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# Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes

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## HIGHLIGHTS

- Structural concretes with mixed recycled aggregate (MRA).
- Fresh concrete properties are not affected by the presence of recycled aggregate.
- The effect of MRA is not statistically significant at replacement ratios ≤50%.
- Compressive strength loss relative to conventional concrete declines with age.
- Replacement of natural with 100% MRA induces losses in mechanical strength of under 19%.

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## ABSTRACT

The mixed recycled aggregate obtained from processed construction and demolition waste accounts for the largest share of recycled aggregate produced worldwide. Efficient and appropriate use of these new resources will help reduce and confront the major environmental problems facing today's economic growth model. The research discussed in this paper assessed the performance of structural concretes containing 20%, 25%, 50%, 75% or 100% mixed recycled coarse aggregate, analysing fresh concrete workability, density and air content and hardened concrete compressive, flexural and splitting tensile strength. An analysis of variance (ANOVA) run on the findings to determine the effect of the factors on the variables showed that curing age and percentage of recycled aggregate had a statistically significant impact on concrete performance. The decline in strength relative to conventional concrete was smaller at longer curing ages. Concretes bearing up to 50% recycled aggregate exhibited declines in performance of 10% or under in most of the properties studied, even at late ages. In light of the present findings, the mixed recycled aggregates used in this research may be deemed apt for use in structural concrete with a characteristic strength of up to 30 MPa.



## 1. Introduction

The construction industry generates large quantities of waste in the erection, demolition, repair and maintenance of buildings and civil works. Theoretically, 80% of construction and demolition waste (C&DW) can be processed to obtain secondary materials usable in new production cycles [1]. The processing and valorisation of new raw materials drives the circular economy model in which products and materials retain their value longer, lengthening their service life [2].

C&DW constitutes an environmental risk, for every year 2 t of such waste is generated per European [2]. The European Commission (EC) deems it a priority waste flow [3], given that it accounts for 34% of the continent's total industrial waste [4], a value only slightly lower than the worldwide figure (~35%) [5]. According to Eurostat, the C&DW recycling and management rate differs substantially across the Union. In Denmark, Germany and the Netherlands nearly 80% of C&DW is reused, whereas the rate in other member countries is closer to 30% [6]. Consequently, the EU's new C&DW management protocol is geared primarily to enhancing confidence in C&DW management processes and product quality [7].

The recycled aggregate resulting from C&DW processing differs in particle size distribution and composition and can be divided into three main categories: recycled concrete aggregate (RCA); recycled masonry aggregate (RMA); and mixed recycled aggregate (MRA). The third accounts for the largest share of aggregate recycled from C&DW [8], constituting around 70% of the total volume in Spain, for instance [9].

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With a view to valorising such waste, in recent years the scientific community has conducted any number of studies on the effect of replacing natural (NA) with recycled C&DW aggregate (RA) on cement-based materials such as concrete [10–19] and mortar [20–22].

Medina et al. [23] observed that concretes bearing coarse aggregate recycled from sanitary ware rejects exhibited 25% higher mechanical strength than the reference and that the use of such waste had no effect on concrete leaching [24]. Pacheco et al. [25] also found compressive strength to be higher in concrete with 30% MRA than in 100% NA concrete. Cachim [26] reported that whilst the use of crushed masonry brick can be used to replace up to 15% of natural aggregate with no strength loss, at 30% replacement concrete performance declined by 20% depending on the type of brick used. Debieb and Kenai [27], in turn, noted that concrete can be made with crushed brick, subject to limiting the replacement of the natural material to 25% in coarse and 50% in fine aggregate.

The use of MRA in the design of structural concrete is not presently addressed in national or international concrete codes and standards, due primarily to the gaps in scientific-technical understanding of performance attributable to a paucity of research. This study aims to contribute to a deeper understanding of the mechanical behaviour of concretes with a granular skeleton comprising 100% mixed recycled aggregate and verify mechanical property inter-relationships, issues not dealt with by the research community to date. Such studies are needed to formulate future standards envisaging the use of this type of recycled aggregate in civil and building construction.

Studies on MRA have been published in the international literature by authors such as: Mas et al. [28,29], who contended that replacement ratios of 20–25% induce declines in strength of <15% in non-structural concrete; Medina et al. [30], who concluded that despite a strength loss of up to 18%, concretes bearing of up to 50% RA are apt for use in housing construction; and Martínez-Lage et al. [9], who noted that compressive strength declined by up to 30% in concrete with 100% MRA.

Mas et al. [28,31] reported that using 75% MRA lowered concrete splitting tensile strength by 21% and flexural strength by 20% relative to concrete with NA, which they attributed primarily to the greater porosity of the masonry in the recycled material. Lovato et al. [31] deemed that the 26% decline in splitting tensile strength observed in concrete with 100% MRA could be ascribed to the brittleness of the recycled relative to the natural aggregate.

