ADVERTIMENT. La consulta d’aquesta tesi queda condicionada a l’acceptació de les següents condicions d'ús: La difusió d’aquesta tesi per mitjà del servei TDX (www.tesisenxarxa.net) ha estat autoritzada pels titulars dels drets de propietat intel·lectual únicament per a usos privats emmarcats en activitats d’investigació i docència. No s’autoritza la seva reproducció amb finalitats de lucre ni la seva difusió i posada a disposició des d’un lloc aliè al servei TDX. No s’autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant al resum de presentació de la tesi com als seus continguts. En la utilització o cita de parts de la tesi és obligat indicar el nom de la persona autora.

ADVERTENCIA. La consulta de esta tesis queda condicionada a la aceptación de las siguientes condiciones de uso: La difusión de esta tesis por medio del servicio TDR (www.tesisenred.net) ha sido autorizada por los titulares de los derechos de propiedad intelectual únicamente para usos privados enmarcados en actividades de investigación y docencia. No se autoriza su reproducción con finalidades de lucro ni su difusión y puesta a disposición desde un sitio ajeno al servicio TDR. No se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al resumen de presentación de la tesis como a sus contenidos. En la utilización o cita de partes de la tesis es obligado indicar el nombre de la persona autora.

WARNING. On having consulted this thesis you’re accepting the following use conditions: Spreading this thesis by the TDX (www.tesisenxarxa.net) service has been authorized by the titular of the intellectual property rights only for private uses placed in investigation and teaching activities. Reproduction with lucrative aims is not authorized neither its spreading and availability from a site foreign to the TDX service. Introducing its content in a window or frame foreign to the TDX service is not authorized (framing). This rights affect to the presentation summary of the thesis as well as to its contents. In the using or citation of parts of the thesis it’s obliged to indicate the name of the author

Sustainability concepts applied to the design of recycled aggregates concrete

DOCTORAL THESIS

Doctoral thesis written by:
Cristián Jiménez Fernández

Directed by:
Marilda Barra Bizinotto
Susanna Valls del Barrio

Barcelona, March 2015

Universitat Politècnica de Catalunya
Departament d´Enginyeria de la Construcció

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Marilda Barra Bizinotto) Principal Co-Advisor

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Susanna Valls del Barrio) Principal Co-Advisor

Abstract

Due to the related problems and the ongoing awareness on environmental issues is that efforts are put in different areas of knowledge, in order to determine, analyze and formulate solutions towards a sustainable future. Among these problems, there are the ones related with the use of concrete in the construction sector. These are essentially related to the natural resources used for their production and to the manufacture of cement, one of its most important components.

As of today, one of the solutions is recycling the concrete for the production of aggregates, which can be used in the elaboration of new concrete mixes. This is in fact not the best solution as, albeit the natural aggregates utilization is reduced and consequently the depletion of natural resources is as well, more quantities of cement are needed to achieve comparable properties to those of the natural aggregates concretes, being cement a relevant contributor to global warming.

A novel method for recycled aggregates concrete design, so-called 'Equivalent Mortar Volume', aims on solving the aforementioned issues by basing its principles on the idea that recycled aggregates are materials that are composed by two phases, the natural aggregate and the attached mortar to it, and by taking into account the attached mortar as part of the new mortar required by design in the concrete mix. With this, the needs for cement are reduced while still using recycled aggregates and achieving similar properties to those of the natural aggregates concretes. The method always starts from a concrete design made with the American Concrete Institute method as a base. The novel essence of the method encourages to investigate more about its properties and the possibilities to broaden its scope, for which the present doctoral thesis is proposed.

On a initial stage, the Equivalent Mortar Volume method is studied and an adaptation of it is proposed in order to broaden its scope by making it able to start with other design methodology than the American Concrete Institute one. This is achieved by designing different concrete mixes and by analyzing the different calculation steps that the method involves. From the work carried out, it is concluded that the method represents a feasible and environmentally friendly solution, and that it can be adapted to another concrete design methodology.

The next stage consists on the obtention and analysis of some of the fresh state, mechanical and durability properties of the different concretes, and to evaluate the use of different methodologies for the concretes design. This was achieved by elaborating extensive experimental campaigns of different concretes mixes and by assessing them when appropiate. The findings of these campaigns show that the concretes designed with the novel method achieve, in the majority of the studied properties, comparable results to those of the natural aggregates concretes.

In the following stage, the rheological properties of the concretes are studied by means of a viscometer apparatus. This was done with the aim of having a deeper understanding of some of the properties that the method affects the most. It was observed that the concretes designed with the novel method can achieve similar rheological properties to those of the natural aggregates concretes, when combining the use of certain admixtures.

The final stage consists on the assessment of the environmental impacts that different selected concrete mixes generate. This was done with a Life Cycle Assessment methodology and comprised the evaluation of four different concrete mixes. The results indicate that the concretes designed with the novel method achieve better environmental performances and that cement is the most influential material for the most of the studied categories, which may be changed if additivated cements are used.

Resumen

Debido a los problemas relacionados y a la actual concienciación sobre los temas medioambientales es que se están haciendo diversos esfuerzos en diferentes áreas del conocimiento, de manera de determinar, analizar y formular soluciones para lograr un futuro sustentable. Entre estos problemas están los que se relacionan con el uso del hormigón, en el sector de la construcción. Éstos se refieren fundamentalmente a la utilización de recursos naturales para la producción de hormigón y a la fabricación de cemento, siendo este último uno de sus principales constituyentes.

A día de hoy, una de las soluciones es el reciclaje de hormigón para la producción de áridos, que luego pueden ser utilizados en la fabricación de nuevos hormigones. Sin embargo, ésta no es la mejor solución, ya que si bien se reduce la utilización de áridos naturales y, por consiguiente, la explotación de recursos naturales, son necesarias mayores cantidades de cemento para lograr propiedades comparables a las de un hormigón de áridos naturales, siendo el cemento un importante contribuidor del calentamiento global.

Un innovador método para el diseño de hormigones de áridos reciclados, llamado 'Equivalent Mortar Volume' (Volumen de Mortero Equivalente), apunta a solucionar los problemas mencionados anteriormente basándose en la idea de que los áridos reciclados son materiales constituidos por dos fases, el árido natural y el mortero adherido a ellos, y en considerar el mortero adherido como parte integrante del nuevo mortero requerido por diseño en el hormigón. De esta manera se reduce la demanda de cemento, se siguen utilizando áridos reciclados y se consiguen propiedades similares a las de un hormigón de áridos naturales. El método siempre parte de la base de un hormigón diseñado con la metodología del American Concrete Institute (Instituto de Hormigón Americano). La esencia innovadora del nuevo método es la que anima a investigar más acerca de sus propiedades y las posibilidades de ampliar su alcance, razones por las cuales se propone la presente tesis doctoral.

En una etapa inicial, el método es estudiado y se propone una adaptación de éste, de manera de poder comenzar desde un diseño hecho con otra metodología diferente a la del American Concrete Institute. Lo anterior se logra mediante el diseño de diversas mezclas de hormigón y el análisis de los diferentes pasos de cálculo que conllevan. Las conclusiones obtenidas son que el método representa una solución viable y medioambientalmente amigable, y que puede ser adaptado a otro método de diseño de hormigones.

La siguiente etapa consistió en la obtención y el análisis de algunas propiedades en estado fresco, mecánicas y de durabilidad de los diferentes hormigones, y en la evaluación de diferentes metodologías de diseño de éstos. Esto se logró mediante la elaboración de extensas campañas experimentales de hormigones y de sus correspondientes análisis. De estas campañas se deduce que los hormigones diseñados con el nuevo método alcanzan, en la mayoría de los casos, propiedades comparables a las de hormigones de áridos naturales.

Posteriormente se realiza un estudio de las propiedades reológicas de los hormigones mediante la utilización de un viscosímetro. Esto se ha hecho con la finalidad de obtener un conocimiento más profundo sobre algunas de las propiedades en las que el método tiene gran incidencia. Se observa que los hormigones diseñados con el nuevo método pueden alcanzar propiedades reológicas similares a las de los hormigones de áridos naturales si se utilizan, de forma combinada, ciertos aditivos.

La etapa final consiste en la evaluación de los impactos ambientales que producen diferentes hormigones seleccionados. Esto se hace con la metodología de Life Cycle Assessment (Análisis de Ciclo de Vida) y contempla la evaluación de cuatro hormigones diferentes. Los resultados indican que los hormigones diseñados con el nuevo método alcanzan mejores comportamientos medioambientales y que el cemento es el que más contribuye en las diferentes categorías de impacto analizadas, lo que podría modificarse si se utilizaran cementos con adiciones.

Acknowledgement

First of all, I would like to thank my doctoral tutors Marilda Barra and Susanna Valls, for all the support they have given me along these years, by providing me with countless advices and ideas that go beyond the subjects that are here presented. Also, I want to show my gratitude to Enric Vázquez, who has been fundamental on the inception and development of this investigation, and whose expertise I consider priceless. In addition, I would like to express my sincere appreciation to Alejandro Josa, whose knowledge has helped me to develop an important part of this work, and for the invaluable conversations and his always diligent assistance.

I want to thank the Technical University of Catalonia (UPC) and, particularly, the Construction Materials and Highways (MATCAR) research group, for the FPI-UPC full scholarship they have granted me, which supported me to develop the doctoral research process. Also, I thank all the administrative and laboratory staff, specially to Eufronio, whose experience and advices I am grateful for the possibility to have shared with.

My special thanks to Diego, Gustavo, Karmele, Alexandra and Flora, whom I will always remember and for which I feel fortunate for the possibility of sharing these years with, far beyond the working hours. To the people in Santander and particularly to Carlos, who is one of the persons that first introduced me on this field, and whose guidance and support were fundamental. Also, to two of my dearest friends, Paulo and Jota, for their friendship, for walking with me on the beginning of this journey and for all the good times yet to come.

I thank all of my friends, for their support and for that they are one of the most valuable gifts I could have, and Karen, for the comprehension, patience and support she gave me all of this time.

Finally, I want to dedicate this Thesis to my brother, my sister, my mother and my father, as they are the pillars of my life, the reason of what I have become, my inspiration and my daily motivation.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Among the main productive sectors of countries, construction is one of the most important ones in terms of volume and capital movement. In Europe, this sector represents about 10% of the gross domestic product and employs around 12 million European Union citizens (European Committee for Standarization, 2015). Within this sector there are other sub-sectors among which building and civil works are the ones that stand out the most. These sub-sectors represent the engine of the different economical activities in construction, referring it to the primary, secondary and tertiary sectors. All of this suggests that, if some variations are produced on the most used material in construction, there will be important changes at an economical, environmental and social levels.

Among the environmental issues, there is a problem related to the indiscriminate use of natural resources, which may turn these activities unsustainable due to the resources depletion. This occurs in a cross-cutting manner among different areas, with greater or lesser intensity depending on the necessity that human activities have over these resources, and to the existing use quotas. These are some of the reasons that make new ideas to appear, like renewable energies for power supply, new fuels and the adaptation of technologies in the transportation sector, or materials recycling and innovation in the construction field. The idea of a 'sustainable development' also arises, which gets stronger with the publication of the United Nations report 'Our Common Future', better known as the 'Brundtland Report', and that describes it as the ability that ensures to meet the needs of the present without compromising the ability of future generations to meet their own needs (Worl Commission on Environment and Development (United Nations), 1987).

During some years until now, sustainable construction (a concept that arises as many others from the sustainable development idea) has been progressively growing and taking into account several fields of interest, being now of great importance due to the awareness-raise of the society towards environmental issues. One of these fields is related to the re-utilization and recycling of waste coming from demolition and construction activities. This goes towards new ideas that imply a reformulation of processes, development of new materials, improvement of existing materials, among others, with the objective of making them more environmentally friendly.

In Europe for example, the impact has been such that new specific committees have been created, together with the development of new standards and guidelines that go towards an integral sustainable development. The progresses are of great importance, but there is still much to do. In the case of construction and demolition waste recycling rates, in the period between 1996 and 2006, Netherlands, Germany and Denmark have overpassed the 80%, while in Spain these numbers lay bellow 20% (European Topic Centre on Resource and Waste Management, 2009). However, recent statistics from the autonomous community of Catalonia, in Spain, show that around 58% of the construction residues were taken to a valorization plant (recovering and recycling) and the rest has been taken to monitored landfills (Agència de Residus de Catalunya, 2010), which far exceeds the average of Spain. Examples like this show us the existing disparities on this subject, and makes us believe that a proper strengthening of the system is needed in order to achieve similar objectives in different places.

In the specific case of concrete, which is a well-known material and the most used in the construction sector (Razaqpur et al., 2010; Glavind and Munch Petersen, 2012), its recycling is only a practice of developed countries, achieving high levels of utilization depending on the local policies and regulations.

Even though concrete is an environmentally friendly material (Glavind and Munch Petersen, 2012), its production volumes and subsequent disposal when treated as a residue generates a problem in urbanized areas, where the space for such practices is limited, together with the fact that it needs natural aggregates (NA) for its production and so it provokes great consumption quantities of natural resources (ACI Committee 555, 2001). These are some of the reasons for which concrete recycling for the production of recycled aggregates (RA), which can be used in the production of new concretes, is of great importance.

1.1 Current situation

Because of the current emphasis on environmental issues is that there are different standards and guidelines for the correct utilization of construction and demolition waste, and also several initiatives towards the correct use of these resources. Recycled aggregates concrete (RAC) is one of these initiatives, as it uses these residues as a part of its components.

In Belgium, the production of RA is estimated to be around 14.5 million tonnes a year, from which more than 99% is used in the construction of roads related works and less than 1% in structural concrete. Concerning this last case, there is a draft regulation identified as prNBN B15-001:2001 in which the use of RA is limited to 20% for structural concretes application, in terms of the total coarse aggregates volume (Vrijders and Desmyter, 2013).

Brazil has some initiatives towards recycling activities, although nearly 90% of the concrete and masonry structures are directly eliminated with no recycling at all, and less than 5% of the total of generated residues pass through a recycling facility. According to Vanderley and Angulo (2013), 10% to 20% RA replacement in concretes does not seem to be interesting for the industry, even though it is technically approved.

Razaqpur and Fathifazl (2013) comment that, by the year 2000 in United States of America, approximately 100 million tonnes of recycled concrete aggregate were produced, from which 68% was used in road works, 14% as fills, 9% as aggregates for asphalt, 6% in concrete and 7% in other applications. In Canada, the objective is to reach a 75% of recycling of the materials used in new constructions, but no specifications are handed out concerning the processes involved in such intentions. The authors think that the reasons behind the limited utilization of RA in structural concrete are their vast use in road constructions, the lack of evidence about their economical advantages when compared to conventional aggregates, the lack of quality and control guidelines, and the available publications sustaining that they possess worse technical characteristics than conventional aggregates.

China is accountable for around 55% of the cement consumption worldwide and generates around 200 million tonnes of concrete waste yearly, together with the contributions of recent years earthquakes. This is why many studies have been elaborated in order to encourage the use of recycled materials, specifically covering several properties of RAC (Xiao, 2013).

One of the most developed countries in terms of waste recycling and RAC production is Germany, with over 70% recycling of residues from different sources. However, only 4% of this is used on concrete applications, even when their standards allow greater percentages of aggregates replacement ratios of up to 45% (Mueller, 2013).

Netherlands is one of the leading countries in waste recycling and re-utilization. One of the reasons for this is their lack of natural resources, due to their special geographical characteristics. Their recycling rates are around 90% of the total produced and their standards state that there are no restrictions of replacement rates for the use of aggregates in concrete. The standards only specify some parameters that the aggregates must comply with (Vázquez, 2013b).

Another of the countries that is leading important developments on this matter is Portugal. Martins (2013) states that the standards for RAC allows the use of 100% RA in the case of non-structural concrete in non-aggressive environments, and up to 25% in structural concretes submitted to certain classes of environmental exposure.

In the year 2008, in Spain, the approximated production quantity of construction and demolition waste were 38 million tonnes, from which only 15% were processed. Similar to other countries, most of the RA are used in road works and only a small part is used in ’emblematic’ constructions of structural concrete (Vázquez, 2013a). The Spanish Code for Structural Concrete (Spanish Ministry of Public Works, 2008) allows up to 20% replacement of RA in structural concretes, and it does not establishes a limit for mass concrete.

1.2 Problem statement

As of today, RAC design is done by simply using conventional proportioning methods, taking into account some of the properties differences between NA and RA, as their density, porosity and water absorption, among which the later one presents the greater variations.

Something that is worth noting, is that the mix designs are based in the use of greater quantities of cement to achieve similar behaviours of those of the natural aggregates concretes (NAC), which implies that, even when RAC helps on reducing the use of natural resources, lessens land-filing, may reduce CO_2 emissions caused by the transportation of aggregates, among others, it increases CO_2 emissions and may raise the cost of a unit of concrete due to the larger cement amounts.

A report from the Environmental Protection Agency from United States of America (Environmental Protection Agency (EPA), 2011) shows the importance, in terms of CO_2 emissions, that cement production implies among several industrial processes. After iron, steel and metallurgical coke production (41 teragrams), cement production achieves the second place with 29 teragrams, overpassing by far the third activity (ammonia production and urea consumption with 11.8 teragrams). Maier and Durham (2012) states that Portland cement is the one that most greenhouse gases produces from all of the components of concrete.

This said, the reduction of the commonly used cement quantities for RAC production should become in an effective measure when attempting on reducing the energy consumption and CO_2 emissions that concretes production implies.

1.3 Motivation

The initiatives towards the improvement of the recycling activities are usually obstructed due to diverse factors, as the economical, technical and management ones, between others. The small rates of RA utilization in concrete production are an example of the aforementioned, being restrained by variables that may be improved.

In the technical aspect for example, RAC have a problem related to their behaviour, when compared to NAC. Economically speaking, while the price of one tonne of RA may be lower than conventional aggregates, in specific cases, the needs for greater amounts of cement in order to achieve similar properties of those of NAC ends up being a decisive factor when deciding between one or another alternative.

The accomplishment of a RAC design that fulfils the existing technical restrictions, that achieves similar or even greater behaviours than NAC, that minimizes the cement consumption and so making it more economical and environmentally friendly, and that represents an innovative and disruptive idea, are enough reasons for the study of such mix proportioning design. In this regard, a novel method for RAC design will be analysed and evaluated.

The so-called 'Equivalent Mortar Volume' method (Fathifazl et al., 2009) meets the aforementioned conditions, and so its improvement based on technical and scientific data becomes necessary; an improvement able to place it as one of the first choices when designing certain structure where concrete is one of the constituting materials.

The novel method reduces the commonly used amounts of cement by taking into account the attached mortar to RA and counting it as part of the total mortar needed by design on the mix. With this, there will be a reduction of the fresh mortar needed by the concrete; consequently reducing the needs for cement as well. Also, due to the reduction of the fresh mortar is that the concrete mixes designed with this method should be further analysed regarding their rheological characteristics, in order to evaluate the possible implications that this reduction has on the concretes fresh state properties. To the author's knowledge, there are no much more studies regarding the rheological properties of recycled concretes apart from the ones presented on this investigation.

Due to the fact that the method is of recent invention, more analyses are required in order to warranty its effectiveness by assuring certain robustness of its data. Also, because of this is that there is a great possibility to discover new applications, generate adaptations related to specific cases, apply different factors as the use of admixtures, types of cement or types of aggregates, among others; in summary, diversifying and broadening its actual scope.

The study of the Equivalent Mortar Volume method for RAC design and of the properties of the concretes designed with it is of high importance, as it may represent a big leap forward in terms of the protection of the environment.

1.4 Objectives

The core objective of this investigation is to study, analyse and offer new solutions and data about the use of recycled aggregates in concrete and the methodologies used for their design.

The specific objectives of this investigation are listed below.

- to study the Equivalent Mortar Volume method for recycled aggregates concretes design, and to determine its feasibility of use, when using other materials and methodologies;
- to obtain and analyse some of the fresh state, mechanical and durability properties of the different studied concretes, designed with different mix proportioning methodologies and comprising the use of natural and/or recycled aggregates for their elaboration;
- to obtain and analyse the rheological parameters of the concretes in terms of the yield stress and plastic viscosity parameters by means of a viscometer apparatus;
- to make an evaluation of the resulting environmental burdens from applying different mix proportioning methodologies on the production of concrete, involving the use of natural and/or recycled aggregates.

1.5 Structure of the document

This document has been divided in nine chapters, some of which presents the findings that have been published in recognized international magazines, one congress and in the 'Recycled Concrete' section of the book 'Progress of Recycling in the Built Environment' Vazquez (2013) presented by the International union of laboratories and experts in construction materials, systems and structures (RILEM). The first-authored publications can be consulted in references Jiménez et al. (2013a), Jiménez et al. (2013b) and Jiménez et al. (2015). Also, the co-authored publications can be consulted in references Vázquez et al. (2013) and Faleschini et al. (2014), in which the first of these references was published as a result of an award granted to excellent papers presented in the International Conference on Sustainable Construction, Materials & Technologies in Kyoto, Japan, in August 2013. These publications will be referenced along this document when appropriate. The document chapters are summarized below.

In Chapter 1, the main aspects encouraging this investigation are mentioned, by presenting a brief introduction to the subject under study, the current situation, the problem statement and the motivation. Also, the main objectives of the investigation are declared and the methodology that has been followed to write the present document is presented.

Chapter 2 presents a comprehensive study of the most relevant characteristics of RAC is presented. These refer to the main properties of RA and RAC, some of the used mix design methodologies and the environmental characteristics of the material.

Chapter 3 shows the a description of the different materials used for the elaboration of the concretes and the experimental campaign results for the selected aggregates.

In Chapter 4, a brief review of the Equivalent Mortar Volume method for RAC design is presented. Also, the three different experimental campaigns mix proportions are shown, together with the selected methodology for the elaboration of the concretes.

Chapter 5 presents the studied fresh state properties and the hardened state mechanical properties results of the different experimental campaigns. The durability properties of these concretes are shown in Chapter 6.

Chapter 7 presents a more comprehensive study of the workability characteristics of the concretes regarding its rheological parameters. This study has been done with the concretes of the third experimental campaign.

Chapter 8 presents an environmental assessment of some of the concretes of the first and second campaigns. This is done by means of the Life Cycle Assessment methodology.

The final conclusions of the different chapters are finally presented in Chapter 9 and 10.

Chapter 2

State of the Art

In this chapter, the most relevant characteristics of the recycled aggregates concretes (RAC) will be presented, like the materials used for its elaboration, production practices, its main properties, applications and innovation. This is done by reviewing the most relevant investigations up to date, emphasizing on the newest ones in order to show the path followed until now, and also the ones that are of fundamental character due to their importance.

2.1 Recycled aggregates concretes materials

The materials used for the elaboration of RAC are mainly the same as the ones used in natural aggregates concretes (NAC). The only one difference are the recycled aggregates (RA), which give are responsible for the name of the mentioned material. The quantities of these materials are the ones that could have a major difference between these concretes.

The RAC will be composed mainly of water, cement, natural aggregates (NA), RA, and additions and admixtures when necessary. The RA is the one conditioning the use of the rest of materials, whether in quantity or type, issues that will be reviewed in the following sections of this chapter.

It is worth noting that in this investigation the RA comprise only the coarse part of them (>4 millimetres), and so these will be the ones to which this chapter will be focused to, and to which RA will be referring to when mentioning them along the rest of this document.

2.1.1 Recycled aggregates

RA are produced by crushing construction and demolition waste (C&DW), in which three main activities can be pointed out:

- New constructions,
- repairs, renovations and maintenance,
- and demolitions.

Once a certain structure is identified for the residues obtaining, a good practice would be to organize a team for an on-site selective recovery of the materials used in the production of RA. With this, handling the material at the recycling facilities would become easier as the separation process gets assisted from a previous stage.

After the recovery, the materials are taken to a treatment plant which can be either on-site or off-site, and a series of stages of selection and cleaning are executed. Among these stages, it is worth mentioning the separation of metallic, soil, gypsum and organic materials. All of this is done in order to obtain a material that is free from impurities that may affect the quality of the RA and the elements where it will be used in.

Once these impurities are eliminated, the following process would be the crushing. This process is of high importance as it will produce the different shapes and sizes of the aggregates, properties that are essential when designing a certain type of concrete. There are different types of crushers, among which the jaw, impact, cone and hammer crushers are the most utilized. 37-DRC (1992) indicates that an adequate sieve size distribution of the RA, for their use in concrete, is better obtained when jaw crushers are used, whereas impact crushers are more suitable for obtaining materials used in road bases layers. Although this, recent investigations indicate that an efficient production is achieved by combining a series of crushers, starting with a jaw crusher which is able to handle larger particles sizes at lower cost, followed by a cone or impact crusher in order to obtain a good quality aggregate (Waste and Resources Action Programme (WRAP), 2013).

After the crushing process, the production finishes by stockpiling the material by type and the different sizes that are required.

2.1.1.1 Main properties

The physical properties of RA differ from the ones of the NA mainly because of the attached mortar they contain.

- Density: The densities are, in general, lower than the ones of conventional aggregates, due to the impurities that they may contain and the attached mortar they have. As the attached mortar is less denser than NA, the average density of the group (attached mortar and NA) is lower. Several publications have reported these differences, which are between 100 kg/m^3 and 400 kg/m^3(Barra, 1996; Corinaldesi, 2010; Kou et al., 2011; Maier and Durham, 2012; Kim and Yun, 2013; Lima et al., 2013; Panda and Bal, 2013; Jiménez et al., 2013a).

- Porosity: Mainly due to the attached mortar and also because of the impurities, RA will normally have greater values on this property. These values lie around 2 to 5 times the porosity of a NA (Barra, 1996; Corinaldesi, 2010; Kou et al., 2011; Thomas et al., 2013).

- Absorption: This is the property that presents the greatest differences among RA and NA. Again, this is mainly due to the attached mortar, and the differences may go from 2 to as high as 10 times the values that NA have (Barra, 1996; Etxeberria et al., 2007; Corinaldesi, 2010; Kou et al., 2011; Maier and Durham, 2012; Martínez-Lage et al., 2012; Florea and Brouwers, 2013; Kim and Yun, 2013; Lima et al., 2013; Thomas et al., 2013; Jiménez et al., 2013a).

- Sieve size distribution and particle shape: These properties are closely linked to the production processes, where their special configurations will lead to the different results and the required characteristics. They should also not vary significantly when compared to NA, thus fulfilling the requirements of the majority of the recommended grading envelopes for concrete production.

The chemical properties are mainly linked to the type of impurities that RA have and to the environmental exposure that the structures, from where they were obtained, were exposed to. These are interesting points that show why the selective demolition or selective materials recovery processes are so important.

- Organic impurities: These will affect the mechanical and durability properties of the concretes. Martín-Morales et al. (2011) indicates that organic impurities will have undesired effects on the concrete's setting speed, and also will affect the adherent capabilities, thus influencing the mechanical and durability performances.
- Chlorides content: C&DW could present important chlorides content depending on their origin. Normally, this kind of contaminants will be present in residues coming from structures being subjected to freeze and thawing cycles because of the use of de-icing salts, from waste-water treatment plants, or from the ones that were placed in marine environments. Chlorides are one of the main agents causing corrosion in concrete rebars, which can lead to important damages due to the expansive effect that iron oxides provoke. The Spanish Code for Structural Concrete(Spanish Ministry of Public Works, 2008) establishes a maximum value of 0.05% of water soluble chlorides (in terms of weight) for both RA and NA when used in reinforced concrete or concretes with skin reinforcement, also, for prestressed concrete, the maximum value is of 0.03%.
- Sulphur content: These can cause damages due to expansive reactions when placed in contact with some of the compounds of cement and water. Spanish Ministry of Public Works (2008) indicates a limit value of 1% in terms of weight.
- Sulphates content: As in the previous case, these compounds could lead to expansion problems when in contact with cement and water. Tovar et al. (2013) studied the expansion caused in mortars with RA when adding sulphates in the form of gypsum, concluding that even with a 2.9% content, a structure should not be damaged along a 50 years lifespan. This content triplicates the prescribed limit by Spanish Ministry of Public Works (2008).

The Spanish Guide of Recycled Aggregates (Asociación Española de Gestores de Residuos de Construcción y Demolición (GERD), 2012) establishes that the majority of the RA produced in Spanish treatment plants fulfil the minimum requirements on their properties, when these installations are in possession of efficient cleaning systems.

2.1.1.2 Composition

The different compositions of the RA are mainly due to the diversity of the C&DW sources. Depending on the geographical locations and the applied constructive techniques, RA will comprise different specific compounds.

In the Spanish building sector, the use of brick as one of its main component, makes C&DW to have great quantities of this type of materials. Also, the use of gypsum as a coating material for walls and ceilings may provoke the aforementioned problems related to sulphates if found among the C&DW.

In the case of the civil works sector, reinforced concrete becomes the main material, which can be related to a greater quality of their residues, as they will comprise less undesired materials and have better overall properties. Although this material will have considerable amounts of reinforcement, these can be easily detected and completely eliminated from the final material.

Residues coming from the construction of roads and highways will comprise significant amounts of bituminous impurities, which, as commented by 37-DRC (1992), will negatively influence the compressive strength of concretes comprising this type of materials.

The Spanish Guide of Recycled Aggregates (Asociación Española de Gestores de Residuos de Construcción y Demolición (GERD), 2012) proposes a RA categorization, in order to objectively classify them according to their compositions. The proposal is composed of five categories, which can be seen in Table 2.1. These have been translated to English for the sake of this document comprehension.

Table 2.1: Proposal for the categorization of different recycled aggregates

Denomination	Name	Characteristics
RCA	Recycled Concrete Aggregates	Na+C>90% Ce<10% B<5% X<1%
MRCA	Mixed Recycled Concrete Aggregates	Na+C>70% Ce<30% B<5% X<1%
RCeA	Recycled Ceramic Aggregates	Na+C<30% Ce>70% B<5% X<1%
MRCeA	Mixed Recycled Ceramic Aggregates	Na+C<70% Ce>30% B<5% X<1%
MRBA	Mixed Recycled Bitumen Aggregates	5%<B<30% X<1%

Acronyms Na, C, Ce, B and X, are referred to natural aggregates, concrete, ceramic materials, bituminous materials and undesired materials respectively, the later being the ones than can not be classified as RA.

Attached mortar to the RA is accountable for the main changes in the properties of these aggregates when compared to natural ones. All of the previously commented physical properties are affected to a greater or lesser extent due to its structure and components. In general terms, RA will have better properties when lower is their attached mortar content.

To date, there is no standardized method for the determination of the attached mortar quantity in RA, although there are several proposals, which will be briefly detailed below:

- Barra (1996) proposes a methodology in which a RA sample is subjected to drastic temperature changes through heating some previously saturated aggregates up to 500ºC for a period of two hours, after which the sample is thrown into water, where the aggregates are again saturated. This procedure is repeated twice, and its purpose is to create tensions within the aggregates due to the rapid evaporation of water, and the differential contractions and expansions that the aggregates different components undergo. Finally, the sample is carefully smashed with a rubber hammer in order to separate the natural stone from the mortar.

- de Juan and Gutiérrez (2009) commented a method in which the aggregates are subjected to a hydrochloric acid solution attack, thus causing the dissolution of the cement paste and consequently separating the mortar phase from the natural stone. This method provides good results as long as the natural stone is not affected by the solution, as it is the case of limestone. Due to the heterogeneous nature of RA, this is a difficult parameter to control.
- Abbas et al. (2007) proposed a method in which the RA are submerged into a sodium sulphate solution and then subjected to freeze and thawing cycles (16 hours at -17ºC and 8 hours at 80ºC). After this the solution is drained, the sample is washed over a 4 millimetres sieve and then is dried, thus obtaining a weight difference with respect to the initial sample condition. The authors determined that, depending on the aggregates, between 3 to 5 freeze and thawing cycles are needed for the separation of the mortar phase from the NA.
- Abbas et al. (2009a) used a image analysis method to validate the results commented in the previous paragraph. It consisted on the preparation of samples of RA by inserting them into a white cement paste, which were then cut and polished. These samples were analysed with an image analysis software, able to detect the white cement paste from the other components and also to separate the areas corresponding to the mortar and the NA phases by tonal decomposition. This method has the disadvantage of having to manually determine the areas corresponding to the bubbles in the cement paste, which have different tonalities and thus difficult to be correctly analysed by the software.
- Khim et al. (2010) presented a methodology of RA beneficiation, based on the separation of the mortar through thermical stresses provoked by micro-waves. The results show that there still are remains of attached mortar, which may have to be manually

classified and separated. This plus the fact that the method consumes high amounts of energy, makes it disadvantageous when compared to the others methods.

Some authors have determined the amount of attached mortar in RA, using different methodologies. According to de Juan and Gutiérrez (2009), depending on the composition, original NA, particles sizes, aggregates quality, among others, the results may greatly vary, going from a 20% up to 70%. Also, the smaller the size of the aggregates, the greater the attached mortar content (de Juan and Gutiérrez, 2009; Abbas et al., 2009a).

2.2 Recycled aggregates concrete mix design

The design of RAC is one of the areas where less innovations have been made as, to date, the modifications are limited to their different applications, or to the amelioration of their characteristics throughout variations on its components.

The different mix design procedures have been based on already existing methods for concrete design, taking into account the changes that RA characteristics confer to the mix, when compared to NA, and so aiming on the obtaining of similar properties of those of NAC.

The most used method is to design a NAC by some of the classic methods (Fuller, Bolomey, ACI, de la Peña) (Fernández Cánovas, 2013), and then simply replacing NA by RA whether by volume or weight, taking into account their main properties. Moreover, some authors recommend that in order to achieve similar properties of those of NAC, the water content should be increased by around 5% and the cement quantity by 15% (ACI Committee 555, 2001; 37-DRC, 1992).

The Spanish Code for Structural Concrete (Spanish Ministry of Public Works, 2008) approves the use of classic methods for the design of RAC, with a maximum of 20% of RA, and recommends the adjustment of the mix design by obtaining previous tests results. In the case of concretes containing more than 20% of RA, it is recommended to increase the cement content, decrease the water/cement (w/c) ratio, include the use of admixtures, or pre-saturate the RA. On the same vein, ACI Committee 555 (2001) presents some recommendations for these mixes design, which include a 5% increase on the water content, or the w/c ratio adjustment if previous compressive strength test results do not achieve the required values. 37-DRC (1992) does also present some data supporting the aforementioned recommendations. It is worth noting that the texts to which this paragraph makes reference to, were written every 8 years approximately, thus giving an idea of the small changes among these recommendations in documents that are of high importance in this matter.

Barra (1996) studied different properties of the RAC when compared to NAC, designing the mixes with a method that takes into account the density, sieve size distribution and humidity of the aggregates, among others. After testing the different concretes, a mix design diagram is proposed, which gives information of the compressive strength, w/c ratio, and quantity of cement by m^3. The main outcome of this is that the proposed diagram bases its results on previously studied aggregates properties, with which the concretes produced by its use will be based not only in previous experience, but also in the changing properties of the aggregates.

Tam et al. (2005) designed a mix proportioning procedure, based on dividing the materials mixing in stages; the first, in which the aggregates are mixed with half of the total water, then, the cement is added and mixed by 30 seconds, and finally the rest of the water is added and mixed all together for 120 seconds. The purpose of such procedure, is to fill the porous structure of the aggregates on a first stage and so to achieve a denser concrete and with an improved interfacial transition zone (ITZ), with which the achievement of a better quality of the concrete is expected. Their conclusions were that the concretes designed using this procedure have better performances than the conventionally designed ones. Tam et al. (2007) made another experimental campaign, which increased the number of results, and observed that the best results were found when the replacement percentage of NA by RA lie in between 25% and 40%.

Other authors (Lin et al., 2004; Chang et al., 2011; López-Gayarre et al., 2011; Park, 2013) designed different mix proportioning methods for RAC using different statistical approaches. These had the purpose of reducing the amount of experiments and tests for an optimal mix design, taking into account some factors that significantly contributed to the final requirements of the concretes. Although the statistical methods were different, all of them had the same general objectives.

Fathifazl et al. (2009) proposed an alternative method for these types of concretes design so called ’Equivalent Mortar Volume method’, totally different from the aforementioned ones as it is based a novel principle, which is to consider RA as two phases materials, namely the attached mortar and the NA. Based on this premise, the mix designs are done by calculating the amount of attached mortar to the RA and taking it into consideration by summing it to the total amount of mortar needed by the mix, achieving by this the reduction of the amounts of water, fine aggregates and cement. Even though the attached mortar of the RA is in a hardened state, the new fresh mortar is calculated to give at least the minimum requirements in terms of workability of the mix. Moreover, there is also the possibility of using greater quantities of new fresh mortar, apart from the ones that come from the calculation, thus achieving with this even better workabilities. This proposal changes the traditional way of thinking, in which it is believed that the improvement of the RAC must be done by increasing the quantities of cement.

2.3 Recycled aggregates concretes main properties

The properties of RAC can have important variations regarding NAC depending on the desired mixes characteristics. One of the most important factors affecting this is the selected replacement ratio of aggregates, which make these differences greater when the replacement is higher.

2.3.1 Fresh state

2.3.1.1 Workability

This is usually known as the ease that concrete’s transportation, placement and consolidation, presents. There are several methods that help on obtaining some values that are related to this property, although they are sometimes inadequate.

One of the most known and used methods is the slump test, in which the workability of a mix is related to the measurement (in centimetres) of the difference in height that the sample of concrete has after being consolidated inside a metallic recipient. Due to the ease on this test execution, and that is cost and time-effective, this method has been adopted worldwide (Fernández Cánovas, 2013).

This property is often affected in RAC, due to the properties of the RA. Lima et al. (2013) observed important reductions in recycled concretes with fly-ash additions, even when greater doses of superplasticizing admixtures were utilized. It can be seen in their results that the workability loss is greater when higher are the RA replacement ratios.

Grdic et al. (2010) studied the behaviour of self-compacting concretes comprising RA in different replacement ratios. They used the inverted cone, slump flow, and L box tests. Although their results were similar for the different concrete types, this was achieved by increasing the water content of the concretes with the increasing amount of RA replacement.

The above-mentioned results agree with the findings of 37-DRC (1992), in which several authors observed changes in the workability characteristics of the concretes when using RA in their composition.

As it was previously mentioned, these tests are sometimes inadequate when aiming on classify a certain mix by its workability. This has been confirmed by several authors (Tattersall and Banfill, 1983; Wallevik, 2003; Tattersall, 2005; Wallevik, 2006; Banfill, 2006), arguing that two different concretes may achieve the same results and have different behaviours regarding their workability. A better way of comparing different mixes and assess them in terms of their workability is by the use of physical quantities, instead of indirect measurements, which can be obtained by studying their rheological properties, namely the yield stress and plastic viscosity.

Rheology is a science that studies the deformational and flowing behaviours of materials. Studies on this field are mainly referred to self-compacting concretes, in which there is a need for a deeper understanding of these properties, and that can not just be assessed by indirect measurements like the ones mentioned on the beginning of this section.

In a document named 'Rheological and mechanical behaviour of concrete mixtures with recycled concretes aggregates', Knaack and Kurama (2012) assessed the rheological properties of concretes comprising RA and designed by means of three different methodologies, one of them being the Equivalent Mortar Volume method that has been previously commented. They found that the rheological properties of the concretes designed with this method were worst than the ones designed with other procedures. Although this, the rheological properties were assessed with the results of a modification of the slump test and not in terms of their physical quantities.

To the author knowledge, the rheological properties of RAC is a field that, to date, has not been studied nor properly assessed. This symbolizes a great opportunity of research, and constitutes a logical way to be oriented to, due to the differences that this type of material has when compared to conventional concretes, and where important differences have been found through methods that are not classifying the material in terms of fundamental physical quantities.

2.3.2 Physical and mechanical properties

2.3.2.1 Density

In most of the cases, mortar has a lower density value than stone, which causes RA to present lower densities than NA, consequently, the density of a RAC will be lower than the one of a NAC. This has been observed in by different authors (37-DRC, 1992; Ismail and Ramli, 2013; Thomas et al., 2013). However, when designing recycled concretes with the Equivalent Mortar Volume method, these differences should not be that significant, as the quantities of materials forming the body of these concretes should be similar to the conventionally designed ones.

2.3.2.2 Compressive strength

This is one of the main properties of NAC, being often used as a starting point when designing a certain mix, and that will control their acceptance or rejection. This property is closely linked to the w/c ratio, being inversely proportional to it, and mostly known as 'Abrams Law' (Neville and Brooks, 2010). RAC present the same behaviour with respect to this law. The difference is that these concretes strength will be also governed by the amount of RA on the mix, which will decrease the strength as the RA amount increases.

The main difficulty RAC present to achieve comparable strengths to those of the NAC is the attached mortar to RA. This supposes an excessive quantity of total mortar in the mix, for which is logical to think that the greater the amount of RA, the less the compressive strength. Also, greater percentages of attached mortar on the aggregates will confer less strength when compared with aggregates having less attached mortar.

Etxeberria et al. (2007) studied the influence that the quantity and production processes of RA have on RAC, concluding that in the case of the compressive strength, a 25% replacement of aggregates does not have a significant influence in concretes with resistances between 30-45 MPa, whereas in 50% and 100% replacements, it is necessary to decrease the w/c ratio in about 4-10% and increase the cement amount in about 5-10% in order to maintain resistances unchanged. Sim and Park (2011) observed continuous drops in the resistance when more replacement of aggregates was used. The Spanish Code for Structural Concrete (Spanish Ministry of Public Works, 2008) indicates that is possible to maintain the strength of the concrete if a maximum of 20% replacement of aggregates is used, which was also confirmed by Sánchez de Juan and Alaejos (2004).

Another of the parameters that have an influence on the concrete's resistance is the quality of the RA. Padmini et al. (2009) and Tabsh and Abdelfatah (2009) found a directly proportional relationship between the quality of the concrete used for the production of RA and the resistance of the RAC; the greater the strength of the original concrete, the greater the strength of the recycled concrete.

Mas et al. (2012) found that the strength loss of recycled aggregates concretes at 90 days is lower than at 28 days, when compared to conventional mixes. They argue that this is because of the cementing effect that RA could have at longer terms, due to the existence of non-hydrated cement in their mortar phase. A similar behaviour has also been observed by Evangelista and de Brito (2007).

Poon et al. (2004) also stated that the saturation state of the aggregates have an influence on this property. They established that greater resistances are achieved when the aggregates are used in a air-dried condition and, contrary to that, the worse effects are observed when the aggregate is used in a saturated surface dry condition.

Fathifazl et al. (2009) observed that similar or even better results in terms of compressive strength were found when designing recycled concretes with the Equivalent Mortar Volume method, when compared to conventional concretes.

2.3.2.3 Modulus of elasticity

Due to the fact that this property is closely related to the NA in concrete, RAC will end up in the worsening of this property when compared to conventional mixes (Xiao et al., 2005; Berndt, 2009; Neville and Brooks, 2010). Sheen et al. (2013) argues that this is because RA have greater deformations than the natural ones.

Tangchirapat et al. (2012) found reductions of about 25% on this property, while Xiao et al. (2012a) reports reductions as high as 46% when 100% replacement of aggregates is used. Padmini et al. (2009) observed similar results, arguing that the reduction is because of the attached mortar on RA, which has lower modulus of elasticity than the stone, thus causing the drop of the whole group.

On the same vein, Silva et al. (2015) states that, if all of the other design parameters of concrete remain unchanged, increasing amounts of RA will end up in concretes with lower modulus.

The design proposed byFathifazl et al. (2009), should solve these problems as it produces concretes with similar amounts of materials to those of the NAC.

2.3.3 Durability properties

These properties are as important as the mechanical ones, as they give us an idea of the behaviour of the material under certain environmental situations in time. The ones that may be the most important are related to the transport of fluids and specific substances throughout the concrete matrix.

2.3.3.1 Water absorption

This property is related to the surface shape and the surface tension of liquids in capillaries of concrete. It is expected to be greater in RAC due to the RA characteristics, where attached mortar creates a more porous system within the whole group, when compared to NA. Sagoe-Crentsil et al. (2001) observed this behaviour when comparing RAC to conventionally designed ones comprising basaltic aggregates.

37-DRC (1992) also goes along the same line, and comments that when the original concrete, from which RA are produced, have lower w/c ratios, the differences on the water absorption capacity are even larger.

Other authors observed that the water absorption measured in RAC having the same amount of RA decreases with increasing curing times, and increases with larger amounts of RA (Olorunsogo and Padayachee, 2002; Levy and Helene, 2004; Kwan et al., 2012; Thomas et al., 2013).

2.3.3.2 Permeability

Permeability is characterized by the facility that a certain fluid has to pass through a material when there is a pressure differential applied to the fluid. The water penetration under pressure test (European Committee for Standarization, 2000a) gives an idea of how impermeable a concrete structure may be and, according to the limits established by Spanish Ministry of Public Works (2008), the maximum depths of penetration for a concrete with enough impermeability are 50 millimetres for mass or reinforced concretes and 30 millimetres for pre-stressed concretes, both under specific environmental exposition classes.

Like water absorption property, permeability is most affected when higher is the w/c ratio and larger is the amount of RA used in concrete. Even though, Thomas et al. (2013) found that there are no noticeable negative effects in RAC with over 60 MPa of strength, regardless of the aggregates replacement amount.

Somna et al. (2012) found that the water penetration values can be improved in RAC, when replacing cement by fly-ash or sugar cane-ash, due to their densificating effect on the concrete's matrix. The optimal replacement percentage was found to be 20%, whereas at 50% there were negative outcomes.

2.3.3.3 Chloride penetration resistance

This is one of the most relevant aspects among the durability properties of concrete, due to its importance in reinforced concretes, which are of massive use in the construction field.

The effects of chlorides ingress into the concretes matrix can be classified as very relevant, depending on the severity of it, as they cause the corrosion of the reinforcing steel thus giving way to the production of iron oxide, which occupies greater volumes than iron. Such expansion generates stresses in the surrounding concrete, thus leading to its deterioration. Chlorides ions provoke corrosion by penetrating into the protective oxide film created around reinforcement due to the alkalinity of the system they are embedded in.

Ying et al. (2013) studied the chlorides transport mechanism by migration in RAC, simulated through finite elements. They concluded that the transport has a relation with the RA replacement amount, being greater with larger replacement amounts.

In general, the reviewed literature shows that RAC have a worst behaviour than NAC regarding chlorides penetration, and that this behaviour gets worse when larger RA replacement amounts are used (Otsuki et al., 2003; Sim and Park, 2011; Xiao et al., 2012b). Although this, Vázquez et al. (2013) states that there could be a positive outcome of using RA as they provide an extra amount of CSH gel, to which chlorides could bind and thus improving the RAC performance regarding this matter.

2.3.4 Environmental characteristics

As concrete is the most utilized man-made material (Mehta and Monteiro, 2006; Knoeri et al., 2013; Ghafari and Costa, 2015), composed of about three-quarters (in volume) of aggregates (Neville and Brooks, 2010) and uses relevant quantities of cement, it may represent an important matter to be aware of on today's environmental problems worldwide.

RAC may represent a solution as they reduce the need for NA by their replacement with RA. However, as it has been previously commented, in order to achieve similar properties of those of the NAC more quantities of cement are needed, which is an important contributor to global warming (Josa et al., 2007; Scrivener and Kirkpatrick, 2008; Meyer, 2009b).

The environmental assessment of the concrete can be done through a Life Cycle Assessment (LCA), which is an acknowledged method for the determining of the potential environmental impacts of a determined product or raw material (Guiné et al., 2004; International Organization for Standarization. Technical Committee ISO/TC 207, 2006a).

Marinković et al. (2010) studied the environmental potentials of the use of RAC as a structural material by comparing it with a NAC. Their results showed that the production of RA imply slightly greater environmental impacts when compared to NA, although they used round-river aggregates that do not need any further processes after their extraction, whereas RA have to be crushed, which is a high energy-consuming process. They have also used more quantity of cement for the production of RAC, which may imply significant differences on the selected impact categories. The authors concluded that the majority of the total environmental impacts of RAC depend on the transport distances of both natural and RA, being similar to those of NAC when the transport distances were lower for the RA, and worse when the transport distances were equal.

On the same vein, Knoeri et al. (2013) analysed the environmental impacts of different RAC by comparison to NAC. At an endpoint level, their results showed beneficial outcomes when using RAC instead of NAC, mainly due to the recycling of reinforced steel and the avoided disposal of rubble. Regarding the global warming potential (GWP) category, they found that similar results can be obtained if the addition of more cement and the transport distances of RA are limited.

Quattrone et al. (2014) investigated the environmental impacts in terms of energy consumption and carbon dioxide (CO_2) emissions of different production processes for RA. They compared an ordinary production process which is mainly composed of crushing the material by means of a jaw crusher followed by an impact crusher, to other mechanical and thermal-mechanical treatments. The authors conclude that the ordinary processing is the one consuming the less energy and emitting fewer CO_2. Even though, they state that the available data is very limited and that the regional electricity generation processes lead to a great disparity on the emission factors. They also deduce that the production of high quality RA can be viable from an environmental point of view, in places where the production of NA is limited and implies long hauling distances.

Although there are several studies about the environmental properties of concretes main constituents, or about specific applications where concrete is used as one of the materials, few investigations have been found on the environmental assessment of RA or RAC. This presents a major opportunity of research, given the characteristics of such materials, where their greatest objective is to confront and offer solutions to the environmental challenges that frequently used non-recycled materials imply. Moreover, as the use of the Equivalent Mortar Volume for RAC design should imply major benefits regarding the afore-mentioned environmental issues, because is a method that not only uses RA but also lessens the commonly used amount of cement of the mixes, the environmental assessment of such concretes becomes of relevant importance and should present promising results.

Chapter 3

Materials Characterization

In this section, a description of the different materials used for the elaboration of the concretes is presented. In the case of the cements and the admixtures, only a brief description will be presented, as their technical information can be consulted in the appendixes of this document. In the case of the aggregates, the complete characterization campaign will be presented, which focuses on their chemical properties, physical properties, and composition.

The complete list of the used materials is presented bellow:

- Tap water
- Cement type CEM I 42.5 R
- Cement type CEM I 52.5 R
- Superplasticizing admixture (Glenium Sky 604)
- Air Entraining admixture (Micro Air 100)
- Fine natural aggregate
- Two coarse natural aggregates (NA)
- Three coarse recycled aggregates (RA)

3.1 Cement and admixtures

Two types of cement have been used in the three experimental campaigns. The concretes of the first and second campaigns have been produced using a cement type CEM I 42,5 R, from CEMEX S.A.B., which is a normal strength cement and rapid setting. The third campaign has been executed using a cement type CEM I 52,5 R, from Ciment Molins Industrial company, which is a high strength cement and rapid setting as well. Both cements have a 95%-100% of clinker in its composition and comply with the prescriptions of the standard EN 197-1 'Cement Part 1: Composition, specification and conformity criteria' CEN/TC 51 (2011). Their technical data sheets can be consulted in Appendix A, in sections A.1 and A.2 respectively.

