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Use of fine recycled concrete aggregates in concrete: A critical review

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ABSTRACT

This paper discusses the state-of-the-art of the fine recycled concrete aggregates (fRCA), focusing on their physical and chemical properties, engineering properties and durability of concretes with fRCA. Based on the systematic review of the published literature, it is impossible to deduce without any further research the guidelines and tools to introduce the widespread application of the fRCA in new concrete whilst keeping the cement contents at least the same or preferably lower. Namely, what is still missing is knowledge on key physico-chemical properties and their relation to the quality of the concrete mix and the concrete performance. This paper sets the foundations for better understanding the quality of fRCA obtained either from parent concrete specifically produced in the laboratory, with controlled crushing and sieving of the recycled aggregates or from field structures. By comparing properties of fRCA with properties of fine natural aggregates, the key limiting properties of fRCA are identified as the high water absorption of fRCA, moisture state of fRCA, agglomeration of particles and adhered mortar. As such, continuous quality of fRCA is hard to be obtained, even though they may be more continuous in terms of chemistry. Advanced characterization techniques and concrete technology tools are needed to account for limiting properties of fRCA in concrete mix design.

1. Introduction

Most of infrastructures in the world are built with concrete. Due to complex interaction between concrete and environment and absence of timely maintenance, many concrete structures are in the state of deterioration. When concrete structures are demolished or renovated, concrete recycling is an increasingly common method of utilizing the rubble [1–5]. Furthermore, concrete recycling provides approach for maintaining sustainable development in concrete structures [6]. There are multiple sources of recycled concrete aggregates. The most common sources are concretes from Construction and Demolition Waste (C&DW) [7–10] and from precast industry [11]. Fine recycled concrete aggregates (fRCA) (< 4 mm) originate from multiple crushing of concrete rubble [12]. The fRCA are currently used in low-grade applications such as a substitute material for natural sand in cementitious renderings and masonry mortars [13–20], road constructions [21–24] and as a filling material for geosynthetic reinforced structures and soil stabilization [25]. There are no case studies, except research papers [19,26–37], which report use of fRCA as a sustainable substitute for natural sand and cement in structural concrete. These studies mainly focus on testing specimens that are made with fRCA from laboratory crushed mortars and concretes, therefore, prepared with material that is different than the actual recycled concrete from outside.

Although the use of fRCA in structural concrete was reported to have positive environmental impact [38], studies have indicated several issues when using fRCA regarding fresh and hardened properties of new concrete. For example, high water absorption of fRCA may lower concrete workability; adhered mortar introduces more fine material in the new concrete; introduction of more interfacial transition zones (ITZs) (Fig. 1) affects transport and mechanical properties of new concrete. In addition, fRCA can be contaminated by chlorides and sulfates (e.g. from de-icing salts, sewage plants or seawater), which may have a significant impact on the durability of new concrete [39]. Moreover, the research and practical experience on proper treatment and utilization of fRCA are limited and/or inconclusive. The limit values for quality control of the physical and chemical properties of recycled concrete aggregates also vary considerably [40]. Finally, the lack of standards for quality evaluation is the main reason for not yet using fRCA in new concrete outside the laboratory. Therefore, use of fRCA in new concrete is restricted [41–44], even though fRCA represents about half of the total C&DW

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weight [45].

2. Drivers and barriers for deployment of fRCA in structural concrete

The drivers for use of fRCA are: CO_2 reduction (contributing to circular economy), waste landfilling, scarcity of raw materials and costs.

1. **CO_2 reduction.** In the last decade, the consequences of global climate change have reached a high level of human awareness. In the coming decades, population growth, infrastructure expansion (specifically in developing nations faced with a lack of infrastructure), waste accumulation and increased number of structures that have to be demolished (in large industrial countries) will be the main drivers for many researches in the field of alternative raw materials and new building techniques. Ensuring new materials such as recycled materials without resource depletion supports sustainability of society [46]. It saves a significant amount of energy and reduces the amount of CO_2, NO_x, and other air pollutants emitted from the manufacturer of aggregates. Hossain et al. [47] reported that the production of 1 t of natural aggregates (river sand and crushed stone) emits 23–33 kg $CO_{2\text{-eq}}$, while the production of 1 t of fRCA from C&DW generates 12 kg $CO_{2\text{-eq}}$.
2. **Waste landfilling.** Instead of ending up at landfills, recycling enables all used materials to be reused. It cuts waste disposal costs, which are likely to rise due to landfill taxes. Therefore, recycling of C&DW have become de facto standard for building sector.
3. **Scarcity of raw materials.** The coarse and fine aggregates are the largest component of concrete. Due to rapidly increasing production and utilization of concrete, the consumption of natural aggregates has increased as well. Fig. 2 shows the origin of natural aggregates and their amounts for different countries. Crushed rock, river sand and gravel are the most utilized aggregates. However, their amounts are decreasing and their extraction leads to serious problems.

The extraction of river sand causes environmental damage worldwide, such as altering the water's course, eroding shoreline, creating dead-end diversions and pits. For instance, Fig. 3 illustrates significant impact of sand removal and dredging in the northern branch of China's largest freshwater lake within 18 years. The sand dredging has largely changed the topography and hydrological characteristics by reducing the water level, increasing turbidity and sediment concentrations [49]. Given the demand for concrete and the impact of extraction of fine natural aggregates (0–4 mm) from rivers and seas, alternative sources are of increasing importance.

4. **Costs.** At present, fRCA is cheaper than river sand. It is desirable to use recycled concrete aggregates in concrete production as long as it is cheaper than natural aggregate and does not increase the demand for expensive constituents of concrete, particularly cement. In addition, by reducing the quarry of natural aggregate the costs for amenity and bio-diversity can be reduced [50].

Contrary to the strong drivers, the following challenges are believed to be critical in future deployment of fRCA in new concrete mixtures.

1. **Variations of fRCA properties.** The variations in physical and chemical properties of fRCA cause a wide range of mechanical and durability properties of mortars and concretes with fRCA and make material delivery inconsistent.
   – Physical variations. The shape of fine aggregates is largely changed from round to angular after recycling of concrete rubble. In addition, the fRCA particles have different particle size distribution and specific surface areas compared to fine natural aggregates.
   – Chemical variations. Due to chemical variations of the type of cement and type of aggregates in parent concrete, the chemical properties of fRCA can be very different. The ultrafine material may also contain different types of impurities.
2. **Costs.** The fRCA contain adhered mortar. In order to improve quality of fRCA, it would be costlier, both economically and environmentally, to remove mortar from fRCA particles and clean the material from various impurities compared to fine naturalaggregates. Furthermore, severely contaminated batches will require multiple treatment steps to produce recycled concrete aggregates with sufficient quality for new concrete, resulting in a more expensive process.
3. **Standards.** The demand for use of fRCA in new concrete structures is huge. This requires a stricter quality control of fRCA compared to fine natural aggregates. However, the lack of a well-developed guidelines for the quality control is preventing a wider use of fRCA in new concrete. Given the increased interest for fRCA in practice, the governments could define also "eco-tax" to encourage the use of fRCA.
4. **Research vs practice.** The quality control of fRCA in the laboratory is more demanding and rigorous than in the concrete factories. For applications of fRCA in concrete factories, the primary concerns are: unknown origin of fRCA, upscaling, and lack of guidelines for testing. This makes applying different fRCA in practice extremely challenging.

To sum up, the literature confirms that fRCA can be used as substitute material for natural sand in new concrete with multiple benefits, but the concrete performance is limited due to variations in physical and chemical properties of fRCA. In the past two decades, much effort has been made toward the characterization of fRCA [50]. The aim of this paper is to provide a systematic review on the main progress and

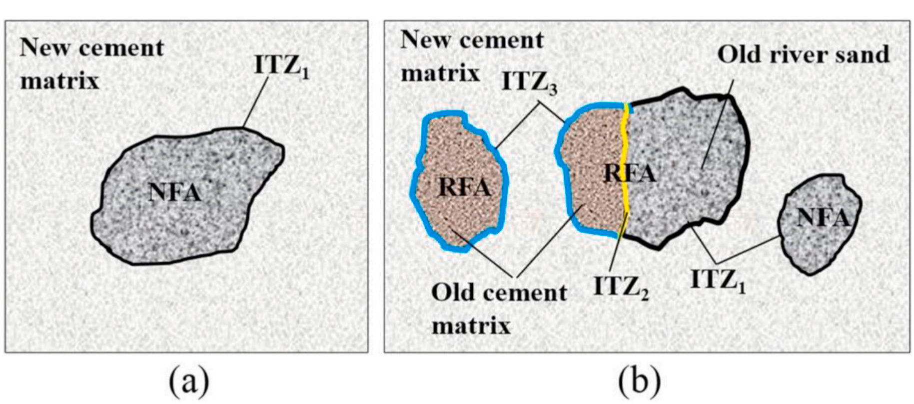


Fig. 1. Different types of ITZs in ultrahigh performance concrete (UHPC) prepared with different fine aggregates: (a) UHPC with natural fine aggregate (NFA) (quartz or river sand), (b) UHPC with NFA partially replaced by recycled fine aggregate (RFA) [37].

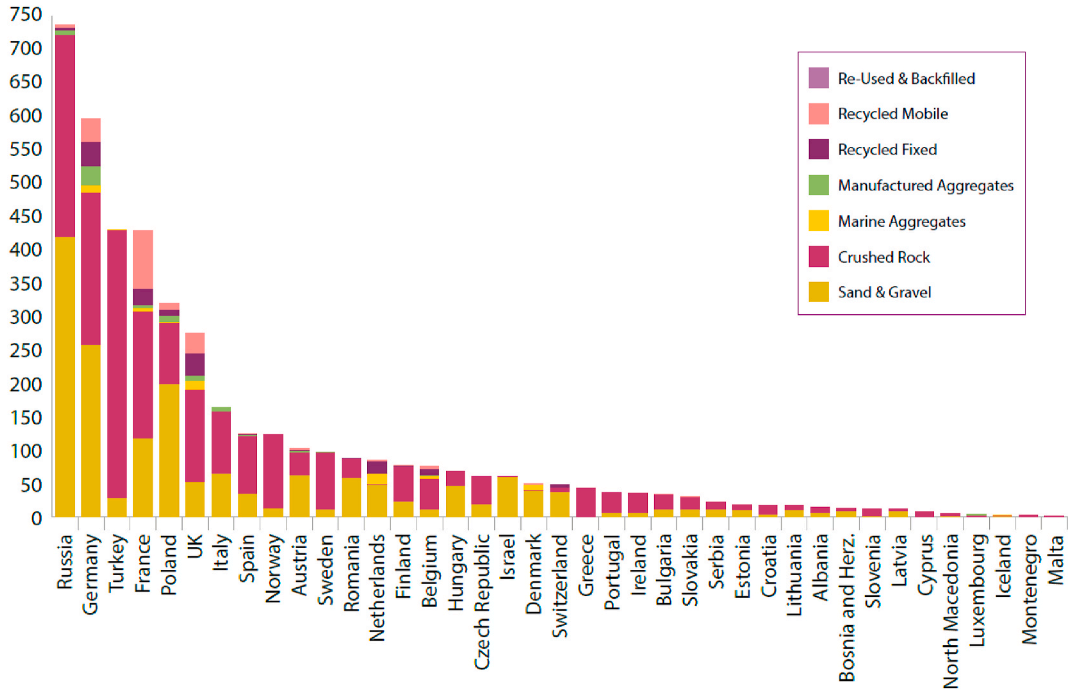


Fig. 2. Aggregates Production 2018 (in million of tonnes by country and type [48].

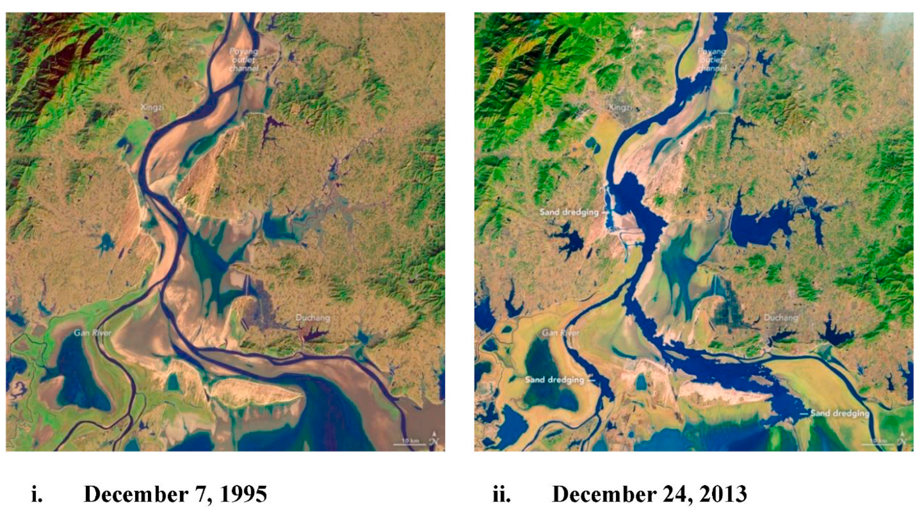


Fig. 3. The impact of intensive sand removal and dredging on the channel that connects Poyang Lake to the Yangtze river [51].

advances in characterization of fRCA, and on understanding of concrete behavior containing fRCA, considering the various properties that are of interest for researchers and engineers. Further studies for deployment of fRCA in structural concrete are also proposed.

3. Properties of fRCA

3.1. Physical properties

The fRCA is a multiphase and multi-scale in nature. At the macro-scale, the fRCA may be considered as a two-phase material, aggregates and binder glued together as shown in Fig. 1. The binder can be cement, filler, mineral additions. At the microscale, there is a third phase in the fRCA, which is composed of the interfaces between aggregates and binder (see Fig. 1). These interfaces influence the physical properties of fRCA. The physical properties, such as particle size distribution, particle shape and water absorption of fRCA affect workability, setting and hardening, strength, durability, and time-dependent behavior (i.e. shrinkage and creep) of mortars and concretes [52]. This section presents an overview of physical properties for fRCA.

3.1.1. Particle size distribution

Particle size distribution is an essential property of aggregates because it dominates the particle packing. Typical particle size distribution of river (A), natural crushed sand and three different fRCA (B, C, D), obtained by dry sieving method are shown in Fig. 4. The fRCA B was produced by rotor crusher, while fRCA C and fRCA D were produced by jaw crusher combined with a cone crusher. The variation of particle size distributions (S-shape) between natural sands (river and crushed) and different fRCA (B, C and D) is high. The different percentages, like the higher percentages of fraction 0-0.250 mm in C and D (15–18 wt%) compared to B (~6 wt%) is due to the number of crushing steps applied during recycling. The fRCA B had one step of crushing in the process, while C and D had three steps.

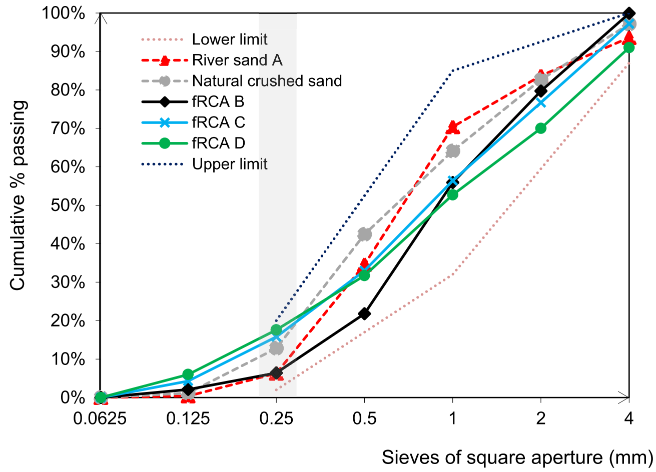


Fig. 4. Particle size distributions of river (A), natural crushed sand and three different fRCA (B, C, D), obtained by dry sieving method.

The multiple crushing contributes to the finer particle size distribution in comparison to one time crushing as also demonstrated by Florea et al. [53]. In their study, three different crushing cycles were considered and their influence on the particle size distribution (PSD) was demonstrated (Fig. 5): RC-1 (crushed once); RC-2 (after 10 crushing times) and RC-3 (from the Smart Crusher technique (SC)). Fig. 5a compares the PSDs of RC-1, RC-2 and RC-3. It is shown that the RC-3 particles are smaller than RC-2 and RC-1 and the SC produced 4 times more particles under 1 mm than RC-1. Fig. 5b shows the PSDs of the fine fractions (0–150 μm and 250–300 μm) of all three materials. The RC-3 fractions are the finest. The RC-2 has increased percentage of fines due to the consecutive crushing compared to RC-1.

Evangelista et al. [54] evaluated the effect of different crusher jaw's aperture sizes on the particle size distribution of the resulting fRCA, showing that the jaw's aperture influences the amount of produced fractions but not the particle size distribution of fRCA. Sosa et al. [55] reported similar particle size distributions for all investigated fRCA although they were obtained from different compressive strengths concretes made with different natural coarse aggregates.

Ulsen et al. [56] studied the effect of different rotor speeds of a vertical shaft impact (VSI) crusher on the particle size distribution of fRCA particles. The results indicated that the rotor speed of the VSI crusher had no effect on the particle shape or particle size distribution of the fRCA. Fan et al. [57] showed that multi-stage crushing of concrete rubble resulted in fRCA with a larger quantity of finer particles, compared to fRCA produced with a single stage crushing process. Nevertheless, the particle size distribution curves of both samples fell within the acceptable range according to ASTM C33-13.

According to the Gomes et al. [58], fRCA match a natural fraction in terms of D_{max}, but not in terms of particle size distribution. In addition, authors studied the effect of chemical treatment (acid) of the fRCA on their particle size distribution. It was found that after the treatment, the aggregates had a slightly finer particle size distribution due to the removal of the cement paste adhered to the surface of the particles.

Lotfi and Rem [59] demonstrated the effect of the Heating-Air classification System on the particle size distribution by processing the materials at different temperatures. Small deviations in particle size distributions of finer fraction (0–0.250 mm) and the coarser fraction (0.250–4 mm) coming from different heating temperature, have been observed.

3.1.2. *Surface texture and particle shape*

The surface texture and particle shape of fRCA depend largely on the parent concrete composition, the recycling technique and the number of crushing cycles. Regarding surface texture, it has been shown that the coarse recycled concrete aggregates are as rough as crushed natural aggregates [60]. Whilst there are no studies which compare surface roughness of fRCA and that of fine natural aggregates, the findings suggest that, due to the adhered cement paste patches, surface roughness of fRCA is higher than of river sand [61]. The shape of fRCA depends largely on the type of recycling technique and the number of crushing cycles. In the typical processing step required for C&DW, the two-stage crushing is done. Subsequently, screening, sieving and removal of impurities and materials such as plastics, iron and steel are applied [62]. Different combinations of these processes can be seen in different recycling plants. The use or removal of some steps depends on the quality of the input C&DW [2].

Fan et al. [57] investigated the effect of crushing process (jaw, cone and roll crushing in different combination) and crushing cycles (single, multi-stage) on the physical properties of fRCA (R1 and R2). It has been shown that R1 particles were rougher in shape and more angular than those in R2, with higher porosity, lower density and higher absorption than R2. The difference in shape could be attributed to the repeated crushing and lack of coarse aggregate in the production of R2.

Gomes et al. [58] studied the change of the particle shape of the coarse and fine recycled concrete aggregates before and after chemical attack (Fig. 6). According to this study, the fRCA particles have less

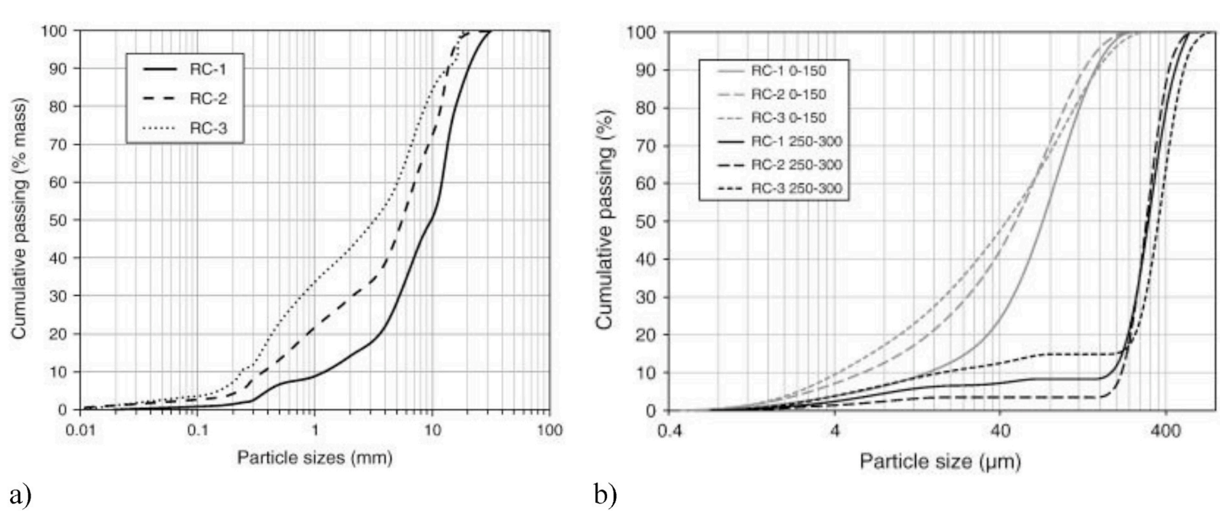


Fig. 5. a. Particle size distributions of three crushed materials, RC-1 (crushed once), RC-2 (after 10 crushing times) and RC-3 (from the Smart Crusher technique) on a logarithmic scale; b. Particle size distributions of RC-1, RC-2 and RC-3, fractions 0–150 μm and 250–300 μm [53].

