could be effectively used in the production of new HPC. These studies have also found similar or improved mechanical and durability properties of RAC when compared with Natural Aggregate Concrete (NAC), even using replacement ratios of up to 100%. Nonetheless, the particular behaviour of HPC implies that other factors, more determinant to those of traditional concretes, have to be taken into consideration, such as total shrinkage and, particularly, autogenous shrinkage [28,29].

The shrinkage phenomenon is defined as the volume reduction or strain due to the water loss by evaporation through the concrete surface or via the reactions of cement hydration [30,31]. Total shrinkage is made up of plastic shrinkage, autogenous shrinkage and drying-shrinkage and is the consequence of diverse factors such as temperature and relative humidity, size and shape of the concrete piece, components, water/binder ratios and age of concrete [18].

Plastic shrinkage occurs prior to the setting time of concrete as a result of water evaporation or suction, resulting mainly in the production of cracking on the surface layers [30]. Autogenous shrinkage, however, is caused by capillary depression during CSH formation as a result of the combination of water and binder. Autogenous shrinkage is especially important in HPC concrete due to the lower water-binder ratios and higher binder amounts, which lead to greater self-desiccation and higher internal stress [28]. Autogenous shrinkage can be significantly reduced or even eliminated via the use of lightweight aggregates and recycled ceramic/masonry aggregates [28,29,32,33].

The drying shrinkage occurs when the free water stored in the capillary pores evaporates due to a low relative-humidity environment. This circumstance leads to a humidity gradient which induces the transport of water particles from the calcium silicate hydrates (CSH) to the capillary pores after which it evaporates [30]. Drying shrinkage produces internal stress, mass loss and consequently volume reduction of the concrete.

The study of Silva et al. [34], which reviewed the influence of recycled aggregates on the drying shrinkage, found that RAC usually exhibits higher shrinkage than the corresponding NAC. However, low replacement levels of natural aggregates by RCA, up to 30%, showed similar or slightly higher shrinkage values than those of NAC [35–37]. According to the mentioned studies, the HPC produced employing any percentage of RCA suffered a greater drying shrinkage than those of concretes produced with natural aggregates [21–23].

In this research work, the influence of using recycled concrete aggregates (RCA) on the plastic, autogenous and drying shrinkage of High Performance concrete (HPC) was analysed. Three different types of RCA, in relation to their parent concrete’s strength, were used. Three replacement ratios (20, 50 and 100 %) were also chosen for each type of RCA to substitute the coarse natural aggregates in order to study the influence of the quality and amount of RCA in the HPC.

2. Experimental details

2.1. Materials

2.1.1.Cement and admixture

The cement used in the HPC production was a commercially available Portland cement (CEM I 52.5R) equivalent to ASTM Type I cement. The Blaine specific surface and density of the Portland cement were 4947.8 cm^2/g and 3.15 g/cm^3, respectively, and its chemical composition is given in Table 1. A rapid hardening Portland cement was employed in order to achieve 1-day compressive strengths higher than 50 MPa, thus fulfilling the minimum requirements to be used in precast and prestressed concrete [38,39].

Table 1. Chemical composition of the Portland cement.

Composition (%)	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*CaO*	*MgO*	*K_2O*	*Cl*	*SO_3*	*LOI*
Cement CEM I 52.5R	21.75	3.38	4.55	64.65	1.63	0.64	0.01	2.66	0.91

The admixture selected for the concrete production was a high performance superplasticizer based on modified polycarboxylate-ether (PCE). The specific gravity of the admixture was 1.08.

2.1.2.Aggregates

The source and type of the natural aggregates used in the production of the concrete were the same as those used in previous studies [24,25] and are those presently used in the production of a commercial High Performance Concrete in a Spanish precast concrete company. The natural fine aggregates employed were two river sands which were mainly composed of silicates divided into two different particle size fractions (0-2mm and 0-4mm) in order to achieve higher compaction. Two types of coarse natural aggregates were used to improve the workability and the mechanical behaviour of the concrete, rounded river gravel (siliceous composition) and crushed dolomitic coarse aggregate. The physical and mechanical properties of the natural aggregates are given in Table 2.

Table 2. Physical and mechanical properties of natural and recycled concrete aggregates.

Natural and recycled aggregates	*Oven-dried particle density (kg/dm^3)*	*Water absorption (%)*	*Assessment of fines. Sand equivalent test (%)*	*Flakiness index (%)*	*Crushing value (%)*	*LA Index (%)*	*Soluble suphate (%SO_3)*	*Chloride content (%Cl^-)*
River Sand 0-2 mm	2.57	1.93	75.00					
River Sand 0-4 mm	2.50	1.02	87.88					
River Gravel	2.61	1.29		17.71	18.92	19.61		
Dolomitic CA	2.68	2.13		7.81	20.15	24.77		
RCA100	2.47	3.74		16.53	22.59	24.01	0.43	0.02
RCA60	2.39	4.90		13.57	23.36	25.24	0.52	0.01
RCA40	2.30	5.91		9.59	25.55	24.31	0.45	0.02

The three coarse RCAs were sourced from crushing parent concretes of different qualities, whose characteristic compressive strengths after 28 days were 100, 60 and 40MPa. The RCAs were crushed and sieved to achieve similar particle size distributions to those of the coarse natural aggregates. The physical properties of the RCAs are also shown in Table 2 (coded as RCA-X, X according to their compressive strength).

In comparison with coarse recycled concrete aggregates, natural aggregates have a higher density and lower water-absorption capacity, a fact which has been reported in several studies [2,3,40]. However, it has been found that when the quality of the original concrete increased, the physical properties of the RCA also improved [8,41,42]. Likewise, the mechanical properties of the RCA were directly related to the compressive strength of the parent concrete [41,43]. The crushing resistance values obtained by RCA were lower than those obtained by both natural aggregates. The fragmentation coefficients were consistent to those presented by Silva et al. [2]. As was expected, their considerably low values were a result of the high qualities of the parent concretes.

The soluble sulphate (0.43-0.52%) and the chloride content (0.01-0.02) of the RCAs fulfilled the maximum requirements of 0.8 and 0.03 %, respectively, established by the Spanish structural concrete code [44] for prestressed elements.

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. As shown in the concretes proportioning in Table 3. The 380 kg cement quantity and effective water/cement ratio of 0.29 were kept constant in all concrete productions (considering effective water as that amount water reacting with the binder or not stored in the aggregates [30]). The recycled aggregates were used as 0, 20, 50 and 100% by volume replacement of both coarse natural aggregates.

Table 3. Proportioning of natural and recycled aggregate concretes.

Mix notation	*Cement (kg)*	*Admixture (kg)*	*River Sand 0-2 mm (kg)*	*River Sand 0-4 mm (kg)*	*River Gravel (kg)*	*Dolomitic Gravel (kg)*	*RA (kg)*	*Total Water (kg)*	*Effecttive W/B*
NAC	380	5.7	215.2	711.8	302.1	784.5	-	135.4	0.29
R100-20	380	5.7	215.2	711.8	241.6	627.6	202	137.1	0.29
R100-50	380	5.7	215.2	711.8	151	392.2	505.1	146.5	0.29
R100-100	380	5.7	215.2	711.8	-	-	1010.2	162.3	0.29
R60-20	380	5.7	215.2	711.8	241.6	627.6	195	138.2	0.29
R60-50	380	5.7	215.2	711.8	151	392.2	487.5	149.8	0.29
R60-100	380	5.7	215.2	711.8	-	-	975.1	170.4	0.29
R40-20	380	5.7	215.2	711.8	241.6	627.6	187.8	139.7	0.29
R40-50	380	5.7	215.2	711.8	151	392.2	469.4	153.1	0.29
R40-100	380	5.7	215.2	711.8	-	-	938.8	175.3	0.29

The NAC proportioning, which was provided by a Spanish precast concrete company, was based on the Fuller dosage method [45]. The concrete proportioning parabola was in accordance with the Gessner parabola provided by the Fuller method in both cases, whether using NA or RCA aggregates. The recycled aggregate concretes, referenced as R-X-Y (X indicating the quality of the RCA and Y indicating the replacement ratio) had a constant cement amount and admixture content (1.5% of the cement weight).

The results from the concrete slump test (UNE-EN 12350-2:2009) using the Abrams cone were dry consistencies of 0-20 mm (S1 class following the BS-EN 206-1:2000). The natural aggregate concrete mixture, which was considered as the reference concrete, replicated the High Performance Concrete mixture used by an existing precast concrete manufacturer. The reference HPC had low water-cement ratio and very low workability in accordance with the design requirements stipulated for the technical requirements of prestressed concrete sleepers [38]. With regards to prestressed concrete elements the main requirement for those mixtures is the high early compressive strength (minimum of 50 MPa after 24 hours [38,39]), in order to bear the tension release from the prestressing wires. However the workability of the concretes mixtures is a minor concern for prestressed concrete manufacturer due to the automated process of concrete pouring and high-intensity vibrating-table for compaction.

All RCAs were used at 80-90% saturation at the moment of concrete production. Additional water was added at mixing time to compensate for the remaining water absorption of the RCAs, thus maintaining constant the effective water-cement ratio. Results revealed that the total water amount of the recycled aggregate concretes increased with the reduced quality of the RCA employed, the reason for this being the recycled aggregates higher water absorption capacity (see Table 2). The total amount of water was considered as the amount of effective water together with the absorbed water of the aggregates [30].

2.3. Tests of concrete

2.3.1.Physical and mechanical properties

The physical (dry-density, water absorption and accessible voids) and mechanical properties (compressive strength and modulus of elasticity) were tested in order to characterize the hardened concrete produced. The dry-density, water absorption and percentage of accessible voids at 28 days (ASTM C 642-13) and the compressive strength at 1, 28 and 90 days (UNE-EN 12390-3:2009) were tested via the use of a cubic specimen of 100x100x100mm. The testing of the modulus of elasticity at 28 days was conducted via the use of cylindrical specimens of 200x100∅ mm following UNE-EN 12390-13:2014 specifications.

2.3.2.Pore size distribution

The testing of porosity and pore structure was performed by Mercury Intrusion Porosimetry (MIP) with a 'Micromeritics Poresizer 9320' mercury intrusion porosimeter, following BS7591 Part 1. This test was carried out on small concrete samples weighing approximately 5.5 g. The crushed samples were obtained from the 100 x 100 x 100 mm cubic specimens. The samples were first immersed in acetone for 4 days to stop the cement hydration and then introduced in a vacuum drier for 2 hours, in order to extract the remaining acetone. Before testing, the samples were dried in an oven at 50ºC for 4 days. The MIP test was conducted on the concrete samples cured at ages 1, 28 and 90 days and each result is the average of the three tested samples. The pore size distribution, total porosity and average pore size were obtained from the MIP tests.

2.3.3.Plastic shrinkage

The setup for the plastic shrinkage test was based on a previous study by Saliba et al. [46]. The plastic shrinkage strain was measured with LVDTs which were connected to a data acquisition system. The LVDTs' length of charge was recorded every minute for 12 hours after concrete casting. The steel mould used in this experiment was a square prism of 600 x 150 x 150 mm covered with Teflon sheeting. One side of the concrete specimen was embedded in the mould while the other side was left exposed to a free-moving Teflon plate via the use of 4 steel rebars (∅10 mm) in each side (see Fig. 1). The LVDT was setup on the mould's remaining steel plate and it was in direct contact with the free-moving Teflon plate.

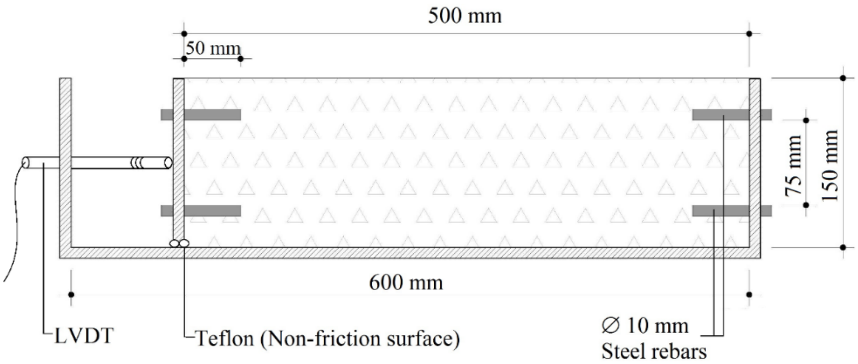


Fig.1. Plastic shrinkage test specimen and setup.

The taking of plastic strain measurements started immediately after concrete casting, in order to record all the linear length changes up to the setting time. The test specimens were kept under the same conditions of 23 ± 2 ºC of temperature and 50 ± 5% relative humidity for the entire test period. Two specimens from each concrete mixture were tested and the mean value was reported.