In the case of the admixtures, a superplasticizer based on polycarboxylates (Glenium Sky 604) and an air entrainer (Micro Air 100) from BASF company have been chosen. Their technical data can be consulted in Appendix B, sections B.1 and B.2 respectively.

3.2 Aggregates

The selected aggregates of this research have been both natural and recycled ones. The fine portion (< 4 mm) has comprised only NA, while the coarse portion (> 4 mm) has used natural and/or recycled ones. One fine aggregate (from four different batches), two natural coarse aggregates, and three recycled ones have been used. The methods for the obtaining of the laboratory samples of the aggregates have followed the prescriptions of EN 932-1 and EN 932-2 standards (European Committee for Standarization, 1997b, 1999). The chemical analyses of the aggregates have been obtained by the methods prescribed in the EN 1744-1 standard (European Committee for Standarization, 2009c). The determination of particles densities and water absorption has followed the EN 1097-6 standard (European Committee for Standarization, 2013), while the dry-rodded bulk density has been obtained by following the ASTM C 29 standard (ASTM International, 2003). The particle size distribution of the aggregates has been obtained through the EN 933-1 standard procedure (European Committee for Standarization, 1997a). The classification for the constituents of the RA has been done with the procedure of the EN 933-11 standard (European Committee for Standarization, 2009b). The attached mortar content of the RA has been determined through the procedure presented by Barra (Barra, 1996). All of these test have been carried out with at least two duplicates and in laboratory conditions.

3.2.1 Aggregates chemical properties

The different aggregates used on this investigation have been subjected to acid soluble chlorides content (%Cl^-), acid soluble sulphates (%SO_3) and sulphur total compounds (%S). These results can be seen in Table 3.1.

Table 3.1: Chemical analyses of aggregates

Aggregate	Designation	%Cl^-	%SO_3	%S
Natural Sand	S	<0.010	0.013	0.025
Natural Gravel 1	G1	<0.010	0.027	0.138
Natural Gravel 2	G2	<0.010	0.057	0.044
Recycled Gravel A	R1	0.025	0.025	0.023
Recycled Gravel B	R2	0.010	0.600	0.180
Recycled Gravel C	R3	0.020	0.760	0.300

Each one of the aggregates, according to the prescriptions of the Spanish Code for Structural Concrete EHE-08 (Spanish Ministry of Public Works, 2008), which has been taken as a base document on this subject, comply with the limit requirements for sulphur total compounds (<1%), acid soluble sulphates (0.8%) and chlorides content (0.05%).

Together with these tests, the aggregates samples were analysed through x-rays diffraction (XRD) and x-ray fluorescence (XRF) in order to detect and determine their mineralogical and elemental compositions. The diffractograms from the XRD for the aggregates listed in Table 3.1 can be consulted in sections C.1, C.2, C.3, C.4, C.5 and C.6 respectively, from Appendix C. XRF results will be shown in terms of oxides.

From the different diffractograms it can be seen that the NA are mainly composed by calcite, as well as Recycled Gravel A which is in fact expected because of the its materials composition. Recycled Gravels B and C present a more heterogeneous composition, primarily comprising quartz and calcite.

Table 3.2 shows the result of the XRF analysis of the different aggregates used in this investigation.

Table 3.2: X-ray fluorescence of aggregates

	S	G1	G2	R1	R2	R3
Compound	%					
Na2O	-	-	-	-	-	1.27
MgO	0.60	0.61	0.74	0.70	0.66	2.00
Al2O3	0.63	0.26	0.53	0.95	5.90	8.11
SiO2	1.35	0.79	1.27	2.60	67.85	32.32
P2O5	-	-	-	-	-	0.13
SO3	0.19	0.14	0.11	0.41	0.45	0.75
K2O	-	-	0.06	-	2.04	1.77
CaO	52.89	53.39	56.24	51.05	11.25	31.48
TiO2	-	-	-	-	-	0.26
Fe2O3	0.27	0.21	0.32	1.25	1.29	2.96
ZnO	-	-	-	0.03	-	-
Rb2O	-	-	-	-	-	0.02
SrO	0.03	0.03	0.03	0.04	-	0.04
BaO	0.17	0.22	-	0.02	-	-
ZrO2	0.11	-	-	-	-	0.02
Loss of ignition	44	44	41	43	10	19

The above presented table shows the elemental composition of the aggregates in which the information given with the diffractograms can be confirmed. NA and Recycled Gravel A have a high quantity of calcium and just low numbers in the rest of the elements, whereas Recycled Gravels B and C present silicon as their main element, followed by calcium, aluminium and other minority elements.

3.2.2 Aggregates physical properties

3.2.2.1 Density and water absorption

This section deals with obtaining the densities of the aggregates, without taking into account the voids existing between the particles or their open porosity, which is the one that is somehow connected to the surface of the aggregate and can thus be saturated.

The fine aggregate has been tested according to the pycnometer procedure. Although one type of fine aggregate was used, it was obtained from four different batches and so the results are shown for each one of them. Each batch is represented with a different name for the sake of clarity.

The density of the sample can be related to three different conditions and thus obtaining three different values, namely the apparent density (D_{AP}), saturated surface-dry density (D_{SSD}) and the oven-dry density (D_{OD}). With this information, the water absorption capacity can be obtained as well. Table 3.3 shows the results of this test.

Table 3.3: Densities and water absorption of the fine aggregate

Aggregate	Designation	D_{AP} (kg/m^3)	D_{SSD} (kg/m^3)	D_{OD} (kg/m^3)	Absorption (%)
Natural Sand 1	S1	2700	2670	2650	0.7
Natural Sand 2	S2	2736	2665	2625	1.6
Natural Sand 3	S3	2763	2708	2677	1.2
Natural Sand 4	S4	2726	2663	2686	0.9

As it can be observed from the above-listed results, the densities of the different fine aggregates batches present little differences with each-other and the absorption values have greater differences. It is worth noting that each of the concretes used in this investigation have been formulated with taking into account these results.

The measurement of the coarse aggregates density and water absorption is done through the same method as the one presented for the fine portion.

As in the case of the fine aggregates, three densities and the water absorption are obtained through this method. The results of these tests are shown in Table 3.4.

Table 3.4: Densities and water absorption of the coarse aggregates

Aggregate	Designation	D_{AP} (kg/m^3)	D_{SSD} (kg/m^3)	D_{OD} (kg/m^3)	Absorption (%)
Natural Gravel 1	G1	2713	2686	2671	0.6
Natural Gravel 2	G2	2718	2696	2683	0.5
Recycled Gravel A	R1	2678	2446	2307	6.0
Recycled Gravel B	R2	2612	2440	2327	4.7
Recycled Gravel C	R3	2676	2436	2292	6.3

The results of both the recycled and natural coarse aggregates show differences between their density and absorption results, being the later the greater ones. This is in fact an expected outcome as the attached mortar to RA is less dense and absorbs more water than the NA, thus it reduces the total density of the RA and increases its total water absorption.

NA show no major differences among their densities and absorption values, whereas RA do. These differences are associated to the RA constituent materials differences, which differ on each specific case as it will be shown further ahead.

3.2.2.2 Bulk density (dry-rodded) and voids

This property aim is to obtain the density of a group of aggregates in a compacted condition while also taking into account the remaining voids between the particles. In this case, only the coarse portion of the aggregates has been tested.

The obtaining of this specific property is due to its requirement as a design parameter when using the American Concrete Institute methodology for concretes design.

The test results are presented in Table 3.5 and they are the average of two test determinations.

Table 3.5: Dry-rodded bulk density of the aggregates

Aggregate	Designation	$BulkDensity_{DR}$ (kg/m^3)	Voids (%)
Natural Gravel 1	G1	1510	43
Natural Gravel 2	G2	1555	42
Recycled Gravel A	R1	1311	43
Recycled Gravel B	R2	1329	43
Recycled Gravel C	R3	1288	44

These results show that there are differences between the NA and RA, which again is due to their composition. RA are composed by less denser particles than natural ones.

These densities are well related with the oven-dry densities from the previous section, showing reductions of about 43% in all of the studied cases. This reduction is in fact the void content of the aggregates.

3.2.2.3 Particle size distribution (sieving method)

This property's objective is to determine the distribution of the different sizes of a specific aggregate, through the separation of a sample of a known mass, by means of sieves of progressively smaller openings. This method is executed using the same procedure for each of the aggregates of this investigation, no matter their size.

The results of the particles size distribution test are presented in Figures 3.1, 3.2 and 3.3, corresponding to the first, second and third experimental campaign respectively. An additional figure (Figure 3.4) showing the distribution of the different batches of fine aggregate is presented for the sake of better comprehension.

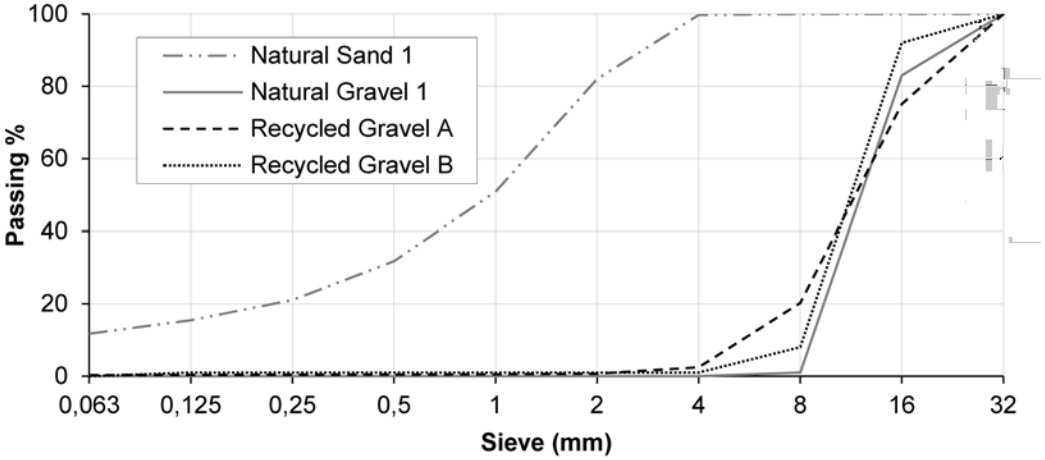


Figure 3.1: Aggregates particle size distributions of the first campaign concrete mixes

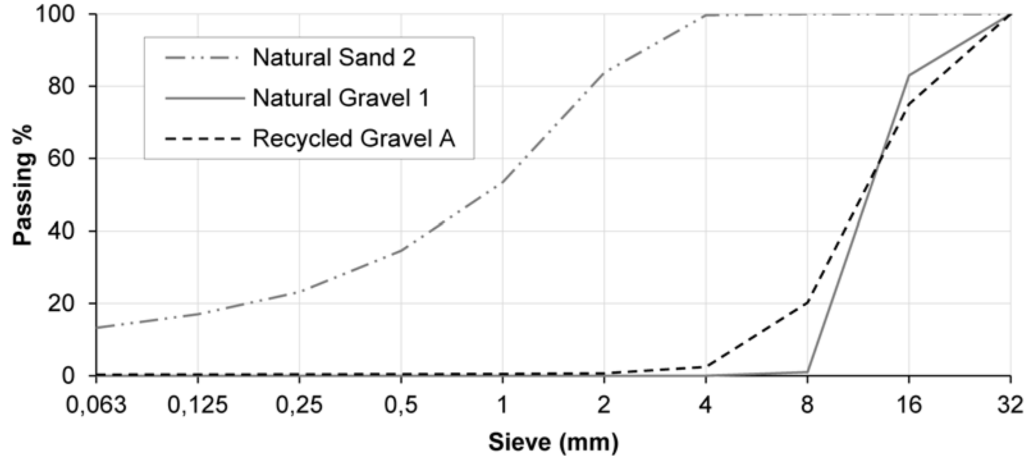


Figure 3.2: Aggregates particle size distributions of the second campaign concrete mixes

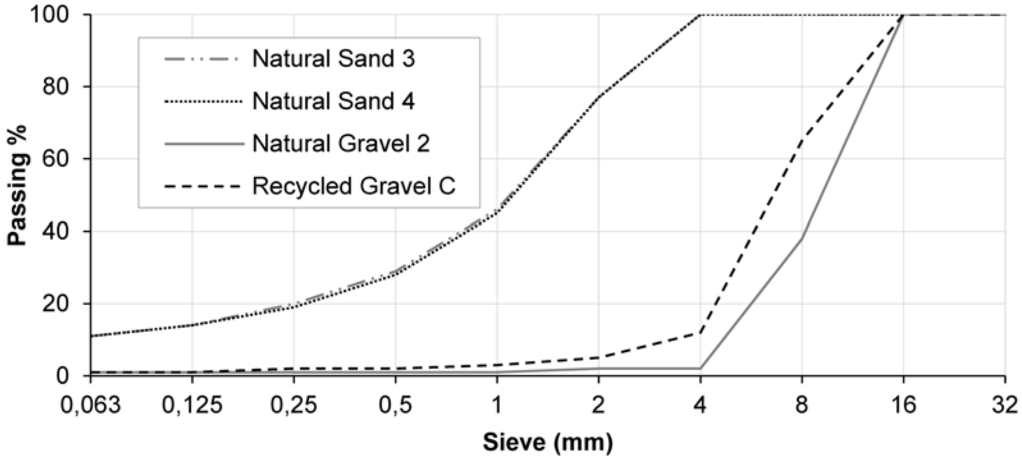


Figure 3.3: Aggregates particle size distributions of the third campaign concrete mixes

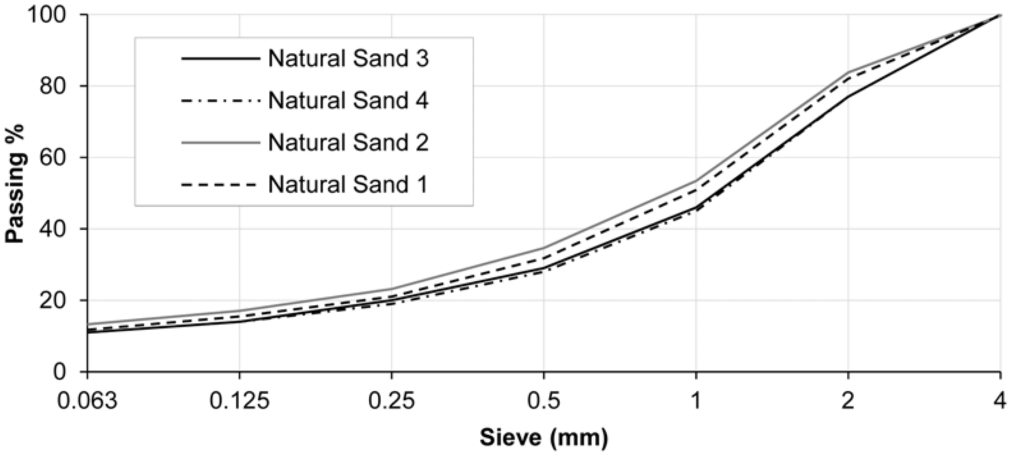


Figure 3.4: Extended view of the particle size distribution of the fine aggregates

Natural sands have almost equal size distributions which was an expected result due to the fact that they correspond to the same type of sand, being the batch they correspond to the only difference among them. They also present a continuous distribution, that is that the amount of material is well divided among different particle sizes.

Coarse aggregates distributions are similar in the case of the Natural Gravel 1, Recycled Gravel A and Recycled Gravel B, and also between Natural Gravel 2 and Recycled Gravel C.

3.2.2.4 Recycled aggregates constituent materials

As RA composition is in most cases heterogeneous, the following procedure is an important test among these materials, which objective is to determine the proportions of their different constituents.

The test is based on the separation of the different materials forming part of the RA by visual recognition into six main categories. These categories can be summarized in: i) concrete products, mortar, NA with attached mortar; ii) natural unbound aggregates; iii) ceramic materials; iv) bituminous materials; v) glass; vi) other minor constituents (clays, metals, plaster, wood, plastic).

The results of this test for Recycled Gravel type A, B and C, are shown in figures 3.5, 3.6 and 3.7 respectively.

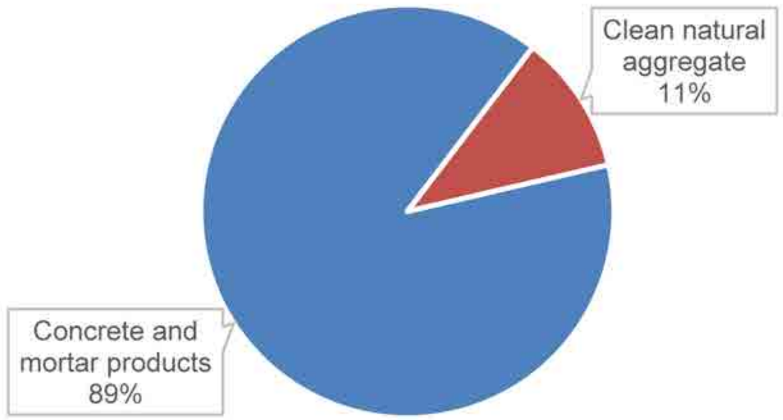


Figure 3.5: Constituent materials of Recycled Gravel A

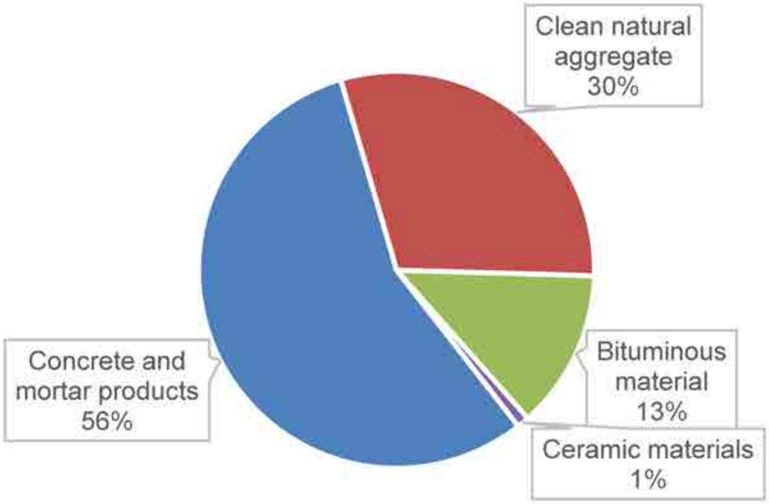


Figure 3.6: Constituent materials of Recycled Gravel B

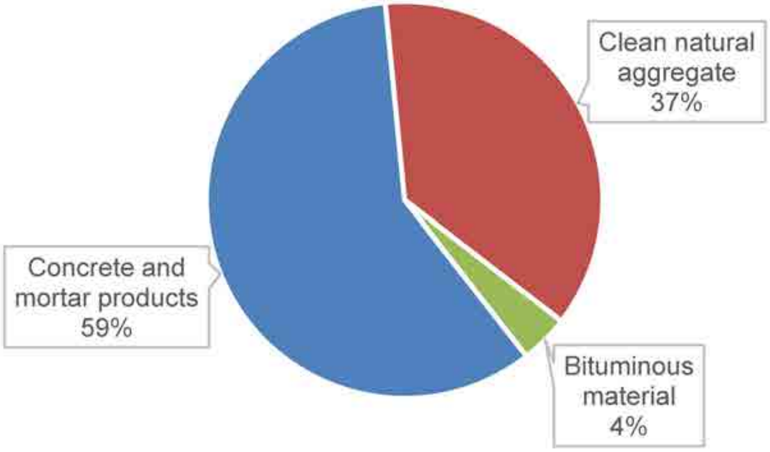


Figure 3.7: Constituent materials of Recycled Gravel C

Recycled Gravel A is a clean aggregate in terms of its constituents, as it is composed mainly by concrete and mortar products with no presence of undesirable materials.

Recycled Gravel B could be qualified as the worst among these three aggregates in terms of its constituents, as it presents a large quantity of bituminous material, which can be related to resistance and adherence problems when used in a cement based matrix. It also presents ceramic materials, which may lead to higher water absorptions and thus problems related with the accurate control of the effective water/cement (w/c) ratio of the designed concretes, although in this case the content is rather small.

Recycled Gravel C is mainly composed of concrete and mortar products and has a high clean aggregates content. It also presents bituminous materials, which may lead to the aforementioned problems, although in this case the content is significantly lower.

It seems that the best option among these aggregates could be the first aggregate due to its lack of undesirable materials, but this is a premature idea as one of the most important parameters controlling the quality of RA is related to their attached mortar content. Also, because of their heterogeneity, these aggregates are quite difficult to be qualitatively ranked as they may present great differences on the types of constituent materials; for example, a RA mainly composed of clean limestone aggregates may behave worst than a RA with high amounts of concrete and mortar products but comprising granitic rocks. A better judgement of the quality of a certain aggregate could be done if a complete analysis of its constituents is performed, quantifying the real amount of bituminous materials, the qualities of the ceramic materials, the attached mortar content, the rocks mineralogies and so on.

3.2.2.5 Recycled aggregates attached mortar content

One of the most important characteristics of the RA is their attached mortar content, as this will have a significant effect on the desired properties of the concrete.

The aggregates were submitted to different methodologies, namely freezing and thawing with natural water, freezing and thawing with a sodium sulphate solution (Abbas et al., 2007), hydrochloric acid dissolution (Nagataki et al., 2000), and thermal attack (Barra, 1996). Freezing and thawing methodologies required too much time, due to the amount of cycles needed to obtain acceptable detachment of the mortar phase from the aggregates. Hydrochloric acid method provoked a partial disintegration of the aggregates due to their mineralogical composition, in which calcareous materials were encountered. Finally, the thermal attack method was selected.

Thermal attack methodology consisted on the saturation of the RA, by submerging the sample in water for 15 minutes, and then placing it inside a 500 ºC preheated laboratory muffle furnace for two hours. The main purpose of this is to create internal stresses within the particles through the rapid evaporation of water. After the two hours inside the muffle, the sample is then thrown in cold water in order to create stresses by the thermal shock. These stresses purpose is to crumble down the attached mortar and separate it from the aggregate, consequently achieving a good division of the two phases of the RA. After this, the sample was visually analysed and, when any remainders of mortar were still found to be attached to the aggregates, they were manually detached with the assistance of a rubber hammer. Finally, the sample is collected and separated into mortar and clean aggregates, which are then weighted in order to determine their percentages.

The results of this test are shown in Table 3.6.

Table 3.6: Attached mortar content of recycled aggregates

Aggregate	Designation	Attached mortar content (%)
Recycled Gravel A	R1	39
Recycled Gravel B	R2	32
Recycled Gravel C	R3	35

From the above presented results, it can be observed that, in the case of this investigation, the attached mortar content has a direct relation with the amount of concrete and mortar products of the RA. They correspond to normal values as it has been seen in the literature (37-DRC, 1992; Fathifazl et al., 2009).

3.2.3 Origin of the recycled aggregates

The RA used in this investigation come from construction and demolition waste (C&DW).

Recycled Gravel A has been produced at the laboratory facilities, by crushing 150 mm x 300 mm concrete test specimens, by means of a jaw crusher. The material was subjected to several trial tests before choosing the final procedure to elaborate it. These tests were headed towards obtaining an appropriate size and shape of the aggregate, for which the variables were the crusher jaw's minimal opening and the amount of times that the sample had to pass through the crushing system. The final procedure was selected to be passing the concrete specimens two times, through an approximately 20 mm minimal opening of the jaw crusher. Other procedures were found to produce inappropriate sizes, or flat and elongated shapes. A photographic diagram with the process is shown in Figure 3.8.

a) Concrete test specimens b) Jaw crusher c) Crushed material

d) Size and shape of the aggregate e) Recycled aggregates pile

Figure 3.8: Photographic diagram of the crushing process for the production of Recycled Gravel A

Recycled Gravels B and C have been obtained from local recycling plants, and so being processed through normally applied methods. These can be summarized in: i) reception and first removal of undesirable material (rebars, non-ferrous metals, wood, plastic); ii) pre-screening; iii) initial crushing, removal of undesirable material; iv) secondary screening, secondary crushing and removal of undesirable material; v) final screening and formation of the different aggregate sizes piles.

Chapter 4

The Equivalent Mortar Volume method

4.1 Introduction

Recycled aggregates concrete (RAC) is a well-known material in developed countries, but is not till these last years that it has been taking more importance, and used in a wider variety of applications. The causes of this 'lack of use' may be several, and some even uncertain, but regarding these concretes design one could imagine that the reason is closely related to the materials needed to achieve a performance close to that of a natural aggregates concrete (NAC). It has been recognized that, in order to achieve this, conventionally designed RAC needs more cement than its counterparts (37-DRC, 1992; Etxeberria et al., 2007; Beltrán et al., 2014), so the potential benefits related to this material remain restricted. Moreover, as there is a need for more cement, the economic advantages, in some cases and when compared to a NAC, rely on government aids aimed at the development of this specific sector rather than the costs related to the material itself. A new initiative that goes towards to the solution of the aforementioned concerns is the so called Equivalent Mortar Volume method (Fathifazl et al., 2009) for the design of RAC. This novel method allows to elaborate RAC of similar or even better characteristics of those of a NAC, while lowering the commonly used amounts of cement.

At present, conventional RAC design is simply calculated by a direct substitution of materials in terms of volume or weight, the former being the most commonly used. This means that, after having the NAC mix proportion already defined, a percentage of replacement is selected and multiplied by the previously defined amount of coarse natural aggregates (NA), thus being this the quantity of coarse RA to be added to the mix. Some guides for these concretes design recommend additional considerations to have into account when designing the mix. The majority of these are related to some of the physical properties of the RA, in particular to those largely distinct to those of NA, like their water absorption.

The main problem of conventional design of RAC is that they treat RA as one phase materials, which means that there is no differentiation between the NA and the attached mortar to them. The consequence of this is that, apart from the already calculated amount of fresh mortar on the mix, there will be and additional quantity of mortar, provided by the RA. This has an adverse effect on the properties of the concrete, caused by an excessive amount of mortar, which is the main reason of its worse performance when compared to NAC.

The Equivalent Mortar Volume method allows to address the aforementioned issues by considering the attached mortar of the RA as part of the total mortar needed by the mix design. This is the result of treating the RA as two-phase materials, where, contrary to conventional methods, there is a differentiation between the NA and the attached mortar. The method also states that, in order to obtain the same hardened properties, RAC should have the same total amount of mortar and NA than those of a NAC, and so the calculations are based on this premises. With this, the obtained concrete will have almost equal amount of materials of that of the NAC thus, presumably, the same hardened properties.

4.1.1 Objectives

The main objectives of this part of the investigation are to study the Equivalent Mortar Volume method, and to determine its feasibility of use, when using other materials and methodologies.

The specific objectives arising from the previous purposes are:

- to design different recycled aggregates concretes, with the novel and conventional methods;

- to propose an adaptation of the novel method to Bolomey design methodology;
- to design different concretes mixes using the adaptation of the method in order to analyse it;
- to determine the advantages of adapting the novel method to Bolomey.

4.1.2 Program of the study

The stated objectives of this study will be addressed by presenting and analysing the theoretical basis of the Equivalent Mortar Volume methodology in a first stage, following what is described in the original published article (Fathifazl et al., 2009). Next, the proposal of the adaptation of the novel method to Bolomey procedure will be presented, starting with a small review on the subject. The following work will continue with the design of NAC and RAC, by using the novel method and the American Concrete Institute methodology (ACI, 2002), as well as the adaptation procedure and Bolomey (Fernández Cánovas, 2013) conventional mix designs. These concretes will be divided in three different campaigns, depending on the desired specific objectives of each one of them, and finally analysed in terms of their design. After this, the concrete mix procedures of the whole investigation will be detailed and the conclusions of the chapter will be presented.

4.2 Equivalent Mortar Volume method review

In this section, a review of the necessary basic steps to design a RAC with the Equivalent Mortar Volume method is presented by following the original published article (Fathifazl et al., 2009), together with some observations on this methodology.

This novel method constitutes a new approach for a better design of RAC, which differentiates itself from other conventional methods by considering RA as a two-phase material, one phase being the NA and the other being the residual mortar (*RM*) attached to it. With this salient characteristic, the design not only better controls the constituent materials of these types of concretes, but also reduces the needed amount of cement on the mix.

As a first step the method involves the determination of a NAC mix proportion, following the American Concrete Institute methodology (ACI, 2002), which will be taken as a starting point for the design of the RAC. After this, the design of the RAC is done, using a parameter termed 'natural aggregate content ratio, R' (4.1), which is basically a ratio between the volume of NA included on the RAC ($V_{NA}^{RCA-concrete}$) and the volume of NA of the previously designed NAC (V_{NA}^{NAC}).

$$R = \frac{V_{NA}^{RCA-concrete}}{V_{NA}^{NAC}} \tag{4.1}$$

Also, the method states that two conditions must be satisfied in order to obtain the same hardened properties in both the NAC and the RAC. These conditions are: 1) to have a volume of total mortar (TM) in the RAC ($V_{TM}^{RCA-concrete}$) equal to that of the NAC (V_{M}^{NAC}), where TM is the sum of the RM and the new mortar of the RAC, and 2) to have a volume of total NA (TNA) in the RAC ($V_{TNA}^{RCA-concrete}$) equal to that of the NAC (V_{NA}^{NAC}), where the TNA is the sum of the new NA and the one included in the RA. So, the resulting equations are:

$$V_{TM}^{RCA-concrete} = V_{M}^{NAC} \tag{4.2}$$

$$V_{TNA}^{RCA-concrete} = V_{NA}^{NAC} \tag{4.3}$$

In order to check if the mix can be made using only RA as the coarse aggregates of its composition, the maximum residual mortar content $RMC_{max}\%$ (4.4) is calculated

$$RMC_{max}\% = \left(1 - V_{DR-NA}^{NAC} \times \frac{SG_b^{NA}}{SG_b^{RCA}}\right) \times 100 \tag{4.4}$$

where V_{DR-NA}^{NAC} is the dry-rodded volume of NA in the NAC and SG_b^{NA} and SG_b^{RCA} are the bulk specific gravities of NA and RA respectively. This verification is necessary to satisfy the conditions of the equations 4.2 and 4.3. In the case of a RA with a high RMC, the necessity of a large quantity of this aggregate may be necessary to comply with equation 4.3, as the amount of NA incorporated by a unit of RA is small. Along the same line, adding such amount of RA can make the mix proportions to fail equation 4.2, as there will be an excessive amount of mortar. Hence, there may be some cases where concretes comprising only RA will not be feasible to make ($RMC\% > RMC_{max}\%$) and, furthermore, some additional NA may be necessary to balance the presented equations. In such cases, a calculation of the minimum NA content ratio (R_{min}) is done as follows

$$R_{min} = 1 - \frac{(1 - RMC)}{V_{DR-NA}^{NAC}} \times \frac{SG_b^{RCA}}{SG_b^{NA}} \tag{4.5}$$

If $RMC\% \leq RMC_{max}\%$, a concrete comprising only RA as the coarse aggregates is possible, and so R could be taken as 0.

Having selected R, the volumes of RA ($V_{RCA}^{RCA-concrete}$) and NA ($V_{NA}^{RCA-concrete}$), in the RAC, are determined with the following equations

$$V_{RCA}^{RCA-concrete} = \frac{V_{NA}^{NAC} \times (1 - R)}{(1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}} \tag{4.6}$$

$$V_{NA}^{RCA-concrete} = V_{NA}^{NAC} \times R \tag{4.7}$$

where SG_b^{OVA} is the specific gravity of the original virgin aggregate (OVA) contained by the RA.

Next, the volume of fresh new mortar for the mix ($V_{NM}^{RCA-concrete}$) can be determined as

$$V_{NM}^{RCA-concrete} = V_M^{NAC} - V_{RCA}^{RCA-concrete} \times \left[1 - (1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}\right] \tag{4.8}$$

where the volume of mortar in the NAC (V_M^{NAC}) is obtained by simply subtracting the V_{NA}^{NAC} from a unit volume of concrete.

Finally, the mix proportion in terms of weights of materials is obtained by making simple relationships with the obtained volumes of each material. The equations are shown bellow

$$FineAggregateWeigth = \frac{V_{NM}^{RCA-concrete}}{V_M^{NAC}} \times W_{OD-FA}^{NAC} \tag{4.9}$$

$$Cement\,Weigth = \frac{V_{NM}^{RCA-concrete}}{V_{M}^{NAC}} \times W_{cement}^{NAC} \tag{4.10}$$

$$Water\,Weigth = \frac{V_{NM}^{RCA-concrete}}{V_{M}^{NAC}} \times W_{water}^{NAC} \tag{4.11}$$

$$NA\,Weigth = V_{NA}^{RCA-concrete} \times SG_{b}^{NA} \tag{4.12}$$

$$RCA\,Weigth = V_{RCA}^{RCA-concrete} \times SG_{b}^{RCA} \tag{4.13}$$

where W_{OD-FA}^{NAC}, W_{cement}^{NAC} and W_{water}^{NAC} are the weights of the oven-dry fine aggregate, cement and water, in the NAC respectively.

From these last equations, it can be observed that the reduction of the cement weight takes place by relating the total weight of cement needed by a NAC to the ratio of the volume of new mortar in the RAC and the volume of mortar needed in the NAC, where the new mortar in the RAC, results from subtracting the attached mortar to the RA to the total mortar needed by the mix.

4.3 Adaptation proposal of the Equivalent Mortar Volume to Bolomey methodology

4.3.1 Background

As it has been previously mentioned, the Equivalent Mortar Volume method starts from the base of a conventional concrete mix proportion, made by means of the American Concrete Institute concrete design, which is one of the most used worldwide (Day, 2006). In order to broaden its scope, an adaptation to Bolomey methodology (Collepardi et al., 2007; Fernández Cánovas, 2013) is formulated and analysed.

Bolomey methodology is based on the work of Fuller (Fernández Cánovas, 2013), which is an acknowledged method to design concretes based on an optimal grading curve, which is the one that produces the maximum compactness of the granular skeleton forming the concrete and, in this case, is represented by a continuous grading curve. Bolomey's main feature and difference regarding Fuller procedure, is that the cement becomes a composing element of the optimal grading curve, thus being taken into consideration when determining the proportions of the concrete's granular structure.

Whereas a design of a concrete through the American Concrete Institute method can be completely calculated by simply following the values it presents as tabulated information, obtained from empirical tests, Bolomey method bases its procedure on a equation 4.14, from which the concretes optimum grading curve is obtained. The former method determines the granular skeleton of the concrete by selecting one of the given volumes of NA, based on the maximum size of the aggregate and the fineness moduli of the fine aggregate, which is a simple and practical way to get an approach to the mix proportion, that has to be tested and adapted if necessary. Bolomey design, on the other hand, uses an optimum grading curve, to which the available aggregates and the cement grain size distributions have to get close by. This is accomplished by rather estimating the proportions of these materials and graphically assessing if they sufficiently fit along with the optimum curve, or by resolving a system of equations that is based on the fineness moduli of the materials, which is a more accurate method than the estimation approach. In any of the cases, it will depend on the expertise of the designer to evaluate if the design fulfils the desired characteristics or not, and so the initial design may have alterations with respect to the final mix proportion.

4.3.2 Procedure

The initial step of the design of the RAC through the novel method, as with the American Concrete Institute method, is to determine a mix proportion on the basis of the Bolomey procedure.

Firstly, the amount of water is determined according to the aggregates maximum size and their shape.

Next, the water/cement (w/c) ratio is selected according to the desired properties of the concrete, and so the cement content can be calculated as in the previous step the amount of water has been already determined.

Having determined the amount of cement for the mix, the aggregates composition is now calculated based on the equation 4.14

$$y = a + (100 - a)\sqrt{\frac{d}{D}} \tag{4.14}$$

where y represents the passing material volume percentage of each of the sieves, d is the opening size of the selected sieve in mm, D is the aggregate maximum size in mm, and a is a parameter that depends on the type of aggregate used (rounded or angular) and the required consistency of the concrete, which is categorized in three different degrees, namely dry-plastic, soft and fluid consistencies.

After having all the aggregates and the cement being fitted to the optimal curve, the final composition can be determined by multiplying the obtained volumes of the different materials by their respective specific gravities.

The next step is to calculate the mix proportion of the RAC, with the obtained NAC mix as a starting point. In order to do this, it is necessary to calculate the volume of dry-rodded NA of the NAC (V_{DR-NA}^{NAC}) from the mix proportion obtained with Bolomey's procedure. While the American Concrete Institute method works with dry-rodded volumes and obtains this value directly from a table, and so directly replacing it within the Equivalent Mortar Volume method, Bolomey method works in absolute volumes basis. The additional requirement will thus be to make some additional physical tests on the materials in order to obtain this value.

The dry-rodded volume of the NA can be related to its absolute volume through the following equation:

$$V_{DR-NA}^{NAC} = V_{NA}^{NAC} \times \frac{SG_b^{NA}}{SG_{DR}^{NA}} \tag{4.15}$$

where SG_{DR}^{NA} is the specific gravity of the NA in the dry-rodded condition. This property is easily determined in laboratory, and as we already have each weight of the materials and

$$NA\ Weigth = V_{NA}^{NAC} \times SG_b^{NA} \tag{4.16}$$

, a simple replacement on equation 4.15 gives us the required value. From now on, the procedure follows as described in section 4.2.

In order to verify the Equivalent Mortar Volume method, determine if its adaptation to Bolomey is possible and assess its main properties, an extensive experimental campaign is done. The experimental campaign will be presented in the following chapters of this document.

4.4 Concretes designs

Different mix proportions have been designed according to the objectives of each part of this investigation. There have been three main campaigns using different concrete designs, and so, the way they have been divided is as follows:

- First campaign: The first campaign objective was to analyse the performance of the Equivalent Mortar Volume method while closely reproducing the original research experience using local techniques and materials. The concretes of this campaign have been designed using the American Concrete Institute and the Equivalent Mortar Volume methods.

- Second campaign: This campaign objective was to analyse some properties of the concretes elaborated through the adaptation proposal, and so to verify if this adaptation is feasible to be applied. These concretes are based on Bolomey method and on the adaptation of the Equivalent Mortar Volume method to Bolomey.

- Third campaign: This campaign objective was to analyse the rheological properties of the concretes elaborated through the adaptation proposal and also, to assess the performance of these mixes when using different types of admixtures.This campaign follows the same design methodologies as the ones presented in the second campaign.

4.4.1 First campaign mix proportions

A first set of concrete mixes were designed according to the American Concrete Institute method, using a 100% of coarse RA. Two different types of coarse aggregates were selected, namely Recycled Gravel A and B, which were treated as one phase aggregates (no differentiation between the NA and the mortar attached to it). The second set of concrete mixes was designed with the Equivalent Mortar Volume procedure and based on the mixes of the American Concrete Institute method, using the same aggregates as the previous case, and additionally comprising a natural coarse aggregate, which corresponded to Natural Gravel 1. Both sets of mixes comprised the use of Natural Sand 1, cement type CEM I 42.5R and superplasticizer and air entrainer admixtures. Also, they were designed with two different w/c ratios.

The intention after the utilization of these specific admixtures on this group was to closely follow the parameters used on the Equivalent Mortar Volume method original research.

The concrete mixes were named after their base design methodology (ACI, American Concrete Institute), followed by the procedure applied to elaborate the RAC, namely direct volume replacement of the aggregates (DVR) or the Equivalent Mortar Volume method (EMV), the Recycled Gravel they include in (A or B), and finally their w/c ratio. The final mix proportions obtained from this campaign are the ones shown in Table 4.1.

Table 4.1: Concrete's mix proportions of the first campaign

Concrete ID	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	RCA-A (kg)	RCA-B (kg)	AE (kg)	SP (kg)
ACI$_{\text{DVR}}$-A/0.45	184	409	752	-	786	-	0.08	1.2
ACI$_{\text{EMV}}$-A/0.45	140	311	577	421	782	-	0.06	2.2
ACI$_{\text{DVR}}$-B/0.45	184	409	746	-	-	798	0.08	1.2
ACI$_{\text{EMV}}$-B/0.45	145	323	600	369	-	788	0.07	1.9
ACI$_{\text{DVR}}$-A/0.6	184	307	839	-	786	-	0.06	0.6
ACI$_{\text{EMV}}$-A/0.6	140	233	644	421	782	-	0.05	1.6
ACI$_{\text{DVR}}$-B/0.6	184	307	833	-	-	798	0.06	0.6
ACI$_{\text{EMV}}$-B/0.6	145	242	669	369	-	788	0.05	1.5

4.4.2 Second campaign mix proportions

In this case, a first set of NAC mixes were designed through Bolomey methodology, in order to obtain a reference by which other mixes could be measured to. A second set of RAC mixes was designed through the DVR method, comprising Recycled Gravel type A. The third set of concretes was designed through the adaptation of the method to Bolomey design procedure and also using Recycled Gravel A. All of the mixes used Natural Sand 2, Natural Gravel 1 and cement type CEM I 42.5R. They were also designed with two w/c ratios and a superplasticizing admixture.

In this campaign, only a superplasticizer admixture was used and just in the case of the 0.45 w/c ratio, as the 0.6 w/c ratio mixes showed an acceptable consistency without it. The air entrainer admixture was not used on this campaign in order to eliminate the concrete's entrapped air variable from the analysis, which may cause significant differences on the properties of the concretes.

All the final mix proportions were obtained after testing them in laboratory by preparing the concrete mix, so there may be slight changes from the initial theoretical calculations, specially in the case of the admixtures quantities.

The concrete mixes were named after their base design methodology (B, Bolomey), followed by the category of concrete they belonged to, namely conventional concrete (CON), RAC through the DVR method (DVR) and RAC through the Equivalent Mortar Volume (EMV). These names continued with the replacement percentage of NA by RA (in terms of weight), and their w/c ratio. Although the designs were made in volumetric terms, the percentages of coarse aggregates replacement are shown in terms of weight in order to have a certain concordance with the Spanish Code for Structural Concrete (Spanish Ministry of Public Works, 2008), in which the replacements are related to the weight of the aggregates. Table shows the obtained mix proportions.

Table 4.2: Concrete's mix proportions of the second campaign

Concrete ID	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	RCA-A (kg)	SP (kg)
BCON/0.45	184	409	796	1085	-	1.5
BDVR20/0.45	184	409	796	842	210	0.9
BEMV20/0.45	169	376	732	941	235	2.1
BCON/0.6	184	307	958	1010	-	-
BDVR20/0.6	184	307	914	819	205	-
BEMV20/0.6	171	286	876	876	219	-

4.4.3 Third campaign mix proportions

The methodologies for the design of this campaign concretes are the same as the ones presented in the previous campaign, although different parameters and materials were used. These mixes comprised the use of Natural Sand 3, Natural Sand 4, Natural Gravel 2, Recycled Gravel C and cement type CEM I 52.5R, and they were produced with two different w/c ratios. A first group of concretes was entirely made using two amounts of superplasticizer admixture, and a second group was produced by closely following the first group mix proportions that used the lower percentage of superplasticizer, plus adding a fixed amount of air entrainer admixture.

On this campaign, the utilization of the admixtures in two stages was intended to test the changes on the rheological properties of the concretes by the use of the air entrainer.

As on the other campaigns, the final mix proportions presented here are the result of testing the initial theoretical ones in laboratory, by preparing a concrete mix and adjusting it if necessary.

The concrete mixes were named after their base design methodology (B, Bolomey) and the main tested property (R, Rheology), followed by the category of concrete they belonged to, namely conventional concrete (CON), RAC through the DVR method (DVR) and RAC through the Equivalent Mortar Volume (EMV) method. These concretes names continued with their replacement percentage of NA by RA (in terms of weight), and their w/c ratios. Showing the aggregates replacement percentages in terms of weight rather than in volume follows the same criteria explained on the second campaign. The following numbers represent the percentage, in terms of cement weight, of the superplasticizer and air entrainer (where applicable) admixtures respectively. Tables 4.3 and 4.4 show the obtained mix proportions.

Table 4.3: Concrete's mix proportions of the third campaign without air entrainer

Concrete ID	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	RCA-C (kg)	SP (kg)
BR$_{CON}$/0.4-1	182	455	835	1031	-	4.6
BR$_{CON}$/0.4-1.2	182	455	835	1031	-	5.5
BR$_{CON}$/0.5-1	182	364	880	1064	-	3.6
BR$_{CON}$/0.5-1.2	182	364	880	1064	-	4.4
BR$_{DVR}$20/0.4-1	182	455	835	794	203	4.6
BR$_{DVR}$20/0.4-1.2	182	455	835	794	203	5.5
BR$_{DVR}$20/0.5-1	182	364	880	820	209	3.6
BR$_{DVR}$20/0.5-1.2	182	364	880	820	209	4.4
BR$_{EMV}$20/0.4-1.5	169	422	774	887	227	6.3
BR$_{EMV}$20/0.4-1.7	169	422	774	887	227	7.2
BR$_{EMV}$20/0.5-1	168	336	812	915	234	3.4
BR$_{EMV}$20/0.5-1.2	168	336	812	915	234	4
BR$_{DVR}$35/0.4-1	182	455	835	633	340	4.6
BR$_{DVR}$35/0.4-1.2	182	455	835	633	340	5.5
BR$_{DVR}$35/0.5-1	182	364	880	649	355	3.6
BR$_{DVR}$35/0.5-1.2	182	364	880	649	355	4.4
BR$_{EMV}$35/0.4-1.5	158	395	725	772	407	5.9
BR$_{EMV}$35/0.4-1.7	158	395	725	772	407	6.7
BR$_{EMV}$35/0.5-1.5	156	313	756	793	427	4.7
BR$_{EMV}$35/0.5-1.7	156	313	756	793	427	5.3

Table 4.4: Concrete's mix proportions of the third campaign with air entrainer

Concrete ID	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	RCA-C (kg)	SP (kg)	AE (kg)
BR$_{\text{CON}}$/0.4-1-0.02	182	455	806	989	-	4.6	0.09
BR$_{\text{CON}}$/0.5-1-0.02	182	364	850	1024	-	3.6	0.07
BR$_{\text{DVR}}$20/0.4-1-0.02	182	455	806	761	194	4.6	0.09
BR$_{\text{DVR}}$20/0.5-1-0.02	182	364	850	788	201	3.6	0.07
BR$_{\text{EMV}}$20/0.4-1.5-0.02	170	425	753	855	210	6.4	0.08
BR$_{\text{EMV}}$20/0.5-1-0.02	169	339	790	985	217	3.4	0.07
BR$_{\text{DVR}}$35/0.4-1-0.02	182	455	806	610	324	4.6	0.09
BR$_{\text{DVR}}$35/0.5-1-0.02	182	364	850	630	337	3.6	0.07
BR$_{\text{EMV}}$35/0.4-1.5-0.02	160	399	707	741	309	6	0.08
BR$_{\text{EMV}}$35/0.5-1.5-0.02	158	317	739	767	404	4.7	0.06

4.4.4 Overall analysis of the mix designs

The utilization of the Equivalent Mortar Volume method for the design of concretes implies, in the studied cases of this investigation, important reductions of the mortar contents of the concretes, when related to their original designs. This is due to the principles of the method, among which is the fact that the attached mortar of the RA is counted as a part of the total mortar needed by design on the mix, thus requiring less amount of new mortar and therefore reducing the needed amount of cement. This reduction is directly related to two complimentary factors; the replacement ratio of NA by RA, and the attached mortar content of the aggregates. The higher their values, the higher the reduction and vice versa.

The mortar reduction of the concretes consequently implies a reduction of the cement content of the designed concretes, which depends again on both the aforementioned factors. In the case of the first campaign, the novel method produced a reduction of 21% and 24% of the cement content in both RAC, when using Recycled Gravels A and B respectively. These reductions were achieved by replacing around 70% of the aggregates. The second campaign resulted in a reduction of 8% and, the third campaign had around 7% and 14% reductions, which depended on the selected replacement ratios of RA. These lasts campaigns reductions were achieved with around 20% and 35% aggregates replacements.

When compared to conventionally designed RAC, the novel method implies the need for an additional amount of NA, which will take the place of the old mortar that was taken as a part of the total needed by design. In this investigation, concretes designed through the novel method needed around 40% and 46% additional NA on the first campaign, around 7% and 12% on the second campaign, and 12% and 22% on the third campaign.

Despite the fact that the mixes designed with the novel method needed an additional amount of NA, their structure, in terms of each material volume, turned comparable to those of the NAC and maybe so it will be with their hardened properties

Conventionally designed RAC end up having an excessive amount of mortar, when counting the new one and the one attached to the RA, thus it is reasonable to assume that they will result in worse performances than the other concretes.

By analysing the mix proportions and the basis of the Equivalent Mortar Volume method, the concretes designed through it should result with advantages, not only in terms of the hardened properties of the concretes due to the better controlled amount of total mortar on the mixes, but also in terms of their environmental and economical impacts, mainly due to the utilization of RA and the reductions on the cement contents. As a possible disadvantage, the workability of the mixes could be negatively affected due to the new mortar content diminution, which may be solved through the use of admixtures. These issues will be addressed in the following chapters of this document.

4.5 Concrete mixes elaboration

Same preparation and mixing procedure was used for all of the concretes in this investigation. Hence, the following explanations apply for the first, second and third campaigns.

As a first step, all the aggregates were dried in a 100± 5ºC forced draught oven and then stored at the laboratory facilities. 24 h prior mixing, they were weighted and placed inside individual hermetic closing drums, together with an amount of water equal to their absorption times their weight. After this, and also right before mixing, they were intensively agitated in order to guarantee a uniform distribution of the absorption water within the aggregates. This procedure was consistently done for every mix, and its purpose is to avoid problems with changing w/c ratios, due to aggregates preparation procedures or corrections based on their absorption and humidity, thus eliminating this variables from the analysis. For example, some recommendations for RAC production (37-DRC, 1992; ACI Committee 555, 2001) suggest that the aggregates should be soaked in water before mixing, but this makes difficult to control the effective w/c ratio of the concrete, thus the final results could be distorted.

Next, the rest of the materials were weighted and put into the concrete mixer, starting with the coarse aggregates and following with the fine aggregates, the cement and finally the water. The admixtures were introduced between 1-2 minutes before the mixing process stopped. They were mixed with a small amount of water, which was taken from the initial mixing water. The mixer device is a Collomatic XM with forced action, which has two appositely spinning beaters, with sets of spades circum-rotating around a vertical axis. The mixing time took 3 initial minutes, after which the concrete mixer was stopped for 3 minutes, to finally end up with 2 more minutes of mixing.