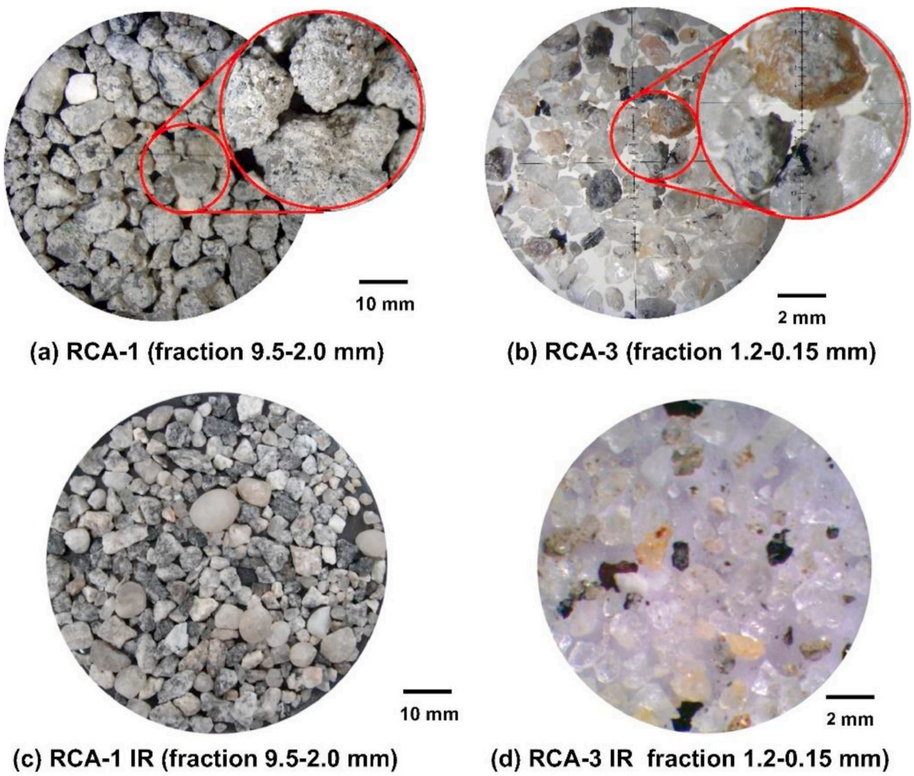


Fig. 6. Microscopic analysis of recycled concrete aggregates samples. Before (a), (b) and after (c), (d) the acid attack [58].

spherical and more elongated shape after leaching due to the removal of the cement paste adhered to the surface of the particles (Fig. 6 (b) and (d)).

The angular fRCA particles will be combined in a disorderly manner, resulting in a variety of contact forms in an aggregate mixture. Although these particle contact forms are not yet investigated for fRCA, a study on particle contact of construction waste mixtures [63] provides an indication of the possible particle-to-particle contacts (Fig. 7). Due to outdoor storage of fRCA, small particles in water tend to agglomerate. Small particles may cluster into agglomerates with a high amount of particle contacts. The angular shape of fRCA particles will affect the rheology of the concrete due to increased resistance of non-spherical shapes to flow and decreased packing limit of angular shapes vs. spherical shapes [64]. A maximization of the packing density of the particles can be achieved by adjusting the grading of the aggregates, consequently improving the overall performance of the concrete mixture [65–68].

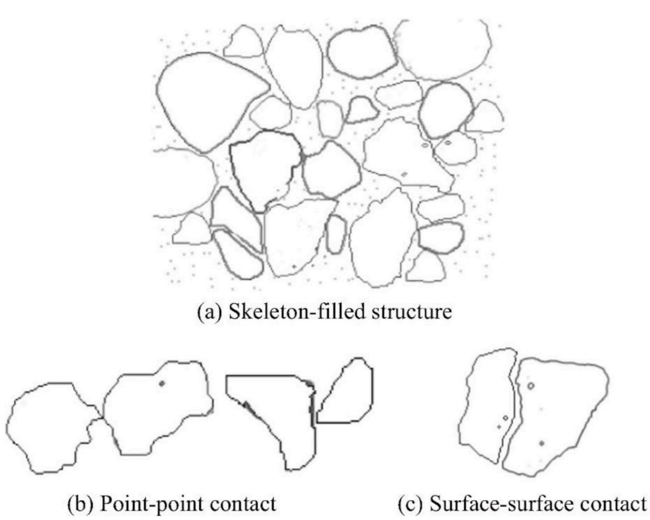


Fig. 7. Skeleton-filled (porosity) particle contact form [63].

3.1.3. Water absorption and density

Water absorption (WA) and density of aggregates are the key parameters in mortar/concrete mix design. To determine the water absorption of fRCA no single method is generally accepted and therefore various test methods are used to determine water absorption of fRCA. The water absorption testing of fRCA is very complicated due to fluctuating fRCA properties, nature of adhered cement paste and content of fines (<250 μm). Several methods were developed for two different purposes: (a) to determine the water absorption over time (kinetics), which is useful for water demand compensation in concrete production, and (b) to measure the total water absorption capacity of fRCA. Different measurements methods of WA of fRCA are summarized in Table 1.

WA values, as determined for coarser and sand fractions by the EN 1097-6:2013, are obtained in two steps: saturating the aggregates (by immersion in water for 24 h) followed by drying. However, challenges arise when this method is applied to recycled concrete aggregates. This method is more suitable for coarse recycled concrete aggregates, because small particles of fRCA readily agglomerate and it is difficult to uniformly transfer the drying energy to the surface of every small particle [77]. Tegguer [72] showed that for coarse recycled concrete aggregates much longer time of saturation is needed (>24 h). Similarly, in studies [52,69,71,72,78], it was observed that the saturation period to determine water absorption and density of fRCA should be longer than 24 h. The content of fines is another concern when it comes to the immersion method. The small particles of fRCA can agglomerate and occlude air, thus resulting in inconsistent weight measurements [55]. Moreover, if the entrapped air is not removed during the test, its volume is included in the total (aggregates + water + entrapped air) and water absorption is underestimated [52]. For this reason, the removal of the entrapped air is critical for the end test results. Different methods are proposed to solve this issue. The volume of the sample was equivalent to two or three layers in order to remove air bubbles by rolling the bottle

Table 1
Summary of the measurement methods for water absorption of recycled concrete aggregates.

Reference	Method	Size fraction of recycled concrete aggregates	Sample weight [kg]	Test duration [h]
European standard method EN 1097-6:2013	(a) Wire basket method; (b) Pycnometer method; warm air is used to evaporate surface moisture and to reach the SSD state of aggregates.	Coarse and fine	(a) 7 (b) 0.25	24
Leite MB [69]	Immersion	Coarse and fine	NA	24
IFSTTAR N°78 [70]	Saturation and drying; the aggregates are dried progressively with different sheets of colored absorbent paper.	Coarse and fine	NA	24
Tam [71]	Real-time assessment of water absorption (RAWA)	Coarse (5/40 mm)	2	144
Tegguer [72]	Hydrostatic weighing method (coarse recycled concrete aggregates)	Coarse (5/20 mm)	NA	144
Zhao [73]	A method based on a relationship between the cement paste content in the fRCA and its WAC (extrapolation)	Fine (0/5 mm)	NA	24
Rodrigues [74]	Pycnometer method and hydrostatic scale with the use of sodium hexametaphosphate to disperse particles and avoid occluded air	Fine (0/4 mm)	1.5	24
Bendimerad [52]	Combined: pycnometer test method and hydrostatic weighing method	Coarse (4/10 and 6.3/20 mm)	NA	240
Rueda [75]	An accelerated test based on use of an electronic moisture analyser	Fine (0.063/4 mm)	0.025	0.5
Yacoub [76]	Vacuum-based method combined with an evaporation method	Fine (1/4 mm)	NA	NA
Li [77]	Centrifugation method; Volumetric flask method	Fine (various fractions in range 0.16/4.75 mm)	1.1 ± 0.01 0.3 ± 0.01	24
Sosa [55]	Electrical conductivity method	Fine (0/4.75 mm)	2.5	24
Li [78]	Measurement of water absorption value of fRCA in paste instead in pure water	Fine (1.18/2.36 mm)	0.1 ± 0.001	24

NA: not applicable.

[52]. In other studies bottle was agitated then manually rotated and slowly shaken multiple times to remove air bubbles trapped between the aggregate particles. The hexametaphosphate solution was used as a particle dispersant to minimize cohesion between particles and release entrapped air [74]. There should be some profound investigations on understanding how air is entrapped and which method or combination of methods from above mentioned studies is the most suitable to be used in the future measurement of water absorption.

Le et al. [79] used three methods to determine the WA of the total fRCA (0–4 mm) and of five different fractions: EN1097-6:2013, IFSTTAR N°78 method and extrapolation method. The values of WA were highly dependent on the test procedure. In particular, the standard method EN 1097-6:2013 seems to underestimate the WA while the IFSTTAR N°78 method overestimates it. However, when these two methods are applied on the coarser fractions of sand (larger than or equal to 0.8 mm) the WA obtained for each are very close. The authors showed that the WA of the finer fraction of fRCA can be estimated by extrapolation. Using the extrapolation method, the WA of the finer fractions is determined from that of coarser ones. Then the WA of whole recycled sand is determined from the proportions and WA of each fraction. By comparing the results, this method seems more accurate than EN 1097-6:2013 and IFSTTAR methods performed on the entire 0–4 mm fraction of fRCA.

Rueda et al. [75] developed a test using electronic moisture analyser to measure the WA of fRCA. However, the equipment does not allow using a large amount of material, so the heterogeneity of fRCA and the reduced sample mass can generate errors in measurement. Nevertheless, the results of WA of fRCA measured by this method [75] and the results using the standard method EN 1097-6:2013 for the same samples, were similar.

Li et al. [78] measured the water absorption of fRCA in fresh paste at plastic stage. The water absorption was calculated by the difference of total water content of paste between the mixture incorporating the fRCA and the reference cement paste. The results showed that the water absorption of fRCA in paste and its evolution is lower than that in water, being up to 44.38%–80.18% of WA_{24h} at 1 h. This finding was explained by cement paste contention of the water. Cement grains have a great advantage in the contention of the water, therefore it is difficult for fRCA to reach its maximum absorption capacity during mixing.

In Table A1 (Appendix) WA and density values for fRCA and natural sand reported in the literature are summarized. The noticeable difference between fRCA and fine natural aggregate results from higher water absorption (WA), as demonstrated in Fig. 8. This can be attributed to the complementary effect of high content of open pores and the rougher surface texture of fRCA particles. The high water absorption capacity of fRCA directly affects the *effective water-to-cement ratio* of paste in cement-based materials, giving poor fresh state consistency [78]. The amount of the absorbed water depends primarily on the abundance and continuity of the pores in the particle, whereas the rate of absorption depends on the size and continuity of these pores [72].

The reported WA values for fRCA vary between 4.28 and 13.1%, with an average of 8.4%. The reported WA values for natural fine aggregate vary between 0.15 and 4.1%, with an average of 1.1%. In addition, the fRCA has lower density than natural sand, (Fig. 8). The obtained saturated-surface-dry densities of fRCA were between 1630 and 2560 kg/m^3, with an average of 2295 kg/m^3. The densities of natural fine aggregate varied between 2530 and 2720 kg/m^3, with an average of 2637 kg/m^3. The scatter with respect to WA and density values between different studies is caused by variations in the quality of parent concrete, which is often unknown (water-to-cementc ratio, type and amount of cement, aggregates origin and gradation, etc.), as well as the differentiation of its properties during its performance time. Moreover, Ulsen et al. [56] reported that different VSI crusher rotor speed had a significant effect on the water absorption of fRCA. The water absorption of four sands, C&DW, VSI-55, VSI-65 and VSI-75, were 12%, 9%, 8.1%, and 7%, respectively, showing the large impact of *increased* VSI rotor speed.

These studies have shown that evaluation of water absorption of fRCA is strongly influenced by the procedure (type and duration of immersion, in water or paste), size fraction of fRCA, specimen weight and agglomeration of small particles . The major issue concerns the weight of samples (Table 1), which is obviously way too low to be representative. In addition, it is difficult to judge the saturated state of fRCA accurately. Tests with more complex histories of monitoring (various durations) are still needed for approval of the validity of tests conducted according to European standards for the characterization of fRCA (water absorption, density). Moreover, no specific testing

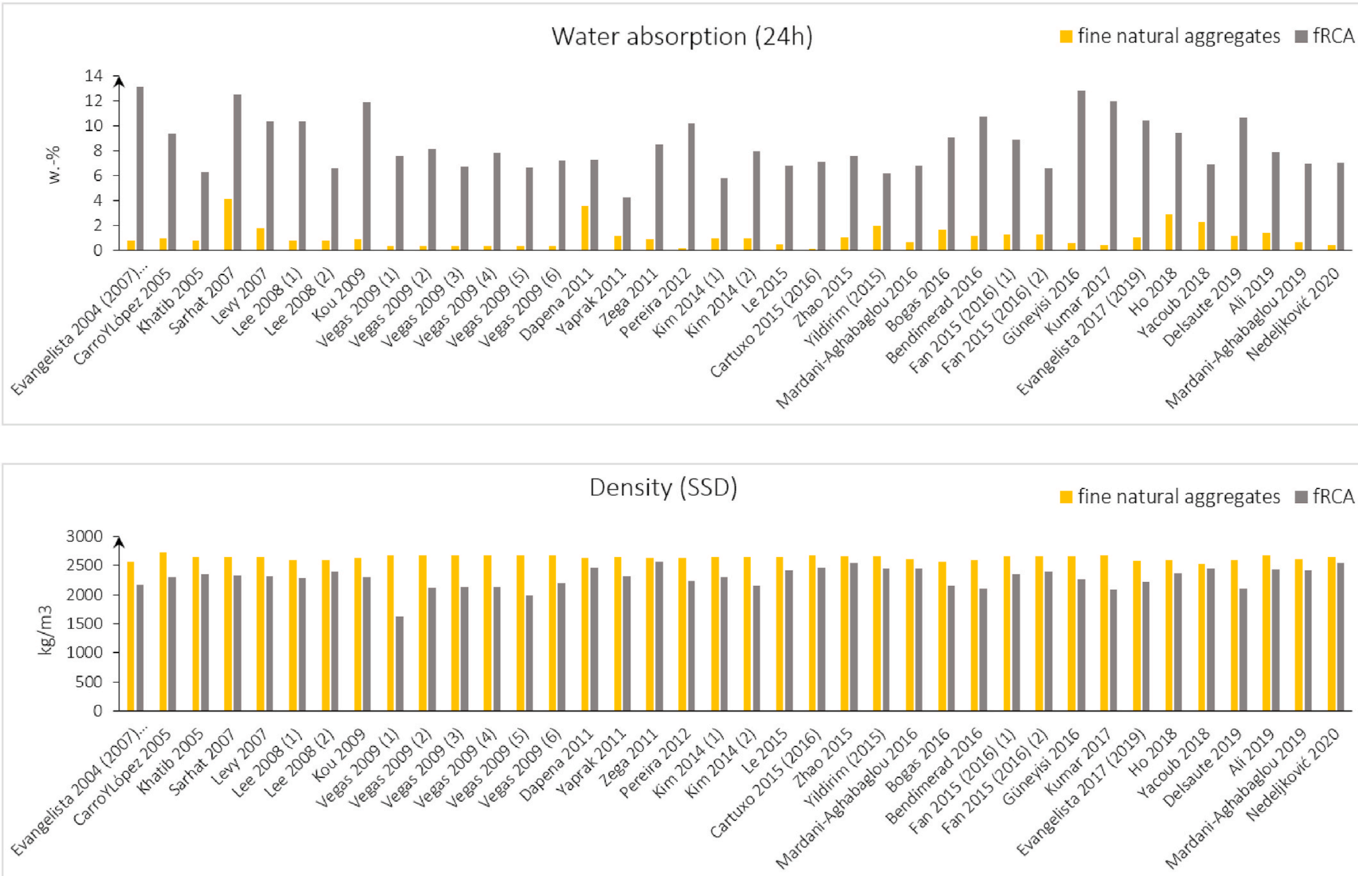


Fig. 8. Water absorption and SSD density of fine natural aggregates and fRCA from literature. (For interpretation of the references in this figure and exact values, the reader is referred to Table A1, Appendix).

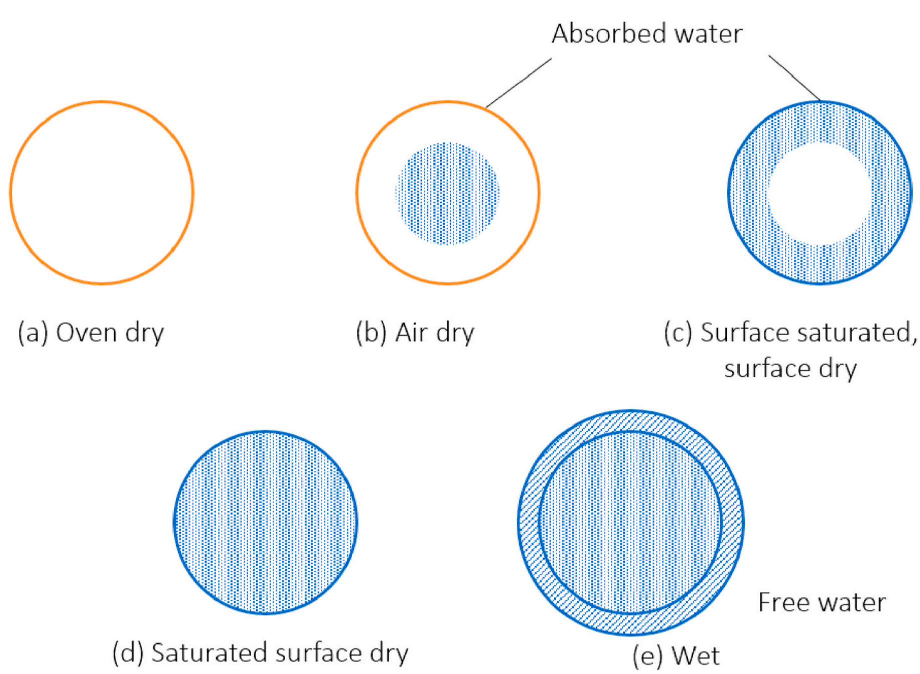


Fig. 9. States of moisture in natural aggregates. Total moisture: (a) none; (b) less than the adsorption capacity drying; (c) less than the absorption capacity, absorbing; (d) absorption capacity; and (e) greater than absorption capacity. Surface moisture: (a, b and c) negative, can absorb water; (d) none, and (e) positive [72].

methodology was adapted for practical purposes.

3.1.4. Moisture states

In the concrete mix design, besides water absorption, moisture state and content of aggregates is largely important. Moisture content of aggregates has an important effect on the rate of water absorption of aggregates. If the aggregates contain certain moisture (e.g. due to storage conditions), the rate of water absorption of such aggregates will be reduced, causing amount of water needed for cement hydration, known as effective water W_{eff}, to increase. For this reason, moisture content has to be accounted in the mix design. The various moisture states in which natural aggregate particle may exist are presented in Fig. 9 [72]. The states of moisture in fRCA are proposed and presented in Fig. 10. In contrast to natural aggregates, the fRCA particles can be found as individual particles (Fig. 10, particles numerated with 1 and 3) or as agglomerates (Fig. 10, particles numerated with 2 and 4). The agglomerates are formed due to inter-particle forces increased by outdoor storage of fRCA, i.e. wet conditions and carbonation. If the voids in these agglomerates are not filled with water then they will entrain air as illustrated in Fig. 10. Generally fRCA particles may be considered as a three-phase material, aggregates and binder glued together (Fig. 10, colored grey) and the third phase is interface between aggregates and binder. Due to the porosity of binder and interfaces in fRCA, the moisture content of fRCA will be higher than that of natural aggregates. In comparison to moisture states in fine natural aggregates, fRCA may have likely three cases: (i) surface saturated, surface dry, (ii) wet and (iii) combination of (i) and (ii) moisture states. The other three moisture states (oven dry, air dry, saturated surface dry) are less likely due to the presence of binder in fRCA particles. The binder contains some physically and chemically bound water which can be only partially eliminated by drying at the temperature (105 °C) used in standard procedure for moisture content and water absorption measurements.

3.2. Chemical properties

3.2.1. Chemical composition

The chemical composition of fRCA can vary considerably, depending on the composition of the original cement, the composition of the fine and coarse aggregates from parent concrete and adhered cement paste characteristics (contamination, deterioration) [80]. Only a few studies on chemical and mineralogical characterization of C&DW recycled concrete aggregates including bricks [81–83] and of laboratory crushed concrete [54,59,84] have been done.

Angulo et al. [82] studied chemical composition of the different sizes of the mixed C&DW aggregate samples. The main oxides found were SiO_2 (48.0–84.2%), Al_2O_3 (5.0–17.2%) and CaO (2.4–13.9%), followed by high LOI values (3.4–19.6%). In their study, most of SiO_2 (up to 70%) comes from natural rocks (granites), clay and ceramics. The CaO originates from the Portland cement containing 35% blast furnace slag. Higher contents of CaO (10–23%) and LOI (9–23%) were found in aggregates from Italy [81] which was probably due to the presence of high amount of limestone aggregates [82]. The authors also reported variation in content of some chemical species and LOI in relation to the size fractions, showing that *size* affects the chemical composition more than the geographical origin of aggregates. Recycled concrete powder (<0.15 mm) contained higher quantities of CaO, Al_2O_3 and LOI than sand and gravel. The LOI has two major sources: (a) combined H_2O from binder and clay; (b) combined CO_2 from the carbonation of the cement's binder and potential presence of limestone aggregates and/or fillers.

Sicakova et al. [84] reported that the recycled concrete powder (<0.125 mm) contained SiO_2 31.1%, Al_2O_3 8.7%, Fe_2O_3 2.7%, CaO 12.4% and other elements 45.1%. Lotfi and Rem [59] reported that for the same size of powder (<0.125 mm) which resulted from heating and grinding of fines by an innovative low-cost classification technology, called Advanced Dry Recovery (ADR), composition was SiO_2 41.2%, Al_2O_3 6.4%, Fe_2O_3 3.0%, CaO 35.2%, while original ADR fines (0–4 mm) composition was SiO_2 75.5%, Al_2O_3 4.6%, Fe_2O_3 1.6%, CaO 11.2%. With these findings, authors demonstrated the significant impact of heating and grinding of fRCA on the chemical composition of finer fractions. The amount of CaO in the recovered finer fraction was comparable with the amount of CaO in low-quality limestone.

Chemical-mineralogical characterisation of different grain-size classes, obtained through laboratory sieving of CD&W, has allowed to recognize a particular grain-size fraction (0.6–0.125 mm) that can be directly reutilized as alternative material in the concrete production [81].

Ulsen et al. [56] reported that different VSI rotor speed did not have an influence on the chemical composition of fRCA with size 0.6–1.2 mm. The cement paste is the only source of Ca, as found also by Angulo et al. [82]. The cement paste is either adhered to the fRCA particle surface or it appears by bonding small grains of quartz [56].

