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Durable Structural Concrete Produced with Coarse and Fine Recycled Aggregates Using Different Cement Types

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Abstract: The durability properties of structural recycled aggregate concrete (RAC) produced with 50% coarse recycled concrete aggregates and up to 20% fine recycled concrete aggregates were analysed and compared to those of conventional concrete (NAC). Both the RAC and NAC mixtures achieved the same compressive strength when using an effective water–cement ratio of 0.47 and 0.51, respectively. All the concretes were produced using three types of cement: CEM II A/L 42.5 R, CEM II A/S 42.5 N/SRC and CEM III/B 42.5 N-LH/SR. The properties of drying shrinkage, chloride permeability, and accelerated carbonation coefficient of the concretes were determined experimentally, and the obtained results were compared with the values estimated by specific standards of exposure to XC1–XC4 (corrosion induced by carbonation can happen due to the presence of humidity) and XS1 (corrosion caused by chlorides from seawater) environments. The results showed that all the concretes achieved maximum drying shrinkage for use in structural concrete. Any concretes produced with CEM IIIB, including the RAC-C50-F20 concrete, achieved very low chloride ion penetrability, ranging between 500 to 740 Coulombs. In addition, all concretes manufactured with CEM IIAL and CEM IIAS, including RAC-C50-F20, were suitable for use in XC3 and XC4 exposure environments, both with 50- and 100-year lifespans.

Keywords: coarse and fine recycled aggregates; supplementary cementitious materials; CEM IIAL; CEM IIAS; CEM IIIB; concrete durability; compressive strength; drying shrinkage; carbonation; chloride penetration

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1. Introduction

Concrete is widely employed in construction due to its remarkable strength and durability. However, the durability of concrete as a permeable material depends significantly on the quality of its constituent materials [1]. Limited investigations have been carried out studying the durability characteristics of concrete made with fine recycled concrete aggregate (FRCA) and coarse recycled concrete aggregate (CRCA) [2–6]. However, in general, the durability of recycled aggregate concrete (RAC) is lower than that of natural aggregate concrete (NAC) due to the influence of factors such as the connectivity of the porous network and water content and the type of cementitious materials (SCM) used having an important influence [2,6–9]. In addition, SCM such as blast furnace slag (BFS) further enhances the sustainability of RAC by reducing carbon dioxide emissions and increasing the circular economy [10,11].

The use of structural RAC in chloride-containing environments has sparked debate among researchers [12]. Some authors indicate that the increase in RCA content could lead to a higher diffusion of chlorides in RAC due to its high porosity [13,14]. However, some studies have also demonstrated that by reducing the amount of adhered cement mortars, the resistance of RAC to chloride ion penetration can be improved, particularly when RCA originates from higher-strength concrete [15]. The penetration of chloride ions is a major contributor to the corrosion of steel reinforcements. The results of numerous studies [7,16–20] conducted on this topic have revealed the following: the diffusion coefficient of chloride ions exhibits a linear increase with the proportional increase in recycled aggregate use; FRCA influences more than the CRCA in concrete diffusion coefficients; and, similar to NAC, chloride ion migration can be reduced by decreasing the water-to-binder ratio or incorporating SCM such as fly ash, silica fume or blast furnace slag (BFS) [7]. According to Li et al. [13], following the ASTM C1202 classification, while the concrete produced with up to 50% of RCA achieved low chloride ion penetrability, the RAC produced with a higher percentage than 50% was classified with medium penetrability, consequently needing the use of SCM to improve the resistance to chloride ion penetration. As confirmed, BFS cement enhances chloride penetration resistance in concrete due to its ability to immobilize chloride ions [21,22]. This enhancement is achieved through physical and chemical mechanisms, through chloride ion adsorption on the C-S-H surface [21] and the formation of Friedel's salt due to the higher aluminate content in the BFS cement [21,22].

Carbonation in concrete is a physicochemical process in which CO_2 penetrates the cement paste and reacts with Portlandite, forming calcite and reducing the concrete pH from 13 to 8–9. The carbonation rate is influenced by the permeability and moisture content of the concrete [2,7]. As a result of carbonation, steel reinforcement loses its protection, and corrosion begins when adequate oxygen and water levels are present [7].

Extensive research has been conducted on the carbonation resistance analysis of RAC [16,18,23,24]. Different factors can influence the carbonation depth of the RAC. These factors include the replacement ratio of recycled aggregates, the origin and quality of the RCA, the crushing technique employed for RCA production, the cement type and quantity used in concrete production, the curing process, and the use of superplasticisers to reduce the water–cement ratio [7,9,25]. Conclusions regarding the impact of RCA on the carbonation resistance of concrete can be ambiguous and conflicting. According to Pedro et al. [26], the carbonation depth increases as the concrete's compressive strength decreases. Certain researchers [8,25] have argued that RAC mixtures produced with coarse CRCA exhibit similar or even higher carbonation resistance than NAC due to aged adhered mortar. Zeng et al. [27] suggested that the optimal replacement percentage of natural aggregates (NAs) with RCA is 50%, which prevents a decrease in carbonation resistance. Etxeberria et al. [24] also reached a similar conclusion when employing a 50% replacement of uncarbonated CRCA. Loti et al. [18] found that RAC produced with up to 50% coarse RCA met the current European standards, thus supporting its use in structural application when up to 50% of CRCA is employed in concrete production. However, more investigation is needed to evaluate the influence of FRCA recycled aggregates on carbonation resistance and, in general, on concrete durability.

Furthermore, the service life of concrete structures against carbonation strongly depends on the type of cement used in concrete production [28,29]. The carbonation depth of concrete mixtures produced using SCM was higher due to the reduction of Portlandite during cement hydration, reducing Ca availability [29,30] and, consequently, causing less resistance to carbonation. Although SCMs reduce alkali reserve usually leads to a reduction in pore size, they can decrease the permeability of cementitious matrices [31]. However, carbonation not only lowers the overall pH but may also result in the coarsening of the pore structure, potentially diminishing its durability and susceptibility to various forms of degradation, including chemical and physical attacks [30]. Consequently, the carbonation concrete's service life decreases as more SCM is used to replace clinker [28,32,33]. However, using limited mineral admixtures in RAC production can improve carbonation resistance. The RCA produced using CEM IIAS achieved a higher carbonation resistance than that produced with CEM IIAL due to the addition of available CaO in the slag cement. In addition, the use of up to 50% of CRCA had little influence on the carbonation depth [34].

According to the shrinkage values obtained, RAC concrete produced with higher percentages of RCA achieved higher shrinkage values [35,36]. Gonzalez and Etxeberria [37] studied the drying shrinkage of RACs produced using only CRCA obtained from different sources. They concluded that the CRCA produced from a lower-strength parent concrete achieved the highest drying shrinkage value. The increase in the RAC shrinkage value is due to the high water absorption of RCAs, which are porous and contain old cement paste [7]. Vintimilla and Etxeberria [36] determined that all concretes with up to 60% CRCA achieved shrinkage values similar to NAC. In addition, they concluded that the use of FRCA increased the shrinkage value when compared to concrete made only with CRCA. Nevertheless, the concretes produced with up to 60% CRCA and 20% FRCA also obtained adequate values ranging from between −200 and −800, following American Concrete Institute (ACI) standards [38]. Simsek et al. [39] conducted a study to evaluate the influence of using 20%, 40%, 60%, 80%, and 100% FRCA or CRCA in the substitution of natural aggregates. They concluded that after 90 days, the RAC with up to 20% FRCA achieved adequate properties. Moreover, several recent studies [36,40] have confirmed the existence of a slight influence of FRCA on structural concrete performance, however not being detrimental and consequently technically viable for their use.

The type of cement used in concrete production also influences the drying shrinkage value. It has been determined that concretes produced using Portland clinker-based cement have very high strength due to the fact that it increases the hydration heat and, as a consequence, leads to higher drying shrinkage [41]. In contrast, the early stage shrinkage caused in SCM cement significantly contributes to final shrinkage, raising the risk of concrete cracking in later stages [42,43].

The main objective of this research work was to conduct a comprehensive analysis of the durability properties of concrete produced using 50% CRCA and up to 20% FRCA. To achieve this objective, all conventional and recycled concretes were designed to obtain the same compressive strength. Thus, all the RAC concretes were manufactured with an effective water–cement value of 0.47 and the NAC with 0.51. Three types of cement, CEM II A/L 42.5 R, CEM II A/S 42.5 N/SRC and CEM III/B 42.5 N-LH/SR, were used for concrete production. The properties of drying shrinkage, chloride permeability, and accelerated carbonation coefficient of the concrete were determined experimentally. The obtained results were compared with the values estimated by specific standards for exposure to XC1–XC4 and XS1 environments.

2. Materials and Methods

2.1. Materials

2.1.1. Cement and Chemical Admixtures

Three different cement types, CEM II A/L 42.5 R, CEM II A/S 42.5 N/SRC and CEM III/B 42.5 N-LH/SR, defined by the European standard EN 197-1 [44], were employed. The three types of cement are sustainable (produced using SCM) and available in Barcelona: (1) CEM II A/L 42.5 R (88% clinker, 12% limestone, excluding the set regulator, added in 5%), with high initial strength, ideal for applications requiring rapid setting; (2) CEM IIAS 42.5 N/SRC (83% clinker, 12% blast furnace slag (BFS) and 5% minority component), providing moderate sulphate resistance and enhanced durability and (3) CEM IIIB 42.5 N-LH/SR (27% clinker, 70% BFS and 3% minority component) with low heat development and sulphate resistance. The composition details of the three cement types are illustrated in Table 1.

Table 1. Composition of cement as a percentage of the total weight.

Cement	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TIO_2	Na_2O
CEM II A-L 42.5 R	61.47	17.87	3.61	2.64	3.69	1.45	0.736	0.183	0.228
CEM II A-S 42.5 N/SRC	59.97	21.66	4.35	3.75	3.47	2.1	0.395	0.327	0.314
CEM III/B 42.5 N-LH/SR	49.4	27.8	8.41	1.96	3.96	4.65	0.48	0.457	0.365

Two chemical admixtures were used in the concrete manufacturing process: (1) a superplasticiser (S) based on polycarboxylate ether (PAE) polymer technology and (2) a multifunctional admixture (P) based on Modified Lignin Sulfonate. The manufacturer's recommendations for these admixtures ranged from 0.3% to 2% S and 0.5% to 1.5% P, based on the cement weight.

2.1.2. Natural Aggregates

Natural limestone aggregates were used for concrete production. One fine fraction (0/4 mm, FNA) and two coarse fractions (4/10 mm CNA1 and 8/20 mm CNA2) were employed. Figure 1 shows the geometrical characteristics of the aggregate fractions. Figure 2 describes the grading distribution of each fraction (determined and classified following EN 933-1 [45] and EN12620 [46] specifications). In addition, the recommended upper and lower limits for fine aggregate, as stipulated in the Structural Concrete Code (SC-BOE) [47], are described. The dry density and water absorption were determined under the EN 1097-6 [48] standard. The obtained property values are shown in Table 2.