After the mixing process, the concrete specimens, for the different tests, were elaborated and cured (Figure 4.1). The curing process consisted on leaving the concrete in the moulds for 24 hours inside the laboratory, with a soaked sacking on top of them which prevented the evaporation on the surface. Afterwards, the specimens were de-moulded and taken into a humidity controlled chamber, in which they were stored until testing.

a) Soaked sacking b) Curing chamber

Figure 4.1: Curing of the concrete specimens

4.6 Conclusions

The Equivalent Mortar Volume method for recycled aggregates concretes design, is a feasible and beneficial idea towards materials saving and environmental protection. Unlike conventional methods for these recycled concretes design, the novel method allows to do designs without the need for extra amounts of cements.

The novel method hands out a new approach on the treatment of recycled aggregates, as it takes into consideration the two phases that form part of it, namely the attached mortar and the natural aggregates. This idea allows to better understand and control the variables affecting the design of recycled aggregates concretes.

Theoretically speaking, the adaptation of the method to other mix proportioning techniques is possible, thus allowing to broaden its scope and extend its use. In order to do this, in this investigation, it was necessary to obtain one more property of the aggregates, which is easy and simple to execute.

Chapter 5

Fresh state and mechanical properties

5.1 Introduction

The fresh state and mechanical properties of concrete are some of the main parameters to be concerned of when designing anything comprising this material. It is well-known that the compressive strength of the concrete is the most important of them all, as it provides, with good accuracy, a wide knowledge of what the concrete performance will be, not only on its mechanical properties but others too. However, in order to have a better understanding of the behaviour of the concrete in certain specific situations, some other parameters are needed too, like the elastic modulus of the material, which will even be as important as the compressive strength when designing structures, as it lets us know how the material will elastically deform under loading. Also, determining properties like the slump turn compulsory when elaborating concrete, as it will give us an idea of the flowing behaviour of this material in its fresh state, which is of major importance when pouring and working with the mix before its hardening.

The use of certain admixtures with the objective of conferring some special property to the mix, require the determination of some other parameters too, like in the case of this investigation, where an air-entraining admixture has been used on some of the mixes. In order to analyse this, the air measurement test is used.

It could be said that other properties like the concrete's density serve as control parameters, adding information for a comprehensive evaluation of the material. This property also gives a great point of comparison when different mix proportion methodologies are used, as it gives an idea of the suitability of the method for certain materials for example. This is something that turns really important when using the Equivalent Mortar Volume methodology, as it modifies the commonly used proportions of recycled aggregates concretes (RAC), turning them comparable to those of the natural aggregates concretes (NAC).

The Equivalent Mortar Volume method should imply differences on this types of tests, as it changes the proportions of the concrete, using less fresh mortar and adding more natural aggregates (NA), if compared to a conventional design of RAC. This changes should make this types of concretes more close to a NAC, at least in terms of their mineral skeleton proportions. All of these changes can be comprehensively assessed with the obtaining of these tests results.

5.1.1 Objectives

This chapter main objectives are to obtain and analyse some of the fresh state and mechanical properties of the different campaigns concretes.

With this, an assessment of the variations between the different mix proportion methodologies will be done, and an evaluation of the use of these methodologies will be presented, concerning the commented properties.

The specific objectives arising from the previous purposes are:

- to elaborate an experimental campaign to determine the fresh state and mechanical properties of the concretes;
- to analyse the obtained data and determine the influence of each design methodology on the slump values, densities, air content, compressive strength and modulus of elasticity of the concretes;
- to gather the results in order to make comparisons between the different concrete campaigns and so to provide general analyses;
- to determine the advantages or disadvantages of using the Equivalent Mortar Volume method concerning this tests, when compared to other mix proportioning methods.

5.1.2 Program of the study

The presented objectives will be addressed by presenting the proposed experimental campaigns and its results.

On a first stage the materials and methods used for such purposes will be presented, briefly explaining the selected laboratory tests. Next, the obtained results will be presented by test type, and subdivided on the different concrete campaigns. On each of these tests, an overall analysis of the results of all the produced campaigns will be done. Finally, the conclusions of the chapter will be presented.

5.2 Materials and methods

The analysis presented in this chapter comprises the concretes mixes from the first, second and third experimental campaigns. Their main design parameters, the materials used for their elaboration, and the final mix proportions have already been presented in subsections 4.4.1, 4.4.2, 4.3 and 4.4, from chapter 4, in which they can be consulted.

The assessment of the fresh state and mechanical properties of these concretes was done by subjecting them to some laboratory analyses. These included the slump test, air content, fresh and hardened densities, compressive strength and static modulus of elasticity, which followed the prescriptions of the standards EN 12350-2 European Committee for Standarization (2009a), EN 12350-7 European Committee for Standarization (2010), EN 1097-6 European Committee for Standarization (2013), EN 12390-3 (European Committee for Standarization, 2009d) and UNE 83316 (AEN/CTN 83 - Concrete committee, 1996) respectively.

The slump test (Figure 5.1) was executed immediately after the end of the 8 minutes of the mixing process and repeating the test when necessary. The air content of the concrete samples was only measured in the concretes of the first and third campaigns with the aid of an air-meter device and, just like in the previous case, it was done immediately after the 8 minutes of mixing, as well as in the case of the fresh state density.

Figure 5.1: Slump test

The hardened state densities of the concretes were measured after 28 days of curing, obtaining the different masses of the samples as described in the aforementioned standard, but in the case of the saturated mass, which was obtained with the aid of a vacuum device. As it can be noticed in Figure 5.2, this device consisted on a transparent methacrylate container with a closing lid and two valves attached to it, one connected to a vacuum pump and the other to a water supply.

Figure 5.2: Vacuum device

In the case of the compressive strength and modulus of elasticity, three samples for each one of these tests were used in order to have enough information, detect abnormal data and prevent inconsistencies on the final values, therefore, the presented results correspond to the average and standard deviation values. The samples were tested at 28 days of curing.

5.3 Slump test

5.3.1 First campaign

The results of the slump test measurements of both the conventionally designed RAC and the one designed through the Equivalent Mortar Volume method, with Recycled Gravels type A and B, are shown in figure 5.3.

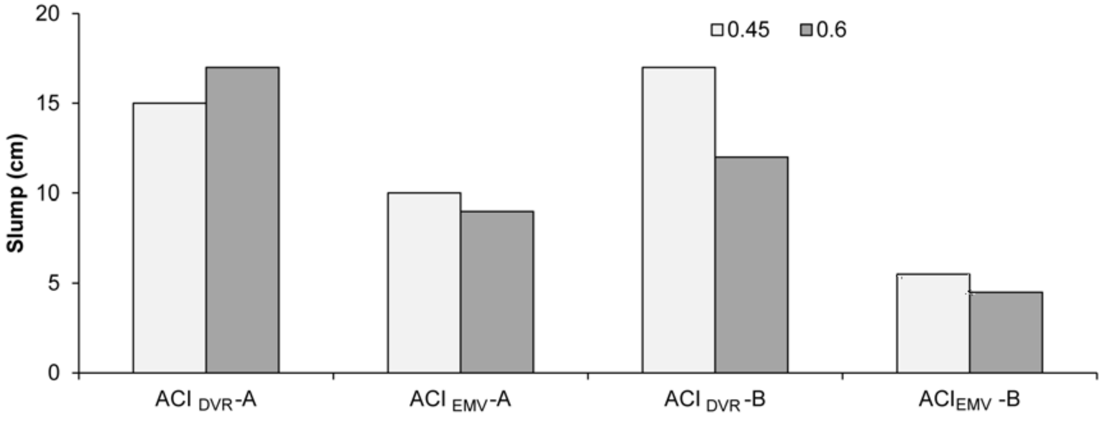


Figure 5.3: Slump test results of the first campaign concrete mixes

The slumps of the concretes designed through the novel method are lower than the ones designed with conventional methods, independent of the type of mix.

ACI$_{EMV}$-A/0.45 and ACI$_{EMV}$-A/0.6 concretes have been produced with 1.8 and 2.7 times the amount of superplasticizer of concretes ACI$_{DVR}$-A/0.45 and ACI$_{DVR}$-A/0.6 respectively. The superplasticizer admixture was dosed in percentages of 0.7 for the two first mixes and 0.3 and 0.2 for the two last ones respectively, in terms of the weight of the cement. In the case of the air-entraining admixture, all these concretes used the same percentage of admixture over the weight of the cement, in this case a 0.02%. This provoked that, contrary to what was mentioned in the case of the superplasticizer, ACI$_{DVR}$-A/0.45 and ACI$_{DVR}$-A/0.6 concretes had 1.3 times the amount of air-entraining admixture than ACI$_{EMV}$-A/0.45 and ACI$_{EMV}$-A/0.6 concretes, which is due to the amounts of cement of each particular mix.

The superplasticizer admixture doses of ACI$_{EMV}$-B/0.45 and ACI$_{EMV}$-B/0.6 were 1.6 and 2.4 times higher than ACI$_{DVR}$-B/0.45 and ACI$_{DVR}$-B/0.6 concretes respectively. Both the first mentioned mixes were designed with a 0.6% of admixture in terms of the cement weight, and the last mixes with 0.3% and 0.2% respectively. The air-entraining admixture had the same proportioning criteria as in the previous case.

It seems clear that, irrespective of the concrete type, the novel method has an important influence on the slump of the mixes. The lower slump values of the concretes designed with the novel method, that could not be adjusted to the values of the conventionally designed recycled concretes with the use of the commented admixtures, may be related to the amount of fresh mortar of these mixes. In the case of the concretes with Recycled Gravel A, ACI$_{EMV}$-A/0.45 and ACI$_{EMV}$-A/0.6 concretes presented 16% less fresh mortar on the mixes than their counterparts, while in concretes with Recycled Gravel B, ACI$_{EMV}$-B/0.45 and ACI$_{EMV}$-B/0.6 had a 14% difference. This is due to the amount of hardened mortar accounted as part of the total needed by design, which takes the place of the fresh one.

With the exception of concrete ACI$_{DVR}$-B/0.45, concretes using Recycled Gravel B have lower slumps than the ones designed with Recycled Gravel A, which may be related to these aggregates composition. Since these aggregates come from crushing processes for their production, they tend to have angular shapes, although these shapes were more noticeable for clean aggregates than the ones with attached mortar to them. In relative terms, aggregate B is more “angular” than aggregate A as it presents higher amount of clean aggregate, hence, it seems reasonable to think that the concretes elaborated with aggregate B could present lower slump values.

When comparing same proportioning criteria but different water/cement (w/c) ratio, there is a reduction on the slump values when higher is the ratio. This may be due to the higher aggregate/cement ratio they have, which makes the concrete mix leaner, with less paste available for lubrication.

5.3.2 Second campaign

Figure 5.4 shows the slump test results for conventional aggregates concrete (B$_{CON}$), conventionally designed RAC with 20% replacement of aggregates (B$_{DVR}$20) and RAC designed with the Equivalent Mortar Volume method and a 20% replacement of aggregates (B$_{EMV}$20), for 0.45 and 0.6 w/c ratios.

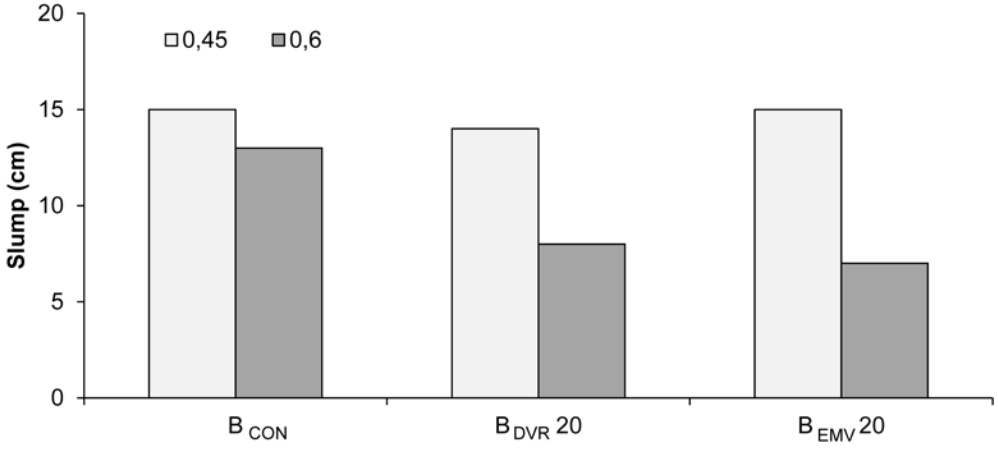


Figure 5.4: Slump test results of the second campaign concrete mixes

The concretes with a 0.45 w/c ratio achieved similar slump values, contrary to the case of the 0.6 w/c ratio mixes, where the slump of B_{CON} mix was higher than both $B_{DVR}20$ and $B_{EMV}20$ mixes. In this campaign, a superplasticizer admixture was used only for the case of the 0.45 w/c ratio mixes, from which one may deduce that the slump differences are due to the use of recycled aggregates (RA) and that they can be corrected by using such admixture. In all the cases the slumps results were into acceptable ranges.

5.3.3 Third campaign

This campaign comprised concretes using superplasticizer and air-entraining admixtures. Figure 5.5 shows the results of NAC, conventionally designed RAC and concretes designed with the Equivalent Mortar Volume procedure, with two different aggregates replacement percentages and two different amounts of superplasticizer (lower and higher), differing in 0.2% in terms of cement weight. Figure 5.6 shows the results of NAC, conventionally designed RAC and concretes designed with the Equivalent Mortar Volume procedure, with two different aggregates replacement percentages, all of them using the same amount of superplasticizer, but one comprising the use of an air-entraining admixture as well (SP and AE respectively). In the legends of the figures, 0.4 and 0.5 values represent the w/c ratio.

Note that Lower 0.4 and 0.5, and SP 0.4 and 0.5 concretes correspond to the same mixes, and they have been separated for comparison purposes.

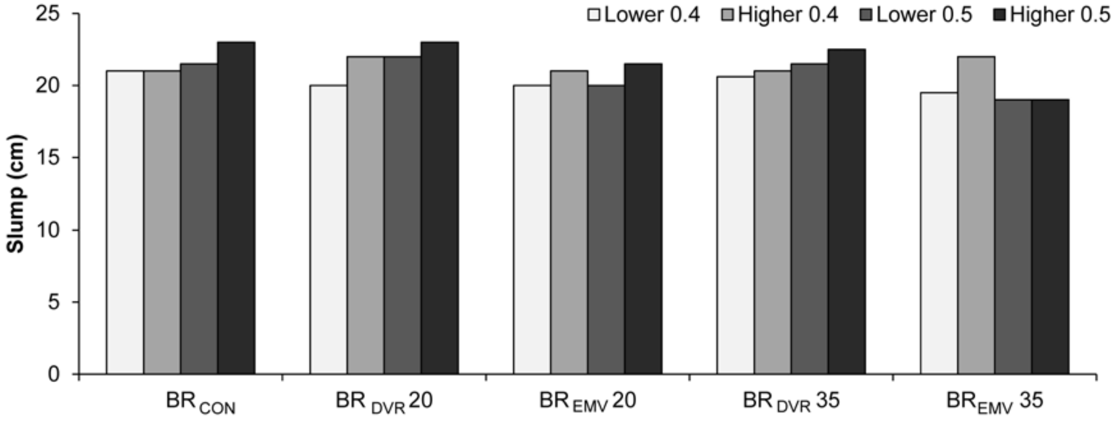


Figure 5.5: Slump test results of the third campaign concrete mixes without entrained air

In this first case, for equal type of concrete mixes and same w/c ratios, it seems clear that there is a tendency to achieve greater slumps when higher dosages of admixture are used, with the exception of BR_{CON}/0.4 and BR_{EMV}/0.5 concretes. This is in fact logical as it is the main purpose of the superplasticizer. Although this, these differences are not high, probably due the small difference on the admixture dosages (0.2%).

For equal type of concrete mixes and admixture dosage, and different w/c ratios, there is a tendency to achieve higher or comparable slumps when greater w/c ratios are used, except in the case of the BR_{EMV}/0.5 concrete.

When taking into account the same design procedure and different aggregates replacement percentages, in most of the cases, an increase of aggregates replacement leads to lower slumps. This may be due to the rougher superficial texture that RA have, which may enhance the mechanical locking between the coarser aggregates and thus reducing the workability.

For different design procedures, the novel methods seems to slightly reduce the slump values in some cases. As it has been explained in a previous section, this is due to the reduced fresh mortar amount of these mixes.

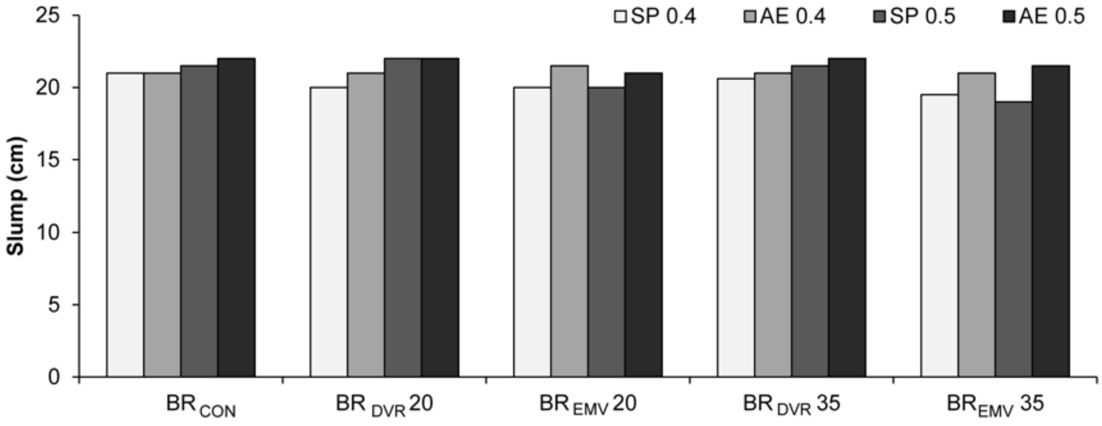


Figure 5.6: Slump test results of the third campaign concrete mixes with entrained air

In this second case, for equal type of concrete and same w/c ratios, the addition of the air-entraining admixture shows a clear tendency to increase the slumps values. This is due to the fact that this admixture increases the paste volume within the concrete mix (Mehta and Monteiro, 2006). Also, in most of the cases, for the same concrete design comprising air-entraining admixture, increasing the w/c ratio slightly increases the slump.

When taking into account different design procedures or aggregates replacement ratios, the addition of an air-entraining admixture does not present a clear tendency.

Although there are small differences between these concrete slumps, it can be said that the different concrete mixes achieve comparable results as they lay between the tolerance limits prescribed by European Committee for Standarization (2000b) (±30 millimetres).

5.3.4 Overall analysis

In general terms, when taking into account the results of the different campaigns, it can be said that the Equivalent Mortar Volume method does have an effect on the consistency of the concretes, when high aggregate replacement ratios are applied, or when no admixtures are used.

Although it seems that high dosages amounts of a superplasticizer admixture may not be enough to achieve comparable slump values on concretes designed with the novel method when compared to those designed by conventional methods, as it has been observed on the first campaign, in the last campaign higher amounts of superplasticizer were enough to achieve comparable slump values.

In the case of the use of the admixture, the slumps of the second campaign concretes without superplasticizer, do not turn comparable to the parent concrete, even with an aggregate replacement of 20%, whereas the ones using it do, in both the second and third campaigns.

5.4 Air content

An air-entraining admixture has been used in the concrete mixes of the first and third campaigns. The first one has the objective of obtaining comparable characteristics to those concretes of the original research (Fathifazl et al., 2009). Because of the geographical location of the original investigation, where there may be freeze and thawing cycles, the use of such admixtures seems coherent. The third one has the objective of analysing the possible benefits that this type of admixture has on the rheological properties of certain concrete mixes.

5.4.1 First campaign

Figure 5.7 shows the results of the entrained air measurement for the first campaign.

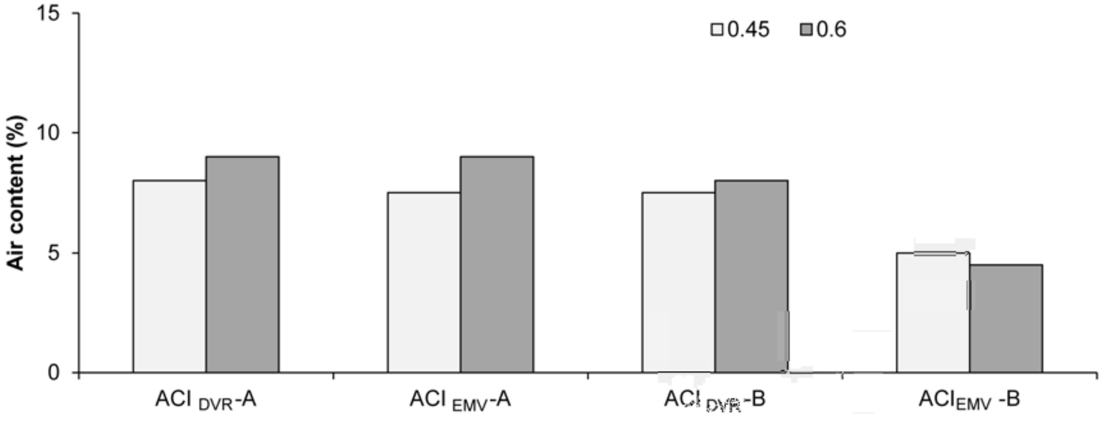


Figure 5.7: Air content of first campaign concrete mixes

From this figure, it seems clear that the air contents of the concrete mixes are high, with the exception of both ACI$_{EMV}$-B/0.45 and ACI$_{EMV}$-B/0.6 concretes. According to Kosmatka et al. (2003), there is a relationship between air content and slump which makes the first property to increase or decrease when the slump is higher or lower respectively(Kosmatka et al., 2003; American Concrete Institute Committee E-701, 2013), specially in concretes of slumps up to 175 millimetres. This explains the lower air contents of the mentioned concretes, where they also have the lowest slump values of the whole campaign.

The concretes of this campaign have been designed to have an air content objective of 6%, which is overpassed by the first three types of concretes (Figure 5.7). This may be explained, as well as in the aforementioned case, by the slump values they have achieved.

Except for the ACI$_{EMV}$-B/0.6, concretes with 0.6 w/c ratio tend to have more entrained air than 0.45 ones. This is an effect of the cement content and the free water on the mix (Kosmatka et al., 2003). 0.45 w/c mixes have more cement and will need more water to cover these particles, thus making the available water to form air bubbles lower.

5.4.2 Third campaign

Figure 5.8 shows the results of the air content measurement of the third campaign concrete mixes.

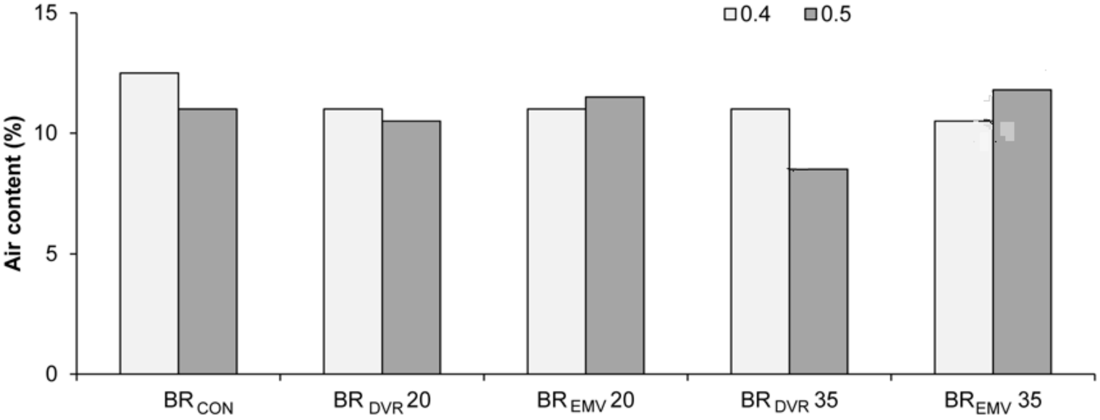


Figure 5.8: Air content of third campaign concrete mixes

Contrary to what was explained before, concretes with slumps over 175 mm tend to loose entrained air more easily, so, above 175 mm, the higher the slump the less the air entrainment in a concrete mix (Kosmatka et al., 2003). According to Du and Folliard (2005), this is due to the lower stability of larger air bubbles created by buoyancy forces.

This effect is not clear when looking at the whole group, maybe due to the differences on the materials of each concrete mix, but when looking at same proportioning method concretes there seems to be a trend following the aforementioned criteria, with the exception of $\mathrm{BR_{EMV}}35$ mixes.

5.4.3 Overall analysis

In general, the concretes of the first campaign present lower air contents when compared to the ones of the third campaign, even when they have been dosed with the same amount of air-entraining admixture in terms of the cement weight (0.02%). This may be due to the differences in their mix proportions and to the fact that the concretes of the third campaign have greater quantities of superplasticizing admixture, which can also entrain air into concrete. According to Lazniewska-Piekarczyk (2014), certain types of superplasticizer can induce to more entrained air as a result of their surfactant effect, which reduces the surface tension of the surrounding water.

5.5 Hardened concrete density

5.5.1 First campaign

Figure 5.9 shows the results of the hardened densities of this campaign concretes, comprising Recycled Gravels A and B respectively.

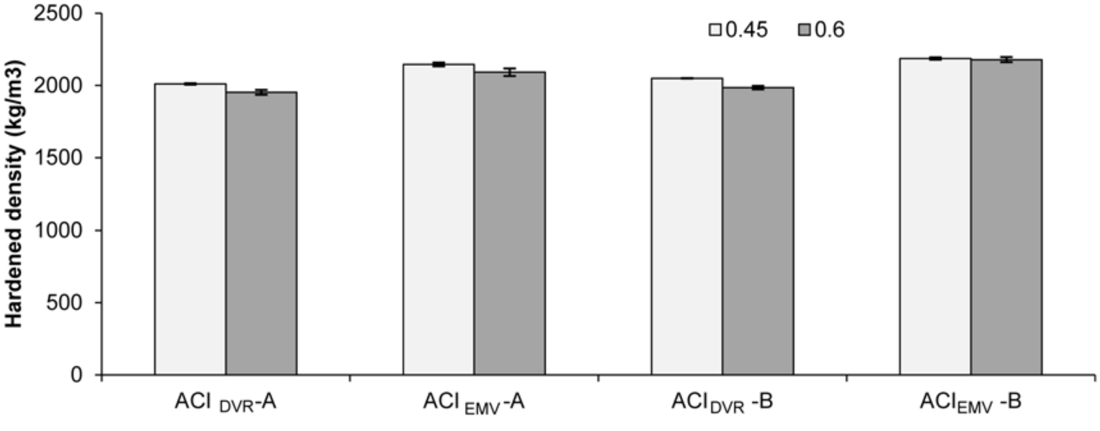


Figure 5.9: Hardened densities of the first campaign concrete mixes

The fact that the concretes designed with the novel method use more NA and have less total mortar explains their greater densities values when compared to conventionally designed recycled concretes.

5.5.2 Second campaign

The obtained densities of this concretes show no major changes between them. The small replacement of NA by RA (20%) may be the reason of their similarities. In any case, 0.6 w/c ratio concretes show lower densities than the 0.45 ones, and the lowest values among them all belong to B$_{DVR}$20 concretes, due to the excessive amount of mortar they have.

The results of these concretes hardened densities are shown in Figure 5.10.

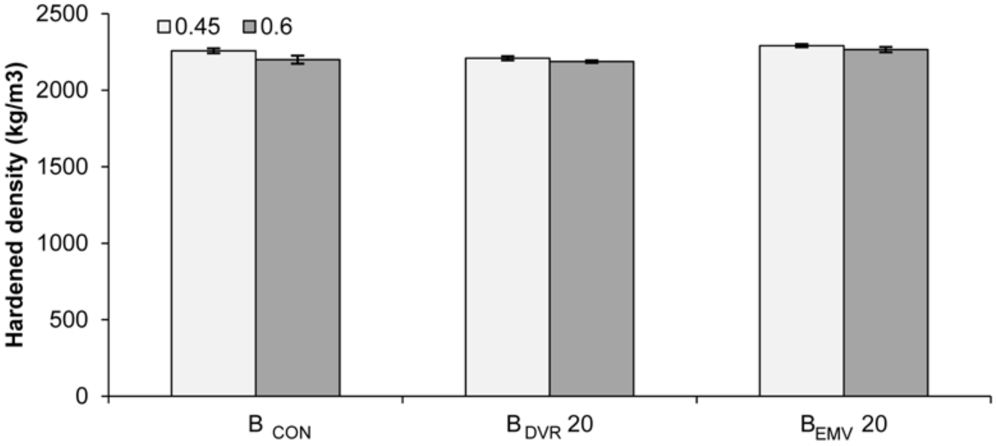


Figure 5.10: Hardened densities of the second campaign concrete mixes

5.5.3 Third campaign

Figure 5.11 shows the results of the concrete mixes without the air entraining admixture. In the legend, Lower and Higher correspond to the amount of superplasticizing admixture used on each concrete.

It seems clear that the greater density values were achieved by concretes having the lower w/c ratio.

Although the differences between the different concrete mixes are small, it is worth mentioning that the lower values, when comparing concretes by their w/c ratio, are shown by BR$_{DVR}$35 concretes. This is an expected outcome due to the excess of mortar that these mixes present; a behaviour that the concretes designed with the novel method do not present, due to the total mortar balance that the method implies.

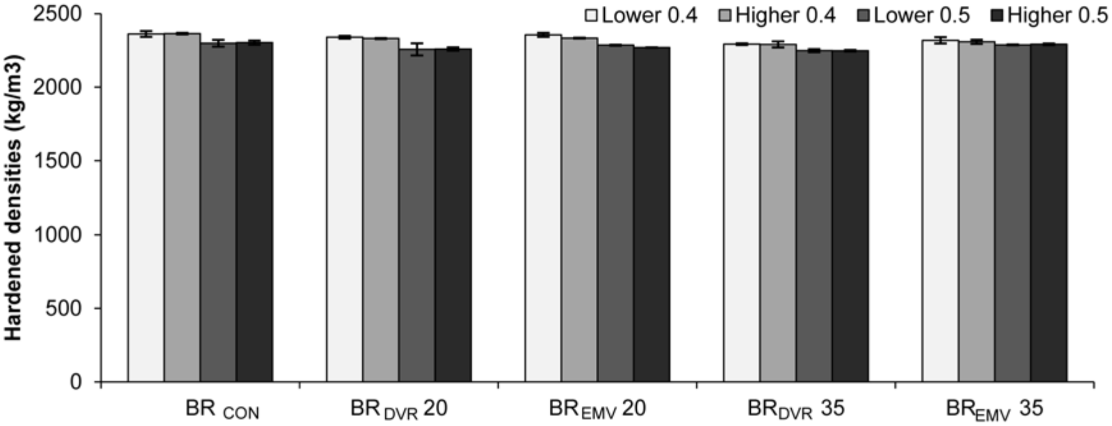


Figure 5.11: Hardened densities of the third campaign concrete mixes without entrained air

Figure 5.12 shows the results of the concretes comprising the air entraining admixture versus the ones that did not. As explained before, SP and AE correspond to the use of superplasticizing and air-entraining admixtures respectively.

It is clear that, irrespective of the concrete type, mixes comprising the air-entraining admixture have the lowest values of densities. This is logical, as the entrained air will occupy space in the concrete without contributing any weight.

Again, as in the previous case, concretes with a lower w/c ratio have the higher density values, except for the case of $BR_{DVR}35$ concretes with air. This exception may be explained by the air content difference of these concretes, where the 0.5 w/c ratio mix has the lowest value (8,5%) and 0.4 w/c ratio mix presents the highest (11%).

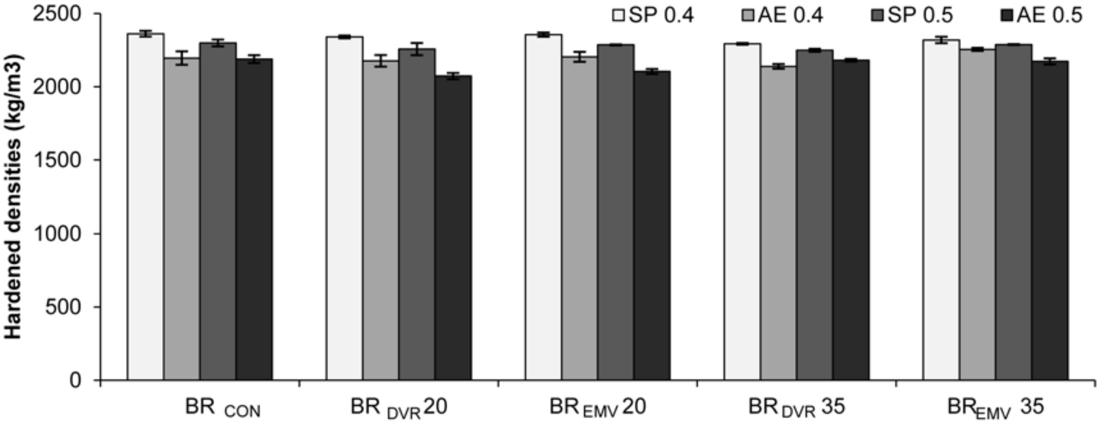


Figure 5.12: Hardened densities of the third campaign concrete mixes with entrained air

5.5.4 Overall analysis

From all the campaigns, the lowest densities are the ones from the first one, followed by the third campaign concretes with air. Although the highest values of entrained air are found in the third campaign concretes, their greater densities may be related to the differences in their mix proportions, were the concretes of the first campaign comprise more RA than the ones of the third, thus lowering their densities. Also, concretes of the third campaign use a finer type of cement, and lower w/c ratios.

Following these two groups comes the concretes of the second campaign, and last, the greater values are found on the concretes of the third campaign with no air-entraining admixture. This again may be due to the difference on the cement type and the w/c ratios, which produce more porosity on the paste when higher values are used, and thus lower density. Also, the densities of the NA used on the third campaign have the greater values.

5.6 Compressive strength

5.6.1 First campaign

Several publications mention the effects that entrained air has on the compressive strength of concretes (Essroc Italcementi Group; Cement Admixtures Association; National Ready Mix Concrete Association, 2001; Mehta and Monteiro, 2006; Neville and Brooks, 2010; Maier and Durham, 2012; American Concrete Institute Committee E-701, 2013), by reducing it about 5% for every 1% of entrained air, thus a normalization equation presented by Maier and Durham (2012) has been used. This equation relates the target air content and the real air content of the mix, with the concrete's compressive strength, in order to obtain a normalized compressive strength. The equation is as follows:

$$\frac{f_c'x*(1-0.05*6.5\%)}{1-0.05*Air\,Measured\%}=f_c'normalized \tag{5.1}$$

where, $f'_c x$ represents the obtained compressive strength, $f'_c, normalized$ represents the normalized compressive strength, 0.05 represents the 5% strength reduction for every 1% of entrained air, and 6.5% represents the target air content used on the original investigation. As the target air content of these concretes was 6%, their compressive strengths have been normalized according to this value.

The normalized values show that there are no major changes between the different methodologies with respect to the compressive strength.

The results with their individual standard deviations are shown in Figure 5.13.

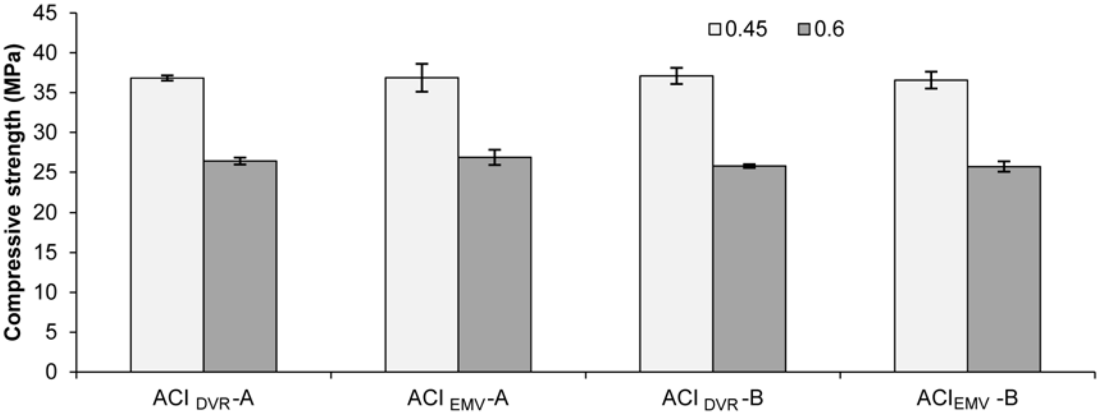


Figure 5.13: Compressive strengths of first campaign concrete mixes

An ANOVA test was carried out, according to the aggregate type and the w/c ratio used, and no significant differences were found. Nevertheless, the compressive strengths of the concretes designed with the novel method have been achieved using less cement than the conventional method. $\mathrm{ACI_{EMV}}$-A mixes were prepared using 311 and 233 kilograms of cement, while $\mathrm{ACI_{DVR}}$-A mixes used 409 and 307 kilograms, both for the 0.45 and 0.6 w/c ratios respectively, which represents about a 24% cement reduction per cubic meter. $\mathrm{ACI_{EMV}}$-B mixes were prepared using 323 and 242 kilograms while $\mathrm{ACI_{DVR}}$-B mixes used 409 and 307 kilograms, both for the 0.45 and 0.6 w/c ratios respectively, which represents about a 21% cement reduction per cubic meter. Moreover, all the mixes designed with the novel method used around 40 litres less water than the conventional one.

These results show that the better controlled amount of total mortar on the mix has a positive outcome on the compressive strength of the concretes.

5.6.2 Second campaign

The results of the second campaign concrete's compressive strengths are shown in Figure 5.14.

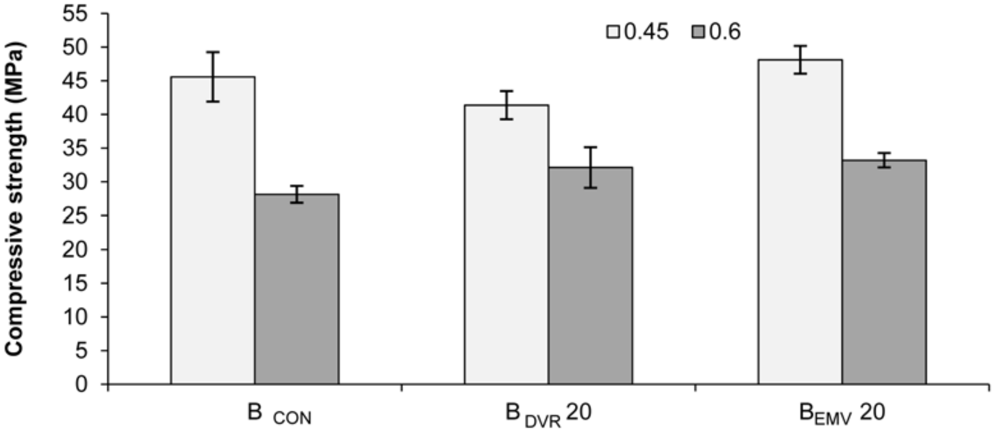


Figure 5.14: Compressive strength of the second campaign concrete mixes

All of these mixes achieved similar strengths when taking into account same w/c ratios, showing no significant differences between groups based in the results of an ANOVA test. Both conventionally designed mixes (NAC and RAC), with a 0.45 w/c ratio, used 409 kilograms of cement and 184 kilograms of water per cubic meter, while the mixes designed with the novel method used 376 and 169 kilograms respectively, which means a reduction of around 8% in both cement and water content. Conventionally designed mixes, with a 0.6 w/c ratio, used 307 kilograms of cement and 184 kilograms of water per cubic meter, while the adaptation used 286 and 171 kilograms respectively, thus achieving a 7% reduction in cement and water content.

These results show that it is possible to achieve similar compressive strengths to those of conventionally designed concretes, and with important reductions on the cement contents.

5.6.3 Third campaign

Figure 5.15 shows the results of the compressive strength test for the third campaign concretes. These concretes have been designed with two w/c ratios and two different amounts of superplasticizer admixture per mix proportioning methodology (Lower and Higher).

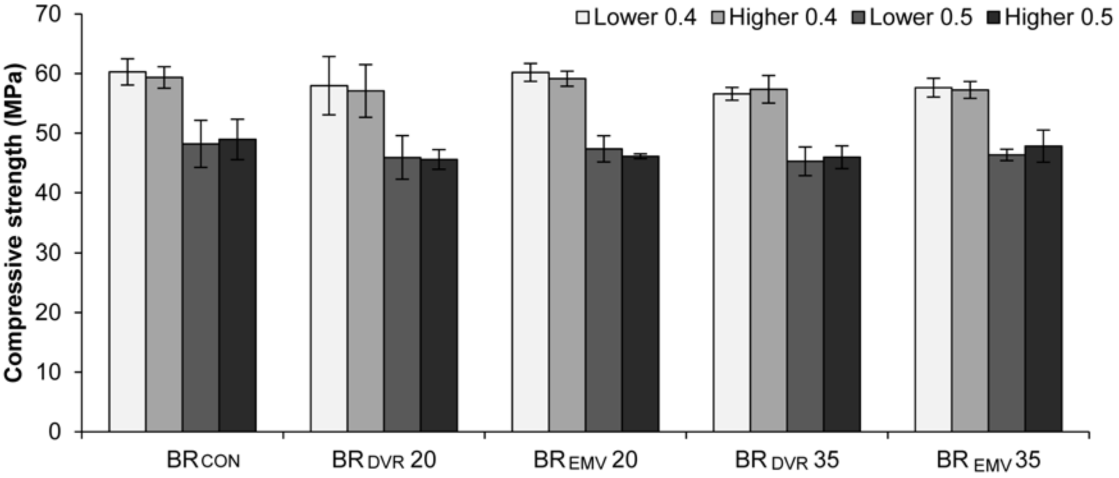


Figure 5.15: Compressive strength of the third campaign concrete mixes without entrained air

When analysing the results of the same design methodology and w/c ratio, and different amount of superplasticizer, no significant differences are found. This said, for the same concrete mix, a 0.2% change of superplasticizer amount (in terms of the cement weight) does not cause a significant change on its compressive strength.

A variation on the w/c ratio from 0.4 to 0.5, caused between 16% and 22% drop on this property, which is expected for the direct relationship that this ratio has with the compressive strength.

For 0.4 w/c ratio concretes, there seems to be a reduction on the resistances of the ones designed with the Direct Volume Replacement method when compared with the conventional mix, which turns significant only in the case of the BR$_{DVR}$35 concretes. A significant difference was found in the BR$_{EMV}$35 concrete with the lower superplasticizer dose as well.

In the case of the concretes with a 0.5 w/c ratio, no significant differences were found, although, in most of the cases, their standard deviations were greater than the ones from the previous concrete mixes.

In any case, it is worth mentioning that the mixes designed with the novel method had around 7% lower amount of cement than the other ones.

Figure 5.16 shows the results of the compressive strength test for the third campaign concretes, with and without using an air-entraining admixture, and comprising the same amount of superplasticizer. As in the previous case, these concretes have been designed with two w/c ratios. Legends SP and AE, correspond to the concretes comprising only superplasticizer, or both superplasticizer and air-entraining admixtures respectively. The following analyses have been done without taking into account the BREMV35/0.5-1-0.02 mix as it seems to be an outlier result.

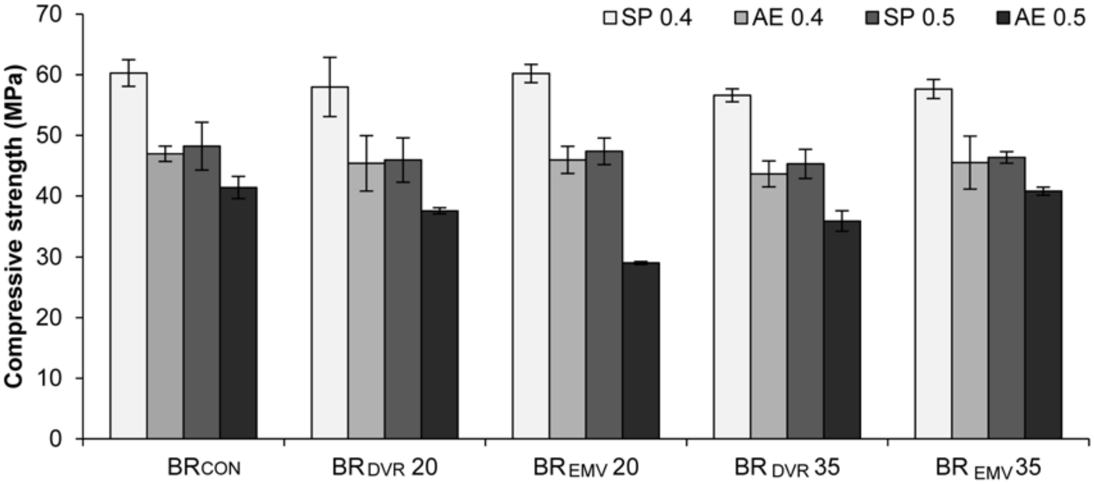


Figure 5.16: Compressive strength of the third campaign concrete mixes with and without entrained air

When analysing the results of the same design methodology and w/c ratio concretes, with and without the air entraining admixture, it can be observed that there are important variations on the compressive strengths. Concretes comprising the air entraining agent with 0.4 w/c ratio had around 22% decrease on the compressive strengths when compared to concretes without the commented admixture and ranging from 21% to 23%. 0.5 w/c ratio concretes had around 17% decrease and ranging from 13% to 21%.

In order to make a proper comparison between the results of the concretes with air entraining admixture, these have been normalized to an amount of entrained air equal to 11%. The normalization has been done following the procedure shown in subsection 5.6.1.

It is worth noting that instead of the 5% reduction of the compressive strength every 1% of entrained air, a 2,5% was used on this campaign as it better fitted the overall results. The results of the normalization are shown in Figure 5.17.

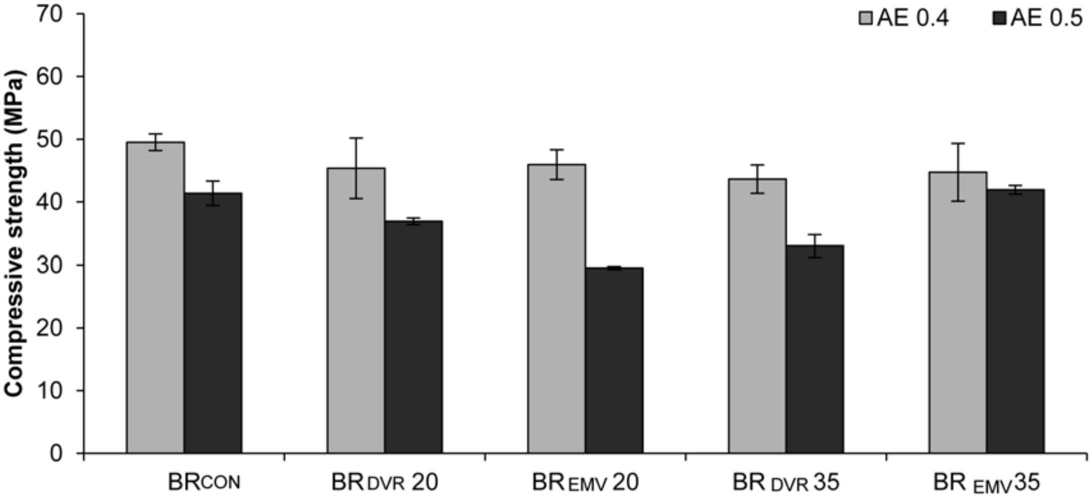


Figure 5.17: Normalized compressive strength of the third campaign concrete mixes with entrained air

When analysing same designing procedure and different w/c ratio, the variation from 0.4 to 0.5 caused important reductions on the compressive strengths of the concretes, with the exception of the BREMV35 concrete, which showed no significant differences on this property regarding the different w/c ratios. Although this, BREMV35/0.4 has important variability within its results.

When comparing same w/c ratio and different design methodology, 0.4 w/c ratio concretes result with no significant difference within their results, although it is noticed that some of them have important variabilities among their results. 0.5 w/c ratio concretes designed with the Direct Volume Replacement method show significant differences when compared to the NAC, whereas the novel method achieves similar results.

Again, like in the previous case, it is worth mentioning that the mixes designed with the novel method had around 7% lower amount of cement than the other ones.

5.6.4 Overall analysis

It has been observed that recycled concretes designed with the novel method achieve same resistances as the ones designed with conventional methods, while lowering the amounts of cement used up to 24%.

Also, when compared to NAC, the novel method achieves comparable resistances while using RA and lowering the amount of cement up to 8%.

It has been confirmed that increasing the w/c ratio of the mixes has a direct effect on their resistances. This has been extensively reported by many authors, following what is stated by the so called Abrams law, where the compressive strength of the concrete is inversely proportional to the w/c ratio (Neville and Brooks, 2010).

It is also confirmed that the entrained air in concrete causes negative effects on its compressive strength, irrespective of the type of concrete. This has been also extensively reported by many authors (Mehta and Monteiro, 2006; Day, 2006; Fernández Cánovas, 2013; Neville and Brooks, 2010). In the majority of the publications, the expected strength loss is mentioned to be of 5% for every 1% of entrained air, although in this investigation other percentages of strength loss have also been encountered to fit better some of the results.

5.7 Modulus of elasticity

5.7.1 First campaign

Figure 5.18 shows the results of the static modulus of elasticity of this campaign concretes.

As this property is closely related to the coarse aggregates properties, between others, there should be important changes between the results of the concretes designed with the different proportioning methods.

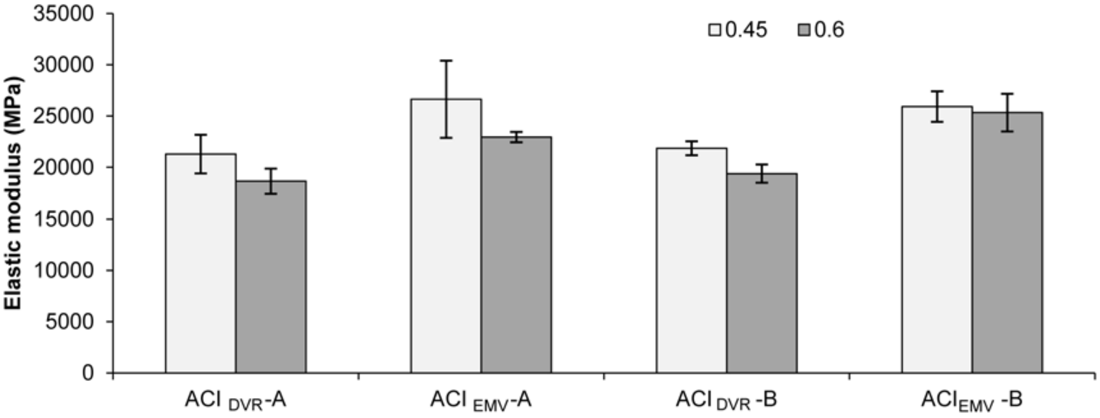


Figure 5.18: Modulus of elasticity of the first campaign concrete mixes

In the majority of the cases the values show that higher elastic modulus are achieved when using the novel method compared to the conventional one, in addition to a reduction in the used amount of cement.