2.3.4.Autogenous shrinkage

Autogenous shrinkage strain measurements were conducted following the recommendations of the Japan Concrete Institute (JCI) [47]. Strain gauges were vertically embedded in the centre of the specimens using cylindrical moulds of 300 x 150 ∅ mm. After casting, the free upper surfaces of the moulds were immediately covered with two layers of adhesive aluminium foil in order to prevent moisture loss from the concrete specimen. The strain gauges were connected to a data acquisition system within the first 10 minutes after the concrete casting and the strain measurements recorded. The concrete specimens were de-moulded 1 day after casting and entirely wrapped in two layers of adhesive aluminium foil, thus preventing them from suffering from inner water evaporation. In order to ensure continuous measurements, readings were taken at 1 min intervals for 3 days in two replicate specimens per concrete mixture. The specimens were kept sealed and stored in a climatic chamber under the same environmental conditions (temperature of 23 ± 2 ºC and 50 ± 5% relative humidity) throughout the whole measurement period.

2.3.5.Drying shrinkage

The drying shrinkage of concretes was determined in accordance with the procedure laid out in ASTM C596 (2009) using 70 x 70 x 285 mm prismatic specimens. Each specimen was fitted with a stainless steel stud at both ends. The prismatic specimens were covered with a wet burlap and a plastic sheet during the initial 24 hours before being removed from the moulds and then cured under water for an additional period of 48 hours. At the age of three days, the specimens were removed from the water tank and wiped with a damp cloth. The initial length reading and the initial mass were immediately recorded using a length comparator and a scale, respectively. Then the specimens were placed in an environmental room at a controlled temperature of 23 ± 2 ºC and 50 ± 5% relative humidity for one year. The drying shrinkage was determined by taking measurements at 1, 4, 7, 14, 21, 28, 56, 90, 180, 360 days and each result was the average obtained from the testing of three specimens per concrete mixture.

3. Results and discussion

3.1. Physical and mechanical properties

The test results on the physical and mechanical properties of natural and recycled aggregate concretes can be observed in Table 4. As mentioned in previous studies [24,25], the dry-density decreased and the water absorption and accessible voids percentage increased as the quality of the recycled aggregates was reduced. Furthermore, the increase in the replacement ratio had negative effects on the physical properties of the recycled aggregates. The modulus of elasticity was also linearly affected by the RCA quality reduction and the increase of the replacement ratios, as were to the physical properties. However, on assessing the compressive strength it was observed that the results between NAC and RAC containing up 100% of RCA100 and up to 50% of RCA60 and RCA40 were similar. The compressive strength of RAC was the least influenced by the quality and the amount of RCA than any other property. At longer ages, up to 90 days, the recycled aggregate concretes exhibited higher compressive strength gains than those of the NAC. The improved Interfacial Transition Zone (ITZ) [8,14] and the internal curing [29,35] could be responsible for the enhancement of the mechanical performance of HPC employing recycled aggregates.

Table 4. Physical and mechanical properties of hardened natural and recycled aggregate concretes.

Mix notation	*Dry-Density (kg/dm^3)*	*Absorption (%)*	*Accessible Voids (%)*	*1-day Compressive strength (MPa)*	*28-day Compressive strength (MPa)*	*90-day Compressive strength (MPa)*	*Modulus of elasticity (GPa)*
NAC	2.51	1.39	3.49	66.83	100.05	111.64	50.41
R100-20	2.50	1.24	3.10	71.10	103.99	118.23	48.54
R100-50	2.48	1.51	3.72	64.59	102.42	116.86	47.93
R100-100	2.43	1.51	3.67	59.88	100.44	117.57	45.63
R60-20	2.44	1.76	4.44	72.09	104.10	116.89	47.79
R60-50	2.40	1.93	4.64	67.14	102.17	114.28	44.28
R60-100	2.34	2.43	5.69	65.76	91.22	101.36	40.09
R40-20	2.47	2.08	5.14	71.98	102.80	115.27	48.29
R40-50	2.43	2.12	5.16	63.39	101.94	113.45	43.04
R40-100	2.39	2.17	5.20	61.36	89.03	99.86	37.15

3.2. Pore size distribution

Pore size distributions of concrete samples were determined for NAC and RAC containing 100% of RCA and their results can be observed in Figs. 2a-c. Moreover, the MIP test was employed to determine the porosity and the average pore size of each concrete mixture (see Table 5). The MIP tests were carried out at 1, 28 and 90 days of curing.

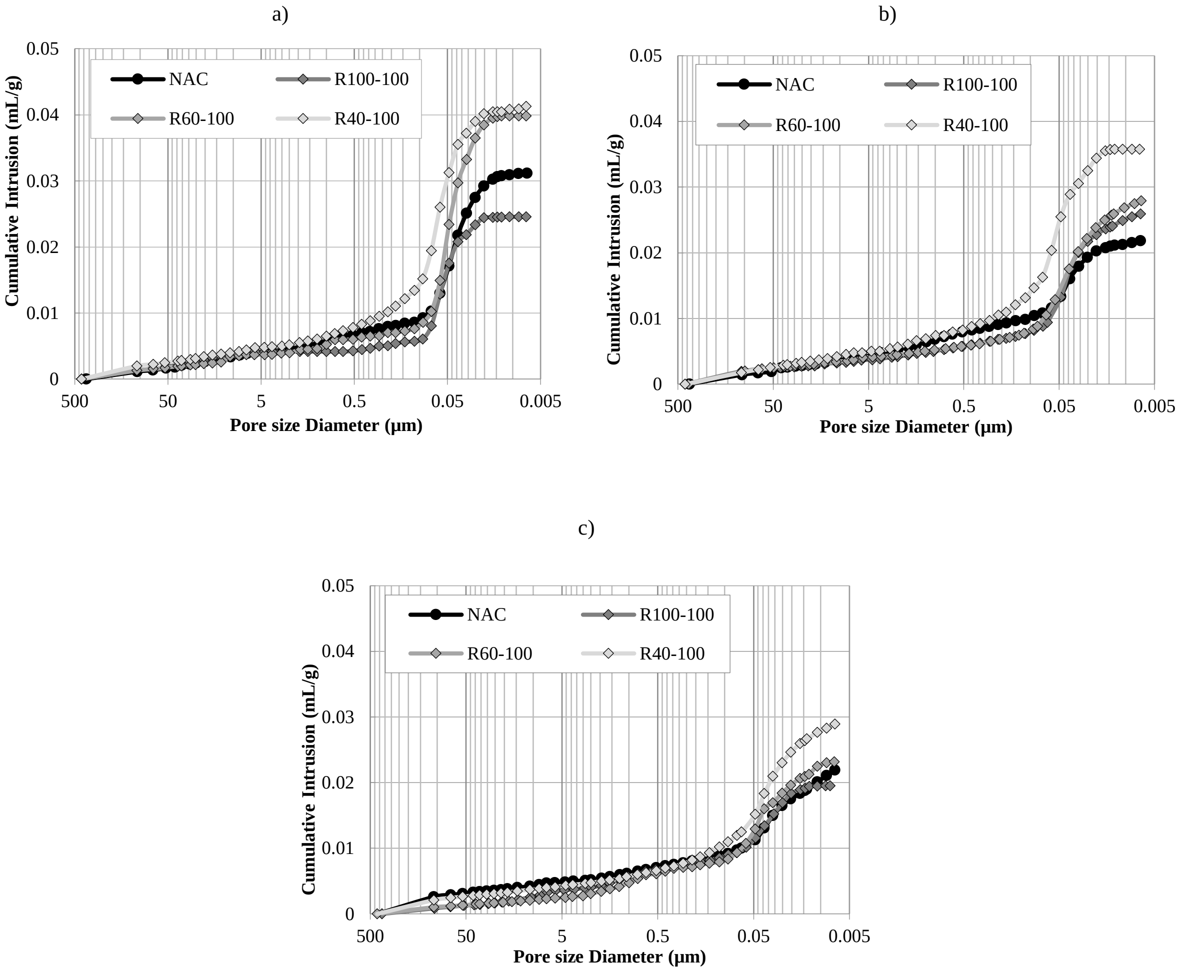


Fig. 2. Pore size cumulative distribution of natural aggregate concrete (NAC) and recycled aggregate concretes containing 100% of RCA100, RCA60 and RCA 40 at the ages of 1 (a), 28 (b) and 90 days (c).

Table 5. Porosity and average pore diameter from MIP test of natural aggregate concrete (NAC) and recycled aggregate concretes containing 100% of RCA100, RCA60 and RCA40 at the ages of 1, 28 and 90 days.

Mix notation	***Porosity (%)***			***Average Pore Diameter (µm)***		
	1 day	**28 days**	**90 days**	**1 day**	**28 days**	**90 days**
NAC	7.30	5.52	5.19	0.054	0.045	0.033
R100-100	6.31	6.11	4.78	0.050	0.048	0.038
R60-100	9.29	6.58	5.31	0.060	0.050	0.036
R40-100	9.67	8.28	6.92	0.063	0.055	0.040

After 1 day of curing, the concrete mixture produced with RCA100 showed significant lower porosity, lower average pore size and lower pores at any size range than those of NAC (See Fig 2a and Table 5). In NAC, the porosity is higher in the aggregate–paste interface than in the paste itself and the pore size is usually larger [48,49]. Nevertheless, the ITZ is improved by the use of recycled aggregates as certain authors have pointed out [14] which could explain the reduction on the porosity of RAC100-100. Nevertheless, RAC containing lower quality RCA which had a higher total water-cement ratios resulted in the worsening of porosities, average pore sizes and pore size distributions at very early ages.

Fig. 2b shows that the pore size distributions of RAC100-100 and RAC60-100, at 28 days of age, were similar to those of NAC, which obtained the lowest pore volumes. Only the RAC produced with the lower quality aggregate (RCA40) had significant higher capillary pore volumes than NAC. The porosity and average pore sizes also showed higher increases as the quality of RCAs decreases.

After 90 days of curing, the RACs containing RCA40 and RCA60 showed the highest improvements of porosity and pore size distributions. The RCA40 and RCA60 could act as internal curing agents, producing an extension of the binder hydration, found to be especially useful in HPC [29,35]. Internal curing in HPC leads to lower internal stress and also enhances cement matrix densification [32]. Furthermore, the pore distribution of RAC100-100 kept similar pore structures to those of NAC due to the presence of the old-mortar attached to the RCA which had the same quality as the new mortar.

3.3. Plastic shrinkage

The development of plastic shrinkage up to 12 hours is shown in Figs. 3a-c. The highest plastic shrinkage strain recorded was that of the concretes produced with low quality recycled aggregates, up to -600 $\mu\varepsilon$. Although there exists an abundant variety of information concerning the testing procedures for measuring plastic shrinkage, a review of that literature revealed in the main higher plastic shrinkage values than those found in our studies [46,50,51].

Throughout the entire testing period, the plastic shrinkage of the concrete mixtures produced with any type of RCA was higher than those produced with NAC. However, the plastic shrinkage of the concrete mixtures made with RCA derived from original concrete with higher strength values was lower than that of concretes prepared with RCA derived from lower strength parent concretes. In concrete with 100% of RCA (Fig. 3a), R100 had a 130% higher plastic shrinkage than that of NAC after 12 hours of age. The R60 and R40 (Figs 3b and 3c, respectively) suffered an average increase of 200% shrinkage in comparison with NAC when using 100% RCA.

Similarly, the increase in the amount of RCA had a negative influence on the plastic shrinkage. While the concrete mixtures with a 20% RCA replacement ratio showed plastic shrinkage increases of 46-152% in comparison with those of NAC, the 50% and the 100% RCA replacement ratios produced 65-150% and 130-208% increases of plastic shrinkage, respectively. The rate of plastic shrinkage is highly dependent on the water-to-binder ratio [46,51]. The RACs contain a higher total water-cement ratio which in the initial stages of curing results in a higher effective water content. However, the additional water added to the mix to compensate for the RCA's remaining water absorption effectively caused in time a higher plastic shrinkage. The higher the RCAs' w/c ratio, then the higher the plastic shrinkage values achieved. These values being a direct result of the RCAs', not only having a higher relative humidity but also a larger porous networks at an early age, which facilitates rapid water evaporation [46].