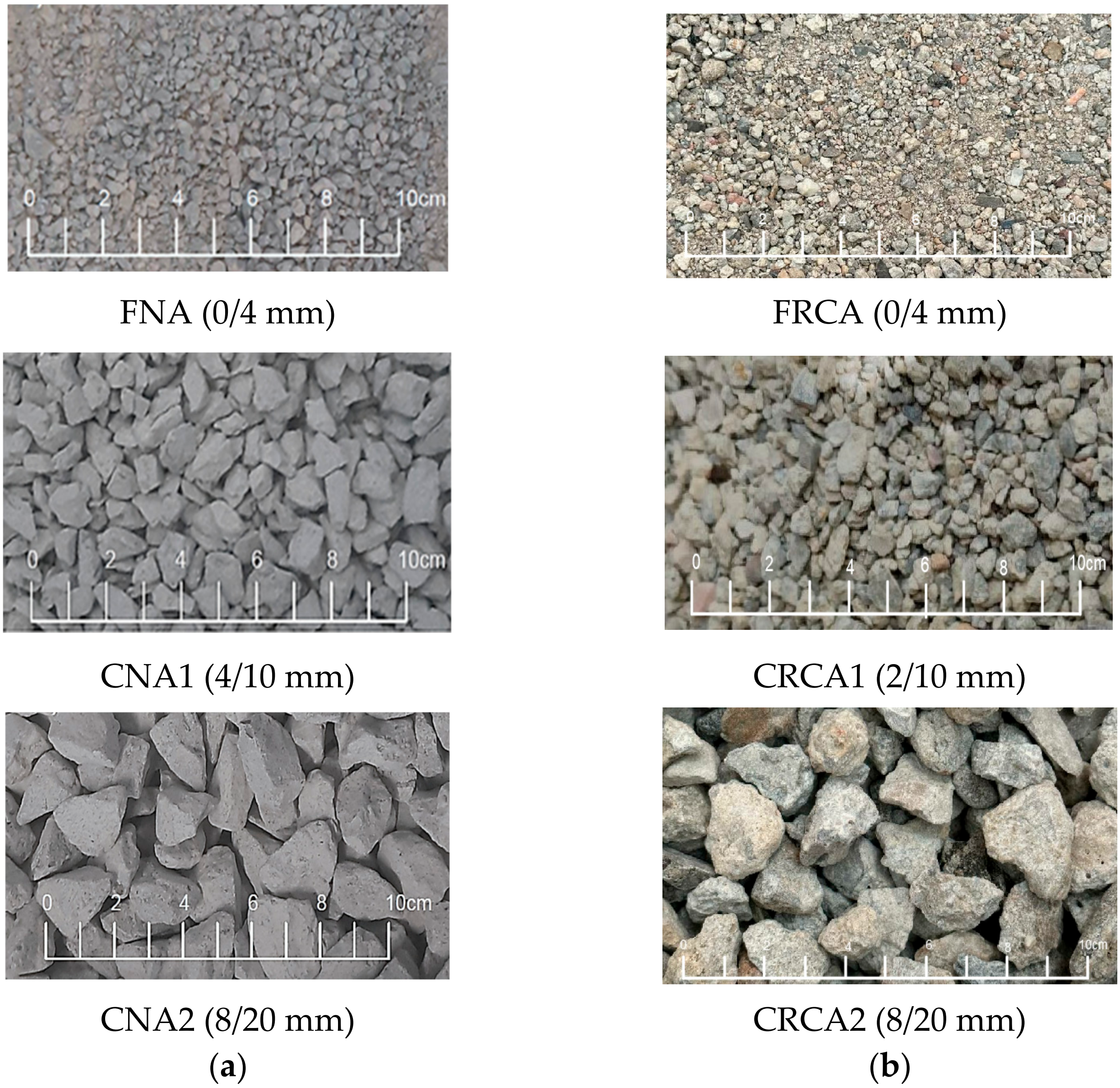


Figure 1. Image of all the fractions: (**a**) raw aggregates; (**b**) recycled aggregates.

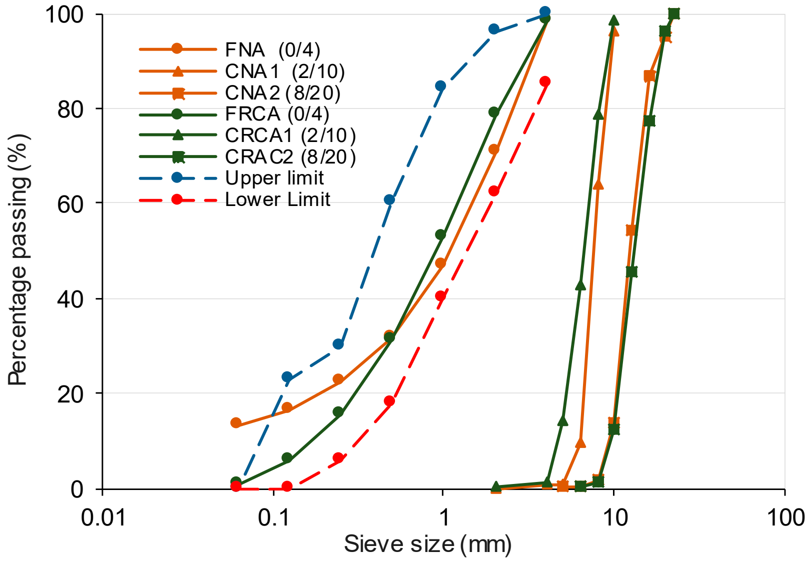


Figure 2. Particle size distribution of natural and recycled aggregates.

Table 2. Properties of natural and type A RCA aggregates studied.

Property (Standard)	Specification	FNA (0/4)	CNA 1 (4/10)	CNA 2 (8/20)	FRCA (0/4)	CRCA-1 (2/10)	CRCA-2 (8/20)	SC-BOE
Density (Kg/m^3)	EN 1097-6 [48]	2.67	2.65	2.68	2.32	2.33	2.36	2.1 [1]
Water Absorption (%)	EN 1097-6 [48]	0.95	0.77	0.73	5.73	5.62	5.16	<7
Humidity (%)		0.37	0.16	0.1	2.73	4.50	4.55	
Sand equivalent (%)	EN 933-8 [49]				100			>70
Los Angeles coefficient (wt%)	EN 1097-2 [49]						35.77	<40
Flakiness index (wt%)	EN 933-3 [50]						12.81	<35
Alkali–aggregate reaction (%)	UNE 146508 [51]				0.042			<0.10

[1] Property defined in EN 206.

2.1.3. Recycled Aggregates

The production of RCA involved crushing, cleaning with water, and sieving construction and demolition waste (CDW) at a recycling plant in Barcelona, Spain [52]. Concrete mixtures were manufactured using one fine fraction (0/4 mm, FRCA) and two coarse fractions (2/10 mm, CRCA-1 and 8/20 mm, CRCA-2). Figures 1 and 2 illustrate the shapes and size distribution of the three RCA fractions, respectively.

The components of the CRCA-2 (8/20 mm) fraction were characterized in accordance with the EN 933-11 [53] specification, and the obtained values are described in Table 3. According to the EN 206 [54] specification, the RA employed in this work were classified as type A (RC90, RCU95, Rb10-, Ra1, FL2- and XRg1-), with concrete (RC) and natural stone (Ru) components representing over 90% of the total content, while the ceramic content constituted less than 10%. Specifically, the aggregates were classified as RCU95 [36].

Table 3. Constituents of type A CRCA-2 (8/20 mm) aggregates.

Type	Concrete, Concrete Products, Mortar (Rc)	Unbound Mortar, Nature Stone (Ru)	Mansory (Rb)	Asphalt (Ra)	Glass (Rg)	Other (x)
CRCA-2	68.3%	28.0%	1.9%	0.98%	0.0%	0.39%
EN 12620	Rc + Ru > 95		≤10%	≤1%	≤1%	-

Due to the presence of adhered mortar in RCAs, the porosity of RCA was higher than that of natural aggregates (NAs), reducing their density and increasing their absorption capacity. As previously documented in scientific studies [2,26,36,55].

Table 2 shows that the obtained dry density value of the different fractions of RCA was higher than the minimum requirement value of 2.1 kg/dm^3 established by the European standard EN 206 [54] for their use in concrete production. Moreover, although the water absorption value obtained by the RCA aggregates was higher than that of the NA aggregates, it was lower than the maximum value of 7% specified by the structural code SC-BOE. Various studies have reported that the absorption capacities of coarse and fine fraction type A RCA could reach 3.9–9.6% [3,56] and 2.4–19.3% [57–59], respectively.

The RCA aggregates also achieved adequate property values of the Los Angeles coefficient, sand equivalent, and flakiness index (see Table 2) for concrete production. Alkali–aggregate reactivity analysis was conducted on the FRCA 0/4 mm fraction. It was established that the specimens exhibited an expansion of less than 0.1% after 14 days, indicating that they could be classified as non-reactive materials.

2.2. Concrete Production and Test Procedures

2.2.1. Concrete Production

All the concrete mixtures were designed to be exposed to XC1–XC4 (corrosion induced by carbonation can happen due to humidity presence) and XS1 (corrosion caused by chlorides from seawater) environments [47]. Those concretes require a minimum characteristic design strength (fck) of 30 MPa (C30/37), using a total water–cement ratio of 0.50 and 300 kg of the three types of cement described in Table 1.

The effective water–cement of 0.47 was maintained constant in all the produced concrete (Table 4). The effective water–cement ratio of 0.47 was determined in conventional concrete (NAC-0.47 concrete) after the effectively absorbed water by aggregates was removed from the total water–cement ratio of 0.50.

Table 4. Mix proportions of concretes were produced with CEM IIAL, CEM IIAS and CEM IIIB.

Materials (kg)	Concrete Types				
	NAC-0.51	NAC-0.47	RAC-C50	RAC-C50-F10	RAC-C50-F20
Cement	300	300	300	300	300
Total water	165	150	175.8	179.5	182.3
CNA 1	354.5	360.1	180.5	180.5	180.5
CNA 2	723.68	737.2	369.3	369.3	369.3
FNA	954.1	971.9	1014.2	875.7	778.4
CRCA 1	-	-	165.8	165.2	165.6
CRCA 2	-	-	338.8	339.1	337.2
FRCA	-	-	-	87.1	174.1
P (%)	1/0.7 [1]	1	1/0.6 [1]	1/0.5 [1]	1/0.3 [1]
S (%)	1	1	1/1.5 [1]	1/1.5 [1]	1/1.5 [1]
effective w/c	0.51	0.47	0.47	0.47	0.47
Slump-IIAS (mm)	175	145	150	155	150
Slump-IIIB (mm)	175	160	135	150	150
Slump-IIAL (mm)	175	150	190	200	195

[1] Plasticizer content utilised in CEM IIAL.

Specifically, the effective absorption capacities of fine and coarse aggregates natural aggregates were 70% and 20% of the total absorption capacities, respectively. In comparison, the effective absorption capacities of FRCA and CRCA were 100% and 70%, respectively, of their absorption capacities in 24 h. Table 2 also presents the average humidity (%) of the RCA when they were employed for concrete production. All coarse fractions of RCA were used with high humidity (between 80 and 90% of their absorption capacity) during manufacturing. The total water content in the concrete was calculated by combining the effective water and the water within the aggregates (humidity plus the amount of effectively absorbed water). Table 4 illustrates how the total water–cement ratio increased with higher volumes of RCA incorporated in the concrete mixes. To achieve the same compressive strength of RAC as NAC, a new control mixture of NAC was formulated with a total water-to-cement ratio of 0.55 and an effective water-to-cement ratio of 0.51 (NAC-0.51).

