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Durable Structural Concrete Using Fine and Coarse Recycled Aggregates (Type A and Type B)

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Abstract. The use of *Recycled concrete aggregate (RCA, type A) and mixed recycled aggregate (MRA, type B) is an alternative for structural concrete production to reduce natural resource exploitation and landfilling of construction waste. However, the lower quality of recycled aggregate compared to that of natural aggregate, and consequently the lower durability of recycled concrete, make it necessary to limit the percentage of replacement of raw aggregates by recycled aggregates. The objective of this study is to analyse the adequacy of using different percentages (following European standards) of coarse and fine type A and type B recycled aggregates for structural concrete production. All the concrete mixtures were produced using 300kg/m3 of cement and an effective water: cement ratio of 0.48 to be exposed to the XC1-XC4 environment. In addition, the conventional concrete (0% recycled aggregates) was also produced using an effective water: cement ratio of 0.52. The physical and mechanical properties, drying shrinkage values, and durability property of sorptivity and water penetration values were determined in all the produced concretes. It was concluded that the concrete produced with up to 60 % coarse RCA and 30 % fine RCA (type A) aggregates achieved adequate properties for structural concrete. In addition, the use of MRA mixed recycled aggregate (type B) was also possible for structural concrete production when it was employed in the replacement of natural aggregates up to 40% for coarse MRA and 15% for fine MRA simultaneously.*

Keywords: *Materials; Durability; coarse and fine recycled aggregates; drying shrinkage; sorptivity, water penetration; recycled concrete aggregates; mixed recycled aggregates.*

1. Introduction

Concrete is a widely used construction material, but its deterioration can have serious consequences on society, the economy, and the environment. For this reason, there is a growing interest in the use of recycled aggregates (RA) to produce more sustainable and environmentally friendly concrete (Cantero et al. 2021).

Recycled concrete aggregates (RCA) have higher porosity, greater absorption capacity, lower density, more abrasion loss, and more crushability than natural aggregates (NA) (Silva, Evangelista, and de Brito 2021). The use of RCA in concrete structures leads to reduce the mechanical strength and durability (de Andrade Salgado and de Andrade Silva 2022). However, according to (Vintimilla and Etxeberria 2023), the concrete produced up to 60% coarse RCA and 30% fine RCA achieved adequate properties for structural concrete use. Similarly, (Cantero et al. 2018) concluded that compressive strength did not vary significantly at a replacement ratio under 50% of coarse mixed recycled aggregate (MRA). In contrast, (Meng et al. 2021) concluded that the concrete produced with 100% fine and coarse MRA using different water-cement ratios (w/c) decreased the compressive strength up to 40-45% with respect to that of conventional concrete (NAC). However, the use of fine RA in concrete structures requires stricter quality control compared to NA (Zhang et al. 2020). Durability is affected more severely than strength in recycled concrete (RAC). The durability of concrete made with RA decreases with increased RA used in the mix concrete (Thomas, Thaickavil, and Wilson 2018). Few studies have been conducted on the durability properties of concrete produced using fine and coarse RA (Berredjem, Arabi, and Molez 2020).

The shrinkage values obtained by RAC, are higher than that of NAC, and the shrinkage increases when a higher percentage of RCA is employed. According to (Vintimilla and Etxeberria 2023), the drying shrinkage of concrete produced with 100% fine and coarse RCA was 99.3% higher than that of NAC. Furthermore, some studies found that the shrinkage in concrete made with 100% MRA was too high and variable to be usable in structural concrete (Etxeberria et al. 2022; Lye, Dhir, and Ghataora 2016).

This research study analyses the adequacy of using up to 60% coarse and 30% of fine RCA (Type A RA) and up to 40% coarse and 15% fine MRA (Type B RA) for durable and sustainable concrete production

2. Materials

CEM II A-L 42.5 R cement was used to produce all the concretes. Two chemical admixtures were also used: a superplasticizer (S,based on PAE, polycarboxylate ether, polymer technology) and a multifunctional admixture (P,based on Modified Lignin Sulfonate).

In the production of NAC concrete, natural aggregates were used, including fine crushed limestone (0/4 mm, FNA) and coarse aggregates (CNA1 of 4/8 mm and CNA2 of 8/20 mm).

2.1 Recycled Aggregates

Fine and coarse fractions of RCA (type A) and MRA) type B) were used.

