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Use of recycled aggregates in concrete

Opportunities for upscaling in Europe

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Contents

Abstract

This Science for Policy Report discusses context, barriers and measures along the supply chain to increase the use of recycled aggregates in concrete. The report is based on state-of-the-art data, EUROSTAT datasets, surveys sent to industrial representatives, policy documents, technical reports, and the authors' remarks.

Construction and demolition waste (CDW) is more than one third of all waste generated in the EU and is mostly composed of concrete. Recycled aggregates are produced from CDW and their use in new concrete reduces the consumption of natural aggregates, a mineral resource.

Moderate incorporation ratios of recycled aggregates are technically-sound. However, recycled aggregates are downcycled and rarely used in concrete. If a 30% mean incorporation of recycled aggregates in the EU was achieved, around 30% of all non-soil CDW generated every year would be recovered.

Some of the main ideas of the report are that:

- Recycled aggregates may be produced with conventional methods, but selective demolition and advanced CDW treatment greatly improve the recoverability potential of CDW;
- Measures to promote the market uptake of recycled aggregates must consider the whole supply chain, including demolition and CDW companies (to ensure supply with quality), as well as concrete producers and society (to ensure demand).

Measures to promote the market uptake of recycled aggregates tackling regulatory, technical, operational, economic and social issues are presented in a specific chapter of the report.

Executive summary

The European construction sector produces a Gross Value Added (GVA) equivalent to 5.5% of the Union's GDP, employing 9% of the European workforce in 12% of the EU-27 industries, most of which are SMEs. To this end, it consumes around half of all extracted materials and produces more than one third of the EU's total waste.

Concrete plays a central role in construction, it is the most widely used building material in the world and it will continue to be used during the green transition to produce safe and durable buildings and infrastructure, which protect citizens against natural disasters, extreme weather events and natural and man-made hazards. At the same time, concrete also represents the largest fraction of Construction and Demolition Waste (CDW) produced in EU: 56.2% (excluding soil & dredging spoil).

The introduction of the circular economy in the construction sector and for concrete is of paramount importance in order to reduce, at once, the quota of mineral fractions in CDW and to reduce the consumption of natural resources.

This report examines the current status of and barriers to using Recycled Aggregates (RA) in concrete to replace Natural Aggregates (NA). RA are produced from CDW, while NA are extracted from natural resources. This means that RA can be used as a secondary raw material to replace the natural raw material.

Policy context

The EU Commission is launching a comprehensive strategy for a sustainable built environment that must ensure coherence across relevant policy areas such as climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalisation and skills in a way that preserves the environment and supports the circular economy.

The EU Waste Framework Directive (2008/98/EC) [1], states in Article 11(2)(b) that, by 2020, 70% by weight of CDW shall be prepared for re-use, recycling and other material recovery, including backfilling operations using waste as a substitute for other materials. In 2018, the European Commission made a revision (European Commission, 2018/851) [2] to the definition of backfilling, making it more stringent than the previous version since, despite this ambitious target, recycled aggregates produced from the concrete fraction of CDW are mainly used for low-grade applications, which in the best case scenario are used as backfill or road base, while a negligible share of recycled aggregates is currently used for concrete applications. Better uses for the concrete fraction of the CDW should be sought and promoted.

More recently, the Commission has undertaken initiatives specifically aimed at the construction sector, such as the European Green Deal [3], the New European Bauhaus [4], the Circular Economy Action Plan [5] and the EU Renovation Wave [6].

The reasons for the low market share of higher added value applications of recycled aggregates are many and vary between the Member States, which also have very different market uptakes of recycled aggregates. Some of the reasons for this disparity are analysed in detail in this document, also with reference to other regulations.

Key conclusions

The coarse fraction of the recycled aggregates, if properly separated before processing to obtain recycled aggregates composed mainly of concrete waste, has sufficient quality for moderate incorporation ratios in medium-performance concrete. Such valorisation of CDW would already be a very significant contribution towards CDW management in the European Union.

Advanced separation and processing methods are required to obtain higher quality aggregates, i.e. to incorporate higher amounts of recycled aggregates, to increase the strength range and/or to use smaller fractions of recycled aggregates (fines and fine aggregates). Therefore, moderate incorporation ratios can be achieved with conventional equipment of the C&D sector, while more advanced equipment can be used for the production of very high-quality recycled aggregates. As CDW plants are mostly SMEs and the market for concrete with recycled aggregates is currently very narrow, any kind of investment is a challenge, without the intervention of public authorities.

In many regions where natural aggregates are cheap and readily available, the main challenge is that concrete producers do not find an incentive to use recycled aggregates, which are more difficult to source and often have inferior properties compared to natural aggregates. This is further exacerbated by the public perception that recycled aggregates are a poor quality product to be avoided, and by the reluctance of designers and contractors to accept recycled aggregates when they are reasonably priced and have good quality. Public authorities, which are the largest contractors in the concrete market, should use green public procurement to boost the use of recycled aggregates and to provide Society with examples of how recycled aggregate concrete is a sound and safe material.

The report also presents measures tailored to different contexts that could tackle the main barriers; these range from training, research and knowledge transfer to improving industrial capacity and promoting increased market demand. Economic instruments, the raising social awareness and the role of certification and regulation are also presented.

1 Introduction

This report discusses the current status and barriers for the use of Recycled Aggregates (RA) in concrete as a replacement of Natural Aggregates (NA). The first are produced from Construction and Demolition Waste (CDW), while the latter are composed of stone and are extracted from nature. This means that RA are a secondary raw material that may replace a primary one. The use of RA in concrete is a direct contribution towards the circular economy. Measures to promote the use of Recycled Aggregate Concrete (RAC) are fully in line with strategic goals of the European Union (EU) and the scientific community has consistently argued that RAC is a technically suitable structural material. However, there are differences between RA and NA –, so the behaviour of RAC is also different from that of Natural Aggregate Concrete (NAC).

Using RA to produce concrete has several benefits for the construction sector and for Society that are priority targets of the European Commission:

- The amount of CDW that needs to be disposed of is reduced. The recovery of CDW as RA keeps the valorisation of CDW in the construction sector, which has operational advantages and, in most cases, is seen as a recycling operation that does not constitute downcycling [7, 8].
- The consumption of NA decreases, reducing the extraction of mineral resources from riverbeds and quarries.
- In most circumstances, replacing NA with RA reduces the carbon footprint of the procurement of aggregates and, provided the RA are of good enough quality, the overall carbon footprint of recycled aggregate concrete (RAC) may also be smaller than that of Natural Aggregate Concrete (NAC).

The importance of these benefits is better understood when considering that the European Green Deal [3] includes specific mentions to the reduction of the extraction of natural resources and to the need to increase the uptake of RA by the concrete industry. Further, the following data show the potential magnitude of RAC towards the reduction of the disposal of waste and of the consumption of natural resources:

- The sector of construction aggregates is the largest non-extractive industry worldwide. According to the 2020-2021 Annual Review of the European Aggregates Association (UEPG) [9], the extraction of aggregates in the European Union (EU-27) in the year of 2019 totalled 2550 million tonnes and this demand is expected to grow as the economic context within the EU-27 improves. Furthermore, the same document states that the demand for aggregates of the concrete industry amounts to 45% of all aggregates extracted in the countries monitored by the UEPG.
- According to EUROSTAT data [10], the 2021 generation of CDW waste in the EU-27 amounts to 840 million tonnes per year, which is 36% of all waste generated.
- The 2019 production of concrete is estimated at 1200 million tonnes, based on the cement production in the EU-27 reported in the 2020 by the European Cement Association (CEMBUREAU) [11]. This estimate is made by considering that the production of concrete is 7 times that of cement, an assumption that is used in other publications to estimate the amount of concrete produced worldwide [12].

The increase of the market uptake of RA as a secondary raw material for the concrete industry is particularly relevant in the current context of the EU since it tackles several targets that are highlighted in initiatives of the European Commission. The generation of CDW in the EU is an environmental challenge that has been acknowledged by the European Commission and special emphasis on CDW is put on the Circular Economy Action Plan [5], which aims at mainstreaming circular economy to the industrial context. The EU Renovation Wave [6], another initiative that derives from the European Green Deal [3], aims at doubling the renovation rate of the European building stock in order to improve energy efficiency. Such increase in renovations will necessarily increase CDW, as well as the need for aggregates for construction. Future integrated policies/funding for the use of recycled materials in the scope of the Renovation Wave are expected, since it explicitly targets the revision of the material recovery targets of the EU defined in 2024 [6] and the promotion of the market for secondary raw materials.

At the same time, RA are typically associated with fewer carbon dioxide emissions and lower cost when compared to NA [13] and the same is valid when RAC and NAC are compared [14], except for specific cases such as:

- RAC made with large incorporation ratios of RA, which may result in RAC having relevantly larger cement content than NAC. The increase in cement content has a counterproductive effect on the cost and environmental impact of concrete [15].
- Unfavourable conditions for the procurement of RA, such as large transport distance [13] or NA being transported by river while the RA are transported by truck [16].

The extraction of NA is associated with impacts [17, 18] on wildlife, ecosystem effects (changes in river courses, landscapes, and biodiversity) and even structural damage that compromises safety, such as erosion of columns of bridges due to excessive extraction of aggregates from riverbeds [19]. Notwithstanding other successful efforts from the sector of construction aggregates to minimize such effects, replacing part of the production of NA with RA would also contribute towards the reduction of the impacts of the extraction of NA.

An analysis of material flows presented in a recent report of the JRC [29] shows that concrete waste is the largest type of CDW generated in every country of the EU27 and projections for the year of 2050 predict that the yearly generation of both CDW and concrete waste will increase. The efficient recovery of concrete waste is central for the 2050 sustainability targets of the EU.

Scientific research argues that the performance of RAC complies with the needs of the construction sector both in terms of mechanical and durability properties of concrete (material behaviour), as well as in terms of overall behaviour of buildings and infrastructure (structural behaviour). Large-scale research projects on the industrial production of RAC are scarce but also agree with these findings [20]. Technical solutions for the differences between NA and RA have already been defined and adopted in standards, which now include requirements and recommendations concerning the properties of RA fit for concrete [21], as well as the specification of RAC [22]. Concerning structural design, specific clauses for RAC are included in the new version of the Eurocode standard for reinforced concrete design (EN1992-1 [23], which is under approval). At the national level, Member States already include standards/national specifications for this purpose for many years, such as [24].

However, in most Member States, RAC is hardly (if ever) produced. This is inferred from UEPG data [9] that show that RA account for only 8.2% of all aggregates produced in the EU-27 in the year of 2019. Such small market uptake is not due to technical aspects alone, since the market uptake of RAC is prevented by lack of know-how by concrete producers and trained personnel for RAC production, absence of steady supplies of RA with suitable quality for concrete production, and operational constraints (e.g. the need for space and investment in bins, feeders and balances in precast factories and ready-mixed plants), as well as by concerns from clients, contractors and customers [20, 25].

An increase in the market uptake of RA and RAC is expected in the future due to policy that promotes CDW recovery. As a matter of fact, the European Green Deal [3] specifically mentions that enforcing legal requirements concerning minimum content of recycled materials in construction products may be an option. This means that the whole construction sector, including the concrete industry, needs to be prepared for such measures. These remarks show that the current context is favourable towards measures that encourage CDW recovery as RA for concrete. This is especially true when accounting for the fact that the cement and concrete industries are already undertaking significant efforts towards the reduction of their environmental impacts and RAC is specifically stated as a means towards lower impact concrete in the CEMBUREAU Roadmap towards climate neutrality by 2050 [26].

This report was produced in this context and aims at identifying key obstacles for the industrial upscaling of RAC as well as proposing measures. The report is structured in the following chapters:

1. Introduction

   The current section, which summarizes the current paradigm for CDW recovery and RAC promotion in the context in the EU.

2. Status of CDW valorisation in EU Member States

   A section that briefly appraises the reported data concerning CDW valorisation and RA uptake in EU Member States and contextualizes them with legislation.

3. State-of-the-art on recycled aggregate concrete

   The common production processes used to produce RA are presented and emphasis is put on RA fit for use as aggregates for concrete. The state-of-the-art on RAC is focused on the properties and structural behaviour of RAC. The findings of relevant industry-oriented research are summarized. Since the use of RAC is driven by sustainability concerns, the carbon footprint of the procurement of NA and RA and of the production of NAC and RAC are compared, including the effect of transport and concrete mix design on the outcome of these comparisons.

4. Regulations and maximum incorporation ratios of recycled aggregates in concrete in the European Union

   The framework for the use of recycled aggregates in the Member States is presented. The maximum incorporation ratio of recycled aggregates allowed in different Member States is compared, the consistency between approaches is discussed, and the hypothetical influence of limitations due to the maximum incorporation ratios on the market uptake of RA by the concrete industry is stated.

5. Circular Economy models and the employment of the construction sector

   A section focused on social aspects related to increased uptake and production of RA by the construction industry.

6. Barriers to and measures for market uptake of recycled aggregate concrete by the concrete industry

   The identification and discussion of the key legislative, operational, procurement and technical obstacles towards the industrial upscaling of RAC. The section finishes with suggestions for the promotion of RA and RAC.

7. Conclusions

   A summary of the findings and main ideas of the report.

2 Status of CDW valorisation in EU Member States

Table 1 presents the generation of CDW over time in the Member States of EU-27 plus the United Kingdom and was produced from EUROSTAT data [10]. This chapter presents EU statistics along with those of the United Kingdom, since the latter is a good example of the valorisation of CDW as RA. However, EUROSTAT has no data for the United Kingdom pertaining to the year of 2020. Due to this, the United Kingdom is excluded from part of the datasets presented.

Table 1. Generation of construction and demolition waste in the European Union and in the United Kingdom. Millions of metric tonnes. Source: EUROSTAT [10]

YEAR		2006	2008	2010	2012	2014	2016	2018	2020
European Union - 27	EU27	726.7	763.5	757.1	729.8	740.0	788.0	838.9	807.17
Belgium	BE	13.1	15.44	16.9	17.1	18.4	19.6	22.7	20.73
Bulgaria	BG	1.0	1.83	0.1	1.0	1.3	2.1	0.2	1.82
Czechia	CZ	8.4	10.65	9.4	8.6	9.4	10.1	15.8	16.50
Denmark	DK	5.8	5.67	3.1	7.5	11.3	12.2	12.0	11.03
Germany	DE	196.5	197.21	191.0	197.5	206.5	220.5	225.3	226.04
Estonia	EE	0.7	1.10	0.4	0.7	0.7	1.2	2.2	1.59
Ireland	IE	16.6	13.55	1.6	1.1	1.9	1.5	1.9	5.28
Greece	GR	6.8	6.83	2.1	0.8	0.5	0.6	2.3	5.42
Spain	ES	47.3	44.93	38.0	26.1	20.4	35.8	38.1	32.54
France	FR	225.3	252.98	260.7	246.7	227.6	224.4	240.2	212.73
Croatia	HR	0.0	0.1	0.0	0.7	0.6	1.4	1.3	1.43
Italy	IT	52.3	69.7	59.3	53.0	51.7	54.6	60.8	66.08
Cyprus	CY	0.3	0.43	1.1	1.0	0.6	0.8	1.1	1.11
Latvia	LV	0.02	0.01	0.02	0.01	0.45	0.11	0.3	0.28
Lithuania	LT	0.35	0.4	0.4	0.4	0.4	0.5	0.62	0.56
Luxembourg	LU	6.77	8.3	8.9	7.1	6.0	8.0	7.3	7.57
Hungary	HU	3.05	3.2	4.1	4.0	3.4	3.6	6.1	4.36
Malta	MT	2.49	1.7	1.0	1.0	1.2	1.3	2.0	3.01
Netherlands	NL	56.72	58.9	78.1	79.2	90.7	98.6	101.7	81.87
Austria	AT	31.32	31.4	20.9	33.5	40.3	44.9	48.9	52.70
Poland	PO	14.14	6.9	20.8	15.4	17.0	18.9	17.0	22.05
Portugal	PT	3.61	1.4	1.3	1.1	1.2	1.7	1.4	1.78
Romania	RO	0.03	0.3	0.7	1.3	1.1	0.3	0.7	1.22
Slovenia	SI	0.99	1.4	1.5	0.5	0.8	0.5	0.7	0.47
Slovakia	SK	0.92	1.3	1.8	0.8	1.4	1.0	0.5	1.15
Finland	FI	23.15	24.5	24.7	16.0	16.3	13.8	15.7	13.69
Sweden	SE	8.94	3.3	9.4	7.7	8.9	9.8	12.4	14.16
United Kingdom	UK	109.55	101.0	118.9	114.11	130.3	136.2	137.8	-

As understood from the table and Figure 1, the crisis of the construction sector resulted in a decrease of CDW generation between the years of 2010-2012. After 2012, the generation of CDW increased due to the recovery of construction activities in the EU. From 2004 to 2018, the total generation of reported CDW increased by 26%. Despite the pandemic and the Ukraine war, an increase of CDW generation over time is expected to continue, especially due to the ageing building stock in Europe: half of the building stock, defined by floor area, is comprised of buildings that are older than 50 years [27], which is the typical design working life of common structures [28]. Therefore, refurbishment and demolition of a significant portion of EU buildings is expected.

Figure 1. Generated CDW in the EU-27 over time. Source: EUROSTAT [10]

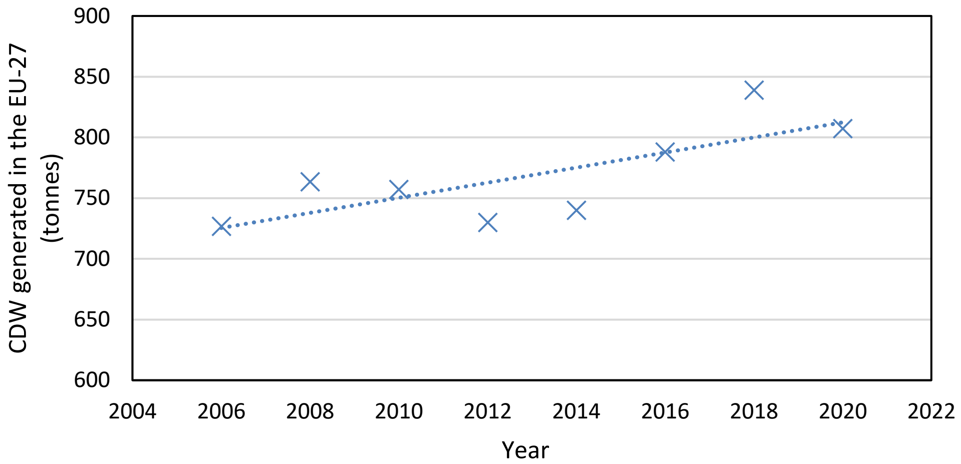


Figure 2 compares the generation of CDW *per capita* in EU-27 in the year of 2018 with the production of NA during the same year. This year was selected since it is the most recent year in which the production of aggregates and the generation of CDW are simultaneously available (from UEPG and EUROSTAT, respectively).

Both the production of CDW and the production of aggregates are country-specific indicators of construction activity; a correlation between the two indicators was expected but not found. As explained next, this may be due to reliability concerns about the reported CDW generation by each Member State. The mean generation of CDW *per capita* in the EU-27 during this year was reported as 1.9 tonne, while the mean production of NA was 5.9 tonne *per capita*.

Figure 2. Generated of CDW and production of NA per capita. Source: EUROSTAT [10], UEPG [9], United Nations [29]

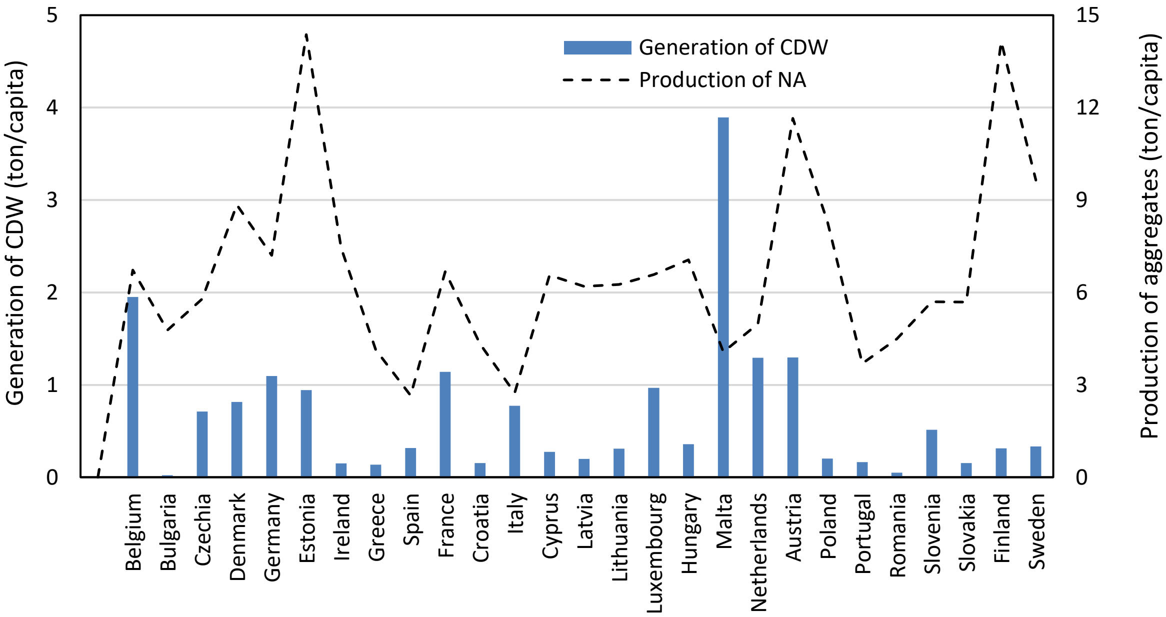


Figure 3 shows the composition of CDW and was produced from EUROSTAT data for the year of 2020 [30]. The types of waste considered in this figure are presented by categories of the European Waste Catalogue ([1]) and the waste codes included in the figure are presented in its caption. These codes were selected using the same criteria presented in [7] for EUROSTAT data coming from the year of 2014. As understood from the figure, the majority of the CDW generated in the EU is included in code W121, which concerns all non-asbestos-containing mineral fractions of CDW. Data from previous years are similar for most Member States.

Figure 3. Generated waste by class of the European Waste Catalogue in 2018. Source: EUROSTAT [30], based on the criteria of [8]

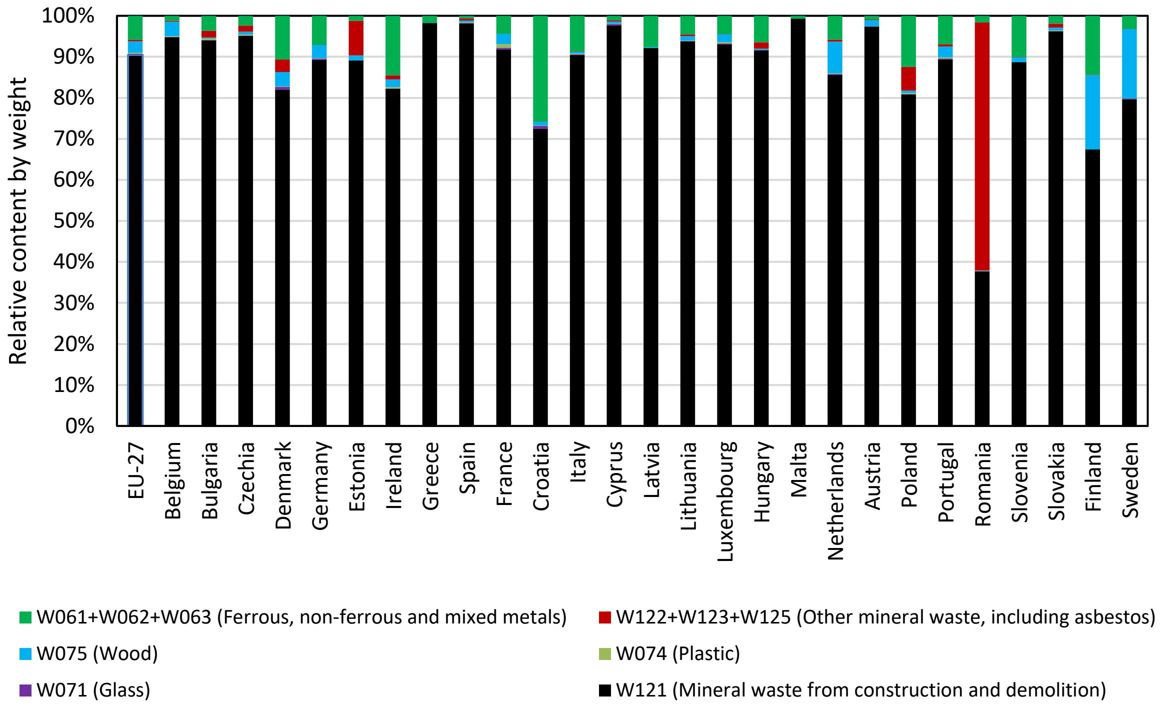


Figure 3 concerns only non-hazardous streams of CDW, which are those included in the 70% target of CDW reuse and recycling or other material recovery of EU Directive 2008/98/EC on waste [1]. Soil waste (codes W126 and W127) consistently corresponds to 57% to 62% of the total annual waste presented in Table 1 but such type of waste is not included in Figure 3 since soil waste is not covered in the target reuse, recycling and other material recovery ratio of EU Directive 2008/98/EC [1]. The mean generation of non-hazardous CDW in the EU in the year of 2018, excluding codes W126 and W127, was 322.79 tonne. This value corresponds to 0.73 tonne per capita.

The recovery of excavated soil waste as RA is not treated in this report, not only because such recovery lies outside the targets of EU Directive 2008/98/EC on waste [1], but also due to quality concerns regarding higher added-value recovery of soil waste (which include the use of RA in concrete). This option is aligned with a recent JRC report [31] in which excavation waste was not considered as well.

Section 3 will show that, out of the CDW included in code W121, the most abundant constituents are concrete, mortar and unbound stone, which are the most suitable ones for the material recovery of RA for concrete production [32].

Table 1 and Figure 3 show that the generation and the composition of CDW are variable between countries. This variability is due to several factors, from economic context to the tradition of the construction industry of each country. The reliability and type of data reported by each country also contributes to the variability and is caused by aspects such as differences in [33, 34]:

— The criteria used for waste classification.

— The methodology used for monitoring/collection of data.

([1]) The classification of the European Waste Catalogue was used since it is the classification system required by Regulation 2150/2002 on waste statistics

— Frequency and quality of inspection/audits.

Differences in the reliability of data are relevant and have been specifically studied [8, 33, 35]. Several publications have proposed models to estimate the generation of CDW and examples may be consulted in [36-38]. Relationships between CDW generation and country-level indicators, such as the turnover of the construction sector [8, 38] show that the variation in CDW generation is hard to explain and may be caused by conjecture - e.g. such as large infrastructure projects at a given time and country. A guideline by the European Commission for waste auditing [39] is expected to contribute to improved data reporting in the near future.

EU Directive 2008/98/EC on waste [1] was a major driver towards the valorisation of CDW in most Member States. Before this Directive, the valorisation of CDW was only a common option in Member States in which NA are costly and scarce, and/or there is lack of space for landfill deposits, such as Belgium and the Netherlands [40].

Box 1. Valorisation of CDW

According to the waste management hierarchy, waste should be reused rather than treated. However, in most cases the reuse of building components is neither cost-effective nor technically viable, and CDWs must be treated. Waste treatment options are [39]:

- Recycling, which is a type of recovery in which waste is reprocessed into a product, material or substance. Recycling excludes energetic recovery and backfilling and contributes towards compliance with EU Directive 2008/98/EC [28].

- Backfilling, which is, according to Directive 2018/851 [2], any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping. Waste used for backfilling must substitute non-waste materials, be suitable for the aforementioned purposes, and be limited to the amount strictly necessary to achieve those purposes. In addition, Commission Decision 2011/753/EU already required Member States to report the amount of CDW used for backfilling separately from the amount of waste prepared for reuse, recycled or used for other material recovery operations.

- Energy recovery or Incineration, in which waste is used to produce energy. This option does not contribute towards compliance with EU Directive 2008/98/EC [28] and is viable only for selected types of combustible CDW (e.g. the use of plastic waste in cement kilns as refuse-derived fuel or the use of wood waste as biomass).

- Disposal or Landfilling, which is the disposal of waste in land except for some cases such as the temporary storage of waste prior to recovery or before transport to another facility for recovery. This operation results in land occupation, does not reduce the extraction of natural resources and should be avoided since it has no added value. Disposal is not a type of recovery and does not contribute to the 70% target of EU Directive 2008/98/EC [28].

Out of the possible types of waste treatment operations for CDW, only recycling and backfilling contribute towards compliance with the target of EU Directive 2008/98/EC. The possibilities of reusing construction elements are briefly discussed in Section 6.

Figure 4 presents statistics on the waste management treatment and landfilling of CDW in the EU-27 in the year of 2020. In this figure, Austria, Czechia, Germany and the Netherlands are presented in dashed lines since part of the data was reported as confidential for relevant EUROSTAT management categories, including code W121 in some instances.

The following general ideas are put forward:

— The mean recycling and backfilling ratio of non-hazardous CDW in the EU-27 is of 87% (7% backfilling and 80% recycling), with 7% landfilling and 6% energy recovery (driven by wood and plastic waste).

— Most Member States (25 out of 27) comply with the target of EU Directive 2008/98/EC [1]: only Finland and Sweden are not complying with the target. Nevertheless, there is very large variability between Member States and some data are clear outliers that suggest limitations in data reliability.