Table 4 shows all the concrete mixtures produced. In addition to the two conventional concretes, NAC-0.47 and NAC-0.51, the RAC was produced using 50% CRCA and 0% FRCA (RAC-C50), 50% CRCA and 10% FRCA (RAC-C50-F10), and 50% CRCA and 20% FRCA (RAC-C50-F20). The five types of concrete were produced using the three types of cement described previously.

The slump values of the concrete samples were determined following the EN 12350-2 [60] specification. It was found that the concretes achieved a slump range between 135–200 mm, which, according to the Structural Concrete Code (SC-BOE) [47], is considered fluid (100–150 mm) and liquid consistency (160–200 mm), and defined as adequate property for building construction. As Table 4 shows, to achieve adequate workability, 1% of S and 1% of P (CEM IIAS and CEM IIIB) were employed. The RAC produced with CEM IIAL showed a slightly higher slump, which can be attributed to the higher dosage of superplasticiser used.

The concrete mixtures were produced employing a vertical axis mixer, adding the materials following a fixed sequence. Initially, aggregates were added, starting with coarser aggregates and terminating with finer ones. They were mixed for 1 min. After the cement was added, water was gradually added while the mixing process continued. Then, the chemical admixtures were added. The complete mixture was then mixed for one additional minute.

The concrete samples underwent manual compaction using a steel rod. Subsequently, a plastic sheet was employed to cover the concrete specimens, which were then subjected to a 24 h air-curing period. After 24 h of casting, the samples were demoulded and stored under controlled conditions at a temperature of 21 °C with a humidity of 95% until the testing ages.

2.2.2. Test Procedure

The concrete's compressive strength was determined using a 3000-kN capacity loading machine. The compressive strength was determined at 7, 28, and 56 days following the UNE-EN 12390-3 [61] specifications. For each testing age, three cubic specimens measuring 100 × 100 × 100 mm were utilised.

The drying shrinkage of all the produced concretes was determined following the EN 12390-16 [62] specification. Each concrete mixture used two specimens of 75 × 75 × 280 mm. After a 24 h casting, they were demoulded. Their initial lengths and weights were measured, and the two specimens of each concrete were placed in a controlled climatic chamber (temperature of 20 ± 2 °C and relative humidity of 50 ± 5%). Length and weight measurements were recorded at intervals of 1, 7, 14, 28, 56 and 91 days.

The chloride permeability in the concrete was assessed following the ASTM C1202 [63] "Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration". Two cylindrical concrete samples of 200 mm in length were employed for each mixture, and from those, two disc specimens of 100 mm in diameter and 50 mm in thickness were obtained. Two disc specimens, one of each sample, were used to determine the concrete's chloride ion penetration after 28 and 56 days of curing. The chloride penetrability of the produced concretes was quantified by measuring the total charge (in Coulombs) passed during a 6 h testing period. A potential difference of 60 V was applied across each side of the specimen, which was immersed, one side in solutions containing sodium hydroxide (NaOH) and the other side in sodium chloride (NaCl).

The accelerated carbonation method following the UNE-EN 12390-12 [64] specification was employed in order to assess the carbonation resistance of the produced concrete mixtures. Each concrete mixture used two prismatic 100 × 100 × 300 mm samples. All concrete specimens underwent a curing process in a humidity chamber for 28 days, followed by a 14-day pre-conditioning period under laboratory conditions (CO_2 concentration of 425 ppm, 20 ± 2 °C, and 50–55% relative humidity, RH). Subsequently, the samples were stored in a chamber with an environment consisting of 3% CO_2, 57% HR and at 20 °C. The carbonation depth of each specimen was measured at specific intervals of 0, 14, 28, 56, 70, and 91 days of exposure to the chamber. In order to determine the carbonation depth, a solution containing phenolphthalein indicator was applied to the freshly fractured surface of the concrete. The solution contained 1 g of phenolphthalein dissolved in 70 g of ethanol and 30 g of water following the UNE-EN 14630 [65] specification.

3. Results

3.1. Compressive Strenght

Table 5 shows the obtained compressive strength values ($fcm_{,cub100}$) of cubic concrete specimens (100 × 100 × 100 mm) and their standard deviation at 7, 28 and 56 days. The concrete specimens were designed for exposure in XC1–XC4 and XS1 environments, with strength class C30/37. Consequently, according to the Structural Concrete Code (SC-BOE) [47], the minimum characteristic and average strength values of 30 MPa and 38 MPa, respectively, were established for cylindrical specimens of 150 mm and 300 mm in length. According to the calculations made by Vintimilla and Etxeberria et al. [36] following the specifications given in the Structural Concrete Code (SC-BOE) [47], the minimum average compressive strength of 100 mm cube ($fcm_{,cub100}$) should achieve 46 MPa. In addition, it was found that the standard deviations in the compressive strength results of all samples were acceptable. The dispersion was more noticeable at 7 days but decreased at 28 and 56 days. This pattern indicated that the obtained results closely aligned with the average value, ensuring measurement reliability.

Table 5. Compressive strength and its standard deviation (between brackets values) in all produced concretes.

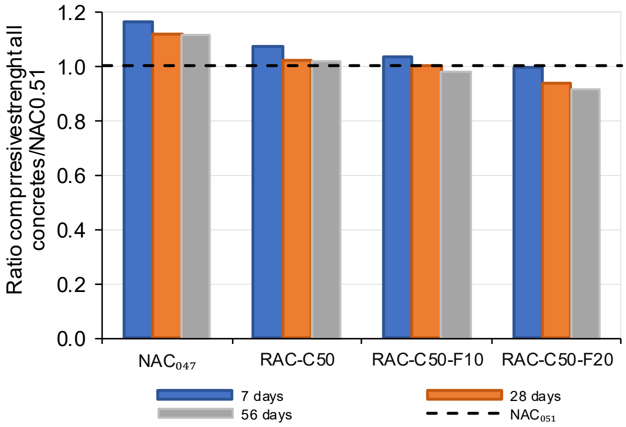
Concrete Reference		IIAL			IIAS			IIIB	
	7d	28d	56d	7d	28d	56d	7d	28 d	56d
NAC_{47}	52.5 (1.3)	62.9 (1.3)	65.5 (1.0)	54.5 (1.3)	69.8 (1.0)	71.3 (1.9)	53.1 (0.8)	67.2 (0.4)	69.9 (0.9)
NAC_{51}	45.2 (2.0)	56.2 (1.6)	58.8 (1.0)	54.1 (2.0)	59.2 (0.5)	64.7 (0.2)	51.5 (0.1)	57.2 (1.2)	59.9 (0.9)
RAC-C50	48.6 (2.5)	57.3 (1.0)	59.9 (1.7)	53.9 (2.5)	59.2 (2.3)	62.8 (1.2)	53.7 (0.3)	61.4 (2.0)	62.0 (1.0)
RAC-C50-F10	46.9 (1.8)	56.3 (1.5)	57.5 (0.3)	52.4 (1.8)	59.7 (1.3)	59.9 (0.2)	53.4 (2.8)	60.6 (1.7)	61.6 (0.7)
RAC-C50-F20	44.9 (2.4)	52.7 (0.3)	53.8 (0.4)	50.2 (2.4)	60.7 (0)	63.7 (1.2)	53.6 (1.5)	62.8 (1.4)	62.9 (1.3)

Compressive strength values for 100 mm cube specimens. ( ) Standard deviation.

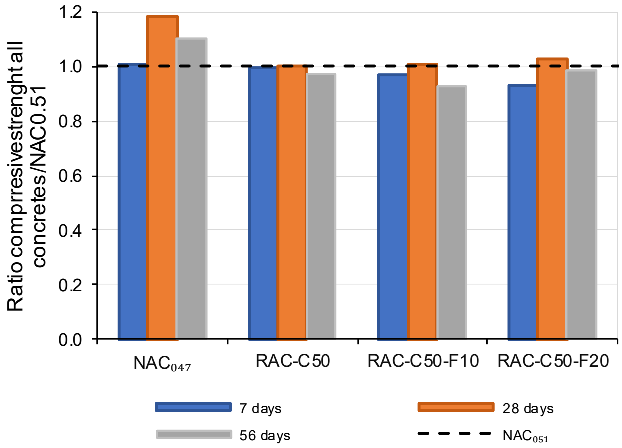
Table 5 shows that the RAC achieved 18% lower compressive strength than that of NAC-0.47 (all concretes were made using the same effective water–cement ratio of 0.47). However, the RAC achieved similar strength to NAC-0.51 concrete, which was made with an effective water–cement ratio of 0.51 (see Figure 3). These findings highlight the influence of recycled aggregates on the mechanical properties of concrete and emphasise the importance of adjusting the water-to-cement ratio to achieve comparable compressive strength to that of NAC.

Although all the RACs had the same effective water–cement ratio, RACs manufactured with type CEM IIAL cement exhibited slightly lower compressive strength than those obtained with type CEM IIAS and type CEM IIIB cement. This difference could be attributed to environmental temperature; the RACs made with CEM IIAL were produced in spring/summer, while the others were produced in autumn/winter [66]. These factors could influence the setting and curing process of the concrete, directly affecting its final strength.

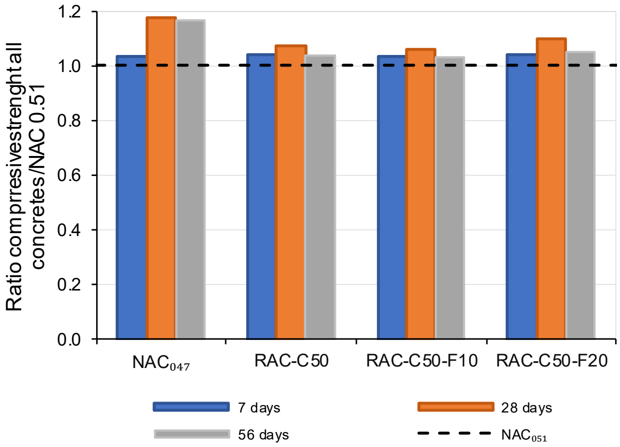
Figure 3a–c describes the ratio of compressive strength value obtained by each concrete with respect to that of NAC-0.51 at 7, 28 and 56 days. In general, NAC-0.47 achieved between 3% and 17% higher strength than NAC-0.51 concrete at different ages.



(**a**) CEM-IIAL



(**b**) CEM-IIAS



(**c**) CEM-IIIB

Figure 3. Relative compressive strength at all concrete ages produced with cements: (**a**) type CEM IIAL; (**b**) type CEM IIAS; (**c**) type CEM III-B.

Figure 3a describes the ratio when the concretes were produced using the cement CEM IIAL. While the RAC-C50 and RAC-C50-F10 achieved similar values to NAC-0.51 at any age, the RAC-C50-F20 obtained a decrease of up to 8.5% at 56 days. Figure 3b shows the results obtained for concrete produced with CEM IIAS. All the RAC, including the RAC-C50-F20, achieved a similar strength to the NAC-0.51 concrete. Similarly, Figure 3c shows that RAC made with CEM IIIB cement achieved a slightly higher strength than NAC-0.51. The results (Figure 3) show that the different substitution levels of RCA (50% CRCA and up to 20% FRCA) did not have a significant detrimental impact on compressive strength. In addition, as discovered in previous work [36], it was verified that the concrete produced with 50% CRCA and 20% FRCA (RAC-C50-F20) achieved similar compressive strength to concrete containing only CRCA (RAC-C50) and NAC when the RAC and NAC were made with an effective water–cement ratio of 0.47 and 0.52, respectively.

