CirCon4Climate – Strengthening Circular Construction Practices for Climate Change Mitigation

SUMMARY REPORT ON BEST CIRCULAR CONSTRUCTION PRACTICES

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1. Structure-specific and waste-specific material flows of CDW

1.1. Raw material consumption and waste generation of the construction industry in the EU

EU's material footprint amounted to 13.7 tons per capita and year in 2020. The largest share of around 7,1 tons per capita and year is accounted for non-metallic minerals, which are mainly used in the construction industry (Fig. 1). Since 2012 there is no significant trend toward a decrease.

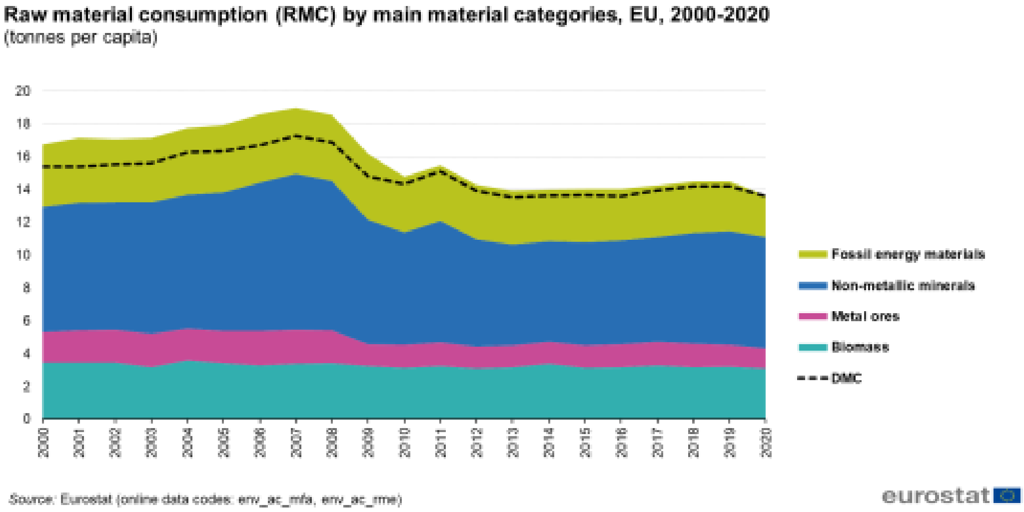


Fig. 1. Raw material consumption per capita (tons per capita) in the European Union 2021 [1]

The total amount of waste generated is 4,8 tons per capita and year. The largest amount is caused by the construction industry with 1,8 tons per capita and year respectively 37,5 % (Fig. 2). Mining and quarrying waste that can be also a source for building material manufacture occurs in an amount of 1,1 tons per capita and year respectively 23,4 %.

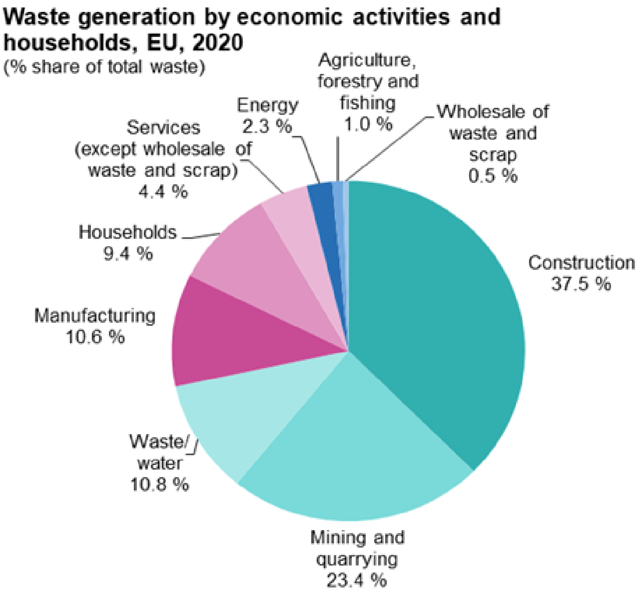


Fig. 2. Waste generation (percent) in the European Union 2020 [2]

The data relevant for the construction sector are summarized in Tab. 1.