In the case of the $\mathrm{ACI}_{\mathrm{EMV}}$-A/0.6, around a 23% increment on the elastic modulus is achieved when comparing it to the $\mathrm{ACI}_{\mathrm{DVR}}$-A/0.6 mix. $\mathrm{ACI}_{\mathrm{EMV}}$-B/0.45 shows around a 19% increment on the elastic modulus when compared to the $\mathrm{ACI}_{\mathrm{DVR}}$-B/0.45 mix. $\mathrm{ACI}_{\mathrm{EMV}}$-B/0.6 shows around a 31% increment on the elastic modulus when compared to the conventional $\mathrm{ACI}_{\mathrm{DVR}}$-B/0.6 mix.

An ANOVA test was carried out in order to statistically verify these results. The test showed that there are significant differences when using the novel method compared to the conventional one, with the exception of the $\mathrm{ACI}_{\mathrm{EMV}}$-A/0.45 and $\mathrm{ACI}_{\mathrm{DVR}}$-A/0.45 mixes. This exception could be explained by the absence of one result on the $\mathrm{ACI}_{\mathrm{EMV}}$-A mix, which would change the analysis if we suppose a value equal to the average elasticity modulus obtained, thus changing the standard deviation and therefore showing a significant difference in the statistical analysis.

The overall results demonstrate that using the novel method instead of the conventional one, will significantly change the results of this property.

5.7.2 Second campaign

Figure 5.19 shows the results of the different concrete mixes of the second campaign.

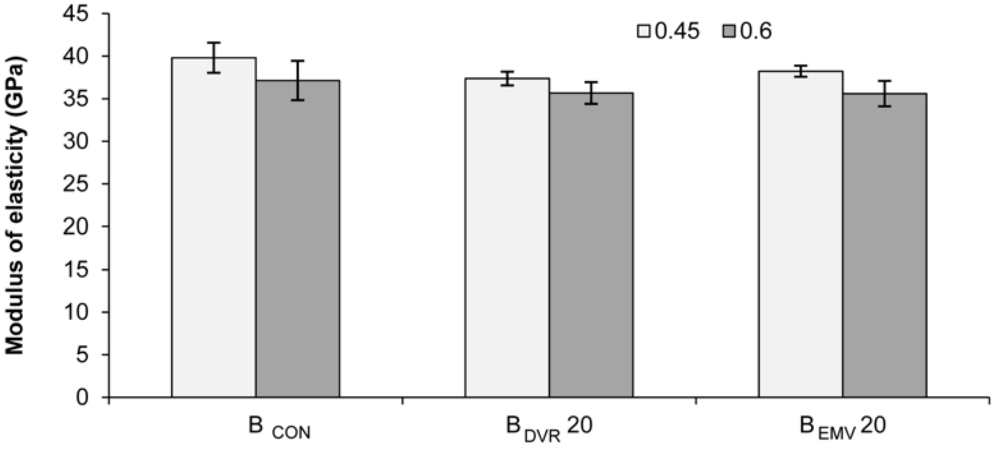


Figure 5.19: Modulus of elasticity of the second campaign concrete mixes

These results are similar to each-other. An ANOVA test showed no significant differences between the different group of concretes. The similarities of these results may be due to the small aggregates replacement ratios of these concretes.

It is worth reminding that $B_{EMV}20$ mixes were elaborated with an around 8% reduction of the cement content, when compared to the B_{CON} and $B_{DVR}20$ concretes.

5.7.3 Third campaign

Figure 5.20 shows the results of the modulus of elasticity of the third campaign concrete mixes comprising two different amounts of superplasticizing admixture and two w/c ratios. As it has been stated earlier, the concretes comprising different amounts of superplasticizer have been designated ’Lower’ and ’Higher’.

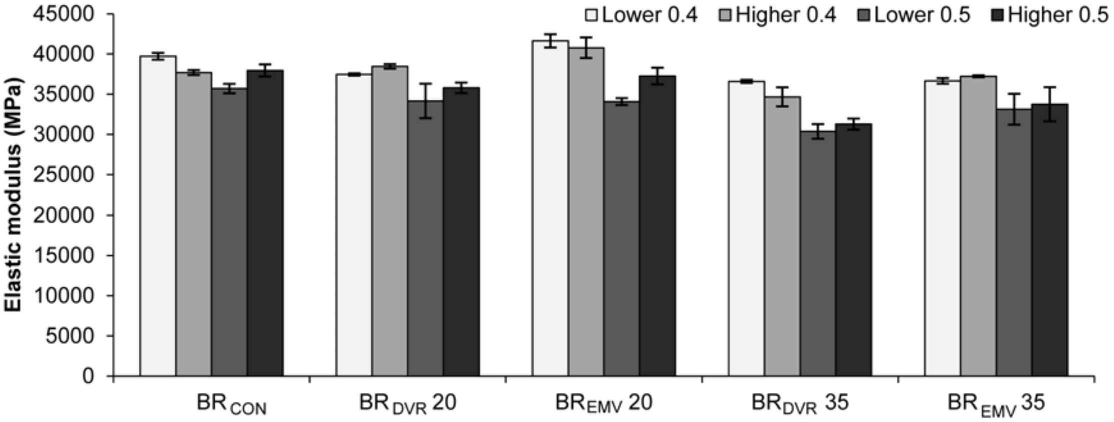


Figure 5.20: Modulus of elasticity of the third campaign concrete mixes without entrained air

When comparing same w/c ratio concretes with the same amount of superplasticizer, significant difference were found in all of the cases. Among 'Lower 0.4' concretes, the highest result was found to be for the novel mix with a 20% of aggregates replacement and all the results of the other mixes were above 36000 MPa. 'Higher 0.4' mixes showed the same behaviour although their lowest mean value was around 34000 MPa in the case of the BR_{DVR}35 mix. 'Lower 0.5' and 'Higher 0.5' mixes greater mean values were found to be the one of the BR_{CON} concretes. It is worth mentioning that in all of the cases, the mean values of the concretes designed with the novel method were greater than the ones of the conventionally designed recycled concretes, and in some cases even greater than the NAC. This last cases may be explained by the elemental composition of the aggregates, which have a strong relationship with this property. RA has a majority of siliceous materials, whereas NA is mainly composed of calcareous materials, thus having a lower elastic modulus.

No clear trend was found regarding the effects of the amount of superplasticizer in the elastic modulus.

In all of the cases, concretes with the lower w/c ratio achieved the greater elastic modulus results.

Figure 5.21 shows the results of the modulus of elasticity of the third campaign concrete mixes with and without the air entraining admixture and two w/c ratios. As commented before, concretes without the admixture have been designated as 'SP' and the ones comprising the admixture 'AE'.

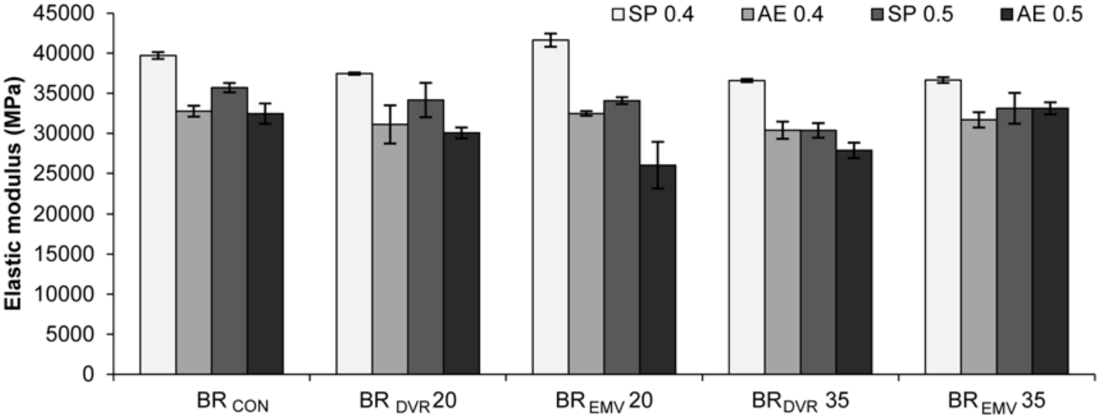


Figure 5.21: Modulus of elasticity of the third campaign concrete mixes with entrained air

Just like in the case of the compressive strength, BR_{EMV}35/0.5-1-0.02 concrete result will not be taken into consideration on this analysis as its value seems to be an outlier.

The air entrainment into concretes has a significant effect on the elastic modulus, showing around 17% reduction in 0.4 w/c ratio concretes when compared to the ones without the admixture, and around 9% in 0.5 w/c ratio concretes. Although in the last case, BR_{EMV}35 concretes had almost the same results, which may be due to other parameters like the better compaction of one of the mixes owed to a higher slump value, which can be consulted in Figure 5.6.

When comparing concretes with different w/c ratio, same design methodology and comprising the air entraining admixture, it can be observed that there are no major differences among their results, in most of the cases with no statistically determined differences. This gives an idea of the effect of the entrained air into concrete, which seems to turn into the most influencing parameter regarding the elastic modulus property.

5.7.4 Overall analysis

As seen in the results of the different campaigns regarding the elastic modulus, it is observed that the novel method for concrete design achieves comparable and in some cases better results than their counterparts, while using lower amounts of cement in their composition.

In general, the results of the different campaigns can be justified because of the existent bond between this property and the concrete's coarse aggregates and porosity. On the one hand, mortar has a lower elasticity modulus than the aggregates due to its porosity and, on the other hand, NA have higher elastic modulus than the other components of the concrete, so, by lowering the amount of mortar of the mix and increasing the amount of NA, the elasticity modulus should be higher. The novel method achieves this by counting the existent mortar, attached to the RA, within the total amount of mortar needed and replacing it with NA, which will end in a concrete mix with quantities of mortar and coarse aggregates similar to those used in NAC mixes.

Also, it has been observed that there is no clear trend regarding a 0.2% difference on the superplasticizer admixture amount of the concretes.

The entrainment of air into concrete does creates significant differences among the results, when compared with concretes without the air entraining admixture. This is in fact logic as the bubbles inside the concrete can be considered as aggregates with no strength at all, which will have an adverse effect on this property.

5.8 Conclusions

As seen in the different experimental campaigns, concretes with lower water/cement ratios achieve better results than higher ratios among the analysed tests.

In general, it has been observed that concretes designed with the novel method can achieve similar slumps to those designed with conventional methods by using higher dosages of superplasticizer admixture.

Due to the basis of the Equivalent Mortar Volume method, the densities of concretes result in similar or greater densities than conventionally designed recycled concretes.

Concretes designed with the novel method achieve similar and in some cases better results than those of the conventionally designed concretes regarding the mechanical properties studied on this chapter.

The use of the air-entraining admixture resulted in worse overall behaviours on the mechanical tests revised on this chapter, when compared to concretes without the commented admixture.

All of these results have been achieved while reducing the cement contents of the concretes, when designed with the Equivalent Mortar Volume method. The reductions were from 7% up to 24% with regard to both conventionally designed natural and recycled concretes.

Chapter 6

Durability properties

6.1 Introduction

The durability properties of concrete are as important as its mechanical performance or its fresh-state characteristics, as they provide important information of the ability of the concretes to resist the actions generated by its surrounding environment. These are important parameters that help to measure the lifespan of a certain structure, and also to determine when it needs mantainance, repair or replacement.

With all this, it is also possible to have an idea of the environmental burdens that one type of concrete has compared to some other, and so to take actions and decide which type fits the best for every specific situation regarding the consequences they may have on the environment. There may be concretes using high amounts of cement and thus being highly polluting when compared to concretes using less cement but, depending on the use, they may imply thinner structural sections, longer lifespans, less maitenance, better quality for re-using, and so on, thus being more environmentally friendly in the long term.

In this same line, recycled concretes arise as a solution towards the environmental problems that natural aggregates concretes (NAC) use present, mainly due to the huge amounts of residues that they represent, because they use the already demolished concrete as aggregates. However, because of these aggregate's characteristics, the mixes need more quantities of cement in order to achieve similar properties of those of the NAC. This, as it has been commented throughout this document, can be solved by the use of the Equivalent Mortar Volume method.

The durability properties are closely related to the mortar phase of the concretes so, as this is one of the main things that the novel method has into account, analysing this properties seems of high importance.

6.1.1 Objectives

The general objectives of this chapter are to obtain and analyse the durability properties of different concrete mixes, designed with different mix proportioning methodologies and comprising the use of recycled aggregates for their elaboration. This will allow an objective assessment of the advantages or disadvantages that the proposed methodologies for the elaboration of concretes have among them.

The specific objectives are:

- to elaborate an experimental campaign with the aim of determining some durability properties of the studied concretes;
- to analyse the obtained data for each concrete mix and to compare them within and among the different concrete campaigns;
- to analyse the behaviour of the different durability properties depending on the type of recycled aggregates used;
- to determine the effect that certain admixtures have on the studied test results;
- to determine the advantages or disadvantages of using the Equivalent Mortar Volume method concerning this tests, when compared to other mix proportioning methods.

6.1.2 Program of the study

The aforementioned objectives will be addressed by presenting the proposed experimental campaigns and its results.

On a first stage the materials and methods used for such purposes will be presented, briefly explaining the selected laboratory tests. Afterwards, each results will be presented by test type, and subdivided on the different concrete campaigns. On each of these tests, an overall analysis of the results of all the produced campaigns will be done. Finally, the conclusions of the chapter will be drawn.

6.2 Materials and methods

The different concrete campaigns have been evaluated through different durability tests. These tests aim is to assess the behaviour of the different mixes to certain environmental induced situations.

The selected tests were the water penetration under pressure, determination of the capillary suction through the Fagerlund method, chloride penetration evaluated by $AgNO_3$ solution spraying, and the determination of the penetration parameters for estimating the resistance against chloride penetration through the accelerated chloride penetration test. These tests were executed by following the European Committee for Standarization (2000a) standard, Asociación Española de Normalización y Certificación (2008b) standard, Otsuki et al. (1992) article, and NORDTEST (1995) standard. All of them were done on hardened concrete test specimens, of an age over 28 days.

The water penetration under pressure test, consisted on applying a pressure of 500±50 kPa to a water supply connected to one face of the concrete specimen, for a period of 72±2 hours. After this period, the specimen is taken off the device and split in two parts, perpendicular to the face of the pressure application. The water front is then examined on each of the split parts of the specimen and marked. The water penetration value will be the maximum depth reached by the water front.

The determination of the capillary suction consists on the periodic measurement of the weight increase of a concrete specimen in contact with a water layer of around 5 millimetre height. In order to do this, the concrete specimens were previously conditioned by following the instructions of Asociación Española de Normalización y Certificación (2008a). The conditioning procedure followed on this research is the accelerated one, which consists on placing the specimens in a 50±2 ºC oven for an initial period of 4 days, then they are taken off the oven and covered with a waterproof paint on their vertical face. After this, they were introduced into a hermetic plastic bag trying to extract the maximum amount of air from it, and then they were placed back into the oven for 3 more days. Then, the specimens were taken out from the plastic bag and placed, for 21 days, into a hermetic drum with 65-75% relative humidity, which was obtained by introducing an opened container with saturated NaCl.

The procedure after the conditioning, starts with the measurement of the specimen weight before any contact is made with the water layer (t=0). After this, the specimens are placed into a container which is then filled with water until the layer height is reached, and their weight is measured in time intervals of 5 min, 10 min, 15 min, 30 min, 1 h, 2 h, 3 h, 4 h, 6 h, 24 h, 48 h, 96 h, and so on, until constant mass is reached. These intervals can be extended after the 96 h measurement. The water absorption coefficient will be obtained by following the next formulas:

$$K = \frac{\delta_a \cdot \varepsilon_e}{\sqrt{m}} \tag{6.1}$$

$$\varepsilon_e = \frac{Q_n - Q_0}{A \cdot h \cdot \delta_a} \tag{6.2}$$

$$m = \frac{t_n}{h^2} \tag{6.3}$$

where, K is the water absorption coefficient $(\frac{g}{cm^2 \cdot min^{0.5}})$, δ_a is the water density considered as 1 g/cm^3 in laboratory conditions, ε_e is the effective porosity of the concrete $(\frac{cm^3}{cm^3})$, m is the water penetration resistance $(\frac{min}{cm^2})$, Q_n is the specimen weight when saturation is reached (g), Q_0 is the specimen weight in the time t0, A is the specimen surface (cm^2), h is the specimen height (cm), and t_n is the time needed to reach saturation (min).

The two chloride related experiments were done after the specimens were immersed in a water-sodium chloride solution for periods of time equal to 35, 60 and 90 days. This solution was prepared with 165 g of sodium chloride for every 1000 g of distilled water and the ratio between the specimens exposed area (cm^2) and the volume of the solution (dm^3) was 50.

As a first step the obtained specimens were immersed in a saturated $Ca(OH)_2$solution until constant mass was reached and after 28 days of curing. Then, the test specimens were sealed with an epoxy resin, leaving only one plane face free from it, which corresponded to the one in direct contact with the solution, thus obtaining a one directional pathway through the specimen. After this, the specimens were immersed in the solution with their free faces pointing up. A container with a sealing lid was used for the latter purpose.

The first test was done by spraying an $AgNO_3$ solution in a concentration of 0.1 mol/l on the fractured surface of the concrete specimens, obtained by splitting the sample by means of a compression testing machine, thus attaining a colour change which delimits the chloride penetration depth. Figure 6.1 shows two regions, separated by the a red line, where the brownish zone below the red line indicates the zone with no presence of chlorides, while the white zone above the red line indicates the affected zone, which turns to this colour due to the precipitation in form of silver chloride. The penetration front is marked and the depth is measured.

Figure 6.1: Chloride penetration depth by $AgNO_3$ solution spraying

The second test for the chlorides determination, termed Nordtest for the sake of the differentiation with the previous test, consists on taking concrete powder samples from the inside part of the specimen, at different depths of it and, afterwards, measuring the chloride content of these powder samples by titration. A device consisting of a crown type bit connected to a power drill was installed in order to obtain the samples. Different methods and devices were tested before starting with the samples extraction. At the end, the commented methodology was chosen because it gave the best results, although it implies an important amount of time due to the velocity of the extraction and the different depths at which the samples need to be obtained. This, plus the large amount of specimens resulted in an extensive campaign. The previous test with the $AgNO_3$ solution served as a benchmark in order to set an approximate depth of samples extraction.

After obtaining the chloride concentrations by depths, a non-linear regression analysis by means of the least squares fit method is performed in order to obtain the chloride transport coefficient (D_e) and the chloride concentration at the surface (C_s). With the results of the regression analysis, the behaviour of the different concrete mixes to the chloride environment exposure were analysed.

6.3 Water penetration under pressure

6.3.1 First campaign

The results of this campaign are shown in Table 6.1. These correspond to the maximum water penetration depth, calculated as the average value between three different specimens.

Table 6.1: Water penetration results of the first campaign concrete mixes

	Water penetration depth (mm)			
	0.45 w/c	σ	0.6 w/c	σ
ACI_{DVR}-A	17	1.0	33	1.4
ACI_{EMV}-A	14	1.0	25	1.5
ACI_{DVR}-B	14	1.4	31	1.0
ACI_{EMV}-B	8	0.7	24	2.1

Is is clear that, irrespective of the type of recycled aggregate (RA) or the water/cement (w/c) ratio used, the water penetration depths are lower for the case where the concrete has been designed with the Equivalent Mortar Volume method.

There is also an improvement of this property when aggregate type B is used, which is more pronounced in the lower w/c ratio case. This behaviour may be due to the non-sorptive characteristic of the bituminous aggregate that it contains, thus acting as a barrier against the water ingress.

6.3.2 Second campaign

Table 6.2: Water penetration results of the second campaign concrete mixes

	Water penetration depth (mm)			
	0.45 w/c	σ	0.6 w/c	σ
BCON	9	1.4	>50	-
BDVR20	29	4.9	>50	-
BEMV20	9	1.5	>50	-

This campaign concrete mixes results show that there is a major enhancement of the concrete permeation characteristics when applying the novel method, for the case of the 0.45 w/c ratio and when compared to the conventional recycled concrete mix, as it can be seen in Table 6.2. It is also observed that the novel method achieves the same result of that of the NAC, which may be due to the closer characteristic that the method provides to these concretes internal structure, when compared to a conventional mix.

In the case of the 0.6 w/c ratio, the results are inconclusive, as the water penetrated all along the specimens depth, but this may give an idea of the minimum limits with respect to the w/c ratios and this property.

It is worth mentioning that this campaign mixes with a 0.6 w/c ratio, showed worst results than the previous campaign mixes, even when using less or no RA at all. This can be explained by the use of the air-entraining admixture, which was only used in the the previous campaign mixes. This admixture creates a less accessible porous system within the concrete matrix (Grupo de trabajo 2/3 - ACHE, 2010).

6.3.3 Third campaign

The results of the third campaign concretes comprising a superplasticizer admixture and both superplasticizer and air-entraining admixtures, are shown in Table 6.3.

Table 6.3: Water penetration results of the third campaign concrete mixes

	Water penetration depth (mm)			
	0.4 w/c	σ	0.5 w/c	σ
BR$_{CON}$ (1)	17	1.2	25	4.2
BR$_{CON}$ (1.2)	14	1.7	28	2.1
BR$_{CON}$ (1)*	14	2.0	15	2.1
BR$_{DVR}$20 (1)	21	2.6	29	3.0
BR$_{DVR}$20 (1.2)	11	1.0	21	3.8
BR$_{DVR}$20 (1)*	9	1.5	16	3.5
BR$_{EMV}$20 (1.5-1)	10	0.6	16	4.0
BR$_{EMV}$20 (1.7-1.2)	15	2.5	24	1.2
BR$_{EMV}$20 (1.5-1)*	8	1.0	9	1.5
BR$_{DVR}$35 (1)	22	1.5	32	1.5
BR$_{DVR}$35 (1.2)	18	2.6	35	2.3
BR$_{DVR}$35 (1)*	9	2.6	11	2.1
BR$_{EMV}$35 (1.5)	15	2.6	29	4.7
BR$_{EMV}$35 (1.7)	11	1.0	25	1.5
BR$_{EMV}$35 (1.5)*	7	2.5	10	0.6

*Concretes comprising an air-entraining admixture

From the above presented table it is clear that, irrespective of the concrete type, there is an improvement of the water penetration property when a lower w/c ratio is used.

When taking into account same concrete proportions and w/c ratio, an increase of 0.2% in the superplasticizer amount does not provides a clear trend on this property.

In the majority of the cases, concretes designed with the Equivalent Mortar Volume method achieve better results than the ones of the conventional recycled concrete mixes. Furthermore, when compared with the NAC, the novel method achieves better or comparable results in most of the cases.

Concretes comprising the air-entraining admixture achieve important improvements when compared with the ones without this admixture for all of the studied cases.

6.3.4 Overall analysis

From the results of all the campaigns it is observed that the novel method improves the concretes resistance to the water penetration under pressure, when compared to conventionally designed recycled concretes, therefore, it can be said that their permeability is lower. When compared to NAC, in the majority of the cases, their results are comparable to them.

The use of admixtures ends up in considerable better results than when no admixtures are used. This is confirmed by observing the results of the second campaign concrete mixes with a 0.6 w/c ratio in which the water profile was detected all along the specimens. By making a comparison with the results of the first campaign mixes, which have been proportioned with more quantities of RA, it seems clear that the lack of admixtures is the main reason for the unsatisfactory impermeability of the concrete, irrespective of the design method, and therefore, these specific concrete mixes should only be considered for structural concrete design in normal or non-aggressive environmental classes of exposure according to the prescriptions of Spanish Ministry of Public Works (2008).

There is also a clear improvement of this property when a lower w/c ratio is used, as a result of the better quality of the cement paste.

6.4 Capillary suction

6.4.1 First campaign

Table 6.4 shows the obtained capillary absorption coefficients for the first campaign concrete mixes.

Table 6.4: Capillary suction results of the first campaign concrete mixes

	0.45 w/c		0.6 w/c	
	k $(\frac{g}{cm^2 \cdot min^{0.5}})$	σ	k $(\frac{g}{cm^2 \cdot min^{0.5}})$	σ
ACI$_{DVR}$-A	0.0054	0.0001	0.0204	0.0014
ACI$_{EMV}$-A	0.0033	0.0000	0.0057	0.0003
ACI$_{DVR}$-B	0.0040	0.0002	0.0177	0.0006
ACI$_{EMV}$-B	0.0024	0.0002	0.0042	0.0002

As it can be noticed, in the case of the 0.45 w/c ratio, the capillary absorption coefficient of ACIDVR mixes are around 1.7 times higher than the ACIEMV ones. For 0.6 w/c ratio mixes, the absorption coefficient of ACIDVR-A is around 3.6 times higher than the ACIEMV-A ones, and ACIDVR-B is about 4.2 times higher than the ACIEMV-B. These results are attributed to the fact that the mixes designed with the novel method have less amount of total mortar than the ones conventionally designed. Also, conventional mixes with a 0.6 w/c ratio present much higher values than 0.45 w/c ratio mixes, which may be due to a worse quality of the paste at high w/c ratios.

There is also an interesting behaviour in the capillary absorption capacity when comparing same proportioning methodology and different type of aggregate. Concrete mixes elaborated with aggregate type B present lower capillary absorption coefficients than the ones elaborated with aggregate type A. This effect may be due to a non-sorptive characteristic of a part of the aggregate. Aggregate type B has 13% of bituminous material, which may aid to the less water intake of the specimen by lessening the capillary porosity of the concrete sample. The later behaviour has been observed by Benazzouk et al. (2004) in an investigation were they have tested cement based composites made with rubber aggregates in proportions ranging from 0% to 40%. Their results show a high correlation of the sorptivity values with the amount of rubber aggregate used in the mix, which decreases with increasing amounts of it.

6.4.2 Second campaign

This campaign results are listed in Table 6.5.

Table 6.5: Capillary suction results of the second campaign concrete mixes

	0.45 w/c		0.6 w/c	
	k ($\frac{g}{cm^2 \cdot min^{0.5}}$)	σ	k ($\frac{g}{cm^2 \cdot min^{0.5}}$)	σ
BCON	0.0022	0.0006	0.0043	0.0010
BDVR20	0.0034	0.0002	0.0052	0.0006
BEMV20	0.0027	0.0003	0.0046	0.0007

For the case of the 0.45 w/c ratio, BOL$_{\text{EMV}}$20 presents lower capillary absorption coefficient than the BOL$_{\text{CON}}$20 and higher than BOL$_{\text{CON}}$, although statistically speaking, after an ANOVA test, the results of the later mix turned out to have no significant difference with BOL$_{\text{EMV}}$20, which means that the novel method improves the recycled aggregates concrete (RAC) quality. For the 0.6 w/c ratio, the results seem to follow the same trend of those of the 0.45 w/c ratio but after an ANOVA test, the results show no significant difference, thus they could be taken as equals.

6.4.3 Third campaign

In this campaign, all the results comprising the different type of mixes and admixture use have been collected in Table 6.6.

Table 6.6: Capillary suction results of the third campaign concrete mixes

	0.4 w/c		0.5 w/c	
	k ($\frac{g}{cm^2 \cdot min^{0.5}}$)	σ	k ($\frac{g}{cm^2 \cdot min^{0.5}}$)	σ
BRcon (1)	0.0011	0.0000	0.0018	0.0001
BRcon (1.2)	0.0011	0.0001	0.0017	0.0000
BRcon (1)*	0.0013	0.0001	0.0018	0.0001
BRdvr20 (1)	0.0018	0.0001	0.0023	0.0002
BRdvr20 (1.2)	0.0018	0.0001	0.0022	0.0002
BRdvr20 (1)*	0.0011	0.0000	0.0015	0.0003
BRemv20 (1.5-1)	0.0014	0.0001	0.0021	0.0001
BRemv20 (1.7-1.2)	0.0015	0.0001	0.0021	0.0001
BRemv20 (1.5-1)*	0.0010	0.0000	0.0015	0.0002
BRdvr35 (1)	0.0021	0.0001	0.0026	0.0001
BRdvr35 (1.2)	0.0021	0.0000	0.0027	0.0001
BRdvr35 (1)*	0.0008	0.0000	0.0015	0.0001
BRemv35 (1.5)	0.0014	0.0001	0.0018	0.0001
BRemv35 (1.7)	0.0013	0.0001	0.0018	0.0001
BRemv35 (1.5)*	0.0008	0.0001	0.0015	0.0002

*Concretes comprising an air-entraining admixture

From these results and when taking into account the same mix proportioning procedure with different amounts of superplasticizer admixture, no significant difference where found. This means that the 0.2% change of the superplasticizer amount does not provoke noticeable changes on this property.

When taking into account same proportioning criteria mixes, with the exception of the NAC, the addition of an air-entraining admixture does causes significant changes by improving their resistance to the capillary absorption of water.

In general, and with the exception of the mixes using an air-entraining admixture, the concretes designed with the novel method show better results than the conventionally designed recycled concretes.

6.4.4 Overall analysis

By taking a look at all the results, there seems to be an important influence caused by the amount of RA used on the mix, the w/c ratio, the use of admixtures and the design procedure. First campaign mixes with a 0.6 w/c ratio and conventionally designed show the higher capillary coefficients, exceeding by far the other campaign results, which indicates that a 100% replacement at this w/c ratio may represent an important deterioration of a given structure due to the action of this property. Also, the second campaign concrete mixes coefficients, for the case of the 0.6 w/c ratio seem to be high when compared to the ones of the first campaign as, even when being proportioned with lower quantities of RA or not at all, they reach values close to some of the ones on the first campaign, which leads us to think that the lack of admixtures is the main reason.

Lower w/c ratios show a clear improvement of this property for all the studied campaigns. This is a well-known effect of the improved quality of the cement pastes, in which there will be less pores.

The results of the third campaign concretes are clearly better than the ones of the other two campaigns. This is in part due to the lower w/c ratios they present but also, it may be reasonable to think that the type of cement and the amount of admixtures used play an important role on these results, as even the 0.5 w/c ratio concretes of the third campaign are better than the 0.45 w/c ratio concretes of the other campaigns. Even though this, there are other parameters that may be involved on this general analysis, as the type and characteristics of the aggregates, consistency of the concretes or mix proportions for example.

It is clear that the Equivalent Mortar Volume method improves the concretes capillary absorption of water property, when compared to other type of recycled concrete mixes designs. This is again due to the improved characteristics of the concrete matrix, by better controlling the amount of total mortar of the mixes.

6.5 Chloride penetration evaluated by $AgNO_3$ solution

6.5.1 First campaign

Table 6.7 shows the results of the chloride penetration depths (in millimitres) of the first campaign concrete mixes.

Table 6.7: Chloride penetration depths of the first campaign concrete mixes

	0.45 w/c			0.6 w/c		
	35 days	60 days	90 days	35 days	60 days	90 days
$\mathrm{ACI}_{\mathrm{DVR}}$-A	18.1	26.6	27.0	25.3	26.0	39.9
$\mathrm{ACI}_{\mathrm{EMV}}$-A	21.0	23.2	25.5	28.2	33.4	37.3
$\mathrm{ACI}_{\mathrm{DVR}}$-B	15.6	20.0	24.4	21.8	24.0	35.2
$\mathrm{ACI}_{\mathrm{EMV}}$-B	13.7	17.0	22.1	22.9	26.2	29.1

As it can be seen in the results in Table 6.7, in the case of the 0.45 w/c ratio, concrete mixes elaborated with the novel method show a better behaviour than the conventional ones in the majority of the cases for short (35d), middle (60d) and long term (90d), being the $\mathrm{ACI}_{\mathrm{DVR}}$-A vs. $\mathrm{ACI}_{\mathrm{EMV}}$-A case, in the short term, the only exception. For the 0.6 w/c ratio mixes, the novel method shows worst behaviour than the conventional method in the short and middle terms but a better behaviour in the long term.

In any case, when comparing the chloride penetration in time, concrete elaborated with the new method shows lower progression rates, a behaviour that may be related to the porous system of the concrete matrix, which means that the concrete will end up with a better performance along time in what chlorides penetration imply.

6.5.2 Second campaign

Table 6.8 shows the chloride penetration depths results (in millimitres) of the second campaign concrete mixes.

Table 6.8: Chloride penetration depths of the second campaign concrete mixes

	0.45 w/c			0.6 w/c		
	35 days	60 days	90 days	35 days	60 days	90 days
B_{CON}	19.0	23.1	29.0	26.4	29.2	total
$B_{DVR}20$	16.5	20.0	25.7	27.0	31.7	total
$B_{EMV}20$	16.5	19.9	25.3	26.8	30.4	total

In the case of this campaign concrete mixes results, 0.45 w/c ratio samples show a slightly better behaviour when designed with the novel method than the other concrete mixes, for the short, middle and long terms, although almost equal to those of the $B_{DVR}20$.

All 0.6 w/c ratio mixes results are similar to each other and only a slightly better behaviour is seen for the B_{CON} mix. The results of the long term are not conclusive, due to the fact that the chloride profile was detected all along the specimens (50 mm) in all cases, thus not being helpful for the analysis and being the reason why these were not taken into account when comparing the different concrete mixes. However, these results may indicate that, for a given w/c ratio, the behaviour of a concrete with such characteristics against chloride penetration is negligible.

6.5.3 Third campaign

The results of the chloride penetration depths (in millimetres) of the third campaign concretes are listed in Table 6.9.

Table 6.9: Chloride penetration depths of the third campaign concrete mixes

	0.4 w/c			0.5 w/c		
	35 days	60 days	90 days	35 days	60 days	90 days
BRcon (1)	9.4	9.5	12.1	11.5	14.8	16.9
BRcon (1.2)	9.6	10.0	12.6	11.1	18.1	20.9
BRcon (1)*	7.3	10.8	16.0	11.5	15.1	20.5
BRdvr20 (1)	10.9	12.9	18.1	14.4	20.8	22.8
BRdvr20 (1.2)	12.0	14.4	17.9	14.1	20.0	24.0
BRdvr20 (1)*	10.8	14.4	17.6	16.0	19.0	21.9
BRemv20 (1.5-1)	9.4	14.1	16.4	10.4	15.9	25.6
BRemv20 (1.7-1.2)	10.9	12.8	16.6	11.5	19.5	26.3
BRemv20 (1.5-1)*	9.0	13.5	14.5	15.4	18.4	20.0
BRdvr35 (1)	12.4	14.5	17.1	16.3	20.1	23.8
BRdvr35 (1.2)	10.9	14.0	17.8	15.0	19.1	26.6
BRdvr35 (1)*	11.8	16.8	17.1	13.5	21.5	25.8
BRemv35 (1.5)	9.4	11.4	15.5	12.0	16.1	27.6
BRemv35 (1.7)	9.9	10.6	15.3	15.3	18.8	25.9
BRemv35 (1.5)*	10.6	13.6	15.5	13.4	20.8	24.1

*Concretes comprising an air-entraining admixture

In general, it is observed that the lowest penetration depths, for concretes without air-entraining admixture, are achieved on both NAC (0.4 and 0.5 w/c ratios). When comparing concretes comprising the use of the air-entraining agent, the lowest penetration depths are achieved by the NAC in both short and middle terms (35d and 60d), but at longer terms (90d) the concretes designed with the novel method have the lower results for the majority of the cases.

When comparing recycled concretes, the use of the novel method shows improvements on this property in the majority of the cases, even when comparing the concretes of 35% aggregates replacement with the conventionally designed 20% aggregate replacement concretes. The only exceptions are found in the 0.5 w/c ratio concretes with 90 days of exposure to the chlorides environment.

The effect of the superplasticizing admixture proportion change does not present a clear trend among the studied concrete mixes. Also, when comparing concretes with and without the air-entraining admixture and having the same amount of superplasticizer, no clear trend is found regarding this property.

Again, as in the other concrete campaigns, the w/c ratio of the concrete mixes plays an important role on the resistance to chlorides ingress, making it better when lower ratios are used.

6.5.4 Overall analysis

Second campaign mixes with a 0.6 w/c ratio show worst results than the concretes of the first campaign. This issue is similar to what has been observed on previously analysed properties, and its explanations may go along the same way, concluding that the lack of admixtures may lead to a lower quality of the cement paste, thus making it unsatisfactory regarding this property.

In all of the campaigns, lower w/c ratios present the best results. This is a result of the improvements of the cement paste that a lower ratio represents.

In most of the cases, the concrete design with the Equivalent Mortar Volume method shows improvements in this property when compared to conventionally designed recycled concrete. Again, the better controlled mortar phase of the concretes may be the reason for this behaviour.

The best results of all of the concretes are observed in the third campaign. Although they have lower w/c ratios, in some cases the results of the higher ratios of the third campaign are better than the lower ratios of the others, thus suggesting that this behaviour may be more related to other variables such as the cement type, admixture amount or mix proportion, among others.

6.6 Chloride penetration evaluated by the Nordtest method

As a difference from the other tests, this evaluation has been made only for the first and second campaign concrete mixes.

6.6.1 First campaign

6.6.1.1 Penetration parameters

Table 6.10 shows the penetration parameters for the first campaign concrete mixes, where the concentration on the surface of the tested specimen (C_s) in terms of the concrete's mass, and the chloride transport coefficient (D_e) are shown.

Table 6.10: Chloride penetration parameters of the first campaign concrete mixes

		0.45 w/c		0.6 w/c	
	Time (days)	C_S (%)	D_e ($\frac{m^2}{s}$)	C_S (%)	D_e ($\frac{m^2}{s}$)
ACIDVR-A	35	0.90	2.24E-11	0.65	6.56E-11
	60	1.16	2.26E-11	1.12	5.47E-11
	90	0.82	2.82E-11	0.96	3.55E-11
ACIEMV-A	35	1.04	2.19E-11	1.14	6.11E-11
	60	1.04	1.98E-11	0.95	3.03E-11
	90	0.78	1.91E-11	0.90	4.17E-11
ACIDVR-B	35	0.94	3.31E-11	0.69	4.13E-11
	60	0.68	2.28E-11	0.93	4.39E-11
	90	0.67	2.38E-11	1.03	2.33E-11
ACIEMV-B	35	0.73	2.60E-11	1.11	3.15E-11
	60	0.69	2.43E-11	1.28	4.85E-11
	90	0.66	2.24E-11	0.60	4.48E-11

As it can be seen, the non-steady states of diffusion in all the cases are higher when using a 0.6 w/c ratio than the 0.45 one. This behaviour follows the trend that has been found in the literature (Frederiksen et al., 1997; Olliver, 1998; Han, 2007; Cement Concrete & Aggregates Australia, 2009). The higher porosity of the 0.6 w/c ratio specimens allows the chlorides to go faster and in bigger amounts into the concrete matrix. Also, as time passes, the tendency of the majority of the diffusion coefficients is to decline.

6.6.1.2 Penetration profiles

The following figures show the chloride penetration profiles of the concretes, separated by age of testing (35, 60 and 90 days) and by w/c ratio. These profiles are plotted in terms of the chloride concentration in mass percentage of the extracted sample versus the depth at which they were obtained.

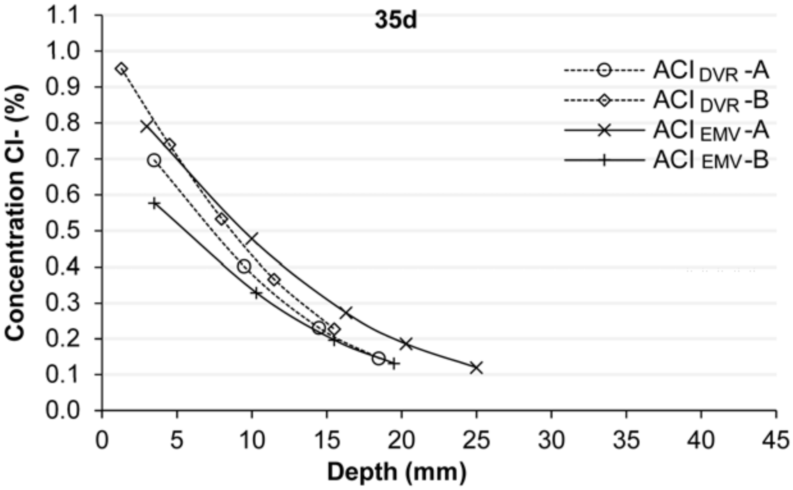


Figure 6.2: Chloride penetration profiles for 0.45 w/c ratio concretes of first campaign at 35 days

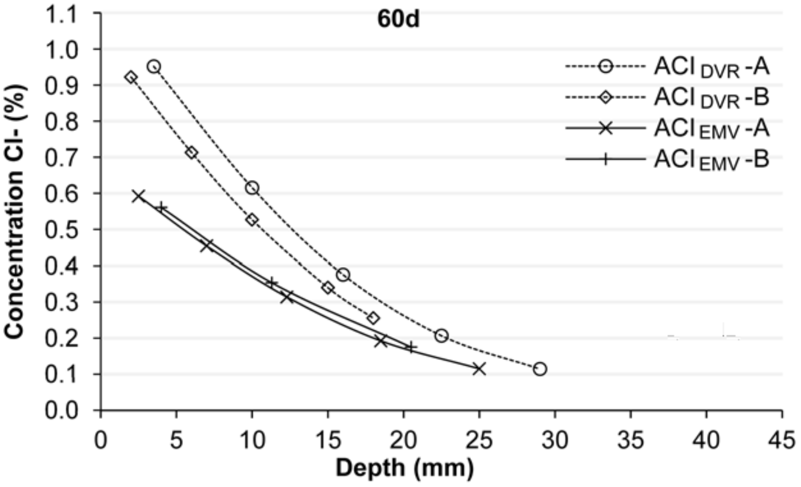


Figure 6.3: Chloride penetration profiles for 0.45 w/c ratio concretes of first campaign at 60 days

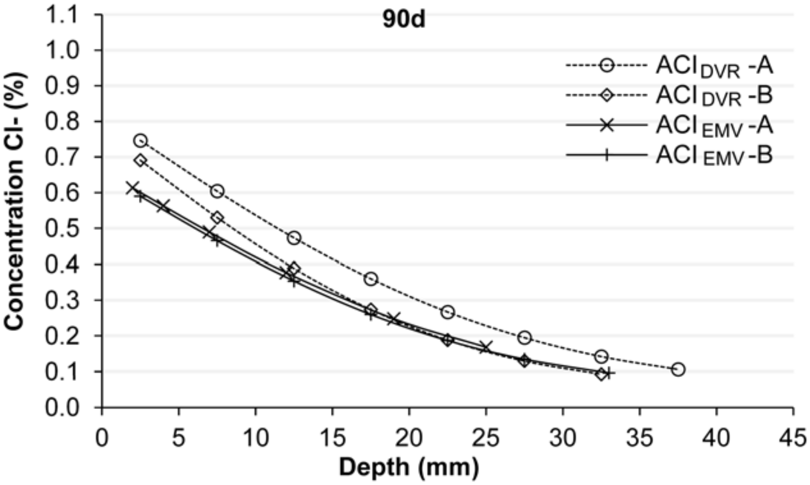


Figure 6.4: Chloride penetration profiles for 0.45 w/c ratio concretes of first campaign at 90 days

Figure 6.2 shows that, in conventionally designed mixes, chlorides concentration decreases more with increasing depth when compared to concretes designed with the novel method. This means that in the novel method mixes may permit the chlorides ingress more deeply. Figure 6.3 shows a similar behaviour but with clear difference on the chloride concentrations, which are higher in all of the cases for the conventionally designed mixes. Figure 6.4 shows similar profiles shapes with some changes on the chlorides concentrations, which are higher for the conventional method.

From these profiles, it could be said that the reason for the more apparent decreasing of the chlorides concentration in the case of the conventionally designed mixes, for the two first ages (35 and 60 days), may be due to their binding capacity, a behaviour that has been commented by Nilsson et al. (1996). Nilsson et al., states that the amount of bound chlorides is a linear function of the amount of C-S-H (Calcium-Silicate-Hydrate) gel, thus, as conventionally designed concretes comprise more total quantity of cement, this behaviour seems reasonable.

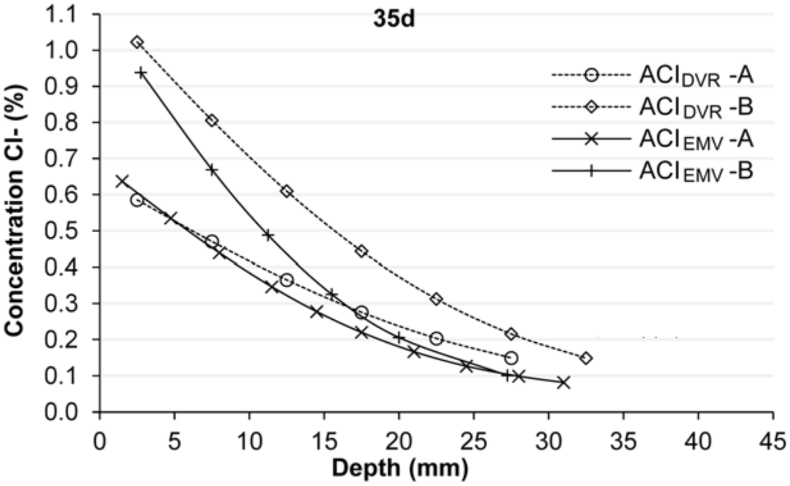


Figure 6.5: Chloride penetration profiles for 0.6 w/c ratio concretes of first campaign at 35 days

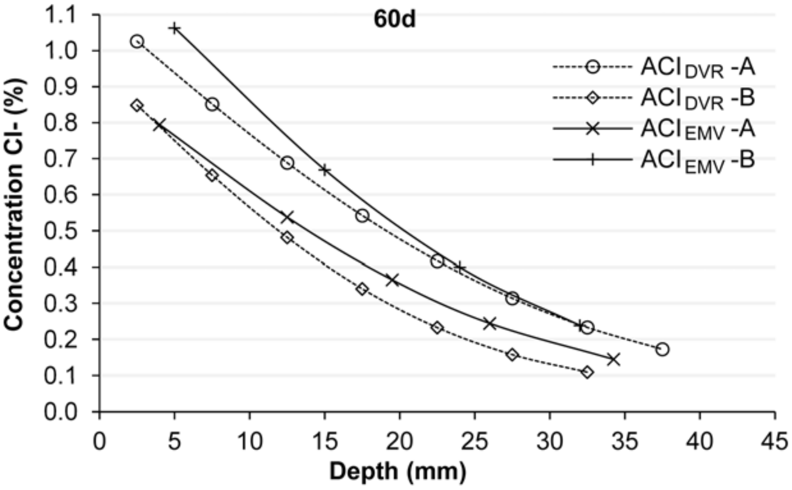


Figure 6.6: Chloride penetration profiles for 0.6 w/c ratio concretes of first campaign at 60 days

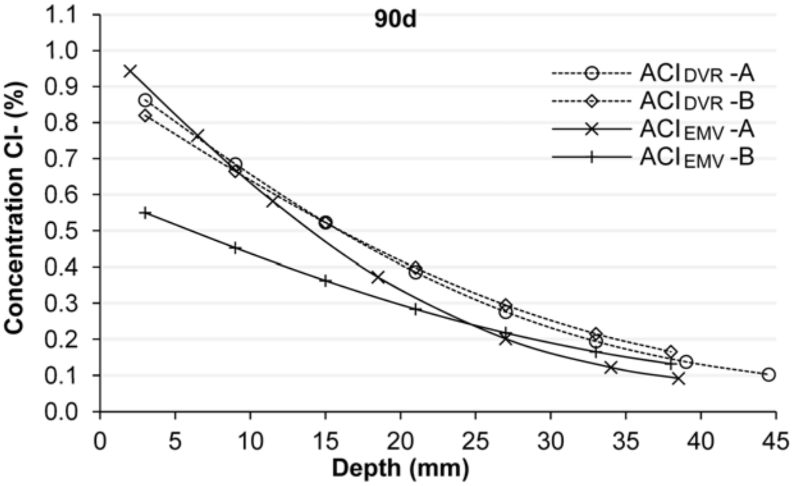


Figure 6.7: Chloride penetration profiles for 0.6 w/c ratio concretes of first campaign at 90 days

As it can be observed in Figures 6.5, 6.6 and 6.7, mixes with 0.6 w/c ratio show a sort of random behaviour, as the different samples profiles change along the chosen test ages, thus presenting non-congruent results. It seems that to a certain w/c ratio, the chlorides penetration behaviour is ruled by other parameters; most probably, the characteristics related with the porosity of the sample take high importance.

6.6.2 Second campaign

6.6.2.1 Penetration parameters

As in the previous campaign, the chloride penetration parameters are listed in Table 6.11.

Table 6.11: Chloride penetration parameters of the second campaign concrete mixes

		0.45 w/c		0.6 w/c	
	Time (days)	C_S (%)	D_e ($\frac{m^2}{s}$)	C_S (%)	D_e ($\frac{m^2}{s}$)
BCON	35	0.50	3.28E-11	0.53	1.41E-10
	60	0.68	2.31E-11	0.80	1.27E-10
	90	0.75	1.81E-11	0.83	1.24E-10
BDVR20	35	0.72	3.41E-11	0.59	1.14E-10
	60	1.18	1.54E-11	0.71	9.61E-11
	90	0.95	1.89E-11	0.83	4.17E-11
BEMV20	35	0.59	4.01E-11	0.54	9.05E-11
	60	0.77	2.13E-11	0.84	6.76E-11
	90	0.70	1.92E-11	0.89	6.56E-11

It is observed that there is a trend indicating that at higher age of testing, the chloride concentration on surface tends to increase and the chloride transport coefficient tends to decrease. These results indicate that the deposition of chlorides on the surface is higher over time, and that there may be a connection with the amount of chlorides penetrating the sample which decreases due to a clogging effect. As times passes, chlorides are filling the concrete voids, thus obstructing the chloride penetration and so lowering their rate of ingress (diffusion coefficient). 0.6 w/c ratio mixes, as in the previous campaign, show the same behaviour when compared to the 0.45 w/c ratio ones in terms of the diffusion coefficient, as they present higher values in all of the cases.

6.6.2.2 Penetration profiles

As it has been already commented in the previous campaign, the following figures show the chloride penetration profiles of the concretes.