Gao and Wang [67] reported that concrete produced with a higher percentage of FRCA caused a reduction of the compressive strength value. However, several researchers suggested that incorporating 30% FRCA as a replacement for natural sand could still achieve satisfactory properties [5,68]. Evangelista and Brito [68] and Pedro and Brito [4] also confirmed the use of up to 30% FRCA for structural concrete production.

According to the results, the NAC and RAC concrete (produced with 50% CRCA and up to 20% FRCA) achieved similar compressive strength when an effective water–cement ratio of 0.51 and 0.47 was used in concrete production, respectively. They all achieved a suitably designed compressive strength of C30/37 for structural applications.

3.2. Drying Shrinkage

Figures 4a–c and 5a–c illustrate the drying shrinkage (μƐ) and mass loss (%) values, respectively, over 91 days for the NAC-0.51 and RAC concretes produced using cement CEM IIAL (a), CEM IIAS (b) and CEM IIIB (c).

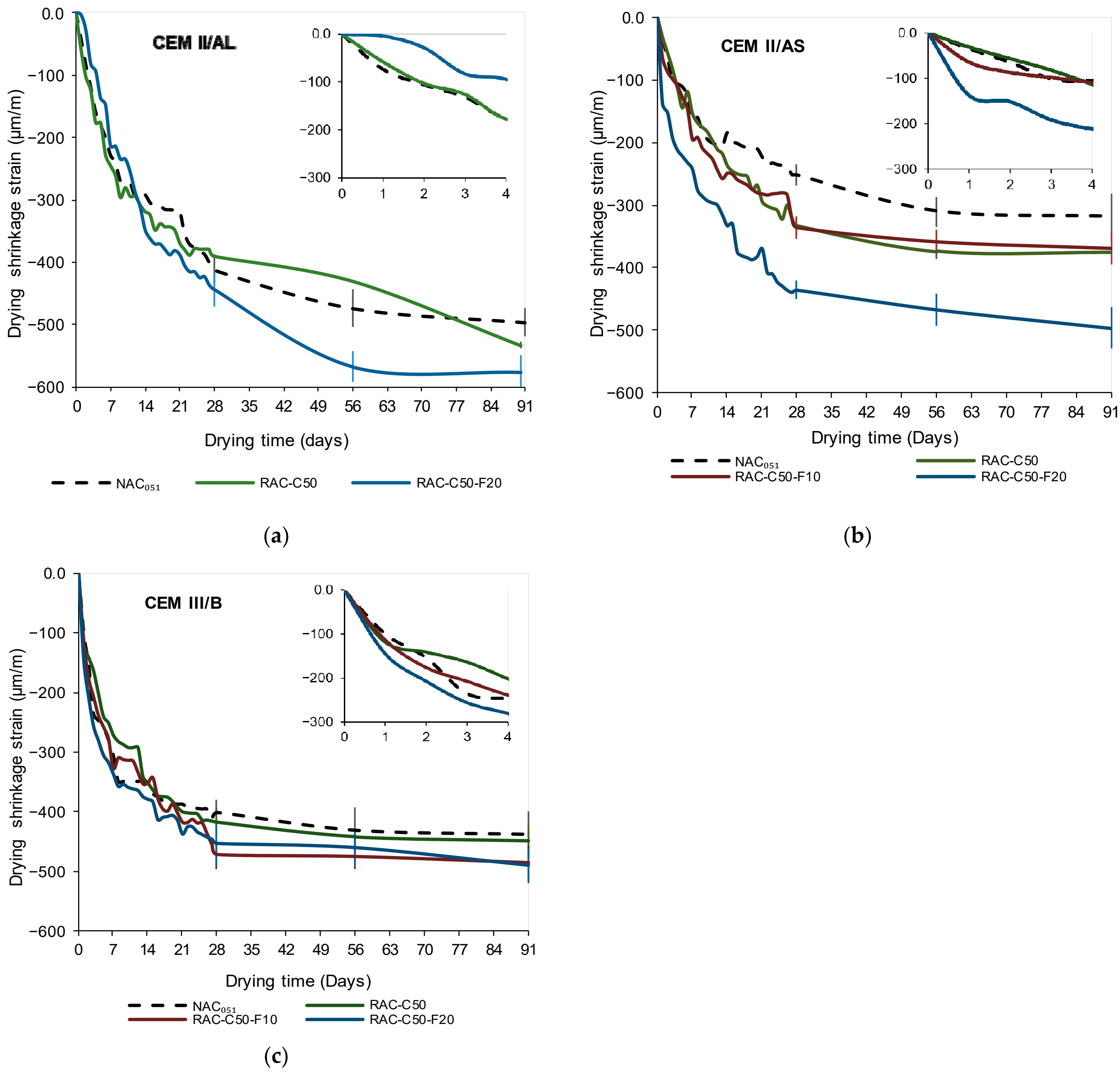


Figure 4. Drying shrinkage development at 91 days: (**a**) CEM II/AL, (**b**) CEM II/AS, (**c**) CEM III/B.

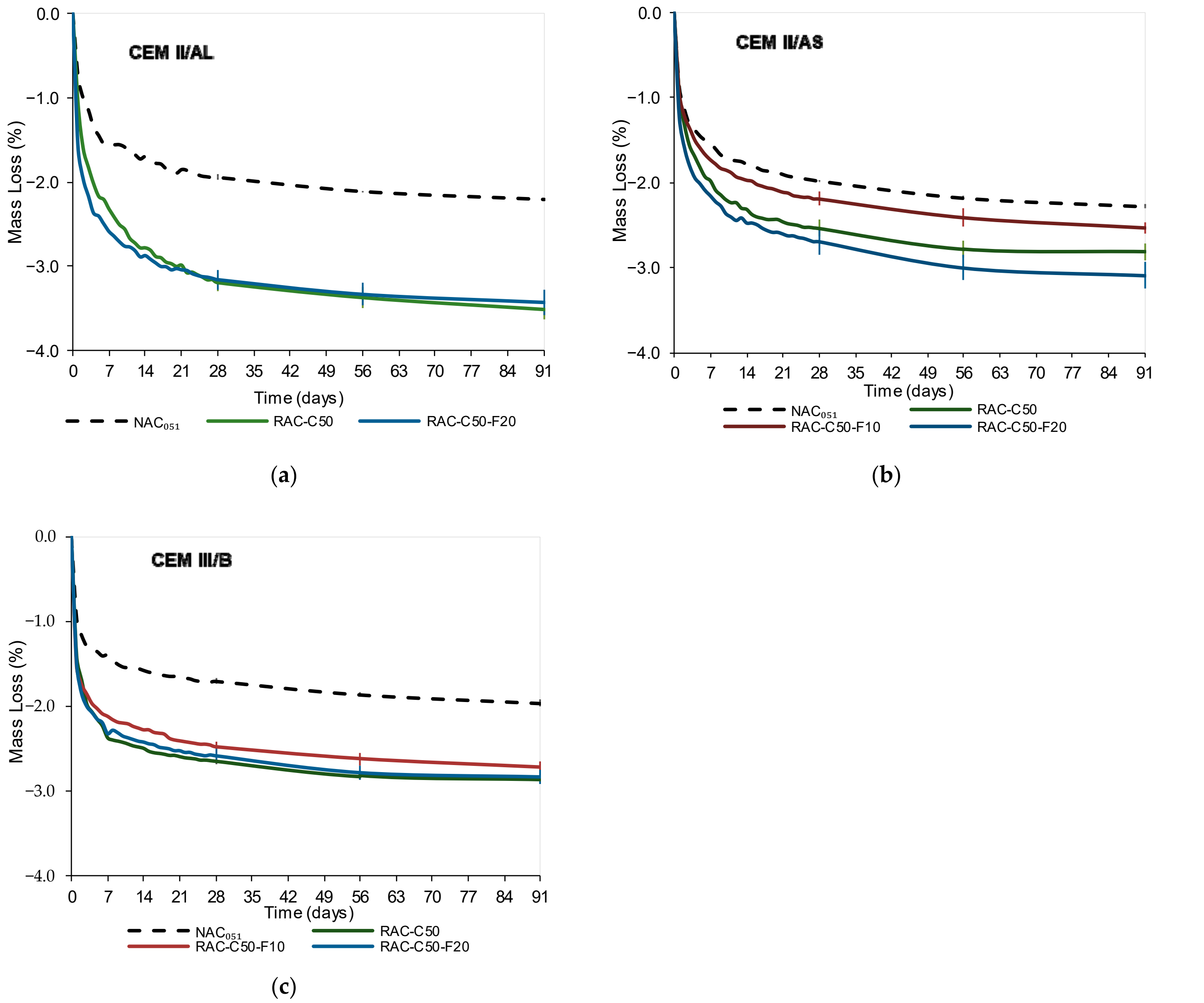


Figure 5. Mass loss development at 91 days: (**a**) CEM II/AL, (**b**) CEM II/AS, (**c**) CEM III/B.

According to shrinkage values, the concretes produced with CEM IIAL achieved a drying shrinkage value between −496.8 and −562.7 µm/m at 91 days (see Figure 4a). The RAC-C50 concrete achieved a 7.3% higher drying shrinkage value than that of the NAC. Furthermore, the RAC-C50-F20 concrete achieved a 13.3% higher drying shrinkage than NAC concrete (the RAC-C50-F10 concrete was not tested).

According to the results obtained from the concretes produced using CEM IIAS (see Figure 4b), the obtained shrinkage values were between −318.82 and −496.52 µm/m. Figure 4b shows that RAC-C50 and RAC-C50-F10 had similar drying shrinkage values, which were 18% and 16%, respectively, higher than NAC-0.51. Moreover, the RAC-C50-F20 concrete had 56% higher drying shrinkage than NAC-0.51.

In accordance with the results obtained from the concretes produced with CEM IIIB (see Figure 4c), all the concretes achieved similar drying shrinkage values, between −437.3 and −489.6 µm/m. Figure 4c shows that RAC-50 only exceeds 3% of the value obtained by NAC-0.51 concrete, while RAC-C50-10 and RAC-C50-20 were 11% and 12% higher than NAC-0.51, respectively. The use of RAC reduced stiffness caused by the amount of adhered mortar in the recycled aggregate [36,69,70]. This property is closely associated with the modulus of elasticity, which is the principal mechanical indicator of material stiffness [69]. Vintimilla and Etxeberria [36] determined that RAC concrete produced using

CEM IIAL with 50% CRCA and 20% FRCA achieved a 19% lower modulus elasticity and a 14% higher drying shrinkage value than those of NAC. Bendimerad et al. [71] confirmed that the increase in drying shrinkage was associated with a decrease in modulus. According to the achieved results, FRCA strongly influenced and increased the shrinkage value; consequently, the concrete produced with 20% FRCA reached the highest shrinkage value regardless of the obtained compressive strength, as all the concretes exhibited similar compressive strength. Despite this increase in shrinkage, all the values were considered acceptable according to ACI [38], which states that the typical drying shrinkage values of NAC range from −200 to −800 when a high water–cement ratio is employed. In addition, in general, RAC presents deviations similar to those NAC, but between them showed a moderate disperse in most cases.