Tab. 1. Raw material and waste relevant for the construction industry

	ton per capita and year	
Raw material consumption of construction industry	7,1	
Waste, generated from construction and demolition (CDW)	1,8	Increase of material stock in the building sector: (7,1 - 1,8) ton/capita and year = 5,3 to/capita and year
Waste, generated from mining and quarrying	1,1	Maximum substitution of nat. raw materials: 100*(1,8 + 1,1)/7,1 = 41 %

From the statistical data first conclusions can be drawn:

- The stock of material stored in the building sector increases. The difference between the material input of the construction sector (7,1 ton per capita and year) and the material output (1,8 ton per capita and year) is to 5,3 ton per capita per year. This corresponds to an increase of approx. 2 m^3 of concrete per capita.
- If the generated CDW is completely used again as secondary raw material or as product, the primary raw material consumption could be reduced by 25 %.
- If the mining waste can also be used as a raw material in the construction industry, the raw material consumption can be reduced by 41 %.

At least for construction waste, the current state of knowledge and the available technologies are sufficient to exploit this potential.

1.2. Structure-specific material flow

CDW is generated during the construction, renovation or "elimination" of a structure. The elimination of a structure results in the largest amount of CDW compared with the other activities. A distinction is made between two approaches toward the removal of buildings or constructions:

- Demolition is the removal of a structure without explicit consideration of its material composition.
- Dismantling (or Deconstruction is the step-by-step selective, controlled, systematic or recycling-friendly demolition with the aim of preserving as much as possible of unmixed materials. In construction, dismantling means to carefully take apart one or more parts of a building or structure without damaging the other parts.

In both cases, a material register of the building must first be drawn up. If this reveals that pollutants are contained, they must be removed before the actual demolition/deconstruction with handheld tools mostly. For the demolition of structures, the use of hydraulic breakers dominates. Other methods are the use of wrecking balls or the blasting of structures. For the dismantling of structures smaller tools, partly handheld tools are used.

The amount of construction waste generated during demolition depends primarily on the size of the structure. This is followed by parameters such as function and compactness of the structure. It can be calculated on the basis of a structure survey or estimated on the basis of structure-specific key figures. For structures that enclose a certain space, there is a correlation between the gross volume and the amount of waste (Fig. 3 and 4).

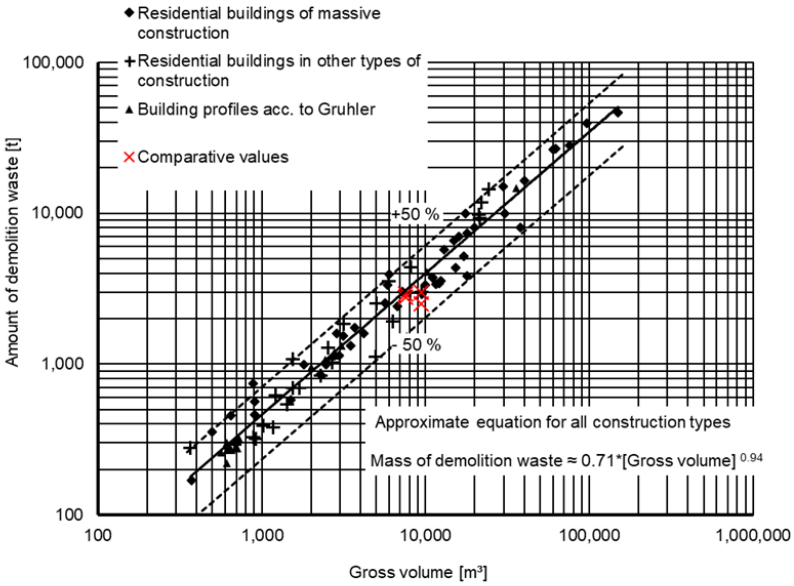


Fig. 3. Dependence of the specific building rubble quantity on the building size for residential buildings [3]