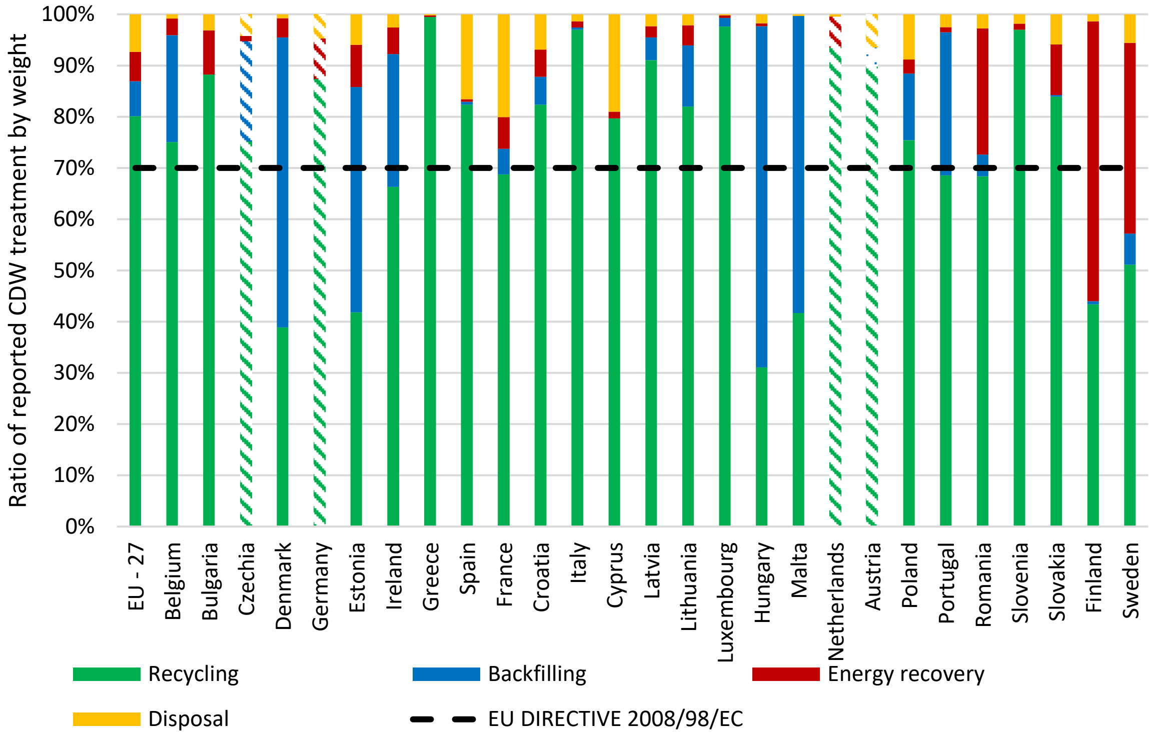
— According to the report prepared by Deloitte for DG ENV [8] the figures for all countries not meeting the target are indicated as poorly plausible.

— In seven out of the 25 of Member States that comply with the target of EU Directive 2008/98/EC [1], compliance is only met when backfilling operations, which constitute downcycling [7], are considered. As will be explained next, the actual number may be significantly higher.

These observations must be considered with caution since reliability in data reporting is a major issue when both the generation and treatment of CDW are analysed. Remarks on the reliability of the reported generated waste have already been stated, while those on the reported data of CDW treatment will be discussed later.

A separate analysis was made for category W121 and the only noteworthy differences were smaller ratios of energetic recovery and of incineration (a type of disposal), with larger recycling and backfilling. Nonetheless, a single country (Finland) reported very relevant energy recovery from waste of category W121, which may be due to different criteria in the classification of waste.

Figure 4. Treatment of CDW in the EU-27 in the year of 2020. Source: EUROSTAT [41]



The differences in the reported values of CDW valorisation between Member States are partly explained by legislation (e.g. the landfilling of recyclable CDW is banned in the Netherlands) and by the geographical distribution of CDW facilities [33]. As is the case of CDW generation, the reliability of the data and methods of data collection also contribute to the differences in reported CDW treatment and valorisation between Member States. As argued in [8, 33, 38], data is limited in extension, timeframe and reliability and may include erroneous statistics (e.g. the consideration of soil waste [8] and the remarks regarding backfilling presented next).

Figure 4 shows the importance of backfilling towards compliance with the 70% recovery target of some Member States. Furthermore, backfilling varies largely between countries and, as argued in [8], the most reasonable explanation for this variation is that backfilling is significantly misreported in EUROSTAT statistics, with concerns that many Member States are reporting backfilling as recycling operations [8]. The actual number of Member States that rely on backfilling for compliance with the target of EU Directive 2008/98/EC [1] may be higher than that reported in Figure 4.

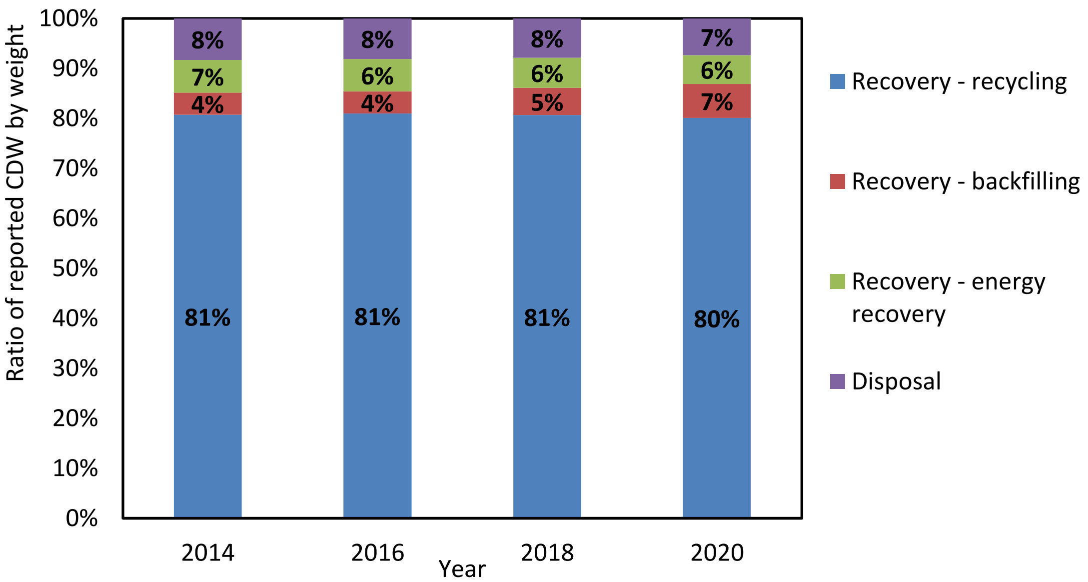
This is problematic, especially when considering that over-reliance on backfilling is not in line with EU Directive 2018/851 [2], which amended EU Directive 2008/98/EC [1] and states that backfilling should be restricted to *the minimum amount possible*. Relying on backfilling as a main driver to comply with the target for CDW reuse/recycling of EU Directive 2018/851 [2] is unwanted because backfilling not only is a form of downcycling, but also because its definition in Regulation 2150/2002 on waste statistics [42] is somewhat ambiguous. The definition of backfilling states that this operation requires that the secondary raw material is replacing a non-waste material but under some conditions, backfilling may be made on purpose to avoid landfilling and report an artificial recovery operation [8].

On the other hand, reports of landfilling may be biased towards lower reported values since the definition of landfilling in Regulation 2150/2002 on waste statistics [42] excludes temporary storage for later treatment of the CDW, with a reference storage period of no more than 3 years stated. However, this may be difficult to monitor. Also, treated waste after processing into RA, may be stored at CDW facilities indefinitely in what is, in practical terms, a landfilling operation (Figure 5). These definitions imply that the targets of EU Directive 2008/98/EC [1] may be artificially complied. The remarks just stated and differences in reliability of data between countries [8, 33, 43] imply that Figure 4 should be analysed with reservations.

Many of the observations concerning the reliability of data are supported by previous reports on CDW management in the EU [7, 8, 33, 44]. Their validity for the reporting of data in 2018 is supported by Figure 6, which shows that the ratio of reported CDW management operations has been stable over time.

Figure 5. Treated waste processed into recycled aggregates stored at a CDW management facility indefinitely

Figure 6. Treatment of CDW in the EU-27 over time. Source: EUROSTAT [41]

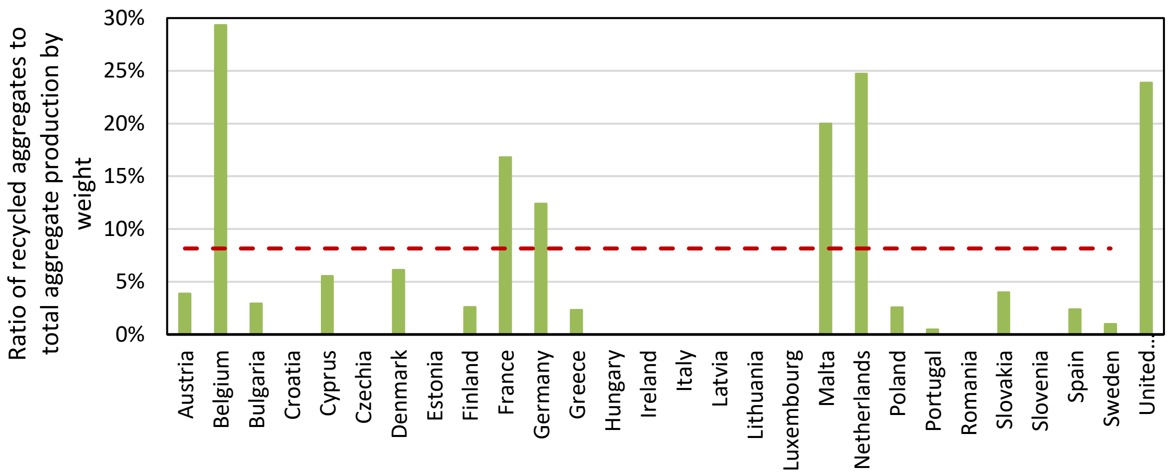


This analysis shows that most Member States formally comply with the 70% target of CDW reuse, recycling and other recovery of EU Directive 2008/98/EC [1] but there is significant margin of improvement in the valorisation of CDW, namely in what concerns avoiding downcycling. Furthermore, due to misreporting (e.g. a significant part of backfilling being reported as other types of treatment), the most effective measure to promote and foster recycling of CDW is to regulate and to guarantee the market for RA, so that waste management operators will seek to valorise their CDW efficiently.

The mean production of RA in the Member States of the EU-27 in the year of 2019 is of 8.2% of all aggregates produced [9]. There is very large variability between countries, as understood from Figure 7, which shows the production of RA in the EU-27 + the United Kingdom.

Differences between countries are caused by several reasons [7, 33, 34, 45], such as availability scarcity of primary raw materials, policy towards CDW valorisation, economic context, lack of adequate facilities for the production of RA, and construction tradition. The relative cost of RA in comparison to NA has been stated as a determining factor for the market uptake of RA [38]. As expected, Belgium and the Netherlands have high relative productions of RA due to scarce access to mineral reserves, while those with abundant and well-dispersed reserves of NA have small relative production of RA (e.g. Portugal).

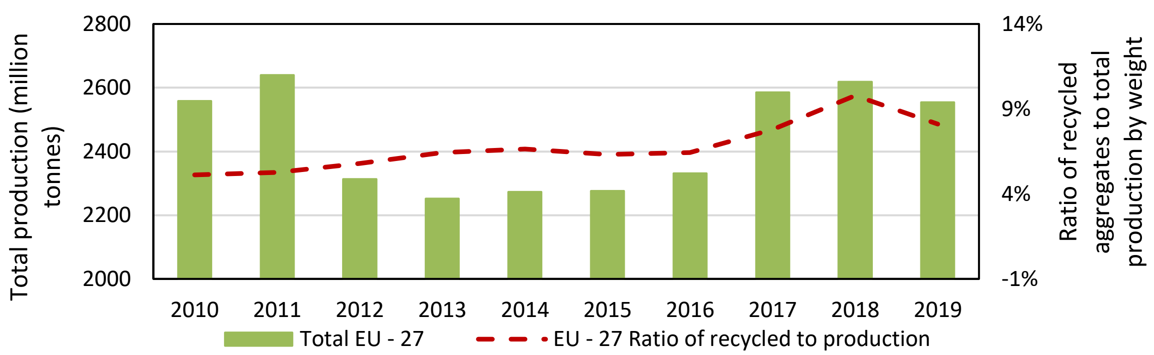
Figure 7. Ratio of reported recycled aggregates to total reported aggregate production in 2019. Source: Annual reviews of UEPG



Surprisingly, some countries reported to UEPG no production of RA (e.g. Italy). The most reasonable explanation for these data is underreporting of RA production to the UEPG. This means that the actual production of RA could be larger than that presented in Figure 7. In [29] specific mention to unreliable Italian data on CDW generation and to the use of RA in road construction is made.

The large variability of RA relative production between Member States shows that obstacles for RA use are more related to regional context (e.g. availability and cost of NA and limitations on landfilling) rather than technical issues. This idea is backed by Figure 8, which shows that the production share of RA is increasing over time and by interviews to industrial agents presented in [29].

Figure 8. Ratio of recycled aggregates to total aggregate production over time of EU-27. Source: Annual reports of UEPG



The increase of the share of RA over time is encouraging. However, it must be emphasized that this figure does not discriminate between end uses of the recycled CDW and that most RA are used in less demanding applications, including backfilling and road construction, which is a low-value use of RA and is expected to decrease in the upcoming years [33, 40]. Furthermore, low value applications decrease the profit margin of RA producers, leading CDW management units towards more landfilling and backfilling of CDW.

Higher-end uses for RA are needed and the production of RA concrete is the one with most potential for the uptake of a substantial amount of the RA produced (that is, of the CDW generated) yearly:

- RECYBETON [20] estimated, under optimistic assumptions, that if all concrete waste was recovered as RA for the production of concrete, RA would take up only 20% of all aggregates needed for the production of concrete;
- A CEMBUREAU report on circular economy [46] argues that RA produced from concrete waste could only meet 10% of the demand of aggregates for the construction industry - this implies that out of the total amount of CDW produced (838.9 million tonnes including soils in 2018), roughly 30% could have been used as RA, greatly reducing landfilling. This is a considerable contribution, especially when accounting for the fact that soil waste is in the region of 60% of all CDW produced.

These observations show that partial incorporation ratios of RA would result in a very meaningful reduction of landfilling and backfilling, while not threatening the industry of aggregates for construction.

Box 2. Appraisal of CDW management and potential for recycled aggregates in the European Union

Current status in numbers:

- Generation of construction and demolition waste in the EU: 1.9 tonne/capita every year, which correspond to 730 kg of mineral waste/capita every year.
- Mineral waste can be recycled as aggregates for the construction industry.
- The industry of construction aggregates produces 5.9 tonne/capita per year in the European Union and the share of recycled aggregates in the European Union is of 8.2% with large variability between countries.

Compliance with the 70% target of EU Directive 2008/98/EC for reuse/recycling:

- Most Member States (25 out of 27) comply with the target of EU Directive 2008/98/EC.
- The target is met with overuse of backfilling, instead of recycling.
- Most recycling consists in recycled aggregates used for low-value applications (e.g. road construction)

Statistics are not consistent between Member states and there are concerns of the quality of data:

- Reported data on CDW generation and treatment: inexplicable variations between Member States and this agrees with previous statements of unreliable data – e.g. the Deloitte report to DG ENV.
- Confidential data from some countries (AU, CZ and DE): limits traceability, analysis and validation
- UEPG annual review: Italy does not produce recycled aggregates.
- Inconsistency of classifications between different EU directives/regulations
- Inert fraction of CDW in Finland reported as used in energetic recoveries.
- Deloitte report: soil waste included in waste treatment statistics of some Member States
- Removal of countries with poor plausibility of data: recycling + backfilling ratio of Member States varies between 61% and 97%, with wide observed variability.

How to improve the valorisation of CDW in a context that is difficult to monitor?

- By creating a market for recycled aggregates that does not promote low-added value applications (backfilling and road construction)
- Using recycled aggregates in concrete is a viable option with higher technical (and economic) value; while poorer fractions can be used for lower-grade applications (substrates).

3 State-of-the-art on recycled aggregate concrete

3.1 Processing of CDW into recycled aggregates

Ideally, RA for concrete production should be produced from concrete waste only. However, Figure 9 shows that CDW is composed of different types of waste, is highly heterogeneous and may arrive at the CDW plant with different degrees of contamination with unintended materials. Therefore, the production of RA requires that preliminary sorting operations are carried out at the construction site and at a CDW management unit to ensure that only adequate CDW is used to produce the RA. CDW that is not used for the production of RA is either landfilled or used for types of recovery that are outside the scope of the report - e.g. the energy recovery of wood waste.

Figure 9. Construction and demolition waste before sorting at the plant.

Highly contaminated CDW | Mixed CDW | Mostly concrete waste

The basic concepts for the valorisation of CDW into RA are:

- RA produced with higher content of concrete and stone waste have better properties than those made with other materials.
- Contaminants such as clay- and gypsum-like materials, asbestos, glass, wood and plastic should be present only in very small amounts, especially if the RA are intended for bounded uses (namely, for use in concrete).
- The content of metals should also be small and this is usually achieved because the magnetism of most ferrous metals facilitates sorting and because the recovery of metals has higher commercial value.
- CDW of small size is composed of soils and other unintended materials. This happens because, during demolition, weaker particles fragment more easily than stronger ones.
- The production of RA requires that CDW be fragmented into smaller sizes and this is met through crushing.
- Sieves are needed both to remove unintended small size CDW in the initial crushing process and to ensure that the RA are produced with uniform and known grading.
- As in the case of CDW, finer fractions of RA have more impurities than the coarse fractions. When CDW is crushed, its weakest constituents tend to fragment to smaller size than their stronger ones.
- Ideally, RA should be washed to remove impurities and decrease contamination with chemical agents (e.g. washing reduces the chloride content of RA). However, washing RA requires investment and poses technical challenges in the treatment of the washing water [20] because of variability in the content and composition of soils and other impurities present in the aggregates.

Equipment commonly used in the production of RA is presented in Figure 10. Most equipment and processes are common to other activities of the construction sector, such as demolitions or the production of NA.

Figure 10. Production stages of recycled aggregates

Fragmentation of a large reinforced concrete element

Reinforcement steel removed from concrete for recycling

Stockpile of mixed CDW for processing into RA

Removed materials from mixed CDW (preliminary sorting)

Jaw crusher with preliminary screen for removal of smaller particles

Trommel for size classification of RA for road construction and other unbound uses

Sieve for size classification

Manual sorting of recycled aggregates

Light materials removed by air sifter

An example of a conventional process for the production of RA is presented next:

- CDW is preliminarily sorted and fragmented at the construction site using conventional equipment and is then sent to a CDW management plant, or treated on-site.
- The management plant (or the on-site CDW treatment unit) receives and stores the CDW accordingly to composition (e.g. unsorted/mixed CDW, concrete waste, ceramics, plastics, wood, metals, and asbestos).
- The CDW intended for the production of RA, which is either composed of concrete waste or of mixed CDW after removal of contaminants (therefore, composed mostly of concrete and masonry waste), is sent to the production line.
- At entry of the production line, preliminary screening by size removes soils and other smaller elements and magnetic separators are used to remove metals.
- During the remaining production process, the CDW is crushed, sieved, undergoes additional magnetic separation stages and lightweight materials (such as paper and plastics) are removed, typically with air sifters. Manual separation is usually carried out to remove other contaminants, such as wood and glass.
- A final sieving stage is carried out and RA are sent to stockpiles ready for sale and in conformity with a declared grading. Some types of RA (e.g. those intended for backfilling) may not be sieved.
- Preferably, the storage of RA should be sheltered to minimize their water content.

Figure 10 and the description provided in this section assume that the CDW management unit has a fixed location. Mobile plants may also be used. Mobile plants are temporarily installed in the construction and/or demolition site and are less equipped: usually only a single crusher and single sieving equipment are used and the sorting of mobile plants is not as capable as that of stationary plants [47]. However, since mobile plants process waste coming from a single site at a time, the quality of RA may be controlled better [48] and high-quality RA may be produced. An example of such case is whenever a mobile plant produces RA at the demolition site of a large concrete infrastructure. An advantage of mobile plants in comparison to stationary ones is that the cost and environmental impacts of the transport of CDW to the waste treatment facility is avoided. The environmental impacts and cost of the production of RA also depend on the type of installation: mobile installations typically consume diesel, while fixed installations are electrified (Section 3.3.2 deals with this topic).

Selective demolition may also be carried out. Since selective demolition ensures that waste is well-separated by composition before processing, high quality RA and better recovery ratios of CDW are achieved. However, due to the labour involved in selective demolition activities and to considerable logistical demands, selective demolition is costly and is not common at the moment [49]. Selective demolition is expected to become more popular in the future, particularly in countries that already recover high amount of CDW, not only because of the aforementioned better recovery ratios achieved with selective demolition, but also due to improved efficiency in the processing of CDW into RA and because with selective demolition certain materials (e.g. concrete elements) may be processed into RA without being classified as waste, simplifying the recovery operation from a legislative standpoint.

The main types of RA are the following:

- All-in RA, whose grading distribution covers a broad range of particle sizes: from fine particles (0 mm) to coarse ones (e.g. 32 mm). The main applications of this type of RA are road construction, backfilling and other unbound uses.
- Coarse RA of very large particle size, which are mostly intended for backfilling and other unbound uses.
- Coarse RA of conventional size (up to 20 - 25 mm), which may be used for the production of concrete, especially if they are produced from concrete waste.
- Fine RA, which are composed of particles of size up to 4 mm and typically are either used in small quantities in concrete as a partial replacement of fine NA, or in road construction [50]. Fine RA are not as suitable for the production of concrete as coarse RA due to their worse composition [51, 52]. Fine RA are prone to a larger content of impurities and, even if only concrete waste is used, the finer particles will be mostly composed of attached mortar instead of stone [53]. An alternative use for fine RA is the partial replacement of silica and limestone in the production of clinker [50], which is the main intermediate product of cement.

Different RA have different quality and different potential for use. This must be considered when defining end uses for the RA and a clear definition of what CDW and RA are more appropriate for each type of application is lacking. Without proper guidelines, since the technical demands of aggregates for road construction, backfilling and other unbound uses are less than those of aggregates to be intended for concrete, the producers of RA and clients have less reservations concerning the use of RA in these lower added-value applications than in what concerns the incorporation of RA in concrete.

Because of the public and industry perception towards RA applications, RA certified for use in concrete (EN12620 [21]) are not available in many Member States, while those certified for road construction (EN13242 [54]) are commonly found. The absence of RA certified for EN12620 [21] is an obstacle to the market uptake of RAC.

3.2 Types of recycled aggregates

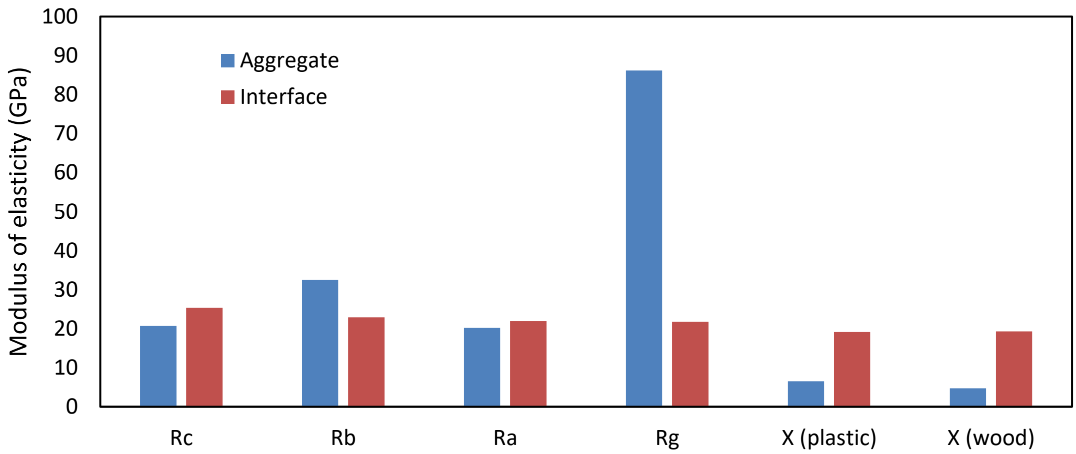
RA have worse properties than NA. This is a natural consequence of the characteristics of CDW, which is composed of materials that are more porous, rougher and weaker than stone. The European Standard EN 933-11 [55] classifies the composition of an RA in terms of the mass proportion of the following constituents:

- Ru - unbound stone, which corresponds to an NA.
- Rc - concrete and mortar.
- Rb - clay masonry, calcium-silicate masonry, aerated non-floating concrete.
- Ra - bituminous materials.
- Rg – glass.
- X - other materials (e.g. clay, soils, metals, non-floating wood, plastic, gypsum-based and rubber).

— FL - floating materials.

As a first approximation, the stiffer an aggregate, the better its quality, since the modulus of elasticity (the property used to evaluate the stiffness of an engineering material) is related to its porosity and strength. Figure 11 shows the modulus of elasticity of different constituents of an RA, obtained through nanoindentation probing of individual particles within a concrete sample [56]. The modulus of elasticity of the interface between aggregates and binder paste is also shown since this is often the weakest phase in concrete and a limiting factor of the strength of concrete [57, 58]. Figure 11 shows that the quality of RA varies largely between constituents and that constituents of type X (plastic and wood) should be avoided due to (among other reasons) low stiffness, which suggests concrete with poor mechanical performance and high porosity.

Figure 11. Modulus of elasticity of different constituents of recycled aggregates. Figure produced from the data of [56]



Constituents of type R_g are stiff but not adequate for concrete because glass particles are usually elongated, flaky and have very smooth surfaces. This has detrimental consequences on the workability of concrete and on the bond between aggregates and cementitious paste. Similar reasoning holds for R_b, which are not as inadequate for concrete as R_g, but are usually flaky, weak and, in many cases, porous. Furthermore, their properties are highly dependent on the specific type of masonry waste as understood in an extensive experimental programme that found that the properties of some types of brick RA were very unsuitable for the production of concrete [47].

Mechanical and shape issues are not the only reason to avoid certain constituents in RA. For instance, gypsum is present in the majority of buildings (e.g. in plaster and drywalls) and has severe detrimental effects if present in non-negligible amounts in RA used in concrete. If an RA is to be used in concrete, gypsum must be removed from the CDW before processing to the maximum extent possible to avoid the expansion and spalling of concrete due to sulphate attacks [59].

The results of Figure 11 and those of slow particle compression tests [60] agree with the idea that RA particles composed of concrete waste are those with the best mechanical properties. Furthermore, the higher the density and the smaller the abrasion mass loss and the 24-hour water absorption, the more suited an aggregates is for concrete production. Table 2 reinforces the idea that RA produced from concrete waste are better than those produced from other CDW. This table is based on a meta-analysis [32] and shows the density, water absorption and Los Angeles abrasion mass loss of the two main types of RA: concrete waste and mixed CDW after sorting and processing at a CDW treatment facility (i.e. RA s composed almost exclusively of R_c, R_u and R_b).

The table shows that fine aggregates have worse properties than coarse ones, especially in the case of concrete waste. This happens because, when concrete waste is crushed, its weakest phase (mortar) will be more present in the smaller particle sizes than in the larger ones [61, 62]. Because of the worse properties of fine RA in comparison to coarse RA, researchers, standards and recommendations favour coarse RA instead of fine RA in concrete [22, 51, 63, 64]. In many countries, the use of fine RA in concrete is forbidden [65].

Due to the better properties of coarse RA produced from concrete waste, this type of RA is that with greater potential for higher added value recovery: the production of RAC. Furthermore, concrete waste is the largest type of CDW generated, with reports ranging from 50% to 70% of all CDW [66, 67]. Out of the total amount of concrete waste generated, the potential amount of coarse RA produced by conventional crushing methods is estimated as 60% [12, 54, 55]. Advanced crushing methods will typically result in higher quality RA but in a lower amount of coarse RA produced, as will be discussed in section 3.3.1.

Table 2. Properties of recycled aggregates by type and size. Source: [32]

Type of CDW		Concrete waste (mainly Rc+Ru)		Sorted CDW (almost exclusively Rc+Ru+Rb)	
Aggregate size		Fine	Coarse	Fine	Coarse
Oven-dried density (kg/m^3)	Sample size	46	292	37	61
	Mean result	2065	2327	2078	2167
Saturated-surface-dry density (kg/m^3)	Sample size	45	288	37	61
	Mean result	2300	2442	2292	2332
24-hour water absorption	Sample size	43	298	36	61
	Mean result	9.5%	4.9%	9.3%	7.2%
Los Angeles abrasion mass loss	Sample size	-	78	-	48
	Mean result	-	32.5	-	36.5

Coarse Recycled Concrete Aggregates (CRCA) is not only the most suited type of RA for the production of concrete, but also the most abundant portion of treated CDW. This means that the reuse/recovery target of EU Directive 2008/98/EC is being met through significant downcycling (road construction and backfilling) of CRCA [1, 40].

The main requirement to ensure good-quality RA is that unintended constituents be removed and that RA are produced with as much concrete waste as possible. This is achieved with greater success if the preliminary separation is thorough [43]. CDW management plants encourage CDW to arrive at their facilities as segregated as possible by applying different charges for mixed and sorted waste.

Even if good-enough quality RA are produced, there are three fundamental fact that prevent the majority of RA from being used as aggregates for concrete:

- The incorporation of RA may not be justifiable due to environmental and technical issues, since under some circumstances, the production of RAC may be associated with larger environmental impacts and cost than the production of NAC (section 3.3.5 deals with this issue).
- The production of RA for road construction and backfilling has smaller environmental impact than the production of RA for concrete, because of less demanding technical requirements. This means that less sieving and sorting stages are needed to produce RA for less demanding applications than those needed for the production of RA that are fit for concrete.
- The production of high-quality RA cannot be made without producing other RA (e.g. fine RA and RA produced with significant portions of masonry waste) since the composition and processing of CDW mean that such materials will always be generated.

The last consideration is a particularly relevant aspect, especially when combined with the fact that the total demand of aggregates for the construction sector is very large and, even if all CDW were recovered as RA, a significant amount of NA would still be required. This means that fully circular economy models for the construction sector require that each aggregate is directed towards its most rational application:

- Higher quality aggregates should be directed towards bounded uses in concrete and other cementitious products. High quality aggregates include RA produced with large content of stone and concrete waste and most NA produced in quarries and pits.
- Poorer quality aggregates should be used in backfilling and unbound applications. This includes RA produced with large amount of ceramic waste and other unintended constituents, as well as porous NA and/or NA with large content of clay.