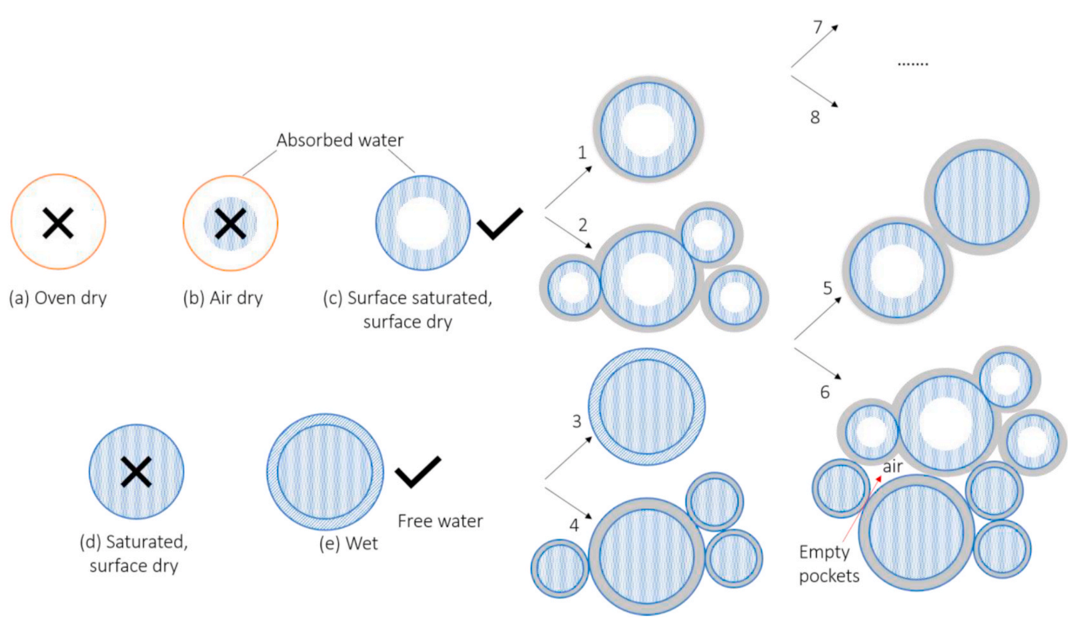


Fig. 10. States of moisture in fRCA, (i) surface saturated, surface dry, (ii) wet and (3) (iii) combination of (i) and (ii) moisture states.

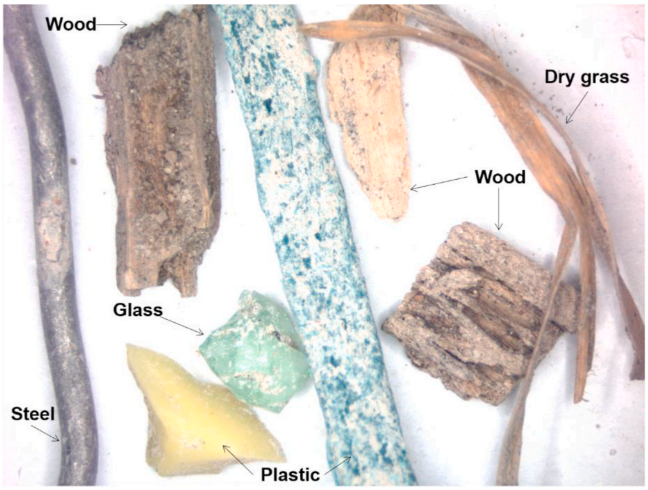


Fig. 11. Stereoimage of different contaminants in fRCA.

3.2.2. Contaminants, chlorides, sulfates, soluble alkalis

Generally, contaminants in the fRCA include wood, iron/steel, different plastics and polymers, glass and plant fibers (Fig. 11) as identified from our own project. Different technologies such as smart demolition and dismantling of End-Of-Life buildings, automated sensor sorting and online quality control sensors have been developed for removing the contaminants [59].

The element contaminants are concentrated in the finest fraction of the fRCA and include Cl^- and SO_4^{2-} and soluble alkalis. Chloride content should be limited in a concrete in order to prevent corrosion of steel reinforcement. Excess of internal sulfate content, that can originate from e.g. gypsum contaminated materials, can cause internal sulfate attack (ISA). The Na_2O-equivalent of cement used for specific concrete are limited in standards to a certain value in order to prevent deleterious alkali aggregate-reaction and amplification of ISA. Knowing the composition of fRCA gives information about how the contaminants will behave in concrete products and how they can influence the long-term properties of the new concrete.

Rodrigues et al. [83] investigated different fRCA types and reported less than 0.01% of water soluble chlorides and less than 1% water soluble sulfates, being below critical values. The amount of acid soluble sulfates was between 0.27-1.53, which is above the allowed amount (0.2/0.8). The total sulfur content of fRCA was below critical value (1%).

Based on another larger study [85], the water soluble chlorides in fRCA were 0.002% while acid soluble chlorides were 0.02%. The water-soluble sulfates were 0.08–0.24% and the total sulfur content was 0.35–0.62%. The Na_2O_{eq} was 0.46–1.5% for fRCA [85]. The crushing of concrete generates more adhered cement paste in fRCA, resulting in higher contents of soluble alkalis and sulfates in fRCA than in coarse recycled concrete aggregates. The alkalis were shown to be less stable in adhered cement paste of fRCA, compared to alkalis contained in minerals such as feldspars [85]. Using SEM analysis, it was demonstrated that sulfates are combined with alumina and calcium in adhered cement paste. This led to conclusion that the source of sulfates are phases such as ettringite and/or monosulfoaluminates or their carbonated products: limestone, gibbsite, and gypsum. Angulo et al. [82] showed that soluble alkalis and sulfates are lower than 1% for the sands and gravels and do not present significant risk in terms of salt efflorescence or secondary ettringite formation according to RILEM recommendation [86] when used in mortar or concrete.

3.3. Summary

The way the fRCA are generated, will have a direct impact on the particle size distribution and quantity of the fines 0-0.250 mm, as demonstrated in Figs. 4 and 5. For instance, the increased number of crushing steps will increase the content of fine material. Compared to natural sand, fRCA contain significantly more fine particles (<250 μm), have different particle size distributions, and tend to be more angular with rough surfaces.

Water absorption of fRCA is significantly higher than that of fine natural aggregates (Fig. 8). The water absorption measurement of fRCA has received significant attention since there are many factors affecting the results. Many studies (Table 1) did attempt to investigate these factors, however, the wide variety of equipment and operational conditions made WA an area of interest for continued study. Moisture states and moisture content of fRCA may affect water absorption rate of fRCA particles to large extent depending on the extent of agglomeration of fRCA particles.

In all reviewed studies, fRCA were non-reactive aggregates. In most studies, the water and acid soluble chloride and sulfate contents in fRCA were not higher than critical values given in EN 12620:2002+A1:2008. Therefore, taking into account these chemical parameters, the fRCA can be considered as a sand replacement and as a mineral additive in cementitious materials according to requirements in European standards for reinforced concrete.

Based on discussions in Sections 3.1.1-3.2.2, the key limiting properties of fRCA are identified as the high water absorption of fRCA, moisture state of fRCA, agglomeration of particles and adhered mortar. As such, continuous quality of fRCA is hard to be obtained, even though they may be more continuous in terms of chemistry. The inconsistent quality, physical and compositional variations in fRCA are caused by recycling of mixed parent concretes, use of different recycling techniques and storage of recycled material. Their effects are emphasized here.

(i). Parent concrete

When the concrete rubble is transported to the recycling plant, it may be mixed with the rubble from different types of construction materials (e.g. traditional, ultra-high strength concrete, light- and heavyweight concretes, fiber reinforced concrete, etc.). Over time, these different concrete types may have undergone degradation processes like carbonation (a process causing corrosion of steel reinforcement in concrete), chloride ingress, alkali silica reaction (a process chemically and physically altering the aggregate as well as the matrix). It is very difficult, if not impossible, to demolish a concrete structure with prior knowledge about origin and properties of all concrete components. The information about the type of a material (cement, aggregates, additives, fibers, coating) of each concrete element (strength class, with/without reinforcement, type of reinforcement) is hard to obtain. The environmental conditions to which the parent concrete has been exposed can also influence the levels of contamination of the parent concrete. Given these sources of varying composition and quality of concrete, variations in the recycled concrete are expected, particularly in the finer fractions.

(ii). Recycling technique

There are numerous recycling techniques for concrete, and most known are:

- jaw crusher (mechanical[1]),
- impact crusher (mechanical),
- rotor crusher (mechanical),
- Smart crusher (mechanical) [87],
- jaw crusher in combination with a vertical shift impact (mechanical), cone or roll,

[1] Mechanical treatment helps size reduction and separation, thermal treatment helps paste removal.

Table 2
Concrete mix design characteristics with fRCA.

	Concrete or mortar with fRCA		cement		SP		natural sand			fRCA				[a]Source/ recycling technique
	type	max agg size	type	[kg/m^3]	type	[wt.% cement]	type	density [kg/m^3]	water abs. [%]	density [kg/m^3]	water abs. [%]	replacement level [%]	treatment	
Evangelista [97]	Concrete	–	CEM I 42.5 N	380	carboxylate	1.3	river	2564	0.8	2165	13.1	0; 10; 20; 30; 50; 100	–	Lab, jaw crusher
Carro-López [31]	SCC	20 mm	CEM I 42.5 R	400	polycarboxylate	1.7	limestone	2720	1	2300	9.3	0; 20; 50; 100	Dry state	Field
Khatib [28]	Concrete	20 mm	CEM I	320	–	–	river	2650	0.8	2340	6.25	0; 25; 50; 75; 100	–	Field
Sarhat [33]	Concrete	15 mm	CEM I	345	–	–	river	2640	4.1	2330	12.5	0; 15; 30; 45; 60; 100	–	Field (37 years old concrete)
Evangelista [26]	Concrete	–	CEM I 42.5 N	380	carboxylate	1.3	river	2564	0.8	2165	13.1	0; 10; 20; 30; 50; 100	–	Lab, jaw crusher
Levy [98]	Concrete	25 mm	OPC + 35 wt.% slag	–	–	–	river	2650	1.8	2320	10.3	0; 20; 50; 100	–	Field (6 months old concrete)
Lee [99]	Mortar	5 mm	ASTM Type I Portland	–	–	–	river	2600	0.8	2280	10.35	0; 50; 100	–	Field, combined jaw crusher and impact crusher
Lee [99]										2390	6.59			
Kou [34]	SCC	20 mm	ASTM Type I Portland	340	polycarboxylate	2.6	river	2620	0.88	2300	11.86	0; 25; 50; 75; 100	SSD	Field
Vegas [18]	Masonry mortar	2 mm	CEM II/B-M (V–S-LL) 42,5 R	–	not specified	–	limestone	2670	0.34	1630	7.6	0; 25; 50; 75; 100	–	Field
Evangelista [29]	Concrete	–	CEM I 42.5 N	380	carboxylate	1.3	river	2564	0.8	2165	13.1		–	Lab, impact crusher
Dapena [19]	Mortar/ concrete	20 mm	CEM I 42.5 N/ SR	380	vinyl copolymer	0.7	limestone	2630	3.56	2460	7.26	0; 5; 10	–	Field
Yaprak [100]	Concrete	20 mm	CEM I 42.5 N	350	not specified	1.2	river	2650	1.22	2310	4.28	0; 10; 20; 30; 40; 50; 100	–	Lab
Zega [30]	Concrete	20 mm	CEM II-M	375	not specified	0.3–0.4	river	2630	0.9	2560	8.5	0; 20; 30	Dry state	Field
Pereira [35]	Concrete	not specified	not specified	350	lignosulfonate	1	river	2620	0.19	2230	10.19	0; 10; 30; 50; 100	–	Lab, jaw crusher
					polycarboxylates	1								
Geng [101]	Concrete	not specified	CEM I 42.5 N	388	poly-carboxylic acid	1.4	river	nd	1.6	nd	7.2	0; 20; 40; 60; 80	–	Field
Kim [102]	Concrete	not specified	OPC	392	air entrainment admixture	0.75	sea sand	2650	1	2290	5.83	0; 30; 35; 60; 70; 100		Field
Khoshkenari [103]	Concrete	12.5 mm	Type II Portland cement + Silica fume	410	sulphonated naphthalene formaldehyde	0.34 (3)	not specified	2470	1.97	1970	14.05	0; 100	–	Lab (concrete, 30 MPa)
Neno [15]	Mortar	4 mm	CEM II/B-L 32.5 N		–	–	river	–	–	–	8.49	0; 20; 50; 100		Lab (C30/37), jaw crusher
Le [79]	Mortar	4 mm	CEM II/A-L 42,5 N CE CP2 NF	–	–		river	2640	0.5	2410	6.8	0; 100	Dry state	Field
													Over-saturated state	
Cartuxo [104, 105]	Concrete	20 mm	CEM I 42.5 R	350	Sikament 400 plus (SP1)	1	river	2678	0.15	2460	7.09	0; 10; 30; 50; 100	Used as-received	Lab (C30/37), jaw crusher
					SikaPlast 898 (SP2)	1								
Zhao [106]	Mortar	5 mm			–	–		2660	1.05	2540	7.54		Dry state	Field

(continued on next page)

Table 2 (*continued*)

	Concrete or mortar with fRCA		cement		SP		natural sand			fRCA				[a]Source/ recycling technique
	type	max agg size	type	[kg/m^3]	type	[wt.% cement]	type	density [kg/ m^3]	water abs. [%]	density [kg/ m^3]	water abs. [%]	replacement level [%]	treatment	
			CEM I 52.5 ‘‘superblanc’’ white cement				calcareous sand					0; 10; 30; 50; 100		
													Over-saturated state	
Zhang [107]	Mortar	2.5 mm	CEM I 42.4 M		–	–	river	–	2.35	–	8.06	–	Pre-carbonated fRCA	Lab (Concrete beams of 30 and 50 MPa)
Yildirim [108]	Concrete	22 mm	ASTM Type III cement	400	–	–	river	2660	1.99	2450	6.22	0; 50; 100	Saturation (0%; 50%; 100%)	Field (building)
Mardani-Aghabaglou [109]	Concrete	25 mm	OPC	425–433	–	–	limestone	2610	0.67	2440	6.81	0; 15; 30; 45; 60	SSD state	Lab, hammer crusher
Bogas [110]	Concrete	–	CEM I 42.5 R				river	2568	1.68	2156	9.05	0; 20; 50; 100	presaturated	Lab (C25/30), jaw crusher
	normal strength			350	polycarboxylate SP	0.2								
	high strength			420	surfactant based AEA									
Bendimerad [111]	Concrete	20 mm	CEM II/A-L 42.5	270	polycarboxylatether	0.24	sandrandcourt	2600	1.2	2100	10.7	0; 30	SSD state	Field
			limestone	45										
Fan [27,57]	Concrete	19 mm	OPC	449 411	G superplastisizer	1	river	2653	1.3	2347 2404	8.9 6.6	0; 25; 50; 100	SSD state	Field
Güneyisi [112]	SCC	16 mm	CEM I 42.5 N	440	polycarboxylicether	1.6	river	2660	0.55	2260	12.8	0; 25; 50; 75; 100	SSD state	Lab (20 MPa), jaw and cone crushers
Kumar [113]	Concrete	20 mm	OPC grade 43	400	polycarboxylatether	0.25	river	2670	0.44	2080	11.91	0; 25; 50; 75; 100	Dry state	Field
Le [61]	Mortar	4 mm	CEM II/A-L 42,5 N	–	–	–	river	2640	0.5	2390	9	0; 100	Dry state	Field
										2410	10		Supersaturated state	
Evangelista [114,115]	Concrete	–	CEM I 42.5 R	360	–	–	river	2580	1.07	2210	10.43	0; 10; 30; 50; 100	–	Lab (28.7 MPa), jaw crusher
Zhang [37]	Concrete	–	CEM I 42.5	759	polycarboxylate	2.5	river	–	2.5	–	6.5	0; 25; 50; 75; 100	–	Lab
			SF + QP											
Shi [116]	Mortar	4.75 mm	CEM I 42.5	–	–	–	river	–	–	2490	5.3	0; 100	coated by CO2 and silica fume, fly ash, and nano-SiO2 slurries	Lab (C30)
Ho [117]	Concrete	19 mm	OPC	525	HPC-F type	–	river	2600	2.88	2360	9.43	0; 25	coated by FA, slag and polyvinyl alcohol materials	Field
				350										
Yacoub [76]	Mortar	4 mm	CEM I 52.5 N CE CP2 NF		–	–	river	2530	2.3	2440	6.86	0; 100	Dry sand	Field
													Pre-saturated sand for 24 h	
Delsaute [118]	Concrete	20 mm		270	polycarboxylatether	0.24		2600	1.2	2100	10.7	0; 30	SSD state	Field

(*continued on next page*)

Table 2 (*continued*)

	Concrete or mortar with fRCA		cement		SP		natural sand			fRCA					[a]Source/ recycling technique
	type	max agg size	type	[kg/m^3]	type	[wt.% cement]	type	density [kg/m^3]	water abs. [%]	density [kg/m^3]	water abs. [%]	replacement level [%]	treatment		
			CEM II/A-L 42.5 limestone filler	45			alluvial sand-silicious								
Ali [119]	Mortar	4.75 mm	OPC	490	–	–	from quarry	2680	1.45	2430	7.89	0; 100	Sodium silicate		Lab (C30/37)
Mardani-Aghabaglou [120]	Mortar	4.75 mm	CEM I 42.5 R	–	–	–	limestone	2610	0.68	2410	6.95	0; 25; 50; 75; 100	SSD		Lab (20 to 30 MPa)

[a] The source of parent concrete for production of fRCA is indicated as Lab or Field, meaning that fRCA was obtained either from parent concrete specifically produced in the laboratory, with controlled crushing and sieving of the recycled aggregates or from field structures without controlled crushing and sieving.

– C2CA (concrete to cement and aggregate) and Advanced dry recovery (ADR) (mechanical and thermal) [59].

Each of these recycling systems has a different rotational speed, type of magnets, heat generation, duration of crushing, crushing cycles. These different technologies lead to recycled concrete fractions that may have different physico-chemical characteristics, that is, different grain size distributions, shapes, textures with corresponding different chemical components and the amount of adhered mortar [56,88–90].

Although crushing can be a multi-stage process, it is not possible to remove completely the paste from the recycled concrete aggregates. The increased number of steps will increase energy consumption of the whole recycling process and also increase the content of ultra-fine material. This causes higher contents of fractions below 63 μm. High amounts of particles <63 μm may affect the workability and delay formation of reaction products in concrete. Lowering the content of the fraction <63 μm is a must to upgrade fRCA for the use in concrete production. Schoon et al. [88] reported that without this step, producing durable concrete with fRCA, would be very expensive and in some cases even impossible.

Different combinations of the concrete recycling operations can be also considered. Akbarnezhad et al. [91] proposed a computational method for selection of optimal concrete recycling strategy by considering the trade-off between costs, use of energy and carbon dioxide emissions of concrete recycling in a particular project. It is also reported that multiple crushed concrete aggregate, will eventually have increase of the volume of old adhered mortar [11]. In Japan, with repeated crushing, more than 50% of fRCA can be recovered [92].

(iii). Storage of the materials

The storage of fRCA is another important aspect which greatly affects the properties of fRCA.

– **Outdoor.** The storage of fRCA is usually outside (without shelter), which causes carbonation of outer layers of sand piles, and agglomeration of the material, specifically in the rainy periods. Therefore, the outer layer of a sand pile may have different properties than the inner layer of a sand pile.
– **Indoor.** Indoor storage is (very rarely) available at some recycling plants and less practical compared to outdoor storage.

Due to (i), (ii) and (iii), the variations in physical and chemical properties [58,82] cause a wide range of mechanical and durability properties of mortars and concretes with fRCA [28,90,93] as it will be shown in section 4.

4. Short and long-term properties of concretes containing fRCA

Generally, the concrete performance is influenced by properties of the aggregates such as the particle size distribution, particle texture and shape, particle stiffness, porosity and initial water saturation. This section deals with the effects of replacing fine natural aggregates with fRCA on the short- and long-term properties of concrete. As shown in Section 3, fRCA have different particle size distributions, moisture states, water absorption and tend to be angular with rougher surfaces compared to natural sand. These differences will significantly affect the packing density, the fresh properties (workability) and hardened properties (strength) of the new concrete mixtures [94–96]. The design of concrete mixtures with fRCA is mainly based on the mix design methods for conventional concrete. Table 2 provides an overview of the concrete mix designs with fRCA from the current literature with some of their main characteristics. Their properties will be reviewed next. It should be noted that Table 2 also indicates the source of fRCA for these mixes: they were obtained either from parent concrete specifically produced in the laboratory, with controlled crushing and sieving of the recycled aggregates or from field structures without controlled crushing and sieving.

