# UPSCALING THE USE OF RECYCLED AGGREGATE CONCRETE

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**ABSTRACT.** This paper presents an overview of several aspects that can further upscale the use of recycled aggregate concrete. It presents the main steps that need to be followed to demolish existing barriers to the use of recycled aggregates, namely those related with; the creation of financial benefits; the implementation of a selective demolition approach; updating normative documents with recent developments; enhancing the quality of recycled aggregates to acceptable levels; and improving the confidence of stakeholders. Further attention is given on how to improve in force standardization on the characterization of recycled aggregates, from the beneficiation of construction and demolition waste, and on the production and structural design of recycled aggregate concrete. Also, given the importance of knowledge dissemination to remove misconceptions and increase confidence on the technical viability of the material, this paper also presents a number of case studies on the successful use of recycled aggregate concrete. Finally, it also describes some knowledge gaps that prevent the wider use of recycled aggregate concrete, wherein additional research is warranted.

**Keywords:** Recycled aggregates; Sustainable construction; Construction and demolition waste; Standards and specifications; Case studies.

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# INTRODUCTION

In the European Union's (EU) Directive 2008/98/CE of the European Parliament on waste [1], there is a pressing need for measures with the objective of "reducing the use of resources, and favouring the practical application of the waste hierarchy", as well as "moving the EU towards a recycling society, seeking to avoid waste generation and to use waste as a resource". All Member States must undertake adequate measures for the further progression of the EU towards a more sustainable society with a high degree of resource efficiency. On construction, the Directive specifically states that "by 2020, the preparing for reuse, recycling and other material recovery of non-hazardous construction and demolition waste (CDW) shall be increased to a minimum of 70% by weight". Processing CDW into recycled aggregates (RA) is widely considered the most effective solution for the considerable generation of waste around the World (Figure 1). Transforming the EU's mineral fraction of CDW (about 322 million tonnes) [2] into RA would correspond to roughly 12% of the total construction aggregate demand within the same region [3]. Since half of the demand for aggregates occurs in the manufacture of concrete [3], there is considerable scope to further incorporate RA in this construction application. Therefore, this paper seeks to provide greater insight on the main steps that need to be followed to upscale the use of recycled aggregate concrete (RAC). Attention is given to the necessary improvements in standards and specifications for the characterization of RA, and for the production and design of structural RAC. Moreover, to remove misconceptions and increase the confidence of stakeholders, this paper also describes some case studies on the successful use of RAC. Furthermore, it describes some knowledge gaps that prevent the wider use of RAC, in which additional research is needed.

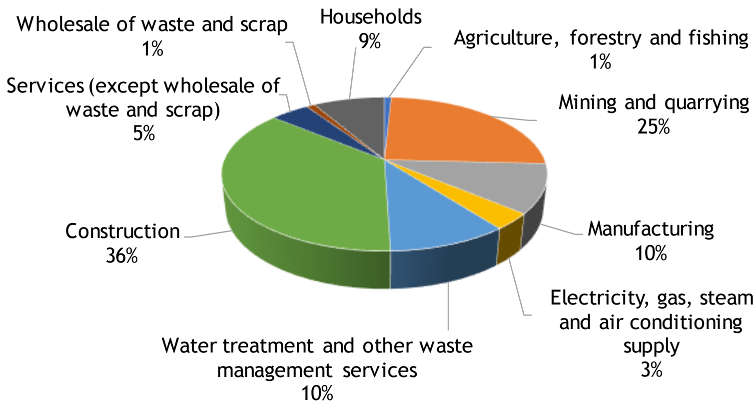


Figure 1 Waste statistics in Europe [2]

# MAIN STEPS NEEDED TO UPSCALE THE USE OF RECYCLED AGGREGATES

The following are the widely known barriers to the use of RA in construction, which, in spite of their long-standing existence, have led to little worldwide efforts made to conquer them: lack of financial advantages with consequent insufficient supply and/or demand; inadequate segregation of waste at the source; low quality of RA; lack of standards and specifications; lack of knowledge by stakeholders. Indeed, moving an industry towards a given practice is a difficult achievement that is restrained by several factors. Apart from profound reform to existing legislation, the steps described herein are some of the ones that can be followed to further upscale the incorporation of RA in the construction industry.