During the first four days of curing within a drying chamber, the concretes produced with lower clinker (CEM IIIB cement, see Figure 4c) achieved the highest shrinkage value. Drying shrinkage mainly occurs during the early ages and tends to stabilise over time [4]. However, this behaviour is more apparent when SCM is employed as a concrete binder [42,43]. The NAC-0.51 produced with CEM IIIB, CEM IIAL and CEM IIAS cement reached −200 μm/m, −170 μm/m and −110 μm/m, respectively. In addition, the shrinkage value increased as the percentage of RCA used increased. The RAC-C50-F20 produced with CEM IIIB cement achieved a drying shrinkage value of −280 μm/m in the first four days of drying. However, as mentioned above, the shrinkage values stabilised over 28 days.

Figure 5a–c show the mass loss (in %) of each concrete produced with CEM IIAL, CEM IIAS and CEM IIIB, respectively. The three NAC-0.51 mixes achieved a similar mass loss of 2.2%, 2.3%, and 1.9%, respectively. As expected, the concrete mass loss increased as the percentage of recycled aggregates rose. Similarly, for the drying shrinkage value, the RAC-C50-F20 produced with CEM IIAL achieved the highest mass loss with 3.5%, followed by the RAC-C50-F20 produced with CEM IIAS and lastly, CEM IIIB with a mass loss of 3.1% and 2.86%, respectively (see Figure 5). These values are consistent with the results found by other researchers [36,37,52,72].

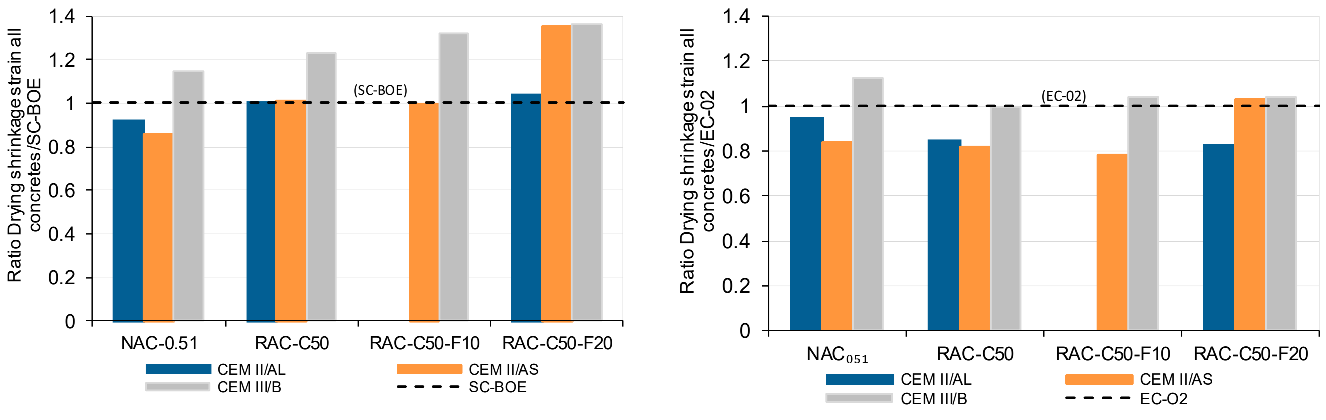
In all cases, higher drying shrinkage was closely associated with a higher mass loss when comparing concretes that employed the same type of cement. All control concretes exhibited an average mass loss of approximately 2%, while the incorporation of fine and coarse recycled aggregates resulted in an increment of approximately 3% to 3.5%.

The formulations provided by the Structural Concrete Code (SC-BOE) [47] and the Eurocode 2: EN 1992-1-1 (EC-02) [73] were used to predict drying shrinkage in RAC concretes. The calculation method used was described in a previous paper [36].

In order to determine the shrinkage value following the Structural Concrete Code (SC-BOE) [47], the following factors should be considered: the compressive strength at 28 days, concrete specimen size, ambient RH, and the type of cement (the CEM IIAL was considered high early strength (Class CR); the CEM II/AS; and CEM IIIB cements were considered ordinary early strength (Class CN)). However, it must be noted that the SC-BOE does not consider the use of RCA.

However, the use of RCA to estimate the shrinkage value is considered in Eurocode 2: EN 1992-1-1 (EC-02) [73]. The influence of CRCA and FRCA was calculated by applying a specific factor (ηshRA) in the formula to determine the drying shrinkage of RAC. The ηshRA is described as $1{+}0.8\ \alpha RA$, where αRA represents the ratio between the recycled aggregates quantity (CRCA and FRCA) and the total quantity of aggregates (coarse and fine aggregates) employed. This factor (ηshRA) is applied when the RCA is employed in replacement of 20–40% of NAs ($0.20 < \alpha RA \leq 0.40$) [36,73]. In this research work, the αRA factors were defined by 0.27, 0.31, and 0.36 for the RAC-C50, RAC-C50-F10, and RAC-C50-F20 concretes, respectively.

To demonstrate the effectiveness of the codes in predicting drying shrinkage in concrete, Figure 6 illustrates the ratio between the experimentally obtained drying shrinkage value of each concrete and the value determined using the following standards: (a) Structural Concrete Code (SC-BOE) and (b) Eurocode 2: EN 1992-1-1 (EC-02).



(**a**) (**b**)

Figure 6. Shrinkage estimation analysis depicted through ratios of (**a**) experimental results/numerical estimation SC-BOE and (**b**) experimental results/numerical estimation EC-02.

According to Figure 6a, the Spanish Structural Concrete Code (SC-BOE) is not exact in the estimation of NAC-0.51 concrete's shrinkage value. It has been observed that the concrete produced with CEM IIAL and CEM IIAS cements achieved a 10–15% lower shrinkage value than the value estimated by SC-BOE. However, the concrete produced with CEM IIIB cement achieved a 15% higher shrinkage value than that of the value estimated for SC-BOE cement. Although the type of cement was considered in the drying shrinkage calculation for the SC-BOE, it was not considered in a higher early shrinkage caused by high BFS content cement (CEM IIIB), which can influence total drying shrinkage [42,43]. Moreover, the compressive strength at 28 days is the primary parameter considered in SC-BOE estimation; this proved to be similar in all NAC-0.51 concretes. However, as Figure 6a, indicates more parameters besides the compressive strength should be considered. Revilla-Cuesta [41] suggested that a partial correction coefficient should be used for every change in concrete composition, including aspects such as the type of concrete (vibrated, high-performance, or self-compacting), the content of RA, the maturity of the RA, and the addition of an alternative binder.

The SC-BOE adequately estimates the shrinkage values for RAC-C50 and RAC-C50-F20 concretes made with CEM IIAL as well as the RAC-C50 and RAC-C50-F10 concrete made with CEM IIAS as the use of RCA slightly increased the shrinkage value of concretes. However, the RCA-C50-F20 made with CEM IIAS achieved a 38% higher shrinkage value than the value estimated by SC-BOE. The SC-BOE adequately estimated the shrinkage value of RCA-C50-F20 made with CEM IIAL as it achieved a lower strength than any concrete produced with this cement. Consequently, it can be stated that the SC-BOE can adequately estimate the drying shrinkage of concrete produced with 50% CRCA and up to 10% FRCA. However, it estimates a lower shrinkage rate than the value obtained experimentally when 50% CRCA and 20% FRCA are employed in concrete production.

In addition, all the concretes made using CEM IIIB reached a higher shrinkage rate than estimated by SC-BOE. Several researchers have reported that the code estimations could create a ±30% dispersion in the results [41,74]. Moreover, this difference increased when recycled aggregates were used. As mentioned previously, concrete with a high BFS content exhibits higher early shrinkage, which can influence total drying shrinkage [42,43]. Furthermore, the specimens were placed in a climatic chamber after a short period of curing (after 1 day of casting) [42], which also influenced the increase in experimentally obtained shrinkage values.

Figure 6b describes the ratio between the experimental results and the values determined by EC-02. The values estimated by EC-02 for concrete produced with CEM IIAL and CEM IIAS were higher than those obtained experimentally. However, similar to SC-BOE, the NAC-0.51 concrete produced using CEM IIIB, EC-02 estimated a lower shrinkage value than it achieved experimentally. Moreover, as mentioned above, EC-02 considers shrinkage increase as a factor due to the use of recycled aggregates. Consequently, the EC-02 prediction of RAC drying shrinkage is more accurate for the experimental results than the values obtained by the SC-BOE.

3.3. Chloride Ion Penetration

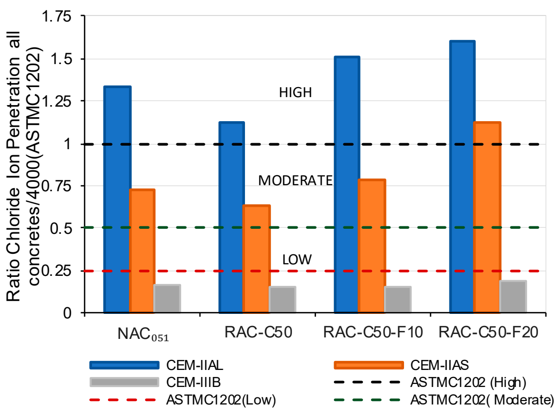
Table 6 describes the chloride ion penetrability values and their standard deviation (values given between brackets) of produced concrete mixtures measured at 28 and 56 days of curing. The ASTMC1202 test classified the chloride ion penetrability as low (1000–2000 Coulomb), moderate (2000–4000 Coulomb), and high (>4000 Coulombs of total passed charge) [75]. This research found that chloride ion penetrability varied significantly according to the type of cement used, as several researchers have stated [32,76–78]. In addition, a direct correlation was observed between the percentage of recycled aggregate replacement ratio and chloride ion penetrability. This is a fact also defined in previous research works [2,4,17].

Table 6. Chloride ion penetrability and the standard deviation (described in brackets) determined in Charge pass in coulombs.

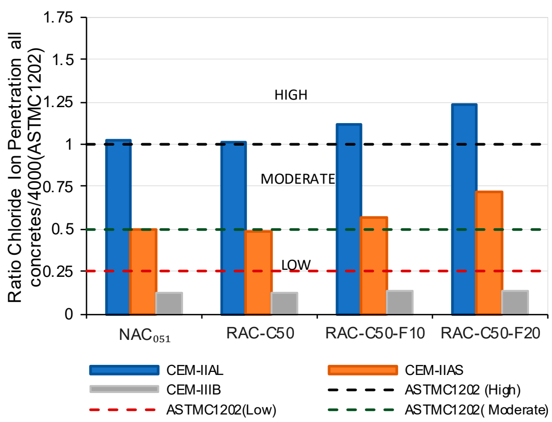
Concrete Types	IIAL (Coulombs)		Δ (%)	IIAS (Coulombs)		Δ (%)	IIIB (Coulombs)		Δ (%)
	28d	56d		28d	56d		28d	56d	
NAC-0.51	5314 (2)	4096 (271)	23	2897 (111)	1976 (129)	32	674 (15)	501 (12)	26
RAC-C50	4479 (441)	4065 (71)	9	2535 (136)	1962 (80)	23	610 (9.0)	503 (8)	18
RAC-C50-F10	6038 (596)	4448 (97)	26	3130 (58)	2293 (5)	27	626 (16)	531 (15)	15
RAC-C50-F20	6401 (569)	4944 (178)	23	4515 (91)	2866 (66)	37	740 (40)	532 (18)	28

( ) Standard deviation. Δ (increase in resistance).