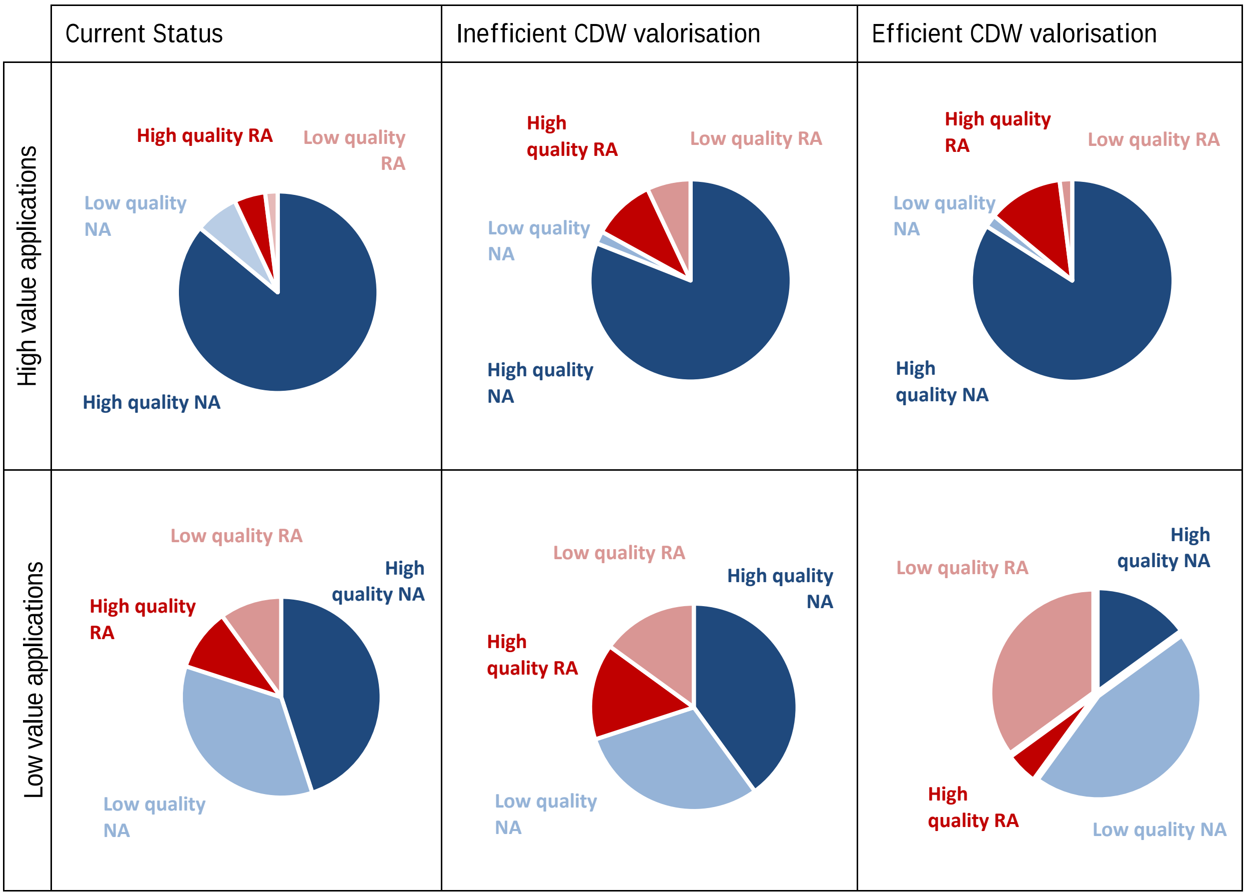
If measures to promote RAC do not take into account these remarks, the outcome may be an inefficient valorisation of CDW that will lead to low quality products and/or high environmental impacts.

For instance, the definition of an arbitrary target for incorporation of RA in concrete may result in concrete producers having to resort to unreasonable options, such as high-quality NA being directed towards less demanding uses to make room for RA in demanding applications and the procurement of RA from far away, when a local source of NA is available, at environmental and economic cost due to increased transport distance.

The selection of aggregates for their most efficient application is the best way to ensure that CDW is properly recovered, minimizing downcycling without leading to inefficient options. Figure 12 illustrates this concept.

In the figure, hypothetical ratios of the relative use of four types of aggregate are compared for three scenarios: i) the current status; ii) a scenario of inefficient valorisation of CDW by increasing the use of RA without taking into account the required quality of the final product; and iii) a scenario for efficient valorisation of CDW. In the latter scenario, lower quality aggregates are used in lower value applications, while high quality aggregates are saved for higher value applications.

Figure 12. Simplified scenarios of the consequences on the applications of natural and recycled aggregates of scenarios for efficient and inefficient valorisation of CDW. The figures are produced with illustrative data



The key underlying ideas of Figure 12 are that:

- Aggregates should be used in agreement with their quality.
- Some RA are currently downcycled at environmental and economic cost and have potential for use in concrete.
- Strategies for the efficient valorisation of CDW should direct RA towards adequate applications without directing NA towards lower value applications.
- Similarly, high quality RA should be used in high quality applications and the demand of aggregates for lower value applications should be met with RA and lower quality NA.

3.3 Recycled aggregate concrete

3.3.1 Recycled aggregates for concrete

This report concerns the use of high quality coarse RA (mostly CRCA) as recycled aggregates for concrete. CRCA constitute the main part of CDW, they are adequate for use in concrete and their use in backfilling operations and in road construction is downcycling and should be avoided.

In order for an RA to be used in concrete, it must comply with requirements that are analogue to those of NA. The following is a qualitative overview of the conditions of standards and recommendations for an RA to be adequate for concrete [34]:

— The aggregate must have adequate strength and stiffness and water absorption must not be too large.

  Aggregates account for about 70% of the volume of the concrete mix [68]. This means that several physical properties of an aggregate will influence the physical properties of concrete relevantly.

  Aggregates with high water absorption may compromise the durability of concrete (due to faster ingress of deleterious substances) and may also pose challenges in the fresh-state behaviour of concrete for ready-mixed producers (see Section 3.3.3). Water absorption is also an indirect measure of the porosity and strength of aggregates and, since the constituents of RA are more porous than stone, RA have higher water absorption than NA.

  The strength of a coarse aggregate is typically evaluated through its Los Angeles coefficient and Annex E of EN206, the European Standard for the specification of concrete, recommends the same coefficient for NA and CRA [22]. Nevertheless, a lower maximum Los Angeles coefficient for CRA has been argued for [24], as a means to control the detrimental effect of the incorporation of CRA on the mechanical properties of concrete.

  Aggregates must comply with minimum demands for volume stability since concrete tends to reduce its length after casting (this phenomenon is known as shrinkage). Since aggregates compose must of the volume of concrete, they are expected to restrict the volumetric reduction caused by shrinkage to avoid cracking. The volumetric stability of an aggregate is checked in countries that follow the EN standards according to EN1367-4 [44]. The same requirement is imposed on RA and NA. Usually RA comply with this requirement, but the requirement may not be met if the content of unintended constituents is large (namely, of constituents of type X - Figure 11.

— The shape of the aggregate should be as round as possible.

  The recommendations for shape are the same for NA and RA [22] and usually they are comfortably met. Still, RA are usually more elongated and flakier than NA because of the shape of constituents R_b, X (glass and metals) and due to the crushing equipment and small number of crushing stages usually used in CDW processing units. The shape of RA may compromise the economic and sustainability cost of concrete. Elongated and flaky aggregates have larger water demand for the same fresh concrete workability, so the cement content of RAC is usually larger than that of NAC [68]. Also, flaky aggregates tend to break prematurely due to concentration of stresses and this decreases the strength of concrete [68].

— An aggregate must have well-controlled and known grading.

  Concrete producers resort to different size fractions of aggregates and combine them to achieve a workable concrete that has small voids content to ensure adequate durability, stiffness and strength. The only noteworthy difference in grading requirement between RA and NA is that the maximum allowed fines content of RA of most standards is smaller than that of NA. This is due to the smallest fractions of RA being of poor quality, including clay particles and other soils that have relevant detrimental effect on the properties of concrete.

— The chemical contamination of an aggregate should be checked and comply with requirements.

  RA may be contaminated with different types of chemical agents and organic matter. This is especially true when the origin of CDW is not well-controlled and it is not that segregated by type of CDW (a frequent case in stationary CDW treatment plants). The same concerns concerning NA apply, such as the presence of organic matter that affects setting and hardening, the content of chlorides and of acid-soluble sulphates, and the potential for alkali-silica reactivity. Alkali-silica reactivity may be problematic whenever sorting does not remove materials rich in sulphates and because the mortar of R_c constituents is potentially rich in alkalis. However, a comprehensive experimental programme [69] argued that RAC is not prone to alkali silica reactions. Alkali-silica reactivity has been suggested to be a specific concern only if RA are produced with larger-than-usual amounts of Ra waste [24, 69].

Some regions impose leaching requirements on RA, with publications [47] arguing that the main concern is the release of sodium, potassium and chloride ions. Nonetheless, research on RA produced from concrete waste argues that the potential for leaching is low [20].

This list is not quantitative since exact figures depend on the standards in place in the region of use and on particular concerns of clients (e.g. the case of chloride content). Furthermore, most documents also state that, even if an RA does not conform to their requirements, aggregates may still be used as long as experiments show that concrete will behave adequately.

The requirements presented in this section are met in most circumstances in which CDW is mainly composed of concrete waste. This is true because most concerns related to the quality of RA are directly related to their composition - e.g. sulphates depend largely on the presence of gypsum drywall and plaster waste and organic matter depends largely on soils. Furthermore, if the amount of concrete waste is maximized, the shape, stiffness and strength of RA are better and the water absorption is smaller. Therefore, standards define classes of RA based on their constituents and restrict the use of RA in concrete to the classes with large contents of R_c+R_u and small to zero content of other constituents.(e.g. the two classes recommended in Annex E of EN206 [22] – see Table 3). The approach of other standards and national documents is similar.

Since most CDW producers are currently producing RA for backfilling and road construction and other uses of EN13242 [54], their production of RA is made with mixed CDW and may not conform with the requirements presented in Table 3 since concerns for the removal of unintended materials (mainly steel, plastic and wood) and for the minimum content of R_c+R_u are not as stringent as those for the use of RA in concrete. This is understood by the typical composition of coarse RA produced from mixed CDW [20–22]:

- R_c+R_u are between 65% to 85% of the total mass of the RA.
- R_b is in the region of 10% to 35%.
- R_g is between 0% and 2%.
- R_a is in the region of 0% and 2% but may be of up to 10%.
- The content of X is below 2%.

On the other hand, the composition of industrial RA produced by processing concrete waste in typical environments of CDW plants conforms with RA of Type A or Type B of Table 3, with over 70% (most usually, over 90%) of constituents R_c + R_u and the remaining composition being mostly R_b [20, 70].

This means that RA for concrete should preferably be produced from concrete waste, while other RA of lower quality applications should be produced from mixed CDW (see Figure 12). Another argument towards the preference of producing RAC using RA from concrete waste only is the variability of CDW and RA [71], which is especially relevant in the case of stationary CDW plants. The quality of RA depends on the composition of CDW and, if only concrete is used, the effect of changes in composition is minimized. Due to these remarks, the regulations of the Member States typically only allow that RA produced from (mostly) concrete waste may be used in structural concrete. Nonetheless, as will be presented in Section 4,there is a very large heterogeneity between regulations, concerning the maximum strength and durability restrictions allowed for RAC, and concerning the maximum incorporation ratio of RA in the concrete composition.

Table 3. Classes of RA defined in Annex E of EN206 [22]. Percentages by total weight of the RA.

Class of RA	Type A	Type B
Minimum content of R_c	90%	50%
Minimum content of R_c+R_u	95%	70%
Maximum content of R_b	10%	30%
Maximum content of R_a	1%	5%
Maximum content of X+R_g	1%	2%

Maximum content of floating materials	2%	2%

Advanced production processes may be used to produce RA with better properties and this has the advantage that such RA are more easily used as a secondary raw material for concrete. Examples of such processes are:

— Electrodynamic fragmentation, in which concrete waste is immersed in water and pulse waves separate the stone fraction of concrete from its attached mortar [72].

— Infrared sorting technologies, which replace manual labour in the screening process of RA [73].

— Advanced mechanical processes and heating systems [74] or advanced mechanical processes that combine grinding with a crushing force that is adapted to a magnitude between the crushing strength of the aggregates and the strength of the cement paste, resulting in the separation of aggregates from the cementitious paste [75].

— Density separation using advanced equipment, such as water or air jigs [76, 77].

— Post-production beneficiation methods, in which RA undergo additional stages that improve their properties, such as forced carbonation [78], wrapping [79] and acid treatment [80].

However, advanced production processes are uncommon and most of them are studied only at the laboratory scale or on pilot applications. The specificity of equipment, investment, environmental impacts and costs during operation, the need for processes to be scalable and the waste generated to produce high-quality RA (both treatment water and the worse quality fractions that are removed to ensure the material has high quality) prevent the current uptake of these high-quality RA production processes [20]. In countries where RA are already used and/or where access to NA is scarce and costly, advanced production processes of RA may become a relevant source of aggregates in the future.

3.3.2 Sustainability of recycled aggregates

This section compares the environmental impacts of NA and RA and covers the concept of life cycle assessment (LCA) and the specificities that make the outcomes of an LCA regional-dependent. This section contextualizes Section 3.3.5, which is presented after the influence of RA on RAC is understood, and assesses the sustainability of RAC. This is relevant because the outcome of a comparison of environmental impacts of NA and RA does not translate directly into the outcome of a comparison between the environmental impact of NAC and RAC. Despite aggregates constituting approximately 70% of the volume of concrete, changes to concrete mix design due to the incorporation of RA [15] may result in RAC having larger environmental impacts even when RA have smaller impacts than NA.

The aggregates industry is the largest non-energy extractive industry in the World [9] and this is due to the large demand of aggregates. Furthermore, aggregates are low value bulky materials whose transport is a non-negligible part of the cost and environmental impacts of the procurement of RA [81]. Usually, the procurement of RA has smaller environmental impacts than the procurement of NA. This occurs for two reasons [13]:

— The environmental impacts of the production of RA are usually smaller than those of crushed NA, since the production process is simpler. RA are fragmented at the demolition site (Figure 11) and then sent for preliminary sieving and crushing, while the production of crushed NA usually requires drilling, explosives and the transport by trucks of fragmented stone to the production line [82].

— The transport distance of RA is typically smaller than that of NA and this decreases the environmental impact of the procurement of RA. Quarries and aggregate pits are usually away from urban centres [81] due to safety concerns and the priority given to investment in the building stock and public spaces [83], while CDW plants are located near urban centres since this is where CDW is generated [81].

The smaller environmental impacts of the production of RA in comparison to those of NA are understood in an study [84] that compared the energy consumption of fine and coarse NA with those of fine and coarse RA produced from mixed CDW using site-specific measurements. In this study, the production of fine RA required 10% less energy than that of fine NA, while the difference for coarse aggregates was of 18%. If the energy used in the sorting of CDW is not included in the production of RA, fine RA require 56% less energy than fine NA and coarse RA require 65% less energy than the production of coarse NA. In the case of [85], the production of RA required 85% less energy than that of NA, with a 7 times lower carbon footprint (15.5 kg of carbon dioxide per tonne of RA produced *versus* 103 kg in the case of NA). The LCA carried out by [85] concerned all-in aggregates with grading 0/30 and the RA were produced from mixed CDW, while the NA was crushed stone produced in a quarry.

The comparison of the findings of the two authors shows that the results of an LCA are site specific. Nonetheless, the comparison shows that the production of RA is typically associated with less energy consumption than the production of NA and that sorting accounts for more than 50% of the total energy consumption of RA. Most processes included in the production of RA (e.g. the fragmentation of large blocks with mechanical equipment, the removal of reinforcement bars from concrete and the sorting of wood, plastics and other materials) are necessarily carried out due to economic, legal and practical reasons of waste management, even when RA are not produced. Therefore, the net reduction of carbon dioxide emissions that results from replacing NA with RA are even larger than initially understood.

The sustainability of NA and RA is typically compared with LCA. However, even though LCA is a standardized procedure [86-88], the LCA developer may take different, legitimate, options that will influence the comparison between the environmental impacts of an NA and those of an RA. This obstacle for reliable and comparable LCA that is not exclusive to the construction sector and is being tackled by the European Commission. To specifically improve the reliability, reproducibility, quality and communication of LCA, significant efforts are ongoing, including the launching of the Product Environmental Footprint. Commission Recommendation (EU) 2021/2279 provides additional context [89].

“Cradle to gate” boundaries include all activities necessary to the production of an aggregate, starting with the extraction/procurement of the necessary raw materials (stone in the case of NA; waste in the case of RA). For NA, these boundaries start at the extraction of NA and their definition is straightforward.

The “cradle to gate” boundaries of RA are defined with different criteria by different authors, despite the publication of guidelines that define boundaries for LCA of RA, including those developed the JRC. Most authors model RA considering that their production process starts when the CDW is transported from the construction/demolition site to the CDW management plant, but some authors only include the activities that start at the CDW treatment plant [85] (namely, treatment and transport for the concrete producer). The latter option considers that CDW would be transported to the CDW management plant anyway (therefore, the “pollute pays principle” dictates that the production of RA should not be burdened with the transport of CDW to the CDW management plant). Of the different criteria of an LCA, most are either consensual or do not affect the comparison of the LCA results to a large extent. However, the boundaries of the system may relevantly influence the LCA, namely in what concerns the processes included and the transport distances to the ready-mixed plant [13, 81].

An overview of comparative “cradle to gate” LCA concerning NA and RA is presented based on [91], in which 28 aggregates coming from 8 scientific papers with site-specific data are used to understand the environmental benefits of replacing NA and RA. Thirteen environmental product declarations were also used for this purpose.

The majority of the NA of both types of data is crushed limestone, which is the most common type of aggregate available worldwide. In this figure and elsewhere, rolled aggregates are aggregates that are extracted from riverbeds and pits. Their environmental impacts differ from those of NA since their extraction is solely made with mechanical equipment without need for drilling and explosives, transport distances inside the production centre are usually smaller than in quarries, and a significant portion of rolled aggregates already has adequate size and does not require crushing. Figure 13 summarizes the comparison presented in [91].

Box 3. Life cycle assessment criteria

The development of a life cycle assessment requires several criteria that, amongst others, include the following:

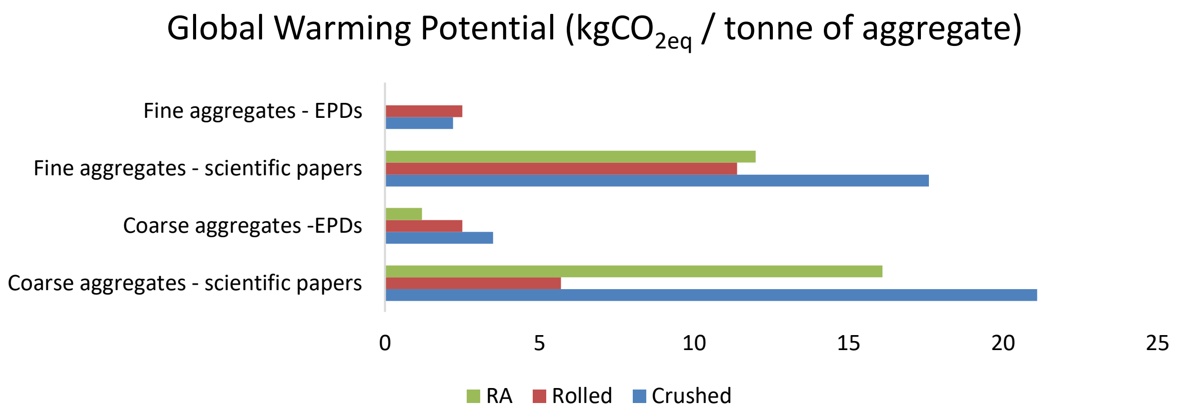
- The functional unit, which is the reference unit used for the comparison. In the case of aggregates, the functional unit is consensually defined as 1 tonne of aggregates. This means that the environmental impacts of the production of 1 tonne of natural aggregates are compared with those of the production of 1 tonne of recycled aggregates. Usually, the functional unit also includes the grading of the aggregates, so that the comparison is made for aggregates of the same size (e.g. the production 1 tonne of aggregates of particle size 11/16).

- The methodology for the calculation of the environmental impacts of each process and the environmental impact indicators that are included in the analysis. Different methodologies may be used. One of the most commonly-used is the CML Baseline, which was developed by the Institute of Environmental Sciences of the Faculty of Science of Leiden University (CML) and is described in [90]. The recent Product Environmental Footprint, released by the European Commission [89], is another example. These methods method comprise several impact categories that include carbon dioxide emissions, emissions that harm the atmospheric ozone layer, and the acidification of soils and water. However, from a regulatory point of view, construction products are regulated by the standard EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products [88].

- The boundaries of the system, which are the processes included in the life cycle assessment. For both natural and recycled aggregates, the common option is that the life cycle assessment is carried from “cradle to gate”. In the case of the life cycle assessments on natural aggregates, this boundary is well-defined and unambiguous. For instance, for the production of natural aggregates in a quarry, a cradle to gate boundary includes the extraction of fragmented stone, its transport within the production site, and the processing (sieving, crushing and washing) of the fragmented stone into natural aggregates. The modelling of the impacts of recycled aggregates usually includes the transport of CDW to the CDW plant, all operations carried out at the plant (e.g. sorting, sieving, crushing, and transport inside the plant) and the landfilling of unintended constituents that are removed from the CDW. However, these boundaries are not consensual. In the case of both natural and recycled aggregates, the transport of the aggregate to the ready-mixed plant may also be considered.

These criteria were illustrated for life cycle assessments on the production of aggregates. Section 3.3.5 deals with life cycle assessments for concrete.

Figure 13. Global warming potential of different types of aggregates determined by meta-analysis of several data sources. Source: [91]



<u>The findings are not consistent (e.g. there is a large difference between impacts stated in EPDs and those of scientific papers) and trends and findings are not consistent across all vectors of analysis</u>. Regional specificities alone do not explain the contradictory findings between EPDs and scientific papers. However, the main trend observed is that the carbon dioxide emissions associated with RA are consistently below those of crushed NA (the GWP of RA is between 34% and 76% of that of crushed NA, which are the main type of NA produced [9]).

The environmental comparison made in this section is in terms of the Global Warming Potential (GWP), but analogue findings to those of GWP are found for other indicators. As an example, in [84] it was found that coarse RA are associated with 65% less GWP and 58% less non-renewable energy consumption in comparison to coarse NA.

Transport distance and type are crucial in determining the environmental impacts of aggregates. In [13] and for actual locations of industrial facilities in Portugal, it was found that, even though RA produced in quarries have better properties than those produced in CDW plants, increased transport distances may prevent the processing of CDW in quarries. This occurs because the larger transport distance not only leads to greater cost of RA, but also to greater environmental impacts when compared to NA. The importance of transport in determining whether RA are more sustainable than NA is also reported in [92] for site-specific Brazilian data.

<u>The influence of the type of transport is particularly interesting since it allows regional deductions</u>. Transport by ship has smaller environmental impact (and cost) than transport by trucks and this is reflected in the conclusions of comparative LCA. An LCA for a case study in Belgrade and two scenarios is presented in [16]. In both scenarios, NA is river gravel and is transported by ship for 100 km. RA is transported by truck and its transport distance is 15 km in one scenario and 100 km in the other. In the first case, NA have marginally smaller carbon footprint than RA (less than 5%), while for the same transport distance the carbon dioxide emissions associated with the procurement of RA are up to 35% larger than those of NA.

A way to minimize transport distances is to resort to mobile CDW recycling plants. In this case, the plant is transported and installed onsite and the transportation distance from the construction/demolition activity to the CDW plant becomes nil. The environmental benefits of mobile plants were specifically studied in [93]. The authors assumed that the transport of the mobile CDW plant to the demolition site is 30 km and, under comparable conditions for coarse NA, coarse RA produced in a stationary CDW plant and coarse RA produced in a mobile CDW plant, the authors found that coarse NA were associated with smaller environmental impacts in all cases and that the mobile plant reduced the carbon footprint by 16% in comparison to production using a stationary one. This investigation was carried out under atypical conditions that skew the comparison in favour of the coarse NA: 65% of CDW was assumed to result in fine RA and the transport distance of the limestone to the ready-mixed plant was 28 km, while the transport distance of the CDW to the stationary CDW plant was 30 km. Usually, the transport distance of coarse RA is smaller than that of coarse NA. Furthermore, the authors considered that the fine RA generated in the production of RA were waste. A sensitivity analysis found that if the fine RA were used (i.e. if they were assumed as a product and shared part of the environmental impacts of the production of the coarse RA), the environmental impacts of RA were smaller than those of NA.

The potential environmental benefits that derive from using RA instead of NA must be analysed on a case-by-case basis and no general potential saving of carbon dioxide emissions can be stated. As shown in this section, RA may even be associated with larger environmental footprint in specific circumstances. The same reasoning is valid for the economic cost [13]. Such specificities are also a hindrance for the interpretation of the results of an LCA since some authors do not disclose all relevant data. This is also true when the LCA results of NA are compared. As stated in [82], a major obstacle of such comparison is that crushed (quarries) and rounded (aggregate pits) are not distinguishable in most datasets.

Box 4. Comparison of environmental impacts of natural and recycled aggregates

Main trends and observations:

- Environmental impacts are regionally-dependent.

- The procurement of recycled aggregates is usually associated with lower environmental impacts than the procurement of natural aggregates.

- Comparisons may be skewed based on specificities of the study (e.g. transport distance and mode of natural and recycled aggregates; assumptions on the valorisation of fine recycled aggregates).

- Regional aspects may already hint at conditions for recycled aggregates to be more sustainable than natural aggregates (geology, transport and distance between aggregate pits/quarries and urban centres).

- Recycled aggregates may be the most sustainable option but their market uptake may be compromised due to cost [13].

This section analysed the environmental impacts of RA in terms of carbon dioxide emissions since this is the indicator that is studied the most and with higher societal awareness. Nonetheless, the incorporation of RA has other societal benefits such as the reduction of landfill disposals and the mitigation of the extraction of NA [83, 94]. Section 3.3.6 of this report deals with this topic.

3.3.3 Overview on recycled aggregate concrete

Aggregates usually account for 70% of the volume of concrete [68, 95]. It is only natural that they substantially contribute to the fresh, mechanical and durability behaviour of concrete [68]. RA are rougher and elongated, therefore they have high specific surface and reduce the workability of concrete. The porosity of RA not only results in higher water absorption (with potential reduction of workability over time), but it also means that RA are weaker than NA and may provide alternative transport mechanisms for the ingress of external agents that compromise the durability of concrete.

The extent of the detrimental effects of RA on concrete depends on the quality of RA and on the concrete mix design. As general rules:

- The higher the strength class of concrete, the higher the stresses the aggregates are subjected to. This means that RA have higher detrimental effects on the mechanical properties of high strength range concrete [96].
- The porosity of RA could affect the durability of concrete because it increases the ingress of external agents (e.g. carbon dioxide, acids and chloride ions), but this effect is not relevant for very compact cement mixes since the pores of RA become isolated [97].
- Lower quality RA have larger detrimental effects than high quality ones [52, 98, 99].

Because of these reasons, not only RA must comply with the requirements presented in Section 3.3.1, but standards and national documents that complement EN 206 [22] (the European standard for the specification and performance of concrete) with country-specific regulations recommend that, unless specific testing is carried out, the incorporation of RA is limited to maximum ratios of RA and to maximum strength classes – see Section 4. For now, it is put forward that the strength class is typically limited to the C30/37 or C35/45 strength classes and this agrees with [16], in which it is stated that moderate strength RAC (with compressive strength of up to 35 MPa) can be obtained using RA of moderate quality.

Box 5. Influence of recycled aggregates on the properties of concrete

Assuming that only recycled aggregates comply with the recommended requirements of European standards, the effect of their incorporation on the properties of concrete is:

- Lower compressive strength: typical decreases in the region of 5% to 15% for total incorporation of coarse recycled aggregates [51, 70, 104-106]).

- Tensile strength: a meta-analysis [107] argues that, under normal circumstances, a tensile strength reduction of 15% for full incorporation of coarse recycled aggregates is expected. However, the decrease in tensile strength depends strongly on the quality of the recycled aggregate and on the strength of the recycled aggregate concrete mix [108]. The effect may range from negligible changes to a moderate reduction.

- Modulus of elasticity (stiffness): very significant decrease, of up to 25% for full incorporation of coarse recycled aggregates [99, 109, 110] in comparison to conventional natural aggregate sources (e.g. limestone and quartzitic aggregates). However, recycled aggregate concrete has similar to higher modulus of elasticity when compared to concrete made with sandstone [107].

- Shrinkage and creep (properties that are responsible for long-term deformations and cracking): relevant increase with huge scatter, which is partly explained by test setups [51, 111-114].

- Durability: recycled aggregate concrete has higher permeability and lower resistance to the ingress of external agents, compromising the durability of concrete in the case of concrete produced in demanding environmental exposure environments [97, 115-117].

- Workability (ability to use a fluid concrete mix when casting and compacting in formwork): recycled aggregate concrete either has lower workability or changes to concrete mix design need to be carried out to mitigate this effect.

Notwithstanding successful examples of high-strength RAC [100], the fact is that RAC of higher strength classes should be produced with reservations since, for higher strength concrete, the strength of its aggregates becomes a limiting factor to the mechanical properties of concrete [20]. Therefore, to avoid similar ceiling effects to those observed for lightweight concrete [101], high-performance concrete made with RAC [102] should be restricted to RA of high quality - e.g. RA produced from precast rejects [103]. This means that using NA is a more rational option for this type of application (Figure 12).

Henceforth, it is assumed that RA comply with the requirements valid in the place of use (see Section 3.3.1), namely that they are coarse RA produced mainly from concrete waste and that the strength class of the concrete that will include RA is moderate (up to the C35/45 strength class).

The influence of the RA incorporation ratio on concrete properties is approximately linear [99, 103]. To better understand the influence of RA on concrete, the previous box was presented for full incorporation ratios of RA, even if standards argue in favour of partial incorporation. Out of the detrimental effects of the incorporation of RA on concrete, the increase in creep and the decrease in the modulus of elasticity are especially relevant. Whenever serviceability conditions (namely those regarding deflections) are relevant, higher volumes of RAC will be necessary in comparison to NAC and this has economic and environmental costs [118].

Since concrete is specified in terms of compressive strength and workability, changes to concrete mix design are made so that:

- The effect of the incorporation of RA on slump is offset.
- The RAC mix complies with the specified strength class, which is defined in terms of compressive strength.

<u>The changes to concrete mix design may compromise the sustainability of concrete since these changes usually include the increase of cement content</u> in order to decrease the water/cement ratio of concrete. Additional methods, such as decreasing the water/cement ratio by increasing the content of plasticizer and/or superplasticizer are not carried out as often due to their economic cost, but they are also a feasible way to decrease the detrimental effect of the incorporation of RA on the properties of concrete - for instance, an

internal study of the Joint Research Centre on the use of CRCA in concrete [119] successfully resulted in satisfactory RAC by using a chemical agent that increased the strength of the RAC mixes and maintaining the cement content of RAC equal to that of NAC for 10%, 25% and 50% incorporation ratios of RA.

The common aspect of the different approaches towards offsetting the effects of RA on concrete properties is that the environmental and economic costs of concrete increases and may become larger than those of NAC [15, 20]. To illustrate the changes in concrete mix design, some examples are provided:

— In a simplified LCA model [120], an estimated cement content from 290 kg/m^3 (NAC) to 320 kg/m^3 (RAC) was assumed. This corresponds to a 10% increase of cement, with non-negligible environmental cost.

— Table 4 shows the changes to a ready-mixed composition of C20/25 strength class needed to ensure the same slump and 28-day compressive strength for several incorporation ratios, as presented in [20]. In this table, the compressive strength and modulus of elasticity are also presented.

Table 4. Increases in cement and plasticizer content for different incorporation ratios. Source: [20].