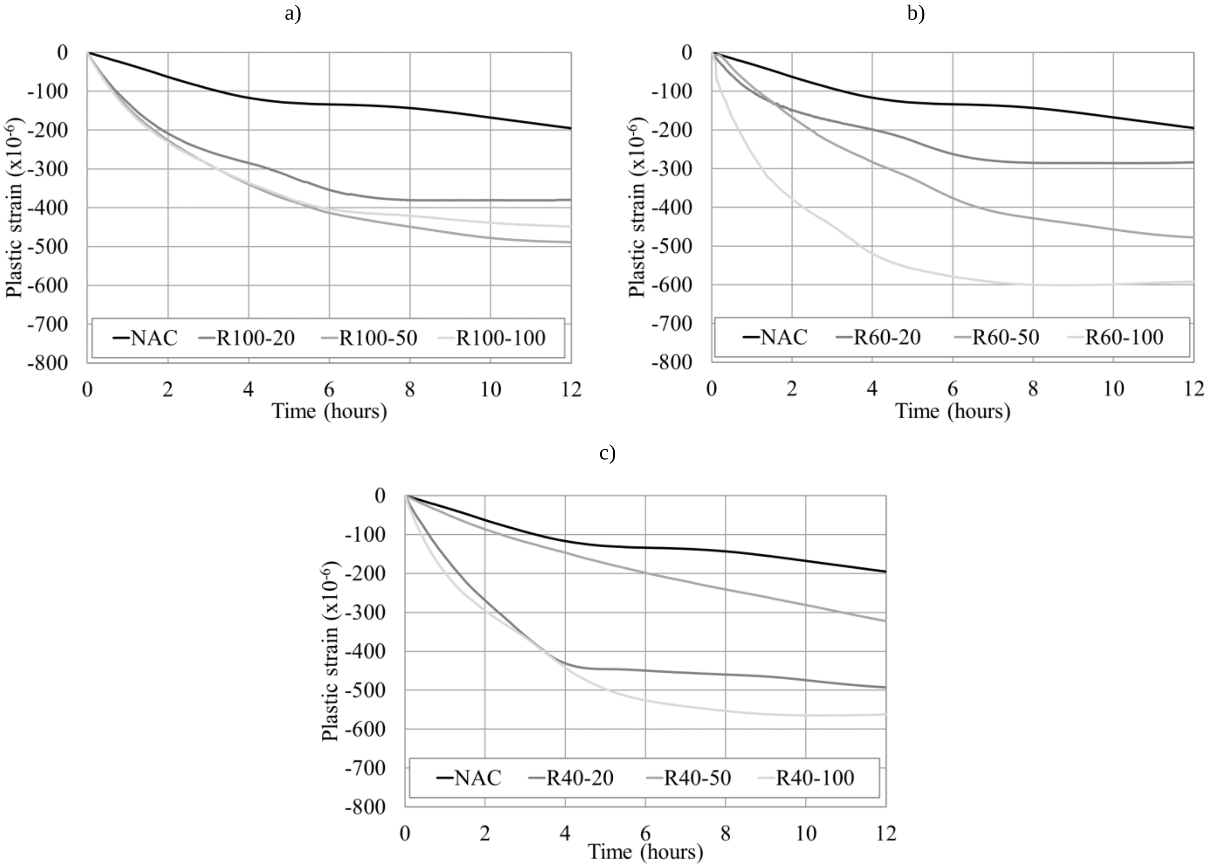


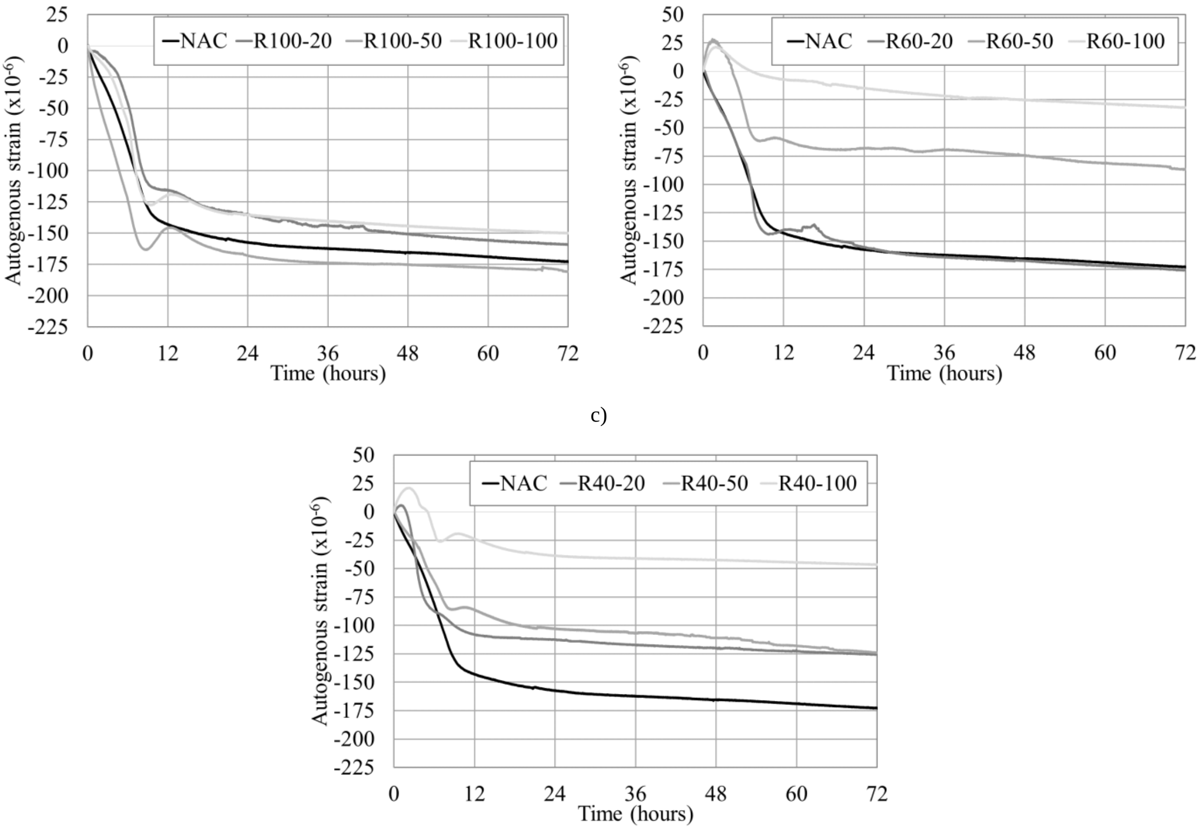
Fig. 3. Plastic shrinkage of natural aggregate concrete (NAC) and recycled aggregate concretes containing RCA100 (a), RCA60 (b) and RCA 40 (c).

Plastic shrinkage cracking spreads when the surface tension increases as a cause of the evaporation of superficial water which effectively increases the capillary pore stress [52]. However, plastic shrinkage strain is reduced when the evaporated water in the binder composite is replaced by bleeding water [53]. The findings of certain studies have determined that highly porous aggregates, such as Lightweight Aggregates (LWA) [54,55] or Mixed Recycled Aggregates [56], can act as internal curing agents and provide water to reduce very early shrinkage. The RCA aggregates which have lower water absorption capacity and smaller pore networks than LWA and MRA aggregates proved to be ineffective in the reduction of the plastic shrinkage.

However, the plastic shrinkage strains found in the laboratory proved to be significantly lower than those proposed by Baghabra et al. [50], whose threshold value of plastic shrinkage strain was established as -1100 με, above which there is a high risk of cracking occurring. Moreover, Won et al. [53] observed through an analysis of his studies that there was no plastic shrinkage cracking occurrence in any of the high-strength concrete mixtures tested under restrain conditions. Consequently, it is highly improbable that the RAC mixtures produced in this study would suffer from plastic shrinkage cracking.

3.4. Autogenous shrinkage

As previously mentioned, the autogenous strain test was performed on sealed concrete specimens immediately (approximately 10 min) after casting, minute by minute measurements being continuously taken and recorded. Figs. 4a-c presents the results from testing the autogenous shrinkage up to 72 hours for NAC and RAC mixtures.


a)

b)

c)

Fig. 4. Autogenous shrinkage of natural aggregate concrete (NAC) and recycled aggregate concretes containing RCA100 (a), RCA60 (b) and RCA 40 (c).

The concrete mixtures produced employing natural aggregates and RCA100 were subjected to an immediate measurement of the autogenous shrinkage after casting, in order to determine and register autogenous shrinkage strain. Certain studies [28,29] revealed an initial non-shrinking or dormant stage in the preliminary hours of concrete mixture setting, however, this phenomenon did not occur in the concrete mixtures tested within this study. The use of rapid-hardening cement could be responsible for the reduction of this dormant period in our test findings, as rapid-hardening cement contains a higher amount of C_3S and finer grinding, which could have the effect of reducing both the layer and barrier effects that produce the dormant period [30,31].

However, it was found that the concrete mixtures produced using RCA60 and RCA40 swelled slightly from the initiation of the testing period up to 2.5 hours after casting. A fact mentioned in other studies dealing with the use of recycled aggregates [28,29]. The maximum expansions registered were 5 - 27 $\mu\varepsilon$ which were considerably lower than the expansion values found by Meddah et al. [28] and Suzuki et al. [29] for concretes containing ceramic aggregates. The higher porosity and higher pore interconnection found in ceramic aggregates facilitates a much quicker and easier transfer of water to the paste than in RAC aggregates.

The autogenous shrinkage starts as the cement hydration reactions consume the water from the capillary pores [30,31]. The formation of capillary-water menisci and the increase of capillary-tension produce the capillary volume reduction which establishes the autogenous shrinkage [28]. The autogenous shrinkage started immediately after casting in the NAC, RAC-100 (at any replacement ratio) and RAC-60-20 concretes. There was a very significant increase in the autogenous shrinkage for the firsts 10-12 hours, reaching almost total development. The autogenous shrinkage of any of the concretes under study was at the point of stabilization after 3 days. The RAC-100 concrete (at any replacement ratios) and RAC-60-20 showed similar or slightly lower autogenous shrinkage than that of the NAC.

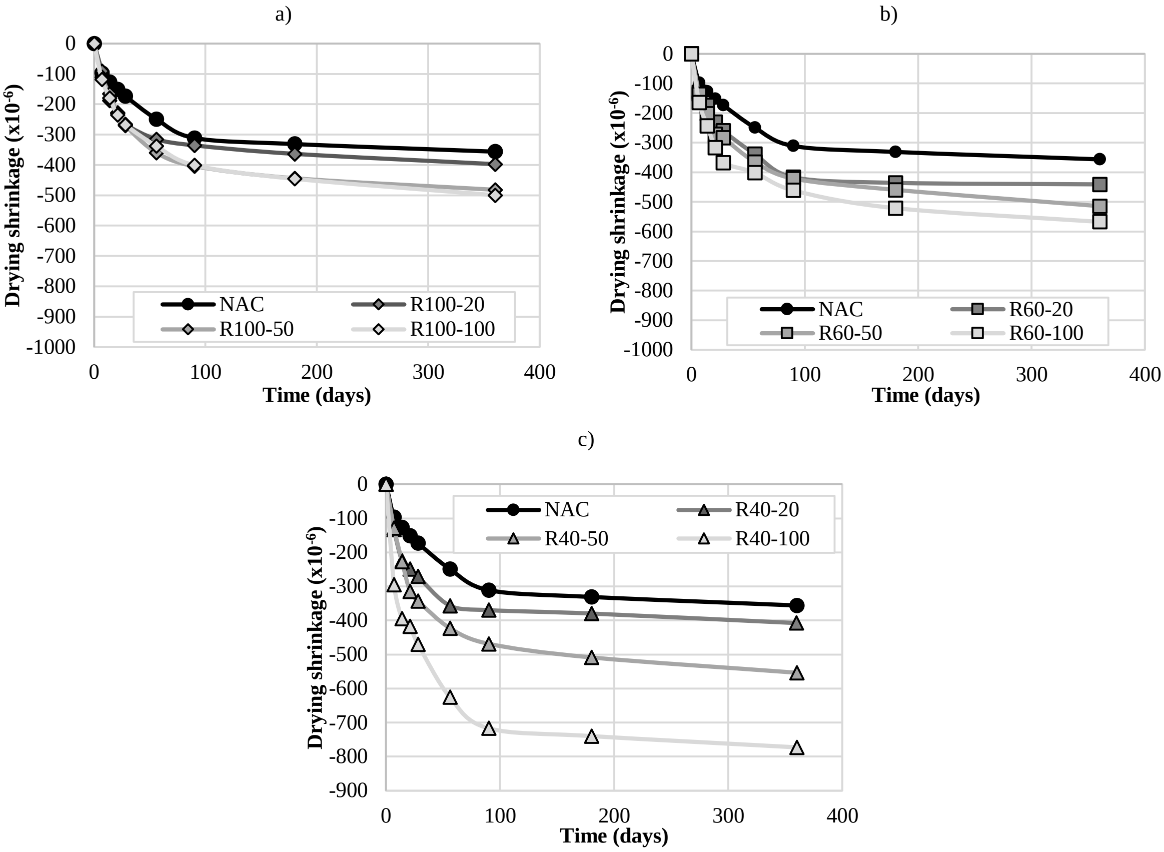
The reduction in the quality of the RCA aggregates and the increase in their replacement ratios improved the prevention of the autogenous shrinkage. After the initial small expansion, the autogenous shrinkage behaviour of the RAC-60 and RAC-40 concretes with 50 to100% replacement ratios was slightly different to that of the NAC. The concretes produced with a higher percentage of RCA suffered lower autogenous shrinkage as a result of the higher amount of water storage within the aggregates. Almost all of the autogenous shrinkage had developed within the 8-10 hours after commencing testing. As Figs.4b and 4c clearly indicate, determined that after 72 hours of commencing continuous testing, the RAC concrete produced employing 100% of RCA60 and RCA40 achieved reductions of 82% and 73%, respectively, with respect to the NAC concrete’s autogenous shrinkage. Additionally, the obtained strain values of the mentioned concretes proved to be below that of -50 με, as a consequence of which these concrete mixtures could be almost considered as non-shrinking concretes.