**Create financial benefits**

The process of producing and using RA from CDW beneficiation is still looked at with distrust from an economical perspective, since natural aggregates (NA) are marketed at very low prices. To increase the attractiveness of RA in relation with their natural counterparts, according to the positive experience of more industrialized countries, the taxation of NA extraction should reflect this process's true environmental impact, thus increasing its market price [4, 5]. This would lead to a more judicious use of NA and would encourage the search for less costlier alternatives. Furthermore, since the segregation of CDW at the source is a prime factor influencing the quality of the resulting RA, to further drive this practice gate fees at CDW recycling plants should be carefully devised depending on the level of mixed waste. Additionally, some industrialized countries have banned or are on the verge of banning non-hazardous CDW in landfills, since it can be easily processed in certified recycling plants. Not only would this save up valuable land space, but it would also ensure that CDW is kept in the sector's supply chain, thus sustaining future practice.

**Implementation of a selective demolition practice**

Despite the environmental-related benefits of a selective demolition approach [6, 7], it is not current practice in many countries as it is widely assumed it is more expensive. In fact, it is capable of being a cost-effective solution if all components are properly segregated and sold rather than mixing all waste in a single container [8]. Obviously, the economic viability of this approach would depend on the factors stated in the previous section and on local factors, such as labour costs and transport distances.

**Update and improve existing standards and specifications**

Existing standards and specifications on the use of RA are outdated in the light of the considerable recent advances, mainly in the area of RAC. In the EU, CDW recycling plants certify their RA for concrete based on the requirements presented in EN 12620:2002+A1:2008 [9]. The classification method of this standard mainly relies on the composition of RA, when in fact it should be mostly based on their physical properties [10]. The authors' recent developments have shown that applying a performance-based classification to RA makes it possible to predict the mechanical and durability performance of RAC with a high degree of confidence [11-20]. However, since it is easy to produce a certifiable RA according to existing standards, many CDW recycling plants have applied minimum processing and thus low-quality RA is normally produced. By updating the normative documents related with this process using more stringent requirements, recycling operators would show proactivity in upgrading their production process since they want to market a certified product, which would be more fitted to the industry's needs. Furthermore, concrete producers and designers feel uneasy when faced with the possibility of using RA, since normative documents do not present clauses capable of adequately predicting the performance of RAC let alone its structural behaviour [10]. By incorporating performance-based classification to RA and its associated practical rules of design into current structural codes, stakeholders would soon show increased confidence on the technical viability of RAC.

**Recycled aggregates with enhanced quality**

Obviously, stakeholders do not want to purchase a material with lower quality with the same or even higher price than that of a higher-quality material, the behaviour of which is already known. Apart from improving the economic appeal of RA, the quality-related differences between the two aggregates should also be reduced. This can first be achieved by implementing the selective demolition practice stated in a previous section, which would minimize contamination, thus increasing the quality of the output RA. Furthermore, as stated, several of the existing CDW recycling plants apply basic processing incapable of significantly increasing the product's quality. This is mostly due to the lenient requirements of the standards that are followed to certify the product. Besides the changes in this regard, the increased quality of RA can be achieved by applying the correct number of processing stages depending on the characteristics of CDW delivered to the plant. Basic processing should include, at least, initial evaluation and triage, two crushing stages, intermediate screening stages and electromagnetic removal of ferrous and non-ferrous metals. In due course, at a more advanced stage of market consolidation, cutting-edge and cost-effective methods could be applied to further beneficiate RA (e.g. mechanical grinding method [21], magnetite-based wet heavy media separation [22]).

**Increase the confidence of stakeholders**

Assuming that the previous steps are followed, generalized mistrust by stakeholders can still prevent the greater use of RA in construction [4]. Concrete producers and designers, unaware of the production requirements and technical feasibility of RAC, may fear the consequences of their lack of knowledge in terms of the production of a low-performance material. Therefore, to solve this problem and further improve stakeholders' confidence, knowledge of the production and properties of RAC should be widely disseminated in specialized courses and, eventually, incorporated into regular Civil Engineering courses. Moreover, greater efforts should be focused on presenting the successful use of RAC in new case studies. Dissemination of such cases within a "green" marketing campaign would demonstrate the feasibility of using these materials at an industrial scale.

## NORMATIVE DOCUMENTS FOR THE PRODUCTION OF RECYCLED AGGREGATE CONCRETE

At the end of the production of RA, these should undergo a certification process prior to commercialization. As stated in the previous section, in the EU, assigning CE Marking to a RA means that the product is in conformity with the requirements of EN-12620:2002+A1:2008 [9]. However, what is widely disregarded is the fact that this standard presents a wide range of limits for the physical properties and composition of RA thus allowing the certification of materials with significantly varying quality. Consequently, operators in CDW recycling plants have generally applied minimum processing stages and quality control during the production of RA [23, 24]. Since low-quality RA is a probable output of this process, stakeholders have had low prospects on the applicability of the material *versus* its conventionally used natural counterpart. To correct this and make CDW recycling plants adapt their practice and produce a fit-for-industry RA exhibiting predictable properties, stricter limits should be imposed by normative documents in vigour.