The components of RCA and MRA coarse fractions were determined following the EN 933-11 specifications. In accordance with the EN 206 specification, RCA was classified as Type A, which consisted of >90% concrete (RC) and natural stone (Ru) components, with ceramic content of <10%. In addition, MRA was classified as Type B, which consisted of >50% RC and Ru components, with ceramic content of <30%. The grading distribution of all the aggregate fractions was determined. Moreover, All the concrete mixtures were produced using a similar global grading distribution. Furthermore, the Los Angeles coefficient (LA) and Flakiness index were lower than the maximum limit defined by the Structural Concrete Code (SC-BOE). The CRCA-2 and CMRA-2 achieved a LA of 40% and 35%, respectively.

Table 1 shows the density and absorption properties of all the aggregate fractions employed. Although the properties of RA were found to differ from those of NAs due to the presence of adhered mortar, the dry density of the type A RCA aggregate was higher than the minimum required value of 2.1 kg/dm^3 for type A aggregates. In addition, the dry density of the different fractions of type B MRA aggregate was also higher than the minimum value of 1.7 kg/dm3 required by European standard EN 206 to be used in concrete production. Regarding absorption capacity, both FRCA (fine RCA) and CRCA (coarse RCA) achieved a lower value than the maximum limit of 7% established by the Structural Concrete Code (SC-BOE). In contrast, the absorption capacity of CMRA was higher than the established limit value. However, the MRA fractions (CMRA and FMRA) were used in low replacement percentages.

Table 1: Properties of all aggregates

	FNA (0/4)	CNA1 (2/10)	CNA2 (8/20)	FRCA (0/4)	CRCA-1(2/10)	CRCA-2(8/20)	FMRA (0/4)	CMRA-1 (2/10)	CMRA-2 (8/20)
Dry density (kg/dm3)	2.67	2.65	2.68	2.31	2.22	2.36	2.28	2.15	2.08
Absorption (%)	0.96	0.77	0.73	6.1	6.63	5.15	6.67	8.75	9

3. Mix proportions and test procedure

3.1. Mix proportions

All the concrete mixtures were designed for XC1-XC4 environments, requiring a minimum characteristic design strength (fck) of 30 MPa (C30/37) and average strength of 38 MPa. Table 2 shows the concretes' mix proportions. All the concretes were produced using 300 kg/ m^3 cement. The NAC$_1$ and all the recycled aggregate concretes (RAC) were produced using an effective water/cement ratio of 0.48. In addition, the NAC$_2$ conventional concrete was made with an effective water/cement ratio of 0.52.

The RAC produced using fine and coarse RCA are designated as RAC-CX-FY1, where X represents the percentage of replacement of coarse natural aggregates, and Y represents the percentage of FRCA used in the replacement of natural sand. Similarly, the concretes produced with Type B aggregates were designated as MRAC-CX-FY1. All fractions of coarse RA were employed with a high humidity content, and the fine RA was used in an oversaturated condition. However, in order to maintain constant, the effective w/c ratio in all the mixtures, the effective water absorption of aggregates was considered in concrete production. The effective absorption capacity of the aggregates was determined by measuring the amount of water absorbed by the aggregates over a 30-minute period. As a result, the effective absorption capacity of the natural fine and coarse aggregates was 70% and 20% of their total absorption capacities, respectively, while the coarse recycled aggregates had effective absorption capacities of 70% of their total absorption capacities.

Table 2. Mix proportions

Mix	Cem (Kg)	Total Water (Kg)	FNA (Kg)	Fine AR (Kg)	CNA 1 (Kg)	Course AR 1 (Kg)	CNA 2 (Kg)	Course AR 2 (Kg)	S (%)	P (%)	Slump (mm)
NAC$_1$	300	157.5	994	-	247	-	831	-	1.5	-	100
NAC$_2$	300	165	981	-	243	-	815	-	1.0	1.2	160
RAC-C50-F20$_1$	300	190.0	762	163	144	121	416	358	1.2	1.5	180
RAC-C60-F20$_1$	300	194.8	762	163	115	145	333	429	1.2	1.5	200
RAC-C60-F30$_1$	300	199.3	667	244	115	145	333	429	1.2	1.5	160
MRAC-C20-F5$_1$	300	172.1	944	43	198	40	665	130	1,2	1.7	200
MRAC-C30-F10$_1$	300	180.5	894	85	173	60	582	195	1.2	1.7	180
MRAC-C40-F15$_1$	300	189.4	809	122	173	94	499	260	1.2	17	180

All concrete mixtures exhibited similar consistency except the NAC1 concrete, which needed a higher amount of admixture. Moreover, the mixtures produced using MRA aggregates required more admixture, possibly due to the increased amount of ceramic material.