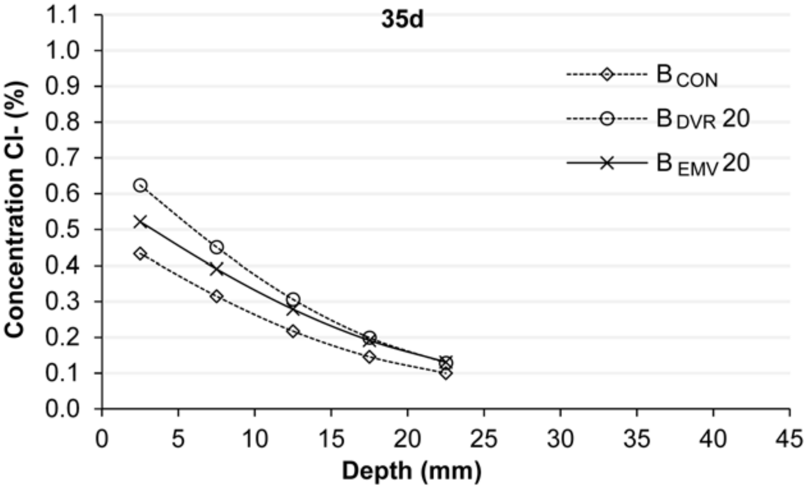


Figure 6.8: Chloride penetration profiles for 0.45 w/c ratio concretes of second campaign at 35 days

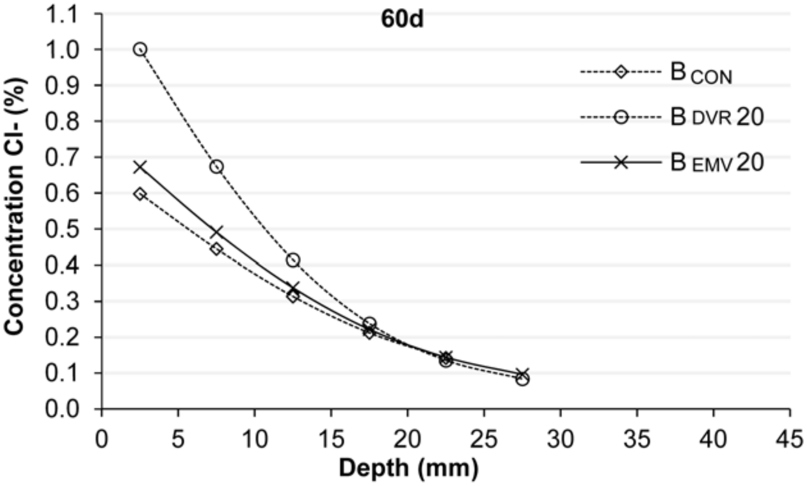


Figure 6.9: Chloride penetration profiles for 0.45 w/c ratio concretes of second campaign at 60 days

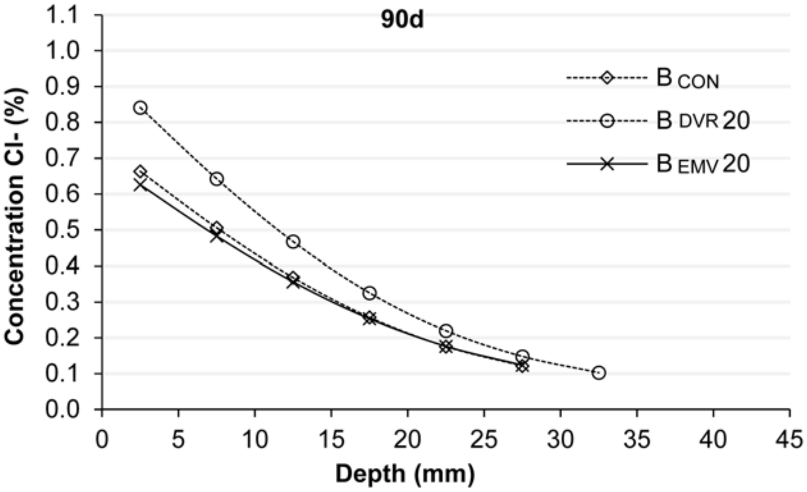


Figure 6.10: Chloride penetration profiles for 0.45 w/c ratio concretes of second campaign at 90 days

From Figures 6.8, 6.9 and 6.10, shown above, it can be notice that in the case of the 0.45 w/c ratio, concrete mixes designed with the novel method achieve similar results of those seen in the case of the NAC. In all of the cases these concretes have lesser chlorides concentrations in the lower depths than the conventionally designed RAC, although it is also noticed that this later mix is the one whose concentrations drop the most with depth among all the concretes.

The last observation goes along the same lines of the previous campaign, where the effect was attributed to a binding action provoked by the C-S-H gel. In this case, $B_{DVR}20$ mix is the one comprising the greater quantity of it, as a result of the contributions of the cement and the attached mortar to the RA.

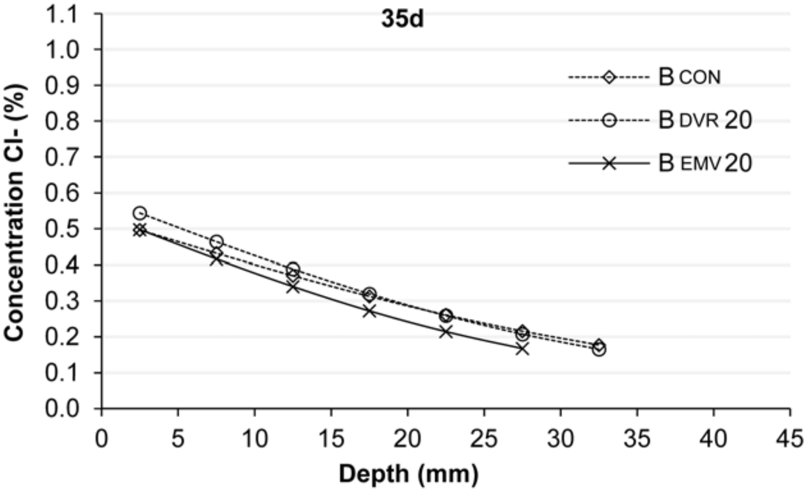


Figure 6.11: Chloride penetration profiles for 0.6 w/c ratio concretes of second campaign at 35 days

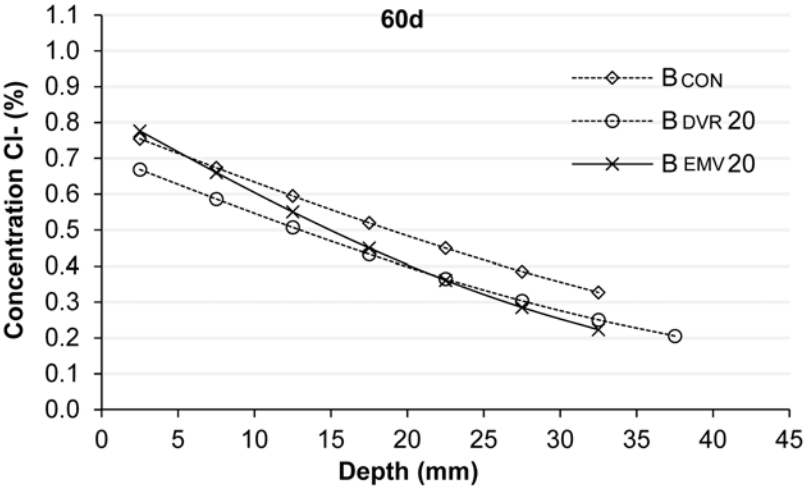


Figure 6.12: Chloride penetration profiles for 0.6 w/c ratio concretes of second campaign at 60 days

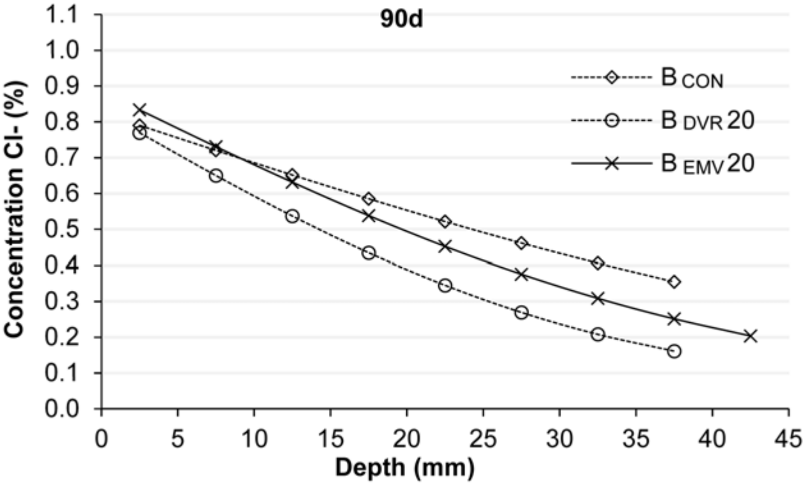


Figure 6.13: Chloride penetration profiles for 0.6 w/c ratio concretes of second campaign at 90 days

Again, as in the first campaign, the 0.6 w/c ratio mixes do not show a clear trend over all the obtained results. However, it can be said that for a given w/c ratio, the porous system of the concrete matrix may be the governing parameter over chlorides penetration. This assumption is of high importance, because it determines a limit for the w/c ratio of a concrete submitted to a certain chloride environment, since it may not be possible to avoid the deterioration of a given structure due to the chlorides attack.

6.6.3 Overall analysis

From this information, it is clear that, irrespective of the concrete type, the w/c ratio plays an important role in the capacity of a concrete to resist the penetration of chlorides. The lower the w/c ratio, the better the concrete's resistance to it. This is due to the improved internal structure that a lower ratio confers, in terms of it porous arrangements and sizes.

An interesting outcome of this analyses, was the behaviour of the different mixes in time with respect to the chlorides concentrations at certain depths. It was observed that, in 0.45 w/c ratio mixes, conventionally designed recycled concrete had a greater decrease on its chlorides concentrations with depth at lower ages than the other concretes, a behaviour that was not well-defined for the longer age, where their concentrations with depth were, in the majority of the cases, greater than the other mixes. This can lead to some assumptions, like the binding capacity of these concretes. Conventionally recycled concretes could bind more chlorides than the other mixes due to the available amount of C-S-H gel they have. Together with what was mentioned before, at lower ages, this behaviour is more noticeable due to the available C-S-H gel surface for the binding process to occur, which at higher ages decreases due to the fact that bound chlorides already occupy the surface.

The previously commented behaviour could not be observed in 0.6 w/c ratio mixes. This may be due to other parameters governing the chlorides ingress into concrete, like its porosity. When the porosity within the concrete matrix is greater and better connected, the chloride binding process seems to be insufficient to make a noticeable difference.

In the majority of the cases, the concretes designed with the Equivalent Mortar Volume method achieve lower chloride concentrations than the conventionally designed concretes, and similar to the NAC. Also, when taking into account a long-lasting structure for example, the novel methods resists better the chloride penetration.

6.7 Conclusions

In general, it has been confirmed that, irrespective of the type, a lower water/cement ratio improves the durability characteristics of the concretes, at least regarding the properties under analysis in this investigation.

The use of an air-entraining admixture is highly recommended to enhance the concretes durability properties. In the majority of the analysed tests, the use of such admixture has resulted in better outcomes.

In general, and although this is more noticeable in conventionally designed recycled concretes, regarding the durability properties, the use of concretes with a 0.6 water/cement ratio is not recommended for structural purposes as they do not present a satisfactory behaviour.

Concretes designed with the Equivalent Mortar Volume method achieve better performances than conventionally recycled concretes in most of the studied durability properties. When compared to natural aggregates concretes, the behaviour of the concretes designed with the novel method is similar in most of the cases.

All of these improvements have been attained with important reductions on the amounts of cement, as a result of using the Equivalent Mortar Volume method. These reductions were between 7% and 24% with respect to the other concretes.

Chapter 7

Rheological properties

7.1 Introduction

It is widely known that concrete's flowing characteristics have been extensively measured through the slump test, which is a simple, fast and cost-effective method. Although this, this method has been considered as inadequate, as it gives only one measurement called the 'S' value, being it the fresh concrete's height loss (in centimetres) after the test is carried out, which may be the same for two different concretes, and also due to the fact that this value is operator sensitive (Tattersall, 2005; Wallevik, 2006; Wallevik and Wallevik, 2011). In order to solve these problems, different apparatus have been developed to measure the concrete's flowing behaviour in terms of fundamental physical quantities, like the BML-Viscometer 3. This is done by shearing a concrete sample at high rotational velocities and then gradually decreasing the velocity in order to measure the shear stress at different stages, as a result of the torque applied by the sample to a measuring device.

It is generally agreed that the fresh concrete's flowing properties can be represented through the Bingham model (Tattersall and Banfill, 1983; Ferraris and de Larrard, 1998; Wallevik, 2003; Banfill, 2006; Wallevik, 2006; Erdogan et al., 2008; Woodhead Publishing, 2012; Feys et al., 2012), in which concrete is defined by two parameters, namely yield stress and plastic viscosity, which are the fundamental physical quantities that the mentioned apparatuses can calculate. The Bingham model is represented by the following equation:

$$\tau = \tau_o + \mu\dot{\gamma} \tag{7.1}$$

where, τ is the applied shear stress, $\dot{\gamma}$ is the shear rate, and τ_o and μ are the yield stress and plastic viscosity respectively. Figure 7.1 shows a representation of the Bingham model, in which a certain yield stress value has to be exceeded in order to achieve the material flow and afterwards, a linear relationship occurs between the shear stress and the shear rate, whose slope represents the plastic viscosity and where the material presents a plastic deformation.

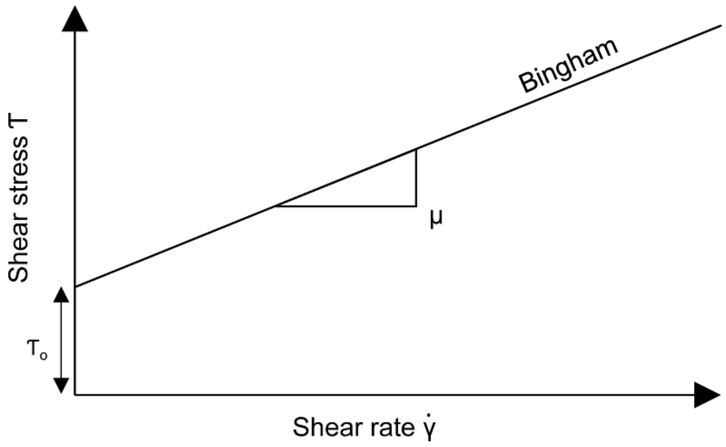


Figure 7.1: Bingham model

Banfill (2006) presented the values of the two rheological parameters among which cement paste, mortar and certain types of concretes lie in between (Table 7.1). Regarding concrete, in order to achieve values close to those of the flowing or the self-compacting concretes, certain admixtures have to be used.

Table 7.1: Rheological parameter values of different cement-based materials

	Cement paste, grout	Mortar	Flowing concrete	Self-compacting concrete	Concrete
Yield stress (Pa)	10-100	80-400	400	50-200	500-2000
Plastic viscosity (Pa·s)	0.01-1	1-3	20	20-100	50-100

Air-entrainers and superplasticizers are among the admixtures that can have certain influence on the rheological parameters. Air-entrainers are mostly known for provoking changes in the plastic viscosities of the concretes, by reducing them, whereas superplasticizers reduce the yield stress value (Wallevik, 2003; Banfill, 2006; Wallevik and Wallevik, 2011). A general representation of these behaviours is shown in Figure 7.2.

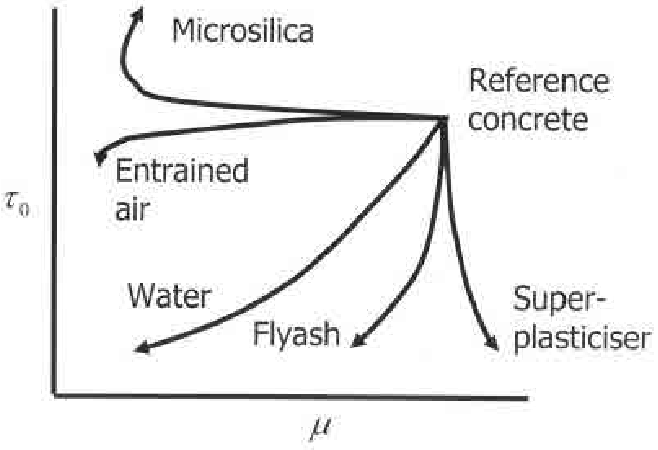


Figure 7.2: Effect of different parameters on the rheological properties of concrete (Banfill, 2006)

The Equivalent Mortar Volume method for concrete proportioning causes a reduction of the fresh mortar compared to other proportioning methods, thus it is expected that it will have an influence on the rheological characteristics of such mixes. This has already been presented by Fathifazl et al. (2009), although the measurements were done through the slump test, thus not presenting physical quantities but only the 'S' value. Even though these concretes may have similar slump values to those of the conventionally designed concretes, as it has been previously commented, they may have different rheological parameters.

7.1.1 Objectives

The general objectives of the present chapter are to obtain and analyse the rheological parameters of the different concretes in terms of the yield stress and plastic viscosity values. With this, a deeper understanding of the fresh concrete's characteristics through an objective assessment of their flowing behaviour and the proper differentiation of the studied mixes according to these properties will be attained.

The specific objectives are:

- to elaborate a experimental campaign in order to obtain and evaluate the rheological properties of different types of concretes, comprising both natural and recycled aggregates;
- to determine if similar slump test values can have both different yield stresses and plastic viscosities;
- to determine if the water/cement ratio influences the rheological parameters of the studied concretes;
- to determine the influence that air-entraining and superplasticizing admixtures have on the rheological parameters of the concretes;
- to evaluate the differences that the use of the Equivalent Mortar Volume method for concrete proportioning has on the rheological parameters of the mixes, when compared to conventionally designed concretes.

7.1.2 Program of the study

The aforementioned objectives will be addressed by presenting the proposed experimental campaign and its results.

On a first stage the materials and methods used for such purposes will be presented, briefly explaining the selected laboratory test. Afterwards, a general view of the results will be presented, and then they will be assessed by subdividing them into the different studied variables affecting the results, namely the water/cement (w/c) ratio, the superplasticizer amount, and the air-entraining admixture effect. Finally, the conclusions of the chapter will be drawn.

7.2 Materials and methods

The obtaining of the rheological properties has been done only in the concretes of the third campaign, whose mix proportions can be consulted in Tables 4.3 and 4.4 from Chapter 4. Their properties have been acquired by means of the BML-Viscometer 3 apparatus (7.3), which consists of two coaxial cylinders (outer cylinder and inner cylinder), a rotating plate, a hydraulic system, and the data acquisition unit. The diameters of the outer and inner cylinders are 290 and 200 millimetres respectively.

The measurement is done by pouring about 17 litres of concrete into the outer cylinder, which is then placed on the rotating plate. Then, the plate starts rotating at an angular velocity of $\Omega = 2\pi f$ (rad/s) and the inner cylinder, connected to the hydraulic system head, goes down into the concrete. When the inner cylinder gets to the bottom, the data is acquired. The inner cylinder, which does not rotates, is connected to a load cell in order to register the torque, as a result of the force transferred by the concrete rotating in the outer cylinder. The inner cylinder has also a special device connected in the bottom, with the purpose of reducing the so called 'bottom effect', which is a three-dimensional effect caused by the shear stress in the bottom surface of the container. This device helps on avoiding height dependence, thus only two-dimensional shearing can be obtained. Also, the cylinders are constructed with blades in the vertical axis, which reduce slippage problems and thus avoids changes in the rotational speeds.

Figure 7.3: BML-Viscometer 3 apparatus

At high rotational velocities, there may be cases where a higher aggregate content could appear towards the area near the outer cylinder. If this happens, the material near this area may behave as a solid, thus causing errors on the measured parameters. This behaviour is known as 'plug flow' and the BML-Viscomenter 3 software allows to manually remove the data points where this phenomenon could happen. Although this, the results that are presented in this chapter correspond to the ones obtained by means of an iterative procedure, when needed, presented by Faleschini et al. (2014), which calculates the Bingham parameters more accurately while taking into account the plug phenomenon.

In the measurement process, the speeds varied from $f_{min} = 0.09$ rps to $f_{max} = 0.44$ rps, and seven torque values were acquired. Also, the test was done at three different times, usually being 16, 20 and 24 minutes, counted from the moment that the mixing process of the concrete started. Although this, it was not always possible to obtain the three measurements at the commented times.

7.3 Rheological parameters

In the tables of this section, the complete list of the rheological parameters of the third campaign are shown. These correspond to concrete mixes comprising only natural aggregates (NA), and two others elaborated with recycled aggregates (RA) but designed with a conventional method and the Equivalent Mortar Volume method. Also, they have been designed with different RA replacement ratios, using different amounts of superplasticizer admixture and some using an air-entraining agent. Table 7.2 shows the concretes comprising the lower amount of superplasticizer used, whereas Table 7.3 shows the concretes comprising the higher. In Table 7.4, the rheological parameters of the concretes designed with the lower amount of superplasticizer plus an air-entraining agent are shown.

Table 7.2: Rheological parameters of concretes with lower superplasticizing admixture dosage

Concrete ID	Time (min)	Slump (cm)	μ (Pa·s)	τ_o (Pa)
BRCON/0.4-1	17	21	37.6	147.3
BRCON/0.5-1	15	22	22.5	130.4
BRDVR20/0.4-1	16	20	45.4	108.8
	20	20	44.9	178.6
BRDVR20/0.5-1	16	22	37.0	149.4
	20	22	36.7	156.8
	24	22	35.9	156.0
BREMV20/0.4-1.5	16	20	91.9	185.2
	24	20	85.8	216.7
BREMV20/0.5-1	16	20	59.1	240.1
	20	20	64.2	256.2
	24	20	72.6	200.8
BRDVR35/0.4-1	16	21	52.2	212.6
	20	21	49.8	215.5
	24	21	50.3	214.0
BRDVR35/0.5-1	16	22	37.0	149.4
	20	22	36.7	156.8
	24	22	35.9	156.0
BREMV35/0.4-1.5	16	20	81.4	233.5
	20	20	81.1	253.3
	24	20	86.7	214.8
BREMV35/0.5-1.5	16	19	67.4	262.2
	20	19	66.9	254.2
	24	19	63.5	253.0

Table 7.3: Rheological parameters of concretes with higher superplasticizing admixture dosage

Concrete ID	Time (min)	Slump (cm)	μ (Pa·s)	τ_o (Pa)
BRCON/0.4-1.2	16	21	47.7	148.1
BRCON/0.5-1.2	16	23	30.0	101.8
	20	23	28.9	95.1
	24	23	26.1	108.4
	26	23	28.4	102.5
BRDVR20/0.4-1.2	16	22	43.2	171.5
	20	22	44.8	178.9
BRDVR20/0.5-1.2	16	23	36.3	130.2
	20	23	32.8	138.3
	24	23	34.8	137.1
BREMV20/0.4-1.7	16	21	90.6	152.7
	22	21	65.5	165.0
	24	21	76.1	156.0
BREMV20/0.5-1.2	16	21	20.8	107.7
	20	21	18.7	118.6
	24	21	18.6	136.2
BRDVR35/0.4-1.2	16	21	43.7	158.4
	20	21	43.3	169.1
	24	21	43.0	173.8
BRDVR35/0.5-1.2	16	23	36.3	130.2
	20	23	32.8	138.3
	24	23	34.8	137.1
BREMV35/0.4-1.7	16	22	71.2	89.6
	20	22	65.2	99.3
BREMV35/0.5-1.7	16	19	86.3	301.2
	20	19	73.2	294.4
	24	19	82.6	242.7

Table 7.4: Rheological parameters of concretes with air-entraining admixture

Concrete ID	Time (min)	Slump (cm)	μ (Pa·s)	τ_o (Pa)
BRCON/0.4-1-0.02	16	21	33.9	227.9
	20	21	39.9	219.1
	24	21	36.3	239.5
BRCON/0.5-1-0.02	16	22	24.6	133.3
	20	22	23.0	141.7
	24	22	23.4	149.3
BRDVR20/0.4-1-0.02	16	21	31.6	199.2
	20	21	31.6	200.8
	24	21	31.7	210.8
BRDVR20/0.5-1-0.02	16	22	20.9	114.1
	20	22	18.7	127.8
	24	22	19.4	133.5
BREMV20/0.4-1.5-0.02	16	22	23.8	77.9
	20	22	53.1	180.0
	24	22	49.7	220.6
BREMV20/0.5-1-0.02	16	21	20.8	107.7
	20	21	18.7	118.6
	24	21	18.6	136.2
BRDVR35/0.4-1-0.02	16	21	26.3	154.7
	20	21	24.6	164.0
	24	21	25.2	168.0
BRDVR35/0.5-1-0.02	16	22	20.9	114.1
	20	22	18.7	127.8
	24	22	19.4	133.5
BREMV35/0.4-1.5-0.02	16	21	37.5	109.7
	20	21	37.6	125.6
	24	21	40.8	129.2
BREMV35/0.5-1.5-0.02	16	22	45.0	297.4

By taking a general look at the results of the afore-presented tables, it seems clear that concretes having the same slump values can have different rheological parameters, whether they use different types and amounts of admixtures, different types of aggregates, or different w/c ratios. Although the slump test is a generalized, simple and quick method, it can be said that it does not accurately represents the rheological characteristics of a certain concrete mix. This has been discussed in literature (Tattersall and Banfill, 1983; Tattersall, 2005; Wallevik, 2006), stating that these properties should be assessed in terms of fundamental physical quantities (yield stress and plastic viscosity) instead of a single value test.

Due to the amount of data and the different possibilities of interactions between the concretes, a better way to show the results has been selected, the so called 'rheographs', which are scattered graphs with the plot of data corresponding to the yield stress τ_o (y axis) versus the plastic viscosity μ (x axis). These are used to give a general idea of a certain behaviour in terms of fundamental rheological parameters.

In the following sub-sections, different rheographs will be presented in order to explain the behaviour of the different concrete mixes when a certain variable is introduced, such as w/c ratio, use of admixtures or changes in their quantities. They will also be useful to compare the effects that the different mix proportioning design methodologies have on the rheological properties of the studied concretes.

7.3.1 Water/cement ratio effect

The figures of this sub-section show the effects that the variation of the w/c ratio, from 0.4 to 0.5, has on the rheological properties of the different concretes. Figure 7.4 presents the results for concretes comprising the lower amount of superplasticizer admixture selected, and Figure 7.5 presents the higher amount. The effect of the variation when use of an air-entraining agent is shown in Figure 7.6.

Note that for these three figures, triangle shaped markers represent the concretes with a 0.4 w/c ratio and the circle markers do so for the 0.5 w/c ratio. Also, natural aggregates concretes (NAC) have black markers, conventionally designed recycled aggregates concretes (RAC) have red markers, and RAC designed with the Equivalent Mortar Volume method have green markers.

7.3.1.1 Lower superplasticizer amount concretes

From Figure 7.4 it can be observed that, except for the concretes designed with the novel method, higher w/c ratio causes a reduction of the plastic viscosity and the yield stress of concretes, the former of these properties being the one which presents the higher differences. Although the mixes designed with the novel method present diminutions on their plastic viscosity with higher w/c ratios, their yield stress remains almost constant, and in some cases higher. There seems to be a limit in which the reduction of the fluid phase of the concretes plays an important role on their yield stress as, in conventional concretes for example, the available water for the mix to flow is greater for the higher w/c ratio and this ends up with lower plastic viscosity and yield stress. In the same way, the mixes designed with the novel method have more water available in their higher w/c ratio, but it seems that is only enough to give the fluidity to the material when in motion, and not to overpass the yield stress (so the material starts flowing) more than 0.4 w/c ratio mixes, probably due to a better interlocking of the coarse particles caused by the mortar content diminution and to its more dispersed characteristic.

It is also clear that the conventionally designed RAC present closer values to those of the NAC, when compared to the concretes designed with the novel method. Conventionally designed RAC present the lowest variations on their results as it is observable from the figure, being clustered in a smaller region then the novel method concretes.

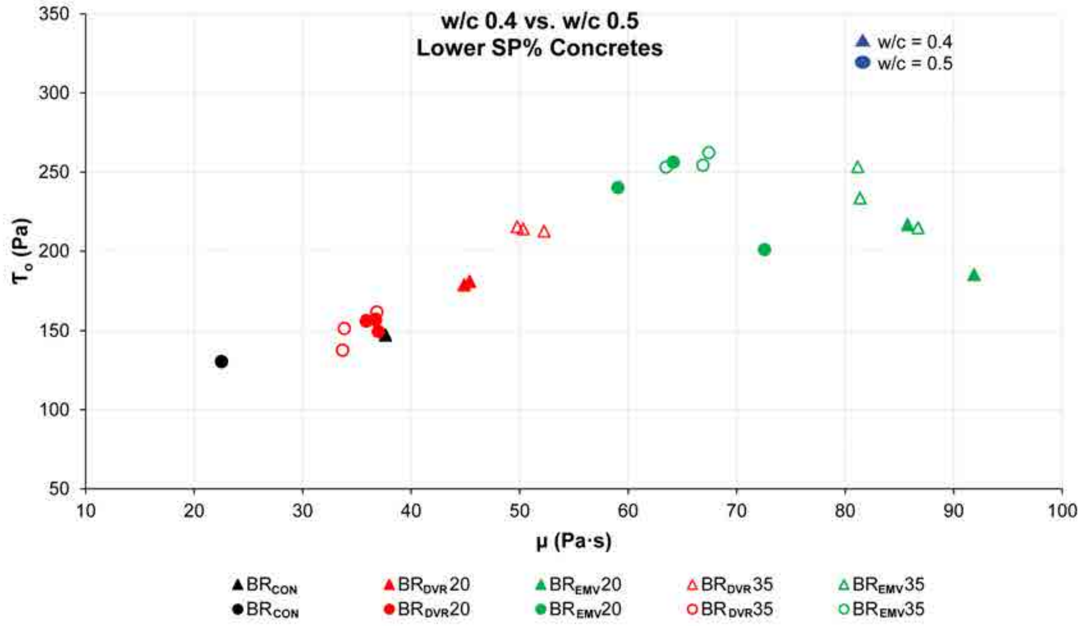


Figure 7.4: Effect of the w/c ratio in the rheological parameters of concretes with lower superplasticizer amount

7.3.1.2 Higher superplasticizer amount concretes

In Figure 7.5, similar effects to those presented in the previous section are observed. conventional mixes present lower plastic viscosity and yield stress when higher are the values of the w/c ratios.

Again, conventionally designed RAC get closer to NAC than the ones designed with the novel method regarding the rheological parameters. Also, they present less variations than the novel mixes, being clustered in smaller regions.

In this case it is clear that, for those mixes designed with the novel method, the lower yield stress values are achieved with the lower w/c ratio. Moreover, $BR_{EMV}35$ mixes present also lower plastic viscosity values.

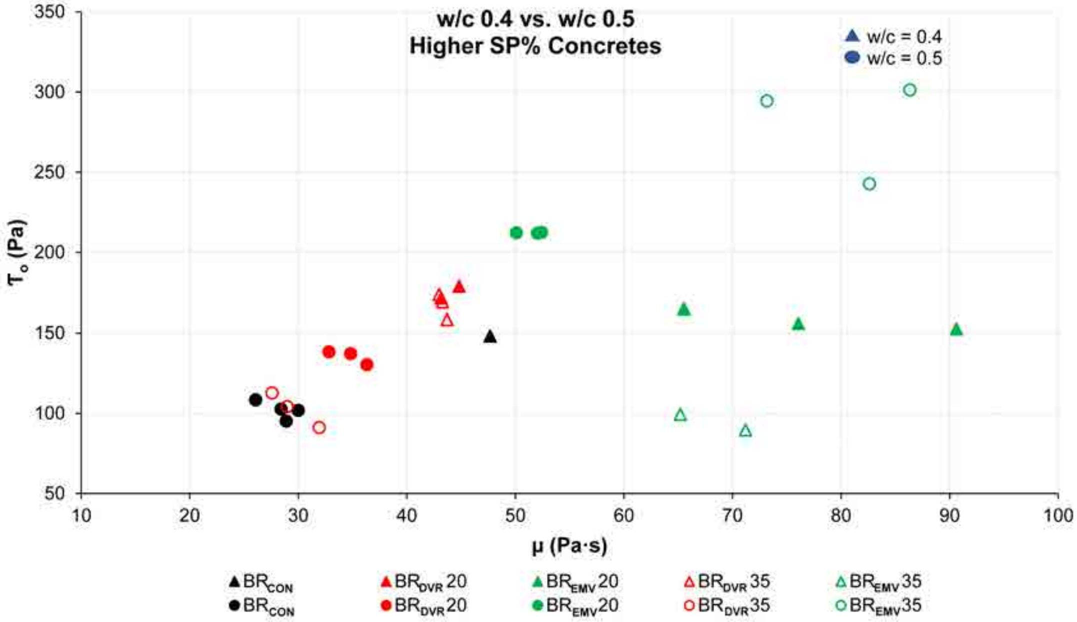


Figure 7.5: Effect of the w/c ratio in the rheological parameters of concretes with higher superplasticizer amount

7.3.1.3 Air-entraining admixture concretes

In the case of Figure 7.6, it is observed that the air-entraining admixture makes the results to have less variations between the different concrete mixes, even for the ones designed with the novel method, which seem to cluster in smaller areas, with the exception of some specific cases that may be disregarded due to the incongruities they present among the other mixes.

Again, like in the previous cases, it is observed that the higher w/c ratio ends up in lower plastic viscosity and yield stress values, with the exception of the BR$_{EMV}$35 mix.

There is an interesting phenomenon happening when comparing the results of the BR$_{DVR}$20 with BR$_{DVR}$35 mixes, and BR$_{EMV}$20/0.4 with BR$_{EMV}$35/0.4 mixes, in which the mix with the highest RA replacement percentage ends up with the lowest plastic viscosity and yield stress. This behaviour can be observed in the previous cases but not as clear as in this type of concretes.

The main outcome of this figure, is that it shows that concretes designed with the Equivalent Mortar Volume method get much closer to conventional mixes, both natural and recycled, when all of them comprise the use of an air-entraining agent.

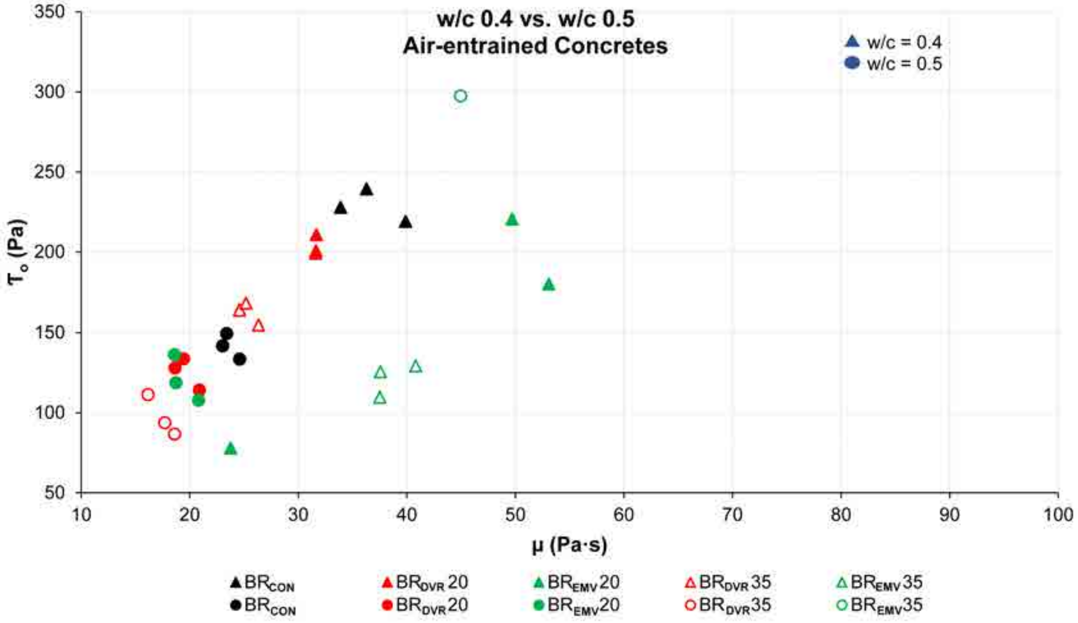


Figure 7.6: Effect of the w/c ratio in the rheological parameters of concretes with air-entraining admixture

7.3.1.4 Overview analysis

Water/cement ratio had a clear influence on the presented results, which causes both plastic viscosity and yield stress to be greater when lower is the w/c ratio.

In some cases, when comparing same design methodologies, it was observed that higher RA replacement ratios led to lower plastic viscosity and yield stress values. This may be due to the shape of these type of aggregates, which is, in most of the cases, less angular than NA due to the attached mortar they have on their surface. Angular aggregates cause both more interlocking and surface contact between them than rounded aggregates, which has a direct effect on the rheological parameters of concretes (Banfill, 2006; Ferraris et al., 2001; Tattersall, 2005; Erdogan et al., 2008).

When comparing the different concrete design methodologies, it was observed that the Equivalent Mortar Volume method increases the plastic viscosity and the yield stress values, in the majority of the situations. Although this, when combining the use of a superplasticizer and an air-entraining admixture, the results of the concrete seem to behave more like conventional concretes. The differences created by the fresh mortar content diminution caused by the basis of the novel method, when compared to conventional ones, are responsible for these results, as there should be more interlocking and greater surface contact of the aggregates, thus causing the rheological parameters to be greater as it has been described by before.

7.3.2 Superplasticizer content effect

The figures of this sub-section show the effects that the variation of the superplasticizing admixture has on the rheological properties of the different concretes. Figures 7.7 and 7.8 present the results of concretes designed with 0.4 and 0.5 w/c ratios respectively.

On these figures, circle shaped markers represent the concretes with the lower amount of superplasticizer admixture and the squared markers do so for the higher amount. Also, as in the previous section, NAC are represented with the black markers, conventionally designed RAC with red markers, and RAC designed through the Equivalent Mortar Volume method with green markers.

7.3.2.1 0.4 water/cement ratio concretes

In the case of these concretes, as it can be observed in the Figure 7.7 for most of the concretes, the rheological parameters are reduced when increasing the superplasticizer admixture dosage, even when using a 0.2% difference.

The parameter being the most affected is the yield stress, which is more noticeable in the mixes designed with the novel method and in less manner in conventional RAC, although the formers present greater variabilities as it can be seen in the clustered region they form. In some cases there is almost no difference on the results and, moreover, NAC present differences on the plastic viscosity and not in the yield stress, but this may be due to the lack or results, which may lead to results that are not significant.

It can also be observed that the novel method mixes with the higher admixture content achieve similar and better results than those mixes designed by conventional methods, regarding yield stress.

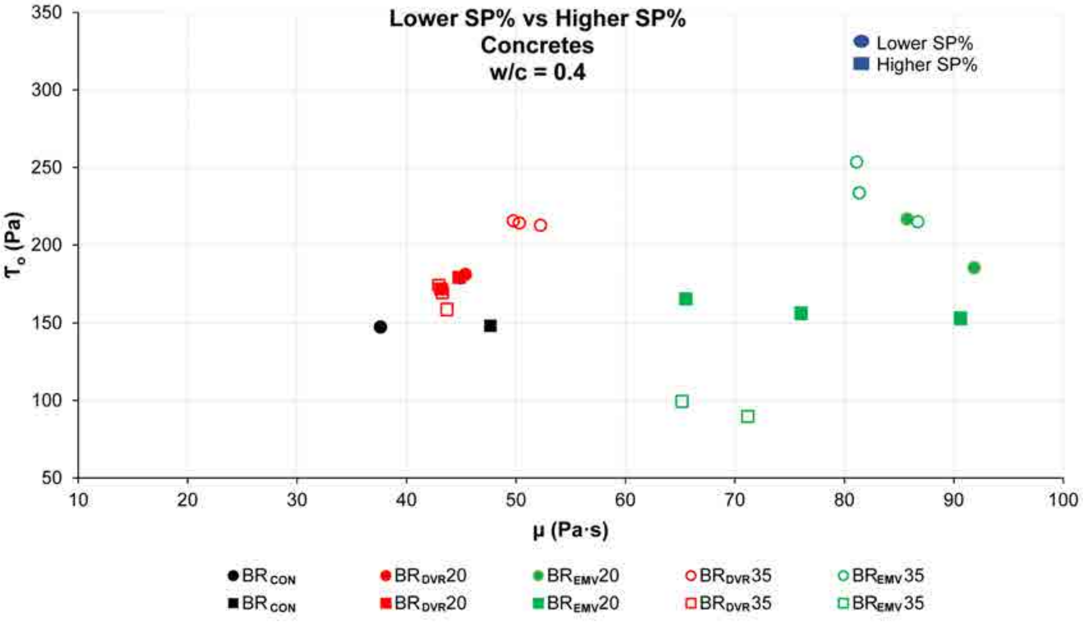


Figure 7.7: Effect of the superplasticizer amount on 0.4 w/c ratio concretes

7.3.2.2 0.5 water/cement ratio concretes

In Figure 7.8, it can be observed that, for most of the cases, there is a reduction of the rheological parameters when increasing the admixture dosage. The cases where such behaviour is not observed is on BREMV35 mixes, but also when looking at the variability of their results, specifically the ones with the higher amount of admixture, one could argue that it is caused by some inaccurate values. Also, NAC present a lower yield stress but greater plastic viscosity, but again, this may be caused by the lack of data as there was only one observation in the case of the BR$_{CON}$/0.5-1.2 mix.

In general, it can be observed that both NAC and conventional RAC behaviour is similar, being both concretes results clustered in proximate areas. Unlike this, the results of the mixes designed with the novel method remain far from the conventional ones.

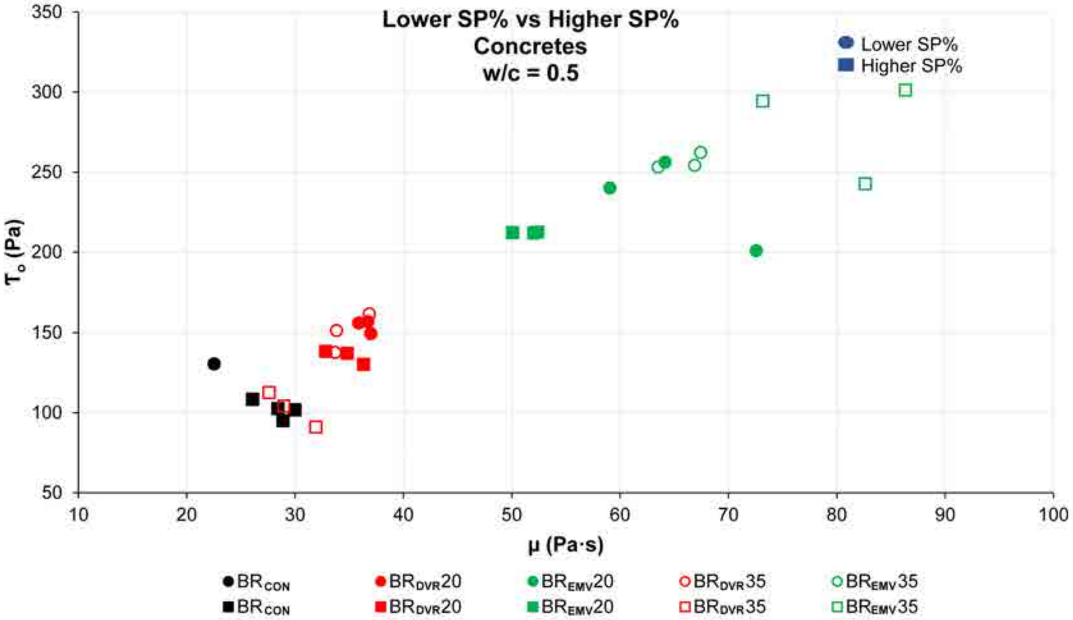


Figure 7.8: Effect of the superplasticizer amount on 0.5 w/c ratio concretes

7.3.2.3 Overall analysis

In general, it was observed that increasing the amount of superplasticizer admixture caused a reduction of the rheological parameters of the concretes, having a greater influence on the yield stress. This behaviour has been extensively commented in the literature (Faroug et al., 1999; Wallevik, 2003; Golaszewski and Szwabowski, 2004; Flatt, 2004; Banfill, 2006; Wallevik and Wallevik, 2011; Woodhead Publishing, 2012) and it is owed to the increased dispersion of cement particles in the paste caused by a reduction in their inter-particle forces, preventing their flocculation and their consequent interlocking, and thus lowering the yield stress.

7.3.3 Air-entraining admixture effect

The figures of this sub-section show the effects that the incorporation of an air-entraining admixture has on the rheological properties of the different concretes. Figures 7.9 and 7.10 present the results of concretes designed with 0.4 and 0.5 w/c ratios respectively.

On these figures, circle shaped markers represent the concretes without the air-entraining admixture and triangle markers do so for the ones comprising the air-entraining agent. Also, as in the previous sections, NAC are represented with the black markers, conventionally designed RAC with red markers, and RAC designed through the Equivalent Mortar Volume method with green markers.

7.3.3.1 0.4 water/cement ratio concretes

In Figure 7.9, it can be observed that there is a reduction of the rheological parameters when using the air-entraining agent for most of the studied cases. There are only few cases where the yield stresses have been increased. In any case, it is clear that the major changes among all the concrete mixes is in their plastic viscosity, showing an average change of around 50%, and as high as 74% in some cases.

The greatest changes among the different design methodologies are observed in the cases of the concretes designed with the Equivalent Mortar Volume method. The main outcome of the use of an air-entraining admixture is that these concretes get closer to those designed by conventional methods than when no such admixture is used.

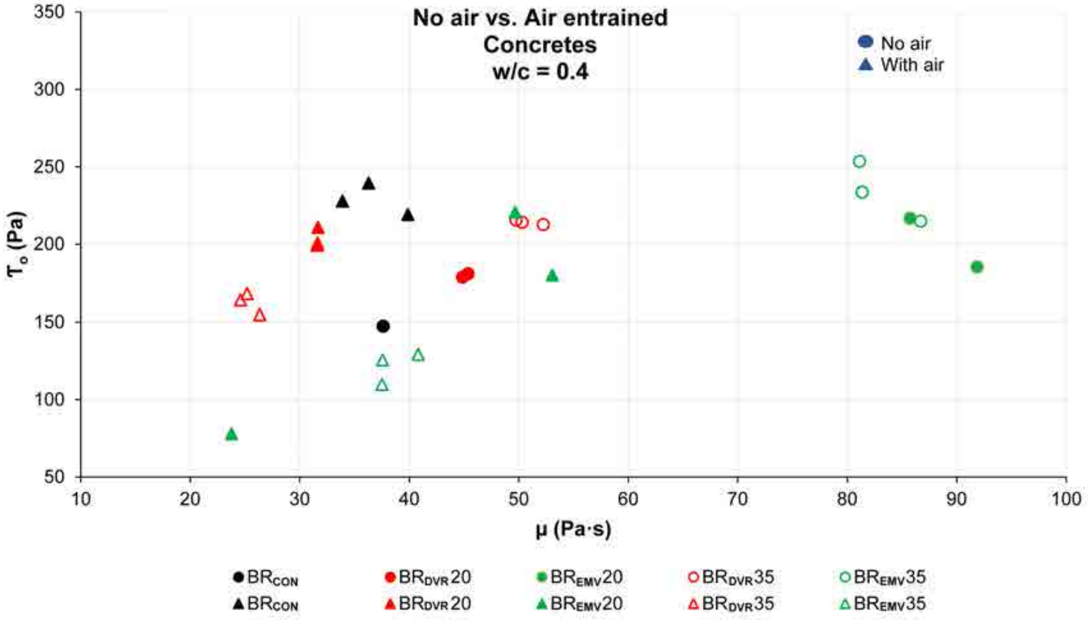


Figure 7.9: Effect of the air-entraining admixture on 0.4 w/c ratio concretes

7.3.3.2 0.5 water/cement ratio concretes

In the case of the Figure 7.8, the effect of the air-entraining admixture is even clearer than in the previous case, demonstrating a significant difference among the majority of the results by the reduction of the rheological parameters. This is observed with the exception of the BRCON/0.5 which has around the same values in both types of concretes and in the BREMV35/0.5 concretes, in which the one comprising the air-entraining agent seems to be an outlier value. In any case, for all of the other concretes, the reductions are greater in their plastic viscosities, with an average of 55% and as high as 74% reductions.

Again, like in the previous case, the greatest reductions were achieved by the concretes designed with the novel method and, apart from the outlier value, the results show that the rheological parameters for the novel mixes with the air-entraining admixture are clustered together with those conventionally designed NAC and RAC.

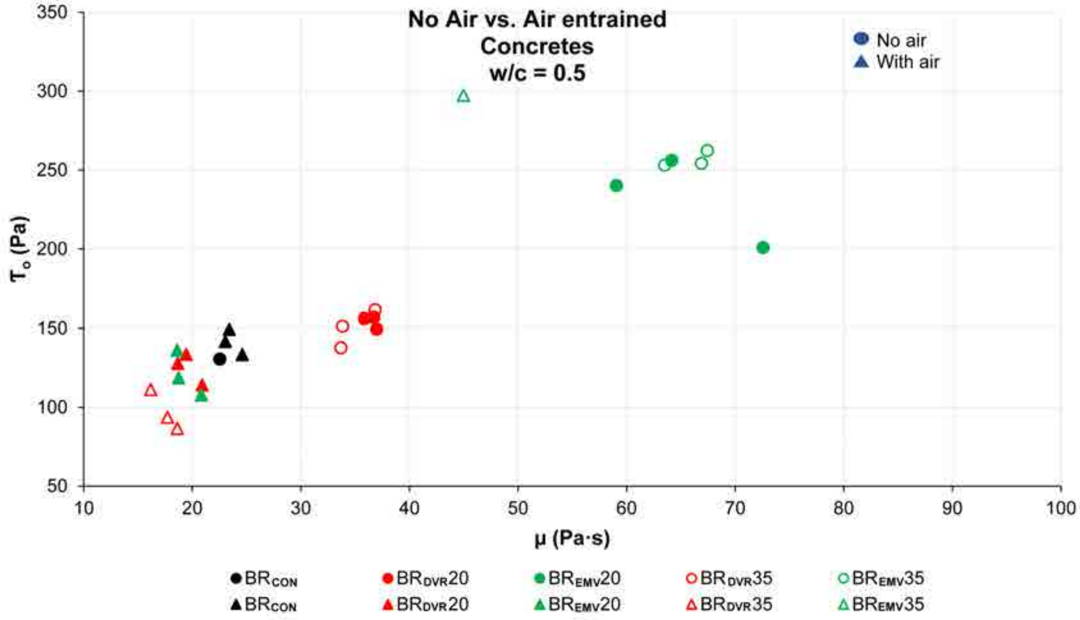


Figure 7.10: Effect of the air-entraining admixture on 0.5 w/c ratio concretes

7.3.3.3 Overall analysis

In both 0.4 and 0.5 w/c ratio cases, the use of an air-entraining admixture caused a clear benefit regarding the concretes rheological parameters. The most noticeable of them was the reduction of the plastic viscosity of the concretes. This is a well-known effect of air-entrainers, termed 'ball bearing effect' (Tattersall and Banfill, 1983), in which these small compressible bubbles influence the flow behaviour by acting as cushions and by allowing an easier movement of the rest of the particles.