Mix	REF	RAC - 1	RAC - 2	RAC - 3	RAC - 4	RAC - 5
Incorporation of fine recycled aggregate	0%	30%	0%	32%	0%	100%
Incorporation of coarse recycled aggregate	0%	0%	30%	30%	100%	100%
Overall incorporation of recycled aggregates	0%	14%	16%	31%	50%	100%
Relative increase of cement content	0%	1%	1%	2%	15%	29%
Relative increase of plasticizer content	0%	42%	1%	2%	14%	29%
28-day compressive strength (MPa)	31.1	31.3	32.1	29.1	40.1	33.3
28-day modulus of elasticity (GPa)	30	28	28	23	25	21

Table 4 shows how the increase of cement content for large incorporation ratios of RA is more than proportional. This is a strong indicator that not only from a technical perspective (controlling the detrimental influence of RA on the properties of concrete), but also from environmental and economic viewpoints, in most cases the most rational approach towards RAC is the partial replacement of NA with RA.

The internal study of the Joint Research Centre on the use of CRCA in concrete [119] had a different methodology but also argues in favour of small to moderate incorporation ratios of RA rather than high incorporation ratios. In this study, the cement and water content were kept constant and three incorporation ratios of RA were tested: 10%, 25% and 50%. For each incorporation ratio, two mixes were produced: one without changes to the concrete mix design and another in which a strength enhancer chemical agent was incorporated. Table 5 shows that the use of the strength enhancer resulted in RAC mixes with similar strength to the NAC mix only for the incorporation of 10% of RA.

Table 5. Viability of a chemical agent to offset strength loss for different incorporation ratios. Source: [20].

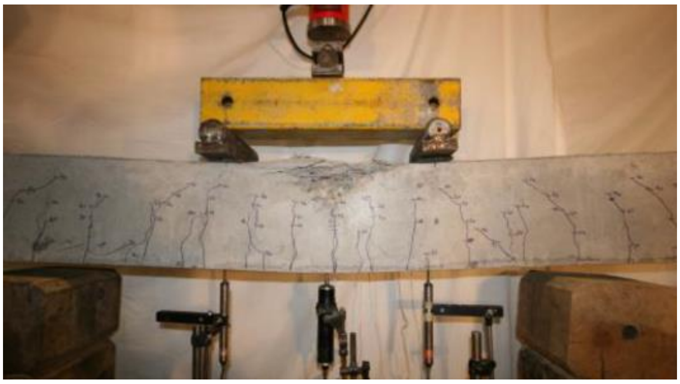
Mix	NAC	RAC - 1	RAC - 2	RAC - 3	RAC - 4	RAC - 5	RAC - 6
Incorporation of fine recycled aggregate	0%	0%	0%	0%	0%	0%	0%
Incorporation of coarse recycled aggregate	0%	10%	10%	25%	25%	50%	50%
Overall incorporation of recycled aggregates	0%	5%	5%	11%	11%	23%	23%
Relative increase of cement content	None	None	None	None	None	None	None
Use of strength enhancer (1% cement weight)	No	No	Yes	No	Yes	No	Yes
28-day compressive strength (MPa)	57.10	52.90	56.70	49.20	49.20	46.90	49.40

3.3.4 Structural design of recycled aggregate concrete

The influence of RA on the structural behaviour of reinforced concrete is not as relevant as its effect on the mechanical and durability properties of concrete. This occurs because reinforced concrete is a composite material in which the reinforcement detailing and properties have a very relevant role in the load-bearing capacity of most resistance mechanisms as well as in the deformation capacity (ductility) of concrete, a relevant parameter for seismic resistance and for structural safety in general.

Many publications on the behaviour of isolated members such as beams failing in bending [51, 121] and shear [122], columns under compression [123], and lap splice resistance to bond failure [124] have shown that RAC is a suitable structural material even for total replacement of coarse NA with coarse RA. Tests on frame structures at reduced [125, 126] and full scale [127] have also shown that the seismic behaviour of RAC is adequate. Figure 14 presents structural tests made on RAC specimens.

Figure 14. Experiments on structural elements made with RAC.



Beam tested for bending

Full scale 3D frame structure under monotonic pushover

It is consensual that the pattern of behaviour of structural elements made with RAC is similar to that of NAC elements [3, 8-10]. In what concerns ultimate limit state design (the structural verifications made to avoid structural collapse), the load-bearing capacity of concrete is marginally affected for most resistance mechanisms, such as resistance to bending. However, the effect of RA may be relevant for resistance mechanisms that do not rely much on the strength of reinforcement, such the bond between concrete and its reinforcement bars and the shear resistance of elements without shear reinforcement [8, 11].

Maintaining the same concrete mix design and changing all coarse NA with coarse RA, the typical decrease of load-bearing capacity for load-bearing mechanisms that rely on reinforcement is in the region of 3% to 7% [127]. This effect is even smaller than what it appears because, since the compressive strength of concrete also decreases when RA are used. As found in [12], for elements whose resistance is conditioned by the reinforcement and since structural checks accounting for the compressive strength of the concrete mix, the effect of RA on resistance is negligible. In other cases, such as the shear resistance of elements without shear reinforcement, allowance needs to be made for the detrimental effect of RA on resistance for large incorporation ratios of RA [128]. Standards and national documents already account for this.

The typical option is that the designer either:

- Designs a structural element with a moderate amount of RA (usually of about 20% to 25% of the total content of aggregates) and, in this case, the code assumes that no changes to conventional reinforced concrete mix design are needed. This approach requires that RA comply with quality criteria (see Section 3.3.1).
- Designs a structural element with a larger amount of RA and needs to check specific clauses for RAC design, such as those present in the new EN standard for reinforced concrete design - prEN1992-1-1 [23].

A noteworthy consideration is that the lower modulus of elasticity and higher creep of RAC result in larger short and long-term structural deformations [129] and this must be accounted for in design and may result in larger concrete volumes whenever this serviceability limit state (the checks made by designers that are related to the use of the building rather than safety, such as compliance with maximum deformations and crack widths) are relevant. Nonetheless, the design procedures that need to be made by a structural designer are the same as those for NAC. For limited information, a first approximation towards the increase of long-term deflections of beams is assumed in [118] as 25%.

Box 6. Structural design of recycled aggregate concrete

Key ideas:

- The structural behaviour of recycled aggregate concrete is adequate.

- Conventional calculation models may be used and recycled aggregate concrete behaves similarly to natural aggregate concrete.

- Resistance mechanisms that strongly rely on reinforcement: incorporation of recycled aggregates has negligible effect on load-bearing capacity

- Resistance mechanisms that rely on reinforcement and concrete: incorporation of recycled aggregates influences behaviour to a moderate extent. Scientific knowledge already allows predicting resistance.

- Structural designers already have standards that allow the structural design of safe recycled aggregate concrete structures.

- Typical approach of standards: no changes to design are needed if the recycled aggregates conform to minimum quality demands and the incorporation ratio is small to moderate. In other cases, specific resistance reduction factors are used for some structural calculations.

- Buildings in which deformations are a concern (e.g. slender buildings and other buildings designed with few walls and columns) may not be adequate for recycled aggregate concrete. Recycled aggregate concrete has higher short and long term deformations than natural aggregate concrete and offsetting this effect requires increasing the volume of concrete used in building, at economic and environmental cost due to increase cement consumption.

3.3.5 Sustainability of recycled aggregate concrete

In most circumstances, the procurement of RA has smaller environmental impacts than the procurement of NA. However, both material properties and structural behaviour of concrete may be affected by the incorporation of RA. <u>This means that a functional unit equal to 1 tonne of aggregate is not suitable to compare the environmental impacts of natural and recycled aggregates:</u>

- When RA are used, the most common change to concrete mix design is the increase of cement content (Table 4). This comes at relevant environmental and economic burdens.
- The detrimental influence of RA on structural behaviour may lead to increases in concrete volume - e.g. when specific types of structural element are designed for shear [63, 128] or whenever deflections are a concern due to the decrease of the modulus of elasticity and increase of creep associated with the incorporation of RA [118].

Any of these cases has environmental costs. Cement is by far the raw material with the largest environmental impact in conventional concrete mix design: while <u>cement amounts to roughly 10% of the volume of concrete, its corresponds to 85% of its carbon dioxide emissions</u> [14]. Fair functional units (e.g. the structural design of a building with the same design working life, load-bearing capacity and serviceability conditions) may result in larger concrete volume of RAC. Therefore, even if 1 m^3 of RAC has smaller environmental impact than 1 m^3 of NAC, hypothetical higher volumes of RAC may lead to higher environmental impacts for the same case of design. Since the main motivation for RAC is the sustainability of the concrete industry, this implies that RAC may not always be the better option.

Since most comparative LCAs analyse a small number of NAC and RAC mixes based on a specific reference mix design (i.e. with a specific cement content, admixture content, type and origin of aggregates and other raw materials), contradictory claims are made in what concerns whether RAC has higher or smaller environmental impacts in comparison to NAC. Furthermore, most research is made with laboratory-design concrete mixes and this may skew comparisons. Therefore, this section aims at the understanding of conditions under which the carbon dioxide emissions of RAC are presumably smaller than those of NAC and presents:

- The results of a large database on NAC and RAC laboratory concrete mix designs and raw materials of different authors [14] is used to perform a comparative LCA that studies the general effect of the incorporation of CRA on the carbon dioxide emissions of concrete.
- An overview of a limited number of LCA studies that addressed specific factors that affect the LCA comparison, such as transport distance and transport mode of natural aggregates.

- LCA studies that are representative of RAC produced in industrial environments.
- The influence of structural design on the findings of an LCA.

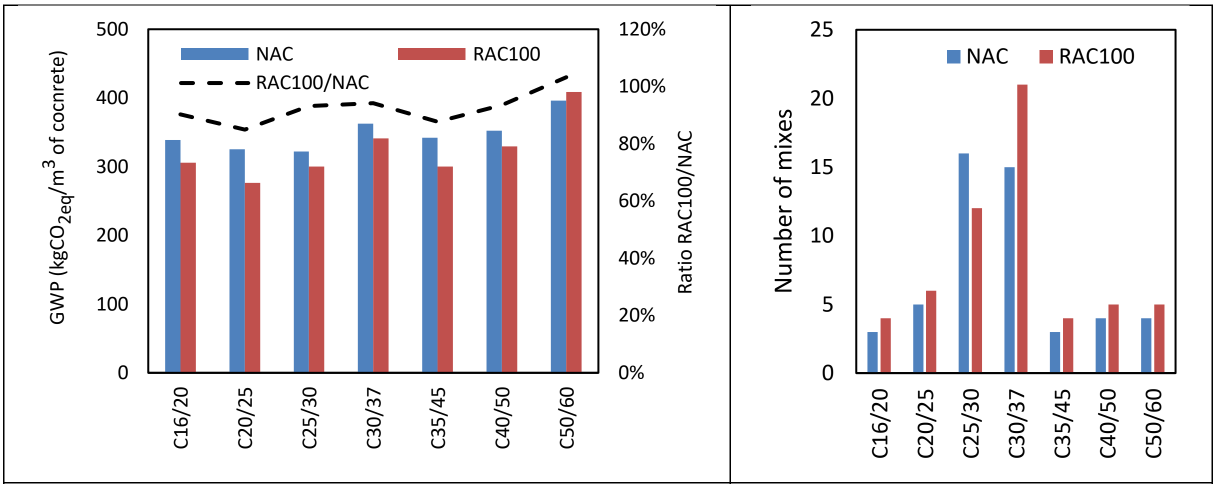
The database used in the comparative LCA [14] covers a total of 57 NAC and 65 mixes of recycled aggregate concrete with 100% replacement of NA with CRCA (RAC100). These mixes have strength classes between C8/10 and C55/67 and concern laboratory-concrete mix designs. All NAC mixes were sourced from papers in which RAC was also produced, so hypothetical biases caused by mix design (e.g. type and content of cement) are averaged out. The mean GWP is presented in Figure 15 for each strength class between the C12/16 and the C50/60, since the other strength class concerned mix designs coming from just one to two publications.

Figure 15 shows that <u>RAC100 tends to have smaller environmental impacts than NAC</u>, with a mean decrease of the GWP of 8%. This decrease of GWP, caused by the replacement of NA by RA, is especially noteworthy when considered that the mean relative impact of cement on these mixes is of 86% for NAC and 93% for RAC100. Despite this comparison being made for NAC and RAC mixes of the same strength class, the workability was not fixed in this study and there is no guarantee that the mixes are fully comparable.

Furthermore, the GWP presented in Figure 15 concern concrete mix designs and raw materials of different countries, but is based on assumptions that apply to Portugal and other countries characterized by relatively short transport distances of NA and RA and transport of raw materials by truck.

Specific site-dependent factors may skew LCA data. For instance, a publication on the environmental impacts of NA and RA from Serbia [16] was presented in Section 3.3.2. It was found that, due to concrete productions in Belgrade typically resorting to river aggregates transported by ship, while RA are necessarily crushed and transported by truck, the impacts of the procurement of RA are larger than those of NA.

Figure 15. Comparison of the GWP of several NAC and RAC100 mix designs compiled in [14].



GWP by strength class	Number of mixes

The same publication [16] also compared the environmental impacts of NAC and RAC. The RAC mixes had full incorporation of RA (RAC100) and their cement content was 5% larger than that of NAC. For a scenario in which NA are transported for 100 km and RA are transported for 15 km, the GWP of RAC100 was 4% larger than that of NAC. If both transport distances are of 100 km (an unlikely event for the procurement of RA in urban centres), the environmental impacts of RAC100 become 11% larger.

The same research team [130] developed upon this work and used multi-criteria optimization considering waste generation, depletion of mineral resources, environmental impacts and cost. <u>The most economical option was the production of NAC with river aggregates, but RAC performed better in environmental terms and the authors argued in favour of increased taxation of the extraction of NA</u>.

Also on the topic of transport distance, different authors have argued that a condition for RAC having lower environmental impact than NAC is that the transport distance of the RA is smaller than that of the NA they replace [81, 131].

A comparative LCA representative of Paris [15] checked whether full or partial incorporation ratios of RA were more advantageous from an environmental standpoint. A preliminary laboratory campaign covering concrete of different strength classes determined the increases of cement content needed so that RAC has the same compressive strength than NAC. RA of different quality were tested and RAC mixes with different incorporation ratios were analysed. For incorporation ratios of 0, 20%, 50% and 100% and low quality RA, the following cement contents were required for compliance with a compressive strength of 30 MPa:

- NAC: 280 kg/m^3.
- RAC with 25% incorporation of RA: 300 kg/m^3 (7% increase).
- RAC with 50% incorporation of RA: 320 kg/m^3 (14% increase).
- RAC100: 380 kg/m^3 (35% increase).

These results show that the increase in cement content is not proportional and that higher incorporation ratios of RA are associated with larger increases of cement content. Additional experiments found that for higher quality CRCA the increase of cement content is smaller (e.g. just 3% for total incorporation of RA produced from high strength concrete waste). The LCA analysis that followed showed that if environmental impacts are to be minimized, high quality RA and small (20%) incorporation ratios of RA are a better option than RAC with larger incorporation ratios (as well as than producing NAC).

The papers mentioned so far concern laboratory concrete, whose concrete mix design may not be the same as that of the concrete industry (namely due to less use of admixtures and a trend towards use of CEM I type of cement in comparison to industry practice). The following appraisal concerns LCA analyses that are representative of industrial realizations of RAC.

In a comparative LCA on ready-mixed NAC and RAC mixes of the C30/37 strength class [131], the carbon footprint of RAC was only 1% smaller than that of NAC. The RAC mix had 28% incorporation of fine and coarse RA. The small reduction of the carbon footprint is due to the fact that the admixture content increased by 11% for this moderate incorporation ratio of RA (Table 6). This increase of admixture was set to ensure that the rheological properties and strength of the RAC mix are those of the analogue NAC mix.

Table 6. Mix designs of ready-mixed concrete mixes representative of Switzerland in kg/m^3 of concrete. Source: [131].

Raw material	NAC	RAC (28% RA incorporation ratio)
Natural river aggregate (fine + coarse)	2006	1394.6
Recycled aggregate (fine + coarse)	-	542.3
Cement	350	350
Admixtures	1.58	1.75
Water (including water absorbed by the aggregates)	80.71	107.58

The authors of the publication [131] argue that the main motivation for RA incorporation on concrete is the preservation of mineral resources, rather than the decrease of the carbon footprint of the concrete industry. For environmental reasons, a 20 km transport distance between the RA producer and the ready-mixed plant was recommended for a scenario based on the Swiss context in which the NA are transported for 35 km by truck.

An LCA study developed for French case studies of RAC [20] is especially relevant since three separate comparative LCA were carried out: one in which the cement content of RAC is increased, another in which the superplasticizer content is increased, and a third one concerning industrial (ready-mixed concrete), in which both cement and superplasticizer are changed. Table 7 summarizes the main aspects of the mix designs analysed and presents the relative GWP in relation to the highest value reported.

This table shows that cement content governs which is the hierarchy of sustainability of the mixes. For the case study in which cement content was increased, the authors concluded that the carbon dioxide emissions of RAC are higher than those of NAC since the transportation distance of RA is not short enough to offset the carbon footprint of the cement added to the mix design (in comparison to NA). Furthermore, when cement content is fixed and the incorporation of RA is compensated by increased content of superplasticizers, virtually no differences in the GWP are observed. In the industrial case studies, the GWP of RAC was similar to that of NAC for incorporations of up to 30% of RA (in relation to the total content of fine and coarse aggregates). Above this threshold, the increase of cement content means that the GWP of RAC becomes larger than that of NAC.

Table 7. Mix designs of RAC concrete mixes with mix different methodologies. kg/m^3 of concrete. Source: [20].

Type of mix	Total RA incorporation	Cement content	Superplasticizer content	Relative GWP to the maximum of each mix methodology
Cement content is changed	0%	270	1.31	50%
	16%	276	1.51	59%
	52%	282	1.40	76%
	13%	276	1.16	58%
	30%	277	1.08	66%
	100%	326	1.18	100%
Cement content is fixed	0%	260	1.92	100%
	8%	260	1.95	100%
	26%	260	2.08	100%
	100%	260	2.34	100%
Industrial ready-mixed concrete	0%	302	2.57*	79%
	14%	306	3.65*	79%
	16%	305	2.60*	80%
	31%	308	2.62*	80%
	50%	346	2.94*	89%
	100%	390	3.32*	100%

The authors [20] emphasized that the transport distance of the RA was larger than that of the NA and that under different contexts, RAC may be more sustainable than NAC, such as shorter transport distance of the RA in comparison to NA and negligible increases of the content of cement. The authors finished by stating that environmental benefits that are not usually accounted for in an LCA are main motivations for RAC, presenting the amount of saved NA and avoided landfilling as indicators that are not present in an LCA but that benefit from RAC use. However, such indicators are not considered in EN15804 [88]. In [50] it is argued that other standards will lead to similar findings.

A more general approach for a comparative LCA between NAC and RAC that is representative of the concrete industry is that presented by the European Cement Research Academy [50]. In this case, a concrete mix design deemed as representative of Europe in the year of 2013 was the basis of the analysis. This mix design was assumed as being of the C25/30 strength class with a cement content of 290 kg/m^3, fly ash amounting to 60 kg/m^3, superplasticizer equal to 1.2 kg/m^3 and 1243 kg/m^3 of coarse aggregates. The coarse aggregates were completely replaced with RA and the only change to the mix design was an 11% increase of cement content to 320 kg/m^3, defined to offset the decrease of compressive strength and based on meta-analysis. The results of the LCA are presented in Table 8 for the RAC100 mix and for two NAC mixes.

Table 8. Global warming potential in kgCO_2eq/m^3 of ready-mixed concrete for different types of aggregates. Source: [50].

Type of mix	GWP (kgCO_2eq/m^3)
NAC - rounded (river) NA	235
NAC - crushed NA	256
RAC	260

It is found that the 11% increase of cement content results in RAC having 11% higher GWP than NAC produced with rounded RA and 1.5% higher GWP in comparison to NAC made with crushed NA. Some assumptions of the analysis are not favourable for RAC: all environmental impacts associated to the production of RA were allocated to the CRA (51% of the total RA produced) and this assumes that the fine RA are waste and all transport distances of raw materials to the concrete factory were assumed as of 100 km. As stated by the authors of the study [131] and stated in several instances of this section of this report, shorter transport distances of RA are expected and in many practical applications RAC may become more sustainable than NAC. Nonetheless, this study is another demonstration of how RAC mixes in which cement content increases relevantly may have larger environmental impacts in comparison to NAC.

In a report by the JRC [29], different scenarios for the use of RA produced from concrete waste are presented:

- Landfilling scenario, in which concrete waste is landfilled.
- Production of RA and their use as aggregates for road construction.
- Low quality recycling, in which fine and coarse RA are produced and used in concrete. Note that this "low quality application" is already better than the conventional use of RA in concrete (incorporation of coarse RA only) and that, presently, most countries forbid the use of fine RA. Furthermore, this process already assumes the use of high-quality recycling apparatus.
- High-quality recycling, in which not only fine and coarse RA are used in concrete, but also concrete fines are used as cement replacement.
- Reuse of concrete.

For a functional unit of 1 tonne of managed concrete waste, the outcome of the LCA was that:

- Landfilling corresponds to net emissions of 14.6 kg/CO^2eq.
- The use of RA for road construction corresponds to net emissions of 14.6 kg/CO^2eq.
- For low-quality recycling, net emissions of 1.8 kg/CO^2eq are observed.
- For high-quality recycling, net savings of 40.3 kg/CO^2eq are found.
- Reuse is associated to net savings of roughly 90 kg/CO^2eq.

These findings show that higher quality recycling is associated with CO_2 savings. To quantify the effect of increased high-quality recycling, the net impacts associated with the 2022 generation of concrete waste and a representative assumption for the mean treatment of concrete waste in the EU27 were compared with forecasts for 2050 concrete waste generation and concrete waste treatment (in which high-quality recycling and reuse become more frequent) and it was found that higher quality applications for concrete was may potentially lead to CO_2 savings of 1.08 million tonnes/year.

3.3.6 Critical view on the use of recycled aggregates in concrete

RA are heterogeneous and composed of different types of waste. To produce RA for high value added applications, the case of RA fit for concrete, the CDW must be mainly composed of concrete waste and certain constituents (e.g. plastics and gypsum-based materials) must be avoided or reduced to very small amounts. Since in most regions the current operations carried out at CDW plants aim at the production of RA for lower value applications (e.g. road construction), the composition, properties and grading of most RA are not in line with the requirements of the concrete industry. Higher quality RA may be produced with advanced processes and such type of RA will comfortably meet requirements for use in concrete. Nonetheless, the production of RA fit for concrete may be made with conventional equipment of the construction and industry - e.g. by producing RA from concrete waste of good (and known) quality. The lack of high quality RA is mostly a matter of market demand.

In most cases, RA has worse properties than NA and changes to concrete mix design are needed to offset these effects. Furthermore, the structural design of RAC may be associated with larger volumes of concrete in comparison to an analogue design made with NAC (e.g. due to the higher deformations of RAC and/or durability concerns).

The changes to concrete mix design and to the structural design may lead to the RAC structure having a larger environmental impact than when NAC is used. As general guidelines:

— The production of RA is typically associated with smaller carbon footprint in comparison to the production of NA.

— Changes to concrete mix design and to concrete performance may imply that the total amount of cement on a concrete building is larger when RA are used and this comes at environmental (and economic) cost.

— The changes to concrete mix design are small to negligible for small incorporation ratios of high quality RA (such as most CRCA) but may be very relevant for full incorporation of RA or whenever fine RA are used. The potential for RA incorporation in concrete is larger for higher quality coarse RA.

The outcome of a comparative environmental LCA depends on the specific context – raw materials used, energy consumptions of equipment, concrete mix design, transport distance and others. Nonetheless, general conditions for the use of RA in concrete leading to environmental benefits may put forward:

— In regions with scarce access to NA, the use of RA reduces transport distances.

— RA should be of good quality and mostly composed of concrete waste, in order to limit detrimental effects on concrete properties and to avoid noteworthy changes to concrete mix design.

— Partial replacement of NA with RA should be preferred to total replacement due to the smaller effects on concrete properties and small to non-existent (detrimental) changes to concrete mix design, provided that the RA are of good quality.

— The incorporation of RA should be mainly made in concrete of the low to moderate strength range (to avoid ceiling effects on concrete strength due to premature rupture of the aggregates caused by the fact that RA are weaker than NA).

— Certain structural designs (such as those of thin elements with stringent deformability requirements) should be made with NAC only, since the influence of RA on deflections will lead to larger concrete volumes with loss of aesthetics and increased cost and environmental impact.

All these remarks show how the environmental consequences of producing RAC depend on several factors and that generalizations should be avoided.

Box 7. Recycled aggregate use in concrete: viability, advantages and potential for counter productivity

- Concrete made with coarse recycled aggregates produced from concrete waste: viable structural material.

- Generally, recycled aggregates decrease the carbon footprint of concrete when transport distances for recycled aggregates are smaller than those of natural aggregates.

- In projects with large incorporation ratio of recycled aggregates and/or related to buildings with deformability concerns, recycled aggregates may increase the carbon footprint and economic cost.

- Recycled aggregates should be mainly used in concrete of the low to moderate strength range for technical reasons.

- Partial incorporation ratios of good quality recycled aggregates in conventional buildings is the best option from a technical, economic and environmental standpoint.

- The environmental consequences of producing recycled aggregate concrete depend on several factors. The previous ideas should be validated through case-by-case assessment.

- No “one size fits all” rule to define conditions for technically viable, sustainable and cost-efficient recycled aggregate use in concrete may be stated!

4 Regulations and maximum incorporation ratios of recycled aggregates in concrete in the EU

Regulations for the use of RA in concrete may be divided in two groups: those related to the quality of the RA (that is, regulations that are complementary to EN12620 [21]) and those that define the maximum allowable incorporation ratio of the RA in concrete (complementing EN206 [22]). These regulations are typically made at the country level, with some exceptions of regulations with regional validity.

The main concerns of standards concerning the quality of the RA were presented in Section 3.3.1 and are common to different regions/countries. A simplified explanation of the common approach of these regulations is that the composition of the RA is used to assume its class (see Table 3). Then, other properties of the RA are used to validate the assumed class. Each national regulation typically includes two or three classes of RA that roughly correspond to the following qualities:

— High quality RA - concrete waste: this quality corresponds either to classes of RA that are explicitly stated as being produced solely from concrete waste or to classes whose content of R_c+R_u constituents is higher than 95%. The “Type A” aggregates of EN206 [22] presented in Table 3 are of this quality.

— High quality RA: this quality corresponds to classes of RA in which the content of R_c+R_u constituents is higher than 80% (in most standards, the typical minimum content is 90%). The “Type B” aggregates of EN206 [22] presented in Table 3 are of this quality.

— Moderate quality RA: this quality is that of other RA allowed in standards for concrete. Note that quality is “moderate” since the documents assume that some quality control requirements are met. For instance, the minimum content of R_c+R_u constituents is at least 70%.

In most cases, only coarse RA may be incorporated in concrete. Also, moderate quality RA are usually only allowed in non-structural concrete.

Table 9 presents the limitations of regulations of ten Member States concerning the use of RA in structural concrete. Not all Member States are represented due to methodological concerns discussed next.

Since the limitations of the regulations needed to be aggregated in order to be presented and this prevented the full description of the approach of each regulation towards environmental exposure classes. Therefore, three classes of exposure were defined: non-demanding (X0), “low demanding” (carbonation-related classes) and demanding (all others). Also, fine aggregates were considered as those either below 2 mm or 4 mm.

As understood from Table 9, the regulations of different Member States define boundary conditions for the use of RA according to different criteria, but the concept is the same:

— As a function of the class of the RA and of the environmental exposure class, a maximum admissible incorporation ratio and a maximum strength class are defined.

— Some countries accept the use of fine RA, but at lower incorporation ratios than coarse RA.

— Most regulations allow the production of RAC with higher incorporation rations than those stated if specific testing is carried out.

— In some countries, environmental exposure conditions are more limiting than the strength class of concrete, whereas in others the opposite is found.

It is also emphasized that whenever chloride ingress is a concern, the use of RA is barred in most regions. This means that in locations in which chloride ingress is a concern, RA can only be used in non-reinforced concrete or in concrete with reinforcement without corrosion concerns (such as glass fibre-reinforced polymer bars), unless specific testing is carried out to validate the use of RA. This is an example of how policy towards the promotion of RAC must make allowance for technical contexts at the regional level, namely in terms of minimum mandatory incorporation ratios.

Considerable differences in regulations among Member States are due to various technical aspects: different regions have different building traditions and RA of different composition, different concerns for environmental exposure and different market confidence in RACs. Nevertheless, an effort to harmonise some parameters of the regulations (such as the possibility of using fine RA and the criteria for defining classes of RA) could improve communication between the actors across Member States (both for policy and monitoring purpose and for industry), facilitating monitoring and exports/imports.

Table 9. Maximum allowed incorporation ratios of RA for structural concrete.

Country	Standard/National Law		Recycled aggregate size	Type of recycled aggregate	Expected limiting factor		Maximum incorporation ratio and limitations
					Strength	Durability	
Belgium	Standard	NBN B15-001:2022	Coarse	High quality RA	x		Reinforced concrete: up to 30% (≤C30/37)
							Non-reinforced concrete: up to 50%
Denmark	Standard	DS 2426	Coarse and fine	High quality RA	x	x	Low to moderate exposure environments only: Fine aggregates: 30% (≤C30/37); coarse aggregates: 100% (≤C40/50)
				Moderate quality RA	x		Low exposure environments only: Fine aggregates: 20%; coarse aggregates: 100% (≤C20/25)
France	Standard	NF EN 206-1/CN	Coarse	High quality RA - concrete waste		x	Up to 30% for low demanding exposure classes
			Coarse	High quality RA	x	x	Up to 15% for low demanding exposure classes (≤C25/30)
			Coarse	Moderate quality RA	x	x	Up to 5% for low demanding exposure classes (≤C25/30)
			Fine	High quality RA	x	x	Up to 5% for low demanding exposure classes (≤C25/30)
Germany	Standard	DIN 1045-2	Coarse	High quality RA - concrete waste		x	Low demanding and carbonation-related exposure classes: 45% total aggregates (fine + coarse)
						x	Chloride-related exposure classes: 35% of total aggregates (fine + coarse)
						x	Chemical attack-related exposure classes: not allowed
				High quality RA		x	Low demanding and carbonation-related exposure classes: 35% total aggregates (fine + coarse)
						x	Chloride-related exposure classes: 25% of total aggregates (fine + coarse)
						x	Chemical attack-related exposure classes: not allowed
Italy	Ministry Decree	NTC:2018	Coarse	From mixed RA to very high quality ones	x		Incorporation ratio depends on origin of the RA and on the strength class; e.g. 60% for non-demanding structural concrete (C20/25) and moderate quality RA; 30% for C30/37 and high quality RA
Netherlands	Standard	NEN 8005	Coarse and fine	High quality RA (assuming parties agree on following CUR112)		x	50% for low to moderate exposure classes only. Larger ratios allowed if changes to design are made (≤C35/45)
				Moderate quality RA		X	20% for low to moderate exposure classes only. Larger ratios allowed if changes to design are made (≤C35/45)
Norway	Standard	NB 26	Coarse and fine	High quality RA	x		10% fine RA and 30% coarse RA (≤C20/25)
					x		20% coarse (≤C45/55)
			Coarse and	Moderate quality RA	x		5% fine RA and 10% coarse RA (≤C20/25)
Portugal	National specification	LNEC E471	Coarse	High quality RA - concrete waste			25% of total aggregates (fine + coarse) (≤C40/50), most environmental exposure classes
				High quality RA			20% of total aggregates (fine + coarse) (≤C35/45), most environmental exposure classes
Spain	Royal Decree	EHE-08	Coarse	High quality RA - concrete waste			20% without changes to design (≤C40/50)
Sweden	Standard	SS-137003	Coarse	High quality RA - concrete waste	x		50% for non-demanding exposure classes (<C30/C37)
					x		30% for low demanding exposure classes (<C35/C45)
							30% for demanding exposure classes (up to XC4, XS1, XD1, XF1) (<C40/C50)
				Moderate quality RA	x		50% for non-demanding exposure classes (<C30/C37)
					x		20% for low demanding exposure classes (<C35/C45)

Only part of the EU-27 is covered in Table 9 since the relevant regulations from some of them could not be consulted. Whenever the regulation of a Member State was not available, data were retrieved from both publications and answers to surveys sent to stakeholders. In this case, at least two different sources were used to validate the information. The validation criterion excluded information from several Member States since information from different sources was highly inconsistent. For instance, in the case of Finland the information provided by different sources was different (maximum incorporation ratios of 30% or 50% under the same conditions), and information on Austria came from a single source.