As certain studies employing lightweight aggregates and recycled ceramic aggregates have pointed out [28,29,33], the saturated aggregates act as water reservoirs thus reducing or even eliminating the autogenous shrinkage. At the initiation of cement hydration the internal capillary tension is reduced by the transportation of water from the RCA pores to the new cement paste via capillarity. As the quality of the RCA is reduced, the pore size distribution of the old cement paste increases [57] thus easing the capillary water transportation to the new cement paste. The water streaming reduces the formation of menisci and lowers the internal capillary tension that produce the development of autogenous shrinkage. This mechanism is also beneficial for the mechanical properties as it acts as internal curing which extends the cement hydration and increases long-term compressive strength gain [29,32,33,58].

3.5. Drying shrinkage

Figs. 5a-c show the results of drying shrinkage obtained up to 1 year. After 90 days, the strains caused by drying shrinkage ranged from -311 to -717 με. Such results are in line with those results determined by several other authors employing_RCA aggregates [16,23,59], as are the typical drying-shrinkage values described by the ACI [60] (-200 to -800 με).

In natural aggregate concrete, the higher the w/c ratio, the greater the amount of shrinkage within the concrete [30,32]. However, in concretes containing highly porous aggregates, the water contained within these aggregates also plays an important role in the amount of shrinkage increase [32,61,62]. The relationship between the RCA replacement ratio and drying shrinkage strain represented in Fig. 6 shows a solid linear correlation for each quality of RCA. The Pearson's r linear correlation coefficients were in a range of 0.92 - 0.99 and the linear regressions had R^2 of 0.86 - 0.99. The highest drying shrinkages occurred in those concretes containing the highest RCA replacement ratios and the lowest RCA qualities. Consequently, the influence of the RCA aggregates was lower when using the highest quality aggregates (RCA100), agreeing with the findings on the matter of both Kou and Poon [23].


a)

b)

c)

Fig. 5. Drying shrinkage of natural aggregate concrete (NAC) and recycled aggregate concretes containing RCA100 (a), RCA60 (b) and RCA 40 (c).

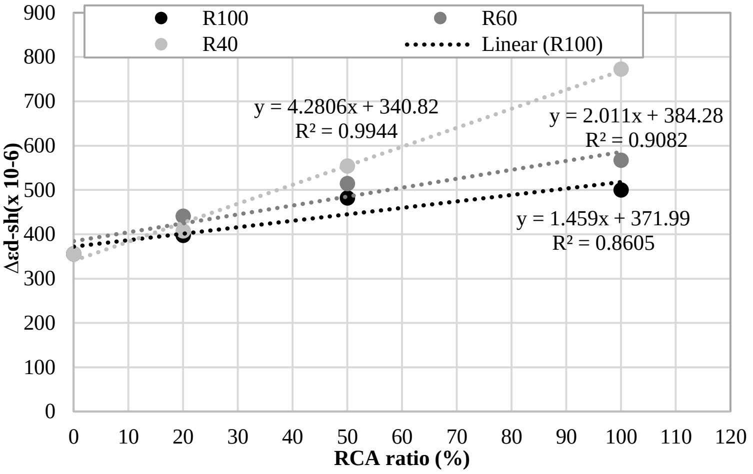


Fig. 6. Relationship between RCA replacement ratio and maximum drying shrinkage strain of RAC.

The concretes produced using RCA100 achieved 54-56% higher shrinkage levels than those of NAC at 28 days of testing. The shrinkage strain increased significantly when the concretes were produced using RCA60 and RCA40. At 28 days of testing, the shrinkage strain of R60 and R40 concrete mixtures were 50-113% and 57-172% higher, respectively than those of NAC. The maximum shrinkage corresponding to 100% replacement of natural aggregates for RCA aggregates. Nevertheless, it was found that the drying shrinkage of all concretes was established after 90 days of testing.

The negative influence of RCA on the drying shrinkage when HPC concretes were produced employing the highest quality recycled aggregates (RCA100) was similar to that found in other studies [23,62]. However, concretes produced using a lower quality recycled aggregates (RCA60 and RCA40) revealed higher increases in the drying shrinkage of the HPC concrete. One can only consider that the water-to-cement ratio of the concretes produced and analysed in this study was lower than those produced by Domingo-Cabo et al. [62] and Kou and Poon [23]. Consequently, producing higher difference between the quality of the new concrete and the quality of the RCA aggregates than they determined in their studies.

The higher amount of cement paste (taking into consideration both the old and new paste) contained in the RAC concrete is the cause of the production of the higher concrete porosity. Moreover, the use of pre-soaked RCA aggregates in the production of RAC concrete, in order to facilitate the proper workability of the fresh concrete, means that there is more water available for evaporation. As shown in Figs. 7a-c, the concretes containing higher amounts of RCA and lower quality RCA were the concretes that had the highest mass losses. These losses directly corresponding to the amount of water evaporated. The water evaporation grew faster and greater as the RCA amount employed increased and the quality decreased. An analysis of test results leading to conclusions similarly to the observations made by Zhutovsky and Kovler [32] in mixes containing lightweight aggregates.

It is widely known that the aggregate's stiffness has a great influence on shrinkage restraint and that a higher aggregate-cement ratio also lowers the shrinkage within the concrete [30]. According to Silva et al. [34], the concretes produced employing less stiff recycled aggregates achieved a lower modulus of elasticity consequently a greater shrinkage within the concrete. Fig. 8 shows the relationship between the recycled aggregate concretes' relative modulus of elasticity (in comparison with that of NAC) and the drying shrinkage after 28 days. The results confirmed that the RAC's modulus of elasticity, which is dependent on the elastic modulus of the coarse aggregate [63], has a significant effect on the drying shrinkage. The relationship between the concrete's relative modulus of elasticity and drying shrinkage strain depicted in Fig. 8 is in accordance with the findings presented by Silva et al. [34] and it also shows a strong linear correlation. The Pearson's r linear correlation coefficient was -0.95 and the linear regression had a R^2 of 0.90.

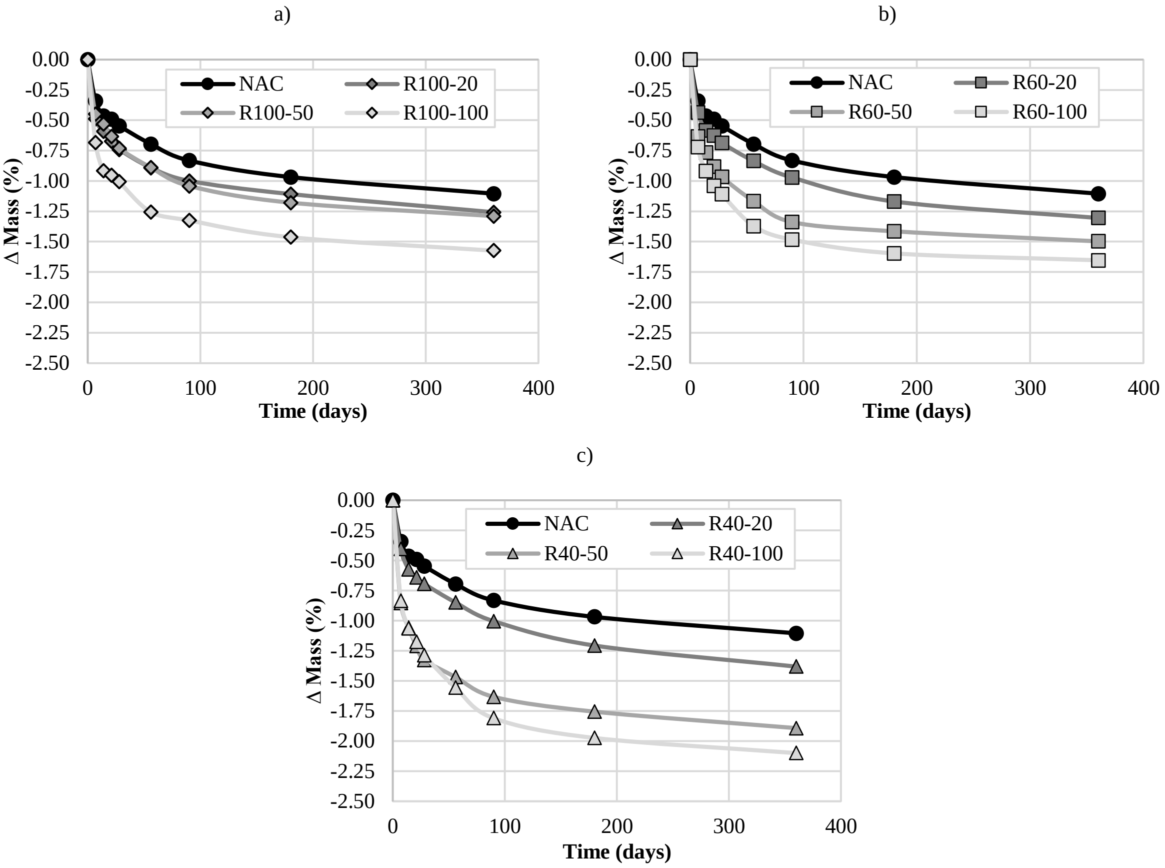


Fig. 7. Mass loss due to drying conditions of natural aggregate concrete (NAC) and recycled aggregate concretes containing RCA100 (a), RCA60 (b) and RCA 40 (c).

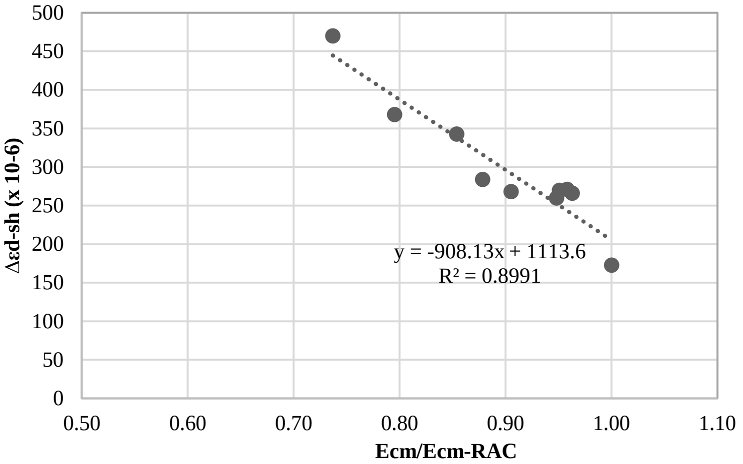


Fig. 8. Relationship between relative modulus of elasticity and drying shrinkage strain of RAC at 28a days.

4. Conclusions

The following conclusions can be made based on the results of this study:

- The dry-density and the modulus of elasticity of HPC produced with recycled aggregates decreased and the water absorption and the porosity increased when the quality of the RCA employed was reduced and their replacement ratio was increased.
- The compressive strength of HPC produced using 100 % of RCA100 and up to 50% of RCA60 and RCA40 recycled aggregates showed similar values to those of NAC. Moreover, a greater enhancement of compressive strength was shown in HPC using RCA.
- The RACs showed higher improvements of porosity and pore size distributions than those from NAC. The particle size distributions of NAC and concretes containing 100% of RCA100 and RCA60 were very similar after 90 days.
- The plastic shrinkage of concretes increased as the employed RCA quality was reduced and the replacement ratio was increased. However the obtained values for all HPC concretes were lower than those required with respect to concrete cracking.
- The autogenous shrinkage of concretes decreased as the quality of RCA employed was reduced and their replacement ratio increased. This was probably due to a higher water storage capacity of RCA.
- The lower quality of the RCA aggregates employed as well as higher replacement ratios had the effect of producing the highest test values of drying shrinkage within the concrete. A downward linear trend was confirmed with respect to both a decrease in the relation of the modulus of elasticity of the RAC's and NAC's and an increase of drying shrinkage

The concretes produced using 100% of RCA aggregates (originating from the same quality as the new HPC) and the concretes produced using 50 % of lower quality RCA (produced crushing concretes with up to 40MPa of compressive strength) from the mechanical and shrinkage point of view could be employed in the production of HPC, as they achieved similar or better properties than those produced with natural aggregates.