Figure 7 shows the ratio between the charge passed from each concrete produced with respect to 4000 coulombs (the maximum value considered a moderate corrosion risk concrete). Figure 7a,b describe the data at 28 and 56 days, respectively. Figure 7a shows that all concretes manufactured with CEM IIAL exhibit high values of chloride ion penetration. The addition of BFS to cement reduced the ion penetrability of the concrete, as Kopecký and Balázs et al. [78] stated.



(**a**)



(**b**)

Figure 7. The ratio of chloride ion penetrability (determined in charge pass) for all concretes with respect to maximum value of 4000 Coulombs: (**a**) 28 days and (**b**) 56 days.

Based on the influence of RCA use, the RAC-C50 achieved lower chloride ion penetrability than that of NAC, independent of cement type. However, it must be mentioned that the RAC-C50 and NAC-0.51 were produced with effective water–cement ratios of 0.47 and 0.51, respectively. In agreement with the study conducted by Kopeckó and Balázs et al. [78], it was shown that an increase in the w/c ratio leads to an increase in the depth of chloride penetration while keeping the same cement content constant. Moreover, when FRCA was employed for concrete production, and more evidently with the use of 20% FRCA in the replacement of natural sand, the chloride ion penetrability increased. In addition, this was more evident when cement without BSF (CEMII AL) or low BSF (CEM IIAS) was used for concrete production. The high porosity and microcracks of the old mortar are present on the RCA surface, resulting in the increased permeability of chloride ions [75,79].

Researchers have demonstrated that RAC exhibits more capillary channels than NAC; these are primarily attributed to the introduction of interfacial transition zones (ITZs) between natural aggregates and old cement mortars, as well as the presence of microcracks in the RCA [2,15]. However, Etxeberria et al. [80] have demonstrated that the total charge passed value for all concretes mixed using CEM IIIB cement with different percentages of recycled mixed aggregates (volumes of 0%, 25%, 50% and 100%) ranged from 800 to 1400 coulombs. The authors have also demonstrated that an adequate cement type was necessary to increase chloride ion penetration resistance in concrete production. Sim and Park [20] concluded that the incorporation of FRCA had a minimal impact on chloride ion penetration. They observed that the type of cement used had a more significant influence on concrete performance than the quantity of recycled aggregates. In addition, Table 6 shows that the standard deviation of concretes produced with CEM IIAL was higher than that produced with CEM IIAS. In addition, the concretes produced with CEM IIIB achieved the lowest deviation standard. These findings highlight variability in concrete properties due to different cement types. Notably, CEM IIAL and CEM IIAS exhibited relatively high standard deviations; however, to ensure accurate values, more than two should be used.

After a curing period of 56 days (see Figure 7b), the chloride penetration resistance increased in all the concretes. However, all the concretes produced using CEM IIAL, including NAC, still had very high chloride ion penetrability values. This fact can be attributed to the limestone base of CEM IIAL concrete [81], which had higher chloride ion permeability than those mixes with a higher replacement of SCM [81,82]. As a consequence, it was concluded that CEM IIAL cement was unsuitable for defined application due to its limited ability to resist chloride ion penetration. The obtained results of chloride penetrability in this work were slightly lower than those determined by Etxeberria and Castillo [83], in which the concrete produced with 50% coarse RCA and the same type of cement with effective water–cement ratio of 0.50 and a cement content 350 kg/m^3 obtained 8799 C at 28 days and 6377 C at 56 days. In concrete produced using CEM IIAS, an improvement in chloride ion penetration resistance was observed from 28 to 56 days, with a range between 23% and 37% in all samples. This fact demonstrates that all concrete mixtures achieved a moderate level of resistance in terms of chloride ion penetration. In addition, all the concretes produced using type CEM IIIB cement had low chloride permeability at 28 and 56 days, independently of the percentage of RCA employed. As mentioned above, BFS cement enhances chloride penetration resistance in concrete due to its ability to immobilize chloride ions [21,22].

3.4. Carbonation Resistance

Table 7 summarises the carbonation depth (in mm) and its standard deviation (between brackets), which was determined by testing each produced concrete after 91 days of exposure to 3% CO_2, 57% RH and 20 °C. Although the NAC-0.51 concretes achieved the lowest carbonation depths (in each type of cement concretes), the RAC-C50 and RAC-C50-F10 concretes reached similar values to that of NAC-0.51 concrete, with the exception of the RAC-C50-F10 concrete produced with CEM IIAL, which had a 12.9% higher carbonation depth than the corresponding NAC-0.51. According to Guo et al. [2], the RAC and NAC achieved similar resistance and carbonation depth when the RAC was produced with a lower w/c ratio.

Table 7. Carbonation depth, their standard deviation, and the accelerated and theoretical natural carbonation coefficient of all concretes.

Concrete Types	Carbonation Depth (mm) at 90 Days			Carbonation Coefficient					
				kacc (mm/day 0.5)			knatTHEO (mm/year 0.5)		
	II AL	II AS	III B	II AL	II AS	III B	II AL	II AS	III B
NAC-0.51	7.7 (0.1)	6.0 (0.1)	12.0 (0.4)	0.81	0.65	1.22	1.84	1.48	2.79
RAC-C50	8.0 (0.4)	6.1 (0.2)	12.1 (0.2)	0.84	0.68	1.27	1.9	1.55	2.89
RAC-C50-F10	8.7 (0.2)	6.3 (0)	12.1 (0.1)	0.97	0.68	1.28	2.19	1.55	2.92
RAC-C50-F20	9.8 (0.0	7.2 (0.2)	12.9 (0.1)	1.04	0.78	1.39	2.37	1.77	3.16

Moreover, the use of 20% FRCA in natural sand replacement proved to reduce the carbonation resistance of concrete. The RAC-C50-F20 concrete achieved the highest carbonation depth in each cement type concrete.

The accelerated carbonation coefficient (*Kacc*) of each concrete was calculated under a steady state condition based on Fick's first law of diffusion, represented by Equation (1).

$$Xc(t) = Kacc \cdot (t)^{0.5} \tag{1}$$

where *Xc* is the determined carbonation depth (mm), *Kacc* is the carbonation coefficient (mm/day$^{0.5}$), and *t* is time (days). The carbonation depth was determined at 0, 14, 28, 56, 70, and 91 days.

As shown in Table 7, the concretes produced with CEM IIAS cement achieved the lowest Kacc values, followed by those made with the CEM IIAL and CEM IIIB. The RAC-C50-F20 concrete produced with CEM IIAS also achieved a lower Kacc than that of the NAC-0.51 produced with CEM IIAL and CEM IIIB. These findings are consistent with Etxeberria et al. [34], who demonstrated that concretes with CEM IIAS display the lowest values of carbonation depth, regardless of the aggregates used. In addition, the test proved that any concrete produced with CEM IIAL achieved a lower carbonation rate than NAC-0.51 produced with CEM IIIB. Several researchers [33,84] have noted that this increase in the carbonation coefficient in concrete made with CEM IIIB is directly related to a reduced clinker content when compared to CEM IIAL and CEM IIAS cement types, as well as the reduced CO_2 buffering capacity. Consequently, the carbonation resistance of recycled concrete decreases when the employed cement was composed of a high volume of mineral admixtures, reducing the CaO content [20,33,85], resulting in the coarsening of the pore structure and potentially diminishing its durability [30].

In addition, the accelerated carbonation coefficient of RAC-C50 concretes increased by less than 4% compared to that of NAC, regardless of the cement type employed. These findings are in line with several research studies [24,27,33,83]. Moreover, the Kacc of concrete produced with 10% FRCA in the replacement of natural sand, using CEM IIAS and CEM IIIB, were 5.2% and 4.8%, higher, respectively, than that of NAC-0.51. However, the concrete produced with CEM IIAL reached a 19.4% higher value than that of NAC. Furthermore, the use of 20% FRCA in replacement of natural sand increased the Kacc value. The RAC-C50-F20 concretes produced with CEM IIAL, CEM IIAS, and CEM IIIB cements achieved 29.1%, 19.7%, and 13.3% higher *Kacc* values, respectively, than the corresponding NAC-0.51 concrete. The findings demonstrate that incorporating FRCA replacements can lead to notable increases in the carbonation depth.

It is important to note that even when concretes achieved the same compressive strength at 28 days, there were variations in the carbonation depth values depending on the type of cement used.

The theoretical natural carbonation coefficient (*knatTHEO*) is related to the *kacc*, and it can be determined using Equation (2) [86,87]. The obtained values of *knatTHEO* are described for each in Table 7. According to previous wok [34], it was determined that the *knatTHEO* of NAC and RAC was 1.6 and 1.8 times higher, respectively, than knat (natural carbonation rate obtained experimentally), guaranteeing similar behaviour in both types of concretes. Leemann et al. [33] supports the use of accelerated carbonation tests as a method for evaluating resistance under natural conditions. Nevertheless, further research is needed to enhance the predictive capability of carbonation depth in RAC and its accuracy with different levels of RCA [88].

$$\frac{Kacc}{KnatTHEO} = \frac{(\varnothing acc)^{0.5}}{(\varnothing natTHEO)^{0.5}}, \quad (2)$$

where $\varnothing acc$ and $\varnothing natTHEO$ are the CO_2 concentrations in the accelerated carbonation (3%) and natural carbonation processes (425 ppm, in Barcelona), respectively.

Table 8 describes the carbonation depth values obtained by each produced concrete, calculated based on the *knatTHEO* rate, over a lifespan of 50 and 100 years. According to The Spanish Structural Concrete Code (SC-BOE) [47], concrete produced for use under XC3 exposure conditions must have a minimum cover of 20 mm for 50 years and 30 mm for 100 years lifespans. Additionally, for concrete XC4 environment conditions, a minimum cover depth of 25 mm for 50 year and 35 mm for 100 years lifespans are obligatory.

Table 8. Carbonation depth after lifespan of 50 and 100 years.

Concrete Types		Carbonation Depth (50 Years)			Carbonation Depth (100 Years)		
		II AL	II AS	III B	II AL	II AS	III B
NAC-051		13.0	10.4	19.7	18.4	14.8	27.9
RAC-C50		13.5	11.0	20.5	19.0	15.5	28.9
RAC-C50-F10		15.5	11.0	20.6	21.9	15.5	29.2
RAC-C50-F20		16.8	12.5	22.3	23.7	17.7	31.6
Min. Cover (mm) [47]	XC3		20			25	
	XC4		30			35	

According to the obtained results, it was determined that all the concretes manufactured with CEM IIAL and CEM IIAS, including RAC-C50-F20, were suitable to be used in XC3 and XC4 exposure environments, both over 50 and 100-year lifespans.

Based on concretes produced using CEM IIIB, while all the concretes were acceptable to be exposed to the XC4 environment for 50 and 100 years, none of the concrete could be considered adequate for exposure to an XC3 environment, even for 50 years. In addition, the theoretical carbonation depth value of NAC-0.51 was 19.7mm in 50 years, and according to the Structural Concrete Code (SC-BOE), the minimum cover is 20 mm.

Moreover, according to Silva et al. [23], in order to prevent corrosion of concretes exposed to environmental conditions classified as XC3 and XC4 (as specified in the EN 206-1), the maximum accelerated carbonation coefficient should be 35 mm/year$^{0.5}$ for XC3 and 50 mm/year$^{0.5}$ for XC4 when 50 years of service life is considered. Consequently, according to those limits, all the concretes produced complied with the minimum requirements established for XC3 and XC4 environments during a 50-year service life.