The most relevant finding of Table 9 is that current regulations are not a limiting factor that is preventing the increased market uptake of RAC: the answers to a survey sent to several organisations and associations of the concrete industry were that the current uptake of RA by the concrete industry was either "unknown and probably low" or very small values were reported, ranging from "below 1%" to "below 10%" (non-consensual answer, with a representative from the same MS arguing that the uptake was "below 5%".

Furthermore, no correlation was found between the reported uptake of RA by the concrete industry and the allowed incorporation ratios of RA in each MS regulation. Answers to the surveys were unanimous in stating that the availability of RA with adequate quality for concrete and no incentives to use them in concrete are a much more relevant barriers than the limitations of technical regulations.

Box 8. Regulations for use of recycled aggregates in concrete

- Different Member States: different limitations on incorporation ratios and allowed environmental conditions.

- The maximum incorporation ratios allowed in regulations are much larger than the current market uptake.

- Most standards: at most 30% incorporation of coarse recycled aggregates in moderately demanding concrete mixes. For less demanding specifications, the admissible incorporation of recycled aggregates is higher.

- Increasing the allowed incorporation ratios is not expected to improve the market uptake of recycled aggregate concrete.

- Ensuring that recycled aggregates of good quality are available near concrete producers and/or providing incentives for their production and use in concrete would be major drivers for the increased uptake of recycled aggregates by the concrete industry.

Regulations are under constant revision and the barriers concerning the use of RA in some MS will differ from those presented in Table 9 in the near future. For instance, a new standard in Germany will allow the use of fine RA in concrete.

5 Circular Economy models and the employment of the construction sector

5.1 Social aspects of construction between ancient traditions and modern challenges

Construction is as old as Civilisation. The building of ancient Roman aqueducts and medieval cathedrals was already organised as a series of complex activities that required craftsmen with different specialisations to work together within a given timeframe. Both raw materials for lower value products and labour for less sophisticated technical activities were mostly sourced locally. Even the use of secondary materials has a historical background: the use of marble from the Colosseum for new construction after the Fall of Rome is an early example of urban quarrying.

The industrialisation brought the use of new materials (e.g. steel and cement) and facilitated the manufacture of products already in use, such as bricks, and gradually allowed the mechanisation and then the automation of various processes. Despite these radical changes, the construction process still retains many of the original characteristics that make it peculiar among modern production. Building major infrastructure and developing real estate still involves companies and workers with different skills and expertise and raw materials and labour are sourced locally whenever possible to reduce costs and environmental burdens. Usually, end users of buildings are unfamiliar with technical aspects and with the potential benefits of higher quality buildings - e.g. sustainability concerns are not considered by the general public. To tackle this, the EU launched Level(s) in 2020 to promote circular and lifecycle thinking in the built environment.

In December 2019, European Commission President von der Leyen announced the European Green Deal [3], the European Union's new growth strategy that intends to make Europe climate neutral by 2050. Job creation and an inclusive and equitable transition are key elements of the strategy, along with reducing energy consumption and the emissions of greenhouse gases and implementing a circular economy. In order to measure progress towards these goals, forecasting the employment effects of the green economic transition is crucial [132]. The outbreak of the COVID-19 crisis in the early 2020 shed a different light on the issue and stimulated the acceleration of the green transition, in parallel with economic and social recovery and with the need to use local sources of materials with reduced potential for disruption. The war in Ukraine, two years later, provided a further reminder of the strategic role of energy and material supplies.

Construction is a key sector for the EU economy and an important source of employment. With more than 13 million direct jobs (9% of EU employment - Table 10). In terms of number of enterprises, 99.9% of the sector consists of SMEs with less than 250 employees and 94% have less than 10 employees [133]. One of the key sensitive points for the wealthy EU economies, and more generally in the Organisation for Economic Co-operation and Development (OECD), relates to the distributional effects of the green economy, and in particular to occupational transformation - e.g. will policies that promote the use of RAC affect the employment of the construction sector in a positive way, or are jobs at risk? How to mitigate the social effects of potential job loss?

Table 10. Provisional data on the construction, industry and market services sector. Period: 2021 onward. Source: EUROSTAT [133]

Activity (NACE R2)	Number of enterprises (thousands)	Turnover **(M €)**	Persons employed (thousands)
Industry, construction and market services (except public administration, defence, compulsory social security and activities of membership organizations)	30 144	31 166 069	155 033
Construction	3 685	1 879 480	13 280
Ratio of construction to total	12%	6%	9%

5.2 Challenges for the EU construction sector in the transition to circular economy

The transition from linear to circular economy models needs to combine the peculiar aspects of the construction sector with the transformative processes that are affecting the labour market and reshaping the world, including action against climate change, demographic ageing, digitalisation and globalisation. By replacing the extraction of resources and the production of goods for own use with the reuse, repair, recycling and rental of goods, employment will shift from extraction and production to reprocessing, waste management and services [134]. And studies on this topic suggest that the adoption of (green) circular economy models increases employment opportunities and costs, with claims that circular economy practice may increase the demand for workers of the recycling industry (including for CDW management facilities) and decrease the demand for construction workers [134]. The transition to new economic models has to consider the need to support workers, industries and regions from which jobs will be relocated [135]. This support needs to be accompanied by incentives to ensure commitment to the transition.

The combination of these challenges requires new approaches and immediate responses from policy-makers and economic actors. A well-designed transition to a circular and climate-neutral economy can help make the society and labour markets more resilient to the adverse effects of globalisation, climate change, resource scarcity and demographic change [136].

The demographic ageing of the EU is expected not only to lead to the shrinking and reorganisation of cities [137], but it will also increase the old-age dependency ratio, challenging populations and labour markets in developed countries, to maintain and strengthen the social resilience and social protection systems. This has effects on the employment of the construction sector and, more generally, on the socio-economic environment in which companies operate. In addition, the construction sector faces a potential talent crisis due to an ageing workforce and the increasing demand for human resources with more digital skills [138]. The shortage of labour, combined with the difficulty of offshoring the production of many building products, could attract foreign workers, especially for less sophisticated technical activities, replicating on a large scale the intra-national and European migration phenomena of the XX century. At the same time, the lack of low-skilled human resources could encourage a new industrialisation of construction products and the automation of manufacturing processes [139].

These remarks highlight the need to capacitate the new generations of workers for the challenges of the circularity of the construction sector.

Existing buildings were not designed for optimal demolition and may have been constructed over the years with materials of variable and unknown quality. To ensure good secondary raw materials of stable quality over time, it is necessary to act on the demolition, separation and treatment processes. Selective demolition, which has yet to be defined in detail by standards, separates the various stages of work by gradually stripping the different materials as homogeneously as possible. At present, the process is labour-intensive, requiring specialised technicians to coordinate the work, but low-skilled workers. Alternatively, conventional demolition can be carried out by using machinery to separate materials directly on site, allowing secondary raw material streams to be recycled for different uses. Because the majority of construction agents are SMEs and good conditions for appropriate CDW valorisation require a proper geographic coverage of CDW management facilities [8] (which leads to CDW management facilities being mostly SMEs as well), investment in equipment and novel production processes and in the training and hiring of skilled workers for proper CDW valorisation is a challenge. This means that concerns about the shortage of construction workers are accompanied by the need to increase the workforce and knowledge of workers of the recycling industry.

Introducing a new approach to design: Design for Adaptability, Reuse and Deconstruction (DfARD) will lead to a simplification of building renovation and demolition procedures in the future, ensuring less use of new materials and not requiring massive use of labour. This will require incorporating new skills into the curricula of young architects and engineers, as well as training for senior professionals but will only lead to relevant decreases of CDW generation and of the consumption of natural resources in the long-term.

5.3 How much can the greening of the built environment affect employment?

In a specific study on the green transition, the International Labour Organization (ILO) estimated in 2018 that the construction sector would be the second largest beneficiary of employment growth globally in 2030, with Europe in line with the world average.

Changes in energy production and use, to achieve the 2 °C average global temperature increase goal set up by the IPCC [140] and stated in the Paris Agreement, can create around 18 million jobs throughout the world economy. These changes include the shift to renewable energy sources and greater energy efficiency - e.g. due to shifting towards electric vehicles or by producing high energy-efficient buildings [141]. This entails a reallocation of employment across sectors, and requires policies to ensure that the transition is fair to all. The move towards a green economy creates jobs globally with the aforementioned estimate of net job growth of 18 million jobs being justified by the creation of 24 million new jobs and the loss of 6 million jobs by 2030 [135]. In Europe, the increase of jobs is expected to be of 0.26%, while the number of jobs in the construction sector are expected to increase by 1.6% globally [135].

The ILO also states [135] that the circular economy will create nearly 6 million new jobs worldwide by adopting the R5 strategy: i) renounce and ii) reduce, before iii) reuse, iv) recover and v) recycle; and moving away from the extraction-manufacture-use-disposal approach. In particular, a shift from mining and manufacturing to waste management (reuse and recycling) and services (repair and rental) is implied.

A report on the impacts of the circular economy on the labour market [134] specifically states that the construction sector will lose jobs due to the adoption of practices such as increased reuse (e.g. DfARD) and automated construction. The authors of the report [134] do state that they did not include the effects of policy to promote energy efficiency in buildings (since their study concerns circular economy only), and that programmes to promote energy efficiency investment could likely lead to an overall increase of construction jobs. An opposing view is presented in another, more recent, report that describes the situation in Europe with projections up to 2050 [142]. The forecast for change in job occupation from 2015 to 2050 is presented in Table 11. In agreement with ILO [135], employment growth in the construction sector is expected to be positive. It is clear that circular economy will have contradictory impacts on different aspects and sectors of Society and, therefore, it is not possible to estimate precisely whether the overall effect on the economy will be positive or negative.

Table 11. Influence of the circular economy in the employment in Europe. Forecast for 2050. Source: [142]

Sector	Share of total jobs in 2015	Range of change in jobs by 2050 compared to 2015
Construction	6.7%	+0.3% to +2.8%
Services	71.7%	Minor change: -2.0% to +0.9%
Agriculture	4.5%	Increase: -0.7% to +7.9%
Mining and extraction	0.5%	Large decrease: -62.9% to -2.9%
Power generation	0.7%	Increase: +3.6% to 22.3%
Manufacturing (energy intensive industries)	2.0%	Minor change: -2.6% to +1.8%
Other manufacturing	13.3%	Minor change: -1.4% to +1.1%

5.4 How the green transition impacts on human resources in construction

5.4.1 Taxonomy and analysis of the greening of the employment profile

A recent study commissioned by DG ENV [143] suggests that, even under the most ambitious scenarios, net job growth by 2030 will be in the order of 700,000 as a result of the sustainable uptake of circular economy activities (Section 5.3).These scenarios are concentrated in a sharp increase in the number of jobs in the fast-growing waste management sector and a relatively large decrease in the construction sector. According to this publication, even though new jobs will be created in the construction sector, more traditional 'non-green jobs' are likely to disappear.

The circular economy will create new jobs, but often the skills required for recycling activities will be very similar to those required for initial production. For example, dismantling an old house is ultimately very similar to building the first one, because the logic of building houses has not changed much over the last few decades and, as assembly becomes more industrialised, so does dismantling.

In studying the social dimension of the green economy, Bowen and Hancké [143] categorise green(able) jobs as follows [143]:

— Green Increased Demand: Existing jobs expected to be in higher demand due to green economy, without significant changes in tasks, skills or knowledge (also considered 'indirect green').

— Green Enhanced Skills: Existing jobs that require significant changes in tasks, skills and knowledge as a result of the green economy.

— Green New & Emerging: New jobs that require a skilled workforce suited to meet the specific needs of the Green Economy.

— Total green jobs, which are the combination of all of the former. Bowen and Hancké [143] needed to correct this indicator to avoid double counting of jobs (this is the reason why the share of total green jobs presented in Tables 12 and 13 differs from the individual share of each category of green job presented in Table 13).

All other jobs are considered and can be divided into "green rival" jobs and "other" jobs, whereby "green rival" jobs are considered similar to one of the three "green" job categories, either because the tasks they perform are very similar or, in the case of new employees, because they require similar skills and other characteristics of the worker.

Following this taxonomy, Bowen and Hancké [143] found that, between the years of 2006-2016, job growth in the EU has been green to some extent, with employment in green(able) jobs increasing in all categories. Table 11 presents the share of total green jobs and the size of the workforce of the main sectors of activity in the EU28. It is observed that construction was the sector with the highest share of green(able) jobs (73%), followed by transport, manufacturing, energy and waste management, and professional services[143]. The construction sector (NACE Section F) also has the highest potential for circular actions in the manufacturing sectors, together with manufacturing and wholesale & retail sector [143].

Table 12. Highest job growth in occupations with new or enhanced green skills. Source: [143]

Sector	Workforce size (thousands of workers)	Share of total green jobs
Agriculture, forestry and fishing	8737	26%
Mining and quarrying	757	54%
Manufacturing	34157	52%
Energy and water supply and waste management	3236	58%
Construction	14716	73%
Wholesale and retail trade and repair	30712	34%
Accommodation and food service activities	10567	22%
Transportation, storage and ICT	18180	61%
Financial and insurance activities	6476	37%
Professional, scientific, technical and administrative activities	22994	52%
Public administration	15176	45%
Education	16639	15%
Human health and social work activities	23820	21%

Table 13 presents the share of each category of green and rivals of green jobs in the EU28 for the construction sector, manufacturing (the sector with the largest workforce) and transportation, storage and ICT (the sector with the second largest share of green jobs). Six observations are made:

— A significant number of green jobs is included in more than one category, since the sum of its three categories is larger than the total share of green jobs by at least 35% (the same trend was observed for all sectors studied in [143]).

— The construction sector is the one with the largest share of total green jobs.

— The construction sector is the one with the largest decrease of the share of rival jobs and one of the sectors with the smallest share of rival jobs in 2016 (Accommodation and food service activities and Human health and social work activities are the only two with lower share).

— If all rival jobs in the construction sector are shifted towards green jobs, a total share of green jobs of 96% is achieved. The only sector with larger potential is Transportation, storage and ICT.

— New and emerging green jobs take up a relatively modest share of total green jobs in construction (24%) but are increasing relevant. Green increased demand jobs take up almost half (42%) of all green jobs and are also increasing at a fast pace, while the share of enhanced skills green jobs decreased moderately during the 10 years covered by the analysis.

— The relative share of green Construction jobs of the category Enhanced skills decreased between 2006 and 2016, while the share of New and emerging and the Increased demand categories increased almost 10%.

Table 13. Share of each category of green job in 2016 and absolute percentage change between 2006 and 2016 (under brackets). Source: [143]

Sector	Total green jobs	Increased demand	Enhanced skills	New and emerging	Rivals
Manufacturing	52% (-1.4%)	34% (-1.5%)	23% (-0.3%)	16% (+1.4%)	29% (-6.4%)
Construction	73% (+6.3%))	45% (+9.5%)	37% (-2.9%)	19% (+9.1%)	23% (-8.8%)
Transportation, storage and ICT	61% (+9.8%)	37% (+2.1%)	30% (+8.5%)	21% (+11.1%)	38% (-3.0%)

Possible justifications for the last observation are:

— The Green Increased Demand jobs in the construction sector include those related to basic tasks that improve energy efficiency, such as building insulation [143]. Public and private initiatives towards more sustainable construction and reduced energy consumption are a driver for the increase of construction jobs in this category. Due to increased awareness towards sustainability and the trend towards energy retrofitting and rehabilitation of the ageing building stock in the EU [27] - in part due to specific funding programmes by Member States, a source of funding that is expected to continue [6], and in part due to rising energy costs [143]), this job category is expected to continue to require a large workforce.

— Green enhanced skills jobs decreased their share in the Construction sector. This moderate decrease is surprising and no reason for it is put forward. The original report [143] does not comment this finding as well.

— Green New and Emerging jobs are increasing due to new trends and technologies and because of disruptive methods, such as environmental analyses of construction projects, modular construction and other automated processes for fabrication, and other digital-based jobs for construction, such as BIM and additive manufacturing. The increased awareness of topics such as sustainability and life cycle assessment, namely in civil engineering and other construction-related higher degree education courses, may be a cause for both the identification of the need of such jobs (the sector is becoming aware of sustainable construction practices) and the availability of workers. Public and private initiatives towards greener construction include the adoption of innovative methods and the development, design and impact assessment of construction and this is also a reason for this increase.

These observations are hypotheses and future studies on this topic are recommended.

5.4.2 Education and skills needed

The transition to clean energy and a green economy is taking place in parallel with and in the context of digitalisation. These simultaneous global trends require a response in terms of education and skills from policy-makers, companies and educational institutions alike.

Climate action generally favours medium-skilled and medium-paid jobs and mitigates job polarisation. Jobs created by the transition to a low-carbon economy in Europe by 2030 are expected to be filled by workers with low to medium education and involve the performance of less advanced tasks [144]. However, the construction sector will still have a higher demand for high educational level jobs in the category of New & Emerging Green jobs [143] - Table 14.

Table 14. Upskilling needs for Green New & Emerging green jobs category vs. green rival jobs in 2016 for manufacturing, construction and transport. Source: [143]

	New & Emerging			Green rival		
Sectors	High education	Medium education	Low education	High education	Medium education	Low education
Manufacturing	38.8	52.2	9.0	32.5	46.9	20.6
Construction	40.8	49.5	9.7	25.2	48.5	26.3

Transportation, storage and ICT	41.8	48.5	9.7	25.1	50.3	24.6

The shift from low education construction jobs to more educated ones is also supported by remarks on the influence of the circular economy on the labour market [134], which specifically state that the growth in construction employment will be concentrated on higher level roles and that high-skilled roles will replace lower-skilled ones. This shift is attributed to circular economy growth in science and engineering roles and in the need for specialised construction managers. The views of report commissioned by the JRC [132] agree with this notion and specifically mention that different stages of the greening process require workers with different skill levels:

— At first, higher-skilled roles are favoured for activities such as technology research.

— At a later stage, demands for lower-skilled labour increase.

Construction follows the general trend for the need of skilled labour in order to develop technology and processes for sustainable industry. However, its requirements for low-education workers are already at high demand due to the remarks presented in Section 5.4.1 when describing Green Increased Demand jobs: many activities of the construction sector, such as installing insulating systems, are common tasks of the construction sector for decades and constitute green jobs.

Such growth may result in skills mismatches if training and educational courses do not follow the need for new high education jobs on Green New and Emerging jobs. As argued in [132], STEM graduates and other workers with digital skills are in high demand and the construction sector must be aware of competition with other sectors in their recruitment.

5.5 Demographic issues: workforce characteristics

The building sector faces the challenge of attracting a sufficiently large talent pool with the right skills in an ever-changing employment landscape. In this context, the renewable energy and sustainable construction sectors have a different public perception than more traditional industries. Sustainable industries have a more positive image, especially among women and young people. The construction sector is traditionally male-dominated and characterised by an ageing workforce. In the green transition, it will be essential for the construction sector to attract more people into its workforce by expanding to different talent profiles, including women and younger age cohorts with increasingly digital skills [145]. The main influences on employment from a gender and intergenerational perspective are highlighted in the following sections.

5.5.1 Effect of aging

The limited, ageing, and inadequately skilled workforce in the construction sector could be a bottleneck for the building renovation flagship initiative of the new EU Green Deal since increased demand for renovation activities will require additional workers. The European Centre for the Development of Vocational Training (Cedefop) forecasts good employment prospects for construction workers. Up to 500 thousand new jobs are expected to be created in the 2020-30 decade, while 3 million construction workers will retire and need to be replaced [138]. The needs for future construction workers are regional-dependent with the Cedefop report [138] arguing that the employment change for construction workers between 2019 and 2020 varied between increases over 5% (Estonia and Ireland) and decreases of more than 5% (Austria, Latvia, Lithuania, Malta, Portugal).

The call for action to policymakers includes points on integrating skills and climate strategies, strengthening public-private partnerships, and providing incentives for technical education, apprenticeships, as well as upskilling and reskilling - which is a particularly relevant aspect in the context of transition to green jobs (Section 5.4.2).

5.5.2 Generational aspects and gender balance

A negative environmental and social image has an impact on the recruitment of new talent in traditional manufacturing sectors, which are unattractive to younger generations, particularly women, because of their impact on the environment and society in general. The EU construction sector is also characterised by a lack of attractiveness for younger workers. On the other hand, female participation and gender inclusiveness are increasing. Several initiatives are underway in the EU to make the construction sector more attractive to younger workers, to encourage apprenticeships and to improve the quality of vocational training programmes. This will contribute to the training of a high level of education workforce that complies with the requirements for Green New & Emerging jobs in construction presented in Table 14.

In the EU, and probably in other high-income countries, the loss of jobs caused by the COVID-19 pandemic hit low-skilled and young workers to a much larger extent than other worker profiles [146]. This is especially concerning because these workers are already in low-paid jobs, live in regions that are lagging behind, and are subject to a higher prevalence of temporary contracts [132]. Measures to promote their training for green jobs and related activities related to the greening of the construction sector should be promoted.

Women's underrepresentation in technical roles in construction is closely linked to the underrepresentation of female students in STEM education [138]. In 2017 in the EU-28, only 20% of all graduates at bachelor or equivalent level in '"Information and communication technologies" and only 27% in "Engineering, manufacturing and construction" were female and the fields of "Natural Sciences, Mathematics and Statistics" have a more gender-balanced distribution of graduating students than "Engineering, Manufacturing and Construction" [147].

Concerning female employment by the construction sector, EUROSTAT statistics for the year of 2018 [148] show that 45% of all employees aged 15 to 64 years in the EU28 are women (all NACE activities), but that the percentage of female workers in the construction sector drops to 10%. When analysing the construction sector, the Cedefop report [138] states that the ratio of female construction workers (considered as those that do general construction tasks during a construction project) is even lower at just 3%. Measures to improve the qualification and training of construction workers to be developed within the scope of the promotion of sustainability in the construction sector should account for this fact and include measures that promote gender inclusiveness.

5.6 Discussion

The workforce of the construction sector is comprised of workers with different background, specialties and levels of education. The sector employs about 10% of the EU workforce and has small representativeness of female workers (10% in the EU 28 vs. an average of 45% for all sectors). Occupational transformation must be ensured in order to avoid that the shift towards circularity models in the construction sector results in unemployment issues, particularly at the local level. The risk of job loss and social concerns due to circularity is especially relevant in the construction sector because over 99.9% of its companies are small enterprises.

Furthermore, the Covid-19 pandemic was followed by a war and both caused serious disruption of supply chains [138] and affected employment. The EU was already taking up measures to promote circular economy models and industrial digitalisation and the construction sector had already been identified as a key target for both paradigm changes. Therefore, the current context favours integrated measures towards gender balance, circular economy models, the use of local resources and the digitalisation of the construction industry. Such measures have potential to decrease the demand for jobs in the construction sector because highly successful circular economy will, ultimately, result in less demand for the production of new building elements [134]. This is expected because fully functioning circular models will result in payback and loan schemes, modular construction developed with DfARD concepts, and other innovations that will increase the reuse of elements of buildings.

Paradoxically, the decrease of job offers may be accompanied by a shortage of labour in the long-term. The EU workforce is ageing and is facing competition from other sectors that are attractive to younger workers.

In the short-term, job losses in construction due to circular economy are non-consensual. Since these hypothetical job losses are motivated by reuse and recycling, they are correlated with increased demand of jobs in the recycling sector, including jobs in CDW management. The potential for occupational transformation between these sectors is large since the activities and know-how of most construction workers are in line with the demands in CDW management plants. Nonetheless, this issue is expected to be a local problem that may not represent the general construction sector, especially when considered that there are reports of lack of workers for construction [138].

The several innovations that come with the sustainability challenges posed on the construction sector require the training of present and future workers, in topics ranging from the concepts on sustainability evaluation, sustainable design and demolition including DfARD, reuse-routes, energy efficiency and digital and automation methods in construction.

There is already a trend towards the increase of green jobs in construction and the sector already has a large share of green jobs. Data from 2006 and 2016 suggest that green job requirements on the construction sector range from low to high educational levels The increased demand for green jobs in construction includes jobs that have existed for several decades (no training needed) to new jobs that require specific and skilled workers.

A key issue is that the success of the paradigm shift towards circular and green construction requires that the end users of buildings understand how to evaluate the sustainability of construction. Currently, end users of buildings are not aware of many technical aspects related to comfort, energy consumption and sustainable design and materials, notwithstanding the large amount of research and technical solutions available in the market. A clear example is RAC: this type of concrete is either unknown, or its use is avoided due to misconceptions about its safety. The need to facilitate the communication of sustainable construction and to compare the sustainability of buildings is clear and, in this context, the European Commission recently launched Level(s).

Box 9. Overview of the effects of circularity in construction in the employment

- The construction sector employs 9% of the EU workforce and is overwhelmingly composed of SMEs.

- Male workers predominate, the EU demography is ageing and lack of workers may become an issue.

- Short-term: circular models may decrease construction jobs and increase recycling ones. Possibility for occupational transformation?

- Sustainable and circular construction requires a specific workforce that includes higher-educational-level workers.

- Higher automation in processes paves the way to promote gender balance in construction.

- The demand for workers in digital processes in construction faces competition with other sectors.

- Level(s) improves communication between stakeholders and guides non-informed building users towards sustainability assessment. Its use should be promoted.

Measures towards the circularity in the construction sector should account for several factors:

— Local effects on jobs and opportunities for occupational transformation.

— The ageing workforce in the EU.

— The opportunity to improve gender balance in construction.

— Novel green jobs require workers with both low and high levels of education and their hiring may be a bottleneck for the greening of the sector.

The higher prevalence of SMEs should be considered when defining policies, since financial incentives may be required to allow local companies to adapt to circular construction.

6 Barriers to and measures for market uptake of recycled aggregate concrete by the concrete industry

6.1 Context for increased market uptake

RAC is a very suitable means to recover CDW without resorting to downcycling, at the same time that the extraction of NA decreases and the carbon footprint of concrete is reduced. As understood in Sections 3 and 4, standards and national regulations for the use of RA in concrete are available. Furthermore, RA of good-enough quality - that is, RA certified for concrete (EN12620 [21]) may be produced with equipment that is common in the construction industry and the production process of RAC is not largely different from that of NAC [20, 25]. However, the current market uptake of RA is small. This is due to several reasons that are presented in this section.

The CDW recycling industry is a high opportunity market in the EU [33], due to Societal awareness and because of the expectation of future EU policies that will promote CDW recovery - in this context, the EU Green Deal [3] and the Circular Economy Action Plan [5] are emphasized. Effective policies to promote the recovery of CDW should account for the high potential of RA for use in concrete. Therefore, an analysis of the current obstacles to increased market uptake and of possible measures that would promote RAC as a conventional structural material is needed.

As a first approximation, the conditions for recycling CDW as RA used in concrete are [149]: technical knowledge regarding RA and RAC, the existence of abundant CDW, a market for RA and the viability of investment in technology for the production of RA certified for concrete. Technical knowledge concerning RA and RAC is available (but not widespread through all agents of the concrete and CDW management industries) and the overwhelming generation of CDW (over 35% of all waste produced in the EU27 - see Section 2) is the main motivation for policies to promote RAC use. However, there is no clear market for RA with quality for concrete and this is a strong argument against such investment in CDW plants.

Currently there is a strong dichotomy against the use of RA in concrete:

- Despite the possibility of producing RA with common technological processes (that is, the separation of concrete waste through sorting followed by crushing and sieving) that are less costly than those used in NA (particularly, in the case of quarried NA, which require drilling and explosives and are usually further away from urban centres than CDW plants), RA certified for concrete and with proper grading are typically more expensive than NA due to economies of scale and lack of appropriate equipment in CDW plants (RA certified for concrete are produced in smaller quantities than NA and typically using more complicated production processes than NA since the majority of CDW plants are designed to produce RA for road construction, which have different requirements in what concerns grading and overall quality).
- Because of the apparently higher cost of RA, concrete producers opt for NA since they find little incentive in adapting their industrial units and production processes to accommodate additional suppliers and materials, especially when considering that the new material (RA) has worse qualities than the NA typically used.

There is no argument against a concrete producer choosing its raw materials based on cost and quality [150], and on the market opportunities they provide - e.g. a concrete producer may find incentive in producing RAC if public tenders stipulate that RAC must be used in the job (a rare occurrence nowadays). Due to this, it comes as no surprise that conventional concrete producers very rarely also produce RAC and that RA certified for concrete is difficult to find in most countries.

Surveys sent to stakeholders strongly support the idea that a major obstacle to the increased market uptake of RAC is the scarce availability of RA certified for concrete, therefore:

- If concrete producers in countries where RAC is seldom (if ever) produced, attempt to establish supply chains for RAC production, they will encounter strong difficulties in finding a supplier of RA with adequate quality.
- In countries where RAC is produced, attempts to increase the uptake of RA by the concrete industry will face strong challenges due to the difficulty in procuring additional sources of RA.

The aforementioned surveys were sent to several stakeholders and the answers cover over 3000 ready-mixed concrete plants (6 Member States, the United Kingdom and a global player), 3500 aggregate extraction sites (from 6 Member States and the United Kingdom), and 295 precast plants (from 3 Member States). There was a bias towards answers from top performing countries in terms of RA use (the Netherlands, Belgium, Germany, United Kingdom); therefore, the overall situation in the EU is expected to be characterized by smaller market uptake of RAC and even more difficulty in finding RA certified for concrete than what is reported here.

Figure 16 presents the answers of ready-mixed plants to the availability of RA certified for concrete (left) and to the frequency of RAC production (right). Strong difficulties in procuring RA are observed, with no country reporting that RA are easy to procure and only two countries (Austria and the Netherlands) reporting that RA are an available raw material. Emphasizing the fact that frequent production of RAC requires availability of RA, Austria and the Netherlands are also the two only countries in which RAC was reported as a standard product.