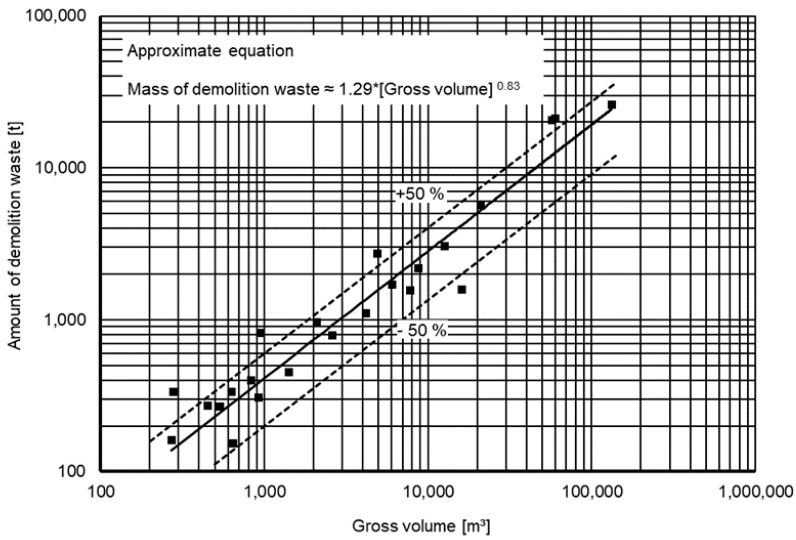


Fig. 4. Dependence of the specific building rubble quantity on the building size for industrial buildings [3]

In Tab. 2 six examples of different buildings, whose features are described [4], are summarized. The mass of CDW generated is compared with the calculated amount acc. to the equation in Fig. 3 and Fig. 4. The differences are rather moderate. The comparison shows that the relationships are suitable for an initial estimate of the amount of construction waste generated during the demolition of structures.

Tab. 2. Comparison of measured and calculated amount of CDW for different buildings [4]

	Year of erection	Age	Function	Gross volume	Measured amount of CDW	Calculated amount of CDW	
				[m³]	[t]	[t]	[t]
						All types of construction	Industrial constructions
1	1970	44	Parking deck	5272	1590		1584
2	1952/ 1957	53	Office building	37000	13726	13976	
3	1952	61	Workshop building	6500	2328	2725	
4	1981	32	Residential building	4890	2634	2085	
5	1996	19	Steel-glass entrance hall	1625	788	740	
6	1935/ 1939	76/ 61	Factory building	11700	2737		3070

1.3. Classification of construction and demolition waste

The European List of Waste [5] is used to systematize the waste generated in the course of production processes or at the end of the product use for a large spectrum of goods and materials. Six-digit number codes with three levels of classification are assigned to the types of waste. The first two digits represent the chapter which takes into account the origin and/or the process of production. The two next digits represent the sub-group, which usually represents a certain type of substance. The last two digits are consecutive. In total, the LoW contains 839 types of waste classified in 20 chapters. Of these, 405 types are classified as hazardous. They are marked with an asterisk (*) after the waste code number. In addition, the directory contains 172 so-called mirror entries. This means that an originally non-hazardous type of waste is listed a second time if it contains hazardous substances. The European List of waste lists 15 hazard criteria, ranging from explosive to ecotoxic.

Construction and demolition wastes include all wastes arising in connection with the erection, reconstruction or renovation and demolition of buildings and structures. They are listed in Chapter 17 of the LoW. In total, this chapter contains 38 entries of which 10 are mirror entries. This means that 28 types of waste are included. In construction practice, construction and demolition waste is divided into the source and material related species excavated soil, road demolition waste, building rubble, construction site waste and gypsum-based construction waste:

- Excavated soil accumulates during the construction of buildings and the renewal or new construction of roads and civil engineering works.
- Road demolition waste comes from renovation or rehabilitation of roads and traffic areas.
- Building rubble originates from the demolition of buildings, civil engineering works and engineering structures. If it originates from underground or engineering structures, it consists mainly of concrete. Building rubble from the demolition of buildings can have different materials. In massive buildings of a younger age or prefabricated buildings, concrete, including reinforcement, dominates. Coatings such as thermal insulation materials or plasters and screeds are additional components. Older buildings consist more frequently of brick masonry.