3.2. Test Procedure

The physical properties of dry density and Absorption (UNE-EN 12390-7:2020) was determined at 28 days. In addition, the mechanical properties of compressive strength (UNE-EN 12390-3) at 28 and 56 days and elastic modulus (UNE-EN 12390-13) at 28 days were determined in all the concretes produced. Cube specimens of 100 mm were used for compressive strength and physical properties. Cylindrical samples 100 mm in diameter and 20 mm long were used to test the modulus of elasticity in the produced concrete. Three specimens were used for each test to calculate the average value.

The capillary water absorption (including sorptivity) was assessed using 100 cubic specimens following the ISO 15148:2002(E). The water penetration under pressure (UNE-EN 12390-9) was determined using cylindrical samples 100 mm in diameter and 20 mm long. The drying shrinkage (EN 12390-16) of the produced concretes was determined using two specimens of 75 × 75 × 280 mm samples. After 24 h of casting, they were placed in a climatic room at 20 ± 2 °C and 50 ± 5 % relative humidity after measuring their initial length and weight for a total of 91 days.

4. Results

4.1. Physical properties

Due to the low density and high absorption of recycled aggregates, concrete made with RCA and MRA exhibited lower density and higher absorption capacity than NAC_1. All produced RAC mixtures showed a significant decrease in density and an increase in absorption capacity. The absorption capacity ranged from 37% to 53% compared to NAC_1. However, all the RAC achieved similar values to those of NAC_2. In addition, the concrete produced using RCA aggregates achieved lower absorption capacity than those produced with MRA. However, the absorption, as well as density values achieved by all the RACs, were acceptable according to (Cantero et al. 2020), who stated that a water content <7% meets good durability standards. It is important to note that all concrete mixtures maintained acceptable densities for use as structural concrete, ranging from 2.2 to 2.4 kg/dm^3(Singh et al. 2022).

4.2. Mechanical properties

The RAC achieved a significantly lower compressive strength than the NAC_1 concrete, even when they were produced using the same effective water-cement ratio of 0.48. The concrete produced with RCA and MRA achieved a decrease of 9-20% and 9-14%, respectively, with respect to that of NAC_1. However, all concrete mixtures reached the minimum required value of average compressive strength of 38 MPa. In addition, all the RAC achieved similar strength to that of NAC_2. The results showed that the modulus of elasticity values ranged from 31.9 to 34.97, indicating a close relationship between the quality of the aggregate used in concrete production and the obtained modulus of elasticity value. However, it is important to note that all concrete mixtures met the minimum criteria for modulus of elasticity, achieving, according to the Spanish Structural Concrete Code (SC-BOE), the minimum value of 33 GPa (Vintimilla and Etxeberria 2023).

Table 3. Mechanical properties of produces concrete.

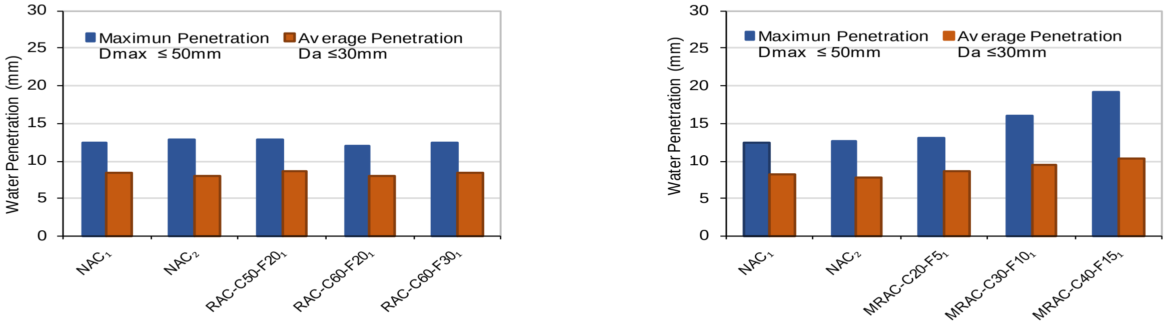
MIX	Fcm		Ecm	pa (kg/dm3)	Abs (%)	S (mm/min0.5)	Dry Shrinkage	Dmax ≤ 50mm
	28	56						
NAC$_1$	53.09	53.44	40.45	2.38	2.8	0.0242	-494.8	12.5
NAC$_2$	44.52	47.74	38.79	2.31	4.18	0.0388	-254.4	12.75
RAC-C50-F20$_1$	45.17	46.32	32.84	2.27	3.88	0.0466	-562.7	12.75
RAC-C60-F20$_1$	44.17	46.59	31.9	2.3	3.85	0.0470	-576.7	12
RAC-C60-F30$_1$	42.88	46.93	31.72	2.27	4.14	0.0593	-688.2	1.2.5
MRAC-C20-F5$_1$	48.16	48.32	34.97	2.32	4.15	0.0324	-531.4	13
MRAC-C30-F10$_1$	47.25	47.74	33.66	2.28	4.21	0.0383	-536.6	16
MRAC-C40-F15$_1$	45.51	45.76	31.94	2.26	4.30	0.0388	-611.7	19.25