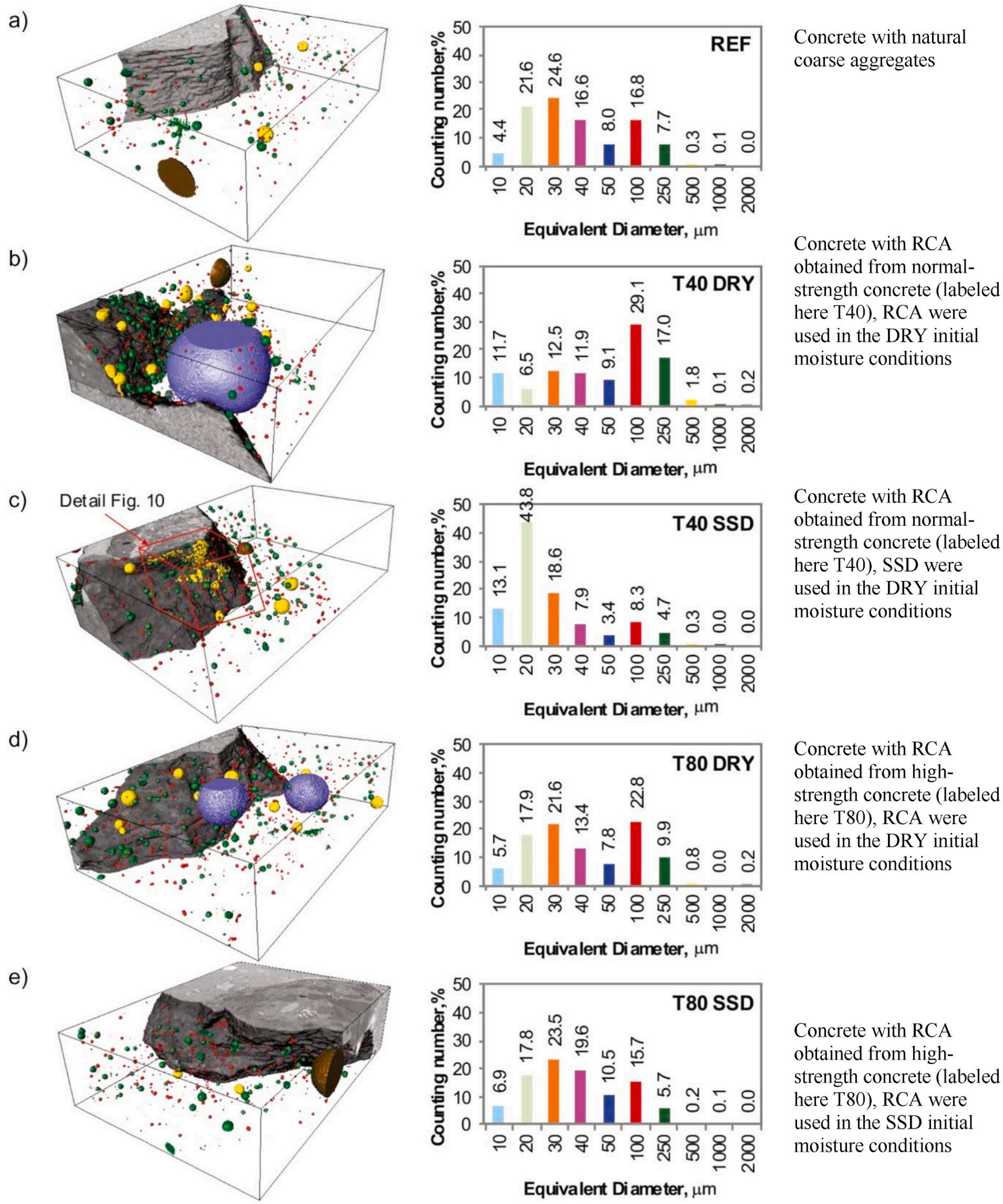


Fig. 12. µCT 3D images showing the size and spatial distribution of the pores inside the new cement matrixes of different concrete mix and the corresponding particle size distribution histograms (concrete prisms size = 5500 × 7500 × 2100 µm). The recycled coarse aggregates (RCA) were obtained by casting normal-strength concrete (40 MPa, labeled here T40) and high-strength concrete (80 MPa, labeled here T80). The two types of RCA (T40 and T80) were used in the DRY and SSD initial moisture conditions, resulting in four recycled concrete mixtures [126].

4.1. Fresh concrete properties

4.1.1. Workability

Grading, shape and mineralogy are anticipated to be the main aggregate fines parameters affecting the flow [121,122] including the effect of interaction with the water reducing admixtures [123,124]. For OPC-based concrete, most design codes require continuous grading to achieve tight packing. Continuous grading curves range from 250 µm to a maximum particle size (Fuller curve). Applying this grading curve to materials with fine constituents such as fRCA may result in mixes that contain insufficient cement and that are less workable. Increasing the amount of fines (particles < 250 µm) increases the required amount of water needed to wet the particle surfaces adequately and to maintain a specified workability [125]. Furthermore, high amounts of open pores

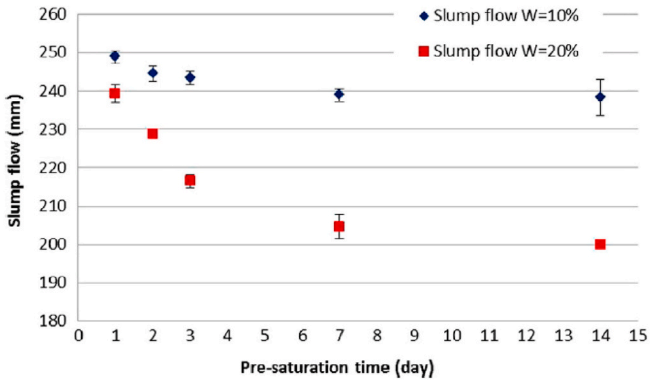


Fig. 13. Workability of mortar as a function of pre-saturation time (error bars correspond to the standard deviation) [79].

(thus higher void content) and the rougher surface texture of crushed particles increase water demand [65]. Generally, concrete with crushed aggregates requires slightly higher cement content in order to reach the same workability as a concrete with round aggregates [94].

Low workability (reduced slump and slump-flow values) is mostly reported for concrete with fRCA due to higher water demand of fRCA than the same concrete made with river sand. The high-water demand is caused by angular shape, increased surface roughness, large open porosity of fRCA particles and the large amount of fines. The bleeding during the concrete production is also favored by the high porosity of fRCA and high amount of fines [126]. This bleeding is magnified when recycled aggregates are used in a dry state in the concrete mix. Fig. 12 compares the size and spatial distribution of the pores inside the new cement matrices of four different concretes with coarse recycled concrete aggregates and the corresponding pore size distribution histograms [126]. Two types of coarse recycled concrete aggregates were used in dry and saturated surface dry moisture conditions. The coarse recycled concrete aggregates were obtained by casting normal-strength concrete (40 MPa, labeled T40) and high-strength concrete (80 MPa, labeled T80). Large bleeding and high air content occur with the dry coarse recycled aggregates originated from a lower strength concrete. Ghorbel et al. [127] and Bouarroudj et al. [96] showed that the use of dry fRCA also increases air content in mortars and concretes. This was attributed to the air still present in the pores of particles which were not filled with water. In order to decrease air content and obtain desired workability of mortars and concretes with fRCA it is necessary to add a certain amount of water to saturate fRCA *before* or *during* the mixing process or to use superplasticizers. From the data in Table 2, it is apparent that the use of superplasticizers is more common.

Le et al. [79] found that the *initial moisture content*, *pre-saturation method* and *pre-saturation time* of fRCA strongly affect mortar's workability. In the pre-saturation stage, part of the water is present in the pores of aggregates (absorbed water) and part in agglomerates of small particles (interstitial water). The time necessary to obtain a moisture equilibrium was shown to be longer than 7 days. Fig. 13 shows that the workability of mortar with pre-saturated fRCA is identical when the pre-saturation time is longer than 7 days. Similarly, Yildirim et al. [108] reported 100% saturation of fRCA for 7 days, while 50% saturation for 2 days. Furthermore, they also showed that replacing fine natural aggregates with fRCA and varying the degree of fRCA saturation had a negligible effect on the workability compared to the corresponding effect of the water-to-cement ratio. Optimal workability was obtained for the specimens with water-to-cement ratio of 0.6, whereas the specimens with water-to-cement ratio of 0.5 were very dry and those with water-to-cement ratio of 0.7 were very fluid and showed bleeding.

When the fRCA is used in the dry state, all the effective water and water absorption are added into the mixer at the same time [79]. The amount of water available for fluidizing the mixture is maximal and the slump flow is the highest (Fig. 14, pre-saturation water content = 0%). When pre-saturation water increases, a part of water is absorbed by the aggregates, therefore the amount of water available for fluidizing the mixture decreases and it is lower than in the mortar made with dry sand. Fig. 14 shows that the slump flow is consequently decreased (from 285 mm to 270 mm). When the fRCA are completely saturated, water available for fluidizing the mixture must remain constant, as well as the slump flow of mortar (the first plateau at W = 14%, slump flow = 220 mm). However, not all of the pre-saturation water is absorbed by the aggregates, therefore a second plateau of slump flow (200 mm) is observed for W = 18%. Authors also suggested that saturation vapor, leads to a more complete saturation of the internal porosity than with a complete immersion in water, which may trap part of the air in porosity.

In a similar study on the influence of saturation state of fRCA (dried or saturated) on the slump of mortars, Zhao et al. [106] showed that the slump of mortars containing dried fRCA is larger than that of mortars containing saturated fRCA. However, authors reported *quicker* slump loss when using dry recycled sand.

Bouarroudj et al. [96] investigated 5 different pre-saturation conditions of fRCA in order to study the water movement between the paste and fRCA:

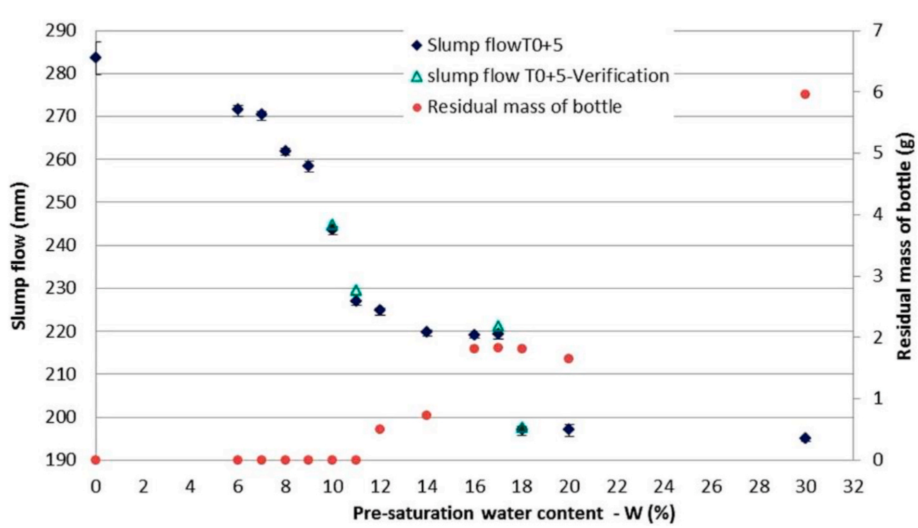


Fig. 14. Slump flow at T0 + 5 min as a function of pre-saturation water content and the residual mass of pre-saturation bottle (error bars correspond to the standard deviation) [79].

Table 3
Concrete compressive strength 28 days depending on the replacement ratio of natural sand by fRCA.

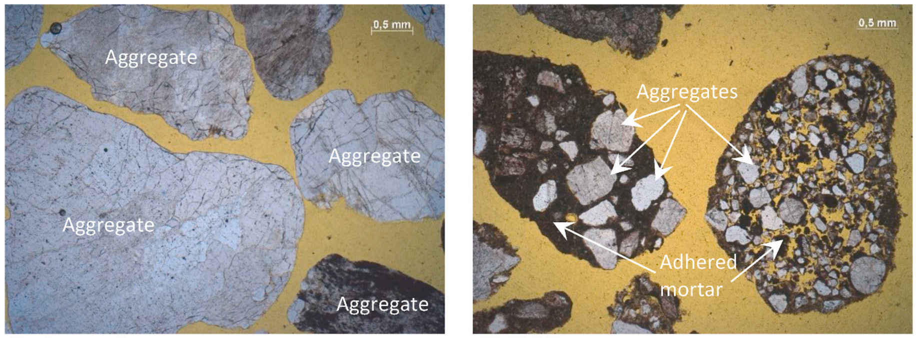
	cement		Concrete compressive strength 28 days													
	type	[kg/m^3]	0%	5%	10%	15%	20%	25%	30%	40%	45%	50%	60%	75%	80%	100%
Evangelista [26,29,97]	CEM I 42.5 N	380	59.3		59		57.3		57.1			58.8				54.8
Carro-López [31]	CEM I 42.5 R	400	80				75					55				40
Khatib [28]	CEM I	320	46.7					35.3				35.2		35.1		30
Sarhat [34]	CEM I	345	40			40.6			42		41.7		41			40.1
Levy [98]	OPC + 35 wt.% slag	–	48.5				56.1					46.3				46.6
Kou [34]	ASTM Type I Portland	340	44.3					44.5				43.4		41.3		38.7
Kou [34]			53.7					64.3				62.3		56.3		53.2
Dapena [19] (RCA20%)	CEM I 42.5 N/SR	380	51.1	46.5	50											
Dapena [19] (RCA50%)			48.1	45.9	49.7											
Dapena [19] (RCA100%)			52	48.4	48.5											
Yaprak [100]	CEM I 42.5 N	350	45		42		41		40	38		36				29
Zega [30]	CEM II-M	375	43.6				42.7		41.4							
Pereira [35]	not specified	350	39.5		40				38.6			37.6				38.6
Pereira [35] (SP1)			53.3		53.7				51			47.8				45.1
Pereira [35] (SP2)			65.2		64.6				65.4			63.2				63
Geng [101]	CEM I 42.5 N	388	46.7				44.5			38.2			31.2		21.5	
Kim [102]	OPC	392	31.5						29.9				31			27.4
Khoshkenari [103] (AW)	Type II Portland cement	410	38													27.9
Khoshkenari [103] (SP)			38													32.8
Cartuxo [104,105]	CEM I 42.5 R	350	49.37		51.17				47.21			43.53				41.2
Cartuxo [104,105] (SP1)			66.79		63.86				61.65			58.73				47.36
Cartuxo [104,105] (SP2)			80.64		77.41				71.73			69.31				64.72
Yildirim [108]	ASTM Type III cement	400	38.28									38.02				32.26
Bogas [110] (NC)	CEM I 42.5 R		50.2				49.9					47.4				43.1
Bogas [110] (HC + SP)		350	81				72.7					67.4				58.8
Bogas [110] (HC + SP + AEA)		420	67.9				61.8					52.1				44.9
Bendimerad [111]	CEM II/A-L 42.5	270	31.4						29							
Fan [27]	OPC	449	56.3					51.4				47.4				37.8
Fan [27]			56.3					53.3				51.3				49.6
Fan [27]			34.1					28.6				24.6				17.8
Fan [27]			34.1					31.3				29.1				27.3
Kumar [113]	OPC grade 43	400	40.72					39.3				37.4		37.34		35.21
Evangelista [114,115]	CEM I 42.5 R	360	33.6		32.1				32.7			32.8				30.7
Zhang [37]	CEM I 42.5	759	122					121				116		112		108

– *dry fRCA* (first mixed with the powders and then the total water is added);
– *paste + dry fRCA* (preparation of the paste with water first then add the dry fRCA);
– 5 min WA + *5%* (add to fRCA a quantity of water equal to WA + 5% for 5 min);
– 24 h WA + *5%* (add to fRCA a quantity of water equal to WA + 5% for 24 h);
– *24 h IM* (add to fRCA all the quantity of water for preparing the mortar (in order to assure that all the particles are immersed in water)).

The mortar made with fRCA saturated with WA + 5% for 24 h had better workability than the one made with immersed fRCA for 24 h. Authors found also that using fRCA in dry condition or saturated with WA + 5% for 5 min gives similar behaviors in the fresh state and leads to the best workability. This is due to the incomplete absorption of water by dry fine aggregate which leads to maximal amount of effective water for fluidizing the mixture.

De Andrade et al. [128] added 80% of the total water absorption capacity (WA_{24h}) of the fRCA to the mixture for saturating the fRCA during the mixing stage. This value was optimal for fRCA saturation, since the recycled aggregates could not absorb 100% of their total water absorption capacity during the short mixing process. These findings are in accordance with studies on workability of concretes with coarse recycled aggregates. Barra and Vázquez [129] and Poon et al. [130] suggested that the saturation point should not be reached because of the risk of the later transfer of water from within the coarse recycled aggregates to the cement paste. Such transfer would modify the water-to-cement ratio in the ITZ between coarse recycled aggregates and the cement paste, affecting the bond strength. Barra and Vázquez [129] stated that concrete with air-dried coarse recycled aggregates (at approximately 90% of potential water content) presented better results than concrete made with saturated surfaced dried coarse recycled concrete aggregates.

In the study of Kou and Poon [34] fRCA were used in air-dried state and additional water was added during the mixing process. The slump increased with an increase in the fRCA content. This was attributed to the high water absorption capacity of the fRCA compared to river sand. As the fRCA content increased, more water was initially added into the



(i) river sand *(ii) fRCA*

Fig. 15. Microphotographs showing examples of: (i) river sand particles; (ii) fRCA particles in plane polarized light obtained with optical polarizing-and-fluorescence microscopy [133].

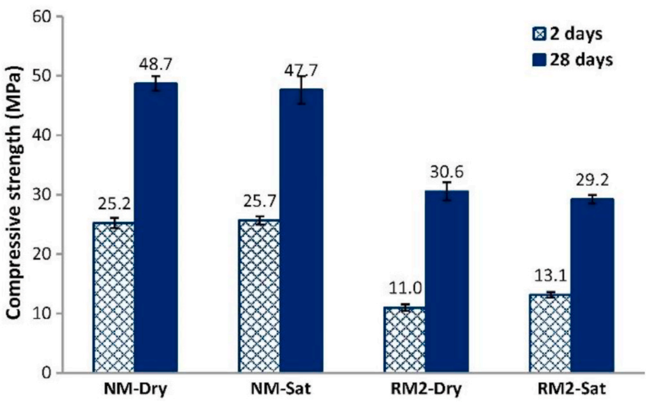


Fig. 16. Compressive strength of mortars after 2 and 28 days (NM/RM2-dry: mortar based on dry natural/recycled sand; NM/RM2-Sat: mortar based on over-saturated natural/recycled sand) [61].

concrete mixes to compensate for the higher water absorption of the fRCA. In addition, with 10 min of immersion, the water absorption of the fRCA only reached 51% of that at 24 h. It was highly probable that part of the additional water could not be taken up by the aggregate particles during the first minutes and hence the excess of water contributed to the increase of the slump flow. Other studies also used the 10 min water absorption value to compensate the available free moisture loss due to the high water absorption of the fRCA [31,35]. However, Behera et al. [131] showed that the 10 min water absorption was not sufficient enough to achieve and maintain the desired flowability. It should be noted that these three studies [31,35,131] focused on the self-compacting concrete. Behera et al. [131] investigated the water absorption kinetics for different mixes based on the fRCA replacement ratio. The water absorption value at 1.5 h has been found to be the optimal value and it was used to saturate fRCA and maintain the flowability up to 1 h. The authors used also high volume of supplementary cementitious materials (SCMs), a polycarboxyl ether-based superplasticizer (SP) to enhance the flowability, and a viscosity modifying agent (VMA) to control segregation resistance or the viscosity of the SCC mixes. A noticeable increase in instant slump flow with high fRCA content was found. The authors explained that the porous structure of fRCA acts as a reservoir for instant water entrapping during the mixing procedure which is later released due to the agitation process and the surface tension. Thus, it imparts a positive influence on the slump flow. For the mix with 50% fRCA, the amount of excess free water was not sufficient for higher slump flow due to comparatively less quantity of fRCA. Moreover, the rough surface of fRCA also resulted in more frictional resistance to the free flow.

Contrary to the results of Behera et al. [131], Güneyisi [112] showed that the SCC mixes with higher % of fRCA exhibited lower slump flow and an increased T500 time. This contradiction in the results may be due to the fact that the SP content and the VMA dosage were not varied in the study of Güneyisi [112]. Similarly, Yaprak et al. [100] showed that the slump of fRCA concrete decreases as the incorporation level of fRCA increases. Moreover, Pereira et al. [35] showed that the efficiency of SPs decreases as the fRCA replacement level increases, as also reported by Cartuxo et al. [104]. In this study [104], the fRCA was added in the mixer with its natural moisture (3.2%). The incorporation of fRCA up to 100% had the following consequences on the concrete's slump: for the same slump value without any SP, the $(w/c)_{ef}$ increased up to 16.3%; with the addition of a lignosulfonate-based superplasticizer, the $(w/c)_{ef}$

Table 4
Concrete tensile strength 28 days depending on the replacement ratio of natural sand by fRCA.

	cement		Concrete tensile strength 28 days										
	type	[kg/m^3]	0%	10%	15%	20%	25%	30%	45%	50%	60%	75%	100%
Evangelista [26,29,97]	CEM I 42.5 N	380	3.85					3.7					2.95
Sarhat [34]	CEM I	345	3.4		3.3			3.2	3.2		3.1		3
Kou [34] (w/c = 0.53)	ASTM Type I Portland	340	2.9				2.6			2.6		2.5	2.4
Kou [34] (w/c = 0.44)			2.9				3.1			3.4		3.3	3.5
Zega [30]	CEM II-M	375	4.3			4.4	4						
Pereira [35]	not specified	350	2.9	2.9				2.7		2.6			2.6
Pereira [35] (SP1)			3.7	3.4				3.3		3.1			3
Pereira [35] (SP2)			4.5	4.2				4.5		3.7			3.4
Kim [102]	OPC	392	2.58					2.7			2.8		2.62
Khoshkenari [103] (AW)	Type II Portland cement	410	4.2										2.8
Khoshkenari [103] (SP)			4.2										3.2
Yildirim [108]	ASTM Type III cement	400	3.21							3.28			2.39
Kumar [113]	OPC grade 43	400	3.97				3.8			3.75		3.7	3.71
Evangelista [114,115]	CEM I 42.5 R	360	3.42	3.1				3.2		3.2			2.84

Table 5
Concrete E_m 28 days depending on the replacement ratio of natural sand by fRCA.

	cement		Concrete Em 28 days							
	type	[kg/m^3]	0%	5%	10%	20%	30%	50%	60%	100%
Evangelista [26]	CEM I 42.5 N	380	35.5				34.2			28.9
Dapena [19] (RCA20%)	CEM I 42.5 N/SR	380	39.4	41.6	33.7					
Dapena [19] (RCA50%)			31.1	30.7	35					
Dapena [19] (RCA100%)			29.3	32.1	25.8					
Zega [30]	CEM II-M	375	35.4			34.8	32.9			
Pereira [35]	not specified	350	34.4		33.7		32.3	32.3		29.9
Pereira [35] (SP1)			41.3		40.6		36	35		34.2
Pereira [35] (SP2)			43.9		43.9		41.9	40.2		39.7
Kim [102]	OPC	392	21.3				23.1		24	20.9
Bendimerad [111]	CEM II/A-L 42.5	270	39				35.6			

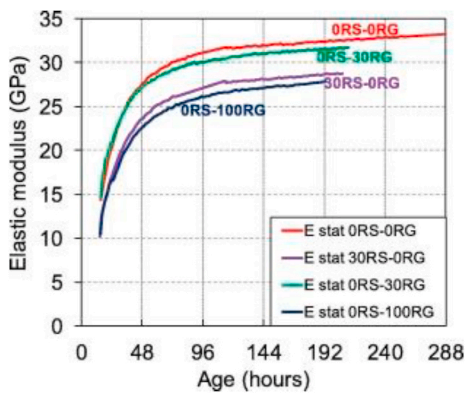


Fig. 17. Effect of substitution rate on the elastic modulus determined from repeated loading tests [139].

decreased up to 15.7%; with the addition of polycarboxylic superplasticizer, the $(w/c)_{ef}$ decreased up to 25.5%.