- Construction site waste is generated during the construction or renovation of buildings. Mostly it is collected in containers and transported to treatment plants.
- Gypsum-based construction waste results from the interior finishing of new buildings or the reconstruction of existing buildings.

The types mentioned differ in the number of material species included and thus in the number of LoW-codes that can be assigned to the respective types (Tab. 3). Road demolition waste is comparatively homogeneous, while construction site waste contains many different types of material. Building rubble takes an intermediate position.

Tab. 3. Summary of the types of construction and demolition waste without hazardous waste classified according to the European List of Waste, mostly illustrated by example figures

Origin	**LoW-Number**	**Constituents**	
Soil, stones and dredging spoil	17 05 04	Soil and stones without hazardous substances	
	17 05 06	Dredging spoil without hazardous substances	
	17 05 08	Track ballast without hazardous substances	
Waste form road demolition	17 03 02	Bituminous mixtures without hazardous constituents	
Construction demolition waste	17 01 01	Concrete	
	17 01 02	Brick	
	17 01 07	Mixtures of concrete, bricks, tiles and ceramics without hazardous constituents	

Construction (site) waste	17 02 01	Wood	
	17 02 02	Glass	
	17 02 03	Plastics	
	17 04 01 – 17 04 11 other than 17 04 09, 17 04 10	Metals (including alloys) other than those contaminated by dangerous substances and other than cables containing oil, coal tar or other dangerous substances	
	17 06 04	Insulating material other than that containing dangerous substances or asbestos	
	17 08 02	Gypsum-based building materials other than those containing dangerous substances	 
	17 09 04	Mixed construction and demolition wastes with the exception of those containing dangerous substances	

The portions of the different types of building materials in the construction and demolition waste in total differ from each other by tens of magnitudes (Fig. 5). The following gradations exist:

- Building materials with proportions of 10 to 50 mass-%: Concrete, bricks including other mineral wall-building materials
- Building materials with proportions to 25 mass-%: Asphalt
- Other mineral waste < 10 mass-%

- Wood: 2 to 4 mass-%
- Metal: 0,2 to 4 mass-%
- Gypsum: 0,2 to 0,4 mass-%
- Plastic: 2 mass-%
- Miscellaneous: 2 to 35 mass-%

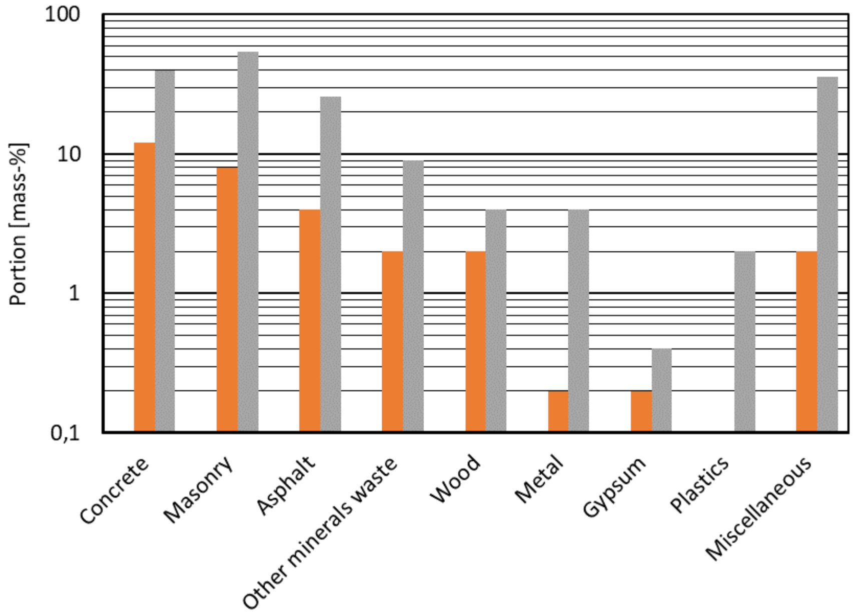


Fig. 5. Range of composition (minimum and maximum) of construction and demolition wastes [6]

"Mixed construction and demolition waste" is generated during an erection of a building as well as during renovation or demolition. This waste consists of the following material groups:

- Mineral components: Concrete, brick, calcium silica brick, aerated autoclaved concrete, mortar, natural stone, stoneware, tiles, gypsum plasterboard
- Metals: Reinforcement, installation material of heating, sanitary, roof drainage, electrical installations
- Wood: Shuttering timber, squared timber, pallets, glued laminated timber, chipboard
- Paper and cardboard
- Plastics.