Acknowledgements

The authors wish to acknowledge the financial support of The Ministry of Economy and Competitiveness by INNPACT Project (IPT-2011-1655-370000).

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Paper VI

Structural behaviour of prestressed concrete sleepers produced with High Performance Recycled Aggregate Concrete

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Submitted to *Materials and Structures* (2014 Impact factor: 1.7; Q1)

Structural behaviour of prestressed concrete sleepers produced with High Performance Recycled Aggregate Concrete

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Abstract

A comparative analysis of the structural behaviour of prestressed concrete sleepers made with High Performance Concrete (HPC) and High Performance Recycled Aggregate Concrete (HPRAC) is presented in this study. Two types of HPRAC sleepers were tested, using 50 and 100% of Recycled Concrete Aggregate (RCA) in replacement of coarse natural aggregates. The RCA employed in this research was sourced from crushing rejected HPC sleepers. The aim of this study was to determine through analysis if the HPRAC sleepers' behaviour fulfilled the European minimum requirements standards for prestressed concrete sleepers and compare their experimental behaviour with that of the HPC sleepers. The three types of prestressed concrete sleepers were subjected to static load tests at rail-seat and centre section (positive and negative load). In the centre section tests a comparative study between the experimental results and the proposed values of four assessment methods of ultimate capacity was carried out. Dynamic load and fatigue tests were also performed at the rail-seat section. The HPRACs and HPC sleepers met all the structural requirements for prestressed concrete sleepers. The experimental results determined the satisfactory performance of the HPRAC-50 and the HPRAC-100, which was very similar to that of the HPC sleepers. The load-strain behaviour recorded via the use of strain gauges on the prestressing bars revealed slightly higher stiffness of the HPC sleepers. The values obtained from the four assessment methods of ultimate capacity were also accurate when applied to HPRAC.

Keywords: *recycled aggregate concrete, high performance concrete, sleeper, structural prestressed concrete, railway sustainability.*

1. Introduction

According to European Union statistics from 2012 onwards [1], construction has become the industrial sector producing the highest amounts of waste. For the last twenty years, the awareness of governments and public institutions of the importance of recycling Construction and Demolition Waste (C&DW) has increased. In spite of developing new standards and directive frameworks to reduce the C&DW disposal in landfills, the recycling ratios are still insufficient, especially in southern European countries. The on-site recycling of demolition materials is the most efficient process of reducing waste landfill and natural aggregates consumption, as well as reducing transportation costs and detrimental environmental impact.

Several types of recycled aggregates can be obtained from C&DW. Recycled Concrete Aggregates (RCA) has been reported as the recycled aggregate type with the most suitable physical and mechanical properties. The predominant composition of concrete particles in RCA prevents the higher sulphate contents and lower densities which are normally caused by the presence of gypsum and masonry particles. Nonetheless, most properties of the RCA are usually poorer than those of natural aggregates, especially the properties of water absorption, porosity and crushing value due to the old mortar attached to the aggregates [2, 3].

Over the last twenty years, there have been many studies which have concerned themselves with the influence of RCA on the physical, mechanical and durability properties of Recycled Aggregate Concrete (RCA) [4–15]. Comparative studies of the RCA with natural aggregates conclude that the lower properties of the RCA have in general negative effects on the properties of the Recycled Aggregate Concrete (RAC). Some typical negative effects are, lower workability due to their higher water absorption, lower compressive strength and lower durability properties due to RCA’s lower mechanical toughness and higher porosity. Nevertheless, RCA can be successfully used in the production of low and medium strength concretes if the recommendations on the maximum replacement ratios, minimum qualities, specific mixing methods or mix designs using mineral admixtures are implemented [2, 10, 14, 16–20].

Currently, few studies have dealt with the use of RCA in High Performance Concrete (HPC) [21–25]. In particular Ajdukiewicz and Kliszczewicz [21], Kou and Poon [23] and our previous studies, Gonzalez-Corominas and Etxeberria [26], were focused on the use of coarse RCA, sourced from the waste of HPC and high quality concrete, in the production of new High Performance Recycled Aggregate Concrete (HPRAC). These studies agreed that the mechanical and durability properties of HPRAC produced with high quality RCA could achieve higher mechanical and durability properties than those of conventional HPC, even when using high replacement ratios (50-100%) without any cement adjustment.

High Performance Concretes are produced to achieve higher compressive strength and higher durability properties than conventional concrete while at the same time maintaining proper workability [27]. These properties are particularly suitable for their application in prestressed concrete elements such as prestressed concrete sleepers. Mono-block prestressed concrete sleepers, which were first employed in the early 40's, have become essential components in high speed rail track constructions worldwide [28, 29]. The extraordinary development of high speed train networks in Europe and Asia [30], has led to a great number of studies on the production of prestressed concrete sleepers in order to develop safer railway structures, which could hold higher loading demands [31].

Several studies have concerned themselves with the structural performance of concrete sleepers, focusing on crack development, fatigue and impact behaviour [32–39]. Other principal concerns have been the durability properties and their service life [38, 40, 41]. However, very few studies have considered the production of environmentally sustainable sleepers [31, 42–45]. These eco-friendly prestressed concrete sleepers have been developed by partially replacing Portland cement for ground granulated blast furnace slag and replacing natural fine aggregate by electric arc furnace oxidizing slag. The results obtained from the analysis of the eco-friendly prestressed concrete sleepers showed an improvement on those obtained from conventional prestressed concrete sleepers.

In this research work, the influence of HPRAC on the structural properties of prestressed concrete sleepers was analysed. The RCA used in the HPRAC sourced from old rejected sleepers and the replacement ratios of natural coarse aggregates were 50 and 100%. Conventional HPC sleepers and HPRAC sleepers underwent static and dynamic load tests at the centre and rail-seat sections as defined in European standards and Spanish specifications for prestressed concrete sleepers [46, 47]. The load-stress behaviours of the prestressing bars were recorded using strain gauges in order to carry out a comparative study of the structural performance of the HPRAC sleepers.

2. Experimental details

2.1. Materials

2.1.1. Cement and admixture

In the production of the HPC, a rapid-hardening Portland cement (CEM I 52.5R) with low alkali content was used. Their specific surface and density were 495 m^2/kg and 3150 kg/m^3, respectively. According to the regulations laid down in the Spanish railway specifications [47], the Portland cement was found to have low alkali content. This rapid-hardening cement was employed in order to achieve high-early strength for the prestressing bars release after 24 hours of curing. The admixture used in the HPC production was a high performance superplasticizer based on modified polycarboxylate-ether with a specific gravity of 1.08.

2.1.2.Aggregates

The natural aggregates were those already used in the production of HPC for commercially-available prestressed sleepers from a Spanish precast concrete company. The natural fine aggregates were two river sands mainly composed of silicates with two different particle size fractions (0-2mm and 0-4mm) in order to achieve higher compaction. Two types of coarse natural aggregates were used, rounded river gravel (siliceous) and crushed dolomite, to improve the workability and the mechanical behaviour of the concrete. The RCA used in replacement of both natural gravels was sourced from crushing old rejected sleepers, whose characteristic compressive strength after 28 days was 100 MPa. The concrete waste was crushed and sieved to achieve RCA with similar particle size distributions to those of the coarse natural aggregates. The physical properties of the natural and recycled aggregates are shown in Table 1.

Table 1. Physical and mechanical properties of natural and recycled concrete aggregates.

Natural and recycled aggregates	*Oven-dried particle density (kg/dm^3)*	*Water absorption (%)*	*Flakiness index (%)*	*Crushing value (%)*	*LA Index (%)*	*Assessment of fines. Sand equivalent test (%)*
River Sand 0-2 mm	2.57	1.93				75.00
River Sand 0-4 mm	2.50	1.02				87.88
River Gravel 4-10 mm	2.61	1.29	17.71	18.92	19.61	
Crushed dolomite 4-10 mm	2.68	2.13	7.81	20.15	24.77	
RCA 4-10 mm	2.47	3.74	16.53	22.59	24.01	

The coarse natural aggregates had higher density and lower water-absorption than the recycled concrete aggregate, a fact also reported in several studies [2, 3, 48]. However, the physical and mechanical properties of the RCA, which are directly related to the strength of the parent concrete [49, 50], were more similar to NA than those found in other studies [8, 49, 51] due to the high quality of the parent concrete.

2.2. Concrete mixtures

All concrete mixtures were produced in a Spanish precast concrete plant. The proportioning of the natural aggregate concrete was that already used in HPC for the production of prestressed concrete sleepers according to the Fuller's dosage method [52]. As shown in the concretes proportioning from Table 2, 380 kg of cement and a total water-cement ratio of 0.35 were used in the HPC production. For the production of HPRAC, the natural coarse aggregates were replaced by 50 and 100% of RCA (in volume). The cement amount and the effective water-cement ratio were kept constant in the HPC and the HPRACs production (considering effective water as that amount water reacting with the binder or not stored in the aggregates [53]).

Table 2. Proportioning of natural and recycled aggregate concretes.

Mix notation	*Cement (kg)*	*River Sand 0-2mm (kg)*	*River Sand 0-4mm (kg)*	*River Gravel (kg)*	*Crushed dolomite (kg)*	*RA (kg)*	*Total Water (kg)*	*Effective W/B*
HPC	380	215.2	711.8	302.1	784.5	0	135.4	0.29
HPRAC-50	380	215.2	711.8	151	392.2	505.1	146.5	0.29
HPRAC-100	380	215.2	711.8	0	0	1010.2	162.3	0.29

The admixture were used in 1% of the cement weight in order to maintain dry consistencies, 0-20 mm in the concrete slump test (UNE-EN 12350-2:2009). The natural fine aggregates were used in saturated conditions and the recycled coarse aggregates at 80-90% of saturation at the moment of concrete production.

2.3. Mechanical properties of HPC and HPRAC

The concretes mixtures were tested prior to sleeper production, in order to ensure that they met the requirements of the Spanish railway technical specification [47]. The compressive strength, splitting tensile strength, flexural strength and modulus of elasticity tests were carried out following the corresponding EN specifications. The results of the mechanical properties obtained as well as the minimum technical requirements according to the Spanish prestressed sleepers' specification can be observed in Table 3.

Table 3. Results from testing the mechanical properties of HPC and HPRAC and the required values for concrete according to the Spanish prestressed sleepers specification [47].

Mix notation	*1-day Compressive strength (MPa)*	*28-day Compressive strength (MPa)*	*28-day Splitting tensile strength (MPa)*	*7-day Flexural strength (MPa)*	*28-day Modulus of elasticity (GPa)*
Requirement	>46.00	>60.00	>4.50	>6.50	
HPC	53.00	100.05	6.40	8.73	50.41
HPRAC-50	50.75	102.42	7.02	10.43	47.93
HPRAC-100	51.50	100.44	6.40	8.50	45.63

HPC and HPRAC with 50 and 100% replacement ratios fulfilled the requirements established for the mechanical properties of concrete mixtures As found in previous studies [25], RCA sourced from parent HPC of 100 MPa could be used in the production of new HPRAC in replacement ratios of up to 100% with no negative effects on the mechanical properties. The high quality of the RCA and the improvement on the Interfacial Transition Zone [8, 14] could be responsible for the enhancement of the mechanical performance of HPC using recycled aggregates.

2.4. Prototype of prestressed concrete sleeper

The prototypes of the prestressed HPRAC sleepers and the reference prestressed HPC sleepers were produced in a Spanish precast concrete plant. The manufacturing procedure, the geometrical dimensions of the sleeper, the prestressing bars and tension were kept constant for all concrete mixtures, in order to analyse the influence of HPRAC in the structural properties and later compare them with the values obtained from the reference HPC sleepers. The concrete mixtures in the sleeper's moulds were compacted in two stages of 30 seconds via the use of a vibrating table. The sleepers were stored immediately after casting in a standard curing room (23±2° and 95% of humidity) for the first 24 hours. After 24 hours, the prestressing tension of the reinforcing bars was released and the sleepers were demoulded. Fig. 1 indicates the schematics of the prestressed concrete sleeper's prototypes. Fig. 2 indicates the stress-strain behaviour of the Ø 9.5 mm prestressing bars (Y1570C) obtained from the tensile strength test.

