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Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste

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HIGHLIGHTS

- Physical, chemical and mineralogical characteristics of fine aggregates from crushed concrete.
- The amount of fines produced during crushing depends on the jaw's aperture.
- The smaller size fractions present high mortar contents and few natural aggregates.
- The mineralogical composition of recycled aggregates is not greatly affected by particle size.
- The particular features of fine recycled aggregates do not justify restraining their use.

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ABSTRACT

This paper assesses the physical, chemical and mineralogical characteristics of fine recycled aggregates obtained from crushed concrete waste, comparing them with two types of natural fine aggregates from different origins.

A commercial concrete was jaw crushed, and the effect of different aperture sizes on the particle size distribution of the resulting aggregates was evaluated. The density and water absorption of the recycled aggregates was determined and a model for predicting water absorption over time is proposed. Both natural and recycled aggregates were characterized regarding bulk density and fines content. Recycled aggregates were additionally characterized by XRD, SEM/EDS and DTA/TG of individual size fractions.

The results show that natural and recycled fine aggregates have very different characteristics. This should be considered in potential applications, both in terms of the limits for replacing amounts and of the rules and design criteria of the manufactured products.

1. Introduction

Concrete is the most used construction material, with estimated annual production of 10 billion cubic meters [1]. Since 60–80% of the concrete volume is taken by aggregates, the overall consumption of natural aggregates (sand and gravel) is very high, generating huge pressure on surrounding ecosystems [2]. The environmental impact of aggregate extraction is particularly severe regarding sands, with distinct problems associated to different extraction or production technologies. Sand extraction from seaside increases erosion and retreating coastline, harming inland protection and fauna and flora habitats, and changing wave and tie behavior [3–6]. Sand extraction from riverbed or lakebed alters flow regimes, affecting surrounding structures and local ecosystems [7–9]. Finally, the production of fine aggregates from comminution of coarse aggregates presents high energetic cost and raises difficulties concerning fresh concrete, given their high angularity [10,11].

Another concern of the construction industry is the significant waste generation, with an estimate of 850 to 880 Mt/year in the European Union (EU) [12,13], 317 Mt/year in the USA and 77 Mt/year in Japan [14]. To approach the problem the EU imposed

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targets for the reduction, reuse and recycling of construction and demolition waste (CDW), establishing that by 2020 70% of the produced CDW must be recycled [13,15]. Several studies on the environmental impact of CDW recycling demonstrated that it is a promising industrial sector [16–20]. However its viability demands that the use of recycled CDW in construction is technically defensible, *i.e.* that the performance of solutions incorporating recycled aggregates is similar to that of traditional solutions, or that a poorer performance is compensated by the associated environmental benefits.

Recycled aggregates are composite materials formed from cement, aggregates, water and eventually admixtures or partial cement replacement materials. The resulting properties are substantially different from those of natural aggregates and strongly dependent on processing and treatment [21,22]. The incorporation of coarse recycled aggregates (CRA) in concrete is already accepted, although with restrictions, by the construction industry. Full substitution is even allowed in some countries in particular situations. However fine recycled aggregates (FRA) are firmly excluded from concrete and mortar production in almost all existing standards and regulations [23]. The reasons are clear: FRA present high heterogeneity, high water absorption ability, and contain contaminants due to the recycling process. However recent studies [24,25] have shown that FRA with acceptable features can be attained by tuning the production process and carrying out pre-treatments for property improvement. However methodologies for property improvement were developed aiming at coarse aggregates [26–29] and their applicability to FRA is not specified.

Resulting from the presence of adhered mortar, FRA have lower density values than FNA [30–35]. As a consequence, water absorption is higher in FRA than in FNA, establishing the deepest distinction between them. Values collected by Evangelista and de Brito [36] show a difference between 4.3% and 13.1% on water absorption ability. Regarding FRA density the same authors found values in the 1.91–2.36 g/cm^3, 2.16–2.48 g/cm^3 and 2.56–2.57 g/cm^3 range for dry, saturated surface dry and apparent particles density, respectively. The scatter of water absorption values in FRA is also linked to the water absorption test carried out, usually based on procedures established for fine natural aggregates (FNA). The application of such procedures is not straightforward because FRA present higher cohesive ability [30,37,38] that results in higher particle size and determination of sample weight is thus adulterated.

It was also established that FRA particles are more angular, irregular and porous than FNA [34]. Open porosity increases the specific surface area; Fumoto and Yamada [39] determined BET surface area values up to 400% higher than in FNA.

A route to improve FRA characteristics is to submit them to comminution processes similar to those applied to FNA [40,41]. Ulsen et al. [42] showed that using tertiary comminution in the production of FRA results in rounder shape and smaller contents of adhered mortar.