One of the greatest obstacles of manufacturing RAC has been the production of a reliable material according to existing codes and standards. The properties and composition of RA may vary significantly depending on the region's predominant type of construction, effectiveness of the triage implemented during construction and demolition activities and on the upgrading processes applied at recycling facilities [13]. Still, since the components of RA are usually the same, albeit with different contents, across different regions, specific standards have been devised to categorize the material in this regard in an attempt to discern its overall quality [25].

In spite of the aforementioned categorization, a comparison between normative documents on the classification of RA shows that there is a general lack of uniformity, wherein there is considerable variation in the content limits for each of their components and requirements for physical properties [10]. In the case of the production of RAC, there is also some variation in the maximum incorporation levels and there is almost no information on how the presence of RA will affect specific properties of the resulting concrete. Therefore, further unification of nomenclatures, classification, limits, applications in construction and design approaches should be carried out internationally. Apart from strengthening existing knowledge on the use of RA, it would also increase stakeholder's confidence on their technical viability.

In the light of the general lack of knowledge on how to make the best use of RA in the production of concrete, the authors developed, in their previous studies, a practical method capable of yielding RAC with predictable behaviour based on the RA's physical properties [13-15, 17, 19, 20, 24, 26, 27]. This performance-based classification disregards the conventional composition-based categorization of RA and considers instead their oven dry density, water absorption and LA abrasion, among other key properties [13]. This subsequently led the authors to carry out a performance-based design of reinforced RAC beams [27] and slabs [28] in conformity with EC2 [29]. The results of these studies revealed the implications of using RA in structural concrete. Within the boundaries of EC2, for the same amount of steel reinforcement, only slight changes to the cross-section geometry were required to exhibit the same service life, load bearing capacity and long-term deformation as those of corresponding natural aggregate concrete (NAC) elements. More recently, the authors also proposed a set of changes to EN 12620:2002+A1:2008 [9] and EN 206:2013+A1:2016 [30] regarding the characterization of RA and their application in concrete. These modifications, which were based on the aforementioned studies' recent advances, are based on a simple, yet comprehensive, update of existing clauses and limits in a way that can improve the confidence by specifiers and stakeholders and, at the same time, further strengthen the evidence supporting the use of RA.

Another aspect that should also be taken into account in upcoming standards is the reliability when designing structural concrete. Considerable attention has always been given on how to correctly estimate the performance of concrete both from a safety and economic point of view. However, even though good experience has come from the use of current codes for the structural performance of conventional concrete, currently used formulae and prediction models have been found to be conservative, present considerable scatter and, sometimes, be inaccurate [31, 32]. Greater efforts should be directed towards evaluating the reliability of in force structural codes to correct inappropriate methods for conventional concrete and, at the same time, establish rules for the incorporation of RA.

# CASE STUDIES ON THE USE OF RECYCLED AGGREGATE CONCRETE

Much of the literature on the use of RA in concrete is based on academic research and laboratory results. The RA used in such experiments are typically comprised of a single constituent (mainly from end-of-life concrete) or exhibit very low contamination levels. However, these “pure” RA are usually unrepresentative of those sourced from CDW recycling plants, which are likely to exhibit considerable variation in composition and properties [23, 33-35]. Since there is a very low acceptance by concrete producers and designers of the material that currently exists in the market, there have been few full-scale applications of RAC capable of demonstrating the material’s feasibility. Therefore, provided that the aforementioned steps to increase the quality of RA are implemented, further case studies such as the ones presented throughout this section are warranted to further increase the confidence of stakeholders.

**Decorative Concrete Elements in Magdeburg, Germany**

In 1999, large concrete elements were used to embellish the landscape for the Federal Gardening Exhibition (Bundesgartenschau) in Magdeburg, Germany (Figure 2). Some of these decorative elements were manufactured using coarse RA from crushed clay bricks, crushed concrete or a mixture of the two. For reasons of design, either white or brown cement was used. The surfaces of the elements were prepared to expose the fracture planes of the coarse aggregates. When combined with the particular colours of the type of cement used, special decorative effects were achieved. All concrete compositions were developed for outdoor exposure [36].