4.3. Durability properties

4.3.1. Water penetration under pressure and sorptivity

Figure 1 shows the average water penetration (Da) and maximum water penetration (Dmax) values obtained by all the produced concretes. According to the Spanish Structural Concrete Code (SC-BOE), the Da and Dmax values of water penetration under pressure should be lower than 30 mm and 50 mm, respectively, for aggressive exposure classes of concrete. Consequently, the obtained results show that all of the mixes, regardless of the percentage and type of RCA or MRA used in concrete production, met the requirements established by the Structural Concrete Code (SC-BOE). Moreover, NAC$_1$ and NAC$_2$ achieved similar values. However, it was clear that the use of MRA influenced increasing the water penetration value compared to that of RCA concrete.

According to Table 3, the sorptivity values obtained for the manufactured RAC were higher than those obtained for the NACs. The concrete produced with RCA showed an increase between 92% to 145% compared to NAC$_1$. Likewise, the concrete made with MRA presented an increase of 33% to 60% compared to NAC$_1$ (see Figure 2). However, the increase was lower when the RAC were compared to the values of NAC$_2$. The concrete produced with RCA obtained 20% to 52% higher value. Moreover, it is noteworthy that the concretes produced with MRA performed even better than NAC$_2$, ranging from -16% to 1.3%. The MRACs showed values similar to that of NAC$_2$ (see Figure 3), which can be attributed to their lower replacement percentages. A sorptivity value less than 0.10 mm/min$^{0.5}$ is considered durable. However, to ensure maximum safety, researchers have proposed reducing this value to 0.05 mm/min$^{0.5}$. Researchers have stated that the quality of concrete is low if the sorptivity value exceeds 0.2 mm/min$^{0.5}$, medium if it ranges between 0.2 mm/min$^{0.5}$ and 0.1 mm/min$^{0.5}$, and good if the coefficient is less than 0.1 mm/min$^{0.5}$ (Pedro, de Brito, and Evangelista 2017). Based on these criteria, it can be inferred that all concretes, except RAC-C60-F30$_1$, were of high quality and durability.



a) b)

Figure 1. The water penetration under pressure

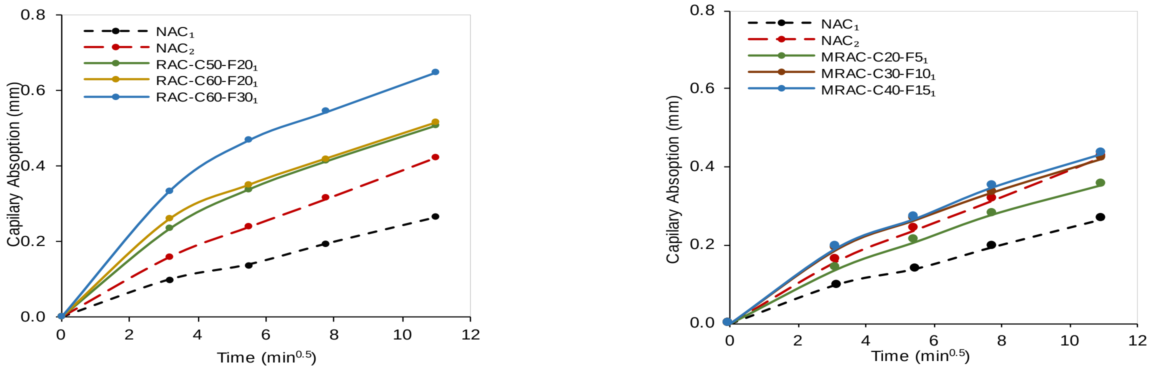


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Figure 2. Sorptivity values.