Carro-López et al. [31] studied the workability of self-compacting concrete (SCC) with different percentages of fRCA (0%, 20%, 50%, 100%) over time (at 15, 45 and 90 min). To achieve suitable SCC mixes, a modified polycarboxylate-based SP was used [31]. The flowability and filling capability of the 50% and 100% fRCA mixes suffered a severe reduction, losing their SCC behaviour. This was caused by an initial increase of plastic viscosity and afterwards an increase of yield stress. Based on the findings, the 20% fRCA replacement ratio was recommended.

These studies clearly indicate that the evaluation of workability depends on saturation state of fRCA, water absorption kinetics of fRCA, the fRCA incorporation ratio and the mixing procedure. Although researchers have given a lot of reasonable explanation on complex flow behaviour through combination of experiments and theories there is no universal approach defined to *obtain* and *maintain* satisfactory workability of mortars/concretes with fRCA.

4.2. Mechanical properties of concretes containing fRCA

4.2.1. Compressive strength of concrete

A number of studies have focussed on the use of fRCA in normal-strength and self-compacting concretes. The compressive strength of concretes with fRCA fluctuated: it was higher, the same or lower [26,34,102,113,132] compared to control mix. Table 3 presents a summary of the 28 days compressive strength results from the literature. The maximum reduction of compressive strength was 6.7%, 11.1%, 31.3% and 50% for concrete with 10%, 30%, 50% and 100% replacement ratio, respectively. It is clear that the compressive strength is rather sensitive to the high replacement level of fRCA (100%), irrespective of the binder composition or cement content. This reduction is attributed mainly to the increased water content in concrete mixes with fRCA needed to achieve the same workability to that of concrete with natural fine aggregates; increase in the fRCA replacement increases the effective water-to-cement ratio of the mixes. Consequently, poor interface bond with the surrounding paste matrix is formed because of the deposition of water near the interface zone [131]. According to Zhang et al. [37], increasing content of the adhered old cement mortar with the fRCA replacement ratio leads to decrease of compressive strength, because the weaker old cement mortar can lower the mechanical properties of the

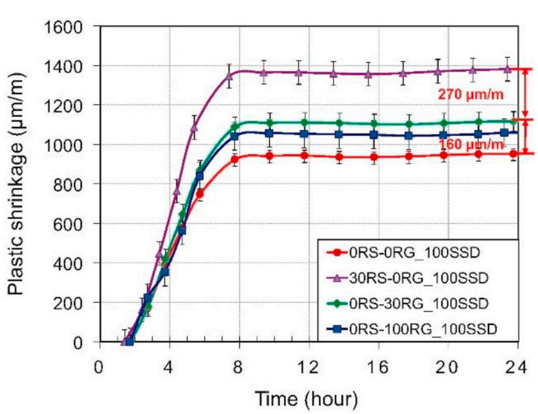


Fig. 18. Effect of substitution rate on plastic shrinkage. (0RS0RA-reference concrete, 30RS0RA-concrete with 30% recycled sand, 0RS30RA-concrete with 30% recycled gravel, 0RS100RA-concrete with 100% recycled gravel) [111].

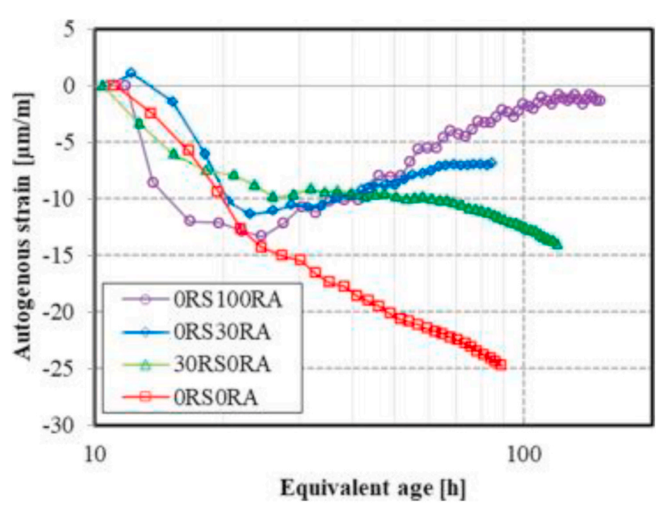


Fig. 19. Development of the autogenous strain according to the equivalent age. (0RS0RA-reference concrete, 30RS0RA-concrete with 30% recycled sand, 0RS30RA-concrete with 30% recycled gravel, 0RS100RA-concrete with 100% recycled gravel) [118].

cement matrix (counting in both the old and the new matrix). Fig. 15 shows an example of morphologies of pure river sand and fRCA particles with their two phases: "old" natural aggregates (white) and adhered mortar (brown) with voids (yellow) [133]. In this study, fRCA are made up by crystalline phases (>70 wt%), notably quartz (>60 wt%), and adhered cement paste (<30 wt%).

In other studies, on the contrary, a strength increase of concrete with fRCA compared to reference concrete was found [26,28,69]. The maximum increase of compressive strength was 3.7%, 5%, 16% for concrete with 10%, 30% and 50% replacement ratio, respectively. The increase in compressive strength was attributed to the filler effect of fRCA, part of which was finer than the natural sand, making concrete more compact and denser, reducing the internal stresses and early propagation of cracks. Another possible reason was the internal curing effect of fRCA, due to which the water initially absorbed inside pores was available at later stages for the hydration of cement. The angular shape and rough surface texture of fRCA particles could lead to improved strength of concrete due to better interlocking between particles as reported for high-strength concrete with crushed fine aggregates [134]. However, strength depends not only on properties of aggregates but also on the volume of the paste [94]. With regard to the paste volume, Table 3 shows that compressive strength did not largely benefit from the high cement content that was incorporated along with the fRCA.

For pre-saturated fRCA, the presence of excessive water in aggregates may increase the size and quantity of pores in the old and new ITZ [135]. Yildirim et al. [108] studied the effect of saturation level of fRCA (0%, 50%, 100%) on the compressive strength of concrete. The strength increased with the saturation degree but decreased with increasing water-to-cement ratio and fRCA content.

Le et al. [61] showed no significant difference between the compressive strengths of mortars made either with dry or over-saturated fRCA (Fig. 16). Nevertheless, the saturation state of fRCA had a significant influence on the distribution of porosity in the ITZ, in accordance with [135]. The porosity in the ITZ of mortars containing fRCA is larger than that of mortars made with natural aggregates. This difference was attributed to a higher effective water-to-cement ratio in the mortar with fRCA.

Contrary to Le et al. [61], Zhao et al. [106] and Bouarroudj et al. [96] showed that the state of moisture (dry or saturated) significantly influences the interface between the new and old cement paste. These authors found that using fRCA in dry condition leads to higher compressive strength, which was explained by better adhesion between dry aggregates and cement matrix. Authors also reported that the compressive strength of mortars decreased with the increase of fRCA replacement ratio, similar to other studies [31,100].

Evangelista and de Brito [25] studied the effect of mixing procedure and mixing duration on the strength of concrete made with fRCA. Two mixing techniques were employed. For the first technique, applied at the first stage of the campaign, the fRCA were inserted into water (2/3 of the required mixing water, plus the water that was estimated to be absorbed), and were mixed during a period of 10 min, after which the remaining constituents were placed. In the second technique, used at both second and third stages, the same mixing procedure was used, except that the duration of mixing was extended to 20 min. The lower strength of the concretes with longer mixing period was found.

Kou and Poon [34] studied properties of self-compacting concrete mixtures prepared with different fRCA and water-to-binder ratios. The compressive strength increased as the water-to-binder ratio decreased at all test ages. The maximum compressive and tensile splitting strength were achieved by using 25–50% fRCA as a replacement of river sand. In another study [109], the compressive strength of the concrete containing up to 60% fRCA was close to that of the control mixture.

According to Pedro et al. [136] the source of the fRCA (produced in the laboratory and with origin from precast concrete elements), did not affect performance of concretes. For the different ages, the compressive

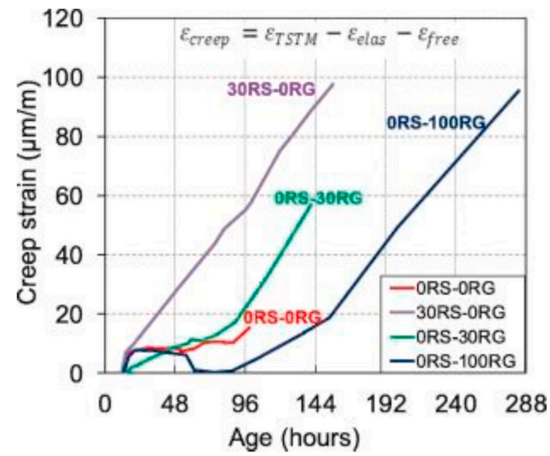


Fig. 20. Evolution of creep strain calculated from free and restrained shrinkage evolutions (RS is recycled sand, RG is recycled gravel) [139].

strength of concrete with 100% fRCA was lower than that with 100% coarse recycled concrete aggregates. This difference was attributed to the higher effective water-to-cement ratio for concrete with fRCA.

Zhang et al. [37] investigated strength of ultra-high performance concrete (UHPC) using fRCA cured under different conditions (standard and autoclaved curing). Autoclaved curing enhanced the quality of ITZ and consequently the mechanical properties of UHPC prepared with fRCA improved. In the study of Salahuddin et al. [137], hot curing (in which samples were first kept in hot water at 90 °C for 48 h and then immersed in water at room temperature) led to better strength and durability of reactive powder concrete with fRCA compared to concrete cured in water at room temperature. The strength was also enhanced with superplasticisers, in particular with polycarboxylate-based [35, 103]. All of the studies reviewed here suggest that compressive strength, similar to workability, strongly depends on the saturation state of fRCA, the water-to-cement ratio and the fRCA replacement ratio.

4.2.2. Tensile strength of concrete

Table 4 presents a summary of the results for 28 days tensile strength. The maximum reduction of tensile strength was 10.2%, 10.8%, 17.8% and 33% for concrete with 10%, 30%, 50% and 100% replacement ratio, respectively. A decrease of tensile strength was reported with the increase of natural fine aggregates replacement with fRCA [25,103,113] and with the increase of water-to-cement ratio [33]. Kou and Poon [34] found increase of tensile strength compared to control concrete with the decrease of water-to-cement ratio (from 0.53 to 0.44) along with addition of fly ash (70 kg/m^3). Zega and Di Maio [30] showed that 20% fRCA as a replacement of river sand did not influence tensile splitting strength compared to control sample, whereas a slight decrease (7%) was found for concrete with 30% fRCA. Yildirim et al. [108] showed that the fRCA saturation had a positive effect on the tensile strength of the concrete. Contrary, Bendimerad et al. [111] show that the effect of initial water saturation of fRCA on the tensile strength at 24 h was negligible.

Pereira et al. [132] studied the influence of superplasticizers on the splitting tensile strength of concrete made with fRCA. The addition of superplasticizers increased the splitting tensile strength up to 26.6% and 52.8% when lignosulfonate and modified polycarboxylates in an aqueous solution, respectively, were used. These gains are in agreement with study [138], where the positive effect of silica fume and superplasticizers on the properties of high-performance concrete (HPC) using fRCA was found. In addition, this study found that recycled aggregates obtained from moderate- or high-strength concrete with original granite or basalt aggregates appeared effective component for HPC, i.e. the performances of HPC with natural aggregates or recycled aggregates are similar. Based on experimental studies, Pereira et al. [132] established a correlation (Eq. (1)) between compressive strength and splitting tensile strength. The authors applied Model Code's recommendation, taking into account different densities of natural fine aggregates (FNA) and fRCA (by which the replacement ratio was considered) and the type of superplasticizer used, which influences the water-to-cement ratio, as follows:

$$f_{ctm} = a \cdot f_c^{\frac{2}{3}} \cdot \left((1-r) \cdot \rho_{FNA} + r \cdot \rho_{fRCA}\right) \cdot \left[\frac{(\mathrm{W/C})_{\mathrm{RC0}}}{(\mathrm{W/C})}\right]^{b} \quad (1)$$

where f_c is the compressive strength previously presented [35], a and b are correlation factors, r is the replacement ratio, ρ_{FNA} and ρ_{fRCA} are densities of natural fine aggregates (FNA) and fRCA, respectively, $(\mathrm{W/C})_{\mathrm{RC0}}$ is the effective water-to-cement ratio of the reference concrete, made with no superplasticizers, (W/C) is the effective water/cement ratio of the mix.

4.2.3. Elastic modulus of concrete

Table 5 compares the results on 28 days elastic modulus obtained from literature. The elastic modulus was negatively influenced by fRCA incorporation (reductions from 9.5% to 17%) [111,132].

A recent study by Bendimerad et al. [139] involved the monitoring of elastic modulus using repeated loading testing since very early age. The authors reported that the substitution of 30% of natural sand by fRCA causes a decrease of the elastic modulus by 4 GPa at an age of 1 week (Fig. 17). Similar results were obtained by other researchers. Velay-Lizancos et al. [140] observed that low substitution (<30%) of natural sand by fRCA significantly decreases the elastic modulus. Omary et al. [141] also observed a significant reduction in elastic modulus with 30% of fRCA. Wang et al. [142] reported that concrete with natural coarse aggregate and 100% fRCA had the elastic modulus reduced by 5.6–13.5% for concretes using, while the decrease ranged from 6.8 to 16.0% for concrete with 50% coarse recycled concrete aggregates and 100% fRCA. Pereira et al. [132] showed that the use of superplasticizers had a positive effect on the elastic modulus, with gains of up to 20.7% for lignosulfonate SP and 33.0% for polycarboxylic SP in comparison to concrete without SP. Although the higher specific surface of fRCA may negatively influence mixes containing superplasticizers because the polymeric chains have a larger contact area, the steric effects produced in concrete made with polycarboxylic superplasticizers may mitigate the negative effect of incorporating fRCA.

4.3. Time dependent deformation of hardened concrete

4.3.1. Shrinkage of concrete

Previous studies showed that the drying shrinkage and creep of mortars and concretes with fRCA, are significantly affected. In particular, the influences of fRCA replacement ratio [28,30,32,95,143–145], the source of fRCA [136,146] and the mineral additions [104,147,148] on drying shrinkage of concrete with fRCA have been studied. Higher drying shrinkage of concretes with fRCA were attributed to the lower elastic modulus of fRCA (due to the presence of old cement mortar, Fig. 15) and their higher water absorption, leading to a greater change in the water content in the concrete. Due to higher water demand of fRCA compared to natural fine aggregates, not only drying, but also the plastic and autogenous shrinkage rate and extent will be different compared to shrinkage of conventional concrete mixtures. Fig. 18 compares plastic shrinkage of different concretes. Higher plastic shrinkage of the concrete with 30% fRCA (mix 30RS0RA) compared to the control sample and concrete with coarse recycled concrete aggregates has been found [111]. The fRCA (0–4 mm) and fines smaller than 63 μm develop a surface area of 5.3 m^2/g and 9.9 m^2/g respectively. As a consequence, the effective water intended for the cement paste is attracted and kept in the menisci created by the fRCA. Therefore, the bleeding water is lower than in the control mix and the plastic shrinkage related to insufficient curing increases [111].

A strong reduction of autogenous deformations was reported for the mix 30RS0RA (Fig. 19) [118]. It should be noted that for each mix, gravel and sand were saturated for 24 h before concrete mixing. Delsaute and Staquet [118] suggested that the high porosity and the internal curing provided by fRCA cause a decrease of the autogenous shrinkage and limit the increase of the coefficient of thermal expansion during the first days after setting for concrete with 30% fRCA, decreasing the risk of concrete cracking. It was also found that the magnitude of swelling was 1 μm/m for concrete with 30% fRCA, while for concrete with 30% and 100% recycled gravel it was higher, with a magnitude of 5 μm/m and 12 μm/m, respectively. Based on calorimetry results, the authors also observed that the substitution of natural sand by fRCA does not change the degree of cement hydration.

Neno et al. [15] reported a 50% higher drying shrinkage of mortar made with 20% fRCA compared to the reference mortar. Similarly, Pedro et al. [136] found an increase of drying shrinkage of *concrete* by about 40% compared with concrete incorporating only coarse recycled aggregates. According to Zhang et al. [149], complete replacement of the natural aggregates with recycled aggregates (including both fine and coarse) increased the drying shrinkage (measured for 472 days) by more than 100% (102.0%–116.9%). The use of 100% fRCA and 0% coarse recycled aggregates results in an increase of drying shrinkage by 23%–41% compared to control mix. In addition, out of the two fRCA's studied, the fRCA1, which has a higher water absorption ratio (11.2% compared with 8.1%) and a lower density (2222 kg/m^3 compared with 2326 kg/m^3), resulted in higher drying shrinkage.

A few studies showed that the drying shrinkage of concrete with fRCA can be reduced: by pre-saturation of fRCA, by addition of SCMs, by carbonation of fRCA, by removal of ultrafine fractions from fRCA. Yildirim et al. [108] showed that saturation of fRCA mitigates the drying shrinkage of concrete with fRCA. A saturation level of 50% for a fRCA content of 50% yielded a concrete with satisfactory performance. The synergistic influences of SCMs with fRCA on the shrinkage characteristics of SCC are observed and found that the ternary blend binder (ordinary Portland cement (OPC), fly ash and silica fume) effectively control the shrinkage strain of concrete made with fRCA than the binary blend mixes (OPC and fly ash) [131]. Compared with the mortar made of noncarbonated fRCA, the mortar made with carbonated fRCA had lower drying shrinkage (from 8 to 13% at 56 days) [107]. The authors suggested that carbonation treatment of fRCA reduced the porosity and water absorption of the attached cement paste in fRCA, which reduced water evaporation and thus the drying shrinkage of the fRCA mortar. With the removal of particles <0.6 mm from the fRCA (0–4.75 mm), the drying shrinkage of the mortars was reported to be lower than 1.0 mm/m [95].

Zhang et al. [149] proposed a time-dependent *drying* shrinkage model for concrete with coarse and fine recycled concrete aggregate. The approach modifies the shrinkage expression in the European Code [150] for concrete with natural aggregates and includes: (1) an influence factor (k_{wa}) accounting for the water absorption capacities of the fRCA and coarse recycled aggregates (CRA) on the development of drying shrinkage and (2) an amplification factor (k_v) accounting for the influence of the lower stiffness of fRCA and CRA on the final drying shrinkage. The proposed model could predict both the time-dependent response and the final value of drying shrinkage of concrete incorporating both fRCA and CRA with a maximum difference of 16%. Moreover, based on experimental study, it was shown that the final drying shrinkage for CRA can be quantified independently of that of fRCA.

4.3.2. Creep of concrete

Similar to shrinkage, several studies have shown that creep was also affected by incorporation of fRCA. A significant increase of the creep is observed when using fRCA, especially at very early age. Cartuxo et al. [104] found that creep deformation increased up to 129% at 28 days and 154% at 91 days in concrete with 100% fRCA compared to concrete with 100% natural fine aggregates. This study has noted the importance of superplasticizer on creep deformation. It was shown that with the

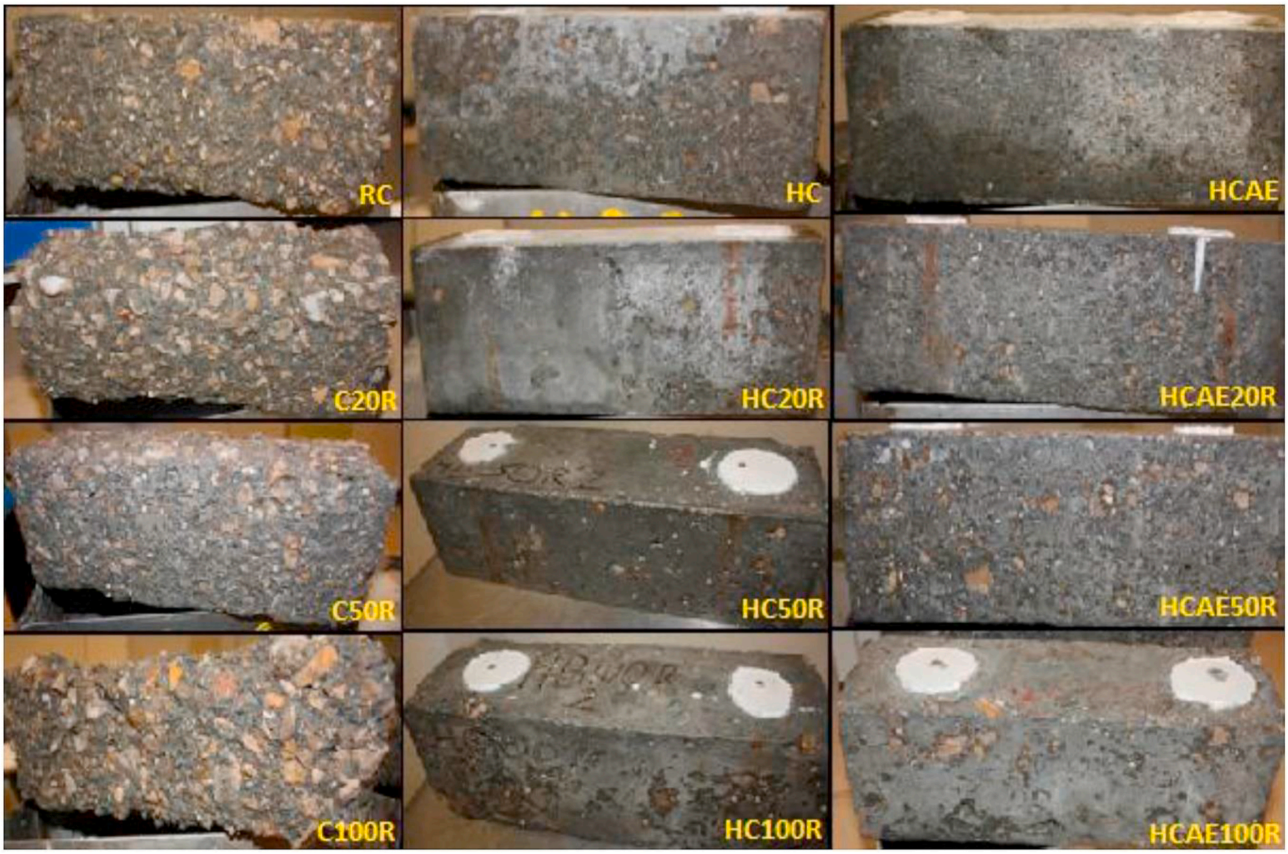


Fig. 21. Degradation of mixes after 300 freeze-thaw cycles (RC: normal strength concrete (w/c = 0.53) without any admixtures; HC: high-strength concrete (w/c = 0.35) with superplasticizer (SP) and no air entraining agent (AEA); HCAE: high-strength concrete with SP and AEA (w/c = 0.35), the numbers correspond to 0%, 20%, 50%, 100% fRCA incorporation level) [110].

addition of lignosulfonate SP in concrete with 100% fRCA, the creep deformation decreased up to 2.2% at 28 days and 1.1% at 92 days, while using polycarboxylic SP the creep deformation decreased up to 35% at 28 days and 37% at 92 days. It has been suggested that polycarboxylic SP decreases the internal moisture transmission and diffusion to external environment, improving the hydration of cement and consequently increasing strength and decreasing creep. It should be noted that the creep coefficients given in this study are higher than those of other authors, as the tests started after one day. In most literature studies, the tests begin at 28 days. Jang et al. [145] showed that the creep strain in concrete with 100% fRCA was about twice that of conventional concrete. Bravo et al. [146] showed a large variation of the shrinkage and creep results depending on the source of the recycled aggregates. As authors suggested, this tendency was expected, since each type of fRCA has its own composition, depending on the parent concrete. A study by Geng et al. [151] showed that the influence of fRCA on the creep behavior of concrete differs when the content of coarse recycled concrete aggregates varies.