Regarding chemical and mineralogical analysis, XRD or XRF have shown diversity inherent to the nature of recycled materials. Solyman [34] determined SiO_2 contents between 60.1% and 81.1%. The higher silica amounts correspond to FRA particles submitted to two crushing stages, showing that crushing parameters influence the quality of FRA. CaO contents range from 4.3% to 12.4%, while other oxides are present only in residual amounts. Similar results were reached by Dhir et al. [43], with contents ranging between 55.8% and 75.9% for SiO_2. 5.2% and 18.1% for CaO, 1.5% and 9.7% for Al_2O_3, and 1.1% and 8% for Fe_2O_3. Both authors found residual amounts of SO_3, in agreement with the nature of the FRA tested.

Heinz and Schubert [44] tested crushed FRA used as addition in concrete and mortar and could not find a beneficial effect on strength. Park et al. [45] evaluated the performance of mortars consisting of fly ash and recycled aggregate powder only, finding a mechanical strength increase as a result of reaction between $Ca(OH)_2$ groups in the FRA and fly ash, with formation of secondary hydration compounds.

Shui et al. [46] submitted FRA to thermal analysis concluding that, although a smaller overall mass loss takes place because of the presence of natural aggregates, FRA's thermal behavior is similar to that of current construction mortars.

Overall, FRA can be used either as FNA replacement in concrete or mortar production [31,47–49], as binder replacement [50], as unbound materials in sub-bases for road construction [51–53] or even as filler materials for asphalt mixtures [54].

The introduction of higher amounts of FRA in the production of concrete represents an opportunity for the construction industry. However full understanding and confinement of the properties of the aggregates and of their effect upon concrete are mandatory. In this context this work aims at systematically studying the physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste. Based on these results, researchers and concrete manufacturers will be able to employ an extensive range of properties on mixes design that can boost the use of FRA, disputing the common preconception that these materials are not suitable for concrete production.

2. Materials and experimental program

The FRA used in this work were obtained from a C25/30.X0. S3.D$_{max}$25.Cl0.1 concrete (NP EN 206-1: 2007) (Table 1). The concrete was poured into moulds with 0.20 × 0.30 × 0.40 m^3 and crushed after a 28 day setting period. Crushing was carried out using a jaw crusher with 40 mm nominal size and three gap apertures (minimum, medium, maximum). The influence of these apertures on FRA particle size, produced fine-to-coarse ratio and fine particle size distribution was studied. Particle size analysis was carried out according to NP EN 933-1: 2014. The FRA were afterwards separated in each of the standard size ranges, allowing characterization of the individual fractions bellow 4 mm. Particle size and distribution in the size ranges bellow 500 μm were additionally characterized by laser diffraction (CILAS L1064) to evaluate the efficiency of aggregate dispersion. Before each measurement particles were suspended in a 1% solution of commercial dispersant Tiron, $(HO)_2C_6H_2(SO_3Na)_2{\cdot}H_2O$, and ultrasonicated during 2 min. Each powder was analysed at least two times for reproducibility assessment.

FRA density and water absorption ability were evaluated according to the procedure proposed by Rodrigues et al. [55]. FRA were thus saturated in a 0.1% solution of sodium hexametaphosphate and weight changes were continuously recorded using a hydrostatic scale.

The setting evolution of FRA was accompanied using a Vicat needle, according to NP EN 196-3:2005 + A1:2009. To evaluate if setting phenomena in FRA was the result of cement hydration, the same test was carried out on pastes containing FRA and saccharose solution in several concentrations (1, 2, 5 and 10 wt%-$C_{12}H_{22}O_{11}$). Apparent density and pore fraction of both FRA and FNA were determined according to NP EN 1097-3: 2002; FRA were additionally characterized regarding each individual size fraction resulting from sieving. The fine content was determined using procedures specified in NP EN 933-8: 2014.

Mineralogical analysis by XRD was carried out with a Panalytical X'pert Pro diffractometer using CuKα_1 radiation. The samples were tested in the 2θ range between 15° and 80°, using a step size of 0.002° and acquisition time of 38 s. All analyses were conducted using grinded powder samples.

Microstructural features of both FNA and individual size fractions of FRA were studied by field emission gun scanning electron microscopy (FEG-SEM) (Jeol JSM-7001F) coupled to energy dispersive spectroscopy (EDS) (Oxford Instruments Inca

Table 1
Composition of source concrete (according to the supplier).

Constituent	Amount (kg/m^3)
II A-L 42.5R cement	189
Fly ash	116
Water	126
Sand	554
Fine gravel	558
Medium gravel	171
Coarse gravel	681
Plasticizer	3