Figure 16 Answers to surveys sent to ready-mixed plants associations and companies. Availability of recycled aggregates fit for concrete and frequency of recycled aggregate concrete production

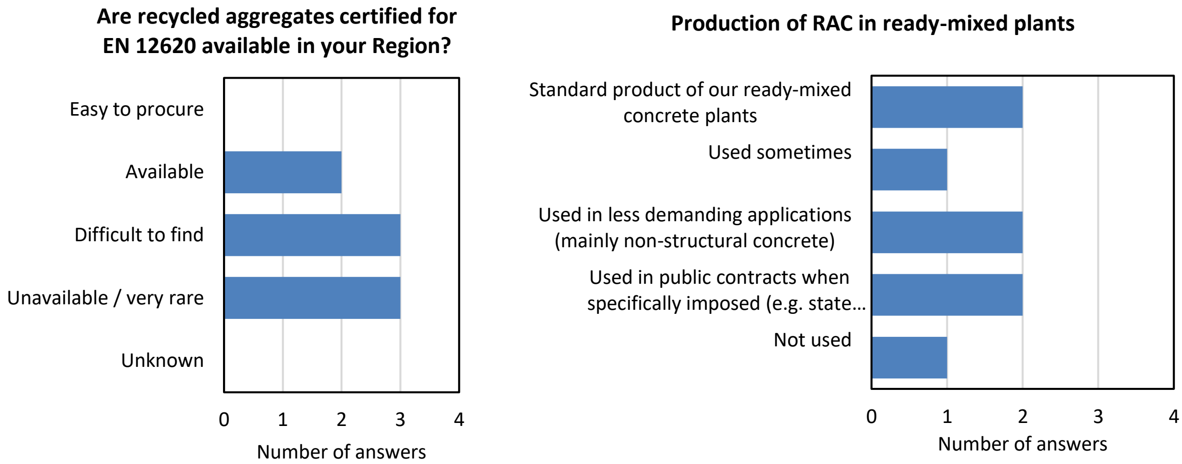
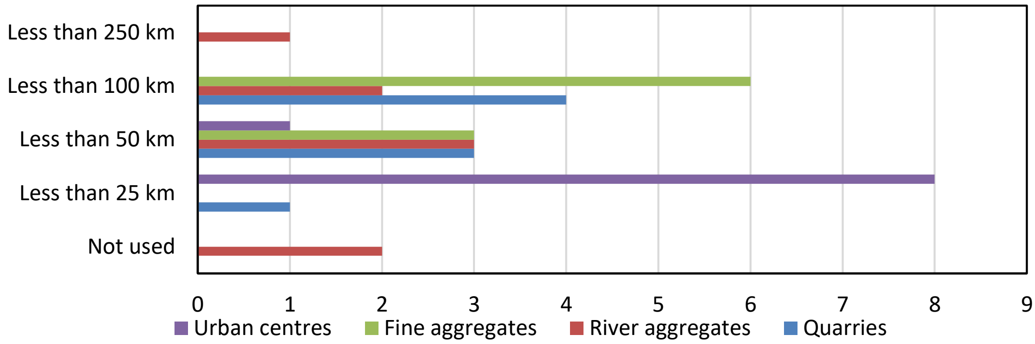


Figure 17 compares transport distances between ready-mixed concrete plants and different types of industrial unit that source aggregates. The distance between concrete plants and urban centres is also included since urban centres are where most CDW is generated. Assuming that urban centres have CDW management facilities nearby, the potential of RA to reduce the transport distances of the concrete production supply chain, at economic and environmental gain, is obvious.

Figure 17 Answers to surveys sent to ready-mixed plants associations and companies. Transport distance between ready-mixed concrete plants and different types of industrial unit



Furthermore, answers to other questions sent in the surveys show that:

— The operational challenges for RAC production are overcome with minor training, or with training directed at two specific topics that are easily overcome (the control of the water content of RA and adaptations to concrete mix design to offset the effects of RA).

— Separated space at the concrete plant for RA storage is an issue and may prevent the use of RA in some ready-mixed plants.

— Estimates by four of the respondents show that the potential ready-mixed concrete plants in which RAC may be produced assuming that RA certified for concrete are available differ from country to country, with answers ranging from 20% to 100%. This shows that RAC is not a solution for every regional context!

— Whenever the detrimental influence of the RA on the properties of RAC is found to be significant, there is a clear preference of the majority of concrete producers to reduce the RA incorporation ratio as a mitigating measure.

— One respondent argued in favour of advanced RA production methods to produce RA with very similar quality to that of NA. His/her reasoning was that the procedures to use of very high quality RA in concrete are practically the same as those when NA are used and this eliminates the need to train industrial agents towards RAC production.

— Half of the respondents are open to the future use of fine RA in concrete, notwithstanding the largest technical challenges (which are discussed in Section 3.3.1) and the fact that most regulations currently bar the use of such aggregates in concrete (Section 4).

— Only six respondents answered to a question regarding how much time is needed to adapt their ready-mixed plants for the production of RAC. Two respondents answered less than three months, three answered less than six months and a single one answered less than one year.

The answers regarding technical and operational aspects were expected: since the production of RAC is made with the same equipment and technology used to produce NAC [1], with only minor operational changes [25], hypothetical adaptations of ready-mixed plants and production processes are not an obstacle when compared to the need of a constant supply of RA certified for concrete and with the existence of a market for RAC.

The survey sent to producers of aggregates agrees with the findings of the survey sent to ready-mixed concrete producers. Most respondents claimed that RA certified for concrete are rarely produced and that the market uptake of RA in their country is either for unknown purposes or for backfilling and road construction. The share of recycled aggregates sold for the production of concrete varied between 0 and 3%, except for the case of Austria - which was stated as "around 10%" (Austria is one of the two countries whose ready-mixed concrete respondent reported that they produce RAC frequently) and Belgium - which was stated as "Unknown, probably below 10%".

The share of RA market uptake by the concrete industry is very small and the technical and regulatory aspects and the other answers to these surveys (Sections 3 and 4) strongly suggest that the main reason for such low market uptake of RA is the lack of a stable supply of RA certified for concrete near the majority of concrete producers.

Box 10. Recycled aggregate availability and recycled aggregate concrete. A supply chain issue?

Surveys sent to stakeholders strongly support the idea that a major obstacle to the increased market uptake of recycled aggregate concrete is the scarce availability of recycled aggregates fit for use in concrete:

- In countries where recycled aggregate concrete is not produced, the procurement of recycled aggregates adequate for concrete will encounter strong difficulties.

- In countries where recycled aggregate concrete is produced (sometimes): attempts to increase the uptake of recycled aggregates by the concrete industry will also face strong challenges in procurement.

- There are no major operational difficulties for recycled aggregate concrete production.

- Some concrete plants may require adaptations in order to use recycled aggregates (namely bins and feeders).

- Not all concrete plants may be adapted for the production of recycled aggregate concrete. This is a local issue that must be evaluated on a case-by-case basis.

- The transport distances of recycled aggregates to concrete producers is typically shorter than that of natural aggregates: this results in economic and environmental gains.

- CDW plants that do not produce recycled aggregates frequently do not have efficient production (namely for sorting and grading of aggregates for concrete use). Due to this, recycled aggregates may be more expensive than natural aggregates, at least in the short-term!

Major observation: all respondents of the survey for ready-mixed concrete production, including a global player, stated that a main challenge for the production of recycled aggregate concrete is the procurement of recycled aggregates with quality for concrete!

The answers to the surveys sent to precast plants are not explicitly included in this section, since precast producers already recover the concrete waste produced in their own plants, which does not require separation from other constituents and has well-controlled properties and composition. Therefore, there is little incentive to the incorporation of RA produced from general CDW in precast concrete. From a technical and logistic standpoints, all remarks regarding ready-mixed concrete (e.g. space and investment in bins and hoppers, need for a reliable and constant supply of RA) are also true for precast RAC production and the arguments presented in this section agree with the answers to the surveys sent to precast producers.

The answers to the surveys agree with the data reported in Section 2 about CDW recovery: most Member States comply with the target CDW reuse/recycling of EU Directive 2008/98/EC [1] but the potential for RA use in concrete is severely underexploited and this leads to landfilling, backfilling and other downcycling of what is a suitable secondary raw material for concrete, the second most used material worldwide after water.

These low quality applications of RA are a short-term solution and the consistent downcycling of the inert fractions of CDW for transport infrastructure will result in future generations having to cope with shortage of mineral and land resources [151]. Furthermore, the study by unit B.5 of JRC [29] presented in Section 3.3.5 showed that higher quality recycling is associated with CO_2 reductions. Higher ratios of concrete reuse and higher added-value recycling of concrete waste may potentially decrease CO_2 emissions by 1.08 million tonnes/year in the EU27, which is a marginal amount compared to the CO_2 production of European industry.

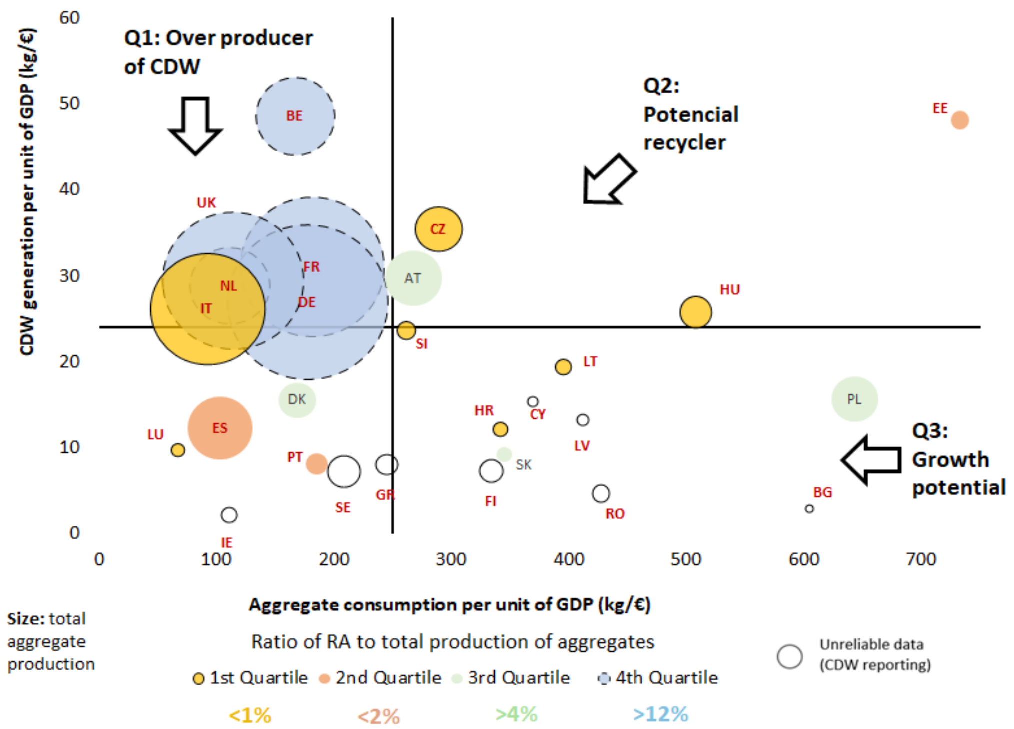
Prior to understanding barriers and measures for increased RA uptake, an overview of the different status of the Member States is now presented. Section 2 presented the current status of CDW recovery in the Member States. That section repeatedly remarked how part of the data are unreliable due to several aspects (e.g. issues in data reporting due to different classification criteria between Member States and the lack of enforcement/monitoring of CDW management protocols). Nonetheless, it was found that there is large variability between Member States not only in terms of CDW generation, but also of type of CDW treatment. Because of this variability, effective measures to promote the uptake of RAC in some Member States are not applicable to others. Figure 18 is a classification of the EU Member States and the United Kingdom in terms of:

— The production of NA and the generation of CDW by gross domestic product (GDP), since this is a good normalisation parameter that represents both the size of the population and the richness of the country.

— The absolute value of the generation of CDW, which is given by the size of the circles of each country.

— The ratio of the production of RA in relation to the total production of aggregates, which is a measure of the Member State's accomplishments in CDW recovery and is presented by quartiles of different colour.

Figure 18 Quadrants for classification of EU27 and the UK by potential for CDW recovery as RA



The origin of Figure 18 is the mean CDW generated by GDP and the mean aggregate production by GDP of the countries analysed. Malta was excluded since their data were clear outliers.

The data are sourced from EUROSTAT [10, 30, 41, 152, 153] (CDW generation and GDP) and UEPG [9] (production of NA and RA). As in the case of Section 2, part of the data used to produce Figure 18 are not reliable (e.g. Italy and Czechia reported to UEPG that no RA were produced in their countries in the year of 2019) and the figure should be analysed with some caution.

The distribution of countries across classifications is not uniformly spread and is well characterized by the four quadrants presented in Figure 18. Unless stated otherwise, all remarks made in the next paragraphs concerning CDW generation and aggregate production are made per unit of GDP.

Quadrant 1: Over producers of CDW

The countries in this quadrant generate significant amounts of CDW but their production of aggregates is below the average. In absolute terms, these countries are both the highest producers of NA and the highest generators of CDW. Their profile is the following:

— These countries have the largest relative production of RA, except for Italy, which reported no production of RA, which is an anomaly that is possibly due to most RA produced in Italy being either processed onsite or by agents that are not affiliated to the UEPG.
— The quadrant includes countries were access to NA is scarce (the Netherlands and Belgium) and the top 5 biggest economies in the EU27+UK, with the exception of Spain.
— This quadrant has mature economies with a well-established construction sector and aged buildings (mostly from after the Second World War and 1960-70). Due to the age of the building stock [27], its renovation rate is quite high, will be further promoted [6], and this is a major driver for an expected high generation of CDW.
— The high RA production rates show that CDW management infrastructure already has broad coverage and CDW recovery as RA is a typical option. However, further reuse and recycling is needed in order to cope with the amount of CDW being generated, namely through improved recycling processes, selective demolition and design methods that allow higher reuse of materials and structural elements.
— Belgium generates a very large amount of CDW and should take measures towards its reduction. Long-term investment in innovation aiming at popularising DfARD and short-term strategies such as measures to promote selective demolition and the investment in high quality RA production facilities are advised.
— Priorities for this quadrant are the production of RA with quality for concrete, societal awareness towards RAC and for circular economy models in the construction sector, the development of high quality RA production processes and the reduction of the generation of CDW, namely through design for deconstruction and selective demolition with high material reuse.

Quadrant 2: Potential recyclers

This quadrant is made up of just four countries, which are average producers of CDW in absolute terms. Poland could be part of this group if data in absolute terms were analysed, but its mean CDW generation per GDP is too low. The quadrant is characterized by high generation of CDW and high consumption of NA, meaning that there is a large potential supply of RA at the same time that there is a large demand of aggregates for construction.

— Except for Austria, the countries in this quadrant have small relative production of RA (third and fourth quartiles), meaning that this quadrant has the most potential for increased CDW recycling, since the potential for RA use is not currently being explored.
— The small recycling ratios of this quadrant hint that the geographical coverage of CDW plants that produce RA is not broad and that there is no societal awareness towards circular economy models.
— Priorities for this quadrant are the development of CDW management infrastructure with broad regional coverage and CDW recovery as RA for all types of applications, including low added value ones (e.g. road construction). This requires both raising societal awareness towards the need and safety of construction products with recycled content and the development and enforcement of legislation that creates favourable conditions for the development of CDW plants (e.g. simplified permit procedures to establish CDW plants, requirements of minimum content of recycled materials in public tenders, landfill taxation).

Quadrant 3: Growth potential

This quadrant concerns countries that currently generate less CDW than the mean but consume more aggregates than the mean. The quadrant is composed of 10 countries, five of which reported in the Deloitte report to the DG ENV [8] as having unreliable data in what concerns CDW generation and treatment.

— Except for Poland and Finland, the total production of aggregates is small in absolute terms.

— Three of the five countries with reliable data are amongst those with relative production of RA below 1%, therefore there is room to drastically increase CDW recycling.

— The characteristics of this quadrant are particularly contradictory and the actual status of these countries should be validated in the future: high consumption of aggregates should be coupled with high generation of CDW. Countries in this quadrant should promote guidelines in data reporting and pre-demolition audits.

— Priorities in this quadrant are the increase of societal awareness towards circular economy and CDW generation (high consumptions of NA in the present will lead to high generation of CDW at the end of the service life of the buildings under construction), the development of a CDW management infrastructure with broad coverage, the increased use of RA for all types of applications, including low added value ones, the improvement of data reporting and the enforcement of legislation on CDW management and treatment.

— <u>Quadrant 4: Frugal countries</u>

The seven countries of this quadrant both generated less CDW and produced less aggregates than the average. The quadrant includes three countries reported in the Deloitte report to the DG ENV [8] as having unreliable data.

— Countries in this quadrant conform to the aim of low consumption of aggregates and low generation of CDW. However, except for Denmark, all countries with reliable data are underperforming in what concerns CDW treatment.

— To direct CDW towards adequate recovery, namely by producing RA, the countries in this quadrant (excluding Denmark) should enforce pre-demolition audits and develop mechanisms that aim at the use of these audits to direct CDW towards rational recovery.

— Due to the small share of RA production in this quadrant, higher value applications (including RAC) should be promoted. This would raise confidence in the use of RA and would result in the adaptation of CDW plants for the production of RA certified for concrete.

— As expected and also observed in Quadrant 3, the countries with unreliable data are those where the reported CDW generation is the lowest. This implies that the actual CDW generated in these countries is potentially higher.

— Priorities for this quadrant are the production of RA with quality for concrete, societal awareness towards RAC and the circular economy in construction, the improvement of data reporting and the enforcement of legislation on CDW management and treatment.

The priorities for each quadrant and the measures proposed in Section 6.3 are supported by literature review and by the authors' experience in CDW management and RAC. <u>References for key concepts are provided next</u>:

— Good geographical coverage of CDW plants is a main requirement for high recycling ratios [8, 33, 151].

— Landfill bans and high landfill taxes, especially in the case of mixed CDW, are instruments that are associated to countries with high CDW recovery ratios (Denmark, Germany and the Netherlands) and make both CDW management and the production of higher quality RA more attractive [154]. These instruments are chiefly used to make both recycling cheaper than landfilling and RA cheaper than NA [8, 33, 154, 155].

— Penalties for non-compliers with legislation are paramount to successful recycling policies [155].

— The monitoring and stringent enforcement of regulations is paramount in order to promote sound CDW management, even in countries that are good performers such as the United Kingdom [156].

— The cost of RA certified for concrete is high when the producer of RA does not produce this type of RA routinely.

— Scarcity of mineral resources and of land are incentives for CDW valorisation as RA [151].

— Green public procurement that stipulate minimum contents of recycled materials are a way to create a market for RA [157], promoting their routine production. Furthermore, the construction sector has been identified by the European Commission as a priority sector for green public procurement [158].

— Low recovery ratios of CDW are associated with lack of regulations (including their enforcement) and absence of green public procurement [151].

— Technological innovations in CDW management, modular construction methods, deconstruction, selective demolition and DfARD promote the market uptake of RA and the reuse of construction elements [151, 157].

— From the perspective of companies, the main drivers for CDW recovery as RA are [151, 159] promoting the image of the company as environmentally-friendly and demands of clients concerning sustainable practices, avoiding disposal costs of CDW, and the enforcement of environmental policy by governmental institutions.

A report commissioned by the DG Internal Market, Industry, Entrepreneurship and SMEs [160] highlighted the main different between Member States that are deemed as advanced recyclers (Germany, Netherlands, Denmark and Belgium, all part of Quadrant 1) and Member States that are lagging behind (Czechia, Italy, Malta, Romania, Poland, Portugal, which represent all quadrants of Figure 18). The findings are summarized in Table 15.

Table 15. Main findings of differences between advanced recyclers and lagging Member States [160]

Topic	Observations and differences
Costs	Green public procurement is rarely used to promote RA in lagging Member States and should be used more often In the case of advanced recyclers, Green public procurement has the potential to improve the uptake of RA
Gate fees	Typically high in the case of advanced recyclers Lagging countries do not enforce monitoring and landfilling costs are lower than gate fees
Landfilling: costs and allowance	Costs are higher in advanced recyclers and very low in lagging Member States Landfilling of recyclable materials is banned in some advanced recyclers Landfilling facilities are not as close to CDW generation sites as recycling facilities in the case of advanced recyclers
Generation of CDW/km^2	Smaller generation (so, smaller recycling market and smaller societal awareness of the environmental problems caused by CDW generation) in lagging Member States
Labour costs	Smaller in lagging Member States. This increases the viability of CDW management methods that include hand sorting and other manual activities
Regulatory framework	Landfill bans in some advanced recyclers and absence of bans in lagging ones The enforcement of selective deconstruction could encourage better quality products in advanced recyclers
Certification procedure and costs	Heterogeneous amongst Member States A trend towards lagging Member States having gaps in regulation is observed
Conventional recycling technology	In lagging Member States, additional conventional recycling sites are required to ensure geographical coverage and bulk capacity
Specialized technology (high quality recycling)	Present in advanced recyclers only It depends on scientific and innovation interests and legislative requirements
Acceptance of recycled materials	In advanced recyclers RA are undergoing gradual public acceptance Green public procurement should have a major role in promoting their suitability for use in RAC. In lagging countries, the acceptances of RA is mostly limited to low quality uses (e.g. road construction)

All quadrants presented in Figure 18 have room for improvement, especially in what concerns the end use of the RA to avoid downcycling of concrete waste (the major portion of CDW).

Due to the different realities between quadrants and inside them (even at the local level), it is understood that ideal conditions for increased used of RAC depend on regional aspects such as the availability and proximity of stable sources of NA and of RA with quality for use in concrete, the technological level and maturity of the CDW management industry (including the capacity for investment), the preference of precast/modular construction and/or of whole life cycle design (including end of life), and regulations that either promote the use of RA in RAC or that address the issue indirectly through forbidding/ severely charging the landfilling of recyclable CDW or that tax the extraction of NA in regions where natural reserves are scarce.

Box 11. Main ideas that must be acknowledged for sound policies for increased recycled aggregate concrete applications

- The same measure applied to different local realities could lead to different outcomes.

- The coverage of CDW facilities and the stable production of high quality recycled aggregates must come before the enforcement of recycled aggregate use.

- Not all recycled aggregates are fit for concrete and not all concrete specifications are suitable for incorporation of recycled aggregates.

- Recycled aggregates that include a relevant amount of ceramic and other lower quality waste are suitable for road construction and should still have a minimum amount of concrete waste to ensure appropriate quality.

- Concrete is a material with a broad application range, from non-structural elements with few technical demands, to high-performance concrete that must comply with strict requirements.

- The understanding of the barriers for recycled aggregate use in concrete is paramount to the assessment of proper measures.

- The coarse fractions of recycled aggregates may be used in concrete. Smaller fractions of recycled aggregates can be used in complementary markets (e.g. as replacement of the calcium and silica constituents needed for cement production) or in concrete, if the recycled aggregate is produced using advanced production equipment.

- Unreliable and/or inconsistent data reporting prevent the proper assessment of the CDW recovery performance of a region as well as the assessment of the effectiveness of measures.

6.2 Barriers to market uptake of recycled aggregate concrete

This section identifies barriers to the market uptake of RA, resulting from the ideas presented in Section 6.1. Its motivation is that holistic appraisals of the barriers for increased market uptake of RA and RAC are lacking [161], with scarce assessments of technical, economic and regulatory barriers. [149].

Table 16 lists the barriers, which are divided by categories (technical, economic, regulatory and engagement, training and awareness).

The main technical barriers are:

- The lack of enforced and easy to implement certification schemes for the properties of RA that would assist concrete production when purchasing RA and in developing concrete mix designs.
- The overwhelming majority of RA are not certified for EN12620 [21] (this is expected to be fixed through investment in CDW plants and by establishing a market for RA for concrete).
- Fine RA and recycled fines have no clear entry point into the market. High quality fine recycled aggregates have been successfully used in concrete and some companies produce them, but this is rare.

Operational adaptations to produce RAC are not a major concern, as understood from the surveys sent to concrete producers. From a technological standpoint, the production of RAC is made with the same equipment used to produce NAC and even though training may be required, workers are expected to readily adapt to a few key points that should be accounted for when producing RAC (such as their water absorption). In what concerns casting and curing, those activities that take place after concrete is mixed, no relevant differences are found [20].

Since the most sustainable and efficient way of incorporating RA is by partial replacement of NA, concerns about the quality and/or heterogeneity of the RA can be minimized by concrete producers through initial mix design tests to define a safe incorporation ratio of RA. These mix design studies are not different from those routinely carried out by producers of concrete.

From a regulatory standpoint:

- Concerning CDW management, the main issues are the lack of enforcement of regulation (in some Member States), non-homogeneity and lack of reliability in data reporting (hindering the monitoring of CDW management performance at the European level), and the lack of consistent and clear guidelines and excessive time spent in requesting permits to manage CDW.
- The lack of clear criteria to differentiate between a material and a waste is also a main obstacle [162], since it

is not clear when waste under processing ceases to be waste and becomes a material from a regulatory standpoint. The classification of what could be materials as wastes limits their potential use as a secondary raw material.

— Indicators to monitor whether production practices are environmentally-sound are lacking [163].

Part of the answers to the surveys stated that the maximum admissible incorporation ratios of coarse RA could be higher and that the use of fine RA is should be allowed. However:

— Concerning the use of RA in concrete, the main issue is not the maximum amount of RA that may be incorporated in concrete (this is discussed in Section 4), but rather the lack of consistency in regulations between Member States and the lack of a simple performance-based certification for RA that would allow easier classification and marking, facilitating the entry of RA into the concrete market.

— The RA producers that are currently able to produce fine RA with quality for use in concrete are very scarce in most countries and barring the use of fine RA is chiefly a limitation in Member States of Quadrant 1.

— Another relevant matter for Member States that are at more mature stages of CDW recycling and reuse is that standards and policies are aimed at linear material recovery. Greater resource efficiency and better circular economy models can be reached if fully circular models are considered in regulations, favouring multi-recycling of materials (e.g. policies should not encourage building components that are totally composed of recycled materials but that cannot be disassembled and recycled at end of life) [164]

Concerning economic barriers:

Economic barriers are a major obstacle and concern both for producers and buyers of RA:

— The RA market started with RA for unbound use and, in most countries, adapting plants for efficient production of RA for use in concrete requires investment. Since most CDW plants are SMEs, funds for investment in industrial equipment are not plentiful. Furthermore, such investments are hard to justify from a business perspective since there is no current market for RA for concrete and there is uncertainty about when such market will take off;

— Due to economies of scale in the production of NA and because CDW plants do not have optimized processes for the production of RA for concrete, in many cases the procurement of NA is cheaper than that of RA.

The lack of funding for investment in equipment for CDW plants is a particularly relevant barrier [33], since CDW companies are typically SMEs and the CDW plants of most Member States were designed to produce RA for unbound use (see Section 2). Because of differences in requirements between RA for unbound use those for concrete (e.g. composition, overall quality and grading), the production of RA in such plants must be carried out outside of their main production line and with less-efficient equipment at higher time, workmanship, fuel consumption and cost demands. For example, in the case of stationary plants:

— Instead of the stationary crusher and sieves (usually trommel screens), mobile crushers and equipment may need to be assigned (at the plant) to this task.

— This means that transport between processing stages will likely occur using dumpers instead of conveyor belts.

— The absence of specific sorting equipment (e.g. air shifters) will also increase labour costs due to less automated sorting.

These barriers are strongly connected and are especially concerning because, when the disposal of CDW and/or the procurement of NA are cheap, there is virtually no incentive to use RA [150, 162].

Other relevant economic barriers are also presented in Table 16. They are not discussed here because the respective entries of the table are self-explanatory.

On the topic of engagement, training and awareness:

— Society and many agents of public authorities and of the construction sector do not prioritise CDW management and circular economy and some representatives of public authorities and managers of companies are not fully knowledgeable on sustainability concepts [163].

— CDW management facilities do not incorporate state-of-the-art knowledge and expertise in their production processes (this barrier is connected to a similar one in economic barriers).

— Difficulties in the establishment of long-standing relationships between agents of the CDW and construction sector due to inherent specificities of construction activities.
— Most concrete producers lack technical knowledge on RAC and have scepticism towards its properties and applications.
— General lack of trust in recycled construction materials and products across all agents of the sector. As an example, lack of trust in RA is considered by stakeholders as a main barrier for higher market uptake in Germany [160], with examples of public tenders that, instead of promoting RAC, discriminate it [160].

In Table 16, some entries are associated with more than one type of barrier. This occurs because the type of barrier is defined from a problem-solving perspective. For instance, in countries were landfilling is cheap, this constitutes not only an economic barrier (recycling CDW becomes less attractive), but also a regulatory one (regulations to further tax or forbid the landfilling of recyclable CDW would overcome this barrier).