Bendimerad et al. [139] found that the creep of the 30% fRCA concrete (30RS-0RG) started developing after 24 h (Fig. 20) due to their high content of old adhered paste. As early age creep occurs due to the formation of calcium silicate hydrate gel (CSH) under loading and the water mobility inside the cement paste [152], the observed evolution was consistent with the composition of 30RS-0RG mixture.

4.4. Durability of concrete

4.4.1. Permeability

Permeability of concrete is the most important factor affecting its durability. Previous studies have examined oxygen and water permeability, water absorption by immersion, capillary water absorption and water sorptivity of concrete with fRCA [29,98,105,109,115,117,120,136,153].

The oxygen permeability for concrete with recycled aggregates doubles when the percentage of fRCA exceeds 46% compared to concrete with natural aggregates [39,154]. It was shown that water absorbed by the fRCA migrates to paste around particles of aggregate and influences the volume of water and pores in paste, increasing gas permeation [153]. The porosity of concrete with fRCA increased with the increase of fRCA percentage [98,101]. Water absorption increased from 15% [98,100] to 46% [29] for concrete with 100% fRCA. Capillary absorption increased more significantly, from 46% to 95% for 100% fRCA concrete [105].

To improve durability, studies recommend concrete mixtures with low water-to-cement ratio, use of superplasticizers [105] and supplementary cementitious materials (SCMs) [115,147,155]. In low water-to-cement ratio concretes, the low porosity of the new paste is predominant. It delays the ingress of water and gasses, obtaining a similar behaviour for the control and recycled concretes [90]. Metakaolin is recognized as an efficient supplementary cementitious material in improving the transport properties of self-compacting concrete made with coarse and fine recycled concrete aggregates [155]. The use of metakaolin (by 10 wt. % cement) resulted in substantial pore refinement of concrete with fRCA by reducing the volume of capillary pores and consequently decreasing water and chloride ion penetration.

4.4.2. Sulfate attack

In the previous researches [156,157] the sulfate attack mechanism in concrete with coarse recycled concrete has been fundamentally studied. A few studies report results on sulfate attack of concrete with fRCA. The use of 50% fRCA showed a beneficial effect on the sulfate resistance of mortar specimen to both sodium and magnesium sulfate attacks [99]. This study showed that the high water absorption and high replacement levels of fRCA have a decisive influence on the sulfate resistance of mortars. However, more data related to optimum replacement level of fRCA should be provided for concrete [99]. It was also reported that the use of fRCA up to a maximum 50% replacement level is effective under severe magnesium sulfate environment, irrespective of type of fRCA [158]. For concrete with coarse and finer fractions of recycled concrete aggregates (20%) and fly ash, Kumar et al. [159] reported a compressive strength reduction of 12% and 40% on average due to sulfate and acid attack, respectively.

4.4.3. Chloride ingress

Chloride resistance is affected negatively by the use of fRCA [115]. The increase of the chloride diffusion coefficient was about 60% for 100% fRCA concrete, relative to the reference concrete. Similar findings were reported by Mardani-Aghabaglou et al. [109]. Pedro et al. [136] showed an increase in the diffusion coefficients with the increase of the simultaneous incorporation of fRCA and coarse recycled concrete aggregates. Kou and Poon [34] found that the resistance to chloride ion penetration increased with fRCA content. This was attributed to the filler effect of the fRCA as it was comprised of a higher percentage of small particles (<0.30 mm) than the river sand. Sim and Park [160] reported that the chloride ion penetration was not affected by the use of fRCA, however compressive strength decreased up to 33% for concrete with 100% fRCA. Cartuxo et al. [105] showed that the chloride resistance of concrete with fRCA was significantly improved with high-performance SP (polycarboxylates-based) compared to concrete without SP and with regular SP.

4.4.4. Carbonation

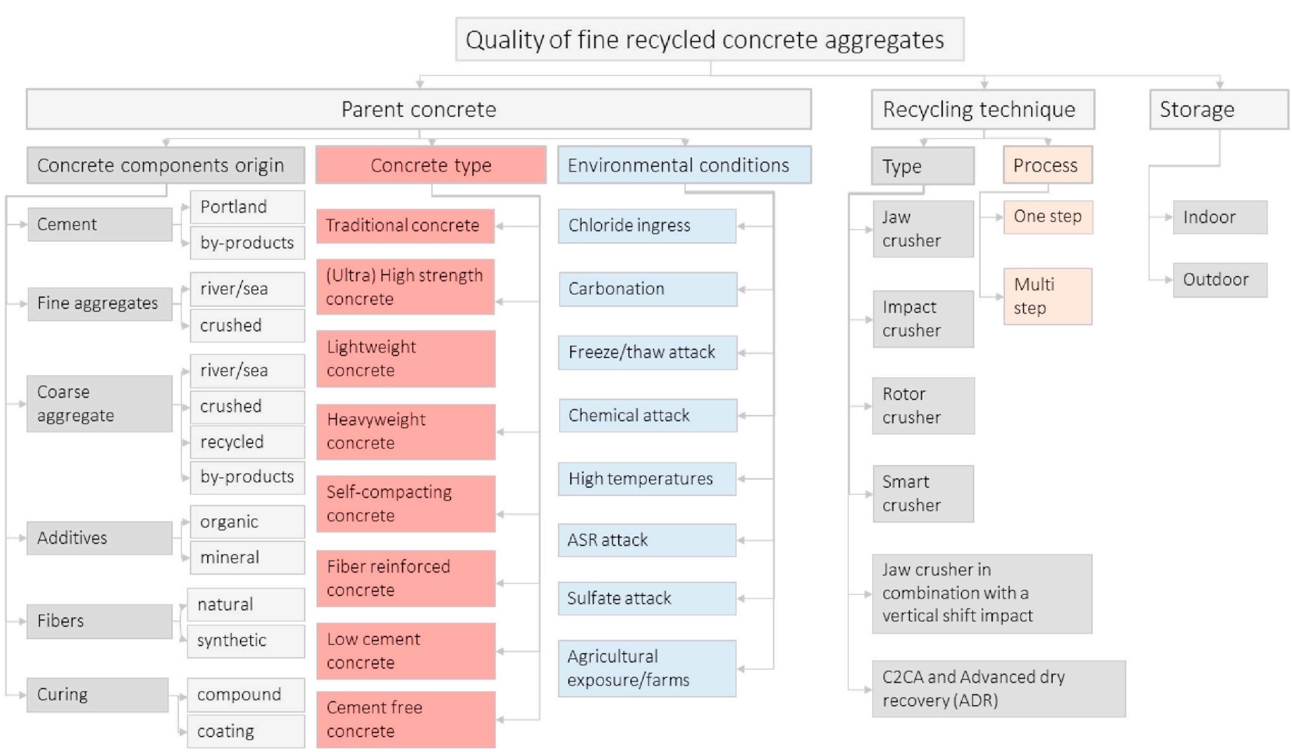
Zega and Di Maio [30] reported carbonation depths at 310 and 620 days of exposure to natural carbonation. Authors found similar carbonation of concrete with fRCA and that of reference concrete because of the lower effective water-to-cement ratio of concrete.

Evangelista and de Brito [29] studied accelerated carbonation (5% CO_2) of concrete made with lab produced fRCA. Carbonation depth increased almost linearly with the replacement ratio. At 21 days a maximum increase of about 40% was measured for concrete with 30% fRCA, while an increase of 110% was measured for concrete made with 100% fRCA. In a more recent study, Evangelista and de Brito [115] studied accelerated carbonation (5% CO_2) of concrete made with fRCA from on-site recycled concrete. A comparison of the two studies [29, 115] leads to the conclusion that carbonation resistance of concrete with fRCA from on-site recycled concrete has worse performance than concrete with lab fRCA.

The carbonation depths (at 5 ± 1% CO_2, 20 °C) of the concrete mixes with fRCA were higher than that of the reference concrete [136]. In this study, the carbonation performance was expressed by the carbonation coefficients, based on Fick's first law, showing that this approach can be used for concrete with recycled aggregates. It is found that the carbonation coefficient tends to increase linearly with the increase in the fRCA replacement ratio. Cartuxo et al. [105] showed that the carbonation resistance, similar to chloride resistance of concrete with fRCA was significantly improved with high-performance SP (polycarboxylates-based) compared to concrete without SP and with regular SP.

Geng and Sun [101] found that the carbonation depth (20% ± 3% CO_2, 20 ± 5 °C, 70 ± 5% RH) of concrete with fRCA increases with decreasing the minimum particle size of fRCA. In addition, an increase in effective water-to-cement ratio increases the rate of carbonation, specifically for concretes with >40% fRCA.

Levy and Helene [161] found that when using coarse recycled concrete aggregates with 100% replacement, the carbonation depth was lower when compared with reference concrete. The authors suggested that the alkalinity provided by recycled aggregates increases concrete resistance to carbonation. This assumption is supported by the evidence from previous observations related to development of alkalinity of water containing fRCA with time [162]. The recycled concrete fines may contain calcium hydroxide. When the recycled concrete fines are in contact with water, the alkali content of the water may increase because



Scheme 1. An overview of factors which may influence the quality of fRCA.

of the solubility of calcium hydroxide and that newly formed by the hydration of unhydrated cement (if any) in the recycled concrete fines.

4.4.5. Resistance to freezing and thawing

Mardani-Aghabaglou et al. [120] evaluated the freeze–thaw resistance of mortar mixtures exposed to 240 freeze–thaw cycles. At replacement levels beyond 25%, concrete with fRCA had improved frost resistance. When the fRCA content increased from 25 to 100%, the strength decreased by 35% and 14%, respectively.

The freeze-thaw action caused a severe degradation in reference and normal strength concrete with fRCA (20%, 50%, 100% replacement level) after 300 cycles (Fig. 21) [110]. Surface scaling tends to be more severe in concrete with fRCA, because its mortar is less resistant. The internal freeze-thaw resistance of concrete did not decrease with the incorporation of fRCA; the higher porosity of fRCA may contribute to better hydraulic pressure dissipation. On the other hand, all high-strength concrete mixes had a very good performance, with a slightly worse behavior of the reference mixes without fRCA. The incorporation of air entraining agent (AEA) had only a slightly beneficial effect. The exception was the 20% replacement of fine natural aggregates by fRCA. In general, the freeze-thaw resistance was more affected by the water-to-cement ratio than by the type of aggregate.

Yildirim et al. [108] showed that the performance of concrete containing fRCA was comparable to that of reference concrete after exposure to 300 freeze–thaw cycles. The saturation degrees of 50% and 100% of fRCA significantly improved concrete resistance to freezing and thawing, especially for mixes containing 50% fRCA at a 50% saturation level. This is in line with the study of Zaharieva et al. [163].

5. Further research and recommendations for practice

As discussed earlier, the widespread use of fRCA is mainly limited by their inherent capability to have similar properties of concrete like concrete with natural sand. Limited repeatability of measurements when testing properties of fRCA and variations in concrete properties (limited robustness) with fRCA are evidenced from the reviewed studies. The workability, volume stability, especially drying shrinkage, and durability of concrete with fRCA remain unsolved issues, which largely hinder the application of this material in engineering practice. On the basis of the reviewed literature, key areas of progress for an augmented testing of fRCA and monitoring of the concrete performance have been identified, with the aim to guide the future implementation of fRCA in concrete.

- Currently, there are no guidelines for evaluation of fRCA quality. For practical applications of fRCA, the uniform guideline for characterization and use of the fRCA in concrete needs to be established. The objectives of national recommendations and standards should include in particular the following topics:
  - grading curves of the different fRCA types,
  - acceptable values for chlorides, sulfates, soluble alkalis amount in fRCA,
  - for testing the water absorption of fRCA no single method is generally accepted and therefore various test methods are used to determine water absorption of fRCA. Development of a standardized test method and measurement technique to quantify water absorption of fRCA is necessary,
  - quantification of the adhered cement mortar in the fRCA,
  - development of an appropriate mix design for concrete with fRCA through a combination of the mix design method for conventional concrete and the trial mixing method,
  - establishment of a prediction model for fRCA particle packing, taking the particle size distribution, particle shape, potential reactivity and composition of fRCA into consideration.
- In literature, binary combinations of rounded or crushed aggregates are frequently used to determine the suitability of the compressible packing model (CPM) for concrete mix design. However, in case of concrete with fRCA, where a combination of fine quartz sand (round type) with a fine aggregate of recycled concrete (crushed type) is commonly found, it is necessary to ensure the reliability of the CPM predictions also for these combinations. De Andrade et al. [128] suggested also that the CPM cannot be applied without considerations related to the significantly higher water absorption capacity of the fRCA when compared to the natural fine aggregates.
- Delsaute and Staquet [164] suggested that the internal curing effect of fRCA could be studied on cement based materials with lower effective water-to-equivalent binder ratio (composition for which the self-desiccation phenomenon is very significant). In addition, the measurement of the internal relative humidity in the cement paste would help to understand how the water is transferred from the recycled aggregate to the cement paste. Such study is performed by Maimouni et al. [165]. However, more experiments with wider range of properties of fRCA (dry, saturated, over saturated) are suggested for further studies.
- As the material failure at the structural scale usually starts by the formation and growth of local microcracks, the quantitative analysis of the cracking process of laboratory specimens contributes to the understanding of the failure behavior of engineering recycled concrete structures. Such studies do exist for concrete with coarse recycled concrete aggregates [166–169], but not for fRCA. Further research should be undertaken to investigate the fracture properties of concrete with fRCA.
- In terms of durability, incorporation of fRCA generally resulted in lower performance of concrete, based on the results from accelerated tests. Although the use of fRCA in concrete leads to lower performance, it did not compromise their use in structural concrete [136]. Moreover, studies on monitoring of long-term performance of concrete with fRCA since the earliest age are scarce. It is thus interesting to further investigate and establish the criteria for long-term behaviour acceptance for concrete with fRCA (shrinkage and creep, carbonation, sulfate attack, chloride ingress).
- Studies on innovative applications of fRCA, such as preliminary studies for high ductility cementitious composites [170], UHPCCs [64] and 3D printed mortars with fRCA [171], should be considered.

Based on 43 concrete/mortar mix designs from reviewed studies and observations from their performances therein, several recommendations on the quality control and practical application of fRCA in concrete can be given:

- For utilizing fRCA in high quality new concrete applications, an advanced quality control of the fRCA should be introduced to minimize contamination. Some of the current developments for contaminants recognition and removal are application of online quality control sensors (hyper spectral imaging and laser induced breakdown spectroscopy) and near infrared sensor sorting and wind sifting. Selective demolition of concrete structures should be promoted and enforced whenever possible in the field. This is an absolute necessity to obtain material with minimum level of contamination.
- Regarding the effect of the source of fRCA on the performance of concrete (especially produced *in laboratory* or obtained from *field structures*), both concrete mixtures, with lab and field fRCA, show a wide range of properties and there is no evidence for worse or better performance of concrete with lab fRCA compared to concrete with field fRCA. Nevertheless, selective demolition of concrete structures should be promoted and enforced whenever possible in the field. This is an absolute necessity to obtain material with minimum level of contamination. Furthermore, the influence of the fRCA quality must be taken into account according to the different types of parent concrete, type of recycling technique and type of storage as demonstrated in Scheme 1. Using neural networks to identify the

fRCA properties that affect the recycled concrete and mortars performance is recommended. For this purpose, the results of all the referenced works together with information on parent concrete, type of recycling technique and type of storage (Scheme 1) should be taken into account.
- The outdoor storage of the fRCA should be avoided. It causes carbonation of outer layers of fRCA piles, and agglomeration of the material. The agglomeration reduces particle packing in a concrete mix.
- The use of fRCA in the partially-saturated condition (80% of the total water absorption capacity (WA24h)) is recommended for improved workability than using dry fRCA. The fRCA could not absorb 100% of their total water absorption capacity during the short mixing process.
- In the previous studies, typical Portland cement (CEM I 42.5 N) was most frequently used (Table 2). The use of high volume of supplementary cementitious materials (silica fume, fly ash, ground granulated blast furnace slag), limestone filler, use of suitable superplasticizers (polycarboxyl-based) and rheology modifiers is recommended to improve flowability and controls segregation resistance or the viscosity of the self-compacting concrete mixes.
- There are no general limits on the use of fRCA in the concrete mix. The optimal percentage of fRCA is found to be 25%, which had no effect on the strength of concrete. With further increase of fRCA content, the specific surface area increases, increasing water demand and cement content.

6. Conclusions

This paper presents a comprehensive and updated literature review on the main progress, advances and limitations in characterization and structural applications of fRCA. In order to perform systematic review, the following data were considered: physical and chemical characteristics of the fRCA; composition and properties of the 43 concrete/mortar mixes. In view of all that has been mentioned so far, the following major conclusions are drawn:

- The fRCA have physico-chemical characteristics depending on the original design and history of the concrete as well as the recycling technique and storage. These physico-chemical characteristics have an influence on the performance of the concrete mix as well as the hardened concrete. Currently, little knowledge, no guidelines or regulations exist to make optimal use of these characteristics of the fRCA in order to make high quality concrete at the same or reduced cement contents. Therefore, large scale introduction and optimal use of fRCA in new concrete is hampered because the risks on expected concrete performance are uncertain and increased cement contents to compensate water demands of fRCA result in higher costs and CO_2 emissions.
- The reuse of fRCA is currently optimized experimentally and hardly based on theoretical effects that can be analysed and predicted separately. Consequently, it is a major challenge to simultaneously include fRCA as well as reduce cement content or at least keep it constant. Compliance to desired engineering properties (workability, strength) was not always feasible: it was mostly the low workability of the mixtures that limited their application. For this reason, practical experience on suitable superplasticizers and rheology modifiers for the concrete with fRCA are necessary.
- Based on the results from all the referenced works, the limiting properties of fRCA are identified as the high water absorption, moisture states of fRCA, agglomeration of particles and adhered mortar. Three moisture states of fRCA are proposed according to the storage condition, which are also aimed for understanding of particles agglomeration effect on water absorption measurements. Quantitative and qualitative characterization techniques and guidelines are necessary for advanced quality control of the fRCA during and after separation. This would be helpful for ensuring the optimal quality required for high end concrete applications.
- Knowledge on the relation between the fRCA treatments and the physico-chemical characteristics of the fRCA, as well as knowledge on optimal packing and interaction with cement in order to keep cement contents low for high performance concrete and knowledge on the microstructure and expectance for long term behaviour of the new concrete should be research priorities.
- From the practical point of view, the performance of structural concrete with fRCA would eventually have to be evaluated by including the deformability of hardened concrete and resistance that they can offer against the corrosion of steel reinforcement. The modifications to well-known models (shrinkage, creep, chloride and CO_2 diffusion) appear the best solution as they can be covered by existing experience and experimental studies, and future large scale lab-tests. This, together with micromechanical properties (concrete matrix and interfaces) will allow a more accurate appraisal of consequences regarding fRCA use. This will also bring clarity for optimizing the existing approaches to design concrete mixtures with fRCA in practice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Density and water absorption of natural sand and fRCA.