Figure 2 Bundesgartenschau in Magdeburg, Germany [37]

**Hong Kong Wetland Park**

The Hong Kong Wetland Park, Hong Kong, was completed in 2006. It has a 10,000 $m^2$ visitor centre including exhibition galleries, AV theatres, souvenir shops, cafes, children’s play areas, classrooms and a resources centre. In the construction of this park, most of the structural concrete contained RA. A total volume of around 13,000 $m^3$ of RAC was used in several applications including pile caps, ground slabs, beams, walls and mass concrete, blinding concrete and other minor concrete works elements. The target slump was set between 75 mm and 100 mm. For concrete grades C20 (or below) and C25 (or above, up to C35), the replacement levels of coarse RA were 100% and 20%, respectively. Since the site engineers were unskilled with the use of RAC at the beginning of the project, the RAC's cement content was intentionally increased by around 4% to compensate for the greater water requirement and to maintain the same w/c ratio. Equivalent target strength values were obtained for both RAC and NAC. Furthermore, comparable standard deviations were observed for RAC and NAC alike thus suggesting equivalent levels of predictability. The contractor's feedback suggested that concrete with 20% RA performed similarly to NAC, no shrinkage-related cracking was observed and no traceable carbonation depth was detected over the first two-year period [38, 39].

**The "Recycled House" in Odense, Denmark**

The "Recycled House" in Odense, Denmark, was built in the early 1990's in an attempt to determine the amount of CDW that could be reincorporated in a new house. New concrete was produced using the crushed material from a nearby bridge and air raid concrete bunker. About 275 $m^3$ of concrete were produced with coarse RA with particle sizes of 4-32 mm. Other CDW also included old bricks, windows and wooden elements [40].

**"Waldspirale" Building Project in Darmstadt, Germany**

One of the most well-known buildings made with RAC is the "Waldspirale" apartment building, designed by Friedensreich Hundertwassers, in Darmstadt, Germany (Figure 3). A consistency-controlled method was developed and implemented for the RAC in this project, due to the greater water requirement of RA, with the objective of reducing the compressive strength's standard deviation, whilst maintaining a constant initial consistency. Throughout the construction phase, the grading curve of all aggregate fractions remained within specific limits. The foundations were built with a C25 concrete exhibiting a 360-380 mm slump flow. A C25 concrete mix, with a 400-420 mm slump flow, was used for walls, slabs and columns. Test results on the mechanical performance of RAC showed that all mixes reached their target strength and some turned out better than expected. The initial mean compressive strength was 52.3 MPa and thus the contractor decided to increase the workability by including additional water, bringing the mean strength down to 42.3 MPa. Specimens made on site presented similar values (49.8 MPa and 41.3 MPa, respectively). The contractor reported that RAC did not show significant differences in behaviour when compared to NAC and that it could be pumped and cast in the same way as a standard concrete mix [41].

Figure 3 The "Waldspirale" apartment building in Darmstadt, Germany [42]

**The Environmental Building at BRE in Watford, United Kingdom**

Another classic case study is the Environmental Building, of the Building Research Establishment (BRE), in Watford, UK. This building incorporates the first-ever use of RA in ready-mixed concrete in the UK. The concrete was produced using crushed concrete aggregates from a 12-storey office block that had been demolished in central London. Over 1,500 $m^3$ of concrete was used in the construction of foundations, floor slabs, columns and waffle floors. For the foundations, a C25 concrete with 75 mm slump was applied. This concrete contained a minimum binder content of 330 $kg/m^3$ and a maximum free w/c ratio of 0.50, due to the ground's relatively high concentration of sulphate. This concrete mix was comprised of cement containing 70% ground granulated blast furnace slag to improve chemical resistance. A C35 concrete with 75 mm slump was used for floor slabs, columns and waffle floors. This concrete mix contained 50% ground granulated blast furnace slag and 50% cement to avoid excessive carbonation. All mixes contained 985 $kg/m^3$ of coarse RCA. For those that were pumped, this content was reduced by 50 $kg/m^3$ and the cement content increased by 10 $kg/m^3$ [36].

**Strong Floor at BRE Cardington Laboratory, United Kingdom**

In 1996, 500 $m^3$ of RAC were placed in one day at the BRE Cardington Laboratory. The construction of a second strong floor (0.5 m thick heavily reinforced slab) was undertaken to show the viability of applying concrete containing 20% medium quality coarse MRA. Apart from the use of about 100 tonnes of coarse MRA, the mix design was almost identical to that for the first strong floor built at Cardington, and with a similar strength development, wherein 60 MPa was attained after 91 days. It was reported that the RA did not affect the production schedule (up to 10 truckloads of concrete were being delivered per hour), nor was there any effect on the pumping and placing of the concrete [36, 43].