7.4 Conclusions

It has been confirmed that concretes with similar slump values can have both different yield stresses and plastic viscosities, thus it is not an accurate representation of the rheological characteristics of the mix.

In general, it has been observed that the rheological parameters of the studied concretes are influenced by the water/cement ratio, amount of superplasticizer admixture, and by the use of the air-entraining agent.

The water/cement ratio influences both the yield stress and the plastic viscosity of the concretes, by lowering their values when higher ratios are used.

The amount of superplasticizer influences the yield stress the most, by decreasing its values at higher dosages of the admixture.

The use of the air-entraining admixture had a greater influence on the plastic viscosity of the mixes, by lowering its values when compared to concretes without the admixture.

The use of a superplasticizing admixture alone in the concretes designed with the Equivalent Mortar Volume method does not seem enough to achieve rheological properties comparable to those of the conventionally designed concretes. Although this, they still remain closer to the limits of self-compacting concretes than of normal concrete and they have been designed with 7% to 14% less cement than the conventional concretes here studied.

When combining the use of the superplasticizer and air-entraining admixtures, the concretes designed with the novel method achieve similar and in some cases better rheological properties of those of the conventionally designed concretes, with the added benefit of using less cement.

Chapter 8

Life Cycle Assessment

8.1 Introduction

It is widely known that concrete is the most used man-made material worldwide (Gautam et al., 2014; Knoeri et al., 2013; Ghafari and Costa, 2015; Mehta and Monteiro, 2006), and that this is mainly because of its excellent properties, versatility, availability and price (Meyer, 2009a; Maier and Durham, 2012). Because of the range of its properties variations, concrete has an outstanding adequacy to many different uses, achieving great workability, resistance and durability properties. However, beside all the good qualities of concrete, it generates relevant environmental impacts due to its huge production amounts and the use of cement, one of its main components, which is well known for being a relevant contributor to global warming (Meyer, 2009b; Josa et al., 2007; Scrivener and Kirkpatrick, 2008).

On the one hand, as concrete is composed of about three-quarters in volume by aggregates (Neville and Brooks, 2010), it represents a major consumer of natural resources and, when demolished after its service life or deterioration, turns into inert waste, which can occupy large volumes in landfills. On the other hand, the usage proportions of cement together with its production process may cause important environmental impacts. World cement production in year 2013 was estimated to be 4 billion tonnes (Bt) (CEMBUREAU, 2013) which is nearly 600 kg/habitant, and accounts for about 7% of the total CO_2 generated worldwide (Scrivener and Kirkpatrick, 2008; Meyer, 2009b; Abbas et al., 2009b; Chen et al., 2014; Yang et al., 2014; White et al., 2015).

Recycled materials arise as a solution towards these problems as they can be used as aggregates in the production of concrete, thus diminishing the use of natural resources. The so-called recycled aggregate concrete (RAC), is a material that is being used since many years already.

Conventionally designed RAC offers some benefits when compared to natural aggregates concrete (NAC) as it uses aggregates coming from concrete recycling, which are converted into a product through a valorization process, thus avoiding or diminishing the use of natural aggregates (NA) and preventing the use of landfills. Although this, some authors (37-DRC, 1992; Etxeberria et al., 2007; Beltrán et al., 2014) have experienced that more cement must be used in order to achieve similar properties of those of NAC. With this, the environmental problem appears again; while avoiding NA depletion and land-filling, more emissions are provoked due to cement manufacturing.

One of the possible solutions is the Equivalent Mortar Volume for RAC mix proportioning (Fathifazl et al., 2009; Razaqpur et al., 2010). This novel method has a beneficial effect on the general properties of the RAC and, predictably, in their environmental impacts, mainly due to the savings in cement that it generates, while keeping the short and long-term performances.

This method has been analysed in previous investigations (Fathifazl, et al., 2011; Fathifazl, et al., 2011; Vázquez, et al., 2013; Abbas, et al., 2009; Jiménez, et al., 2012; Jiménez, et al., 2014) and the results seem to be promising. Its properties correspond with the theoretical assumptions, where the obtained mechanical and durability tests results are similar and in some cases better than the parent concrete mixes (conventionally designed RAC and NAC), owed to the better-controlled amount of total mortar on the concrete mixes.

As well as the commented properties improvement and due to the lower amounts of cement and the replacement of NA by recycled aggregates (RA), there should be some additional environmental and economic advantages. The first of these advantages can be evaluated through a Life Cycle Assessment (LCA) which, according to ISO 14040:2006 standard (International Organization for Standarization. Technical Committee ISO/TC 207, 2006b) definition, it is a ’compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle’.

8.1.1 Objectives

The aim of this part of the investigation is to make an evaluation of the resulting environmental burdens from applying different mix proportioning methodologies on the production of concrete, involving the use of natural and/or recycled aggregates. The specific objectives are:

- to determine the environmental impacts that the studied mix proportioning methods imply in the production of concretes;
- to evaluate the environmental burdens of the different stages within the concrete systems;
- to establish the best option among these concretes, in terms of their environmental impacts;
- to determine if the Equivalent Mortar Volume method provides environmental benefits to the studied concretes, while achieving equal performances than its counterparts;
- to evaluate the environmental effects of using different types of binders on the production of these concretes.

8.1.2 Program of the study

This chapter objectives will be addressed by analysing some of the mixes present on this document through the LCA methodology. On the first sections, a brief explanation of the LCA method, followed by the methodology used in this chapter, in which a description of the selected concretes and their categorization, and some explanations of other aspects related to the LCA are presented. After, the results of the environmental analysis of the selected concretes will be presented and discussed, from both a general and a more specific view, and with regards to the concretes main processes and the chosen impact categories, then finalizing with the conclusions of the chapter.

8.2 Life Cycle Assessment background

LCA is and acknowledged methodology to determine the environmental burdens of a certain product system. It is composed of four main phases in which a deep analysis of the different unit parts of an entire system is done. Initially, the system is disaggregated into different units which are then united in order to have results from a broaden range, summarizing the environmental burdens of every contributively step in the process. The main phases of this methodology are:

1. Definition of the scope and objectives: This step states the studied case and details its main characteristics, together with declaring the objectives of the study. It also defines the product system to be analysed, which gives a general view of the boundaries enclosing the case, and the methodology used to accomplish the declared objectives.

2. Inventory analysis: In this stage all the related data to the case in study is gathered and analysed, taking special attention on the units that could turn in a matter of high relevance in terms of the final results. It is of high importance to properly identify and analyse the important inputs and outputs, as they may be a decisive point in the conclusions.

3. Impact evaluation: After all the information has been gathered and analysed, the inputs and outputs of the data are addressed to a certain impact category in a process known as 'classification'. The impact category, as defined by ISO 14040 (International Organization for Standarization. Technical Committee ISO/TC 207, 2006a), is 'a category representing interesting environmental issues, to which the results of the inventory analysis of the life cycle can be assigned'. As an example, one of the most known impact categories due to its relevance on today's affairs, is the Global Warming Potential (GWP), which is the contribution that a greenhouse gas has over the global warming. After this, the data is multiplied by a characterization factor in order to be transformed into an equivalent quantity relative to the basic unit of a certain impact category and so transforming all into common measurement figures. As an example, methane (CH4) emissions, from a certain product, have to be multiplied

by a characterization factor in order to be expressed and summarized into the basic unit of GWP impact category, which is carbon dioxide equivalents (CO2-eq.).

4. Interpretation of results: In this step, and according to the analysis and findings of the previous ones, all the results are evaluated in order to obtain the conclusions and proper recommendations. These will be drawn according to the defined objectives and scope of the study, and strongly affected by the points that were of significant attention during the analyses.

This methodology is broadly used in different industry sectors which aim on environmentally analyse a certain product, with the objective of knowing the environmental burdens that it represents in quantitative terms. With this, not only the products environmental information can be declared, but also decisions could be made in order to take actions over some process with high environmental impacts, or materials affecting the product's performance, thus being able of selecting a greener option that may turn the final product into a more environmentally friendly one. Also, with the results of the analysis, comparisons could be made between products attaining the same functionalities, and so the better environmental option can be defined. All of this gives the user the capability of making a more informed decision when selecting a certain product.

8.3 Methodology

8.3.1 Description of the concretes

Four concrete mixes were selected from this investigation to make the environmental analysis, namely ACIDVR-A/0.45, ACIEMV-A/0.45, BCON/0.45 and BEMV20/0.45. Their main design parameters, the materials used for their elaboration, and the resulting mix proportions have already been presented in subsections 4.4.1 and 4.4.2, from chapter 4, in which they can be consulted. As a reminder, the first two concretes correspond to a conventionally designed RAC and a RAC designed through the use of the novel method respectively, both based on a initial design through the American Concrete Institute method. The last two concretes correspond to a NAC and a RAC designed through the use of the novel method respectively, both based on Bolomey's procedure for their design. For the analysis, these were separated in two groups; the American Concrete Institute based ones and Bolomey based mixes. The aim of this was to select and make groups of concretes fulfilling an equal set of parameters in terms of workability, resistance and durability, as it is defined in the European Standard for concrete EN 206-1 (European Committee for Standarization, 2000b), thus having same functionalities and so being able to make comparisons between equivalent materials.

The two groups of concretes were categorized according to their main properties and so they were designated as C35-S3-D_{max}20-X0 and C40-S3-D_{max}20-X0 (American Concrete Institute and Bolomey based mixes respectively); where C corresponds to the acronym for concrete; 35 and 40 represent their resistance class in terms of the concretes characteristic strength (fck), measured at 28 days in N/mm2 by single compression test and considering the average of three 150 mm diameter by 300 mm height cylindrical testing specimen (European Committee for Standarization, 2009d); S3 represents their consistency class, measured in cm according to EN 12350-2 standard (European Committee for Standarization, 2009a) and ranging from 10-15 with a ±2cm tolerance; D_{max}20 represents the maximum size of the aggregate; and X0 represents the exposure class, related to environmental characteristics of the surroundings of the concrete (in this case a non-aggressive environment).

The concretes composition and main properties will be reminded in Tables 8.1 and 8.2.

Table 8.1: Mix proportions of the selected concretes for the Life Cycle Assessment

Concrete Id	Water (kg)	Cement (kg)	Natural aggregate (kg)	Recycled aggregate (kg)	Super-plasticizer (kg)	Air Entrainer (kg)
ACI$_{DVR}$-A/0.45	184	409	752	786	1.2	0.08
ACI$_{EMV}$-A/0.45	140	311	998	782	2.2	0.06
B$_{CON}$/0.45	184	409	1881	-	1.5	-
B$_{EMV}$20/0.45	169	376	1673	235	2.1	-

EN 206-1 standard recommends some limiting values for the composition and the properties of the concrete, depending on the selected exposure class. For the non-aggresssive exposure class (X0), selected on this part of the investigation, there are no specific requirements regarding maximum water/cement (w/c) ratio, minimum cement content and

Table 8.2: Main properties of the selected concretes for the Life Cycle Assessment

Concrete Id	Entrained Air (%)	Slump (cm)	f_{ck} (N/mm^2)	Max. water penetration (mm)	Aggregates max. size (mm)
ACIDVR-A/0.45	9	15	35.2	<20	20
ACIEMV-A/0.45	8	10	35.5	<20	20
BCON/0.45	-	15	41.2	<10	20
BEMV20/0.45	-	15	43.7	<10	20

minimum air content. The only recommendation is that the strength class of the concrete should be higher than 12 N/mm^2 (in terms of the cylindrical 150x300 mm specimen).

In the case of the durability properties, the Spanish Code for Structural Concrete "EHE-08" (Spanish Ministry of Public Works, 2008) states that for class I exposition type of environment (non-aggressive environment), the concrete should have at least a 0.65 w/c ratio and 200 kg of cement per m^3. Also, it is recommended to have a characteristic compression resistance (f_{ck}) of at least 20 N/mm^2 and, for some exposition classes, a maximum penetration depth of water under pressure of 50 mm according to EN 12390-8 (European Committee for Standarization, 2000a).

As it can be seen in the Tables 8.1 and 8.2, all concretes fulfil the properties prescribed within their classification and, furthermore, they can be used in other type of exposition environments as well. Again, in the case of the prescriptions of the EHE-08 code, these concretes could be used in exposure environments such as non-marine with high medium-humidity or marine, in either areal, submerged or tidal zones, with chlorides induced corrosion risk. The selection of this specific exposure class was made thinking on concretes submitted to most typical performances, without the use of reinforcement.

8.3.2 Life Cycle Assessment

8.3.2.1 Objectives

The objectives of this part of the investigation are the ones that have been already proposed in Subsection 8.1.1.

8.3.2.2 Declared Units

Two declared units (DU) have been selected for the analysis. These are used to have a certain class of reference from which the results of the assessment can be related to, providing a common set of parameters that a certain product must fulfil in order to be compared in relative terms.

The DUs of this study are:

- the production of $1m^3$ of concrete class C35-S3-D_{max}20-X0 in a central mix plant, and
- the production of $1m^3$ of concrete class C40-S3-D_{max}20-X0 in a central mix plant

These declared units have been chosen in order to put some boundaries to the large options of existing concrete types and to the fact that they represent commercially used concretes.

Note that the only difference between these DU is the concrete's resistance class. The reason for the selection of two DU was based on the need to broaden the analysis range by using different concrete mixes and, as there were no mixes available comprising the same required characteristics at the time of the selection of these concretes, two groups had to be formed.

8.3.2.3 System boundaries

As it can be deduced from the DU, the system comprises all the activities and materials needed to elaborate $1m^3$ of concrete in a central mix plant, being this a plant were all the materials are mixed together and are then transported already as a 'final product' to the users location.

The system involves the processes for the extraction of raw materials and for the production of cement, admixtures, NA, RA and water. Also, it includes the transportation of cement and admixtures to the central plant location and the processes, machinery and energy used for the production of the concrete.

In this analysis, the subsequent phases of construction, use and maintenance of the product are excluded, thus being often termed 'cradle to gate' analysis. The reason for this is that this analysis aims on emphasizing the environmental properties inherent to the material itself at a design stage, and as concrete has many uses, different results could appear depending on the selected application. Moreover, as the studied concretes fulfil the same set of properties, they are assumed to achieve equal performances, so no differences shall appear during their lifespan. In any case, this study could be added to the boundaries of another system comprising these excluded phases if necessary.

Figure 8.1 shows a scheme of the system boundaries.

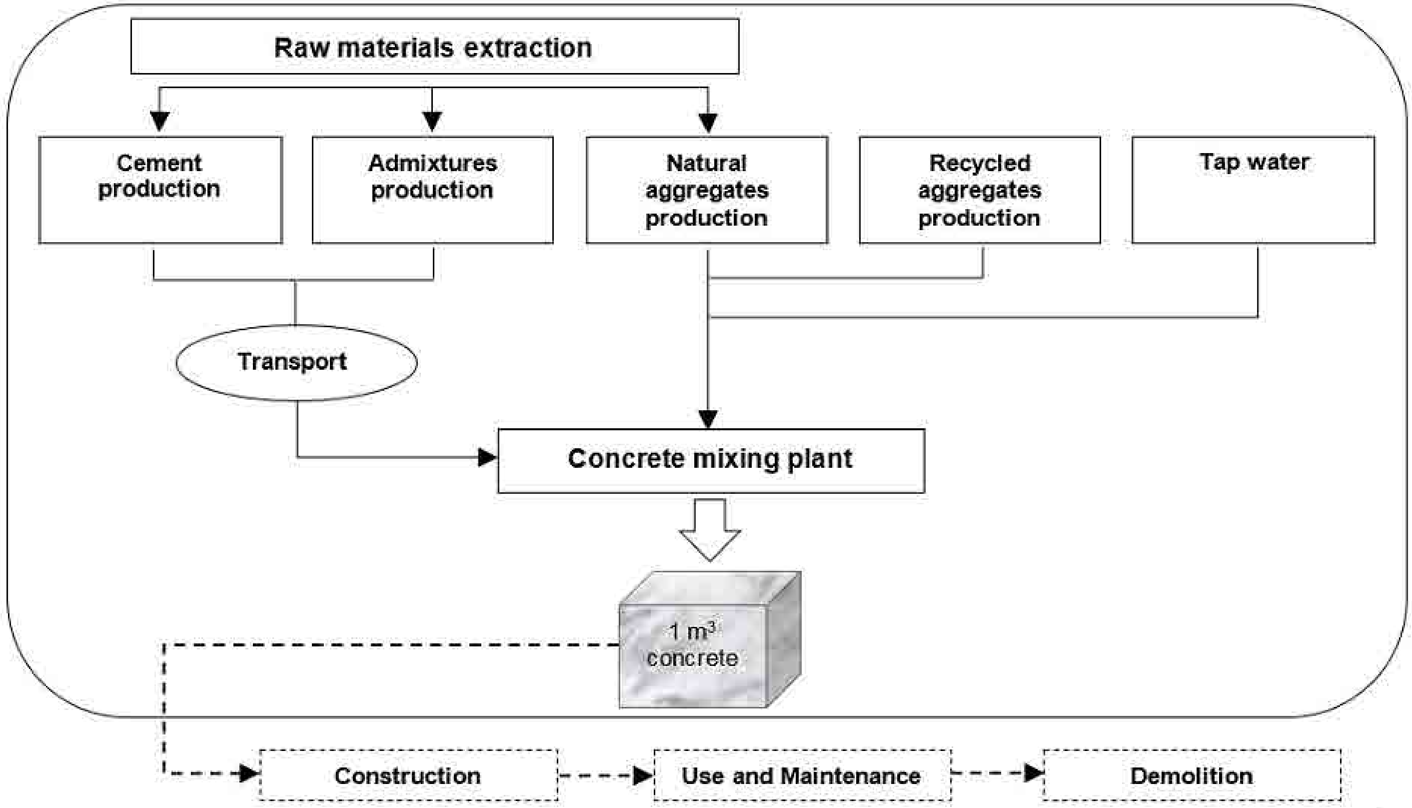


Figure 8.1: System boundaries of the Life Cycle Assessment

All the materials used for the concrete systems come from local suppliers from the surroundings of Barcelona city, in Spain. Although this, their environmental information correspond to the available one in the databases or specialized documents consulted in this study. The transportation system was the one suitable for these cases and available in the consulted databases. The transport distances of the cement and admixtures correspond to normal distance between the concrete plant facilities and suppliers (Mendoza and Part, 2012; Gabarrell et al., 2012). The aggregates are supposed to be produced at plant so no additional transport distances are considered from suppliers. Cement, admixtures and NA production include raw materials extraction processes, transportation inside the factory and machinery use. The concrete plant and energy usage come from existing examples of concrete production, which were adapted to the actual system requirements. Same production processes and energy requirements were applied for both concrete groups as they have almost equal characteristics. The RA production only takes into account crushing and screening operations as the previous demolition and transport of waste stages are taken as part of the previous life cycle system. This means that the environmental data concerning this specific material is taken into consideration only from the reception of this material at plant and its subsequent mentioned processes.

8.3.2.4 Data sources

The environmental data concerning most of the processes and materials of this analysis were acquired from Ecoinvent v.3.01 database (Swiss Centre for Life Cycle Inventories, 2013), which is a widely used and acknowledged data source, and the last up to date version. In the cases of the RA, their information was taken from a the publication of Marinkovic et al. (Marinković et al., 2010) in which a comparative environmental analysis of RA and NA is done. The environmental information of both superplasticizing and air entrainer admixtures were obtained from public access documents made by the European Federation of Concrete Admixture Associations (European Federation of Concrete Admixture Associations, 2006, 2005), which can be consulted in Appendix D. It is worth mentioning that the information obtained for RA and both admixtures comes from

European publications, and from recognized sources. The software Simapro 8.0 (PRé Consultants, 2014) was used to organize the data, assemble each system case and obtain the environmental results.

8.3.2.5 Allocation

Allocation is a distribution of the inputs and/or outputs of a determined process into the system being analysed. In this particular case for example, an unavoidable allocation problem appears due to the concrete recycling outputs, which are coarse and fine aggregates. The fact that fine aggregates are not used in the elaboration of concrete in this investigation, and that they are a sub-product of the recycling process, makes them take part on the environmental loads that this process represent. Thus, the two sub-products (coarse and fine aggregates) should share the total environmental load. This distribution is made in rather in a physical or economical way.

In this analysis, a mass allocation procedure was selected, according to what ISO 14044 and EN 15804 standards state (International Organization for Standarization. Technical Committee ISO/TC 207, 2006c; European Committee for Standarization, 2012). This is based on the fact that both the fine and coarse parts have similar prices in the local market, thus not having a significant difference among them when based on this terms, hence being the physical property relation an appropriate solution. This relation was based on the works presented by Nagataki and Marinkovic (Nagataki et al., 2004; Marinković et al., 2010), in which they take into account reclamation ratios of 60% for the coarse part and 40% for the fine part. This means that, for every 1 ton of recycled material, 600 kg and 400 kg of coarse and fine aggregates are produced respectively.

8.3.2.6 Impact assessment

The analysis was done using the CML methodology, which summarizes a series of mid-point impact categories with proper characterization factors. The mid-point method looks at the effects of a certain impact before the end of the entire chain of problems is reached, e.g., we can determine the effects that a certain product has on global warming, but we won't analyse the effects it has on human health, like skin cancer.

The selected impact categories of this analysis are:

- Abiotic Depletion Potential (ADP): measured in kg of antimony equivalents (kg Sb eq.), is an impact category related to the depletion of minerals caused by their extraction.
- Abiotic Depletion Potential of fossil fuels (ADP fossil fuels): is measured in Mega Joules (MJ) and it is related to the depletion of fossil fuels caused by their extraction.
- Global Warming Potential (GWP): measured in kg of carbon dioxide equivalents (kg CO^2 eq.), deals with the global warming caused by the trapped heat of a certain greenhouse gas emitted to the atmosphere.
- Ozone Layer Depletion Potential (ODP): measured in kg of trichlorofluoromethane equivalents (kg CFC-11 eq.), this category deals with the substances depleting the ozone layer on the stratosphere, and thus provoking a higher amount of solar radiation getting to the surface of the earth.
- Human Toxicity Potential (HTP): measured in kg of 1.4 dichlorobenzene equivalents (kg 1.4 DB eq.), is a category related to the potential harm of a chemical in the environment.
- Fresh Water Aquatic Ecotoxicity (FAETP): measured in kg of 1.4 dichlorobenzene equivalents (kg 1.4 DB eq.), deals with the effect of toxic substances over fresh water.
- Marine Aquatic Ecotoxicity (MAETP): measured in kg of 1.4 dichlorobenzene equivalents (kg 1.4 DB eq.), deals with the effect of toxic substances over marine water.
- Terrestrial Ecotoxicity (TETP): measured in kg of 1.4 dichlorobenzene equivalents (kg 1.4 DB eq.), deals with the effect of toxic substances over terrestrial ecosystems.
- Photochemical Oxidation (POCP): measured in kg of ethylene equivalents (kg C_2H_4 eq.), deals with the formation of excessive amounts of ozone near the earth's surface.
- Acidification (AP): it is measured in kg of sulphur dioxide equivalents (kg SO_2 eq.) and it is related to the impacts that acidic substances have on ecosystems.

- Eutrophication (EP): measured in kg of phosphate equivalents (kg $PO_4{}^3$ eq.), deals with the formation of excessive plant growth due to an enrichment of nutrients.

8.3.2.7 Sensitivity analysis

A sensitivity analysis is carried out with the aim of analysing the effects of possible variations within the product system. In this case, the variation of the system is made through changes in the materials, specifically, the cement.

Portland cement is recognized to be an important contributor to environmental problems related to the construction industry, thus taking into account other types of cement rather than the one used for the elaboration of the concretes in this investigation (Portland cement type I), in order to check the influence they have on the total emissions of these concretes, seems an important matter to be analysed.

In this case, the GWP impact category is selected to make the comparison, as it is the one where cement accounts for the highest burdens, apart from being one of the most significant categories, due to its recognition as an environmental benchmark on many areas. The selected cement types used for this evaluation are Portland cement type I (P; almost no additions), Portland cement type II (F; with additions of fly ash between 11-35%) and Portland cement type II (S; with additions of blast furnace slag between 18-30%). The replaced amount of these alternative cements corresponds to the same amount of the cement in the original mixtures. It is worth mentioning that this analysis is made under theoretical basis, meaning that the concretes with the replacement of both Portland type II cements have not been elaborated, thus their properties are assumed. In any case, both cements type II have been selected as they are supposed to confer at least the same properties than cement type I does to the concrete. The data has been obtained from Ecoinvent v3.01 database (Swiss Centre for Life Cycle Inventories, 2013) and processed with the software Simapro 8.0 (PRé Consultants, 2014).

Table 8.3: Inventory data of the different concrete systems per declared unit

Stage	Data per DU	Unit	Product System			
			C35-S3-D$_{\mathrm{max}}$20-X0		C40-S3-D$_{\mathrm{max}}$20-X0	
			*ACIDVR-A/0.45	ACIEMV-A/0.45	*BCON/0.45	BEMV20/0.45
Materials	Tap water	kg	184	140	184	169
	Cement	kg	409	311	409	376
	Natural aggregate	kg	752	998	1881	1673
	Recycled aggregate	kg	786	782	0	235
	Admixtures	kg	1.3	2.2	1.5	2.1
Facilities	Concrete plant	u	4.6E-07	4.6E-07	4.6E-07	4.6E-07
Transport	Lorry 16-32 t**	tkm	30.8	23.5	30.8	28.4
Energy	Production	MJ	55	55	55	55

*Reference concrete

**EURO5 (European emission regulation class)

8.4 Results and discussion

In this section, the results of the inventory analysis are presented as a result of gathering, organizing and managing all the information related to the product system under study. Next, this information is related to a certain impact category which will then be analysed from both a general perspective and a more specific one. The later is intended to closely look at the different stages composing the entire product system. Finally, the results of the sensitivity analysis will be presented an commented.

8.4.1 Inventory analysis

The inventory data of the present study can be seen in Table 8.3. It is divided into the two concrete categories selected for the analysis, with two concretes each, specifying the phase of the product system and the single unit data per DU.

The major changes occurring among the concretes are due to their materials compositions as it can be seen in Table 8.3. Concretes designed through the Equivalent Mortar Volume method present important differences when compared to the reference concretes, mainly due to the methods basis. Their main constituents (water, cement and aggregates) differ due to the proportioning procedure, in which it is worth noting that cement contents decrease 24% and 8%, in the cases of the first and second categories of concretes respectively.

As a consequence of the reduced amount of new mortar, the admixtures amounts in both concretes proportioned by the Equivalent Mortar Volume method had to be increased when compared to the reference mixes, so that the slump test values between them turn comparable.

The values related to transportation vary according to the amount of transported material rather than the covered distance to suppliers. This is due to the fact that all the concretes are supposed to be produced in the same place, and that all of the different concrete types use the same materials from the same suppliers. Regarding transportation stage, cement content becomes the most influencing parameter as it account for more than 99% of the whole figure, whereas admixtures account less than 1%.

Facilities and Energy stages present the same values on each one of the studied concretes as they have no relevant differences concerning the plant and technologies for their production.

8.4.2 Impact assessment of concrete systems

As it was mentioned before, after the characterization of every single unit of the system, these can be summarized in order to have a wide perspective of the total emissions related to a certain impact category.

The results from the characterization phase of the LCA are presented in Table 8.4, in which the total results for every one of the chosen impact categories are listed according to the concrete systems, which are divided in the same two categories as it has been done before. The percentage difference from the results of every impact category, related to the concretes designed trough the novel method with respect to the conventionally designed ones, is also presented on each group.

Table 8.4: Characterization phase results per concrete type and impact category

			C35-S3-D_{max}20-X0			C40-S3-D_{max}20-X0		
Impact category	Abbreviation	Unit	ACIDVR-A/0.45	ACIEMV-A/0.45	Δ%	BCON /0.45	BEMV20 /0.45	Δ%
Abiotic depletion	ADP	kg Sb eq.	3,22E-04	3,20E-04	-1	4,60E-04	4,24E-04	-8
Abiotic depletion (fossil fuels)	ADP (fossil fuels)	MJ	2,20E+03	1,82E+03	-17	2,32E+03	2,18E+03	-6
Global warming	GWP	kg CO_2 eq.	4,03E+02	3,16E+02	-21	4,10E+02	3,81E+02	-7
Ozone layer depletion	ODP	kg CFC-11 eq.	8,83E-06	7,71E-06	-13	9,68E-06	9,23E-06	-5
Human toxicity	HTP	kg 1,4-DB eq.	3,79E+01	3,29E+01	-13	4,22E+01	3,96E+01	-6
Fresh water aquatic ecotoxicity	FAETP	kg 1,4-DB eq.	2,86E+01	2,43E+01	-15	3,13E+01	2,93E+01	-6
Marine aquatic ecotoxicity	MAETP	kg 1,4-DB eq.	1,02E+05	8,84E+04	-13	1,13E+05	1,06E+05	-6
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq.	1,18E-01	1,06E-01	-10	1,37E-01	1,30E-01	-5
Photochemical oxidation	POCP	kg C_2H_4 eq.	4,27E-02	3,53E-02	-17	4,61E-02	4,30E-02	-7
Acidification	AP	kg SO_2 eq.	1,15E+00	9,40E-01	-18	1,20E+00	1,12E+00	-7
Eutrophication	EP	kg PO_4^{3} eq.	2,45E-01	2,01E-01	-18	2,54E-01	2,38E-01	-6

In both cases, the results of the concretes designed with the Equivalent Mortar Volume method are lower than their analogous concretes for every one of the selected impact categories.

8.4.2.1 C35-S3-D$_{\mathbf{max}}$20-X0

ACIEMV-A/0.45 concrete behaves almost as same as the ACIDVR-A/0.45 concrete in ADP impact category, with only 1% difference due to the emissions balance among their stages. ACIEMV-A/0.45 concrete uses less cement and consequently reduces the emissions due to transportation as well, but its counterpart has fewer amount of NA and admixtures, thus causing, in this case, a total emissions balance between them.

For all of the other impact categories the difference is much higher, ranging from 10% up to 21%, the latter being the GWP impact category where such difference is owed to the cement contents differences and to the fact that cement is, by far, the largest contributor on this impact category. Cement generates such amounts of emissions due to the energy usage in its production process (about one third for Portland cements without additions) and the chemical decomposition of calcium carbonates, at high temperatures when producing clinker, into calcium oxides and carbon dioxide (CO_2, the other two thirds for Portland cements without additions). In fact, every kilogram of produced Portland cement type I releases around 800 grams of CO_2 (Josa et al., 2004) a figure that may be lower depending on the selected type of cement.

8.4.2.2 C40-S3-D$_{\mathbf{max}}$20-X0

BEMV20/0.45 concrete has fewer emissions in all of the studied impact categories, ranging from 5% to 8%. The lowest difference belongs to TETP impact category, which is related to toxic substances emitted on terrestrial ecosystems in terms of 1,4DB-eq. kg, where cement, NA and admixtures are the largest contributors. Contrary to what was mentioned in the C35-S3-D$_{max}$20-X0 concretes, the ADP impact category has the largest difference between both concretes, mainly due to the differences in cement and NA content. BCON/0.45 concrete is completely elaborated with NA and has more cement than BEMV20/0.45 concrete, and although the later uses more quantity of admixture, this has a considerable lower significance on the results due to the utilized amounts. Cement and NA mineralogies are characterized by elements that are directly related to natural non-renewable resources, thus having a direct relationship with ADP impact category (Guiné et al., 2004). This, together with the important role that they play in the concrete, occupying more than 80% of its volume, explains the weight that they imply on the results of this particular case.

8.4.3 Disaggregated impact assessment of concrete systems

After analysing the results from a general perspective, these are partitioned into different stages, which gives a better idea of what are the specific processes or materials influencing the most to the general results. This disaggregation is presented in Figure 8.2, where the first and second columns represent ACI$_{\text{DVR}}$-A/0.45 and ACI$_{\text{EMV}}$-A/0.45 concretes respectively, and in Figure 8.3, where the first and second columns represent B$_{\text{CON}}$/0.45 and B$_{\text{EMV}}$20/0.45 concretes respectively.

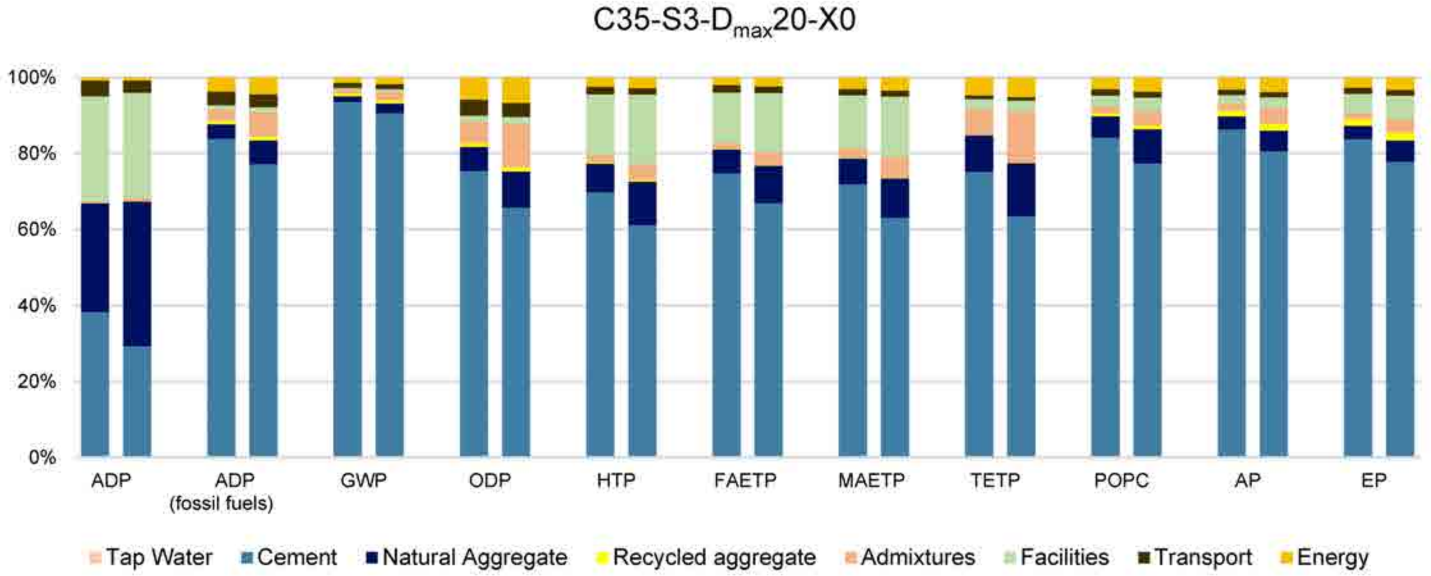


Figure 8.2: Disaggregation of C35-S3-D_{max}20-X0 concretes impact categories into stages percentage contribution

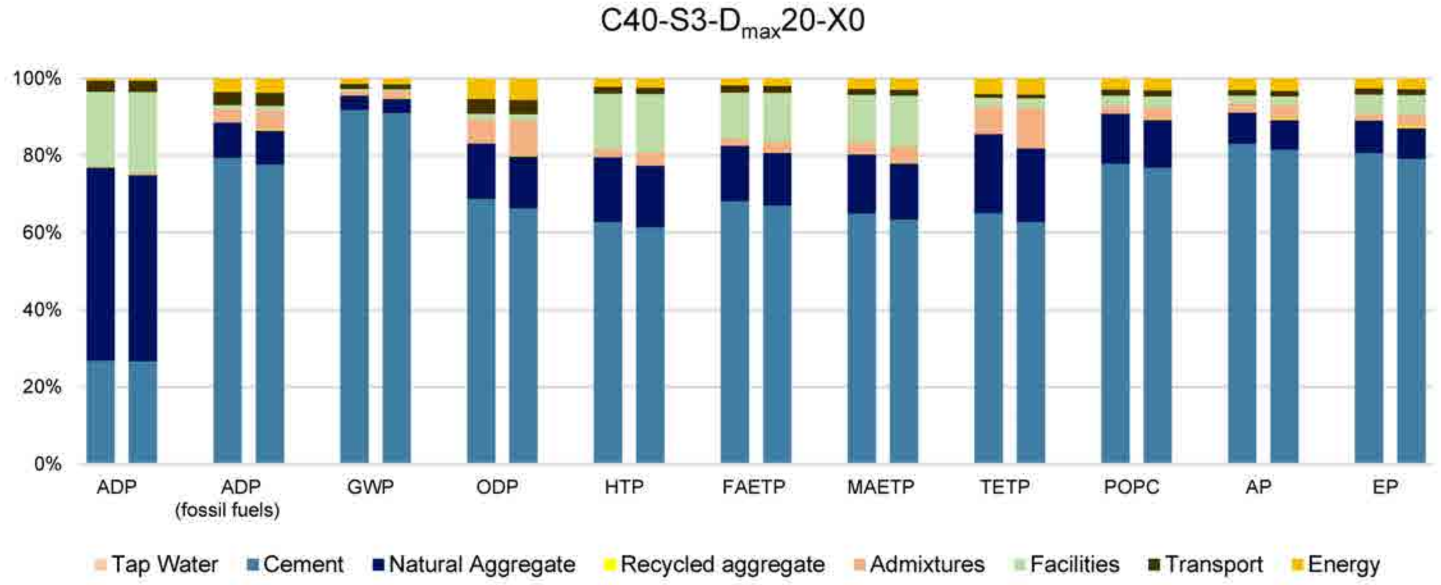


Figure 8.3: Disaggregation of C40-S3-D$_{max}$20-X0 concretes impact categories into stages percentage contribution

8.4.3.1 C35-S3-D$_{\text{max}}$20-X0

From Figure 8.2 it is clear that, irrespectively of the concrete type, cement is the single element contributing the most to almost all of the impact categories, with just one exception on the ACI$_{\text{EMV}}$-A/0.45 concrete for the ADP impact category in which it accounts for 29% of the emissions and where NA rises up to 38%. The explanation is on the needed quantities of materials to elaborate 1 m^3 of concrete. Whereas cement production initially needs around 1.5 times the amount of material to obtain the final product, mainly due to released CO_2 in the calcination process during clinker production, aggregates represent over 3.5 times the amount of cement on the mix. With the exception of the ADP impact category, cement emissions on the rest of them range from 70% to 94% of their total amounts in the ACI$_{\text{DVR}}$-A/0.45 concrete, and from 61% to 91% in the ACI$_{\text{EMV}}$-A/0.45 concrete. In both cases the highest percentage represents the GWP category. After GWP impact category, cement has a great influence in AP, EP, ADP fossil fuels and POPC impact categories, which are closely related to the combustion of fuels during cement production (Josa et al., 2004).

NA have an important influence on the results of categories like ADP and TETP, where the former is influenced by the extraction of the product itself thus contributing to its depletion, and the latter by the production process. As the ACI$_{\text{EMV}}$-A/0.45 concrete needs more NA than ACI$_{\text{DVR}}$-A/0.45 concrete, its emissions are greater in about 33% in this point.

Admixtures emissions take importance, mostly, in ODP and TETP impact categories. Although their emissions could be potentially harmful, their utilization amounts per m^3 of concrete are so low that they do not end up making an important contribution to the final results of the majority of the impact categories. ACI$_{\text{EMV}}$-A/0.45 concrete uses more than 2.2 times (in terms of % over cement weight) more admixtures amounts and its emissions are higher on this specific system unit by 77%. A larger amount of admixtures is necessary to compensate the workability problems that the lack of fresh mortar supposes to ACI$_{\text{EMV}}$-A/0.45 mix compared to ACI$_{\text{DVR}}$-A/0.45.

The facilities stage emissions are more relevant in ADP, HTP, MAETP and FAETP impact categories. The reason of their impacts may be explained, in part, by the utilization of copper and some types of plastics, whose extraction directly affects the ADP category, and their processing to HTP, MAETP and FAETP categories. There are no differences on the related emissions of this stage between the studied concretes as they can be produced at the same installations.

Transportation stage has no major influence on the different impact categories. The only transportation is made from the cement and chemical admixtures factories to the concrete plant, since construction, maintenance and demolition phases are not included. In any case, transportation's major effects can be seen in ADP, ADP fossil fuels and ODP impact categories. The first two categories may be related to the utilization of fossil fuels, in the combustion process for the energy of the vehicle and when used as a raw material for the production of plastics. The ODP category may be related to the use of some types of coolants in the refrigeration system of the vehicles (Environmental Protection Agency (EPA), 2014).

Energy usage does not represent an important part of the total emissions due to the defined system limits. Although this, its major influences are over ADP fossil fuels, ODP and TETP impact categories. The first two categories can be explained by the use of fuels and chemicals for the operational processes in power plants, whereas TETP category may be related to the produced spoils from lignite mining, for the production of electricity in power plants. Be recalled that this stage deals with the energy required for the production of concrete only.

Tap water and RA emissions are mostly negligible in the majority of the selected impact categories.

In summary, materials stage alone, which includes tap water, cement, RA and NA, and admixtures, is accountable for at least 67% of the total emissions of every impact category in both concrete mixes, and as high as 97%. This was an expected outcome, due to the exclusion of the construction, maintenance and demolition phases from the system boundaries, due to the variability they could cause on the final results, depending on the broad scope of the specific final applications of concrete. Facilities stage is the second stage in importance, when globally looking at the results of the impact categories, having its highest influence in ADP impact category with a 28%. Energy is the next stage having the highest influences in most of the impact categories with its highest on the ODP one, with around 6% of the total emissions. Transportation is the least influencing stage among all of the defined stages, with its highest values being around 4% of the total emissions in the ODP impact category.

It seems clear that putting more effort towards cement's environmental performance, or its use reduction, would substantially improve the concretes environmental performance as well.

8.4.3.2 C40-S3-D_{max}20-X0

Just like in the previous case, as shown in Figure 8.3, the majority of the emissions, with the exception of the ADP category, are attributable to the cement. Cement in ADP category accounts for 27% of the total emissions whereas NA owns 50% and 48% for BCON/0.45 and BEMV20/0.45 respectively. In the rest of the categories, cement emissions go from 63% to 92% in the case of BCON/0.45 concrete and from 61% to 91% in the case of BEMV20/0.45 concrete, the higher figures being relative to GWP category, followed by AP, EP, ADP fossil fuels and POPC, as well as in the previous cases

NA has as well an important influence, especially in ADP, HTP, MAETP, FAETP and TETP impact categories. As these concretes use around double amount of NA than the previous category, their implication among the different impact categories is indubitable higher. Unlike the previous concrete category, and because of the mix proportions, BEMV20/0.45 concrete produces 11% less emissions related to NA, in every impact category, than BCON/0.45 concrete.

The admixtures amount were increased more than 1.5 times (in terms of % over cement weight) for BEMV20/0.45 concrete, and its emissions are higher on this specific system unit by 40%. This goes along the same line that the previous concretes category, being the ODP and TETP the most influenced impact categories.

Facilities, transportation and energy stages behave similarly to what was mentioned in the case of C35-S3-D_{max}20-X0 concretes.

RA and tap water are again the lowest contributors although, in this case, RA only affects BEMV20/0.45 concrete.

The difference between the concretes single units is not as high as in the previous case. This is mainly due to the mix proportions, where in the one hand, replacement of RA is lower and, on the other hand, one of these concretes is completely elaborated with NA.

In summary, materials stage is again the main contributor in the whole figures, with at least 75% and as high as 97% of the total emissions on each category for both concrete mixes. Facilities are the second most influencing stage, when taking a general view over the results of the impact categories, with its highest values in the ADP category, rounding the 20% of the total emissions. Energy stage stands after, with its highest values being around 5% of the total emissions in the ODP impact category. Transportation is again the lowest contributor to the overall results of the different impact categories, reaching its highest influence in the ODP category with a 4% of the total emissions.

Even though some stages where taken out from the analysis, cement production and its use might be key points to be aware of, when aiming to improve the environmental performance of a whole construction project, though this depends on the specific case (more important in civil engineering works, with higher percentage of concrete per DU, than in buildings).

8.4.4 Sensitivity analysis

As it has been previously commented, and as a result from the analysis, cement turns to be the single material contributing the most to almost all of the studied impact categories of this LCA, thus it seems appropriate to run a sensitivity analysis concerning other types of binder for the elaboration of the concrete, and to check with this if their use in concrete provokes any amelioration regarding GWP related emissions.

Three different cement types will be used for the analysis. The first, and the one to which this analysis is made for, is Portland cement type I, resistance class 42.5 N/mm^2. The other cements are Portland type II with additions of fly ash (11%-35%) and Portland type II with additions of blast furnace slag (18%-30%), also with resistance class of 42.5 N/mm^2.

After the analysis and regarding CO_2 emissions, the replacement of Portland type I cement by the fly ash additivated cement results in a total reduction of 17% of the emissions. The replacement of Portland type I by the blast furnace slag additivated cement on the other hand represents a total emissions reduction of 27%.

The results of the total emissions in kg CO_2 eq. of each one of the concretes of this analysis, regarding the use of different types of cement for their elaboration, is shown in Table 8.5.

Table 8.5: Sensitivity analysis of different cements

		C35-S3-D$_{max}$20-X0		C40-S3-D$_{max}$20-X0	
Cement type	Unit	ACIDVR-A/0.45	ACIEMV-A/0.45	BCON/0.45	BEMV20/0.45
Portland I	kg CO_2 eq.	403.0	316.5	410.4	380.6
Portland II (fly ash)	kg CO_2 eq.	332.2	262.6	339.6	315.5
Portland II (blast furnace slag)	kg CO_2 eq.	294.0	233.6	301.4	280.4

There is an important difference on the reductions of CO_2 between fly ash and blast furnace slag additivated cements. This is due to the proportioning percentages used in the manufacture of these types of cements. Ground granulated furnace slag production generates higher quantities of CO_2 emissions than the production of fly ash, but the later ones are frequently dosed in higher quantities. Their emissions differences may be related to the production processes of each one of them, as, when produced with the intention of being part of cement, ground granulated furnace slag has an important extra input as it has to be milled down to a size similar to that of cement, while on the contrary fly ash does not need such process as it already has a suitable size to be used together with cement.

While these figures are important, fly ash and blast furnace slag cement types keep on having a significant influence on the total CO_2 emissions of the concretes that they are used on. Fly ash and slag cements represent a reduction of around 2% and 3% respectively, in terms of the weight that these materials have over the whole concrete system, when compared to the weight that Portland type I cement represents on its corresponding concrete system.

These theoretical figures suppose promising advances if proper measures are taken regarding cementitious materials for concrete production. If these binders make no difference on the desired properties of the concrete, they should be selected when designing certain mix, if the concern is to improve their environmental value, at least regarding CO_2 emissions.

8.5 Conclusions

This Life Cycle Assessment shows how different mix proportioning methods (American Concrete Institute, Bolomey and Equivalent Mortar Volume) can influence the environmental impact categories of the studied concretes, when equivalent short and long-term behaviours are attained and natural aggregates and/or recycled aggregates are used. Four concretes were subjected to the analysis, two of them acting as references (ACI$_{\text{DVR}}$-A/0.45, B$_{\text{CON}}$/0.45) and designed through conventional methods, and other two (ACI$_{\text{EMV}}$-A/0.45, B$_{\text{EMV}}$20/0.45) designed through a novel method.

The results show that cement is, by far, the most influencing material in almost all of the analysed impact categories of the different concrete systems, in terms of its released emissions. Thus leading the efforts on lowering its environmental burdens, while keeping the concretes short and long term behaviour, may represent a big leap forward on this field. However, it should be noted that when comparing complete Functional Units like bridges or buildings, the effect of cement and concrete can be very low in relation to the total impact and may influence positively other life cycle stages or parameters as construction, maintenance or energy efficiency.

After cement, natural aggregates and facilities are the most significant contributors to the majority of the impact categories for the different concrete systems. Their major influences are found in the Abiotic Depletion Potential (ADP) impact category, where natural aggregates accounts from 28% up to 50% of the emissions, and facilities accounts from 19% to 28% of them. After ADP impact category, natural aggregates major influence is on the Terrestrial Ecotoxicity impact category (TETP), contributing with at least 9% and up to 21% of the emissions. In the case of the facilities, also after ADP impact category, the major influence is observed in Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP) and Marine Aquatic Ecotoxicity (MAETP) impact categories, contributing with at least 12% and up to 18% of the emissions.

Chemical admixtures emissions influence are rather small, and a significant increase on their quantities does not jeopardize the obtained environmental achievements on the concretes of this investigation. Their main emissions contributions are related to Ozone Layer

Depletion (ODP) and TETP impact categories. Based on these results, the use of chemical admixtures with the aim of lowering the commonly used amounts of cement, while achieving equal performances on the designed concretes, or with the aim on improving the performance of the concretes, while maintaining the same amounts of cement, should be encouraged.

In all of the studied concrete systems, the materials stage represents the major emissions' contributions, reaching at least 67% of every impact category and over 96% in the Global Warming Potential (GWP) category.

In accordance with the results, the Equivalent Mortar Volume method accomplishes better environmental performances than conventional methods for designing recycled aggregates concrete (ACI_{DVR}-A/0.45) and natural aggregates concrete (B_{CON}/0.45). Albeit this is achieved by adding more quantities of admixtures on the mix, their emissions contribution is small, thus resulting in an appropriate solution.

The results of the sensitivity analysis indicate that the use of cements with additions of fly ash and blast furnace slag, improve the concretes environmental performances, regarding GWP impact category, by reducing their CO_2 emissions in around 17% and 27% respectively, when compared to concretes using Portland cement type I. However it must be taken into account that the same short and long term behaviour must be ensured for the different mixtures compared.

Chapter 9

Conclusions and Future Perspectives

9.1 Conclusions

In this investigation, the use of recycled aggregates (RA) for the elaboration of recycled aggregates concretes (RAC) has been studied and analysed from a sustainable point of view. Different concrete mixes, comprising the use of natural aggregates (NA) and/or RA, have been assessed from their design perspective, from their fresh, mechanical and durability main properties, and from their environmental performance. With this, the present investigation offers new solutions and contributes with new information regarding the use of RA in RAC.

The obtained results of this thesis show that it is possible to design RAC that no only help to lessen the use of natural resources, but also diminishes the commonly used amounts of cement that are needed to achieve comparable results to those of the natural aggregates concretes (NAC).

The specific conclusions of this investigation are listed below:

- From the mixes design point of view, it can be said that the novel Equivalent Mortar Volume method for the design of RAC is a feasible and beneficial idea towards the reuse and recycling of materials and environmental protection, when compared to other design methodologies. In addition, its adaptation to another mix proportioning methodology is possible, with which its scope has been extended.