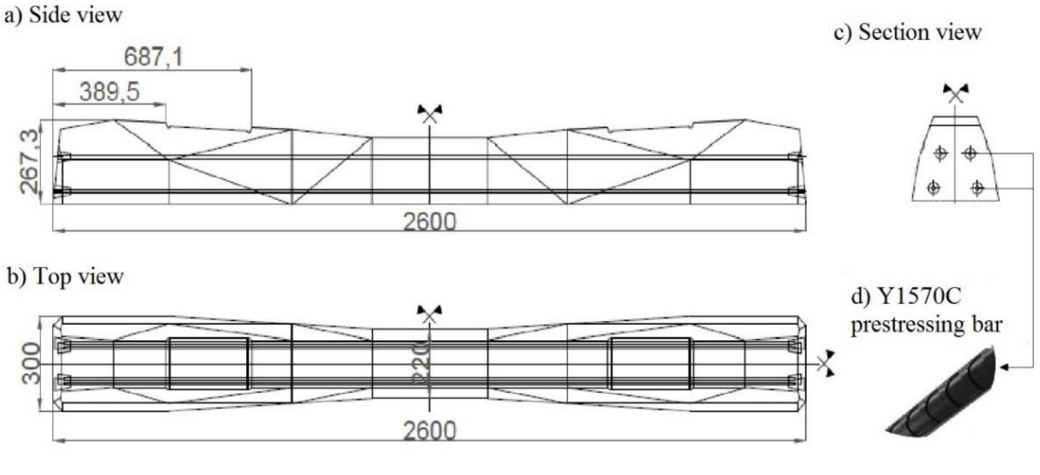


Fig. 1. Schematics of a prestressed sleeper: (a) side view, (b) top view, (c) section view (unit: mm) and (d) detail of the prestressing bar of Ø9.5 mm.

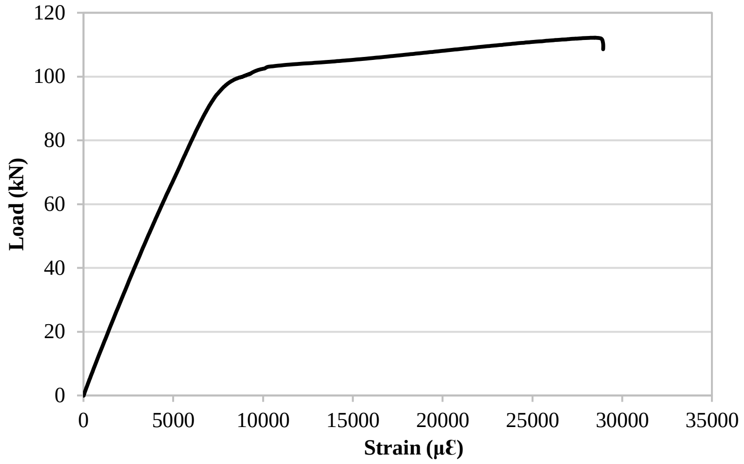


Fig. 2. Load-strain results from tensile strength test of the prestressing bars.

3. Test setups

Five structural tests were carried out in accordance with the European Standards (EN 13230-2:2009) and the Spanish railway technical specification for prestressed concrete sleepers (ET 03.360.571.8:2009) [47]: 1) Static positive load test at the rail-seat section, 2 and 3) Static negative and positive load test at the centre section, respectively 4) Dynamic test at the rail-seat section, and 5) Fatigue test at the rail-seat section.

3.1. Static positive load test at the rail-seat section

The arrangement for positive bending test on the rail-seat section is shown in Fig. 3. The load *Fr* was applied perpendicularly to the base of the sleeper and centred in one of the rail-seat sections. The tested rail-seat section was located between 389.5 mm and 687.1 mm from the edge of the sleeper. The sleeper had only one support under the testing rail-seat section and the opposite non-tested edge was unsupported.

Fig. 3. Setup of the static positive load test at the rail-seat section [46].

The procedure followed in the static test at the rail-seat section is shown in Fig. 4. The initial vertical loading force was increased up to the initial reference load (Fr_0), which in the case of 1435 mm track gauge was 156 kN according to the Spanish specification [47], with a loading rate of 60 kN / min. After the initial reference load, the loading was increased in 10 kN intervals, maintaining the load in every interval for 30 seconds up to the first crack formation. After the first crack appearance, a new series of loading and unloading intervals started, increasing 10 kN in every loading interval.

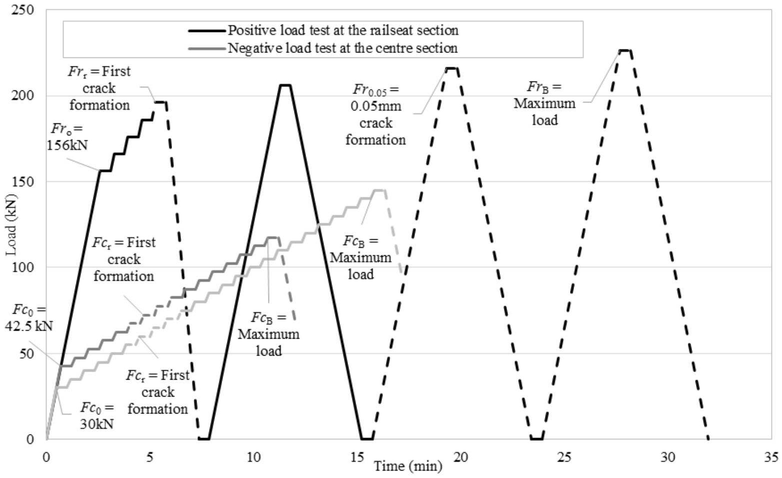


Fig. 4. Static test procedures at the rail-seat and centre sections for positive and negative load tests [46].

The Spanish technical specification for prestressed concrete sleepers [47] indicates that the load which produces the first crack formation (Fr_r) should be higher than the initial reference load (Fr_0). Also the load ($Fr_{0.05}$), which produces a crack of 0.05 mm width at the bottom after the removal of the load, and the ultimate load (Fr_B) should be higher than 280 kN and 390 kN, respectively.

Two traditional HPC sleepers and six HPRAC sleepers for each replacement ratio were tested for the static positive load test at the rail-seat section. Two strain gauges were placed on the two inferior prestressing bars, one per side, centred in the rail-seat section perpendicularly to the load plane in order to analyse the stress-strain behaviour.

3.2. Static load test at the centre section

3.2.1.Negative design

The arrangement for the negative load test at centre section is shown in Fig.5 (a). In order to carry out the negative bending test, the sleeper was placed upside down on the testing frame. The load *Fc* was applied at the centre of the sleeper and perpendicularly to its base.

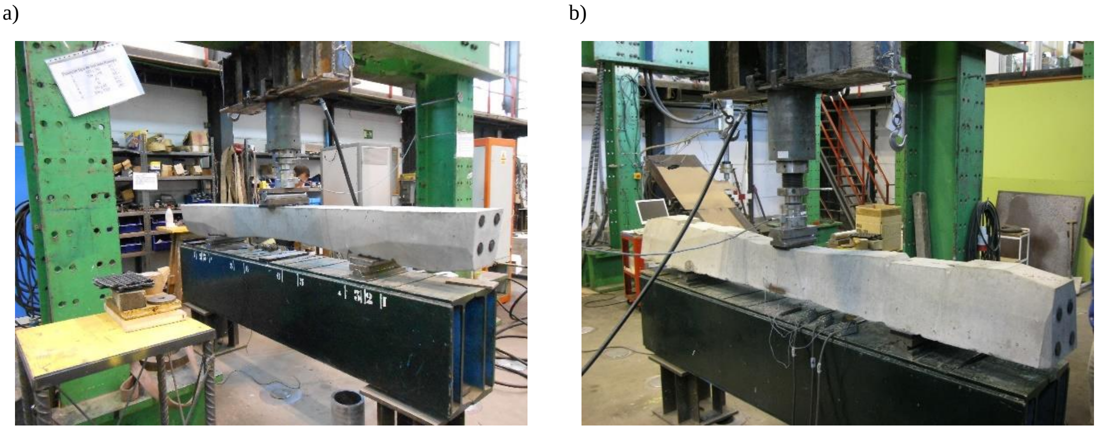


Fig. 5. Test arrangements at the centre section for the negative (a) and positive load test (b) [46].

The static test procedure at the centre section for negative design approval test is shown in Fig. 4. According to the Spanish specification [47], the initial reference load was 42.5 kN which were attained with a loading rate of 60 kN / min. Once the initial reference load was reached, it was maintained for 30 seconds. After that time, the load was increased in 5 kN intervals, maintaining the load in each interval for 30 seconds up to the sleeper's ultimate bending load. The load which produced the first crack formation was recorded during the test.

The criterion for the acceptance was that the load producing the first crack (Fc_r) had to be higher than the initial reference load (Fc_0), which was 42.5 kN according to the Spanish specifications [47]. Two HPC sleepers and three HPRAC sleepers for each replacement were tested in the static negative load design. Strain gauges were installed on the superior bars in the centre section to register the maximum strain under negative bending.

3.2.2. *Positive design*

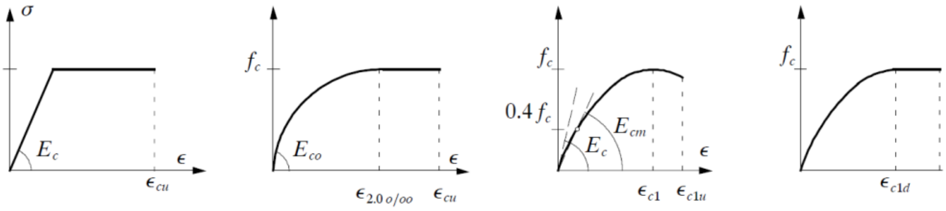
The test arrangements for the positive centre load test were the same as those from the negative load test, except for the sleepers were placed in its ordinary position as shown in Fig. 5 (b). The test method followed the procedure described in Fig. 4 which was the same as in the negative load test but with a reference load of 30 kN. The only acceptance requirement was that the load which produced the first crack (Fc_r) had to be higher than the initial reference load (Fc_0). Two HPC sleepers and three HPRAC sleepers for each replacement were tested in the positive design,. Two strain gauges were installed on the inferior bars for each sleeper tested in order to register the maximum strain under positive bending.

3.2.3. *Prediction of the ultimate capacity of the HPC and HPRAC sleepers at centre sections.*

A comparison between the experimental static test results at centre section and the values obtained following different methods for the prediction of ultimate capacity of reinforced or prestressed concrete sections was carried out. Different hypothesis to contemplate the concrete behaviour at the ultimate limit state were considered with the underlying purpose to validate them when applied to recycled aggregate concretes. Therefore, it was assessed whether the methods used for the calculations of the ultimate capacity of reinforced or prestressed concretes yield reasonable values for the different replacements of coarse aggregate.

Four different stress-strain diagrams for concrete at ultimate state were considered; the bi-linear stress-strain; the quadratic parabola diagram; the parabola rectangle according to Eurocode 2 [54] and a variation of the last one according to SIA262 [55] (see Fig. 6). All the diagrams depicted in Fig. 6 represent a simplification of the concrete behaviour under ultimate states.

The ultimate strain allowed and determined by Eurocode [54] for concrete was ε_{cu}=0.0026. The ultimate strain value had an essential role in the prediction of the ultimate cross-section capacity. Different authors [56] claimed that there was no difference in the ultimate strain between conventional concrete and recycled aggregate concretes with the same compressive strength. However, they yield dissimilar behaviours in the softening branch.



Type 1: bilinear Type 2: quadratic parabola Type 3: according to EC2 Type 4: SIA262

Fig. 6. Stress-strain relationship for concrete in compression under ultimate state.

The material model chosen for the prestressed bars was a bilinear model with hardening, taking the recommended hardening coefficient k=1.1 as proposed in the Eurocode 2 [54]. In this case, as it was described in the previous sections, the steel's class was Y1570 and the maximum strain allowed before failure was ε_{uk}=20% (see Fig. 7).

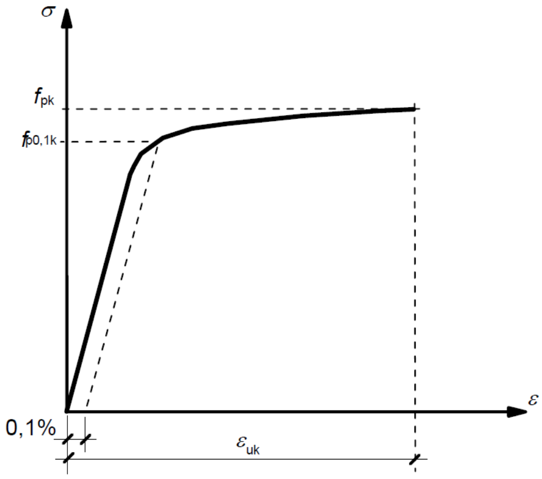


Fig. 7. Material model for prestressed steel

3.3. Dynamic test at the rail-seat section

The test arrangement for both the dynamic and static tests at the rail-seat section were the same (see Fig. 3). The test procedure followed in the dynamic test at the rail-seat section is shown in the Fig. 8. The test is based on the application of series of 5000 loading-unloading cycles with a frequency of 5 Hz. For all series, the loading-unloading cycles started at a minimum test load (Fr_u) of 50 kN. In the initial series, the maximum test load was the initial reference test load for the rail-seat section (Fr_0), which according to the Spanish specification was 156 kN. For the following series, the maximum test load was increased 20 kN in each series. After each loading interval, a crack measurement was performed. The maximum time employed in the inspection was 5 min.