Table 16. Barriers to the increase of the market uptake of recycled aggregates and recycled aggregate concrete

Type of barrier	Description
Regulatory/Economic	Lack of CDW infrastructure with geographical coverage [33, 120, 165-167]
Regulatory	Permits to receive and treat CDW may take time and clear guidelines for permit requesting may not be available
Regulatory/Engagement, training and awareness	Reluctance of local authorities in authorising CDW management facilities, including in regions where coverage is an issue (e.g. France) [33]
Regulatory	Different public agencies do not have consistent and clear guidelines and regulations for CDW management [33]
Technical/Regulatory	The rational valorisation of CDW is hindered due to uncertainties in the materials of demolitions and in the CDW that arrives at a CDW facility [4]
Technical	Quality of RA and CDW is heterogeneous [120, 165], posing technical concerns
Economic	In the absence of specialized equipment for sorting, mixed CDW streams are too costly to sort and RA become expensive to produce [33]
Engagement, training and awareness	Lack of knowledge in setting up CDW plants, resulting in inefficient productions of RA (at worse quality and higher cost) [33, 164]
Engagement, training and awareness	Lack of high quality CDW recycling (e.g. to allow high quality RA and the use of fine RA), notwithstanding scientific knowledge being available [33, 120, 165]
Economic	Overall economic viability (cost of NA vs cost of RA, cost of recycling, cost of landfilling) [166]
Economic/Regulatory	NA are plentiful, available nearby and cheap in some regions [13, 33, 164] and RA may be more expensive than NA [120, 160] [156] [159] [168]
Economic/Regulatory	Lack of a market for RA prevents investment in CDW plants [33, 159]
Economic/Regulatory	Landfilling, when legal, is frequently the most economically-attractive option for companies (insufficient taxation and lack of landfill bans) [33]
Regulatory	Illegal landfilling, due to costs and absence of close CDW management plants [33]
Regulatory	Inefficient valorisation of CDW is not penalised and environmental benefits are not reflected on costs [159, 167]
Economic	Low market value of aggregates implies that investment in CDW plants may only return profit after long periods [159]
Economic	CDW plants are mostly SMEs with difficulties in scaling up businesses and improving quality of production [151, 168]
Regulatory/Engagement, training and awareness	Some public tenders bar the use of RA [159]

Regulatory	Absence of guidelines or regulations for End of waste criteria and assumption by regulations that most products of construction and demolition should, by definition, be classified as waste [160]
Technical	Steady supply of RA to meet demands [120, 165, 168]
Technical/Regulatory	Lack of standards/framework for RA use in concrete [165] or standards in use are not harmonized in the European space [169]
Regulatory/Technical	Standards treat recycled aggregates as a different type of aggregate [120], creating scepticism (but all NA are treated as the same, even though they can be significantly different)
Regulatory	Lack of reliable statistics regarding the types of CDW generated, preventing sound evaluation of CDW valorisation status [33, 163]
Regulatory	Lack of monitoring and enforcement of legislation (e.g. illegal landfilling, minimum contents of recycled materials in public works, ...) [8]
Regulatory	Lack of standardized European-level statistics on concrete recycling, facilitating monitoring and discussion between stakeholders [120]
Engagement, training and awareness	Lack of interest in waste management (including CDW) and use of recycled materials in construction by all actors [167], including at the educational level in some Member States (e.g. Croatia and Cyprus [33])
Engagement, training and awareness	RA are perceived as of low quality [33, 120, 156, 159, 160, 166, 168]
Engagement, training and awareness	Concrete producers are not experienced in RAC production [168]
Engagement, training and awareness	Skill mismatches (see Section 5) between the needs of the workforce and those available [135, 163, 168] (CDW industry , concrete industry, contractors and designers, and authorities/policy makers)
Engagement, training and awareness	Difficulties in communication/coordination between stakeholders and between agents of the construction industry [45, 159, 166]

The different barriers identified here RA are present in virtually all Member States, albeit with different relative importance. This is a very important aspect that is caused by the specificities and local character of the construction industry. The quadrants presented in Figure 18 can be used as a rough approximation of the status of the Member States, as presented in Section 6.1. A similar reasoning is valid for the barriers within each Member State, where local/regional variability is expected [162].

Two clear examples are provided on the location-dependent character of these barriers:

— Local differences: coverage of CDW facilities, which is directly related to the availability and cost-competitiveness (due to transport distance) of RA. Urban centres typically have facilities in their vicinities and this barrier is a larger problem in rural areas.

— National differences: investment needs in CDW plants. This is an especially pressing matter in Member States where the economic environment is more difficult (typically, those with lower GDP/capita, which are in Quadrants 2, 3 and 4).

Regional conditions will always influence the market-competitiveness of RA [162] and this should be accounted for when defining local targets for monitoring purposes.

This section concludes that, when the priority is to ensure that underperforming Member States increase their market uptake of RA, technical barriers are few and most of them are easy to circumvent (e.g. by reducing the amount of RA in concrete or by making rational adjustments to concrete mix design) and that the main obstacles are supply chain issues (mainly coverage of CDW facilities and steady supply of RA), absence of funding for SMEs to invest in RA production processes, lack of knowledge and communication between agents of the demolition, CDW management and concrete sectors, and lack of awareness and trust in secondary materials and products. In what concerns higher performing Member States (namely those in Quadrant 1 of Figure 18), obstacles are also on the supply chain, on lack of facilities with improved production methods for RA and on the under-use of the finer fractions of RA, which lead to losses of efficiency.

In both performing and underperforming Member States, the relative cost of high quality RA is often higher than that of NA, mostly due to economies of scale, the lack of performance based classifications for RA, the lack of a market for RA and RAC and scarce societal awareness towards RA, RAC and the circular economy of the construction sector and these issues are preventing higher RAC market adoption.

These concerns are similar to those of other regions coming from very different contexts - e.g. Australia [168], Brazil [170], and China [166, 171].

Table 16 concerns only barriers that are specific to RA and RAC uptake. Relevant barriers for the minimization of waste and increased reuse of building elements were not included (such as the need for skilled personnel for DfARD), but will be discussed in the next section, since sound measures for promoting CDW management need to consider the possibilities of reuse and waste reduction.

6.3 Measures towards increased recycled aggregate concrete production

Recommendation one:

Public authorities need to understand the full picture

Public authorities at the local, regional and national should be trained The CDW management and construction sectors have several specificities The understanding and monitoring of the implications of measures to promote CDW valorisation and RA and RAC uptake across the various actors of the concrete and CDW management industry is challenging.

The main question when defining measures to promote RAC is how to change the paradigm of the construction sector and treat CDW as a by-product of the construction industry rather than as a waste. This change can only be achieved through policy [158].

Measures to promote RAC should account for both the supply of RA and its demand by concrete producers. At the same time, measures must promote the engagement public and private sectors and include integrated strategies that address employment and social aspects, industry needs and the greening of the construction sector jointly [2].

Policy-making and monitoring of the efficiency of policies to promote RA and RAC applications is very challenging. It is paramount to train the public authorities in order to understand the effect of policies, to monitor their results to learn from them and to adapt legislation as the market responds to it [33]. This is important because the lack of awareness of governmental agencies concerning the relevance of sustainable issues in the building sector has been identified as a barrier to increased RAC uptake [154].

Recommendation two:

Reliable statistics for monitoring of CDW recovery performance at national and local levels.

Use the European Commission's Guidelines for waste audits.

Reliable statistics that allow the regular monitoring of CDW valorisation states are paramount for sound CDW management and policy making The statistics used for the monitoring of CDW valorisation status are treated differently in different Member States, resulting in difficulties in assessing environmental performance. Some of the statistics are developed in a way that not all useful information is captured.

Waste generation and treatment statistics are the basis for CDW management policy-making. Without sound statistics national and local monitoring and policy-making are compromised:

— Provide guidelines for proper CDW generation and treatment data reporting.

- Homogenise the interpretation of the European criteria for waste classification and treatment across the Member States [43, 120].
- Create new waste classification criteria that include useful indicators for CDW treatment and recovery monitoring [7] that account for:
  - On site reuse and recycling.
  - Additional codes for materials that have higher reuse and recycling potential (namely, concrete waste) [43, 172]. Different codes for different types of mineral waste would allow a better understanding of the potential for CDW valorisation.

Guidelines and rules developed by Member States for data reporting should take advantage of the European Commission's *Guidelines for the waste audits before demolition and renovation works of buildings* [39].

Recommendation three:

Ensure broad geographical coverage of CDW recycling facilities. Capacitate concrete producers for RA use

Without nearby CDW facilities, proper CDW management is not practical, environmentally sound or cost-efficient.

Facilities with capacity for the production of RA with quality for use in concrete are required before the market uptake of RAC is promoted.

Financial incentives for CDW plants (which are mostly SMEs) and faster and simpler permit application processes should be promoted across the Member States.

In most Member States, the majority of CDW plants produce RA for road construction and moderate investment is required so that RA for concrete are produced.

Concrete plants may need incentives to adapt their production process for RA use.

The supply chain for RAC starts at the CDW generation and treatment stages, which require installations (mobile or stationary) for waste processing into RA. RA fit for concrete may be produced with conventional equipment for sorting, crushing, grading, but investment is needed, since most CDW plants were designed to produce RA for road construction.

Develop a broad infrastructure of CDW recycling infrastructure by:

- Clarifying and accelerating the permit application process for CDW plants and ensuring that local authorities account for land space for such activities [158].
- Providing funding for the creation/revamping of CDW plants (or other adaptable industrial plants), which are predominantly SMEs that face financial challenges when investing in equipment. As argued in a report to the European Commission [160], EU funded instruments should be used for this purpose.
- Accounting for mobile CDW facilities (rural areas) and waste transfer stations, which are particularly attractive in regions where the waste infrastructure is not as developed and a highly efficient network of waste transfer stations and CDW treatment plants may be developed.
- Reducing the economic burden on CDW plants by providing investment loans at low rates and land leases for CDW management companies [173], subsidizing and giving tax exemptions to RA producers (decreasing the production cost of the RA) or concrete producers (making RA commercially attractive) [154].
- Providing financial incentives to good performers in CDW management [156, 171]. These financial instruments could be designed so that they are provided conditional to compliance with given targets (e.g. the production of RA certified for EN 12620 [21]).

Incentives should be provided for the revamping of industrial (namely concrete) plants to address implementation barriers and to ensure, if the incentives are designed in a way that regular RA incorporation targets are met, that RA producers have guaranteed buyers of RA.

To avoid “not in my backyard” reception from the public, this recommendation requires that authorities raise sensitivity amongst the general public towards the social importance of CDW management and valorisation (see Recommendation 10)

Recommendation four:

Create a demand, ensure a market

Concrete producers will only resort to RA if there is a reason

Environmental labelling, eligibility for public tenders, and profitability are key

Types of action:

-Drive the costs of RA down and, if needed, the costs of NA up

- Tax or ban landfilling

- Feed taxes back as subsidies for RA and RAC acquisition

- Impose RA and RAC in green public procurement

- Promote recycled concrete labelling

The construction industry is highly competitive and RAC must be cost-competitive to subsist as a construction product. However, in most circumstances, NA are cheaper than RA.

Use economic instruments to make RA are cost competitive [130, 168]:

— Based on the polluter pays principle [33] and focusing taxes on landfilling so that the companies responsible for the generation of CDW seek material recovery to reduce costs [156].

— Tailor landfill taxes to regional specificities, type of waste and previous treatment (treated or untreated, processed or unprocessed) [158].

— The high variation between Member States in landfilling taxation in the EU [164] (2017 data: from 3 €/tonne in Lithuania to more than 100€/tonne in Belgium [161]) imply that some Member States are not taxing CDW landfilling to the extent intended.

— Direct the revenues from landfill taxes to promote sustainable construction practices, including RAC [158, 174, 175], through subsidies distributed to RA producers and consumers (e.g. VAT exemptions/reductions to buyers of RA and RAC [33]), but condition the subsidies to high quality RA, since otherwise the incentive may encourage downcycling of RA.

— Tax the producers and users of NA, depending on local specificities [158]. Taxes on material consumption may not promote the use of RA effectively and lead to imports (e.g. between Ireland and Northern Ireland [154]) and use of other sources of natural materials [154, 158].

Economic instruments alone are not effective and complementary approaches are needed [33], including restrictions on landfilling [43, 168], which require inspection to avoid illegal dumping [167].

Use green public procurement [157] to:

— Create a critical mass of demand to develop a market for RA and RAC.

— Show that RAC is viable material to the technical community and society.

— Prevent tenders [120, 158] from hindering the use of RA since this contradicts the European Commission’s identification of the construction sector as a priority for green public procurement [120, 158].

Create a “recycled concrete” label [120] and award it to concrete with a minimum recycled content (aggregates, binder or other materials). Use this label in conjunction with public tender requirements and rating systems, as well as in public outreach and for fiscal incentives (e.g. reduced taxes for “recycled concrete”).

Create an eco-labelling system for companies that comply with requirements for CDW recovery practices. This eco-labelling may be reflected in several ways, such as a certification scheme or by having access to membership to an association, as is the case of the Belgian Association of Demolition Waste Recycling Corporations (VVS), in which a membership requirement is that the CDW plant has minimum production process requirements [162].

Consider:

- Policies for alternative business models that promote circular economy models and waste minimization [149]. Examples are payback and loan schemes for the public sector - e.g. precast non-structural elements such as road barriers.
- Integrated the measures proposed here with current EU policy and strategies. For instance, the EU Renovation Wave [6] will fund renovation works, which are associated with CDW generation. Mechanisms that stipulate the proper valorisation of this CDW as a requirement for funding could be devised.

Recommendation five:

Legislation to enforce policy, inspection to enforce legislation

Harmonize and enforce legislation
Simplify permit processes
Impose pre-demolition and pre -development plans and audits
Restrict landfilling
Clarify end of waste criteria

Harmonize EU legislation [160] because different Member States have different waste legislation with different levels of maturity and implementation [176] and this prevents proper CDW management - e.g. the lack of a proper legislative framework is hindering CDW recovery in Eastern Europe [160].

Enforce pre-demolition audits, contributing to the soundness of CDW generation statistics and to improved CDW recycling.

Promote waste management plans:

- To have better estimates of the generation of CDW.
- To commit construction agents with minimum goals for CDW valorisation and treatment.
- Have the plan audited by a third party that may propose changes to it whenever better options can be sought.
- Carry out post-demolition follow-ups to check for compliance with the plan and penalize future permit requests in case of non-compliance.

Enforce circular building assessment tools to ensure that buildings are designed with circularity principles to maximize reuse and higher value recycling at their end of life. A circular economy score, to be validated by a third party, could be promoted and enforced in public contracts.

Impose that demolitions comply with the Construction and Demolition Waste Management Protocol [158].

Enforce clear end of waste criteria to avoid that secondary raw materials may be classified as wastes when they could be classified as products. This will reduce operational costs in waste control [177] and avoid reservations by possible users of secondary materials due to bad public perception towards waste use. A clear definition of end-of-waste criteria is needed to facilitate CDW valorisation and the UEPG's *Guidance on End of Waste Criteria for Recycled Aggregates* [177] may be used to assist policy makers in this topic.

Create a more favourable regulatory environment for selective demolition and other demolition methods that improve CDW recovery [31, 33], namely by enforcing pre-demolition planning [160].

Inspection and enforcement of legislation are fundamental [156, 158] and illegal activities should be punished [171]. The importance of the enforcement of legislation is understood in [176], where it is stated that a major reason for the comparatively poor performance of Greece in what concerns CDW management is that illegal disposals of CDW are common.

Recommendation six:

Provide guidelines and standards and train the supply chain

Construction agents should be aware of the possibilities for CDW valorisation and RAC production
The agents of the CDW and concrete industries should understand the needs and limitations of each other
A skilled workforce is fundamental to ensure RAC penetrates the market

Develop detailed guidelines and standards to support the circular models in construction [166].

Create and disseminate guides with information and contact points for the application for permits (e.g. to receive and process waste), for high quality demolition (e.g. if waste audits are enforced) and for funding applications and other incentives (e.g. tax exemptions/reductions for sellers of high quality RA).

Incorporate employment and skill aspects into circular policies and instruments [134] to solve skill mismatches and possible local effects on employment.

Standards for the use of recycled aggregates should be enforced [158] in the Member States where regulations are unclear or absent.

Develop and disseminate performance-based classifications for RA and since high-quality RA are losing opportunities in the market because their incorporation ratios could be much higher than those of standards (see sections 3 and 4).

Sponsor industry-wide training programmes [43] (e.g. by tax exemptions/reductions and social security rebates [135]). Such training should include production processes, quality assurance and the identification of the responsibilities of the different agents of the supply chain.

Academic curricula should be adapted for the ongoing trend towards circularity and sustainability in construction. This is already occurring in most Member States, but there is the risk of bottlenecks in the green transition [143] due to shortage of skilled workers. Degrees related to the construction industry should include the basic understanding of environmental impact assessments, encourage the use of circular economy models and of industrial symbiosis. Civil Engineering students should become acquainted with RAC structural design, specificities and production, transferring knowledge from universities to their employers.

Academic and industrial training courses should not only address CDW reuse and recovery, but also life cycle thinking, tackling the CDW generation problem at its beginning [178]. Examples of topics that should be promoted are DfARD and the choice of local materials. The advantages and methods of selective demolition should also be disseminated [157].

Disseminate Level(s) throughout the construction sector.

Recommendation seven:

Accelerate innovation through knowledge transfer and synergies

Several agents of the CDW management and concrete industries have no knowledge on RAC
The procurement of RA by the concrete industry is complicated due to lack of suppliers
Most CDW management plants are not acquainted with the needs of the concrete industry

Promote knowledge transfer between experts on CDW management, RA and RAC (typically academia), concrete producers, structural designers and CDW plant managers (industrial agents) and public authorities [168].

Share experiences between well-performing countries and lagging ones to drastically improve the market uptake of RA, particularly of Member States that lie outside Quadrant 1 of Figure 18.

Promote synergies for circular economy models [43, 45] and real time web-based platforms that allow construction agents to interact would address supply chain issues, facilitating the understanding of the needs and limitations of each agent of the supply chain, the procurement of RA.

Establish networks of construction and CDW agents and local authorities at the local level to maximize RA upscaling, namely by sharing experiences in RAC [168], presenting new legislation and developments, and promoting joint investment. Best practices recommendations, design issues and concrete recycling technologies should be presented and distributed to all relevant actors [172].

Recommendation eight:

Research and innovation in improved methods for reuse and recycling

Improved methods increase the profitability of the CDW valorisation industry Higher reuse and recycling ratios are achieved Difficult challenges of CDW recycling are solved through innovation - e.g. improved quality of fine recycled aggregates and the incorporation of recycled fines in cement

Advanced sorting and processing methods to improve the quality of RA should be promoted, including:

- Fundamental research on advanced production process and high quality techniques that improve demolition methods, CDW sorting and processing, RA treatment, the use of recycled fines and fine recycled aggregates for cement production, DfARD towards more circular economy models.
- Industrialization projects towards the adoption of already proven scientific concepts (e.g. the use of coarse RA produced from concrete waste in concrete; the development of supply chains from the demolition site to the concrete producer), where knowledge transfer from academia to industry is promoted.
- Transnational cooperation, where Member States that are lagging behind in CDW recovery benefit from the knowledge acquired in Member States where CDW recovery is already in place. To achieve this target, funding for research projects related to CDW recovery and RAC in which both types of Member State participate, smaller scale dissemination and networking projects for academics, and projects for CDW recovery and RAC that specifically include training of researchers and industrial agents from underperforming countries as ancillary objectives (e.g. within the scope of a EU Horizon call) are proposed.

Recommendation nine:

Large scale, nation-wide holistic industry-oriented programmes

Large scale industrial programmes involve several agents of the CDW and concrete industries Societal awareness towards CDW valorisation and RAC are raised through impactful projects Knowledge transfer between academia and industry is promoted

These programmes should seek industrial applications of innovations in CDW treatment and RA and RAC production, favouring higher end applications and the maximum number of industrial agents possible. The research programme should be designed in a way that:

- Knowledge transfer is promoted (academia to industry, industry to academia and industry to industry).
- Significant milestones in CDW valorisation are met at the industrial and technical levels (e.g. the industrial production of a 100% recycled aggregate concrete building or the development of an installation that recycles concrete waste into high quality coarse recycled aggregates, fine recycled aggregates and recycled cement).
- The development of regions where CDW management is underperforming is promoted.
- Societal awareness towards RAC and the circular construction is promoted through large-scale realizations.

Another topic that should be explored within the scope of this type of measure is to implement research and industrial of DfARD concepts, modular construction and selective demolition, particularly in countries of Quadrant 1.

Recommendation ten:

Increase public outreach and clear communication.

Circular models require public trust and support

Society has scepticism and concerns regarding recycled materials in construction
The general public is not as aware of sustainable options in construction as in other sectors (e.g. food and clothing)
Public outreach and clear communication are key

Use green public procurement in large public construction projects to raise awareness towards RAC and promote it as a safe concrete product [156].

Regularly update and disseminate statistics of CDW generation, treatment and recycling to the general public.

Promote circular economy concepts and applications in the construction sector to the general public [120], including environmental associations.

Raise the importance and viability of environmentally-friendly construction and of CDW recycling across all agents of the construction sector, including clients [33, 166].

Use eco-labelling and green rating systems [45, 120] to facilitate communication between construction agents, clients and society, by:

- Adopting performance-based classification systems for the quality of RA.
- Using green rating systems to classify construction.
- Awarding "recycled concrete" certification to producers and/or concrete mixes that comply with minimum content of recycled materials.

Recommendation eleven:

Do not underestimate the importance of local authorities

The local specificities of the construction industry imply the CDW valorisation is dependent on local context
Local authorities are the best informed for decision-making and monitoring of progress in CDW valorisation
Flexibility and autonomy in valorisation targets and policy instruments is intended

Local authorities are the best suited to fully understand social implications, technical and operational viability, investment needs and supply chain issues associated with the increased market uptake of RAC. National authorities should ensure that local authorities have appropriate training to fully understand the implications of policy (see Recommendation 1) and should design flexible policies that should be tailored to local realities.

The following are general recommendations for local authorities:

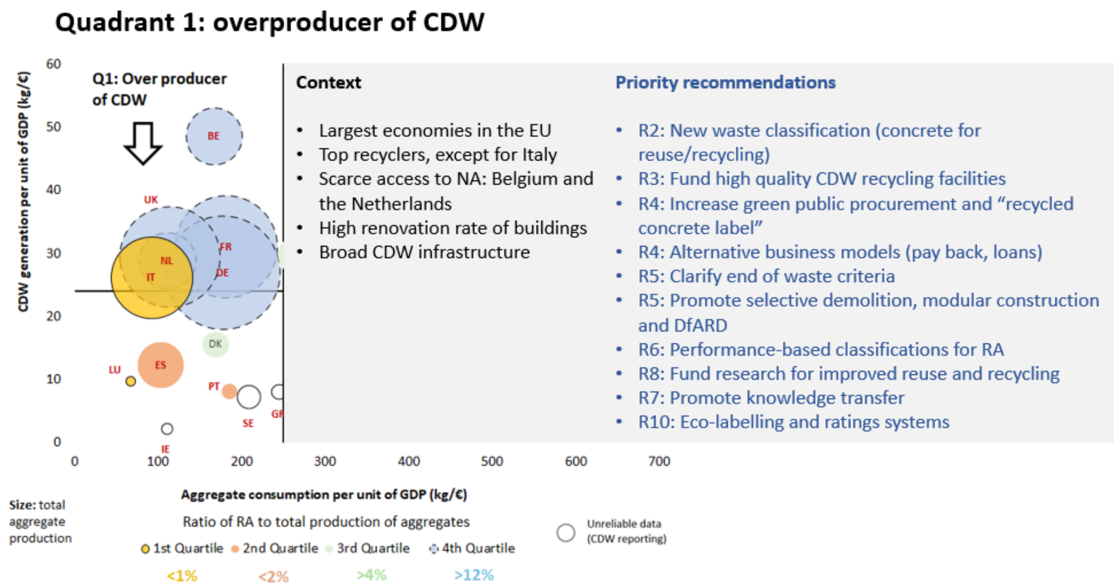
- Identify the relevant stakeholders.
- Make informed decisions on RA promotion and CDW management by collecting statistics for CDW generation, treatment and end-use that are evaluated in short time frames.
- Valorise pre-demolition audits and CDW recovery and reuse plans and perform routine inspections to ensure that the agreed conditions for licencing the activity were fulfilled [15].
- Assist local agents in bureaucratic processes - e.g. permit requests and funding applications. Provide fast answers to queries and requests.
- Ensure that moderately populated locations are well covered by CDW management facilities with enough capacity for waste forecasts - a maximum 30 km distance from urban areas to CDW management plants is argued for in [33].
- Compare CDW generation and the capacity of CDW plants to produce RA of good quality with forecasts for concrete demand and road construction. Understand whether incentives for local development of CDW treatment plants and/or waste transfer stations are needed before measures that promote RAC are implemented and

estimates the potential for RA use in concrete and in road construction in the short- and medium-term.

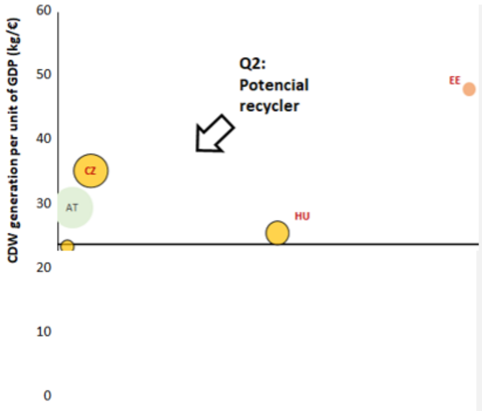
- Communicate the aforementioned information to national authorities to assist policy makers, namely in:
  - Defining target national and regional goals for RA use.
  - Defining investment programmes and faster permit application processes for the development of a capable CDW recycling infrastructure.
  - Understanding the technical limitations posed by regulations.
- At the local level, the previous information may be used to define local targets for RA incorporation (which may increase over time) and minimum incorporation ratios that concrete producers, and developers of buildings and other infrastructure should comply with in order to have access to local financial incentives.
- Engage different agents of the sustainability and construction sectors (e.g. environmental associations, CDW plants, cement companies, concrete producers and producers of aggregates) to better understand social problems and bottlenecks and to encourage the development of synergistic local supply chains that integrate circularity.

Mapping of recommendations

Ten recommendations for each Quadrant are presented in Figure 18, based on their context. These recommendations aim at solving immediate bottlenecks for each quadrant, but are of general nature and dependent on local specificities and in the quality of the data reported to EUROSTAT (see Sections 2 and 6.1).



Quadrant 2: potential recycler

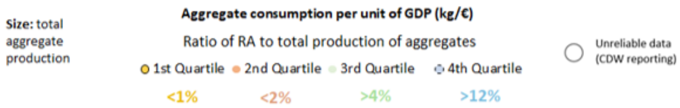


Context

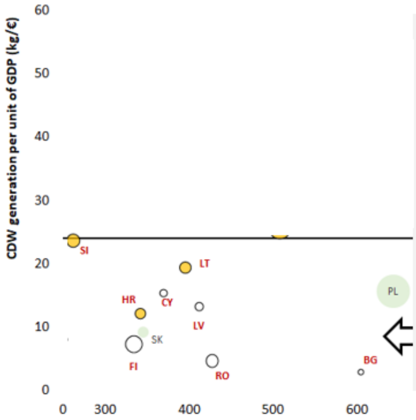
- Only four Member States
- Large potential supply of RA and large demand for NA
- Small relative production of RA (except for Austria)
- CDW infrastructure and awareness to RA are lacking

Priorities

- R1: Train public authorities
- R2: Provide guidelines for data reporting and do inspections
- R3: Fund the development of CDW infrastructure and simplify permit processes
- R3: Subsidize RA for all applications
- R4: Increase landfill taxes and restrict landfilling
- R5: Impose the construction and demolition waste protocol
- R6: Guidelines and standards for RA and RAC
- R7: Promote knowledge transfer and synergies
- R10: Increase public awareness, green public procurement and trust in RAC
- R11: Empower local authorities



Quadrant 3: growth potential

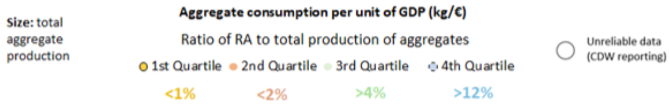


Context

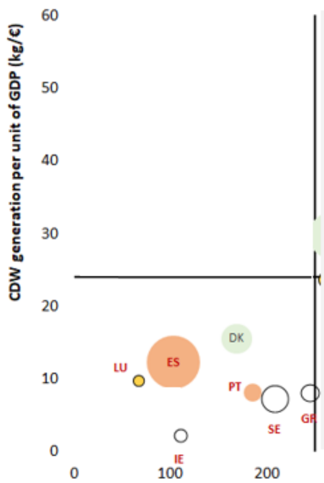
- Small generation of RA at the moment, but large demand for NA
- 10 Member States, half reported as having unreliable data
- Small relative production of RA

Priorities

- R1: Train public authorities
- R2: Guidelines for data reporting and inspections
- R3: Fund the development of CDW infrastructure and simplify permit processes
- R3: Subsidize RA, increase landfill taxes, restrict landfilling
- R5: Enforce pre-demolition audits and waste management plants R5: Do inspections and penalize non-compliers
- R6: Develop guidelines and standards for RA and RAC
- R6: Revise academic curricula
- R7: Benefit from the experiences of well-performing countries
- R10: Increase public awareness towards CDW management
- R11: Empower local authorities



Quadrant 4: frugal countries



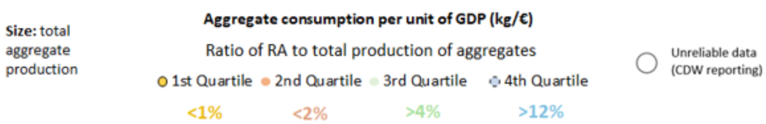
Context

- Generate less CDW and produce less NA than the mean
- The data of 3 out of seven Member States is reported as unreliable
- Underperforming in RA production, except for Denmark
- Higher end applications should be sought

Priorities

- R2: Guidelines for data reporting and inspections
- R3: Fund CDW facilities and concrete plants
- R5: Enforce pre-demolition audits and waste management plants
- R5: Clarify end of waste criteria
- R6: Guidelines and contact points to industry
- R6: Sponsor training programmes for industry
- R7: Promote knowledge transfer and establish networks
- R9: Fund nation-wide industry programmes
- R10: Green public procurement, eco-labelling and ratings systems
- R11: Empower local authorities

300 400 500 600 700



7 Conclusions

This report presents measures that could be used to promote the market uptake of recycled aggregates and recycled aggregate concrete by the concrete industry.

This is relevant because recycled aggregates are produced from construction and demolition waste, which is more than 35% of all waste generated in the European Union and its current recovery practices are mostly towards backfilling and road construction. Both are downcycling operations when the recycled aggregate is composed mostly of concrete waste (the bulk of construction and demolition waste). Backfilling should be restricted to the minimum amount possible, as specifically stated in DIRECTIVE 2018/851 of the European Union, and road construction is decreasing. Alternative, higher end uses for recycled aggregates are needed and their use in concrete is the most natural option, due to:

— Synergies between the construction and demolition waste and the concrete industries..
— The use of natural aggregates in concrete, which can be replaced with recycled ones.
— The comprehensive scientific research and demonstration projects (even though few) on this topic, which confirm that coarse recycled aggregate concrete is technically sound and safe.
— There is evidence that, in most circumstances, the partial replacement of natural aggregates with recycled ones decreases the carbon footprint of concrete production to some extent.
— Due to the large volume of concrete production, a mean incorporation of 10% to 20% of recycled aggregates in concrete produced in the European Union would use most concrete waste generated.

However, the market uptake of recycled aggregates is low and answers to surveys sent to industrial representatives of the aggregates and concrete sectors confirmed that supply chains are not established, recycled aggregates certified for use in concrete are very hard to find and recycled aggregate concrete is either not produced (the case of most Member States) or produced very rarely.

To avoid losing the opportunity to kick-start a market for recycled aggregate concrete in Europe under a favourable context (the European Green Deal, the New European Bauhaus, the Circular Economy Action Plan and the EU Renovation Wave are all directly related to recycled aggregate concrete), recycled aggregate concrete should be promoted. This report addresses this need by presenting the status of the Member States concerning construction and demolition waste recovery and the technical, economical, operational and contextual barriers amongst the several actors involved (from authorities and the agents of the construction of demolition activities to concrete producers and designers). The influence of local specificities was emphasized.