	Natural sand		fRCA	
	Density (SSD)	Water absorption (24h)	Density (SSD)	Water absorption (24h)
	kg/m^3	w.-%	kg/m^3	w.-%
Evangelista [26,29,97]	2564	0.8	2165	13.1
Carro-López [31]	2720	1	2300	9.3
Khatib [28]	2650	0.8	2340	6.25
Sarhat [33]	2640	4.1	2330	12.5
Levy [98]	2650	1.8	2320	10.3

(continued on next page)

Table A1 (*continued*)

	Natural sand		fRCA	
	Density (SSD)	Water absorption (24h)	Density (SSD)	Water absorption (24h)
	kg/m^3	w.-%	kg/m^3	w.-%
Lee [99]	2600	0.8	2280	10.35
Lee [99]	2600	0.8	2390	6.59
Kou [34]	2620	0.88	2300	11.86
Vegas [18]	2670	0.34	1630	7.6
Vegas [18]	2670	0.34	2110	8.09
Vegas [18]	2670	0.34	2140	6.73
Vegas [18]	2670	0.34	2130	7.84
Vegas [18]	2670	0.34	1980	6.65
Vegas [18]	2670	0.34	2200	7.18
Dapena [19]	2630	3.56	2460	7.26
Yaprak [100]	2650	1.22	2310	4.28
Zega [30]	2630	0.9	2560	8.5
Pereira [35]	2620	0.19	2230	10.19
Kim [102]	2650	1	2290	5.83
Kim [102]	2650	1	2150	7.95
Le [79]	2640	0.5	2410	6.8
Cartuxo [104,105]	2678	0.15	2460	7.09
Zhao [106]	2660	1.05	2540	7.54
Yildirim [108]	2660	1.99	2450	6.22
Mardani-Aghabaglou [109]	2610	0.67	2440	6.81
Bogas [110]	2568	1.68	2156	9.05
Bendimerad [111]	2600	1.2	2100	10.7
Fan [27,57]	2653	1.3	2347	8.9
Fan [27,57]	2653	1.3	2404	6.6
Güneyisi [112]	2660	0.55	2260	12.8
Kumar [113]	2670	0.44	2080	11.91
Evangelista [114,115]	2580	1.07	2210	10.43
Ho [117]	2600	2.88	2360	9.43
Yacoub [76]	2530	2.3	2440	6.86
Delsaute [118]	2600	1.2	2100	10.65
Ali [119]	2680	1.45	2430	7.89
Mardani-Aghabaglou [120]	2610	0.68	2410	6.95
Nedeljković [133]	2647	0.3	2543	7

References

[1] F. De Larrard, H. Colina, Concrete Recycling: Research and Practice, CRC Press, 2019.
[2] J. De Brito, F. Agrela, R.V. Silva, Construction and demolition waste, in: New Trends in Eco-Efficient and Recycled Concrete, Elsevier, 2019, pp. 1–22.
[3] S. Santos, P.R. Da Silva, J. De Brito, Self-compacting concrete with recycled aggregates–a literature review, J. Build. Eng. 22 (2019) 349–371, https://doi.org/10.1016/j.jobe.2019.01.001.
[4] W. Chen, R. Jin, Y. Xu, D. Wanatowski, B. Li, L. Yan, Z. Pan, Y. Yang, Adopting recycled aggregates as sustainable construction materials: a review of the scientific literature, Construct. Build. Mater. 218 (2019) 483–496, https://doi.org/10.1016/j.conbuildmat.2019.05.130.
[5] N. Tošić, S. Marinković, T. Dašić, M. Stanić, Multicriteria optimization of natural and recycled aggregate concrete for structural use, J. Clean. Prod. 87 (2015) 766–776, https://doi.org/10.1016/j.jclepro.2014.10.070.
[6] S. Marinković, J. Dragaš, I. Ignjatović, N. Tošić, Environmental assessment of green concretes for structural use, J. Clean. Prod. 154 (2017) 633–649, https://doi.org/10.1016/j.jclepro.2017.04.015.
[7] D. Pedro, J. De Brito, L. Evangelista, Influence of the use of recycled concrete aggregates from different sources on structural concrete, Construct. Build. Mater. 71 (2014) 141–151, https://doi.org/10.1016/j.conbuildmat.2014.08.030.
[8] A. Ossa, J. García, E. Botero, Use of recycled construction and demolition waste (CDW) aggregates: a sustainable alternative for the pavement construction industry, J. Clean. Prod. 135 (2016) 379–386, https://doi.org/10.1016/j.jclepro.2016.06.088.
[9] A. Rao, K.N. Jha, S. Misra, Use of aggregates from recycled construction and demolition waste in concrete, Resour. Conserv. Recycl. 50 (1) (2007) 71–81, https://doi.org/10.1016/j.resconrec.2006.05.010.
[10] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: a review, Construct. Build. Mater. 68 (2014) 501–516, https://doi.org/10.1016/j.conbuildmat.2014.07.003.
[11] C. Thomas, J. De Brito, V. Gil, J.A. Sainz-Aja, A. Cimentada, Multiple recycled aggregate properties analysed by X-ray microtomography, Construct. Build. Mater. 166 (2018) 171–180, https://doi.org/10.1016/j.conbuildmat.2018.01.130.
[12] L. Evangelista, J. De Brito, Concrete with fine recycled aggregates: a review, Eur. J. Environ. Civ. Eng. 18 (2) (2014) 129–172, https://doi.org/10.1080/19648189.2013.851038.
[13] R. Silva, J. De Brito, R. Dhir, Performance of cementitious renderings and masonry mortars containing recycled aggregates from construction and demolition wastes, Construct. Build. Mater. 105 (2016) 400–415, https://doi.org/10.1016/j.conbuildmat.2015.12.171.
[14] R. Oliveira, J. De Brito, R. Veiga, Incorporation of fine glass aggregates in renderings, Construct. Build. Mater. 44 (2013) 329–341, https://doi.org/10.1016/j.conbuildmat.2013.03.042.
[15] C. Neno, J. De Brito, R. Veiga, Using fine recycled concrete aggregate for mortar production, Mater. Res. 17 (1) (2014) 168–177, https://doi.org/10.1590/S1516-14392013005000164.
[16] S.C. Kou, C.S. Poon, Effects of different kinds of recycled fine aggregate on properties of rendering mortar, J. Sustain. Cem.-Based Mater. 2 (1) (2013) 43–57, https://doi.org/10.1080/21650373.2013.766400.
[17] E.F. Ledesma, J.R. Jiménez, J. Ayuso, J.M. Fernández, J. De Brito, Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production–Part-I: ceramic masonry waste, J. Clean. Prod. 87 (2015) 692–706, https://doi.org/10.1016/j.jclepro.2014.10.084.
[18] I. Vegas, I. Azkarate, A. Juarrero, M. Frías, Design and performance of masonry mortars made with recycled concrete aggregates, Mater. Construcción 59 (295) (2009) 5–18, https://doi.org/10.3989/mc.2009.44207.
[19] E. Dapena, P. Alaejos, A. Lobet, D. Pérez, Effect of recycled sand content on characteristics of mortars and concretes, J. Mater. Civ. Eng. 23 (4) (2011) 414–422, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000183.
[20] I. Nováková, B.A. Buyle, Sand replacement by fine recycled concrete aggregates as an approach for sustainable cementitious materials, in: Proceedings of the International Conference of Sustainable Production and Use of Cement and Concrete, Springer, 2020.
[21] M. Solyman, Classification of Recycled Sands and Their Applications as Fine Aggregates for Concrete and Bituminous Mixtures, Universität Kassel, 2005. PhD thesis.
[22] S. Delvoie, Z. Zhao, F. Michel, L. Courard, Market analysis of recycled sands and aggregates in NorthWest Europe: drivers and barriers, IOP Conf. Ser. Earth Environ. Sci. 225 (1) (2019) 12055.
[23] R. Kemp, E. Barteková, S. Türkeli, The innovation trajectory of eco-cement in The Netherlands: a co-evolution analysis, Int. Econ. Econ. Pol. 14 (3) (2017) 409–429, https://doi.org/10.1007/s10368-017-0384-4.
[24] A. Radević, G. Mladenović, D. Jevtić, D. Zakić, M. Askrabić, Influence of Fine Recycled Aggregate on the Properties of Asphalt Mixtures, Savremena teorija i praksa u graditeljstvu XIII, 2018, pp. 127–138, https://doi.org/10.7251/STP1813127R.

[25] C.S. Vieira, P.M. Pereira, M. de Lurdes Lopes, Recycled Construction and Demolition Wastes as filling material for geosynthetic reinforced structures. Interface properties, J. Clean. Prod. 124 (2016) 299–311, https://doi.org/10.1016/j.jclepro.2016.02.115.
[26] L. Evangelista, J. De Brito, Mechanical behaviour of concrete made with fine recycled concrete aggregates, Cement Concr. Compos. 29 (5) (2007) 397–401, https://doi.org/10.1016/j.cemconcomp.2006.12.004.
[27] C.C. Fan, R. Huang, H. Hwang, S.J. Chao, Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes, Construct. Build. Mater. 112 (2016) 708–715, https://doi.org/10.1016/j.conbuildmat.2016.02.154.
[28] J.M. Khatib, Properties of concrete incorporating fine recycled aggregate, Cement Concr. Res. 35 (4) (2005) 763–769, https://doi.org/10.1016/j.cemconres.2004.06.017.
[29] L. Evangelista, J. De Brito, Durability performance of concrete made with fine recycled concrete aggregates, Cement Concr. Compos. 32 (1) (2010) 9–14, https://doi.org/10.1016/j.cemconcomp.2009.09.005.
[30] C.J. Zega, Á.A. Di Maio, Use of recycled fine aggregate in concretes with durable requirements, Waste Manag. 31 (11) (2011) 2336–2340, https://doi.org/10.1016/j.wasman.2011.06.011.
[31] D. Carro-López, B. González-Fonteboa, J. De Brito, F. Martínez-Abella, I. González-Taboada, P. Silva, Study of the rheology of self-compacting concrete with fine recycled concrete aggregates, Construct. Build. Mater. 96 (2015) 491–501, https://doi.org/10.1016/j.conbuildmat.2015.08.091.
[32] A. Lotfy, M. Al-Fayez, Performance evaluation of structural concrete using controlled quality coarse and fine recycled concrete aggregate, Cement Concr. Compos. 61 (2015) 36–43, https://doi.org/10.1016/j.cemconcomp.2015.02.009.
[33] S. Sarhat, An experimental investigation on the viability of using fine concrete recycled aggregate in concrete production, in: Proceedings of the International Conference on Sustainable Construction Materials and Technologies, Coventry, UK, 2007.
[34] S. Kou, C. Poon, Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates, Cement Concr. Compos. 31 (9) (2009) 622–627, https://doi.org/10.1016/j.cemconcomp.2009.06.005.
[35] P. Pereira, L. Evangelista, J. De Brito, The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates, Construct. Build. Mater. 28 (1) (2012) 722–729, https://doi.org/10.1016/j.conbuildmat.2011.10.050.
[36] G. Van Der Wegen, R. Haverkort, Recycled construction and demolition wastes as a fine aggregate for concrete, in: Sustainable Construction: Use of Recycled Concrete Aggregate: Proceedings of the International Symposium Organised by the Concrete Technology Unit, University of Dundee and Held at the Department of Trade and Industry Conference Centre, Thomas Telford Publishing, London, UK, 1998.
[37] H. Zhang, T. Ji, X. Zeng, Z. Yang, X. Lin, Y. Liang, Mechanical behavior of ultra-high performance concrete (UHPC) using recycled fine aggregate cured under different conditions and the mechanism based on integrated microstructural parameters, Construct. Build. Mater. 192 (2018) 489–507, https://doi.org/10.1016/j.conbuildmat.2018.10.117.
[38] B. Estanqueiro, J. Dinis Silvestre, J. De Brito, M. Duarte Pinheiro, Environmental life cycle assessment of coarse natural and recycled aggregates for concrete, Eur. J. Environ. Civ. Eng. 22 (4) (2018) 429–449, https://doi.org/10.1080/19648189.2016.1197161.
[39] F. Debieb, L. Courard, S. Kenai, R. Degeimbre, Mechanical and durability properties of concrete using contaminated recycled aggregates, Cement Concr. Compos. 32 (6) (2010) 421–426, https://doi.org/10.1016/j.cemconcomp.2010.03.004.
[40] M. Martín-Morales, M. Zamorano, I. Valverde-Palacios, G.M. Cuenca-Moyano, Z. Sánchez-Roldán, Quality control of recycled aggregates (RAs) from construction and demolition waste (CDW), in: Handbook of Recycled Concrete and Demolition Waste, Woodhead Publishing, 2013, pp. 270–303.
[41] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manag. 30 (11) (2010) 2255–2264, https://doi.org/10.1016/j.wasman.2010.04.012.
[42] J. Rueda, P. Alaejos, Quantitative effect on water demand of absorption and fine particles content of recycled concrete sands, J. Mater. Civ. Eng. 31 (5) (2019), 04019038, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002668.
[43] M. Khedmati, Y.R. Kim, J.A. Turner, Investigation of the interphase between recycled aggregates and cementitious binding materials using integrated microstructural-nanomechanical-chemical characterization, Composites, Part B 158 (2019) 218–229, https://doi.org/10.1016/j.compositesb.2018.09.041.
[44] P. Belin, G. Habert, M. Thiery, N. Roussel, Cement paste content and water absorption of recycled concrete coarse aggregates, Mater. Struct. 47 (9) (2014) 1451–1465, https://doi.org/10.1617/s11527-013-0128-z.
[45] C. Ulsen, H. Kahn, G. Hawlitschek, E.A. Masini, S.C. Angulo, Separability studies of construction and demolition waste recycled sand, Waste Manag. 33 (3) (2013) 656–662, https://doi.org/10.1016/j.wasman.2012.06.018.
[46] F. Pacheco-Torgal, Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020, Construct. Build. Mater. 51 (2014) 151–162, https://doi.org/10.1016/j.conbuildmat.2013.10.058.
[47] M.U. Hossain, C.S. Poon, I.M. Lo, J.C. Cheng, Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA, Resour. Conserv. Recycl. 109 (2016) 67–77, https://doi.org/10.1016/j.resconrec.2016.02.009.
[48] UEPG Annual review 2019-2020. https://uepg.eu/mediatheque/media/UEPGAR20192020_V13_(03082020)_spreads.pdf.
[49] J.X. Lu, P. Shen, H. Zheng, B. Zhan, H.A. Ali, P. He, C.S. Poon, Synergetic recycling of waste glass and recycled aggregates in cement mortars: physical, durability and microstructure performance, Cement Concr. Compos. (2020) 103632, https://doi.org/10.1016/j.cemconcomp.2020.103632.
[50] V.W. Tam, M. Soomro, A.C.J. Evangelista, A review of recycled aggregate in concrete applications (2000–2017), Construct. Build. Mater. 172 (2018) 272–292, https://doi.org/10.1016/j.conbuildmat.2018.03.240.
[51] A. Jesse, Sand mining at Poyang Lake, using landsat data from the U.S. Geological survey, NASA Earth Observ. (2016).
[52] A. Bendimerad, E. Roziere, A. Loukili, Combined experimental methods to assess absorption rate of natural and recycled aggregates, Mater. Struct. 48 (11) (2015) 3557–3569, https://doi.org/10.1617/s11527-014-0421-5.
[53] M.V.A. Florea, H. Brouwers, Properties of various size fractions of crushed concrete related to process conditions and re-use, Cement Concr. Res. 52 (2013) 11–21, https://doi.org/10.1016/j.cemconres.2013.05.005.
[54] L. Evangelista, M. Guedes, J. De Brito, A.C. Ferro, M.F. Pereira, Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste, Construct. Build. Mater. 86 (2015) 178–188, https://doi.org/10.1016/j.conbuildmat.2015.03.112.
[55] M.E. Sosa, L.E. Carrizo, C.J. Zega, Y.V. Zaccardi, Water absorption of fine recycled aggregates: effective determination by a method based on electrical conductivity, Mater. Struct. 51 (5) (2018) 127, https://doi.org/10.1617/s11527-018-1248-2.
[56] C. Ulsen, H. Kahn, G. Hawlitschek, E.A. Masini, S.C. Angulo, V.M. John, Production of recycled sand from construction and demolition waste, Construct. Build. Mater. 40 (2013) 1168–1173, https://doi.org/10.1016/j.conbuildmat.2012.02.004.
[57] C.C. Fan, R. Huang, H. Hwang, S.J. Chao, The effects of different fine recycled concrete aggregates on the properties of mortar, Materials 8 (5) (2015) 2658–2672, https://doi.org/10.3390/ma8052658.
[58] P.C.C. Gomes, C. Ulsen, F.A. Pereira, M. Quattrone, S.C. Angulo, Comminution and sizing processes of concrete block waste as recycled aggregates, Waste Manag. 45 (2015) 171–179, https://doi.org/10.1016/j.wasman.2015.07.008.
[59] S. Lotfi, P. Rem, Recycling of end of life concrete fines into hardened cement and clean sand, J. Environ. Protect. 7 (6) (2016) 934, https://doi.org/10.4236/jep.2016.76083.
[60] W.F. Santos, M. Quattrone, V.M. John, S.C. Angulo, Roughness, wettability and water absorption of water repellent treated recycled aggregates, Construct. Build. Mater. 146 (2017) 502–513, https://doi.org/10.1016/j.conbuildmat.2017.04.012.
[61] T. Le, G. Le Saout, E. Garcia-Diaz, D. Betrancourt, S. Rémond, Hardened behavior of mortar based on recycled aggregate: influence of saturation state at macro-and microscopic scales, Construct. Build. Mater. 141 (2017) 479–490, https://doi.org/10.1016/j.conbuildmat.2017.02.035.
[62] M. Hiete, Waste management plants and technology for recycling construction and demolition (C&D) waste: state-of-the-art and future challenges, in: Handbook of Recycled Concrete and Demolition Waste, Elsevier, 2013, pp. 53–75.
[63] Z. Li, L. Liu, S. Yan, M. Zhang, Y. Xie, Properties of microscopic particle morphology and particle contact of renewable construction waste mixtures, Construct. Build. Mater. 207 (2019) 190–205, https://doi.org/10.1016/j.conbuildmat.2019.02.135.
[64] J. Jiang, W. Zhou, Y. Gao, L. Wang, F. Wang, H.Y. Chu, G. Xu, B. Vandevyvere, Z. Sierens, J. Li, Feasibility of manufacturing ultra-high performance cement-based composites (UHPCCs) with recycled sand: a preliminary study, Waste Manag. 83 (2019) 104–112, https://doi.org/10.1016/j.wasman.2018.11.005.
[65] S.A.A.M. Fennis, Design of Ecological Concrete by Particle Packing Optimization, Delft University of Technology, The Netherlands, 2011. PhD thesis, http://resolver.tudelft.nl/uuid:5a1e445b-36a7-4f27-a89a-d48372d2a45c.
[66] A.K.H. Kwan, W. Fung, Packing density measurement and modelling of fine aggregate and mortar, Cement Concr. Compos. 31 (6) (2009) 349–357, https://doi.org/10.1016/j.cemconcomp.2009.03.006.
[67] P. Nanthagopalan, M. Haist, M. Santhanam, H.S. Müller, Investigation on the influence of granular packing on the flow properties of cementitious suspensions, Cement Concr. Compos. 30 (9) (2008) 763–768, https://doi.org/10.1016/j.cemconcomp.2008.06.005.
[68] G.C. Cho, J. Dodds, J.C. Santamarina, Particle shape effects on packing density, stiffness, and strength: natural and crushed sands, J. Geotech. Geoenviron. Eng. 132 (5) (2006) 591–602, https://doi.org/10.1061/(ASCE)1090-0241(2006)132:5(591).
[69] M. Leite, Avaliação de propriedades mecânicas de concretos produzidos com agregados reciclados de resíduos de construção e demolição, State University of Feira de Santana, Brazil, 2001. PhD thesis.
[70] IFSTTAR, Test Method No. 78:2011. Tests on Aggregates for Concrete: Measurement of Total Water Absorption by a Crushed Sand, 2011. Paris.
[71] V.W. Tam, X.F. Gao, C.M. Tam, C.H. Chan, New approach in measuring water absorption of recycled aggregates, Construct. Build. Mater. 22 (3) (2008) 364–369, https://doi.org/10.1016/j.conbuildmat.2006.08.009.
[72] A.D. Tegguer, Determining the water absorption of recycled aggregates utilizing hydrostatic weighing approach, Construct. Build. Mater. 27 (1) (2012) 112–116, https://doi.org/10.1016/j.conbuildmat.2011.08.018.
[73] Z. Zhao, S. Remond, D. Damidot, W. Xu, Influence of hardened cement paste content on the water absorption of fine recycled concrete aggregates, J. Sustain. Cem.-Based Mater. 2 (3–4) (2013) 186–203, https://doi.org/10.1080/21650373.2013.812942.
[74] F. Rodrigues, L. Evangelista, J.D. Brito, A new method to determine the density and water absorption of fine recycled aggregates, Mater. Res. 16 (5) (2013) 1045–1051, https://doi.org/10.1590/S1516-14392013005000074.