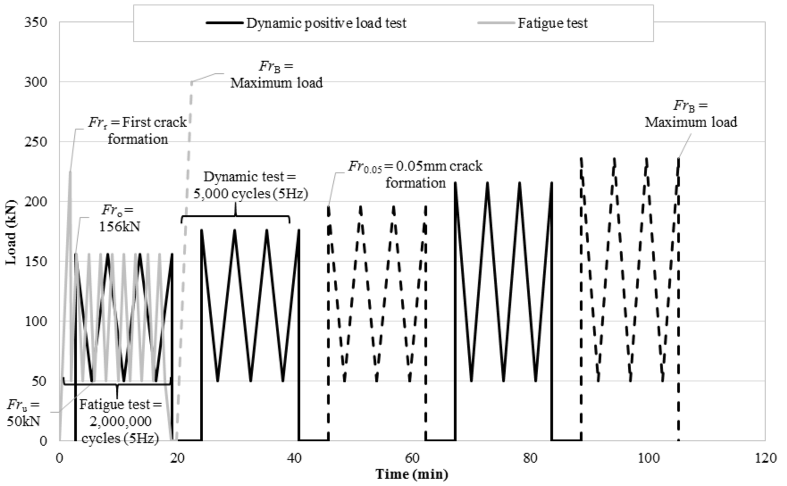


Fig. 8. Dynamic and fatigue test procedures at the rail-seat section [46].

According to the Spanish specification [47], the load ($Fr_{0.05}$) which produces a crack width of 0.05 mm at the bottom after the load removal has to be higher than 1.5 times the initial reference test load (234 kN). The maximum positive test load (Fr_B) has to be higher than 2.2 times the Fr_0, which 343 kN. Two conventional HPC sleepers were tested for the dynamic bending test at rail-seat section, whereas six tests were conducted for HPRAC sleepers in each replacement ratio.

3.4. Fatigue test at the rail-seat section.

The test arrangement for the fatigue test at the rail-seat section was the same as that from the rail-seat section test shown in Fig. 3. The test procedure followed in the fatigue test at the rail-seat section is shown in Fig. 8. The sleepers were initially loaded until the appearance of the first crack. Immediately after the first crack formation, the fatigue loading cycles, which consisted of 2 million cycles of 5 Hz frequency, started. The cycles were restricted to a loading range from a minimum load (Fr_u) of 50kN to a maximum load (Fr_0, reference load) of 156 kN. Finally, the sleeper was loaded until failure with a rate of 120 kN/min to obtain the ultimate load (Fr_B) after the fatigue series.

According to the acceptance criteria from the Spanish specifications, the crack width has to be lower than 0.1 mm and 0.05 mm when loaded at Fr_0 and when unloaded, respectively. The failure load (Fr_B) after the 2 million loading cycles has to be higher than 2.5 times the initial reference load (Fr_0), which is 390 kN. For each concrete mixture, one sleeper was tested according to the requirements from the Spanish specification [47]. Two strain gauges were installed in the centre of each inferior bar in order to study the strain behaviour.

4. Results and discussion

4.1. Static positive load test at the rail-seat section

Both the conventional HPC sleepers and HPRAC sleepers fulfilled the first crack formation regulation requirements. No cracks appeared under the initial reference load (156 kN). As Table 4 shows, the load which produced the formation of the first crack (Fr_r) was very similar to that applied to all the sleepers (219-221 kN). However the results obtained by HPRAC showed a higher variability to those of HPC. In spite of showing higher standard deviations, the Fr_r value of HPRAC sleepers were sufficiently high to ensure their acceptance requirements according to the Spanish standard [47].

Table 4. Results from conventional HPC and HPRAC sleepers with 50 and 100% of RCA for the static and dynamic load tests at rail-seat (RS) and centre (C) sections and their correspondent minimum requirements [47] (standard deviation in brackets).

			Requirement	*HPC*	*HPRAC-50*	*HPRAC-100*
Static tests	**Positive load at RS section**	**Fr_r (kN)**	156.0	221.0	226.0	219.3
				(15.0)	(21.0)	(33.5)
		$Fr_{0.05}$ (kN)	280.0	396.0	386.0	384.3
				(0.0)	(16.7)	(18.6)
		Fr_B (kN)	390.0	501.0	476.0	464.3
				(5.0)	(38.0)	(47.8)
	Negative load at C section	**Fc_r (kN)**	42.5	52.5	57.5	52.5
				(0.0)	(0.0)	(0.0)
		Fc_B (kN)		112.5	111.0	115.8
				(0.0)	(6.3)	(2.4)
	Positive load at C section	**Fc_r (kN)**	30.0	70.0	66.7	71.7
				(0.0)	(9.4)	(2.4)
		Fc_B (kN)		140.0	140.0	141.7
				(0.0)	(4.1)	(2.4)
Dynamic tests	**Positive at RS section**	**Fr_r (kN)**	156.0	244.0	225.0	218.0
				(10.0)	(24.2)	(32.6)
		$Fr_{0.05}$ (kN)	234.0	353.0	348.2	348.2
				(10.0)	(14.9)	(15.9)
		Fr_B (kN)	343.0	413.0	423.0	419.7
				(10.0)	(25.8)	(24.3)
	Fatigue test at RS section	**Fr_r (kN)**	156.0	206.0	256.0	196.0
		Crack width loaded	> 0.1 mm	OK	OK	OK
		Crack width unloaded	> 0.05 mm	OK	OK	OK
		Fr_B (kN)	390.0	486.0	506.0	466.0

The average results of the $Fr_{0.05}$ load, which produced cracks of 0.05-mm width, as well as the Fr_B, failure load, of all sleepers satisfied the minimum requirements [47]. The average $Fr_{0.05}$ load value obtained by the HPRAC sleepers were 3% lower than that of the HPC sleepers for both replacement ratios. Moreover, the average failure load (Fr_B) of the HPRAC-50 and the HPRAC-100 sleepers were 5% and 3%, respectively, lower than that of the conventional HPC sleepers. However, the difference between the average values obtained from the HPC and the HPRAC sleepers proved to be lower than the standard deviation values of the HPRAC. It is also worth mentioning that the results of the HPRAC were slightly higher than those of the prestressed concrete sleepers commonly used in South Korea [31, 43].

Fig. 9 shows the results given by the strain gauges installed at the centre of the rail-seat section in the inferior bars of the sleepers. The behaviour results obtained from the HPRAC sleepers were very similar to those obtained from the HPC sleepers. However the flexural stiffness of the HPC sleepers was slightly greater than that of the HPRAC sleepers.

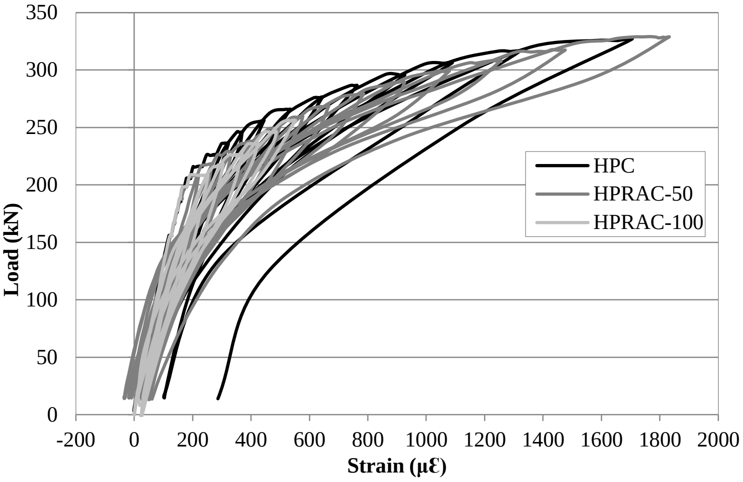


Fig. 9. Load-strain results from static load test at rail-seat section of HPC and HPRAC sleepers.

According to Koh et al. [31], the recovery capability indicator of damaged sleepers can be measured via the subtraction $Fr_r - Fr_{0.05}$. The recovery indicator of the HPC sleepers (175 kN) was very similar to that of the HPRAC sleepers (160-165 kN). Moreover the obtained results were significantly higher than those results obtained by conventional prestressed concrete sleepers presented by Koh et al. [31]. Those results pertaining to those normally used by the Korean railway industry.

4.2. Static load test at the centre section

4.2.1.Negative design

The results obtained via the static negative load test at the centre section of all three types of concretes are indicated in Table 4. In all the tested HPC and HPRAC sleepers, the first crack formation appeared after exceeding the Fr_0 value, which is the initial load reference value. The results from HPRAC sleepers were generally similar than those from HPC sleepers, however HPRAC-50 sleepers reached the highest loads preceding the first crack appearance. Consequently, the results revealed that the use of HPRAC at any replacement ratio had no influence on the static negative load's results.

The results obtained of conventional and eco-friendly prestressed concrete sleepers tested by Koh et al. [31, 42] were significantly higher than the values obtained in this research work. The concretes used in those studies had a characteristic compressive strength of 58-73 MPa at 28 days and the initial cracking formation loads (Fc_r) were 92 - 110 kN. Although the lower compressive strength of the sleepers tested by Koh et al. studies [31, 42] (the compressive strength of the HPC and the HPRAC mixtures was of 100-102.5 MPa, see Table 3), the Fc_r values obtained by Koh et al. were higher than those found in this study due to the use of higher amount of prestressing bars.

All three sleepers described similar slopes on the elastic zone, as shown in Fig. 10. The HPC and HPRAC-100 sleepers had also very similar plastic behaviour. All concrete sleepers showed small yielding, the same load being applied for the first crack formation and very similar strain results obtained for each step of loading.

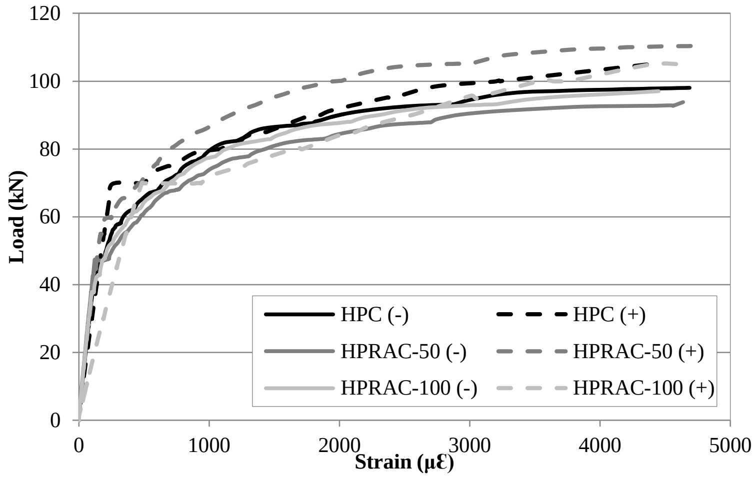


Fig. 10. Load-strain results from static negative and positive load tests at centre section of HPC and HPRAC sleepers.

In the HPRAC-50 sleepers, the formation of the first crack was produced at higher loads than that applied on the other concrete sleepers, as previously mentioned. Moreover, since the occurrence of the first crack, the HPRAC-50 sleepers showed slightly higher yielding and higher strain values than those found in the HPC and HPRAC-100 sleepers.

4.2.2. Positive design

For all sleepers, the positive loads (Fc_r) which caused the formation of the first crack at the centre section were much higher than the initial reference load (Fc_0) (See Table 4). The results of HPC and HPRAC-100 were very similar. The average Fc_r and Fc_B load values achieved by the HPRAC-100 sleepers were only 2% and 1%, respectively, higher than those of the HPC sleepers. The HPRAC-50 sleeper achieved 5% lower Fc_r load value than that of the HPC sleepers, and the Fc_B value of the HPRAC-50 was similar to that of the HPC sleepers. In spite of the minor variations in the test results between HPC and the HPRAC sleepers, their behaviour, according to their standard deviations on the static positive load test, was considered the same. The HPRAC sleepers' results deviation were higher than those of the HPC sleepers, nonetheless most of them represented less than 5% of variability, which ensured their wide acceptance according to the requirements given by the Spanish regulation.