**Samwoh Eco-Green Building in Singapore**

The Samwoh Eco-Green Building was the result of a demonstration project envisaging the construction of the first structure in Singapore using concrete with up to 100% recycled concrete aggregates (RCA) [44]. The objective of this project was to evaluate the feasibility of using RCA produced from CDW in structural concrete. This project involved two stages, including the extensive evaluation of the performance of concrete containing RCA and construction and structural monitoring of a three-storey building containing the material. A C40 grade concrete, with up to 100% RCA, was used for all structural members (i.e. beams, columns, slabs and walls) of the building in the second stage of the project. In-situ performance monitoring of the RAC was based on fibre-optic sensors installed to measure the columns' deformation. The good experience acquired in the construction of this building enabled alterations in the building code requirements of Singapore to allow the use of RCA in all buildings.

## NEW TRENDS ON SUSTAINABLE CONCRETE

At this point in time, in spite of the extent of literature backing up the technical feasibility of the use of RA from CDW in the production of structural concrete, some gaps in knowledge have been identified and should be the subject for further research. One of such research topics is in line with one of the aforementioned steps, which involves the development of additional processes capable of enhancing the quality control of RA throughout the supply chain. Since the amount of contamination in CDW is typically high, cost-effective measures capable of minimizing deleterious constituents, other than the ones already known, should be developed. The production of high-quality RA with consistent properties would enable easier certification with stricter requirements and thus would increase the confidence of key stakeholders.

Although much has been studied on the main properties of RAC, there are some that require additional attention to close important knowledge gaps. Shrinkage- and creep-related deformation should be further researched given the notable decline of these two properties with increasing RA content. Experience has shown that designers prefer not to use RAC, since improper use of the material can have serious implications on a concrete structure's performance. Therefore, more information on this matter is required to further improve existing prediction models on the deformation of concrete elements over a long period of time. In parallel, the knowledge on the structural behaviour of RAC should also be strengthened given the few studies assessing its macro-structural performance. Current findings suggest similar load bearing capacity and mechanisms of failure between reinforced RAC and NAC elements [29, 30], even though the former are likely to present greater deformability [31]. Thus, further research still needs to be carried out, namely on long-term deflection, shear strength, fatigue, punching shear, load redistribution, and pre-stressed concrete, to properly adjust structural codes.

The issue of multiple recycled concrete is a topic that will need additional attention in a near future, when faced with a more developed CDW management system. Of the few existing studies, the results suggest that the inclusion of RA subjected to high number of cycles of recycling will hinder the performance of concrete. However, this decline happens within acceptable limits and the performance of the resulting concrete is predictable thus enabling its application [32].

Another topic that is currently gaining increasing interest is the optimization of the use of concrete based on multiple criteria. Current thinking on the use of concrete is mostly based on its structural behaviour and cost. However, there are other factors that need to be taken into account throughout the life cycle of RAC and even conventional concrete. One of them is the environmental impact of the material. Although the use of RA does have environmental advantages, one should not e.g. use them in circumstances in which the road haulages distances significantly exceed those required for NA, thus making it a worse alternative from an environmental perspective and perhaps also from a financial point of view. Another factor that has been given attention only recently is the durability of reinforced concrete. Even though this factor is supposedly considered in existing normative documents, reality shows that there are many cases of concrete exhibiting corrosion-related expansion and consequent loss of structural capacity. Therefore, the development of an easy-to-use multi-criteria decision tool is in order so that concrete can be optimized according to a specific scenario by simultaneously considering their mechanical, durability, structural, and environmental performances, as well as cost [45]. Such a tool could be used to identify the main differences between concrete mixes in terms of quality, environmental and economic performance, and sets out to optimize the mixes based on the scenario put forward by the client (i.e. business as usual, green, strength, service life and cost).

## CONCLUSIONS

It is clear that greater acceptance by professionals in the construction industry is needed before actual application of RAC can be widespread in most countries. Even though sufficient evidence exists on the material's viability, to compel construction companies towards the use of RAC, a profound reform of existing legislation, and normative documents for the characterization of RA and the production of RAC is required. Such improvement, apart from enforcing the incorporation of a minimum amount of waste, should also have a direct role on the increased financial appeal of RA in comparison with NA to further drive the interest of stakeholders to search for a cost-effective alternative. Moreover, besides the modification of standards and specifications taking into consideration recent developments on RAC technology, further unification of nomenclatures, classification, limits, applications in construction and design approaches should be carried out internationally. Finally, to demonstrate the feasibility of RAC, further dissemination should be carried out. This can be made in the form of successful case studies, thereby showing the applicability of the material in circumstances that are more familiar to professionals in the industry, and also in specialized courses capable of removing all doubts and misconceptions.

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