4. Conclusions

The results of this study lead to the following conclusions:

- The compressive strength of RAC using 50% CRCA and up to 20% FRCA was lower than that of NA when being produced with the same w/c ratio. Consequently, the RAC must have a 0.04 lower effective water–cement ratio than that of the NAC to achieve the same compressive strength.

- All the RAC using 50% CRCA and up to 20% FRCA achieved a suitably designed compressive strength of C30/37 for structural applications.

The durability properties of RAC concretes, (RAC and NAC proved to have similar compressive strength):

- RAC produced with 50% CRCA and up to 10% FRCA achieved a similar shrinkage value to that of NAC, independent of the cement type employed. Although the use of 20% FRCA increased the drying shrinkage values of the concretes, the total drying shrinkage values obtained by RAC-C50-F20 concretes were acceptable for a structural concrete application.
- A comparative study of both the EC-02 and SC-BOE standards determined that the first provided higher accuracy in predicting drying shrinkage of RAC than the latter, independent of the type of cement employed. However, there are no standards which precisely estimate the shrinkage value of NAC produced with CEM IIIB. This is probably due to the fact that the standards are mainly based on considering the compressive strength at 28 days as the prime factor instead of the initial shrinkage value.
- The use of BFS cement reduced ion chloride penetrability independently of the type of aggregates used. Concretes made with CEM IIIB, including RAC-C50-F20, reached a very low ion penetrability, suitable for structural applications. In addition, the CEM IIAS concretes achieved moderate ion penetrability, except for the RAC-C50-F20, which achieved a high chloride ion penetrability due to the use of 20% FRCA. Moreover, all of the concretes, including NAC with CEM IIAL cement, achieved high penetrability and were unsuitable for structural applications.
- All concrete produced with CEM IIAS, including the RAC-C50-F20, achieved a lower carbonation coefficient than NAC with CEM IIAL cement. However, concretes manufactured with CEM IIAL and CEM IIAS were suitable for use in XC3 and XC4 exposure environments at 50 and 100-year lifespans.
- The carbonation resistance of RAC decreased when the cement employed had a high BFS. In addition, incorporating 20% FRCA can lead to notable increases in carbonation depth.

This study also underscores the critical importance of cement type selection in the durability and strength of structural recycled aggregate concrete, particularly under specific conditions. The concrete using CEM IIAS cement has been shown to meet durability requirements in accordance with shrinkage value, chloride penetrability and carbonation resistance, even with replacement rates of up to 50% CRCA-10% FRCA. However, while the concrete using CEM IIAL achieved low chloride penetration resistance, the concrete produced with CEM IIIB achieved low carbonation resistance, independently of the type of aggregates used for concrete production.

As futures research lines, it is recommended to conduct long-term research to assess the durability and resistance to factors such as corrosion and carbonation in structures built with recycled aggregates.

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References

1. Alabi, S.A.; Mahachi, J. Chloride ion penetration performance of recycled concrete with different geopolymers. *Mater. Today Proc.* **2020**, *38*, 762–766. [CrossRef]
2. Guo, H.; Shi, C.; Guan, X.; Zhu, J.; Ding, Y.; Ling, T.-C.; Zhang, H.; Wang, Y. Durability of recycled aggregate concrete—A review. *Cem. Concr. Compos.* **2018**, *89*, 251–259. [CrossRef]
3. Plaza, P.; del Bosque, I.S.; Frías, M.; de Rojas, M.S.; Medina, C. Use of recycled coarse and fine aggregates in structural eco-concretes. Physical and mechanical properties and CO_2 emissions. *Constr. Build. Mater.* **2021**, *285*, 122926. [CrossRef]
4. Pedro, D.; de Brito, J.; Evangelista, L. Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties. *Constr. Build. Mater.* **2017**, *154*, 294–309. [CrossRef]
5. Guo, Z.; Chen, C.; Lehman, D.E.; Xiao, W.; Zheng, S.; Fan, B. Mechanical and durability behaviours of concrete made with recycled coarse and fine aggregates. *Eur. J. Environ. Civ. Eng.* **2020**, *24*, 171–189. [CrossRef]
6. Berredjem, L.; Arabi, N.; Molez, L. Mechanical and durability properties of concrete based on recycled coarse and fine aggregates produced from demolished concrete. *Constr. Build. Mater.* **2020**, *246*, 118421. [CrossRef]
7. Le, H.-B.; Bui, Q.-B. Recycled aggregate concretes—A state-of-the-art from the microstructure to the structural performance. *Constr. Build. Mater.* **2020**, *257*, 119522. [CrossRef]
8. Thomas, C.; Setién, J.; Polanco, J.; Alaejos, P.; de Juan, M.S. Durability of recycled aggregate concrete. *Constr. Build. Mater.* **2013**, *40*, 1054–1065. [CrossRef]
9. Kwan, W.H.; Ramli, M.; Kam, K.J.; Sulieman, M.Z. Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Constr. Build. Mater.* **2011**, *26*, 565–573. [CrossRef]
10. Sereewatthanawut, I.; Prasittisopin, L. Environmental evaluation of pavement system incorporating recycled concrete aggregate. *Int. J. Pavement Res. Technol.* **2020**, *13*, 455–465. [CrossRef]
11. Xing, W.; Tam, V.W.; Le, K.N.; Hao, J.L.; Wang, J. Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Constr. Build. Mater.* **2022**, *317*, 125950. [CrossRef]
12. Velardo, P.; del Bosque, I.S.; de Rojas, M.S.; De Belie, N.; Medina, C. Durability of concrete bearing polymer-treated mixed recycled aggregate. *Constr. Build. Mater.* **2022**, *315*, 125781. [CrossRef]
13. Li, X. Recycling and reuse of waste concrete in China. *Resour. Conserv. Recycl.* **2008**, *53*, 36–44. [CrossRef]
14. Adessina, A.; Ben Fraj, A.; Barthélémy, J.-F. Improvement of the compressive strength of recycled aggregate concretes and relative effects on durability properties. *Constr. Build. Mater.* **2023**, *384*, 131447. [CrossRef]
15. Zhan, B.J.; Xuan, D.X.; Zeng, W.; Poon, C.S. Carbonation treatment of recycled concrete aggregate: Effect on transport properties and steel corrosion of recycled aggregate concrete. *Cem. Concr. Compos.* **2019**, *104*, 103360. [CrossRef]
16. Bravo, M.; De Brito, J.; Pontes, J.; Evangelista, L. Durability performance of concrete with recycled aggregates from construction and demolition waste plants. *Constr. Build. Mater.* **2015**, *77*, 357–369. [CrossRef]
17. Evangelista, L.; de Brito, J. Durability performance of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2010**, *32*, 9–14. [CrossRef]
18. Lotfi, S.; Eggimann, M.; Wagner, E.; Mróz, R.; Deja, J. Performance of recycled aggregate concrete based on a new concrete recycling technology. *Constr. Build. Mater.* **2015**, *95*, 243–256. [CrossRef]
19. Sucic, A.; Lotfy, A. Effect of new paste volume on performance of structural concrete using coarse and granular recycled concrete aggregate of controlled quality. *Constr. Build. Mater.* **2016**, *108*, 119–128. [CrossRef]
20. Sim, J.; Park, C. 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 Manag.* **2011**, *31*, 2352–2360. [CrossRef]
21. Pinto, S.R.; da Luz, C.A.; Munhoz, G.S.; Medeiros-Junior, R.A. Resistance of phosphogypsum-based supersulfated cement to carbonation and chloride ingress. *Constr. Build. Mater.* **2020**, *263*, 120640. [CrossRef]
22. Nishida, T.; Otsuki, N.; Ohara, H.; Garba-Say, Z.M.; Nagata, T. Some Considerations for Applicability of Seawater as Mixing Water in Concrete. *Sustain. Constr. Mater. Technol.* **2013**, 27. [CrossRef]
23. Silva, R.; Neves, R.; de Brito, J.; Dhir, R. Carbonation behaviour of recycled aggregate concrete. *Cem. Concr. Compos.* **2015**, *62*, 22–32. [CrossRef]
24. Etxeberria, M. Evaluation of Eco-Efficient Concretes Produced with Fly Ash and Uncarbonated Recycled Aggregates. *Materials* **2021**, *14*, 7499. [CrossRef]
25. Xiao, J.; Lei, B.; Zhang, C. On carbonation behavior of recycled aggregate concrete. *Sci. China Technol. Sci.* **2012**, *55*, 2609–2616. [CrossRef]
26. Pedro, D.; de Brito, J.; Evangelista, L. Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Constr. Build. Mater.* **2014**, *71*, 141–151. [CrossRef]
27. Zeng, X. Progress in the research of carbonation resistance of RAC. *Constr. Build. Mater.* **2020**, *230*, 116976. [CrossRef]