Fig. 10 indicates the results of the static positive load test, which was obtained by strain gauges adhered to the inferior bars which were located at the centre section. The gauges of the HPC and HPRAC-50 sleepers showed similar elastic slopes, however the gauges of the HPRAC-50 sleepers showed lower yield point than those obtained by the HPC sleepers. The gauges of the HPRAC-100 sleepers showed lower slopes on the elastic zone, however they achieved a similar yield point to that of the HPC sleepers.

4.2.3. Prediction of the ultimate capacity of HPC and HPRAC sleepers at centre sections.

After introducing all the parameters in a specific sectional analysis software, it was possible to obtain the ultimate bending capacity values of the cross-section in both their negative and positive orientations. The output of the analysis for positive loading is described in Fig. 11.

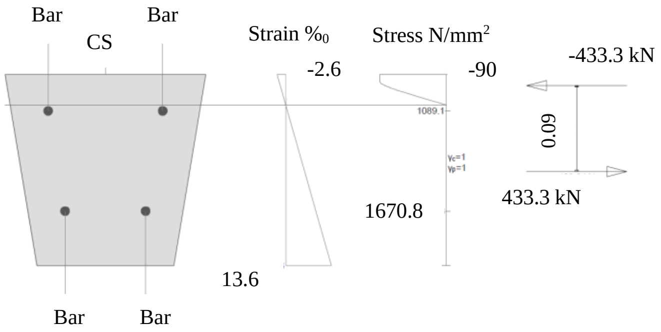


Fig. 11. Cross-sectional strain-stresse on concrete and steel.

As expected, the failure was produced due to the crushing of the concrete's specimens' compression head as detected in the experimental work. However a high ductile behaviour of the cross-section was detected just before the failure occurred, and the prestressed bars reached deformations of up to 15%. In Table 5 the ultimate moment, M_u, of the cross-section using the different methods is described. The corresponding applied load, as described previously in section 3 (test setup) is also indicated in the same table. The load was calculated by applying the expression:

$$F_u = \frac{4 \cdot M}{L} \tag{1}$$

Where F_u corresponds to the external applied load in the 3-point bending test, L corresponds to the total span length and M to the applied moment in the mid-span cross-section due to the external load.

Table 5. Ultimate moment and load of the cross-section using the different methods.

	Bilinear	*Quadratic parabola*	*Parabolic-rectangle (EC2)*	*SIA 262*
Mu (negative design)	40.2 kNm	41.65 kNm	39.9 kNm	40.8 kNm
Fu (negative design)	105.6 kN	109.4 kN	104.8 kN	107.15 kN
Mu (positive design)	46.1 kNm	47.6 kNm	45.5 kNm	46.7 kNm
Fu (positive design)	121.07 kN	125.02 kN	119.50 kN	122.65 kN

Table 6 shows the ratio between the ultimate load values, which were determined in accordance with the different methods of calculations applied in a cross-section capacity analysis (F_u) with respect to the measured failure load in the tests (F_{test}).

Table 6. Calculated load ratios (F_u/F_{test}) for the HPC and HPRAC mixtures on the negative and positive static designs.

	Negative design			*Positive design*		
	HPC	**HPRAC-50**	**HPRAC-100**	**HPC**	**HPRAC-50**	**HPRAC-100**
Bilinear	0.94	0.95	0.91	0.86	0.86	0.85
Quadratic parabola	0.97	0.99	0.94	0.89	0.89	0.88
Parabolic-rectangle (EC2)	0.93	0.94	0.90	0.85	0.85	0.84
SIA 262	0.95	0.97	0.93	0.88	0.88	0.87

As expected the differences between the four cross-section diagrams used were minimal, however, in all cases the Quadratic parabola method was the one which adjusted better to the test data. In addition, it was observed that the prediction of the ultimate capacity was basically the same in all cases, which confirms that the hypothesis made for the ultimate strain was sufficiently accurate.

The ultimate concrete strain used in the analysis showed, in general good agreement when assessed the positive design section capacity, however it could be a bit conservative when applied to negative design, due to the higher contribution of the concrete. In any case, the value proposed in the EC2 [54] achieved good results and always in the safety side for any type of concrete.

4.3. Dynamic test at the rail-seat section

The results of the dynamic positive load test at the rail-seat section are summarized in Table 4. The HPRAC sleepers, for both replacement ratios, as well as the conventional HPC sleepers met all the requirements defined by the Spanish specifications. The load values which caused the initiation of the crack formation in the HPRAC sleepers were very similar to those values obtained from the static load test. However, the HPC sleepers achieved slightly higher values in dynamic test than in the static load test. Consequently the influence of the replacement ratio in this test can be confirmed. The Fr_r average value of the HPRAC-50 and the HPRAC-100 sleepers were 8 and 11% lower than that of the HPC sleepers, respectively.

The $Fr_{0.05}$ loads average values, which produced a crack width of 0.05 mm, of the HPRAC and the HPC sleepers were higher than the required value of 234kN (Spanish regulations). The $Fr_{0.05}$ load values of the HPRAC sleepers were the same for both RCA replacement ratio concretes and were slightly lower (1.4%) than those of the HPC sleepers. The average ultimate load values, Fr_B, of all the sleepers were higher than those designated as the minimum requirement value of 343 kN. The HPRAC sleepers with 50 and 100% RCA replacement ratios achieved 2.4 and 1.6% higher average ultimate loads, respectively than those of the HPC sleepers. The standard deviations achieved in the HPRAC sleepers were higher than those of the HPC sleepers for all the obtained load test results.

The results achieved by the HPRAC sleepers were very similar to those described by Carpio et al. [34]. In both cases the used conventional HPC sleepers had similar designs. However those sleepers were produced with prestressing bars of 7 mm (smaller diameter than in this research study), thus achieving lower load values in any dynamic test. In contrast, Koh et al. [31, 42] found higher values at the dynamic load test than those obtained by the HPRAC sleepers, however, the difference between these values was smaller than that observed in the static load tests.

According to Koh et al. [31], when compared to static tests, there are certain factors that influence the lowering of strength in dynamic tests. Those factors being: pronounced micro-cracks, weakened bonding strength due to delamination and severe loading conditions. As a result of this phenomenon the minimum requirements for dynamic tests are moderated in most of the international standards. The required load values for the dynamic tests are 16 and 12% lower than those required for the static test according to the Spanish specification. The conventional HPC sleepers achieved 10.9 and 17.6% lower $Fr_{0.05}$ and Fr_{B} values in the dynamic test than those in the static test. However, the dynamic results obtained by the HPRAC sleepers were only 9.4-9.8% and 9.6-11.1% lower than the static $Fr_{0.05}$ and Fr_{B}, respectively. Therefore, the HPRAC sleepers showed superior dynamic behaviours than those of HPC or those considered as the minimum requirements.

4.4. Fatigue test at the rail-seat section.

The fatigue test results, at the rail-seat section, are summarized in Table 4. Firstly, a positive load was applied at the rail-seat section until an initial crack was formed (cracking load, Fr_r) and later 2-million-cycle fatigue load was applied. After the fatigue cycles were applied, the width of the crack was measured in loaded and unloaded conditions. According to the Spanish specification, the crack widths shall not be wider than 0.1 mm and 0.05 mm in loaded and unloaded conditions, respectively. HPC and HPRAC sleepers reported minor cracks which fulfilled both requirements. After the crack measurements, the sleepers were subjected to increased loads until their failure. All the maximum loads of the HPRAC sleepers as well as the HPC sleepers met the minimum requirements of load failure of 390 kN. The HPRAC-50 sleeper achieved the highest failure load and the HPRAC-100 sleeper the lowest. Nonetheless, the HPRAC sleepers' results only varied less than ±5% in comparison to the HPC sleeper's results.

Carpio et al [34] verified that the use of larger diameter prestressing reinforcements and corrugated rebars instead of smooth bars had a beneficial influence on the ultimate fatigue load. Nevertheless, the HPRAC sleepers achieved higher fatigue load values than those obtained by conventional prestressed concrete sleepers according to other researchers [31, 42]. The sleepers tested by them employed a significantly higher amount of reinforcement than that employed in the HPRAC sleepers. In addition, the HPRAC sleepers also achieved similar or higher fatigue load results to those values described by Carpio et al. [34] which used corrugated rebars. Therefore, the high strength of the HPRAC concrete permitted a reduction in the amount of reinforcement while still keeping an adequate dynamic performance.

During the 2 million cycles of the fatigue load test, the strain values were obtained and registered via the use of strain gauges located on the inferior bars at the rail-seat section. Fig. 12 shows the relationship between the strain and loading cycles when the sleepers were both loaded with the initial reference load *Fr*$_0$ and also the lower load *Fr*$_u$. The strain values obtained via the strain gauges were very similar for the HPRAC and HPC sleepers. At first, the strain values of the HPC sleepers were slightly lower than those obtained from the HPRAC sleepers. However, the HPC sleepers showed higher strain increase during the first 400,000 cycles than the HPRAC sleepers. In the following cycles, all three types of sleepers showed similar strains until the test ending. In the following cycles, the strain of the HPC and the HPRAC sleepers achieved stable values of between 120 and 150 µƐ, thus showing similar results between the different sleeper types. Overall, it can be concluded that the fatigue behaviour of the HPRACs sleepers was similar to that of the common HPC sleepers.

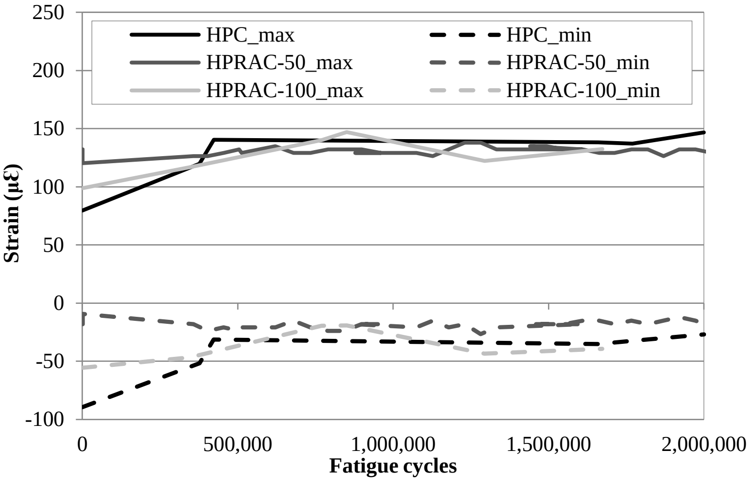


Fig. 12. Strain - cycles results from the fatigue test at the rail-seat section of HPC and HPRAC sleepers (solid line: strain under initial reference load; dash line: strain under minimum load).

5. Conclusions

The main conclusions drawn from the analysis of the structural behaviour of the conventional high performance concrete and the high performance recycled aggregates concrete sleepers subjected to the common static and dynamic tests defined by most international standards, are:

According to the static positive load test at rail-seat section:

- The crack formation load, as well as the failure load of the HPRAC sleepers were slightly lower than that of the HPC sleepers. However the HPRAC and the HPC sleepers fulfilled all European regulation minimum requirements for the first crack and 0.05mm crack formation, as well as the failure load.

According to the static load tests at centre section:

- The cracking loads extensively fulfilled the European regulation minimum requirements, regardless of the materials employed in the sleeper production. Both cracking loads and ultimate loads from HPRAC sleepers were similar or higher than those from HPC sleepers.
- The simplified methods to predict the ultimate capacity of HPC achieved reasonable values when they were applied to HPRAC. The ultimate concrete strain used in the analysis could be considered slightly conservative when applied to negative design, due to the higher concrete contribution. However, results showed that values obtained according to the proposed method stated in the EC2 were good, and were within the safety standards laid down for any type of concrete.

According to the dynamic load test:

- Although the cracking loads of the different HPRAC sleepers were lower than those of the HPC sleepers, the ultimate loads of the HPRAC sleepers were higher than those of the HPC sleepers on the rail-seat section. The load-strain results of the fatigue test revealed lower strain of the HPC sleepers during the initial cycles. However, after the initial cycle period, the HPC and the HPRAC sleepers showed the same strain behaviour up to the end of testing.

In general, the HPRAC sleepers' values presented a higher standard deviation and their load-strain ratio was slightly lower than that of HPC. However, the analysis of the HPC and the HPRAC sleepers confirmed that they met all the European structural requirements for prestressed concrete sleepers. The HPRAC mixtures which contained 50 and 100% high quality recycled concrete aggregates sourced from parent HPC concretes showed very similar structural properties to those of conventional HPC. The concrete waste of rejected sleepers can be reused as RCA, replacing up to 100% of natural aggregates in prestressed concrete sleepers with no significant influence on the structural behaviour.

Acknowledgements

The authors wish to acknowledge the financial support of The Ministry of Economy and Competitiveness (Spain) by the INNPACT Project (IPT-2011-1655-370000).

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