As long as construction and demolition waste is properly separated before processing, and the recycled aggregates are predominantly composed of concrete waste and have a very small amount of deleterious contaminants (e.g. gypsum, bituminous materials), the coarse fraction of the recycled aggregates is expected to have sufficient quality for moderate incorporation ratios in concrete within the medium strength range. If higher quality aggregates are intended, namely to incorporate higher amount of recycled aggregates, increase the strength range and/or to use smaller fractions of recycled aggregates (fines and fine aggregates), advanced separation and processing methods are required. These remarks imply that moderate incorporation ratios may be achieved with conventional equipment of the construction and demolition sectors (which may not be available at the construction and demolition waste plants, since most were developed for the production of recycled aggregates for road construction) and that specific equipment may be used to produce very high quality recycled aggregates. Since construction and demolition waste plants are mostly small and medium enterprises and there is currently no market for recycled aggregate concrete, any type of investment is challenging, unless public authorities intervene.

The main obstacles for concrete producers are ensuring a steady supply of recycled aggregates with quality for use in concrete, the lack of space in their installations to store the recycled aggregates, and the need to perform minor training for their workforce (e.g. visual inspection of recycled aggregates, adaptations to concrete mix design). Such challenges are easily overcome (provided space is available). Precast concrete producers are already using recycled aggregates from their own products (therefore, of high and known quality) in what is now a common practice. The main challenge on the side of concrete producers is finding a reason to use recycled aggregates, which are more difficult to procure and have worse properties than natural aggregates, when in many regions natural aggregates are cheap and readily available. This is aggravated by the perceived notion by the general public that recycled aggregates are a low quality product that should be avoided and by the reservations of designers and developers in accepting recycled aggregates, when relatively cheap good-quality natural aggregates are available.

In the short-term and for most Member States, recycled aggregates will become an attractive raw material for concrete producers if public authorities intervene in a holistic way that should consider the context of each Member State.

The last subsection of the report presents measures tailored to the different contexts that could be used to address their most relevant barriers. These measures range from training, research and knowledge transfer to improvement of industrial capacity and promotion of increased market demand. Economic instruments, increased societal awareness and the role of certifications and regulations are also presented.

References

1. EU-DIRECTIVE-2008/98/EC of the European Parliament and the Council of 19 November 2008 on waste and repealing certain Directives, 2008, Official Journal of the European Union.
2. EU-DIRECTIVE-2018/851, Directive 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. 2018, Official Journal of the European Union.
3. COMMUNICATION FROM THE COMMISION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - The European Green Deal. 2019: European Commission, COM/2019/640 final.
4. ReportA9-0213/2022 of the European Parliament, *REPORT on the New European Bauhaus*, Committee on Industry, Research and Energy Committee on Culture and Education, 2022.
5. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF REGIONS: A new circular economy Action Plan for a cleaner and more competitive Europe. 2020, COM/2020/98 final.
6. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. 2020, COM/2020/662final.
7. norden, *ENCORT-CDW: Evaluation of the European recovery target for construction and demolition waste*, in *Nordic Working Papers*, M. Arm, et al., Editors. 2014, Nordic Council of Ministers: Copenhagen, Denmark.
8. Deloitte, *Resource efficient use of mixed wastes. Improving management of construction and demolition waste - Final report. Prepared for the European Commission DG ENV*.
9. UEPG, Annual review 2020-2021. 2021, European Aggregates Association (UEPG): Brussels, Belgium.
10. EUROSTAT, ENV_WAS: European statistics on waste. 2023, EUROSTAT.
11. CEMBUREAU, Activity report 2020. 2021: Brussels, Belgium.
12. Monteiro, P.J.M., S.A. Miller, and A. Horvath, Towards sustainable concrete. Nature Materials, 2017. 16(7): p. 698-699.
13. Dias, A.B., et al., Environmental and economic life cycle assessment of recycled coarse aggregates: a Portuguese case study. Materials, 2021. 14(18): 5452.
14. Braga, A.M., J.D. Silvestre, and J. de Brito, Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. Journal of Cleaner Production, 2017. 162: p. 529-543.
15. Ben-Fraj, A. and R. Idir, Concrete based on recycled aggregates - Recycling and environmental analysis: A case study of Paris' region. Construction and Building Materials, 2017. 157: p. 952-964.
16. Marinković, S., et al., Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management, 2010. 30(11): p. 2255-2264.
17. Basavarajappa, H.T., M.C. Manjunatha, and L. Jeevan, Sand mining, management and its environmental impact in Cauvery and Kabini river basins of Mysore District, Karnaka, India using geomatic techniques. International Journal of Civil Engineering and Technology, 2014. 5(9): p. 169-180.
18. British Geological Survey Commisioned Report CR/03/029N, River mining: aggregate production and supply in developing countries. 2003, University of Exeter.
19. Sousa, J.J. and L. Bastos, Multi-temporal SAR interferometry reveals acceleration of bridge sinking before collapse. Nat. Hazards Earth Syst. Sci., 2013. 13(3): p. 659-667.
20. Recybéton, Concrete recycling: research and practice, F. Larrard and H. Colina. 2019, Florida, U.S.A.: CRC Press.
21. EN-12620+A1, Aggregates for concrete, with 2008 amendment 2008, CEN.
22. EN-206, Concrete: Specification, performance, production and conformity. Incorporating corrigendum May 2014. 2013, CEN: Brussels, Belgium.
23. CEN TC250/SC2-N1896, Stable version of prEN 1992-1-1:2021-09. 2021, CEN.
24. LNEC-E471, Guide for the use of coarse recycled aggregates in concrete - Guia para a utilização de agregados reciclados grossos em betões de ligantes hidráulicos. 2009, National Laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil - LNEC): Portugal.
25. Pacheco, J. and J. de Brito, Recycled aggregate concrete: properties and behaviour, applications and production challenges, in fib Symposium 2021: Concrete structures: New trends for eco-efficiency and performance. 2021: Lisbon, Portugal.
26. CEMBUREAU, Cementing the European Green Deal - Reaching climate neutrality along the cement and concrete value chain by 2050. 2020.
27. European Commission. EU Building Stock Observatory Web Tool. 2016; Available from: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en#document.

28. EN-1990, Eurocode: Basis of structural design. 2002, CEN: Brussels, Belgium.
29. United Nations, World Population Prospects 2022: File GEN/01/REV1: Demographic indicators by region, subregion and country, annually for 1950-2100 - POP/DB/WPP/Rev.2022/GEN/F01/Rev.1. 2022.
30 EUROSTAT, ENV_WASGEN: Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. 2023.
31. Damgaard, A., et al., Background data collection and life cycle assessment for construction and demolition waste (CDW) management. Publications Office of the European Union. EUR – Scientific and Technical Research series No. JRC 130992. 2022 https://doi.org/10.2760/772724
32. Silva, R.V., J. de Brito, and R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials, 2014. 65: p. 201-217.
33. RE4Project, D1.2 Statistics assessment. 2017, CETMA.
34. Pacheco, J. and J. de Brito, Recycled aggregates produced from construction and demolition waste for structural concrete: constituents, properties and production. Materials, 2021. 14(19): 5748.
35. Villoria Saez, P., et al., Best practice measures assessment for construction and demolition waste management in building constructions. Resources, Conservation and Recycling, 2013. 75: p. 52-62.
36. Mália, M., et al., Construction and demolition waste indicators. Waste Management & Research, 2013. 31(3): p. 241-55.
37. Wu, Z., et al., Quantifying construction and demolition waste: An analytical review. Waste Management, 2014. 34(9): p. 1683-1692.
38. Menegaki, M. and D. Damigos, A review on current situation and challenges of construction and demolition waste management. Current Opinion in Green and Sustainable Chemistry, 2018. 13: p. 8-15.
39. European Commission, Guidelines for the waste audits before demolition and renovation works of buildings, EU Directorate-General for Internal market, Entrepreneurship and SMEs. 2018, EU Construction and Demolition Waste Management.
40. Debacker, W. and S. Manshoven, Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system, Buildings as Material Banks. 2016.
41. EUROSTAT, ENV_WASTRT: Treatment of waste by waste category, hazardousness and waste management operations. 2023.
42. EC Regulation 2150/2002, of the European Parliament and of the Council of 25 November 2002 on waste statistics (Text with EEA relevance, Consolidated text). 2002, Official Journal of the European Union.
43. Villoria Saez, P. and M. Osmani, Deliverable 1.1 Recovery technologies for construction and demolition waste, in COST Action Mining the European Anthroposphere (MINEA). 2018.
44. CETMA, et al., D1.1 Data collection on CDW, in RE4 Project: - REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction. 2017.
45. Giorgi, S., et al., Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five European countries policies and practices. Journal of Cleaner Production, 2022. 336: 130395.
46. CEMBUREAU, Cement, concrete & the circular economy. 2016, CEMBUREAU.
47. Dhir, R.K. and K.A. Paine, Performance related approach to the use of recycled aggregates. 2007, Waste and Resources Action Programme (WRAP) Aggregates Research Programme: Banbury, Oxon, UK.
48. Tam, V.W., C.M.J.C. Tam, and B. Materials, Crushed aggregate production from centralized combined and individual waste sources in Hong Kong. 2007. 21(4): p. 879-886.
49. Silva, R.V., J. de Brito, and R.K. Dhir, Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. Journal of Cleaner Production, 2017. 143(1): p. 598-614.
50. European Cement Research Academy, Closing the loop: What type of concrete re-use is the most suitable option?, C. Muller, J. Reiners, and S. Palm, Editors. 2015, Dusseldorf, Germany.
51. Sato, R., et al., Flexural behavior of reinforced recycled concrete beams. Journal of Advanced Concrete Technology, 2007. 5(1): p. 43-61.
52. Bravo, M., et al., Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. Journal of Cleaner Production, 2015. 99: p. 59-74.
53. Artoni, R., et al., Resistance to fragmentation of recycled concrete aggregates. Materials and Structures, 2016. 50(1): 11.
54. EN-13242:2002+A1:2007, Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction. 2002, CEN: Brussels, Belgium.
55. EN-933-11, Tests for geometrical properties of aggregates. Classification test for the constituents of coarse recycled aggregate. 2009, CEN: Brussels, Belgium.
56. Sáez del Bosque, I.F., et al., Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate. Cement and Concrete Composites, 2017. 81: p. 25-34.

57. Mehta, P.K. and P.J. Monteiro, Concrete: microstructure, properties and materials (3rd edition). 2006: McGraw-Hill.
58. Scrivener, K.L., A.K. Crumbie, and P. Laugesen, The Interfacial Transition Zone (ITZ) between cement paste and aggregate in concrete. Interface Science, 2004. 12(4): p. 411-421.
59. Newman, J. and B.S. Choo, Advanced concrete technology: Constituent materials. 2003, Oxford, UK: Elsevier: Butterworth-Heinemann.
60. Pepe, M., et al., Mechanical behaviour of coarse, lightweight, recycled and natural aggregates for concrete. Proceedings of the Institution of Civil Engineers - Construction Materials, 2018. 173(2): p. 70-78.
61. Juan, M.S. and P.A. Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate. Construction and Building Materials, 2009. 23(2): p. 872-877.
62. Abbas, A., et al., Proposed method for determining the residual mortar content of recycled concrete aggregates. Journal of ASTM International, 2008. 5(1).
63. Tošić, N., et al., Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2. Structural Concrete, 2021. 22: p. 2916– 2938.
64. Pacheco, J., et al., Uncertainty models of reinforced concrete beams in bending: code comparison and recycled aggregate incorporation. Journal of Structural Engineering, 2019. 145(4): 04019013.
65. Goncalves, P. and J. de Brito, Recycled aggregate concrete (RAC) - comparative analysis of existing specifications. Magazine of Concrete Research, 2010. 62(5): p. 339-346.
66. Tam, V.W.Y., Economic comparison of concrete recycling: A case study approach. Resources, Conservation and Recycling, 2008. 52(5): p. 821-828.
67. Kim, G.-D. and T.-B. Kim, Development of recycling technology from waste aggregate and dust from waste concrete. Journal of Ceramic Processing Research, 2007. 8(1): p. 82-86.
68. Alexander, M.G. and S. Mindess, Aggregates in concrete. Modern concrete technology series. 2005, New York, United States of America: Taylor & Francis.
69. Dhir, R.K., et al., ASR testing on recycled aggregates guidance on alkali limits and reactivity. 2005, DTI/WRAP Aggregates Research Programme STBF 13/14C, ISBN: 1-84405-185-4.
70. Etxeberria, M., et al., Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cement and Concrete Research, 2007. 37(5): p. 735-742.
71. Khoury, E., et al., Heterogeneity of recycled concrete aggregates, an intrinsic variability. Construction and Building Materials, 2018. 175: p. 705-713.
72. Narahara, S., et al., Evaluation of concrete made from recycled coarse aggregates by pulsed power discharge, in 2007 IEEE Pulsed Power Conference, Vols 1-4. 2007. p. 748-751.
73. Vegas, I., et al., Upgrading the quality of mixed recycled aggregates from construction and demolition waste by using near-infrared sorting technology. Construction and Building Materials, 2015. 75: p. 121-128
74. Lotfi, S., C2CA Concrete Recycling Process, in TU Delft Materials and Environment. 2016, TU Delft.
75. Florea, M.V.A. and H.J.H. Brouwers, Properties of various size fractions of crushed concrete related to process conditions and re-use. Cement and Concrete Research, 2013. 52: p. 11-21.
76. Ambrós, W.M., et al., Usage of air jigging for multi-component separation of construction and demolition waste. Waste Management, 2017. 60: p. 75-83.
77. Cazacliu, B., et al., The potential of using air jigging to sort recycled aggregates. Journal of Cleaner Production, 2014. 66: p. 46-53.
78. dos Reis, G.S., et al., Effect of the accelerated carbonation treatment on the recycled sand physicochemical characteristics through the rolling carbonation process. Journal of CO_2 Utilization, 2020. 39: 101181.
79. Wang, J., et al., Comparison of recycled aggregate treatment methods on the performance for recycled concrete. Construction and Building Materials, 2020. 234: 117366.
80. Kumar N, N., et al., Strength properties of recycled aggregate concrete treated with low concentration acetic acid. 2018. 7(3.12): 4.
81. Göswein, V., et al., Transportation matters – Does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates. Resources, Conservation and Recycling, 2018. 137: p. 1-10.
82. Jullien, A., et al., Variability in the environmental impacts of aggregate production. Resources, Conservation and Recycling, 2012. 62: p. 1-13.
83. Ioannidou, D., et al., Land-cover-based indicator to assess the accessibility of resources used in the construction sector. Resources, Conservation and Recycling, 2015. 94: p. 80-91.
84. Hossain, M.U., et al., Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resources, Conservation and Recycling, 2016. 109: p. 67-77.

85. Simion, I.M., et al., Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. Journal of Environmental Engineering and Landscape Management, 2013. 21(4): p. 273-287.
86. ISO-14040, Environmental management - Life cycle assessment - Principles and framework. 2006, ISO: Geneve, Switzerland.
87. ISO-14044, Environmental management - Life cycle assessment - Requirements and guidelines. 2006, ISO: Genève, Switzerland.
88. EN-15804, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. 2012, CEN: Brussels, Belgium.
89. COMMISSION RECOMMENDATION 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations C/2021/9332.
90. Guinee, J.B., Handbook on life cycle assessment operational guide to the ISO standards. The International Journal of Life Cycle Assessment, 2002. 7(5): p. 311-313.
91. Dias, A., et al., Environmental and Economic Comparison of Natural and Recycled Aggregates Using LCA. Recycling, 2022. 7(4): 43.
92. Rosado, L.P., et al., Life cycle assessment of natural and mixed recycled aggregate production in Brazil. Journal of Cleaner Production, 2017. 151: p. 634-642.
93. Estanqueiro, B., et al., Environmental life cycle assessment of natural and recycled aggregates for concrete. European Journal of Environmental and Civil Engineering, 2018. 22(4): p. 429-449.
94. Ioannidou, D., et al., Is gravel becoming scarce? Evaluating the local criticality of construction aggregates. Resources, Conservation and Recycling, 2017. 126: p. 25-33.
95. Sengul, O., C. Tasdemir, and M.H. Tasdemir, Influence of aggregate type on mechanical behavior of normal- and high-strength concretes. Materials Journal, 2002. 99(6): p. 528-533.
96. Pacheco, J., et al., Experimental investigation on the variability of the main mechanical properties of recycled aggregate concrete. Construction and Building Materials, 2019. 201: p. 110-120.
97. Thomas, C., et al., Durability of recycled aggregate concrete. Construction and Building Materials, 2013. 40: p. 1054-1065.
98. Bravo, M., et al., Durability performance of concrete with recycled aggregates from construction and demolition waste plants. Construction and Building Materials, 2015. 77: p. 357–369.
99. Soares, D., et al., Use of coarse recycled aggregates from precast concrete rejects: Mechanical and durability performance. Construction and Building Materials, 2014. 71: p. 263-272.
100. Pedro, D., J. de Brito, and L. Evangelista, Mechanical characterization of high performance concrete prepared with recycled aggregates and silica fume from precast industry. Journal of Cleaner Production, 2017. 164: p. 939-949.
101. Bogas, J.A., J. de Brito, and J.M. Figueiredo, Mechanical characterization of concrete produced with recycled lightweight expanded clay aggregate concrete. Journal of Cleaner Production, 2015. 89: p. 187-195.
102. Pedro, D., et al., Technical specification proposal for use of high-performance recycled concrete aggregates in high-performance concrete production. Journal of Materials in Civil Engineering, 2018. 30(12): 04018324.
103. de Brito, J., et al., Structural, material, mechanical and durability properties and behaviour of recycled aggregates concrete. Journal of Building Engineering, 2016. 6: p. 1-16.
104. Malešev, M., V. Radonjanin, and S. Marinković, Recycled concrete as aggregate for structural concrete production. Sustainability, 2010. 2(5): 1204-1225.
105. Kou, S.C. and C.S. Poon, Enhancing the durability properties of concrete prepared with coarse recycled aggregate. Construction and Building Materials, 2012. 35: p. 69-76.
106. Rao, M.C., S.K. Bhattacharyya, and S.V. Barai, Influence of field recycled coarse aggregate on properties of concrete. Materials and Structures, 2011. 44(1): p. 205-220.
107. Pacheco, J., et al., Scatter of constitutive models of the mechanical properties of concrete: comparison of major international codes. Journal of Advanced Concrete Technology, 2019. 17(3): p. 102-125.
108. Angulo, S.C., et al., On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete. Materials and Structures, 2010. 43(4): p. 519-528.
109. Hansen, T.C. and E. Boegh, Elasticity and drying shrinkage of recycled aggregate concrete. Journal of the American Concrete Institute, 1985. 82(5): p. 648-652.
110. Kou, S.C., C.S. Poon, and H.W. Wan, Properties of concrete prepared with low-grade recycled aggregates. Construction and Building Materials, 2012. 36: p. 881-889.
111. Hasaba, S., et al., Drying shrinkage and durability of concrete made from recycled concrete aggregates. Japan Concrete Institute, 1981. 3: p. 55-60.

112. De Pauw, P., et al., Shrinkage and creep of concrete with recycled materials as coarse aggregates, in Proceedings of the International Symposium on Sustainable construction: Use of recycled concrete aggregate, R.K. Dhir, N.A. Henderson, and M.C. Limbachiya, Editors. 1998, Thomas Telford: London, UK. p. 213-225.
113. Adam, M.K. and C.K. Yahya, Creep and shrinkage of normal strength concrete with recycled concrete aggregates. Materials Journal, 2015. 112(3).
114. Tošić, N., A. de la Fuente, and S. Marinković, Creep of recycled aggregate concrete: Experimental database and creep prediction model according to the fib Model Code 2010. Construction and Building Materials, 2019. 195: p. 590-599.
115. Olorunsogo, F.T. and N. Padayachee, Performance of recycled aggregate concrete monitored by durability indexes. Cement and Concrete Research, 2002. 32(2): p. 179-185.
116. Silva, R.V., et al., Carbonation behaviour of recycled aggregate concrete. Cement and Concrete Composites, 2015. 62: p. 22-32
117. Silva, R.V., et al., Prediction of chloride ion penetration of recycled aggregate concrete. Materials Research, 2015. 18(2): p. 427-440.
118. Marinković, S., et al., Environmental assessment of green concretes for structural use. Journal of Cleaner Production, 2017. 154: p. 633-649.
119. Master Builders Solutions Italia – Technological Laboratory, Evaluation of recycled aggregates in concrete. 2022, Joint Research Centre of the European Commission.
120. CSI, The Cement Sustainability Initiative: recycling concrete, Geneve, Switzerland.
121. Evangelista, L. and J. de Brito, Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates. KSCE Journal of Civil Engineering, 2017. 21(1): p. 353-363.
122. Choi, H.B., et al., Experimental study on the shear strength of recycled aggregate concrete beams. Magazine of Concrete Research, 2010. 62(2): p. 103-114.
123. Ajdukiewicz, A.B. and A.T. Kliszczewicz, Comparative tests of beams and columns made of recycled aggregate concrete and natural aggregate concrete. Journal of Advanced Concrete Technology, 2007. 5(2): p. 259-273.
124. Gaurav, G. and B. Singh, Bond strength prediction of tension lap splice for deformed steel bars in recycled aggregate concrete. Materials and Structures, 2017. 50(5): 230.
125. Xiao, J., Y. Sun, and H. Falkner, Seismic performance of frame structures with recycled aggregate concrete. Engineering Structures, 2006. 28(1): p. 1-8.
126. Xiao, J., et al., Shake-table model tests on recycled aggregate concrete frame structure. Structural Journal, 2012. 109(6): p. 777-786.
127. Pacheco, J., et al., Destructive horizontal load tests of full-scale recycled aggregate concrete structures. ACI Structural Journal, 2015. 112(6): p. 815-826.
128. Pacheco, J., et al., Uncertainty of shear resistance models: influence of recycled concrete aggregate on beams with and without shear reinforcement. Engineering Structures, 2020. 204(1): 109905.
129. Tosic, N., et al., Long-term behaviour of reinforced concrete beams made with natural or recycled aggregate concrete and high-volume fly ash concrete. Construction and Building Materials, 2018. 176: p. 344-358.
130. Tosic, N., et al., Multicriteria optimization of natural and recycled aggregate concrete for structural use. Journal of Cleaner Production, 2015. 87: p. 766-776.
131. Kleijer, A.L., et al., Product-specific Life Cycle Assessment of ready mix concrete: Comparison between a recycled and an ordinary concrete. Resources, Conservation and Recycling, 2017. 122: p. 210-218.
132. Czako, V., Employment in the Energy Sector Status Report 2020. 2020, Publications Office of the European Union: Luxembourg.
133. EUROSTAT, Enterprise statistics by size class and NACE Rev.2 activity (from 2021 onwards) [SBS_SC_OVW__custom_4672113].
134. Cambridge Econometrics, Trinomics, and ICFMay, Impacts of circular economy policies on the labour market, DG ENV. 2018, European Commission: Brussels, Belgium.
135. ILO2018 World Employment and Social Outlook 2018 - Greening with jobs.
136. University of Cambridge Institute for Sustainability Leadership (CISL). (2020). Working towards a climate neutral Europe: Jobs and skills in a changing world, UK: CLG Europe.
137. Aurambout, J.P., Schiavina, M., Melchiori, M., Fioretti, C., Guzzo, F., Vandecasteele, I., Proietti, P., Kavalov, B., Panella, F. and Koukoufikis, G., Shrinking cities, European Commission, 2021, JRC126011.
138. Cedefop, Skill set and match: Cedefop's magazine promoting learning for work, Issue 24. 2022.
139. Duchêne, V., et al., Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing I. European Commission DG Internal Market, Entrepreneurship and SMEs, Editor. 2016, IDEA Consult, VTT, AIT: European Union.

140. IPCC, Climate Change 2014. Synthesis report. 2014.
141. European Commission Directorate-General for Energy, Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU : final report. 2019.
142. European Commission, Directorate-General for Employment, Social Affairs and Inclusion, Hancké, B., Bowen, A., The social dimensions of 'greening the economy' : developing a taxonomy of labour market effects related to the shift toward environmentally sustainable economic activities, Publications Office, 2020, https://data.europa.eu/doi/10.2767/448791.
143. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. 2018, COM/2018/773 final
144. Eurofound (2019), Future of manufacturing – Energy scenario: Employment implications of the Paris Climate Agreement, by Lewney, R., Alexandri, E. (Cambridge Econometrics), Storrie, D. (Eurofound) and Antón, J.-I. (University of Salamanca), Eurofound Research Report, February 2019.
145. Cárcel-Carrasco, J., et al., Digital skills for workplace mentors in construction sector apprenticeships (CONDAP). in INNODOCT 2019. 2019. Valencia, Spain: Editorial Universitat Politècnica de València.
146. World Bank Group, Which jobs are most vulnerable to COVID-19? What an analysis of the European Union reveals. 2020, Research & Policy Briefs From the World Bank Malaysia Hub.
147. EUROSTAT, EDUC_UOE_GRAD02: Graduates by education level, programme orientation, sex and field of education. Last update: 09/08/2022 22:00. 2022.
148. EUROSTAT, LFSA_EGAN22D: Employment by sex, age and detailed economic activity (from 2008 onwards, NACE Rev. 2 two digit level) - 1 000. Last update: 15/12/2022 22:00. 2022.
149. Serra, S., C. Soares, and L. Sarti Júnior, Chapter 11: Asset management of recycled concrete applications, in recycled concrete - Technologies and performance. 2023, Elsevier: United Kingdom. p. 337-362.
150. Kartam, N., et al., Environmental management of construction and demolition waste in Kuwait. Waste Management, 2004. 24(10): p. 1049-1059.
151. Peters, M., et al., Buildings as material banks and the need for innovative business models. 2017, BAMB - Buildings as Material Banks.
152. EUROSTAT, Annual enterprise statistics for special aggregates of activities (NACE Rev. 2) [SBS_NA_SCA_R2__custom_3629360]. NACE R2 = F. E Turnover or gross premiums written - million euro. Data from 2018. 2022.
153. EUROSTAT, Eurostat - GDP and main components (output, expenditure and income) [NAMQ_10_GDP__custom_3629640] - Gross domestic product at market prices. 2022.
154. European Environment Agency, Effectiveness of environmental taxes and charges for managing sand, gravel and rock extraction in selected EU countries. 2008: Copenhagen, Denmark.
155. RE4Project, D1.4 Overview on the current status on policy measures and regulatory frameworks. 2017, CETMA.
156. Ajayi, S.O. and L.O. Oyedele, Policy imperatives for diverting construction waste from landfill: Experts' recommendations for UK policy expansion. Journal of Cleaner Production, 2017. 147: p. 57-65.
157. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of EU waste legislation, including the early warning report for Member States at risk of missing the 2020 preparation for re-use/recycling target on municipal waste. 2018, COM/2018/656 final.
158. European Commission, EU construction & demolition waste management protocol, Ecorys,. 2016.
159. Abarca-Guerrero, L., G. Maas, and H. Van Twillert, Barriers and Motivations for Construction Waste Reduction Practices in Costa Rica. Resources, 2017. 6(4): 69.
160. Bilsen, V., et al., Development and implementation of initiatives fostering investment and innovation in construction and demolition waste recycling infrastructure. 2018, European Commission: Brussels, Belgium.
161. Villoria Sáez, P. and M. Osmani, A diagnosis of construction and demolition waste generation and recovery practice in the European Union. Journal of Cleaner Production, 2019. 241: 118400.
162. Vyncke, J. and E. Rousseau, Recycling of construction and demolition waste in Belgium: Actual situation and future evolution, in Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, E.K. Lauritzen, Editor. 1993, CRC Press: Odense, Denmark. p. 60-74.
163. Mangla, S.K., K. Govindan, and S. Luthra, Prioritizing the barriers to achieve sustainable consumption and production trends in supply chains using fuzzy Analytical Hierarchy Process. Journal of Cleaner Production, 2017. 151: p. 509-525.
164. Sharp, J., et al., Framework for policies, regulations and standards, in BAMB - Buildings as Material Banks. 2019.
165. Chen, W. and R. Jin, Chapter 7: Recycled Concrete for Nonstructural Applications, in Recycled Concrete - Technologies and Performance. 2023, Elsevier: United Kingdom. p. 233-263.

166. Jin, R., et al., An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. Resources, Conservation and Recycling, 2017. 126: p. 86-98.
167. Yuan, H., Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China. Journal of Cleaner Production, 2017. 157: p. 84-93.
168. Tam, V.W.Y., Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. Journal of Cleaner Production, 2009. 17(7): p. 688-702.
169. RE4Project, D1.3 Overview on the current status of construction of prefabricated elements with recycled materials. 2017, ROS, CETMA, QUB, CBI.
170. Nunes, K.R.A., et al., Evaluation of investments in recycling centres for construction and demolition wastes in Brazilian municipalities. Waste Management, 2007. 27(11): p. 1531-1540.
171. Huang, B., et al., Construction and demolition waste management in China through the 3R principle. Resources, Conservation and Recycling, 2018. 129: p. 36-44.
172. Jin, R. and Q. Chen, Overview of concrete recycling legislation and practice in the United States. Journal of Construction Engineering and Management, 2019. 145(4): 05019004.
173. Hao, J.L., M.J. Hills, and V.W.Y. Tam, The effectiveness of Hong Kong's construction waste disposal charging scheme. Waste Management & Research, 2008. 26(6): p. 553-558.
174. Hiete, M., et al., Matching construction and demolition waste supply to recycling demand: a regional management chain model. Building Research & Information, 2011. 39(4): p. 333-351.
175. Ulubeyli, S., A. Kazaz, and V. Arslan, Construction and demolition waste recycling plants revisited: Management issues. Procedia Engineering, 2017. 172: p. 1190-1197.
176. Tost, M. and G. Ammeerer, Sustainable supply of aggregates in Europe. 2022: Leoben, Austria.
177. UEPG Guidance: End of waste criteria for recycled aggregates from construction & demolition waste. 2022.
178. Manfredi , S. and R. Pant, *Supporting environmentally sound decisions for construction and demolition (C&D) waste management. A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA).* 2012, Joint Research Centre, Institute for Environment and Sustainability: Publications Office.

List of abbreviations and definitions

CDW	Construction and demolition waste
CRCA	Coarse Recycled Concrete Aggregates
DfARD	Design for Adaptability, Reuse and Deconstruction
EU-27	European Union (27 Member States)
FL	Type of constituent of recycled aggregates: floating materials
LCA	Life-cycle assessment
NA	Natural aggregates
NAC	Natural Aggregate Concrete, which is exclusively made with natural aggregates
RA	Recycled aggregate
RAC	Recycled Aggregate Concrete, which is made with partial or total incorporation of recycled aggregates
RAC100	Concrete made with total incorporation of coarse recycled aggregates
UEPG	European Aggregates' Association
X	Type of constituent of recycled aggregates: category of other materials, such as clay, soils, metals, non-floating wood, plastic, gypsum-based and rubber
Ra	Type of constituent of recycled aggregates: bituminous materials
Rb	Type of constituent of recycled aggregates: clay masonry, calcium-silicate masonry, aerated non-floating concrete
Rc	Type of constituent of recycled aggregates: concrete and mortar
Rg	Type of constituent of recycled aggregates: glass
Ru	Type of constituent of recycled aggregates: unbound stone

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