- Concerning the workability of the concretes evaluated with the slump test, it has been observed that the concretes designed with the Equivalent Mortar Volume method can achieve similar slump values to those designed with conventional methods, if higher dosages of admixtures are used.

- The assessed mechanical properties of the concretes resulted in similar, and in some cases better performances when designed with the Equivalent Mortar Volume method, in comparison to both conventionally designed NAC and RAC. Regarding the durability properties of the concretes, RAC designed with the novel method resulted in better performances than conventionally designed RAC for most of the cases and, when compared to NAC, the results were similar for most of the studied properties. These results have been obtained while reducing the amounts of cement from 7% up to 24% in the concrete mixes designed with the novel method, with regard to both conventionally designed NAC and RAC.

- The use of the air-entraining admixture resulted in worse overall behaviours on the mechanical tests revised on this investigation, in comparison to concretes not using the commented admixture. On the contrary, its use is highly recommended to improve the concretes durability properties, as, in most of the analysed tests, the use of such admixture has resulted in better outcomes.

- From the rheological properties obtained in this investigation, it is observed that concretes with similar slump values can have both different yield stresses and plastic viscosities, thus it is concluded that the slump test does not accurately represents the rheological characteristics of the mix. Also, the use of a superplasticizing admixture alone in the concretes designed with the Equivalent Mortar Volume method does not seem enough to achieve rheological properties comparable to those of the conventionally designed concretes, although they still remain closer to the limits of self-compacting concretes. When combining the use of the superplasticizer and air-entraining admixtures, the concretes designed with the novel method achieve similar and in some cases better rheological properties of those of the conventionally designed concretes, with the added benefit of using less cement.

- Finally, from the environmental assessment it can be concluded that cement is, by far, the most influencing material in almost all of the analysed impact categories of the different concrete systems, in terms of its released emissions. Thus leading the efforts on lowering its environmental burdens, while keeping the concretes short and long term behaviour, may represent a big leap forward on this field. Also, the concretes designed with the Equivalent Mortar Volume method accomplish better environmental performances than conventionally designed RAC and NAC. Albeit this is achieved by adding more quantities of admixtures on the mix, their emissions contribution is small, thus resulting in an appropriate solution. Based on these results, the use of chemical admixtures with the aim of lowering the commonly used amounts of cement, while achieving equal performances on the designed concretes, or with the aim on improving the performance of the concretes, while maintaining the same amounts of cement, should be encouraged.

9.2 Future perspectives

The present investigation has elucidated some of the question marks of the use of RA and of RAC, specially regarding new solutions towards better designs that are more environmentally friendly. However, there are still remaining issues to be solved and investigated, some of which will be summarized bellow:

- The Equivalent Mortar Volume method has been adapted to Bolomey mix proportioning design methodology but, as there are several other approaches for the design of concretes, it is encouraged to further study the possibilities of its adaptation to other methods in order to broaden its scope.
- Apart from the results presented in this document, a further study of the mechanical and durability properties of the concretes designed with the novel method is encouraged, specially when other water/cement ratios and aggregates replacement percentages are used. With this, important information of the limits in which the method confers satisfactory properties to the concretes could be obtained.

- Other important properties that are worth to be evaluated due to their importance in structural concrete design, are the fatigue behaviour and the bonding behaviour between steel bars and concrete. These properties have been only slightly evaluated in recycled concretes and, with the use of the Equivalent Mortar Volume method, their results may vary as the novel method greatly influences the internal structure of the concretes.

- In this document, the rheological parameters of the concretes have been studied using two water/cement ratios and two types of admixtures, namely superplasticizing and air-entraining admixtures. Further studies of the rheological behaviour of the concrete mixes are recommended, with other water/cement ratios and/or using other types of admixtures, in order to broaden the knowledge on this specific subject. It is worth reminding that there are no much more studies regarding the rheological properties of RAC apart from the ones presented in this document.

- From the sustainability point of view, a complete evaluation of the economical and social implications that the Equivalent Mortar Volume method implies, could improve and add value to the results that this investigation has obtained.

- Also, a Life Cycle Assessment of a complete functional unit, like bridges or buildings, would improve the results obtained in this investigation. A study where not only the concrete is evaluated but other life cycle stages or parameters are evaluated as well, could show the role that the material and its alternatives play as a part of a real construction project.

Chapter 10

Conclusiones y Perspectivas Futuras

10.1 Conclusiones

La presente investigación, estudia y analiza la utilización de áridos reciclados (AR) para la elaboración de hormigones de áridos reciclados (HAR) desde el punto de vista de la sostenibilidad. Se han evaluado diferentes hormigones, utilizando AR y/o áridos naturales (AN) en su composición, respecto de su diseño, de sus propiedades en estado fresco, mecánicas y de durabilidad, y respecto de su desempeño medioambiental. Con lo anterior, la presente investigación ofrece nuevas soluciones y contribuye nueva información a la utilización de AR en HAR.

Los resultados obtenidos en esta investigación muestran que es posible diseñar HAR que no solo ayuden a disminuir el uso de recursos naturales, sino que también reduzcan las cantidades de cemento que son utilizadas normalmente para alcanzar prestaciones comparables a las de hormigones de áridos naturales (HAN).

Las conclusiones específicas de la presente tesis se detallan a continuación:

- Desde el punto de vista del diseño de mezclas, se puede concluir que el método del Volumen de Mortero Equivalente (Equivalent Mortar Volume) para dosificar HAR, representa una idea factible y beneficiosa en torno a la reutilización y reciclaje de materiales y la protección del medioambiente, en comparación con otras metodologías de diseño. Además, su adaptación a otro método de dosificación es viable, con lo cual se extiende su alcance.

- Respecto de la trabajabilidad de los hormigones, evaluada a través del método del cono de Abrams, se ha observado que si los hormigones diseñados con el método del Volumen de Mortero Equivalente utilizan mayores cantidades de aditivos, pueden alcanzar medidas de consistencia similares a las de los diseñados mediante métodos convencionales.

- La evaluación de las propiedades mecánicas de los hormigones diseñados con el método del Volumen de Mortero Equivalente, resultó en desempeños similares, e incluso mejores en algunos casos, en comparación con los HAN y HAR diseñados convencionalmente. Respecto de las propiedades de durabilidad, los HAR diseñados con el nuevo método obtienen, en la mayoría de las propiedades estudiadas, mejores prestaciones que los HAR diseñados convencionalmente, y similares resultados en comparación con los HAN. Todo lo anterior se ha obtenido junto con una reducción de las cantidades de cemento de los hormigones diseñados con el nuevo método, en valores que van desde un 7% hasta un 24% en comparación con los HAN y HAR diseñados convencionalmente.

- En general, las propiedades mecánicas de los hormigones en los que se ha utilizado el aditivo oclusor de aire, resultaron en peores resultados que los que no lo han utilizado. Por el contrario, el uso de este aditivo es altamente recomendado cuando se pretenden mejorar las propiedades de durabilidad de los hormigones, ya que con su utilización, en la mayoría de los casos estudiados, se han obtenido mejores resultados.

- Desde el punto de vista de las propiedades reológicas obtenidas en esta investigación, se observa que los hormigones que han alcanzado valores similares de consistencia, medida a través del método del cono de Abrams, obtienen valores de límite de fluencia y viscosidad plástica distintos, por lo que se concluye que el método del cono de Abrams no representa con exactitud las propiedades reológicas de las mezclas. También, la sola utilización del aditivo superplastificante en los hormigones diseñados mediante el método del Volumen de Mortero Equivalente, no es suficiente para alcanzar propiedades reológicas comparables a las de los hormigones diseñados con métodos convencionales, aunque de todas formas se encuentran cerca de los límites que poseen los hormigones auto-compactantes. Los hormigones diseñados con el nuevo método alcanzan propiedades reológicas similares, y en algunos casos mejores, en comparación con los hormigones diseñados convencionalmente, cuando se combina la utilización de aditivos superplastificantes e oclusores de aire, con la ventaja de utilizar menos cantidades de cemento.

- Finalmente, desde el punto de vista de la evaluación medioambiental, se concluye que el cemento es, con diferencia, el material que más influye en términos de emisiones, en la mayoría de las categorías de impacto analizadas. Por consiguiente, dirigir los esfuerzos hacia la disminución de su carga medioambiental, mientras se preserve el comportamiento de los hormigones a corto y largo plazo, puede significar un gran paso adelante en estos ámbitos. También se observa que los hormigones diseñados con el método del Volumen de Mortero Equivalente alcanzan mejores resultados medioambientales que los HAR y HAN diseñados convencionalmente. Si bien esto se logra mediante la utilización de mayores cantidades de aditivos, la contribución de emisiones de estos últimos es baja, por lo que resulta en una solución apropiada. Basado en estos resultados, la utilización de aditivos en hormigones debería ser fomentada cuando la finalidad es reducir las cantidades de cemento comúnmente utilizadas, alcanzando a su vez iguales desempeños, o cuando se pretenden mejorar las prestaciones de los hormigones a la vez que se mantengan las cantidades de cemento.

10.2 Perspectivas futuras

La presente investigación ha dilucidado algunas de las interrogantes del uso de AR y HAR, especialmente respecto de nuevas soluciones, que se dirijan hacia mejores diseños que sean medioambientalmente más amigables. Sin embargo, aún quedan asuntos por resolver e investigar, algunos de los cuales serán resumidos a continuación:

- El método del Volumen de Mortero Equivalente ha sido adaptado a la metodología de diseño de mezclas de Bolomey, pero dado que existen varios métodos de diseño de hormigones es que se anima a seguir estudiando las posibilidades de adaptar el nuevo método a otras metodologías de diseño, de manera de poder extender su alcance.

- Aparte de los resultados presentados en esta investigación, se anima a realizar más estudios acerca de las propiedades mecánicas y de durabilidad de los hormigones diseñados con el nuevo método, especialmente cuando se utilizan otras relaciones agua/cemento y otros porcentajes de reemplazo de áridos. Con lo anterior se podría obtener información importante acerca de los límites en los cuales el método confiere propiedades consideradas como satisfactorias a los hormigones.

- Otras propiedades importantes que merecen ser evaluadas, dada su importancia en el diseño de hormigón estructural, son el comportamiento a fatiga y el comportamiento de adherencia entre el acero y el hormigón. Estas propiedades han sido escasamente evaluadas en hormigones reciclados y, con el uso del método de Volumen de Mortero Equivalente, los resultados que se han encontrado podrían variar, dada la influencia que tiene el nuevo método en la estructura interna de los hormigones.

- En el presente documento se han estudiado las propiedades reológicas de los hormigones, utilizando dos relaciones agua/cemento y dos tipos de aditivos, un superplastificante y un oclusor de aire. Se recomienda por tanto ahondar en las propiedades reológicas de los hormigones, utilizando otras relaciones agua/cemento y/o utilizando otros tipos de aditivos, de manera tal de aumentar el conocimiento de este tema en concreto. Cabe recordar que no existen muchas otras investigaciones sobre las propiedades reológicas de HAR, aparte de las comentadas en este documento.

- Desde el punto de vista de la sostenibilidad, una completa evaluación de las implicaciones económicas y sociales que supone la utilización del método del Volumen de Mortero Equivalente, podría mejorar y añadir valor a los resultados obtenidos en esta investigación.

- También, un Análisis de Ciclo de Vida (Life Cycle Assessment) de una unidad funcional completa, como lo es un puente o un edificio, mejoraría los resultados obtenidos en este trabajo. Un estudio en el que no solo se evaluase el hormigón, sino también otros parámetros y etapas del ciclo de vida, podría mostrar el rol que toma este material y sus alternativas, como parte de un proyecto de construcción real.

Appendix A

Cement technical data sheets

A.1 CEM I 42,5 R

CEM I 42,5 R

UNE-EN 197-1:2000

CEMENTO GRIS RECOMENDADO PARA HORMIGON ESTRUCTURAL, PREFABRICADO Y PRETENSADO

MÁXIMA RESISTENCIA A EDADES TEMPRANAS

El cemento CEMEX - CEM I 42,5 R - se ha diseñado para garantizar prestaciones muy superiores a las exigidas en la normativa vigente, haciéndolo muy adecuado para la mayoría de aplicaciones.

Su alta resistencia a corta edad lo hace especialmente idóneo para trabajos de desencofrado rápido, para su aplicación en prefabricados de hormigón, elementos de hormigón pretensado, así como en lechadas de inyección para vainas de postensado y hormigones proyectados.

Es un cemento sin adiciones que favorece la creación de una reserva alcalina alta en el hormigón pasivando el acero de las armaduras.

RECOMENDACIONES DE USO

Hormigón de resistencia elevada
Hormigones de planta y morteros estabilizados
Prefabricados de hormigón
Hormigón pretensado
Apto para lechadas de cemento

PRECAUCIONES

Almacenar en lugares secos y estancos.
No mezclar con yeso ni con otros cementos.

CEM I 42,5 R

UNE-EN 197-1:2000

CEMENTO GRIS RECOMENDADO PARA HORMIGON ESTRUCTURAL, PREFABRICADO Y PRETENSADO

Máxima resistencia a edades tempranas

Formatos:
Envasado
en sacos de 25 Kg
Granel

ESPECIFICACIONES

Especificaciones UNE EN 197-1:2000

Componentes	
Clínker	95 a 100 %
Componentes minoritarios	0 a 5 %
Características químicas	
Pérdida por calcinación (P.P.C.)	≤ 5,0 %
Residuo indisoluble (R.I.)	≤ 5,0 %
Sulfato (SO_3)	≤ 4,0 %
Cloruros (Cl)	≤ 0,1 %
Características físicas	
Principio de fraguado	≥ 60 minutos
Expansión	≤ 10 mm
Resistencias a compresión	
2 días	≥ 20,0 MPa
28 días	≥ 42,5 MPa ≤ 62,5 MPa

CEMEX RECOMIENDA:

- Mantener los sacos cerrados, en un entorno fresco y seco, protegidos de la lluvia, de la humedad y aislados del suelo.

- En la manipulación de los sacos de cemento se recomienda extremar las medidas de seguridad para evitar posibles lesiones, así como utilizar ropa y equipos de protección personal tales como botas, guantes y gafas. Utilizar ayudas mecánicas siempre que sea posible.

A.2 CEM I 52,5 R

SUPER DRAGON

SD

PORTLAND CEMENT

EN 197-1 - CEM I 52,5 R

DESCRIPTION:

Our **SUPER DRAGON** is a high strength cement, designed principally for the precast concrete industry. Its main features are:

- High initial and final strengths.
- Rapid hardening, even in cold weather.

CEMENT FEATURES:

	Standard value	Specifications according to standard	
Clinker (%)	98	min. 95 - max. 100	
Minor component (%)	2	min. 0 - max. 5	
Loss of ignition (%)	2,5	max. 5,0	(1)
Sulfhate, SO_3 (%)	3,4	max. 4,0	
Chlorides, Cl^- (%)	0,04	max. 0,10	
Insoluble residue (%)	0,70	max. 5,0	
Blaine specific surface (cm^2/g)	4600	-	(2)
Soundness Le Chatelier (mm)	0,5	max. 10	
Initial setting time (min)	110	min. 45	
Final setting time (min)	170	max. 720	
1 day compressive strength (MPa)	27	-	(3)
2 days compressive strength (MPa)	40	min. 30,0	
7 days compressive strength (MPa)	52	-	
28 days compressive strength (MPa)	61	min. 52,5	

(1) Chemical (2) Physical (3) Mechanical

AENOR certifies compliance of this cement with the specifications of the UNE-EN 197-1 standard (common cements), evaluating it in accordance with what is established in the Particular Regulation RP 15.01 (Aenor quality certification). Therefore, it also has the corresponding CE compliance certificate. This cement contains a chrome (VI) reducing agent. AENOR also certifies the fulfillment of the regulation limit of the soluble Cr (VI) content according to UNE-EN 196-10.

SUPER DRAGON
SD
PORTLAND CEMENT

SHIPPING AND STORAGE:

- Available in bulk and in 35 Kg bags.
- The bags must be stored in dry, ventilated places. They must be protected from ground and atmospheric moisture.
- Bulk cement must be stored in watertight silos.

RECOMMENDED FOR:

- Reinforced concrete.
- Pre-stressed concrete.
- High-resistance concrete.
- Precast in general, especially in structural elements, whether pre-stressed or not.
- Concrete for rapid removal of formwork and mouldings even in cold weather.

NOT SUITABLE FOR:

- Compacted dry concrete.
- Concrete with potentially reactive aggregates exposed to aggressive environments.

PRECAUTIONS FOR USE IN WORKS:

Given the high clinker content of this cement and its high reactivity, it is very important to maximize the curing of the end product processes, especially in hot, dry and occasionally windy climates.

CIMENTS
MOLINS
INDUSTRIAL

SAT
TECHNICAL ATTENTION SERVICE
+34 93 680 60 30
sat@cmi.cemolins.es

AENOR
Empresa Registrada
ER-0093/1998
UNE-EN-ISO 9001

AENOR
Producto Certificado

Please contact us for further information.

ED.01/09

Appendix B

Admixtures technical data sheets

B.1 Superplasticizer - Glenium Sky 604

BASF
The Chemical Company

MasterGlenium SKY 604

Antes: GLENIUM SKY 604

Aditivo superplastificante / reductor de agua de alta actividad para hormigón preparado.

CAMPO DE APLICACIÓN

MasterGlenium SKY 604 es un aditivo superplastificante / reductor de agua de alta actividad basado en policarboxilatos para aplicaciones en hormigón preparado, donde se demande alta resistencia inicial. Su excelente poder plastificante y sus elevadas resistencias iniciales, incluso a dosificaciones bajas, hacen del MasterGlenium SKY 604 el aditivo ideal para la industria del hormigón preparado y obra civil.

Consultar con el Departamento Técnico cualquier aplicación no prevista en esta relación.

PROPIEDADES

- Excelente poder plastificante.
- Elevadas resistencias iniciales, incluso con bajas dosificaciones.
- Confección de hormigones de mayor docilidad.
- Mejora la durabilidad del hormigón y sus resistencias.
- Apto para la fabricación de HAC

MODO DE UTILIZACIÓN

MasterGlenium SKY 604 se adiciona al hormigón con la última parte del agua de amasado.

No adicionar el producto sobre la masa seca de cemento y áridos.

DOSIFICACIÓN

La dosificación habitual se encuentra entre el 0,3% y el 1,0% sobre peso de cemento según incremento de trabajabilidad y reducción de agua deseada.

Dosificaciones superiores son posibles con ensayos previos que permitan determinar la dosificación óptima.

LIMPIEZA DE HERRAMIENTAS

Los equipos y herramientas sucias de MasterGlenium SKY 604 pueden limpiarse simplemente con agua.

PRESENTACIÓN

MasterGlenium SKY 604 se presenta a granel, en contenedor de 1000 kg y en garrafas de 25 kg.

CONDICIONES DE ALMACENAMIENTO/ TIEMPO DE CONSERVACIÓN

Almacenar en sus envases originales herméticamente cerrados y protegidos de temperaturas extremas. Evitar su congelación.

Almacenado correctamente, MasterGlenium SKY 604 puede conservarse hasta 12 meses.

MANIPULACIÓN Y TRANSPORTE

Para su manipulación deberán observarse las medidas preventivas usuales para el manejo de productos químicos, por ejemplo usar gafas y guantes. Lavarse las manos antes de una pausa y al término del trabajo. No comer, beber y fumar durante la aplicación.

La eliminación del producto y su envase debe realizarse de acuerdo con la legislación vigente y es responsabilidad del poseedor final.

Para más información, consultar la Hoja de seguridad del producto.

MASTER®
» BUILDERS
SOLUTIONS

MasterGlenium SKY 604

Antes: GLENIUM SKY 604

Aditivo superplastificante / reductor de agua de alta actividad para hormigón preparado.

HAY QUE TENER EN CUENTA

Se recomienda la realización de ensayos previos a la utilización del producto.

No emplear dosificaciones inferiores ni superiores a las recomendadas sin previa consulta con nuestro Departamento Técnico.

Consulta la compatibilidad entre aditivos antes de su utilización.

Propiedades	
Función principal:	Reductor de agua de alta actividad / superplastificante.
Efecto secundario:	Riesgo de disgregación a dosis elevadas.
Aspecto físico:	Líquido amarillento turbio.
pH, 20º C	5,5 ± 1
Densidad, 20º C:	1,048 ± 0,02 g/cm^3
Viscosidad 20º C Brookfield Sp00/50rpm:	< 100 cps.
Contenido en cloruros:	< 0,1%
Los datos técnicos reflejados son fruto de resultados estadísticos y no representan mínimos garantizados. Si se desean los datos de control, pueden solicitarse las "Especificaciones de Venta" a nuestro Departamento Técnico.	

CE

MARCADO CE DE PRODUCTO BAJO LA DIRECTIVA UE DE PRODUCTOS DE LA CONSTRUCCIÓN DE LA UNIÓN EUROPEA

MasterGlenium SKY 604

Antes: GLENIUM SKY 604

Aditivo superplastificante / reductor de agua de alta actividad para hormigón preparado.

NOTA:

La presente ficha técnica sirve, al igual que todas las demás recomendaciones e información técnica, únicamente para la descripción de las características del producto, forma de empleo y sus aplicaciones. Los datos e informaciones reproducidos, se basan en nuestros conocimientos técnicos obtenidos en la bibliografía, en ensayos de laboratorio y en la práctica.

Los datos sobre consumo y dosificación que figuran en esta ficha técnica, se basan en nuestra propia experiencia, por lo que estos son susceptibles de variaciones debido a las diferentes condiciones de las obras. Los consumos y dosificaciones reales, deberán determinarse en la obra, mediante ensayos previos y son responsabilidad del cliente.

Para un asesoramiento adicional, nuestro Servicio Técnico, está a su disposición.

BASF Construction Chemicals España, S.L. se reserva el derecho de modificar la composición de los productos, siempre y cuando éstos continúen cumpliendo las características descritas en la ficha técnica.

Otras aplicaciones del producto que no se ajusten a las indicadas, no serán de nuestra responsabilidad.

Otorgamos garantía en caso de defectos en la calidad de fabricación de nuestros productos, quedando excluidas las reclamaciones adicionales, siendo de nuestra responsabilidad tan solo la de reingresar el valor de la mercancía suministrada.

Debe tenerse en cuenta las eventuales reservas correspondientes a patentes o derechos de terceros.

Edición: 01/02/2014

La presente ficha técnica pierde su validez con la aparición de una nueva edición

CONTACTO

BASF Construction Chemicals España, S.L.
Carretera del Mig, 219
08907 L'Hospitalet de Llobregat
Barcelona
Tel: 93 261 61 00
Fax:93 261 62 19
Basf-cc@basf-cc.es
www.master-builders-solutions.basf.es

B.2 Air Entrainer - Micro Air 100

M**ASTER**AIR 100

Aditivo incorporador de aire para hormigón.

Antes: Micro Air 100

USOS RECOMENDADOS

- ✓ Hormigón expuesto a ciclos hielo y deshielo.
- ✓ Producción de hormigón o mortero liviano.
- ✓ Hormigón arquitectónico.
- ✓ Hormigón bombeable.

DESCRIPCION

MasterAir 100 es un aditivo que incorpora en el hormigón burbujas de aire ultra estables, microscópicas y de poco espaciamiento, características especialmente útiles en hormigones con dificultad de ocluir y retener un contenido de aire deseado.

Master Air 100 es un aditivo líquido cuya concentración permite un uso fácil y preciso, produciendo hormigón de calidad uniforme.

VENTAJAS

- Aumenta durabilidad a ciclos hielo-deshielo.
- Mejora trabajabilidad y cohesión.
- Mejora calidad de la matriz de poros en el hormigón endurecido.
- Mejora capacidad de ocluir y retener aire en hormigones: de baja trabajabilidad; con alto contenido de adiciones y/o finos; con cementos de alto contenido de álcalis; sometidos a altas temperaturas; o con tiempos de mezclado extendidos.
- Reduce la permeabilidad.
- Mejora el aspecto superficial.
- Aumenta durabilidad a descamación por sales para deshielo.
- Reduce segregación y exudación, especialmente durante transporte y/o bombeo.

CARACTERÍSTICAS DE DESEMPEÑO

Investigaciones en durabilidad han demostrado que la mejor protección para el hormigón contra los efectos adversos de ciclos hielo-deshielo son: adecuado contenido de aire en matriz endurecida; adecuado sistema de poros en términos de tamaño y espaciamiento; y adecuada resistencia, asumiendo el uso de buenos agregados y técnicas apropiadas de fabricación, transporte, colocación, manejo y curado.

APLICACIÓN

Dosificación

MasterAir 100 no posee un rango estándar de dosis. La dosis de MasterAir 100 para obtener un determinado contenido de aire variará en función de las materias primas, diseño de mezcla, condiciones de producción y colocación. Factores típicos que influyen en la cantidad de aire incorporado son: temperatura ambiente y de la mezcla, dosis y tipo de material cementicio, tipo y granulometría del árido fino, razón árido fino/grueso, relación w/c, trabajabilidad inicial, métodos de producción, transporte, colocación y terminación.

La dosis de MasterAir 100 dependerá de la cantidad de aire a incorporar bajo las condiciones de obra. En mezclas de prueba comience con una dosis de 25 a 100 cc por cada 100 kg de material cementicio. En mezclas que contienen reductores de agua o controladores de fraguado la dosis será algo menor que en mezclas sin estos aditivos.

Debido a los diversos factores que afectan el contenido de aire incorporado -y por tanto la dosis de MasterAir 100- el contenido de aire debe ser determinado sistemáticamente durante toda la obra.

Estas verificaciones permitirán ajustar la dosis de MasterAir 100 para obtener un contenido de aire en el rango de diseño en el punto de descarga.

BASF
The Chemical Company

MasterAir 100

Aditivo incorporador de aire para hormigón.

Incorporación y mezclado

MasterAir 100 puede ser adicionado a la mezcla utilizando dosificadores especializados, o bien manualmente usando un dispositivo de medición que asegure una precisión ±3% de la cantidad requerida (volumen o peso).

Resultados óptimos se obtienen usualmente adicionando MasterAir 100 junto al agua de amasado. Sin embargo el procedimiento de carguío puede variar según equipos y condiciones de obra de forma de obtener resultados consistentes.

DATOS TÉCNICOS

Peso específico

1,020 ± 0,005 a 20° C.

RECOMENDACIONES

Corrosividad

MasterAir 100 no es corrosivo y no inicia o promueve la corrosión del acero de refuerzo. MasterAir 100 no posee en su composición cloruro de calcio u otros compuestos basados en cloruros.

Compatibilidad

MasterAir 100 es compatible con la mayoría de los aditivos BASF para hormigones y morteros. Para mayores consultas contacte a su asesor técnico.

Almacenamiento

MasterAir 100debe almacenarse a temperatura superior a 2°C, evitando su congelación y contaminación.

Vida útil

Almacenado en condiciones óptimas MasterAir 100 posee una vida útil mínima de 18 meses.

Manipulación

MasterAir 100 debe ser manipulado usando elementos de protección personal para productos químicos no peligrosos (lentes de seguridad y guantes). Para mayor información consulte la Hoja de Seguridad del producto.

Empaque

MasterAir se suministra en tineta de 20 kg y tambor de 200 kg.

MASTER®
BUILDERS
SOLUTIONS

The Chemical Company

NOTA:

La presente ficha técnica sirve, al igual que todas las demás recomendaciones e información técnica, únicamente para la descripción de las características del producto, forma de empleo y sus aplicaciones. Los datos e informaciones reproducidos, se basan en nuestros conocimientos técnicos obtenidos en la bibliografía, en ensayos de laboratorio y en la práctica.

Los datos sobre consumo y dosificación que figuran en esta ficha técnica, se basan en nuestra propia experiencia, por lo que estos son susceptibles de variaciones debido a las diferentes condiciones de las obras. Los consumos y dosificaciones reales, deberán determinarse en la obra, mediante ensayos previos y son responsabilidad del cliente.

Para un asesoramiento adicional, nuestro Servicio Técnico, está a su disposición.

BASF Construction Chemicals Ltda. se reserva el derecho de modificar la composición de los productos, siempre y cuando éstos continúen cumpliendo las características descritas en la ficha técnica.

Otras aplicaciones del producto que no se ajusten a las indicadas, no serán de nuestra responsabilidad.

Otorgamos garantía en caso de defectos en la calidad de fabricación de nuestros productos, quedando excluidas las reclamaciones adicionales, siendo de nuestra responsabilidad tan solo la de reingresar el valor de la mercancía suministrada.

Debe tenerse en cuenta las eventuales reservas correspondientes a patentes o derechos de terceros.

Edición: 26/02/2014

La presente ficha técnica pierde su validez con la aparición de una nueva edición

BASF SA
Avenida das Nações Unidas,
14.171, Morumbi
04794-000 Sao Paulo – SP, Brasil
Tel: +55 11 2718 5507
www.basf-cc.com.br

BASF Construction Chemicals Ltda.
Rio Palena 9665
Núcleo Empresarial ENEA
Santiago de Chile, Chile
Tel: +56-2 2799 4300
www.basf-cc.cl

BASF Construction Chemicals Perú S.A.
Jr. Plácido Jiménez N° 630
Lima 1.Peru
Tel: +51-1 219 0630

www.basf-cc.com.pe

BASF Química Colombia S.A.
Tel: +57 1 632 20 90
www.basf-cc.com.co

BASF Venezolana S.A.
Tel : + 58 212 9586711
www.basf-cc.com.ve

BASF Ecuatoriana S.A.
Tel : + 593 2397 9500
www.basf-cc.com.ec

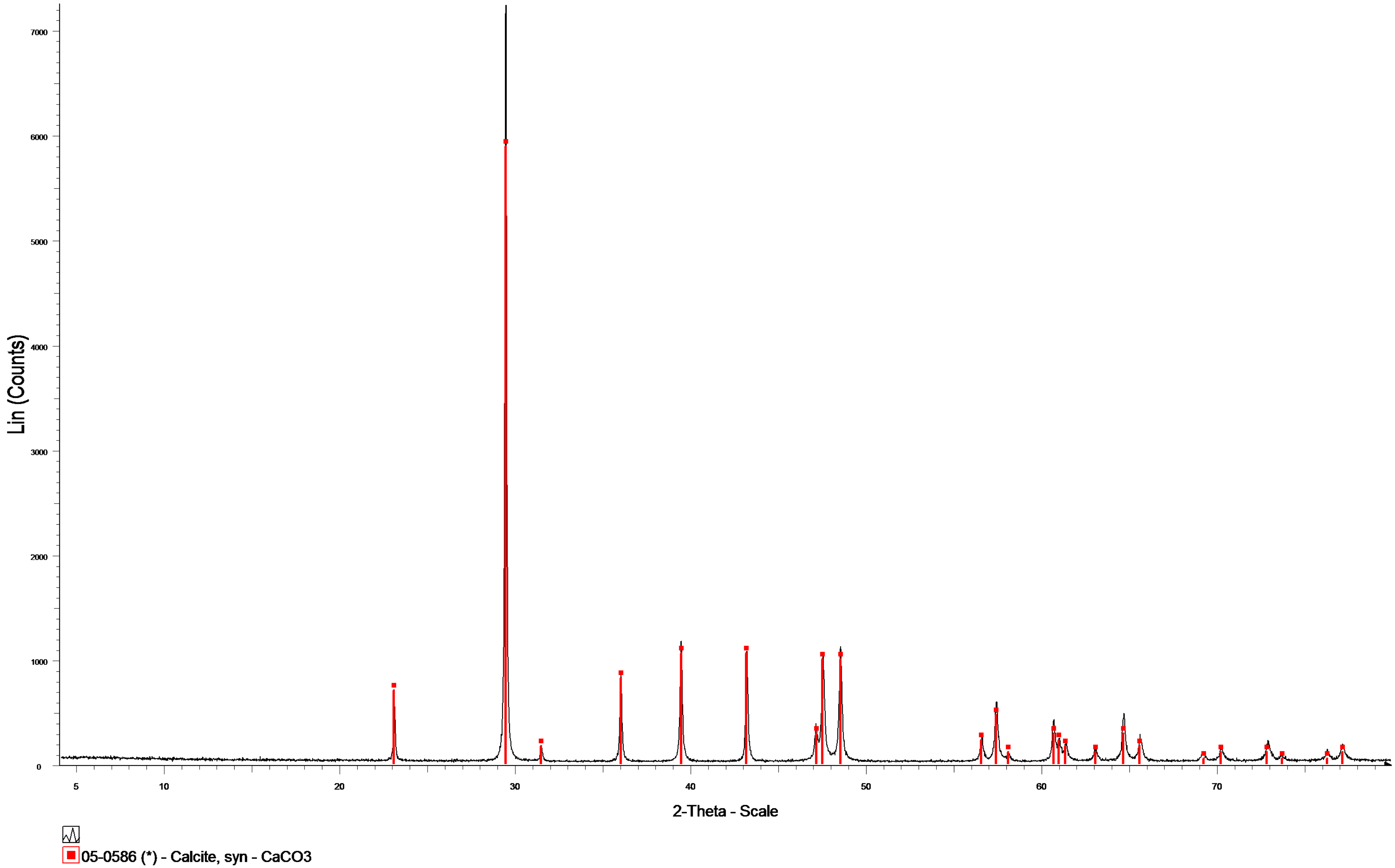
Para obtener más información: Visítenos: www.basf-cc.cl

Appendix C

Aggregates diffractograms

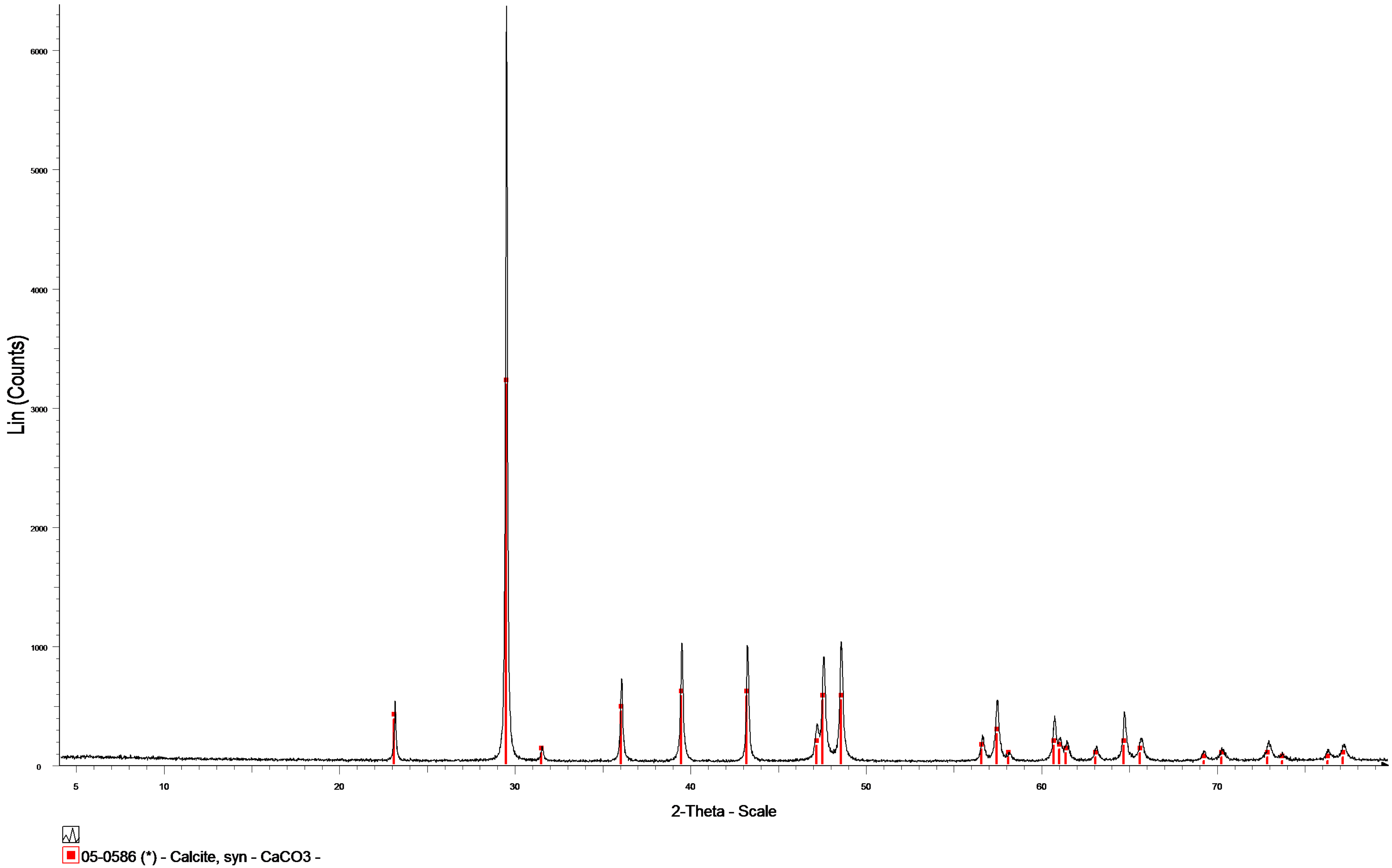
C.1 Natural Sand

Natural sand



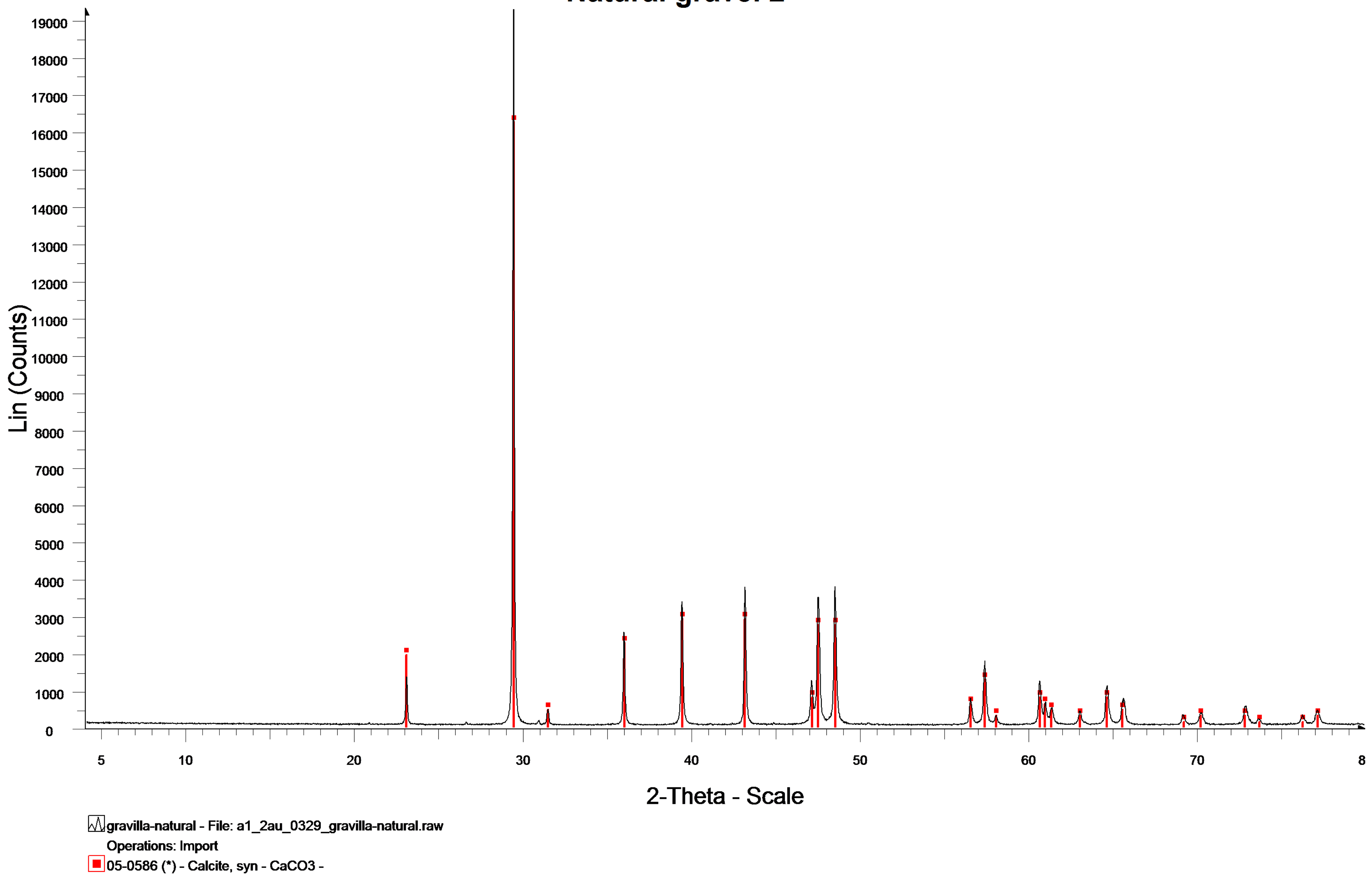
C.2 Natural Gravel 1

Natural gravel 1

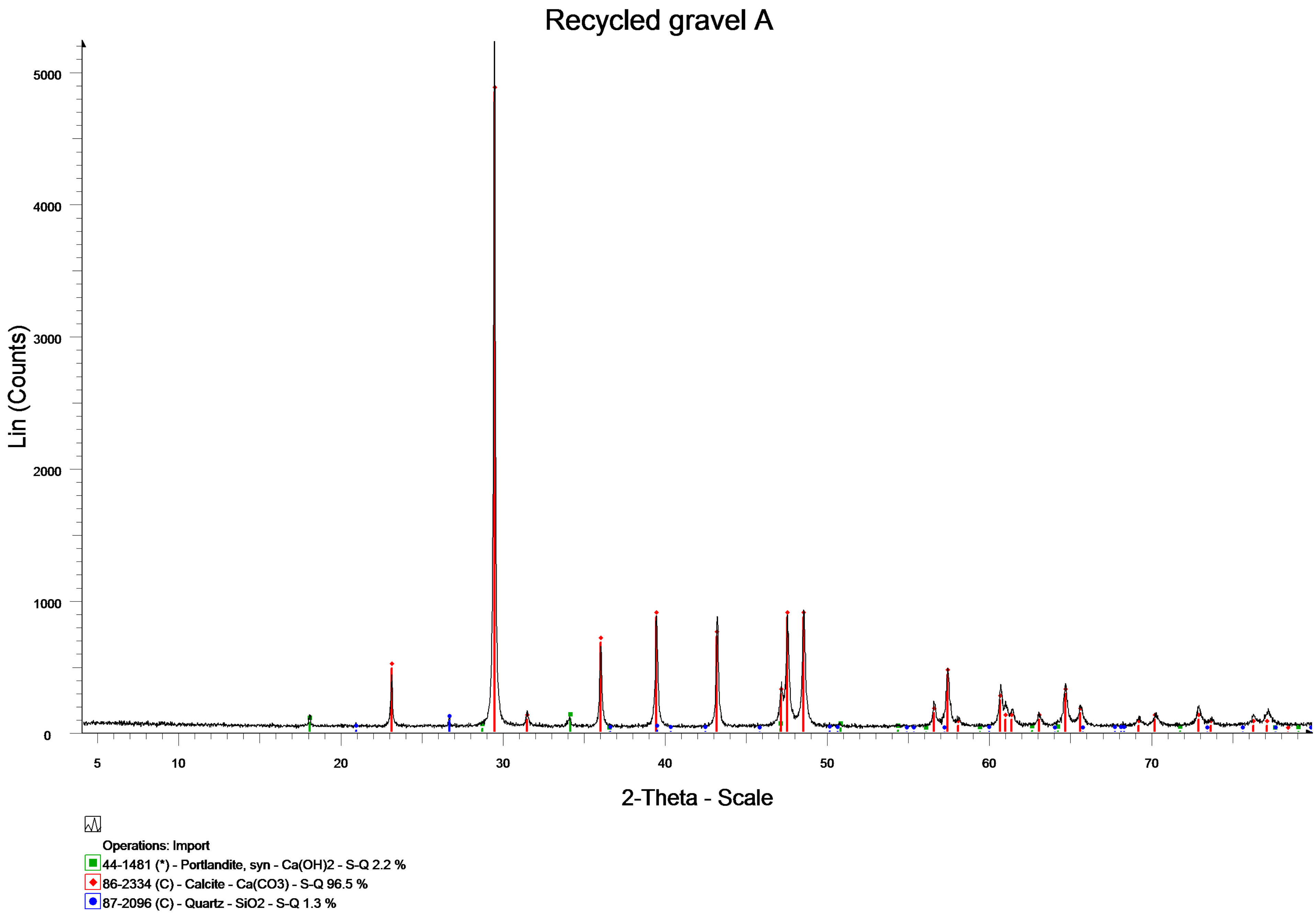


C.3 Natural Gravel 2

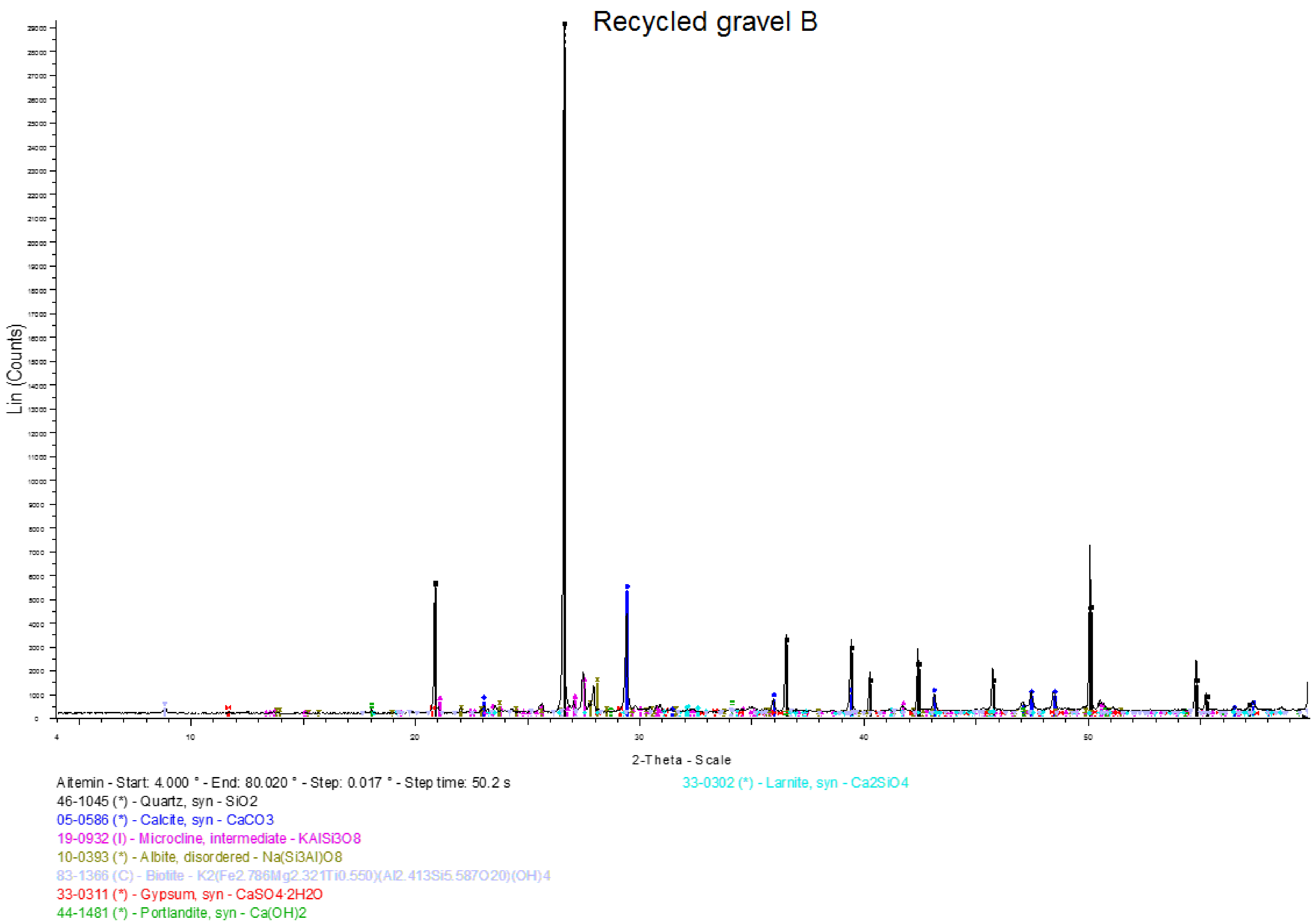
Natural gravel 2



C.4 Recycled Gravel A

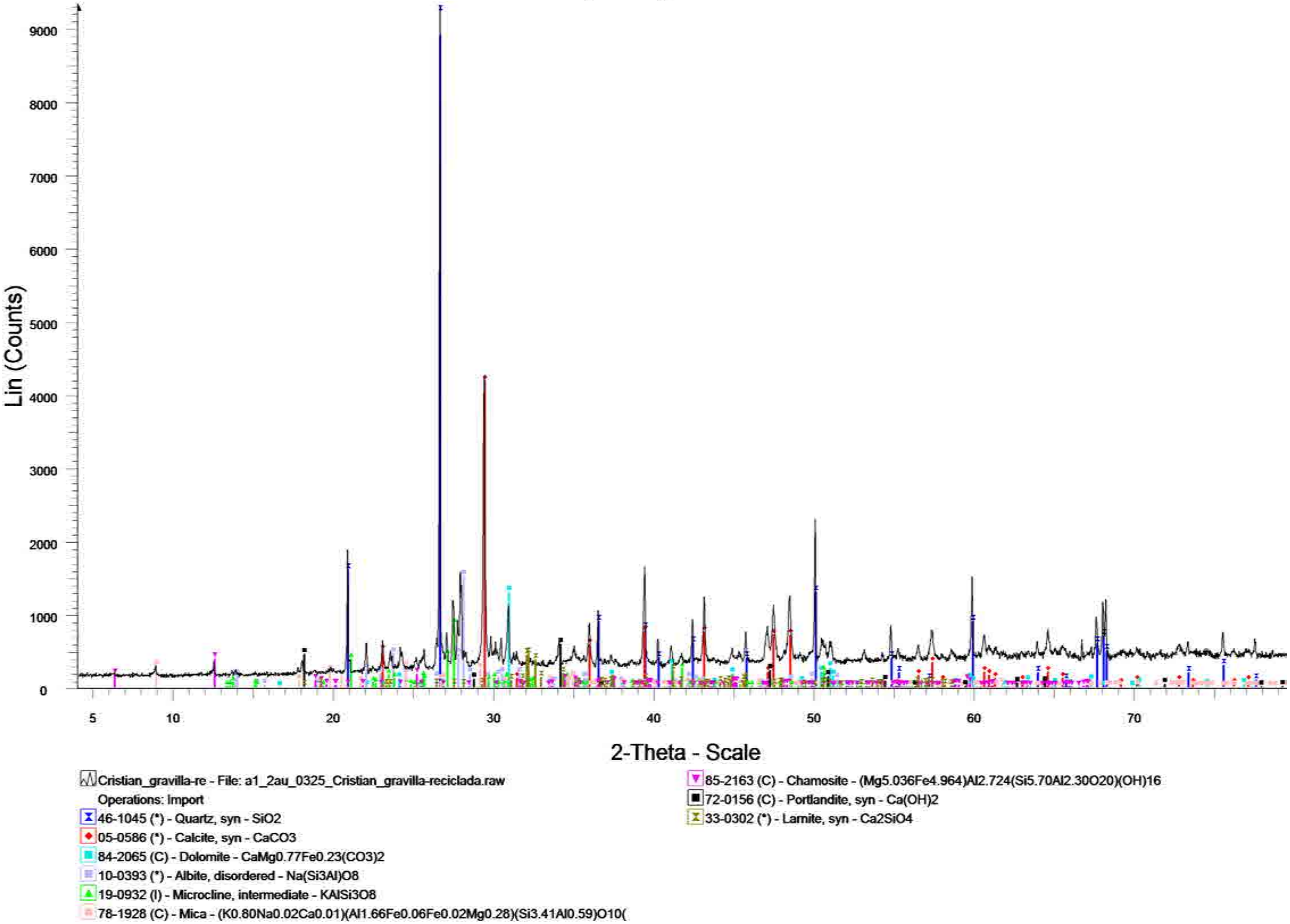

Recycled gravel A
Lin (Counts)
5000
4000
3000
2000
1000
0
5
10
20
30
40
50
60
70
2-Theta - Scale
Operations: Import
44-1481 (*) - Portlandite, syn - Ca(OH)2 - S-Q 2.2 %
86-2334 (C) - Calcite - Ca(CO3) - S-Q 96.5 %
87-2096 (C) - Quartz - SiO2 - S-Q 1.3 %

C.5 Recycled Gravel B

Recycled gravel B
Lin (Counts)
29000
28000
27000
26000
25000
24000
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
4
10
20
30
40
50
2-Theta - Scale
Aitemin - Start: 4.000 ° - End: 80.020 ° - Step: 0.017 ° - Step time: 50.2 s
46-1045 (*) - Quartz, syn - SiO2
05-0586 (*) - Calcite, syn - CaCO3
19-0932 (I) - Microcline, intermediate - KAlSi3O8
10-0393 (*) - Albite, disordered - Na(Si3Al)O8
83-1366 (C) - Biotite - K2(Fe2.786Mg2.321Ti0.550)(Al2.413Si5.587O20)(OH)4
33-0311 (*) - Gypsum, syn - CaSO4·2H2O
44-1481 (*) - Portlandite, syn - Ca(OH)2
33-0302 (*) - Larnite, syn - Ca2SiO4

C.6 Recycled Gravel C

Recycled gravel C



Appendix D

Admixtures environmental declarations

D.1 Superplasticizer

European
Federation of
Concrete Admixture
Associations

EFCA ENVIRONMENTAL DECLARATION
SUPERPLASTICISING ADMIXTURES – March 2006.