Concretes made with MRA are less dense than the conventional materials due to the lower density and higher absorptivity of mortar and masonry [16]. The effect is more intense when the recycled aggregate is used to replace natural sand [6,31,32].

Studies [12,33] conducted on the combined use of RCA and MRA showed that compressive strength was not significantly affected at replacement ratios of up to 75%.

This research explored the feasibility of using 20%, 25%, 50%, 75% or 100% MRA in place of natural coarse aggregate in structural concrete with a characteristic strength of 30 MPa. Consistency and entrained air content were determined in fresh concrete, compressive, splitting tensile and flexural strength in hardened concrete and bulk density in both. The findings were subsequently tested with univariate ANOVA to assess the effect of the factors age and replacement ratio (percentage of MRA) on the response variables.

## 2. Materials and Methods

### 2.1. Materials

The natural aggregate used was characterised by an irregular morphology and sharp arris attributable to crushing. Its chemical composition was primarily siliceous, with an $SiO_2$ content of over 60 wt% and smaller proportions of $Al_2O_3$, $Fe_2O_3$, MgO and $Na_2O$. Quartz, the majority mineral, was found together with feldspars (albite and orthoclase) and phyllosilicates (chamosite and biotite). Three particle size fractions were identified in this aggregate: 22/12 mm (NG-C); 12/6 mm (NG-M); and 6/0 mm (NS).

The recycled aggregate supplied by a C&DW treatment plant in the region of Extremadura (southwestern Spain) had two particle size fractions, 22/12 mm (MRA-C) and 12/6 mm (MRA-M).

The European standard EN 197-1 [34]-compliant CEM I 42.5 R portland cement used was sourced from Lafarge Holcim.

BRYTEN NF, a modified water-base polycarboxylate superplasticiser furnished by FUCHS Lubricantes, was added to the mixes.

#### 2.1.1. Recycled and natural aggregates

In keeping with the composition of the recycled aggregates given in Table 1, and further to Spanish concrete code EHE-08 [35], the MRA-C and MRA-M coarse aggregates were classified as mixed recycled aggregates, for their Rc + Ru was under 95%. They also complied with EHE-08 pollutant ceilings for use in concrete manufacture.

The physical, mechanical and chemical properties of the aggregates are listed in Table 2, which shows that irrespective of their nature they met the requirements laid down in European standard EN 12620 [37] on aggregates for concrete.

Due primarily to their higher porosity, the recycled aggregates had a lower density than the natural materials in all particle sizes. The values were found to lie in the 2.27 $Mg/m^3$ to 2.53 $Mg/m^3$ range reported by other authors [12,38]. These aggregates also absorbed more water than the NA, a consequence of the adhered mortar and masonry particles present in the new materials, which exhibited absorption percentages within the range (4.49 –10%) observed by other authors [38–40] for this type of recycled aggregates.

As the adhered mortar tended to smooth its sharpest angles, RA had a lower flakiness index than NA. The recycled materials had a higher Los Angeles coefficient than the NA, likewise due to the adhered mortar and the presence of masonry. Here also the values ranged within the 20–40% reported in the literature for recycled aggregate [38,39,41].

All the RAs studied met the chloride, soluble sulfate and total sulfate content requirements laid down in European standard EN-12620 [37].

### 2.2. Concrete design

Six types of concrete were prepared for this study: one conventional concrete with natural coarse aggregate (NC) and five concretes bearing 20% (MC-20), 25% (MC-25), 50% (MC-50), 75% (MC-75) or 100% (MC-100) MRA.

Batching was performed as in the British mix approach [46] with the following starting data: concrete 28 d characteristic strength ($f_{ck}$) = 30 MPa; concrete strength class = 42.5 R; w/c ratio = 0.45; and maximum aggregate size = 20 mm.

The mix proportions resulting from batching are given in Table 3. All the mixes designed complied with the minimum cement and maximum w/c ratio laid down in Spanish structural concrete code EHE-08 [35]. The $(w/c)_{effective}$ ratio was constant across all the mixes to ensure comparability between the performance of the new and the conventional concrete.

**Table 1**
Coarse recycled aggregate constituents (EN 933-11 [36] classification).

| Class | Type | Amount (wt%) | | |
|---|---|---|---|---|
| | | MRA-C | MRA-M | EHE-08 |
| Rc | Concrete, concrete products, mortar | 46.98 | 43.98 | – |
| Ru | Unbound aggregate, natural stone | 44.92 | 43.84 | – |
| Rc + Ru | | 91.90 | 87.82 | >95% |
| Rb | Fired clay/masonry materials | 7.15 | 10.93 | <5% |
| Ra | Asphalt | 0.56 | 0.87 | ≤1% |
| FL | Floating particles | 0.17 | 0.02 | ≤1% |
| X | Plaster | 0.04 | 0.34 | – |
| X + Rg | Other and glass | 0.19 | 0.02 | ≤1% |