4.3.2. Drying Shrinkage

Drying shrinkage (see Figure 3) is a critical property of concrete that significantly impacts its durability. Recycled aggregates used in concrete production had a higher water content due to their lower density and greater water absorption, which affects the drying shrinkage. Additionally, the presence of fine materials in recycled aggregates, such as ceramics and fine aggregates, can increase the number of pores and total porosity of the concrete (Cavalline and Weggel 2013), leading to greater drying shrinkage (Zhang et al. 2020). Although the amount of MRA replacement used was lower than RCA, it was observed that the concrete produced with MRA achieved higher shrinkage values. The greatest shrinkage occurred mainly in the early stages of concrete's lifespan, with this effect tending to stabilize over time. Figure 3 shows that the concrete produced using 30% of fine RCA and that made with 15% of fine MRA achieved the highest values. The RAC-C60-F30$_1$ obtained a shrinkage value of -688.3 µε, while the MRAC-C40-F15 sample had a shrinkage value of 611.7 µε. Those values were significantly higher than the NAC$_1$ value of -494.8 µε and NAC$_2$ -254.4 µε. However, all RAC complied within the limits established by the American Concrete Institute (ACI), defined in ranges between 200-800 µε. Thus, it is critical to recognize that the use of recycled aggregates in concrete production increased the drying shrinkage value. Consequently, the type and amount of RA to be used must be selected carefully to ensure the desired level of durability

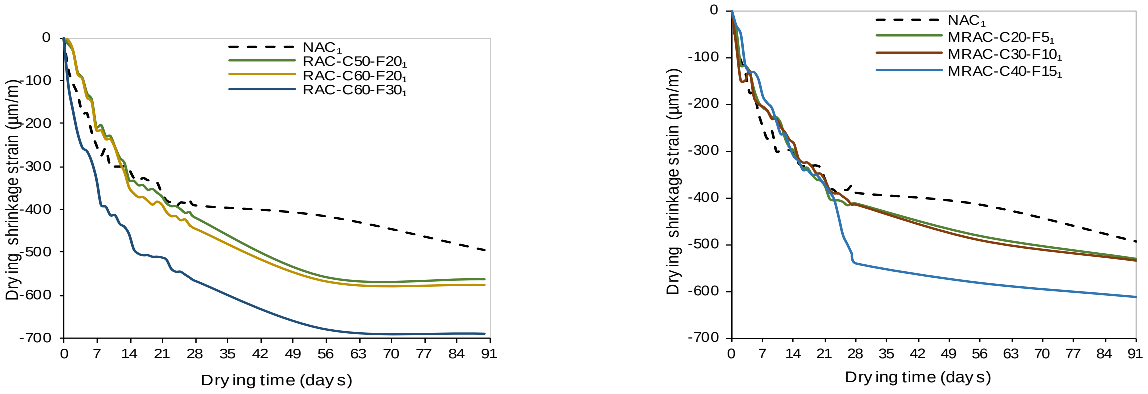

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Figure 3. The drying shrinkage values of all concretes

5 Conclusions

This study suggests that it is feasible to produce concrete using high percentages of recycled aggregates, including fine recycled aggregates. The results showed that up to 60% of coarse RCA and 30% of fine RCA (type A) can be used in structural concrete production without affecting its durability, mechanical strength, or physical characteristics. Additionally, the use of MRA (type B) is also possible for structural concrete production, with replacement levels up to 40% for coarse MRA and 15% for fine MRA. However, long-term durability studies are necessary to evaluate the performance of recycled aggregate concrete over time.

- Recycled aggregates concrete (using coarse and fine RA) and conventional concrete produced with an effective water-cement of 0.48 and 0.52, respectively, achieved similar and adequate density and mechanical properties values according to minimum requirements established by the Structural Concrete Code (SC-BOE).
- Although the RAC exhibit a lower elastic modulus than conventional concrete, they reached the minimum requirements established by the Structural Concrete Code.
- All concrete samples met the required values for water penetration under pressure, according to SC-BOE. However, an increase in sorptivity and drying shrinkage was observed in the cases of RAC-C60-F30$_1$ and MRAC-C40-F15$_1$.
- The drying shrinkage values for all the concretes fell within the acceptable range of 200-800 με. However, it was observed that the type and the percentage of replacement of recycled aggregates significantly influenced this property.

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