28. Sideris, K.K.; Manita, P. Influence of Blended Cements on the Service Life of Reinforced Concrete Structures against Carbonation Induced Corrosion. In *International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of CBMs and Concrete Structures*; Springer Nature Switzerland: Cham, Switzerland, 2023; pp. 1048–1054. [CrossRef]
29. Kirthika, S.; Singh, S. Durability studies on recycled fine aggregate concrete. *Constr. Build. Mater.* **2020**, *250*, 118850. [CrossRef]
30. von Greve-Dierfeld, S.; Lothenbach, B.; Vollpracht, A.; Wu, B.; Huet, B.; Andrade, C.; Medina, C.; Thiel, C.; Gruyaert, E.; Vanoutrive, H.; et al. Understanding the carbonation of concrete with supplementary cementitious materials: A critical review by RILEM TC 281-CCC. *Mater. Struct.* **2020**, *53*, 136. [CrossRef]
31. Borges, P.H.; Costa, J.O.; Milestone, N.B.; Lynsdale, C.J.; Streatfield, R.E. Carbonation of CH and C–S–H in composite cement pastes containing high amounts of BFS. *Cem. Concr. Res.* **2010**, *40*, 284–292. [CrossRef]
32. Flegar, M.; Bašić, A.D.; Bukvić, O.; Serdar, M. Carbonation of Concretes with Different Binder Chemistry–A Comparative Analysis. In *International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of Cement-Based Materials and Concrete Structures. SynerCrete 2023*; Jędrzejewska, A., Kanavaris, F., Azenha, M., Benboudjema, F., Schlicke, D., Eds.; RILEM Bookseries; Springer: Cham, Switzerland, 2023; Volume 44. [CrossRef]
33. Leemann, A.; Loser, R. Carbonation resistance of recycled aggregate concrete. *Constr. Build. Mater.* **2019**, *204*, 335–341. [CrossRef]
34. Etxeberria, M. Carbonation resistance of recycled aggregate concrete using different cement types. In *RILEM Bookseries*; Springer: Cham, Switzerland, 2023; Volume 44, pp. 1065–1076. [CrossRef]
35. Silva, R.; de Brito, J.; Dhir, R. Prediction of the shrinkage behavior of recycled aggregate concrete: A review. *Constr. Build. Mater.* **2015**, *77*, 327–339. [CrossRef]
36. Vintimilla, C.; Etxeberria, M. Limiting the maximum fine and coarse recycled aggregates-Type A used in structural concrete. *Constr. Build. Mater.* **2023**, *380*, 131273. [CrossRef]
37. Gonzalez-Corominas, A.; Etxeberria, M. Effects of using recycled concrete aggregates on the shrinkage of high performance concrete. *Constr. Build. Mater.* **2016**, *115*, 32–41. [CrossRef]
38. Mcdonald, D.B.; Brooks, J.J.; Burg, R.G.; Daye, M.A.; Gardner, N.J.; Novak, L.C. Report on Factors Affecting Shrinkage and Creep of Hardened Concrete Reported by ACI Committee 209, 2014. Available online: https://scholar.google.es/scholar?hl=es&as_sdt=0%2C5&q=Mcdonald%2C+D.B.%3B+Brooks%2C+J.J.%3B+Burg%2C+R.G.%3B+Daye%2C+M.A.%3B+Gardner%2C+N.J.%3B+Novak%2C+L.C.+Report+on+Factors+Affecting+Shrinkage+and+Creep+of+Hardened+Concrete+Reported+by+ACI+Committee+20 (accessed on 14 September 2023).
39. Şimşek, O.; Sefidehkhan, H.P.; Gökçe, H. Performance of fly ash-blended Portland cement concrete developed by using fine or coarse recycled concrete aggregate. *Constr. Build. Mater.* **2022**, *357*, 129431. [CrossRef]
40. Sosa, M.E.; Zega, C.J. Experimental and Estimated Evaluation of Drying Shrinkage of Concrete Made with Fine Recycled Aggregates. *Sustainability* **2023**, *15*, 7666. [CrossRef]
41. Revilla-Cuesta, V.; Evangelista, L.; de Brito, J.; Skaf, M.; Manso, J.M. Shrinkage prediction of recycled aggregate structural concrete with alternative binders through partial correction coefficients. *Cem. Concr. Compos.* **2022**, *129*, 104506. [CrossRef]
42. Yang, J.; Wang, Q.; Zhou, Y. Influence of Curing Time on the Drying Shrinkage of Concretes with Different Binders and Water-to-Binder Ratios. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 2695435. [CrossRef]
43. Hooton, R.; Stanish, K.; Angel, J.; Prusinski, J. The Effect of Ground Granulated Blast Furnace Slag (Slag Cement) on the Drying Shrinkage of Concrete—A Critical Review of the Literature. In *SP-263 Slag Cement Concrete*; American Concrete Institute: Indianapolis, IN, USA, 2009; pp. 79–94. [CrossRef]
44. *EN 197-1:2001*; Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements. European Committee for Standardization: Brussels, Belgium, 2011.
45. UNE-EN 933-1; Tests for Geometrical Properties of Aggregates Part 1: Determination of Particle Size Distribution—Sieving Method. 2012. Available online: www.aenor.es (accessed on 14 September 2023).
46. UNE-EN 12620: 2003+A1; Aggregates for Concrete, 2009. Available online: www.aenor.es (accessed on 14 September 2023).
47. Boletín Oficial del Estado (BOE), Structural Concrete Code. 2021. Available online: https://www.boe.es/eli/es/rd/2021/06/29/470 (accessed on 14 September 2023).
48. UNE-EN 1097-6; Determination of Particle Density and Water Absorption, 2014. Available online: www.aenor.es (accessed on 14 September 2023).
49. UNE-EN 933-8: 2012+A1; Assessment of Fines—Sand Equivalent Test, 2015. Available online: www.aenor.es (accessed on 14 September 2023).
50. UNE-EN 933-3; Determination of Particle Shape—Flakiness Index, 2012. Available online: www.aenor.es (accessed on 14 September 2023).
51. *UNE 146508*; Determination of the Alkali-Silica and Alkali-Silicate Potential Reactivity of Aggregates. Accelerated Mortar bar Test. Spanish Standard: Madrid, Spain, 2018.
52. Etxeberria, M.; Konoiko, M.; Garcia, C.; Perez, M. Water-Washed Fine and Coarse Recycled Aggregates for Real Scale Concretes Production in Barcelona. *Sustainability* **2022**, *14*, 708. [CrossRef]
53. UNE-EN 933-11; Classification Test for the Constituents of Coarse Recycled Aggregate, 2009. Available online: www.aenor.es (accessed on 14 September 2023).
54. *UNE-EN 206: 2013+A1*; Specification, Performance, Production and Conformity. Spanish Standard: Madrid, Spain, 2016.

55. Nedeljković, M.; Visser, J.; Šavija, B.; Valcke, S.; Schlangen, E. Use of fine recycled concrete aggregates in concrete: A critical review. *J. Build. Eng.* **2021**, *38*, 102196. [CrossRef]
56. Silva, S.; Evangelista, L.; de Brito, J. Durability and shrinkage performance of concrete made with coarse multi-recycled concrete aggregates. *Constr. Build. Mater.* **2021**, *272*, 121645. [CrossRef]
57. Wagih, A.M.; El-Karmoty, H.Z.; Ebid, M.; Okba, S.H. Recycled construction and demolition concrete waste as aggregate for structural concrete. *HBRC J.* **2013**, *9*, 193–200. [CrossRef]
58. Zega, C.J.; Di Maio, Á.A. Use of recycled fine aggregate in concretes with durable requirements. *Waste Manag.* **2011**, *31*, 2336–2340. [CrossRef]
59. Sosa, M.E.; Zaccardi, Y.A.V.; Zega, C.J. A critical review of the resulting effective water-to-cement ratio of fine recycled aggregate concrete. *Constr. Build. Mater.* **2021**, *313*, 125536. [CrossRef]
60. *UNE EN 12350-2*; Testing Fresh Concrete—Part 2: Slump Test. Spanish Standard: Madrid, Spain, 2019.
61. *UNE-EN-12390-3*; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Spanish Standard: Madrid, Spain, 2019.
62. *UNE EN 12390-16*; Determination of the Shrinkage of Concrete. Spanish Standard: Madrid, Spain, 2019.
63. *ASTM C1202*; Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. American Society for Testing and Materials: West Conshohocken, PA, USA, 2012; pp. 1–8.
64. *UNE-EN12390-12*; Determination of the Carbonation Resistance of Concrete—Accelerated Carbonation Method. Spanish Standard: Madrid, Spain, 2020.
65. *UNE EN 14630:2007*; Determination of Carbonation Depth in Hardened Concrete by the Phenolphthalein Method. Spanish Standard: Madrid, Spain, 2007.
66. Ortiz, J.; Aguado, A.; Agulló, L.; García, T. Influence of environmental temperatures on the concrete compressive strength: Simulation of hot and cold weather conditions. *Cem. Concr. Res.* **2005**, *35*, 1970–1979. [CrossRef]
67. Gao, D.; Wang, F. Effects of recycled fine aggregate and steel fiber on compressive and splitting tensile properties of concrete. *J. Build. Eng.* **2021**, *44*, 102631. [CrossRef]
68. Evangelista, L.; de Brito, J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2007**, *29*, 397–401. [CrossRef]
69. Kim, J. Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. *Constr. Build. Mater.* **2022**, *328*, 127071. [CrossRef]
70. Lye, C.-Q.; Dhir, R.K.; Ghataora, G.S. Shrinkage of recycled aggregate concrete. *Mater. Struct.* **2018**, *51*, 129. [CrossRef]
71. Bendimerad, A.; Delsaute, B.; Rozière, E.; Staquet, S.; Loukili, A. Advanced techniques for the study of shrinkage-induced cracking of concrete with recycled aggregates at early age. *Constr. Build. Mater.* **2020**, *233*, 117340. [CrossRef]
72. Etxeberria, M.; Gonzalez-Corominas, A. The assessment of ceramic and mixed recycled aggregates for high strength and low shrinkage concretes. *Mater. Struct.* **2018**, *51*, 129. [CrossRef]
73. *EN 1992-1-1:2021*; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules—Rules for Buildings, Bridges and Civil Engineering Structures. European Union: Brussels, Belgium, 2021.
74. Wang, Q.; Geng, Y.; Wang, Y.; Zhang, H. Drying shrinkage model for recycled aggregate concrete accounting for the influence of parent concrete. *Eng. Struct.* **2019**, *202*, 109888. [CrossRef]
75. Zhu, P.; Hao, Y.; Liu, H.; Wang, X.; Gu, L. Durability evaluation of recycled aggregate concrete in a complex environment. *J. Clean. Prod.* **2020**, *273*, 122569. [CrossRef]
76. Vázquez, E.; Barra, M.; Aponte, D.; Jiménez, C.; Valls, S. Improvement of the durability of concrete with recycled aggregates in chloride exposed environment. *Constr. Build. Mater.* **2014**, *67*, 61–67. [CrossRef]
77. Mohammed, T.U.; Rahman, M. Effects of cement types on chloride ingress in concrete. In Proceedings of the 3rd ACF Symposium on Assessment and Intervention of Existing Structures, Sapporo, Japan, 10–11 September 2019.
78. Kopecskó, K.; Balázs, G.L. Concrete with Improved Chloride Binding and Chloride Resistivity by Blended Cements. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 7940247. [CrossRef]
79. Wu, J.; Zhang, Y.; Zhu, P.; Feng, J.; Hu, K. Mechanical Properties and ITZ Microstructure of Recycled Aggregate Concrete Using Carbonated Recycled Coarse Aggregate. *J. Wuhan Univ. Technol. Mater. Sci. Ed.* **2018**, *33*, 648–653. [CrossRef]
80. Etxeberria, M.; Gonzalez-Corominas, A. Properties of Plain Concrete Produced Employing Recycled Aggregates and Sea Water. *Int. J. Civ. Eng.* **2018**, *16*, 993–1003. [CrossRef]
81. Githachuri, K.; Alexander, M.G. Durability performance potential and strength of blended Portland limestone cement concrete. *Cem. Concr. Compos.* **2013**, *39*, 115–121. [CrossRef]
82. Otieno, M.; Beushausen, H.; Alexander, M. Effect of chemical composition of slag on chloride penetration resistance of concrete. *Cem. Concr. Compos.* **2013**, *46*, 56–64. [CrossRef]
83. Etxeberria, M.; Castillo, S. How the Carbonation Treatment of Different Types of Recycled Aggregates Affects the Properties of Concrete. *Sustainability* **2023**, *15*, 3169. [CrossRef]
84. Leemann, A.; Nygaard, P.; Kaufmann, J.; Loser, R. Relation between carbonation resistance, mix design and exposure of mortar and concrete. *Cem. Concr. Compos.* **2015**, *62*, 33–43. [CrossRef]
85. Pedro, D.; de Brito, J.; Evangelista, L. Performance of concrete made with aggregates recycled from precasting industry waste: Influence of the crushing process. *Mater. Struct.* **2015**, *48*, 3965–3978. [CrossRef]

86. Parrott, L.J. Cement and Concrete Association; Building Research Establishment. A Review of Carbonation in Reinforced Concrete; Cement and Concrete Association. 1987. Available online: http://worldcat.org/isbn/0721013651 (accessed on 15 June 2023).
87. Heede, P.V.D.; De Belie, N. A service life based global warming potential for high-volume fly ash concrete exposed to carbonation. *Constr. Build. Mater.* **2014**, *55*, 183–193. [CrossRef]
88. Carević, V.; Ignjatović, I.; Dragaš, J. Model for practical carbonation depth prediction for high volume fly ash concrete and recycled aggregate concrete. *Constr. Build. Mater.* **2019**, *213*, 194–208. [CrossRef]