[75] J. Rueda, E. Dapena, P. Alaejos, S.M. De Llano, An accelerated test to assess the quality of recycled concrete sands based on their absorption capacity, Construct. Build. Mater. 78 (2015) 464–469, https://doi.org/10.1016/j.conbuildmat.2014.12.039.
[76] A. Yacoub, A. Djerbi, T. Fen-Chong, Water absorption in recycled sand: new experimental methods to estimate the water saturation degree and kinetic filling during mortar mixing, Construct. Build. Mater. 158 (2018) 464–471, https://doi.org/10.1016/j.conbuildmat.2017.10.023.
[77] Z. Li, J. Liu, Q. Tian, Method for controlling the absorbed water content of recycled fine aggregates by centrifugation, Construct. Build. Mater. 160 (2018) 316–325, https://doi.org/10.1016/j.conbuildmat.2017.11.068.
[78] Z. Li, J. Liu, J. Xiao, P. Zhong, A method to determine water absorption of recycled fine aggregate in paste for design and quality control of fresh mortar, Construct. Build. Mater. 197 (2019) 30–41, https://doi.org/10.1016/j.conbuildmat.2018.11.115.
[79] T. Le, S. Remond, G. Le Saout, E. Garcia-Diaz, Fresh behavior of mortar based on recycled sand–Influence of moisture condition, Construct. Build. Mater. 106 (2016) 35–42, https://doi.org/10.1016/j.conbuildmat.2015.12.071.
[80] A. Katz, Properties of concrete made with recycled aggregate from partially hydrated old concrete, Cement Concr. Res. 33 (5) (2003) 703–711, https://doi.org/10.1016/S0008-8846(02)01033-5.
[81] G. Bianchini, E. Marrocchino, R. Tassinari, C. Vaccaro, Recycling of construction and demolition waste materials: a chemical–mineralogical appraisal, Waste Manag. 25 (2) (2005) 149–159, https://doi.org/10.1016/j.wasman.2004.09.005.
[82] S.C. Angulo, C. Ulsen, V.M. John, H. Kahn, M.A. Cincotto, Chemical–mineralogical characterization of C&D waste recycled aggregates from São Paulo, Brazil, Waste Manag. 29 (2) (2009) 721–730, https://doi.org/10.1016/j.wasman.2008.07.009.
[83] F. Rodrigues, M.T. Carvalho, L. Evangelista, J. De Brito, Physical–chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants, J. Clean. Prod. 52 (2013) 438–445, https://doi.org/10.1016/j.jclepro.2013.02.023.
[84] A. Sicakova, K. Urban, The influence of discharge time, kind of additive, and kind of aggregate on the properties of three-stage mixed concrete, Sustainability 10 (11) (2018) 3862, https://doi.org/10.3390/su10113862.
[85] R. PN RECYBETON, RECYclage complet des BETONs, 2011. France.
[86] R.I.L.E.M. Recommendation, Specifications for concrete with recycled aggregates, Mater. Struct. 27 (9) (1994) 557–559.
[87] M.V.A. Florea, Secondary Materials Applied in Cement-Based Products: Treatment, Modelling and Environmental Interaction, PhD Thesis, Eindhoven University of Technology, The Netherlands, 2014, https://doi.org/10.6100/IR772902.
[88] J. Schoon, K. De Buysser, I. Van Driessche, N. De Belie, Fines extracted from recycled concrete as alternative raw material for Portland cement clinker production, Cement Concr. Compos. 58 (2015) 70–80, https://doi.org/10.1016/j.cemconcomp.2015.01.003.
[89] A. Domingo-Cabo, C. Lázaro, F. López-Gayarre, M.A. Serrano-López, P. Serna, J. O. Castaño-Tabares, Creep and shrinkage of recycled aggregate concrete, Construct. Build. Mater. 23 (7) (2009) 2545–2553, https://doi.org/10.1016/j.conbuildmat.2009.02.018.
[90] C. Thomas, J. Setién, J. Polanco, P. Alaejos, M.S. De Juan, Durability of recycled aggregate concrete, Construct. Build. Mater. 40 (2013) 1054–1065, https://doi.org/10.1016/j.conbuildmat.2012.11.106.
[91] A. Akbarnezhad, Z.S. Moussavi Nadoushani, A computational method for selection of optimal concrete recycling strategy, Mag. Concr. Res. 67 (11) (2015) 543–558, https://doi.org/10.1680/macr.14.00211.
[92] T. Noguchi, State-of-the-art Recycling Technologies for Building Materials in Japan, Recycling Technologies for Concrete, 2008.
[93] N. Otsuki, S.-i. Miyazato, W. Yodsudjai, Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete, J. Mater. Civ. Eng. 15 (5) (2003) 443–451, https://doi.org/10.1061/(ASCE)0899-1561(2003)15:5(443).
[94] M. Westerholm, B. Lagerblad, J. Silfwerbrand, E. Forssberg, Influence of fine aggregate characteristics on the rheological properties of mortars, Cement Concr. Compos. 30 (4) (2008) 274–282, https://doi.org/10.1016/j.cemconcomp.2007.08.008.
[95] L. Li, B.J. Zhan, J. Lu, C.S. Poon, Systematic evaluation of the effect of replacing river sand by different particle size ranges of fine recycled concrete aggregates (FRCA) in cement mortars, Construct. Build. Mater. 209 (2019) 147–155, https://doi.org/10.1016/j.conbuildmat.2019.03.044.
[96] M.E. Bouarroudj, S. Remond, F. Michel, Z. Zhao, D. Bulteel, L. Courard, Use of a reference limestone fine aggregate to study the fresh and hard behavior of mortar made with recycled fine aggregate, Mater. Struct. 52 (1) (2019) 18, https://doi.org/10.1617/s11527-019-1325-1.
[97] L. Evangelista, J. De Brito, Criteria for the use of fine recycled concrete aggregates in concrete production, in: Proceedings of the International RILEM Conference on the Use of Recycled Materials in Building Structures, 2004. Barcelona.
[98] S. Levy, P. Helène, Durability of concrete mixed with fine recycled aggregates, Exacta 5 (1) (2007) 25–34.
[99] S.T. Lee, R.N. Swamy, S.S. Kim, Y.G. Park, Durability of mortars made with recycled fine aggregates exposed to sulfate solutions, J. Mater. Civ. Eng. 20 (1) (2008) 63–70, https://doi.org/10.1061/(ASCE)0899-1561(2008)20:1(63).
[100] H. Yaprak, H.Y. Aruntas, I. Demir, O. Simsek, G. Durmus, Effects of the fine recycled concrete aggregates on the concrete properties, Int. J. Phys. Sci. 6 (10) (2011) 2455–2461, https://doi.org/10.5897/IJPS11.253.
[101] J. Geng, J. Sun, Characteristics of the carbonation resistance of recycled fine aggregate concrete, Construct. Build. Mater. 49 (2013) 814–820, https://doi.org/10.1016/j.conbuildmat.2013.08.090.
[102] S.W. Kim, H.D. Yun, Evaluation of the bond behavior of steel reinforcing bars in recycled fine aggregate concrete, Cement Concr. Compos. 46 (2014) 8–18, https://doi.org/10.1016/j.cemconcomp.2013.10.013.
[103] A.G. Khoshkenari, P. Shafigh, M. Moghimi, H.B. Mahmud, The role of 0–2 mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete, Mater. Des. 64 (2014) 345–354, https://doi.org/10.1016/j.matdes.2014.07.048.
[104] F. Cartuxo, J. De Brito, L. Evangelista, J.R. Jimenez, E.F. Ledesma, Rheological behaviour of concrete made with fine recycled concrete aggregates–Influence of the superplasticizer, Construct. Build. Mater. 89 (2015) 36–47, https://doi.org/10.1016/j.conbuildmat.2015.03.119.
[105] F. Cartuxo, J. De Brito, L. Evangelista, J.R. Jiménez, E.F. Ledesma, Increased durability of concrete made with fine recycled concrete aggregates using superplasticizers, Materials 9 (2) (2016) 98, https://doi.org/10.3390/ma9020098.
[106] Z. Zhao, S. Remond, D. Damidot, W. Xu, Influence of fine recycled concrete aggregates on the properties of mortars, Construct. Build. Mater. 81 (2015) 179–186, https://doi.org/10.1016/j.conbuildmat.2015.02.037.
[107] J. Zhang, C. Shi, Y. Li, X. Pan, C.S. Poon, Z. Xie, Influence of carbonated recycled concrete aggregate on properties of cement mortar, Construct. Build. Mater. 98 (2015) 1–7, https://doi.org/10.1016/j.conbuildmat.2015.08.087, 2015.
[108] S.T. Yildirim, C. Meyer, S. Herfellner, Effects of internal curing on the strength, drying shrinkage and freeze–thaw resistance of concrete containing recycled concrete aggregates, Construct. Build. Mater. 91 (2015) 288–296, https://doi.org/10.1016/j.conbuildmat.2015.05.045.
[109] A. Mardani-Aghabaglou, M. Tuyan, K. Ramyar, Mechanical and durability performance of concrete incorporating fine recycled concrete and glass aggregates, Mater. Struct. 48 (8) (2015) 2629–2640, https://doi.org/10.1617/s11527-014-0342-3.
[110] J.A. Bogas, J. De Brito, D. Ramos, Freeze–thaw resistance of concrete produced with fine recycled concrete aggregates, J. Clean. Prod. 115 (2016) 294–306, https://doi.org/10.1016/j.jclepro.2015.12.065.
[111] A.Z. Bendimerad, E. Rozière, A. Loukili, Plastic shrinkage and cracking risk of recycled aggregates concrete, Construct. Build. Mater. 121 (2016) 733–745, https://doi.org/10.1016/j.conbuildmat.2016.06.056, 2016.
[112] E. Güneyisi, M. Gesoglu, Z. Algın, H. Yazıc, Rheological and fresh properties of self-compacting concretes containing coarse and fine recycled concrete aggregates, Construct. Build. Mater. 113 (2016) 622–630, https://doi.org/10.1016/j.conbuildmat.2016.03.073.
[113] R. Kumar, S.C.B. Gurram, A.K. Minocha, Influence of recycled fine aggregate on microstructure and hardened properties of concrete, Mag. Concr. Res. 69 (24) (2017) 1288–1295, https://doi.org/10.1680/jmacr.17.00030.
[114] L. Evangelista, J. De Brito, Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates, KSCE J. Civ. Eng. 21 (1) (2017) 353–363, https://doi.org/10.1007/s12205-016-0653-8.
[115] L. Evangelista, J. De Brito, Durability of crushed fine recycled aggregate concrete assessed by permeability-related properties, Mag. Concr. Res. (2018) 1–9, https://doi.org/10.1680/jmacr.18.00093.
[116] C. Shi, Z. Wu, Z. Cao, T.C. Ling, J. Zheng, Performance of mortar prepared with recycled concrete aggregate enhanced by CO_2 and pozzolan slurry, Cement Concr. Compos. 86 (2018) 130–138, https://doi.org/10.1016/j.cemconcomp.2017.10.013.
[117] H.L. Ho, R. Huang, W.T. Lin, A. Cheng, Pore-structures and durability of concrete containing pre-coated fine recycled mixed aggregates using pozzolan and polyvinyl alcohol materials, Construct. Build. Mater. 160 (2018) 278–292, https://doi.org/10.1016/j.conbuildmat.2017.11.063.
[118] B. Delsaute, S. Staquet, Development of strain-induced stresses in early age concrete composed of recycled gravel or sand, J. Adv. Concr. Technol. 17 (6) (2019) 319–334, https://doi.org/10.3151/jact.17.319.
[119] B. Ali, Effect of aqueous sodium silicate on properties of recycled aggregate mortar, SN Appl. Sci. 1 (10) (2019) 1296, https://doi.org/10.1007/s42452-019-1342-2.
[120] A. Mardani-Aghabaglou, A. Beglarigale, H. Yazıcı, K. Ramyar, Transport properties and freeze-thaw resistance of mortar mixtures containing recycled concrete and glass aggregates, Eur. J. Environ. Civ. Eng. 23 (1) (2019) 53–69, https://doi.org/10.1080/19648189.2016.1262289.
[121] R. Cepuritis, S. Jacobsen, S. Smeplass, E. Mørtsell, B.J. Wigum, S. Ng, Influence of crushed aggregate fines with micro-proportioned particle size distributions on rheology of cement paste, Cement Concr. Compos. 80 (2017) 64–79, https://doi.org/10.1016/j.cemconcomp.2017.02.012.
[122] R. Cepuritis, S. Jacobsen, B. Pedersen, E. Mørtsell, Crushed sand in concrete–effect of particle shape in different fractions and filler properties on rheology, Cement Concr. Compos. 71 (2016) 26–41, https://doi.org/10.1016/j.cemconcomp.2016.04.004.
[123] M. Westerholm, Rheology of the Mortar Phase of Concrete with Crushed Aggregate, Luleå tekniska universitet, 2006. PhD Thesis.
[124] H. Justnes, S. Ng, Concrete Admixtures–Interactions with cement, supplementary cementing materials and fillers, in: 3rd International Symposium on Design, Performance and Use of Self-Consolidating Concrete. SCC, RILEM Publications SARL, 2014.
[125] T. Celik, K. Marar, Effects of crushed stone dust on some properties of concrete, Cement Concr. Res. 26 (7) (1996) 1121–1130, https://doi.org/10.1016/0008-8846(96)00078-6.

[126] M. Leite, P. Monteiro, Microstructural analysis of recycled concrete using X-ray microtomography, Cement Concr. Res. 81 (2016) 38–48, https://doi.org/10.1016/j.cemconres.2015.11.010.
[127] E. Ghorbel, G. Wardeh, H. Gomart, P. Matar, Formulation parameters effects on the performances of concrete equivalent mortars incorporating different ratios of recycled sand, J. Build. Phys. 43 (6) (2020) 545–572, https://doi.org/10.1177/1744259119896093.
[128] G.P. de Andrade, G. de Castro Polisseni, M. Pepe, R.D. Toledo Filho, Design of structural concrete mixtures containing fine recycled concrete aggregate using packing model, Construct. Build. Mater. 252 (2020) 119091, https://doi.org/10.1016/j.conbuildmat.2020.119091.
[129] M.B. De Oliveira, E. Vazquez, The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete, Waste Manag. 16 (1–3) (1996) 113–117, https://doi.org/10.1016/S0956-053X(96)00033-5.
[130] C.S. Poon, Z.H. Shui, L. Lam, H. Fok, S.C. Kou, Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete, Cement Concr. Res. 34 (1) (2004) 31–36, https://doi.org/10.1016/S0008-8846(03)00186-8.
[131] M. Behera, A. Minocha, S. Bhattacharyya, Flow behavior, microstructure, strength and shrinkage properties of self-compacting concrete incorporating recycled fine aggregate, Construct. Build. Mater. 228 (2019) 116819, https://doi.org/10.1016/j.conbuildmat.2019.116819.
[132] P. Pereira, L. Evangelista, J. De Brito, The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates, Cement Concr. Compos. 34 (9) (2012) 1044–1052, https://doi.org/10.1016/j.cemconcomp.2012.06.009.
[133] M. Nedeljković, J. Visser, T.G. Nijland, S. Valcke, E. Schlangen, Physical, chemical and mineralogical characterization of Dutch fine recycled concrete aggregates: a comparative study, Construct. Build. Mater. 270 (2020) 121475, https://doi.org/10.1016/j.conbuildmat.2020.121475.
[134] H. Donza, O. Cabrera, E. Irassar, High-strength concrete with different fine aggregate, Cement Concr. Res. 32 (11) (2002) 1755–1761, https://doi.org/10.1016/S0008-8846(02)00860-8.
[135] L. Evangelista, M. Guedes, Microstructural studies on recycled aggregate concrete, in: New Trends in Eco-Efficient and Recycled Concrete, Woodhead Publishing, 2019, pp. 425–451, https://doi.org/10.1016/B978-0-08-102480-5.00014-2.
[136] D. Pedro, J. De Brito, L. Evangelista, Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: mechanical, durability and long-term properties, Construct. Build. Mater. 154 (2017) 294–309, https://doi.org/10.1016/j.conbuildmat.2017.07.215.
[137] H. Salahuddin, L.A. Qureshi, A. Nawaz, S.S. Raza, Effect of recycled fine aggregates on performance of Reactive Powder Concrete, Construct. Build. Mater. 243 (2020) 118223, https://doi.org/10.1016/j.conbuildmat.2020.118223.
[138] A. Ajdukiewicz, A. Kliszczewicz, Influence of recycled aggregates on mechanical properties of HS/HPC, Cement Concr. Compos. 24 (2) (2002) 269–279, https://doi.org/10.1016/S0958-9465(01)00012-9.
[139] A.Z. Bendimerad, B. Delsaute, E. Rozière, S. Staquet, A. Loukili, Advanced techniques for the study of shrinkage-induced cracking of concrete with recycled aggregates at early age, Construct. Build. Mater. 233 (2020) 117340, https://doi.org/10.1016/j.conbuildmat.2019.117340.
[140] M. Velay-Lizancos, I. Martinez-Lage, M. Azenha, J. Granja, P. Vazquez-Burgo, Concrete with fine and coarse recycled aggregates: E-modulus evolution, compressive strength and non-destructive testing at early ages, Construct. Build. Mater. 193 (2018) 323–331, https://doi.org/10.1016/j.conbuildmat.2018.10.209.
[141] S. Omary, E. Ghorbel, G. Wardeh, Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties, Construct. Build. Mater. 108 (2016) 163–174, https://doi.org/10.1016/j.conbuildmat.2016.01.042.
[142] Y. Wang, H. Zhang, Y. Geng, Q. Wang, S. Zhang, Prediction of the elastic modulus and the splitting tensile strength of concrete incorporating both fine and coarse recycled aggregate, Construct. Build. Mater. 215 (2019) 332–346, https://doi.org/10.1016/j.conbuildmat.2019.04.212.
[143] C.S. Poon, S.C. Kou, H.W. Wan, M. Etxeberria, Properties of concrete blocks prepared with low grade recycled aggregates, Waste Manag. 29 (8) (2009) 2369–2377, https://doi.org/10.1016/j.wasman.2009.02.018.
[144] S. Manzi, C. Mazzotti, M. Bignozzi, Short and long-term behavior of structural concrete with recycled concrete aggregate, Cement Concr. Compos. 37 (2013) 312–318, https://doi.org/10.1016/j.cemconcomp.2013.01.003.
[145] S.J. Jang, H.D. Yun, Mechanical properties of ready-mixed concrete incorporating fine recycled aggregate, Mag. Concr. Res. 67 (12) (2015) 621–632, https://doi.org/10.1680/macr.14.00258.
[146] M. Bravo, J. De Brito, J. Pontes, L. Evangelista, Shrinkage and creep performance of concrete with recycled aggregates from CDW plants, Mag. Concr. Res. 69 (19) (2017) 974–995, https://doi.org/10.1680/jmacr.17.00031.
[147] V. Corinaldesi, G. Moriconi, Influence of mineral additions on the performance of 100% recycled aggregate concrete, Construct. Build. Mater. 23 (8) (2009) 2869–2876, https://doi.org/10.1016/j.conbuildmat.2009.02.004.
[148] M. Bravo, J. De Brito, L. Evangelista, J. Pacheco, Durability and shrinkage of concrete with CDW as recycled aggregates: benefits from superplasticizer's incorporation and influence of CDW composition, Construct. Build. Mater. 168 (2018) 818–830, https://doi.org/10.1016/j.conbuildmat.2018.02.176.
[149] H. Zhang, Y. Wang, D.E. Lehman, Y. Geng, K. Kuder, Time-dependent drying shrinkage model for concrete with coarse and fine recycled aggregate, Cement Concr. Compos. 105 (2020) 103426, https://doi.org/10.1016/j.cemconcomp.2019.103426.
[150] Eurocode 2: Design of Concrete Structures, General Rules and Rules for Buildings, British Standards Institutions, London, UK, 1992.
[151] Y. Geng, M. Zhao, H. Yang, Y. Wang, Creep model of concrete with recycled coarse and fine aggregates that accounts for creep development trend difference between recycled and natural aggregate concrete, Cement Concr. Compos. 103 (2019) 303–317, https://doi.org/10.1016/j.cemconcomp.2019.05.013.
[152] B. Delsaute, C. Boulay, S. Staquet, Creep testing of concrete since setting time by means of permanent and repeated minute-long loadings, Cement Concr. Compos. 73 (2016) 75–88, https://doi.org/10.1016/j.cemconcomp.2016.07.005.
[153] T. Fumoto, M. Yamada, Durability of concrete with recycled fine aggregate, Symp. Pap. 234 (2006) 457–472.
[154] M. Quebaud, Caractérisation des granulats recyclés, étude de la composition et du comportement de bétons incluant ces granulats, Béthune, Université d'Artois, 1996.
[155] K. Kapoor, S. Singh, B. Singh, Permeability of self-compacting concrete made with recycled concrete aggregates and metakaolin, J. Sustain. Cem.-Based Mater. 6 (5) (2017) 293–313, https://doi.org/10.1080/21650373.2017.1280426.
[156] V. Bulatović, M. Malešev, M. Radeka, V. Radonjanin, I. Lukić, Evaluation of sulfate resistance of concrete with recycled and natural aggregates, Construct. Build. Mater. 152 (2017) 614–631, https://doi.org/10.1016/j.conbuildmat.2017.06.161.
[157] L.R. Santillán, F. Locati, Y.A. Villagrán-Zaccardi, C.J. Zega, Long-term sulfate attack on recycled aggregate concrete immersed in sodium sulfate solution for 10 years, Mater. Construcción 70 (337) (2020) 212, https://doi.org/10.3989/mc.2020.06319.
[158] S.T. Lee, Influence of recycled fine aggregates on the resistance of mortars to magnesium sulfate attack, Waste Manag. 29 (8) (2009) 2385–2391, https://doi.org/10.1016/j.wasman.2009.04.002.
[159] B.V. Kumar, H. Ananthan, K. Balaji, Experimental studies on utilization of coarse and finer fractions of recycled concrete aggregates in self compacting concrete mixes, J. Build. Eng. 9 (2017) 100–108, https://doi.org/10.1016/j.jobe.2016.11.013.
[160] J. Sim, C. Park, Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate, Waste Manag. 31 (11) (2011) 2352–2360, https://doi.org/10.1016/j.wasman.2011.06.014.
[161] S.M. Levy, P. Helene, Durability of recycled aggregates concrete: a safe way to sustainable development, Cement Concr. Res. 34 (11) (2004) 1975–1980, https://doi.org/10.1016/j.cemconres.2004.02.009.
[162] R.S. Ravindrarajah, C. Tam, Recycling concrete as fine aggregate in concrete, Int. J. Cem. Compos. Lightweight Concr. 9 (4) (1987) 235–241, https://doi.org/10.1016/0262-5075(87)90007-8.
[163] R. Zaharieva, F. Buyle-Bodin, E. Wirquin, Frost resistance of recycled aggregate concrete, Cement Concr. Res. 34 (10) (2004) 1927–1932, https://doi.org/10.1016/j.cemconres.2004.02.025.
[164] B. Delsaute, S. Staquet, Impact of recycled sand and gravels in concrete on volume change, Construct. Build. Mater. 232 (2020) 117279, https://doi.org/10.1016/j.conbuildmat.2019.117279.
[165] H. Maimouni, S. Remond, F. Huchet, P. Richard, V. Thiery, Y. Descantes, Quantitative assessment of the saturation degree of model fine recycled concrete aggregates immersed in a filler or cement paste, Construct. Build. Mater. 175 (2018) 496–507, https://doi.org/10.1016/j.conbuildmat.2018.04.211.
[166] M. Guo, S.Y. Alam, A.Z. Bendimerad, F. Grondin, E. Rozière, A. Loukili, Fracture process zone characteristics and identification of the micro-fracture phases in recycled concrete, Eng. Fract. Mech. 181 (2017) 101–115, https://doi.org/10.1016/j.engfracmech.2017.07.004.
[167] T. Li, J. Xiao, Y. Zhang, B. Chen, Fracture behavior of recycled aggregate concrete under three-point bending, Cement Concr. Compos. 104 (2019) 103353, https://doi.org/10.1016/j.cemconcomp.2019.103353.
[168] E. Ghorbel, G. Wardeh, H. Fares, Mechanical and fracture properties of recycled aggregate concrete in design codes and empirical models, Struct. Concr. 20 (6) (2019) 2156–2170, https://doi.org/10.1002/suco.201800335.
[169] M. Guo, F. Grondin, A. Loukili, Numerical analysis of the failure of recycled aggregate concrete by considering the random composition of old attached mortar, J. Build. Eng. 28 (2020) 101040, https://doi.org/10.1016/j.jobe.2019.101040.
[170] D.Y. Gao, M. Lv, L. Yang, J. Tang, G. Chen, Y. Meng, Experimental study of utilizing recycled fine aggregate for the preparation of high ductility cementitious composites, Materials 13 (3) (2020) 679, https://doi.org/10.3390/ma13030679.
[171] T. Ding, J. Xiao, F. Qin, Z. Duan, Mechanical behavior of 3D printed mortar with recycled sand at early ages, Construct. Build. Mater. 248 (2020) 118654, https://doi.org/10.1016/j.conbuildmat.2020.118654.