SUPERPLASTICISERS

Admixtures are an important component of concrete, together with the cement, water, aggregates and, where applicable, reinforcing steel. Superplasticisers currently make up about 38% of all admixtures sold in Europe. Normal plasticisers account for a further 40% and are the subject of a separate EFCA Declaration Sheet.
EFCA Declaration Sheets also exist for Waterproofing admixtures, Accelerators, Retarders and Air entraining admixtures.

Superplasticisers, also known as High Range Water Reducing admixtures, are synthetic, water-soluble organic chemicals that significantly reduce the amount of water needed to achieve a given consistence in fresh concrete. This effect can be utilised in two ways:

- To reduce water content for increased strength and reduced permeability / improved durability

- As a cement dispersant at the same water content to increase consistence and workability retention

With a slightly higher admixture dosage, both these effects can be achieved in the same mix.

This Eco-profile is only valid for superplasticisers and is representative for all four main groups of superplasticisers used in concrete:

- Sulphonated naphthalene formaldehyde
- Sulphonated melamine formaldehyde
- Vinyl copolymers
- Poly carboxylic ethers.

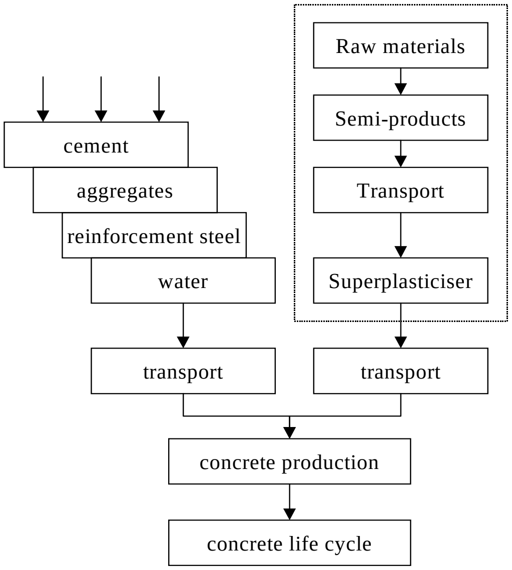
These may be factory blended with each other or with ‘normal plasticisers’ to give superplasticisers with carefully targeted properties.
The superplasticisers are dissolved in water and typically contain 30-45% active matter.

SCOPE OF THE ECO-PROFILE

The Eco-profile covers cradle-to-gate production of superplasticisers in Europe. Transport of superplasticisers from fabricator to customer is not included.
Members of EFCA, the European Federation of Concrete Admixtures Associations collected manufacturing data for synthesis and blending of superplasticisers in 2000-2001. This environmental declaration is based on the figures from 8 of Europe’s largest admixture producers and is an average of the superplasticiser types detailed above. The variation between these types and between manufacturers is relatively small in LCA’s of concrete, but the figures should not be taken as absolute values for that manufacturer or a superplasticiser type.

ENVIRONMENTAL IMPACT

The figure below reveals how the Eco-profile for superplasticisers fits in a concrete life cycle. This Eco-profile includes processes shown within the dotted line. To complete the life cycle, environmental data from other materials and processes should be added.



ECO-PROFILE SUPERPLASTICISERS

Eco-profile for 1 kg superplasticisers, 30-45% solids

Raw materials - input	*Unit*	*Value*
coal, brown	g	82
coal, hard	g	51
crude oil	kg	0.16
natural gas	m3	0.22
Emissions to air		
CO$_2$	kg	0.72
CO	g	0.55
NO$_x$	g	1.8
SO$_x$	g	3.6
N$_2$O	mg	67
Methane	g	1.2
Butane	mg	11
Pentane	mg	14
Methanol	mg	60
Ethene	mg	8.9
Benzene	mg	7.4
Non-methane VOC	g	0.29
PAH	µg	39
Acetic acid	mg	63
Ammonia	g	2.1
Arsenic (As)	µg	58
Chromium VI (Cr)	µg	16
Mercury (Hg)	µg	94
Nickel (Ni)	mg	0.46
Vanadium (V)	mg	1.2
Dioxins	ng	43
CFC-10	µg	2.0
CFC-114	µg	1.8
Halon-1211	µg	4.1
Halon-1301	µg	5.0
Emissions to water		
Chemical Oxygen Demand	g	2.6
PAH's	µg	67
Oils, unspecified	g	0.63
Barite	mg	51
Nickel (Ni)	mg	3.9
Emissions to soil		
Chromium VI (Cr)	mg	0.22
Oils, unspecified	g	0.66

The membership of EFCA, the European Federation of Concrete Admixture Associations, EFCA, currently consists of the following national associations:

Belgium	**FIPAH**	**Norway**	**NCCA**
France	**SYNAD**	**Spain**	**ANFAH**
Germany	**DB**	**Sweden**	**SACA**
Italy	**ASSIAD**	**Switzerland**	**FSHBZ**
Netherlands	**VHB**	**United Kingdom**	**CAA**

Indicators for 1 kg superplasticisers, 30-45% solids

Solid waste	*Unit*	*Value*
Non-hazardous waste	g	21
Hazardous waste	g	0.45
Total energy		
Total energy	MJ	18.3

ACCOUNTABLES

The Eco-profile is derived from primary data supplied by EFCA and its member organisations.

An independent consultancy from The Netherlands, INTRON, verified the primary data and computed the Eco-profile.

Additional information for LCA practitioners:

- The Eco-profile on this sheet is valid for admixtures in a range of solids percentages. Even though this percentage may vary substantially it is not a major contributor to the total Eco-profiles and individual admixtures will all be within an acceptable range. The average profile should therefore not be related to the solids percentage of an individual admixture.
- The data collection has been carried out according to ISO 14040 series on Life Cycle Assessment.
- INTRON used literature data on raw material production primarily based upon the Eco-Invent (v1.2) database. Close proximity substitution has been applied.
- Eco-Invent data contain capital goods.
- LCI data for electricity production are based on the European fuel mix.
- Substances that contribute more than 1% to the environmental impact on any of the following environmental categories have been included in the Eco-profile: ADP, GWP, ODP, HTP, TETP, FAETP, POCP, AP and EP.
- The substances in the Eco-profile typically amount to at least 90-95% of the environmental impact in any category.

Environmental Consultant
INTRON B.V.
Dr Nolenslaan 126, 6136 GV Sittard
Postbus 5187, The Netherlands

For more information please contact:
The EFCA secretary
tel. +44 (0) 1564 77 63 62
fax +44 (0) 1564 77 63 62
www.efca.info or www.admixtures.org.uk

D.2 Air Entrainer

European
Federation of
Concrete Admixture
Associations

EFCA ENVIRONMENTAL DECLARATION
AIR ENTRAINING ADMIXTURES – DECEMBER 2005.

AIR ENTRAINING ADMIXTURES

Admixtures are an important component of concrete, together with the cement, water, aggregates and, where applicable, reinforcing steel.

Air entraining admixtures currently make up about 5% of all admixtures sold in Europe.
Air entrainers are based on solutions and blends of abietic acid, natural resins and rosins, synthetic anionic or non-ionic surfactants.
Air entrainers are used to develop a large number of small air bubbles in concrete which are homogeneous and stable after the mixing process. The incorporated air bubbles affect the properties of both the fresh and the hardened concrete. In the fresh state cohesion is increased and the air can significantly reduce any tendency for the mix to bleed. The "ball bearing effect" of the air bubbles lubricates the mix, increasing the workability especially in low cement content or in dry mixes. In the hardened state the remaining air bubbles interrupt the porous system of the concrete, reducing the capillary suction (water adsorption). The bubbles also act as an expansion area for freezing water in the pore system leading to increased freeze-thaw resistance.

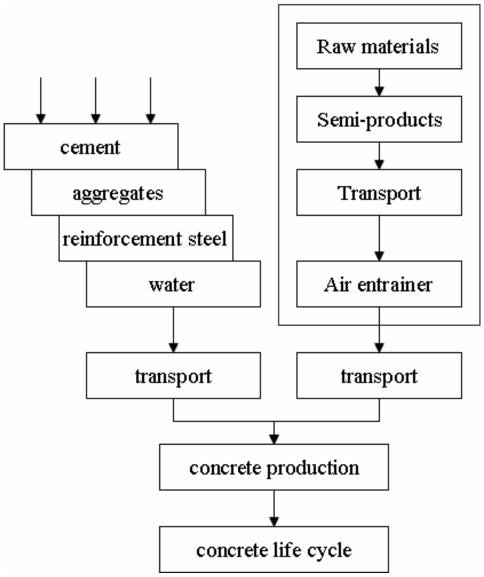
This Eco-profile is valid for air entraining admixtures based on anionic and non-ionic synthetic surfactants, alkyl ether sulphates, sulfonic acid and abietic acid,.
These chemicals may be factory blended together and/or with other chemicals to give carefully targeted properties.
The air entrainers are dissolved in water and typically contain 3-12% active matter.

SCOPE OF THE ECO-PROFILE

The Eco-profile covers cradle-to-gate production of air entrainers in Europe. Transport of air entrainers from manufacturer to customer is not included.
Members of EFCA, the European Federation of Concrete Admixtures Associations collected manufacturing data for synthesis and blending of air entrainers in 2005. This environmental declaration is based on the figures from four of Europe's largest admixture producers and is an average of the air entrainer types described. The variation between these types and between manufacturers leads to relatively small differences in LCA's of concrete, however the figures should not be taken as absolute values for any one manufacturer or air entrainer type.

ENVIRONMENTAL IMPACT

The figure below reveals how the Eco-profile for air entrainers fits in a concrete life cycle. This Eco-profile includes processes shown within the dotted line. To complete the life cycle, environmental data from other materials and processes should be added.



ECO-PROFILE AIR ENTRAINERS

Eco-profile for 1 kg air entrainers, 3-14% solids

Raw materials - input	*Unit*	*Value*
coal, brown	g	8.7
coal, hard	g	6.7
crude oil	g	11
natural gas	dm3	26
Emissions to air		
CO_2	g	86
CO	g	0.11
N_2O	mg	8.6
NO_x	g	0.35
SO_x	g	0.32
Butane	mg	0.92
Ethane	mg	3.9
Ethene	mg	0.36
Hexane	mg	1.4
Methane	g	0.62
Pentane	mg	1.2
Propane	mg	1.5
Benzene	mg	1.1
PAH	µg	9.1
Ammonia	mg	6.4
Dioxins	µg	0.0072
Arsenic (As)	µg	8.6
Chromium VI (Cr)	µg	3.3
Mercury (Hg)	µg	19
Nickel (Ni)	µg	46
Vanadium (V)	µg	94
CFC-10	µg	0.66
Halon-1211	µg	0.78
Halon-1301	µg	0.29
Emissions to water		
Chemical Oxygen Demand	g	0.59
Oils, unspecified	mg	59
Nitrogen	mg	25
Nitrate	g	0.24
Phosphate	mg	29
Barite	mg	4.2
Copper (Cu)	mg	0.71
Nickel (Ni)	mg	0.74
Vanadium (V)	mg	0.14
PAH’s	µg	5.8

Indicators for 1 kg air entrainers, 3-14% solids

Emissions to soil	*Unit*	*Value*
Chromium VI (Cr)	µg	17
Mercury (Hg)	µg	0.15
Oils, unspecified	mg	37
Metolachlor	mg	1.2
Solid waste		
Non-hazardous waste	g	0.29
Hazardous waste	mg	59
Total energy		
Total energy	MJ	2.1

ACCOUNTABLES

The Eco-profile is derived from primary data supplied by EFCA and its member organisations.

An independent consultancy from The Netherlands, INTRON, verified primary data and computed the Eco-profile.

Additional information for LCA practitioners:

- The Eco-profile on this sheet is valid for admixtures in a range of solids percentages. Even though this percentage may vary substantially it is not a major contributor to the total Eco-profiles and individual admixtures will all be within an acceptable range. The average profile should therefore not be related to the solids percentage of an individual admixture.
- INTRON used literature data on raw material production primarily based upon the Eco-Invent (v1.2) database. Close proximity substitution has been applied.
- Eco-Invent data contain capital goods.
- LCI data for electricity production are based on the European fuel mix.
- Substances that contribute more than 1% to the environmental impact on any of the following environmental categories have been included in the Eco-profile: ADP, GWP, ODP, HTP, TETP, FAETP, POCP, AP and EP.
- The substances in the Eco-profile typically amount to at least 90-95% of the environmental impact in any category.

The membership of EFCA, the European Federation of Concrete Admixture Associations, currently consists of the following national associations:

Belgium	**FIPAH**		
France	**SYNAD**	**Norway**	**NCCA**
Germany	**DB**	**Spain**	**ANFAH**
Italy	**ASSIAD**	**Sweden**	**SACA**
Netherlands	**VHB**	**Switzerland**	**FSHBZ**
United Kingdom	**CAA**		

Environmental Consultant
INTRON B.V.
Dr Nolenslaan 126, 6136 GV Sittard
Postbus 5187, The Netherlands

For more information please contact:
The EFCA secretary
tel. +44 (0) 1564 77 63 62
fax +44 (0) 1564 77 63 62
www.efca.info or www.admixtures.org.uk

Bibliography

Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91). Technical report, American Concrete Institute, 2002.

T. C. 37-DRC. *Recycling of Demolished Concrete and Masonry*. Spon Press, 1992. ISBN 0203626451.

A. Abbas, G. Fathifazl, O. Isgor, A. Razaqpur, B. Fournier, and S. Foo. Proposed method for determining the residual mortar content of recycled concrete aggregates. *Journal of ASTM International*, 5(1), 2007.

A. Abbas, G. Fathifazl, B. Fournier, O. B. Isgor, R. Zavadil, A. G. Razaqpur, and S. Foo. Quantification of the residual mortar content in recycled concrete aggregates by image analysis. *Materials Characterization*, 60(7):716–728, 2009a. ISSN 1044-5803. doi: 10.1016/j.matchar.2009.01.010. URL `http://www.sciencedirect.com/science/article/pii/S1044580309000254`.

A. Abbas, G. Fathifazl, O. B. Isgor, A. G. Razaqpur, B. Fournier, and S. Foo. Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Sustainability of Civil Engineering Structures - Durability of Concrete*, 31(8):555–563, 2009b. ISSN 0958-9465. doi: 10.1016/j.cemconcomp.2009.02.012. URL `http://www.sciencedirect.com/science/article/pii/S0958946509000304`.

ACI Committee 555. Removal and Reuse of Hardened Concrete - ACI 555-01. Technical report, American Concrete Institute, Detroit, 2001.

AEN/CTN 83 - Concrete committee. UNE 83316 - Concrete tests. Determination of the modulus of elasticity in compression, 1996.

Agència de Residus de Catalunya. Construction Waste report 2010. Technical report, Barcelona, 2010. URL `http://residus.gencat.cat/es/consultes_i_tramits_-_nou/estadistiques/estadistiques_de_runes/`.

American Concrete Institute Committee E-701. ACI Education Bulletin E4-12 Chemical Admixtures for Concrete. Technical report, American Concrete Institute, 2013.

Asociación Española de Gestores de Residuos de Construcción y Demolición (GERD). Guía Española de Áridos Reciclados procedentes de RCD. Technical report, Madrid, 2012.

Asociación Española de Normalización y Certificación. UNE 83966. Concrete durability. Test methods. Conditioning of concrete test pieces for the purpose of gas permeability and capilar suction tests., 2008a.

Asociación Española de Normalización y Certificación. UNE 83982. Concrete durability. Test methods. Determination of the capillar suction in hardened concrete. Fagerlund method., 2008b.

ASTM International. C 29. Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate, 2003.

P. F. G. Banfill. RHEOLOGY OF FRESH CEMENT AND CONCRETE. In *Rheology Reviews*, volume 2006, pages 61–130. 2006.

M. Barra. *Estudio de la durabilidad del hormigón reciclado en su aplicación como hormigón armado*. PhD thesis, Polytechnical University of Catalonia, 1996.

M. G. Beltrán, A. Barbudo, F. Agrela, A. P. Galvín, and J. R. Jiménez. Effect of cement addition on the properties of recycled concretes to reach control concretes strengths. *Journal of Cleaner Production*, 79:124–133, May 2014. ISSN 09596526. doi: 10.1016/j.jclepro.2014.05.053. URL `http://linkinghub.elsevier.com/retrieve/pii/S0959652614005307`.

A. Benazzouk, O. Douzane, and M. Quéneudec. Transport of fluids in cement rubber composites. *Cement and Concrete Composites*, 26(1):21–29, Jan. 2004. ISSN 09589465.

doi: 10.1016/S0958-9465(02)00119-1. URL `http://linkinghub.elsevier.com/retrieve/pii/S0958946502001191`.

M. L. Berndt. Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction and Building Materials*, 23(7):2606–2613, 2009. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2009.02.011. URL `http://www.sciencedirect.com/science/article/pii/S0950061809000415`.

CEMBUREAU. Activity report 2013. Technical report, 2013.

Cement Admixtures Association. Admixture Sheet. ATS 5 Concrete Air entraining admixtures. Technical report, Cement Admixtures Association, West Midlands.

Cement Concrete & Aggregates Australia. Chloride Resistance of Concrete. Technical Report June, 2009.

CEN/TC 51. EN 197-1:2011. Cement - Part 1: Composition, specifications and conformity criteria, 2011.

C. Y. Chang, R. Huang, P. C. Lee, and T. L. Weng. Application of a weighted Grey-Taguchi method for optimizing recycled aggregate concrete mixtures. *Cement and Concrete Composites*, 33(10):1038–1049, 2011. ISSN 0958-9465. doi: 10.1016/j.cemconcomp.2011.06.005. URL `http://www.sciencedirect.com/science/article/pii/S0958946511001077`.

W. Chen, J. Hong, and C. Xu. Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. *Journal of Cleaner Production*, pages 1–9, Apr. 2014. ISSN 09596526. doi: 10.1016/j.jclepro.2014.04.048. URL `http://linkinghub.elsevier.com/retrieve/pii/S095965261400403X`.

M. Collepardi, S. Collepardi, and R. Troli. *Concrete Mix Design*. ENCO s.r.l., 2007.

V. Corinaldesi. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Construction and Building Materials*, 24(9):1616–1620, Sept. 2010. ISSN 09500618. doi: 10.1016/j.conbuildmat.2010.02.031. URL `http://linkinghub.elsevier.com/retrieve/pii/S0950061810000747`.

K. W. Day. *Concrete Mix Design, Quality Control and Specification*. Taylor & Francis Group, 2006. ISBN 0419243305.

M. S. de Juan and P. A. Gutiérrez. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials*, 23(2):872–877, 2009. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2008.04.012. URL `http://www.sciencedirect.com/science/article/pii/S0950061808001086`.

L. Du and K. J. Folliard. Mechanisms of air entrainment in concrete. *Cement and Concrete Research*, 35(8):1463–1471, Aug. 2005. ISSN 00088846. doi: 10.1016/j.cemconres.2004.07.026. URL `http://linkinghub.elsevier.com/retrieve/pii/S0008884604003369`.

Environmental Protection Agency (EPA). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. Technical report, Environmental Protection Agency, Washington DC, 2011.

Environmental Protection Agency (EPA). Ozone Layer Protection Glossary, 2014. URL `www.epa.gov/ozone/defns.html`.

S. T. Erdogan, N. S. Martys, C. F. Ferraris, and D. W. Fowler. Influence of the shape and roughness of inclusions on the rheological properties of a cementitious suspension. *Cement and Concrete Composites*, 30(5):393–402, 2008. ISSN 09589465. doi: 10.1016/j.cemconcomp.2008.01.003. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-41149126369&partnerID=40&md5=7a0345e4a0f87413016b55840bdbba0b`.

Essroc Italcementi Group. C - 11: Air-Entrainment: Benefits & Pitfalls. Technical report, Italcementi Group.

M. Etxeberria, E. Vázquez, A. Marí, and M. Barra. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37(5):735–742, 2007. ISSN 0008-8846. doi:

10.1016/j.cemconres.2007.02.002. URL `http://www.sciencedirect.com/science/article/pii/S0008884607000415`.

European Committee for Standarization. EN 933-1:1997. Test for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method., 1997a.

European Committee for Standarization. EN 932-1. Test for general properties of aggregates. Part 1: Methods for sampling., 1997b.

European Committee for Standarization. EN 932-2. Test for general properties of aggregates. Part 2. Methods for reducing laboratory samples., 1999.

European Committee for Standarization. EN 12390-8. Testing hardened concrete. Part 8: Depth of penetration of water under pressure. 2000a.

European Committee for Standarization. EN 206-1. Concrete - Part 1: Specification, performance, production and conformity, 2000b.

European Committee for Standarization. Testing fresh concrete - Part 2: Slump-test, 2009a.

European Committee for Standarization. EN 933-11. Test for geometrical properties of aggregates. Part 11: Classification test for the constituents of coarse recycled aggregate, 2009b.

European Committee for Standarization. EN 1744-1. Test for chemical properties of aggregates. Part 1: Chemical analysis, 2009c.

European Committee for Standarization. Testing hardened concrete - Part 3: Compressive strenght of test specimens, 2009d.

European Committee for Standarization. Testing fresh concrete - Part 7: Air content - Pressure methods, 2010.

European Committee for Standarization. EN 15804. Sustainability of construction works-Environmental product declarations-Core rules for the product category of construction products, 2012.

European Committee for Standarization. Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption, 2013.

European Committee for Standarization. European Committee for Standarization, 2015. URL `http://www.cen.eu/work/areas/construction/Pages/default.aspx`.

European Federation of Concrete Admixture Associations. Declaration-Air Entraining Admixtures. Technical report, EFCA, 2005.

European Federation of Concrete Admixture Associations. Declaration-Superplasticising Admixtures. Technical report, EFCA, 2006.

European Topic Centre on Resource and Waste Management. EU as a Recycling Society. Technical Report April, Copenhagen, 2009.

L. Evangelista and J. de Brito. Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 29(5):397–401, 2007. ISSN 0958-9465. doi: 10.1016/j.cemconcomp.2006.12.004. URL `http://www.sciencedirect.com/science/article/pii/S0958946507000030`.

F. Faleschini, C. Jiménez, M. Barra, D. Aponte, E. Vázquez, and C. Pellegrino. Rheology of fresh concretes with recycled aggregates. *Construction and Building Materials*, 73: 407–416, Dec. 2014. ISSN 09500618. doi: 10.1016/j.conbuildmat.2014.09.068. URL `http://linkinghub.elsevier.com/retrieve/pii/S0950061814010848`.

F. Faroug, J. Szwabowski, and S. Wild. INFLUENCE OF SUPERPLASTICIZERS ON WORKABILITY OF CONCRETE. *Journal of Materials in Civil Engineering*, 11(May): 151–157, 1999.

G. Fathifazl, A. Abbas, A. G. Razaqpur, O. B. Isgor, B. Fournier, and S. Foo. New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *American Society of Civil Engineers*, (October), 2009.

M. Fernández Cánovas. *Hormigón*. Garceta, Madrid, 10th edition, 2013. ISBN 978-84-1545-250-8.

C. Ferraris, F. D. Larrard, N. Martys, S. Mindess, J. Skalny, and A. C. Society. Fresh Concrete Rheology : Recent Developments. Technical report, 2001.

C. F. Ferraris and F. de Larrard. Testing and Modelling of Fresh Concrete Rheology. Technical report, National Institute of Standards and Technology, Gaithersburg, 1998.

D. Feys, J. E. Wallevik, A. Yahia, K. H. Khayat, and O. H. Wallevik. Extension of the Reiner Riwlin equation to determine modified Bingham parameters measured in coaxial cylinders rheometers. *Materials and Structures*, 46(1-2):289–311, July 2012. ISSN 1359-5997. doi: 10.1617/s11527-012-9902-6. URL `http://www.springerlink.com/index/10.1617/s11527-012-9902-6`.

R. J. Flatt. Towards a prediction of superplasticized concrete rheology. *Materials and Structures/Materiaux et Constructions*, 37(June):289–300, 2004.

M. V. A. Florea and H. J. H. Brouwers. Properties of various size fractions of crushed concrete related to process conditions and re-use. *Cement and Concrete Research*, 52(0):11–21, 2013. ISSN 0008-8846. doi: http://dx.doi.org/10.1016/j.cemconres.2013.05.005. URL `http://www.sciencedirect.com/science/article/pii/S000888461300118X`.

J. Frederiksen, H. Sorensen, A. Andersen, and O. Klinghoffer. *HETEK, The effect of the w/c ratio on chloride transport into concrete - Immersion, migration and resistivity tests*. Road Directorate - Ministry of Transport, 1997. ISBN 87 7492 735 8.

X. Gabarrell, A. Josa, and J. Rieradevall. Life cycle assessment of granite application in sidewalks. *International Journal of Life Cycle Assessment Volume pp*, 17 SRC -:580–592, 2012.

N. Gautam, V. Krishna, and A. Srivastava. Sustainability in the Concrete Construction. *International Journal of Environmental Research and Development pp*, 4(1 SRC - GoogleScholar FG - 0):81–90, 2014.

E. Ghafari and H. Costa. Júlio, E., . Statistical mixture design approach for eco-efficient UHPC. *Cement Concrete Composites Volume pp*, 55 SRC -:17–25, 2015.

M. Glavind and C. Munch Petersen. Green concrete in Denmark. (1):1–7, 2012.

J. Golaszewski and J. Szwabowski. Influence of superplasticizers on rheological behaviour of fresh cement mortars. *Cement and Concrete Research*, 34(2):235–248, Feb. 2004. ISSN 00088846. doi: 10.1016/j.cemconres.2003.07.002. URL `http://linkinghub.elsevier.com/retrieve/pii/S0008884603002618`.

Z. J. Grdic, G. A. Toplicic-Curcic, I. M. Despotovic, and N. S. Ristic. Properties of self-compacting concrete prepared with coarse recycled concrete aggregate. *Construction and Building Materials*, 24(7):1129–1133, 2010. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2009.12.029. URL `http://www.sciencedirect.com/science/article/pii/S0950061809004401`.

Grupo de trabajo 2/3 - ACHE. *Manual de Tecnología de Aditivos para Hormigón*. ACHE (Asociación Científico-Técnica de Aditivos para Hormigón), 2010. ISBN 978-84-89670-70-9.

J. Guiné, M. Gorré, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Weneger, S. Suh, H. Udo de Haes, H. de Bruijn, R. van Duin, and M. Huijbregts. *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*, volume 7. Kluwer Academics, 2004. ISBN 0-306-48055-7.

S.-H. Han. Influence of diffusion coefficient on chloride ion penetration of concrete structure. *Construction and Building Materials*, 21(2):370–378, Feb. 2007. ISSN 09500618. doi: 10.1016/j.conbuildmat.2005.08.011. URL `http://linkinghub.elsevier.com/retrieve/pii/S0950061805002552`.

International Organization for Standarization. Technical Committee ISO/TC 207. ISO 14040. Environmental management. Life cycle Assessment. Principles and framework, 2006a.

International Organization for Standarization. Technical Committee ISO/TC 207. ISO 14040. Environmental management: Lyfe cycle assessment - Principles and framework, 2006b.

International Organization for Standarization. Technical Committee ISO/TC 207. ISO 14044. Environmental management. Life cycle assessment. Requirements and guidelines, 2006c.

S. Ismail and M. Ramli. Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44(0):464–476, 2013. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.03.014. URL `http://www.sciencedirect.com/science/article/pii/S0950061813002195`.

C. Jiménez, D. Aponte, E. Vázquez, M. Barra, and S. Valls. Equivalent Mortar Volume (EMV) method for proportioning recycled aggregate concrete: Validation under the Spanish context and its adaptation to Bolomey methodology for concrete proportioning. *Materiales de Construcciónn*, 63(311):341–360, Oct. 2013a. ISSN 0465-2746. doi: 10.3989/mc.2012.01112. URL `http://materconstrucc.revistas.csic.es/index.php/materconstrucc/article/view/1107/1233`.

C. Jiménez, M. Barra, S. Valls, D. Aponte, and E. Vázquez. Durability of recycled aggregate concrete designed with the Equivalent Mortar Volume (EMV) method: Validation under the Spanish context and its adaptation to Bolomey methodology. *Materiales de Construcción*, 60(313):e006, Oct. 2013b. ISSN 1988-3226. doi: 10.3989/mc.2013.00913. URL `http://materconstrucc.revistas.csic.es/index.php/materconstrucc/article/view/1449/1576`.

C. Jiménez, M. Barra, A. Josa, and S. Valls. LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods. *CONSTRUCTION & BUILDING MATERIALS*, 2015. doi: 101016/j.conbuildmat.2015.03.051.

A. Josa, A. Aguado, A. Heino, E. Byars, and A. Cardim. Comparative analysis of available life cycle inventories of cement in the EU. *Cement an Concrete Research*, 34:1313–1320, 2004.

A. Josa, A. Aguado, A. Cardim, and E. Byars. Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. *Cement and Concrete Research*, 37:781–788, 2007.

O. Khim, A. Akbarnezhad, Z. Min, T. Chat, H. Junbao, and T. Wan. MECHANICAL PROPERTIES OF CONCRETE INCORPORATING MICROWAVE-TREATED RECYCLED CONCRETE AGGREGATES, 2010.

S.-W. Kim and H.-D. Yun. Influence of recycled coarse aggregates on the bond behavior of deformed bars in concrete. *Engineering Structures*, 48(0):133–143, 2013. ISSN 0141-0296. doi: 10.1016/j.engstruct.2012.10.009. URL `http://www.sciencedirect.com/science/article/pii/S0141029612005275`.

A. M. Knaack and Y. C. Kurama. Rheological and mechanical behavior of concrete mixtures with recycled concrete aggregates. *Structures Congress 2012*, Chicago, I(Fhwa 2008):2257–2267, 2012. doi: 10.1061/9780784412367.198. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-84866667071&partnerID=40&md5=b4f943e0f654db4bef7726e61b6aa094`.

C. Knoeri, E. Sanye Mengual, and H. Althaus. Comparative LCA of recycled and conventional concrete for structural applications. *The International Journal of Life Cycle Assessment*, 18(5):909–918, Jan. 2013. ISSN 09483349. doi: 10.1007/s11367-012-0544-2. URL `http://link.springer.com/10.1007/s11367-012-0544-2`.

S. Kosmatka, B. Kerkhoff, and W. Panarese. *Design and Control of Concrete Mixtures*. Portland Cement Association, fourteenth edition, 2003. ISBN 0893122173.

S.-c. Kou, C.-s. Poon, and F. Agrela. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. *Cement and Concrete Composites*, 33(8):788–795, Sept. 2011. ISSN 09589465. doi: 10.1016/j.cemconcomp.2011.05.009. URL `http://linkinghub.elsevier.com/retrieve/pii/S0958946511000989`.

W. H. Kwan, M. Ramli, K. J. Kam, and M. Z. Sulieman. Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Construction and Building Materials*, 26(1):565–573, 2012. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2011.06.059. URL `http://www.sciencedirect.com/science/article/pii/S0950061811003229`.

B. Lazniewska-Piekarczyk. The methodology for assessing the impact of new generation superplasticizers on air content in self-compacting concrete. *Construction and Building Materials*, 53:488–502, 2014. doi: 10.1016/j.conbuildmat.2013.11.092.

S. M. Levy and P. Helene. Durability of recycled aggregates concrete: a safe way to sustainable development. *Cement and Concrete Research*, 34(11):1975–1980, 2004. ISSN 0008-8846. doi: 10.1016/j.cemconres.2004.02.009. URL `http://www.sciencedirect.com/science/article/pii/S0008884604000882`.

C. Lima, A. Caggiano, C. Faella, E. Martinelli, M. Pepe, and R. Realfonzo. Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash. *Construction and Building Materials*, 47(0):547–559, 2013. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.04.051. URL `http://www.sciencedirect.com/science/article/pii/S0950061813003929`.

Y.-H. Lin, Y.-Y. Tyan, T.-P. Chang, and C.-Y. Chang. An assessment of optimal mixture for concrete made with recycled concrete aggregates. *Cement and Concrete Research*, 34(8):1373–1380, 2004. ISSN 0008-8846. doi: 10.1016/j.cemconres.2003.12.032. URL `http://www.sciencedirect.com/science/article/pii/S0008884604000109`.

F. López-Gayarre, C. López-Colina, M. A. Serrano-López, E. García Taengua, and A. López Martínez. Assessment of properties of recycled concrete by means of a highly fractioned factorial design of experiment. *Construction and Building Materials*, 25(10): 3802–3809, 2011. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2011.04.039. URL `http://www.sciencedirect.com/science/article/pii/S0950061811001796`.

P. L. Maier and S. A. Durham. Beneficial use of recycled materials in concrete mixtures. *Construction and Building Materials*, 29:428–437, Apr. 2012. ISSN 09500618. doi: 10.1016/j.conbuildmat.2011.10.024. URL `http://linkinghub.elsevier.com/retrieve/pii/S0950061811005733`.

S. Marinković, V. Radonjanin, M. Malesev, and I. Ignjatović. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management Volume pp*, 30(11):2255–2264, Nov. 2010. ISSN 0956053X. doi: 10.1016/j.wasman.2010.04.012. URL `http://www.ncbi.nlm.nih.gov/pubmed/20434898`.

M. Martín-Morales, M. Zamorano, a. Ruiz-Moyano, and I. Valverde-Espinosa. Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08. *Construction and Building Materials*, 25(2):742–748, Feb. 2011. ISSN 09500618. doi: 10.1016/j.conbuildmat.2010.07.012. URL `http://linkinghub.elsevier.com/retrieve/pii/S095006181000379X`.

I. Martínez-Lage, F. Martínez-Abella, C. Vázquez-Herrero, and J. L. Pérez-Ordóñez. Properties of plain concrete made with mixed recycled coarse aggregate, Dec. 2012. ISSN 09500618. URL `http://www.sciencedirect.com/science/article/pii/S0950061812005156http://linkinghub.elsevier.com/retrieve/pii/S0950061812005156`.

I. Martins. Recycling in Portugal: Overview of CDW. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 134–145. RILEM, first edition, 2013.

B. Mas, A. Cladera, J. Bestard, D. Muntaner, C. E. López, S. Pina, and J. Prades. Concrete with mixed recycled aggregates: Influence of the type of cement. *Construction and Building Materials*, 34(0):430–441, 2012. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2012.02.092. URL `http://www.sciencedirect.com/science/article/pii/S0950061812001717`.

P. Mehta and P. Monteiro. *Concrete. Microstructure, Properties, and Materials.* 2006.

J. Mendoza and D. Part. M., . Planning strategies for promoting environmentally suitable pedestrian pavements in cities. *Transportation Research Issue pp*, 17 SRC -:442–450, 2012.

C. Meyer. The greening of the concrete industry. *Sustainability of Civil Engineering Structures - Durability of Concrete*, 31(8):601–605, 2009a. ISSN 0958-9465. doi: http://dx.doi.org/10.1016/j.cemconcomp.2008.12.010. URL `http://www.sciencedirect.com/science/article/pii/S0958946509000031`.

C. Meyer. The greening of the concrete industry. *Cement and Concrete Composites*, 31(8): 601–605, Sept. 2009b. ISSN 09589465. doi: 10.1016/j.cemconcomp.2008.12.010. URL `http://linkinghub.elsevier.com/retrieve/pii/S0958946509000031`.

A. Mueller. Recycling in Germany: Overview regarding CDW in Germany. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 106–114. RILEM, first edition, 2013.

S. Nagataki, A. Gokce, and T. Saeki. Effects of recycled aggregate characteristics on performance parameters of recycled aggregate concrete. In *CANMET-ACI International Conference on the Durability of Concrete*, Barcelona, 2000.

S. Nagataki, A. Gokce, T. Saeki, and M. Hisada. Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*, 34: 965–971, 2004.

National Ready Mix Concrete Association. CIP 15 - Chemical Admixtures for Concrete. Technical report, National Ready Mix Concrete Association, Silver Spring, 2001.

A. Neville and J. Brooks. *Concrete Technology*. 2010.

L.-O. Nilsson, E. Poulsen, P. Sandberg, H. E. Sorensen, and O. Klinghoffer. *HETEK, Chloride penetration into concrete - State of the Art*. Road Directorate - Ministry of Transport, 1996. ISBN 87 7491 736 6.

NORDTEST. NT BUILD 443. Concrete, Hardened: Accelerated Chloride Penetration, 1995.

J.-P. Olliver. *Durability of Concrete*. Sao Paulo, 1998. ISBN 0103-9830.

F. T. Olorunsogo and N. Padayachee. Performance of recycled aggregate concrete monitored by durability indexes. *Cement and Concrete Research*, 32(2):179–185, 2002. ISSN 0008-8846. doi: 10.1016/S0008-8846(01)00653-6. URL `http://www.sciencedirect.com/science/article/pii/S0008884601006536`.

N. Otsuki, S. Nagataki, and K. Nakashita. Evaluation of AgNO3 solution spray method for measurement of chloride penetration into hardened cementitious matrix materials. *ACI Materials Journal*, 1992.

N. Otsuki, M. Asce, S.-i. Miyazato, and W. Yodsudjai. Influence of Recycled Aggregate on Interfacial Transition Zone , Strength , Chloride Penetration and Carbonation of Concrete. (October):443–451, 2003.

A. K. Padmini, K. Ramamurthy, and M. S. Mathews. Influence of parent concrete on the properties of recycled aggregate concrete. *Construction and Building Materials*, 23 (2):829–836, 2009. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2008.03.006. URL `http://www.sciencedirect.com/science/article/pii/S0950061808000901`.

K. C. Panda and P. K. Bal. Properties of Self Compacting Concrete Using Recycled Coarse Aggregate. *Chemical, Civil and Mechanical Engineering Tracks of 3rd Nirma University International Conference on Engineering (NUiCONE2012)*, 51(0):159–164, 2013. ISSN 1877-7058. doi: http://dx.doi.org/10.1016/j.proeng.2013.01.023. URL `http://www.sciencedirect.com/science/article/pii/S1877705813000246`.

W. Park. Genetic-algorithm-based mix proportion design method for recycled aggregate concrete. *Transactions of the Canadian Society for Mechanical Engineering*, 37(3):345–354, 2013. ISSN 03158977.

C. S. Poon, Z. H. Shui, L. Lam, H. Fok, and S. C. Kou. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, 34(1):31–36, 2004. ISSN 0008-8846. doi: 10.1016/S0008-8846(03)00186-8. URL `http://www.sciencedirect.com/science/article/pii/S0008884603001868`.

PRé Consultants. Simapro 8.0, 2014.

M. Quattrone, S. C. Angulo, and V. M. John. Energy and CO2 from high performance recycled aggregate production. *Resources, Conservation and Recycling*, 90:21–33, 2014. ISSN 18790658. doi: 10.1016/j.resconrec.2014.06.003.

A. Razaqpur and G. Fathifazl. Recycling in North America: State-of -the-Art of RCA-concrete in North America. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 50–58. RILEM, first edition, 2013.

A. Razaqpur, Y. Xiao, and M. Zhang. How to produce high quality concrete mixes with recycled concrete aggregate. *In J Cheung R P Chu eds Construction Waste Recycling and Civil Engineering Sustainable DevelopmentProceedings of the ICWEM Shanghai SARL pp*, pages 0–11, 2010.

K. K. Sagoe-Crentsil, T. Brown, and A. H. Taylor. Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research*, 31(5):707–712, 2001. ISSN 0008-8846. doi: 10.1016/S0008-8846(00)00476-2. URL `http://www.sciencedirect.com/science/article/pii/S0008884600004762`.

M. Sánchez de Juan and P. Alaejos. Influence of recycled aggregate quality on concrete properties. In E. Vázquez, C. F. Hendriks, and G. Janssen, editors, *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures*, pages 545–553. RILEM, Barcelona, 2004.

K. Scrivener and R. Kirkpatrick. Innovation in use and research on cementitious material. *Cement and Concrete Research pp*, 38(2 SRC - GoogleScholar FG - 0):128–136, 2008.

Y.-N. Sheen, H.-Y. Wang, Y.-P. Juang, and D.-H. Le. Assessment on the engineering properties of ready-mixed concrete using recycled aggregates. *Construction and Building Materials*, 45(0):298–305, 2013. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.03.072. URL `http://www.sciencedirect.com/science/article/pii/S0950061813002821`.

R. V. Silva, J. D. Brito, and R. K. Dhir. Prediction of the shrinkage behavior of recycled aggregate concrete : A review. *CONSTRUCTION & BUILDING MATERIALS*, 77:327–339, 2015. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2014.12.102. URL `http://dx.doi.org/10.1016/j.conbuildmat.2014.12.102`.

J. Sim and C. Park. Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. *Waste Management*, 31(11):2352–2360, 2011. ISSN 0956-053X. doi: 10.1016/j.wasman.2011.06.014. URL `http://www.sciencedirect.com/science/article/pii/S0956053X11002790`.

R. Somna, C. Jaturapitakkul, and A. M. Amde. Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete. *Cement and Concrete Composites*, 34(7):848–854, Aug. 2012. ISSN 09589465. doi: 10.1016/j.cemconcomp.2012.03.003. URL `http://linkinghub.elsevier.com/retrieve/pii/S0958946512000467`.

Spanish Ministry of Public Works. *EHE-08. Spanish Code for Structual Concrete*. Spanish Ministry of Public Works, Madrid, first edition, 2008.

Swiss Centre for Life Cycle Inventories. Ecoinvent Database v.3.01, 2013.

S. W. Tabsh and A. S. Abdelfatah. Influence of recycled concrete aggregates on strength properties of concrete. *Construction and Building Materials*, 23(2):1163–1167, 2009. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2008.06.007. URL `http://www.sciencedirect.com/science/article/pii/S0950061808001785`.

V. W. Y. Tam, X. F. Gao, and C. M. Tam. Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research*, 35 (6):1195–1203, 2005. ISSN 0008-8846. doi: 10.1016/j.cemconres.2004.10.025. URL `http://www.sciencedirect.com/science/article/pii/S0008884604004788`.

V. W. Y. Tam, C. M. Tam, and Y. Wang. Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach. *Construction and Building Materials*, 21(10):1928–1939, 2007. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2006.05.040. URL `http://www.sciencedirect.com/science/article/pii/S0950061806002133`.

W. Tangchirapat, S. Khamklai, and C. Jaturapitakkul. Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates. *Materials & Design*, 41(0):

150–157, 2012. ISSN 0261-3069. doi: 10.1016/j.matdes.2012.04.054. URL `http://www.sciencedirect.com/science/article/pii/S026130691200297X`.

G. H. Tattersall. *Workability and Quality Control of Concrete*. Taylor & Francis Group, London, 2005. ISBN 0-203-47314-0.

G. H. Tattersall and P. F. G. Banfill. *The rheology of fresh concrete*. Pitman Advanced Publishing Program, 1983. ISBN 0273085581.

C. Thomas, J. Setién, J. A. Polanco, P. Alaejos, and M. Sánchez de Juan. Durability of recycled aggregate concrete. *Construction and Building Materials*, 40(0):1054–1065, 2013. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2012.11.106. URL `http://www.sciencedirect.com/science/article/pii/S0950061812009427`.

G. Tovar, M. Barra, S. Pialarissi, D. Aponte, and E. Vázquez. Expansion of mortars with gypsum contaminated fine recycled aggregates. *Construction and Building Materials*, (38):1211–1220, 2013.

J. Vanderley and S. Angulo. Recycling in Brazil: An overview of the present situation of CDW in managing and recycling. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 42–50. RILEM, first edition, 2013.

E. Vázquez. Recycling in Spain: Overview of CDW. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 145–165. RILEM, first edition, 2013a.

E. Vázquez. Recycling in the Netherlands. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 130–133. RILEM, first edition, 2013b.

E. Vazquez. Recycled Concrete. In *Progress of Recycling in the Built Environment*, pages 177–179. 2013. ISBN 9789400749078. doi: 10.1007/978-94-007-4908-5.

E. Vázquez, M. Barra, D. Aponte, C. Jiménez, and S. Valls. Improvement of the durability of concrete with recycled aggregates in chloride exposed environment. *Construction and Building Materials*, 67:61–67, 2013. ISSN 09500618. doi: 10.1016/j.conbuildmat.2013.11.028.

J. Vrijders and J. Desmyter. Recycling in Belgium: An Overview of the present situation in Belgium from the Recycling Industry and Research about CDW. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 37–42. RILEM, Barcelona, first edition, 2013.

J. E. Wallevik. *Rheology of Particle Suspensions. Fresh Concrete, Mortar and Cement Paste with Various Types of Lignosulfonates*. PhD thesis, The Norwegian University of Science and Technology, 2003.

J. E. Wallevik. Relationship between the Bingham parameters and slump. *Cement and Concrete Research*, 36(7):1214–1221, July 2006. ISSN 00088846. doi: 10.1016/j.cemconres.2006.03.001. URL `http://linkinghub.elsevier.com/retrieve/pii/S0008884606000615`.

O. H. Wallevik and J. E. Wallevik. Rheology as a tool in concrete science: The use of rheographs and workability boxes. *Cement and Concrete Research*, 41(12):1279–1288, Dec. 2011. ISSN 00088846. doi: 10.1016/j.cemconres.2011.01.009. URL `http://linkinghub.elsevier.com/retrieve/pii/S000888461100010X`.

Waste and Resources Action Programme (WRAP). The quality protocol for the production of aggregates from inert waste. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 238–239. RILEM, 2013.

C. White, L. Daemen, M. Hartl, and K. Page. Intrinsic differences in atomic ordering of calcium (alumino) silicate hydrates in conventional and alkali-activated cements. *Cement and Concrete Research Volume pp*, 67 SRC -:66–73, 2015.

Woodhead Publishing. *Understanding the rheology of concrete*. Woodhead Publishing Limited, 2012. ISBN 978-0-85709-028-7.

Worl Commission on Environment and Development (United Nations). Our Common Future. Technical report, 1987.

J. Xiao. Recycling in China: An overview of study on recycled aggregate concrete. In E. Vázquez, editor, *Progress of Recycling in the Built Environment*, pages 58–106. RILEM, first edition, 2013.

J. Xiao, J. Li, and C. Zhang. Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, 35(6):1187–1194, 2005. ISSN 0008-8846. doi: 10.1016/j.cemconres.2004.09.020. URL `http://www.sciencedirect.com/science/article/pii/S0008884604004284`.

J. Xiao, W. Li, Y. Fan, and X. Huang. An overview of study on recycled aggregate concrete in China (1996-2011). *Construction and Building Materials*, 31(0):364–383, 2012a. ISSN 0950-0618. doi: 10.1016/j.conbuildmat.2011.12.074. URL `http://www.sciencedirect.com/science/article/pii/S0950061811007641`.

J. Xiao, J. Ying, and L. Shen. FEM simulation of chloride diffusion in modeled recycled aggregate concrete. *Construction and Building Materials*, 29:12–23, Apr. 2012b. ISSN 09500618. doi: 10.1016/j.conbuildmat.2011.08.073. URL `http://linkinghub.elsevier.com/retrieve/pii/S095006181100506X`.

K.-H. Yang, Y.-B. Jung, M.-S. Cho, and S.-H. Tae. Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete. *Journal of Cleaner Production*, 2:1–10, Mar. 2014. ISSN 09596526. doi: 10.1016/j.jclepro.2014.03.018. URL `http://linkinghub.elsevier.com/retrieve/pii/S095965261400239X`.

J. Ying, J. Xiao, and V. W. Y. Tam. On the variability of chloride diffusion in modelled recycled aggregate concrete. *Construction and Building Materials*, 41(0):732–741, 2013. ISSN 0950-0618. doi: http://dx.doi.org/10.1016/j.conbuildmat.2012.12.031. URL `http://www.sciencedirect.com/science/article/pii/S0950061812009889`.