From published sorting analyses, it can be derived that in mass-related considerations the mineral constituents dominate, followed by most diverse materials, which are summarized as "miscellaneous" in Fig. 6. Next is wood, then paper, cardboard and paperboard. Metals and plastics are present in roughly the same small mass proportions. The ranges in variation that follow from the indicated standard deviations are considerable.

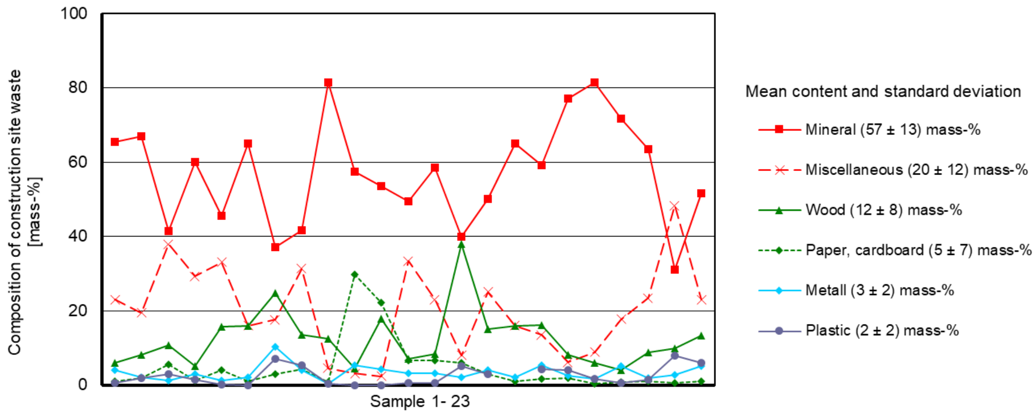


Fig. 6. Composition of mixed construction and demolition waste generated during construction and renovation (Data from [3])

Although the mineral components dominate also in the mixed construction and demolition waste the lighter components determine the appearance of this waste. Wood and paper are especially dominant in the volume. Although the mass proportion of mineral construction waste is more than half, the volume required for intermediate storage or transportation of the mineral components is less than a quarter of the total volume required.

1.4. Waste management key figures

The classification of construction and demolition waste according to types is one of the necessary prerequisites for material flow management. Thus, the waste streams can be structured and the sub-streams are uniformly designated. These designations can be found, for example, in the acceptance catalogues of recycling companies. Structuring also forms the basis for national and European construction waste statistics. These create a basis for comparability for the calculation of the recycling rates of the Member States of the EU.

The quantity of construction and demolition waste taken from statistical surveys is the basis for the calculation of the population-specific values. In Germany, this value is about 0.9 t/capita*year if the waste type "stones, soil and dredged spoil" is excluded. In order to be able to assess this value internationally, indicators must be available that are based on the same definitions for construction and demolition waste and were determined using similar survey methods. This is at least partly possible in the case of construction and demolition waste generated in Europe. The quantities generated in the Member States of the European Union are structured according to the waste code numbers in Tab. 3 and compiled by Eurostat, the statistical authority of the European Union. According to an evaluation based on this, the amount of construction and demolition waste without stones, soil and dredged spoil ranges between 0.02 and 2 t/capita*year (Fig. 7). This wide range is caused on the one hand by the different quality of the data collection and by differences in the data assessment methods. On the other hand, technical aspects such as the regionally preferred types of materials and constructions or the age and the condition of the existing building stock play a role. In addition, there are influences from the respective economic situation in the construction industry. The realization of large-scale projects in the period under consideration, which required the demolition of residential, commercial and industrial buildings, can also have an influence. The temporal fluctuations may be due to all these factors.

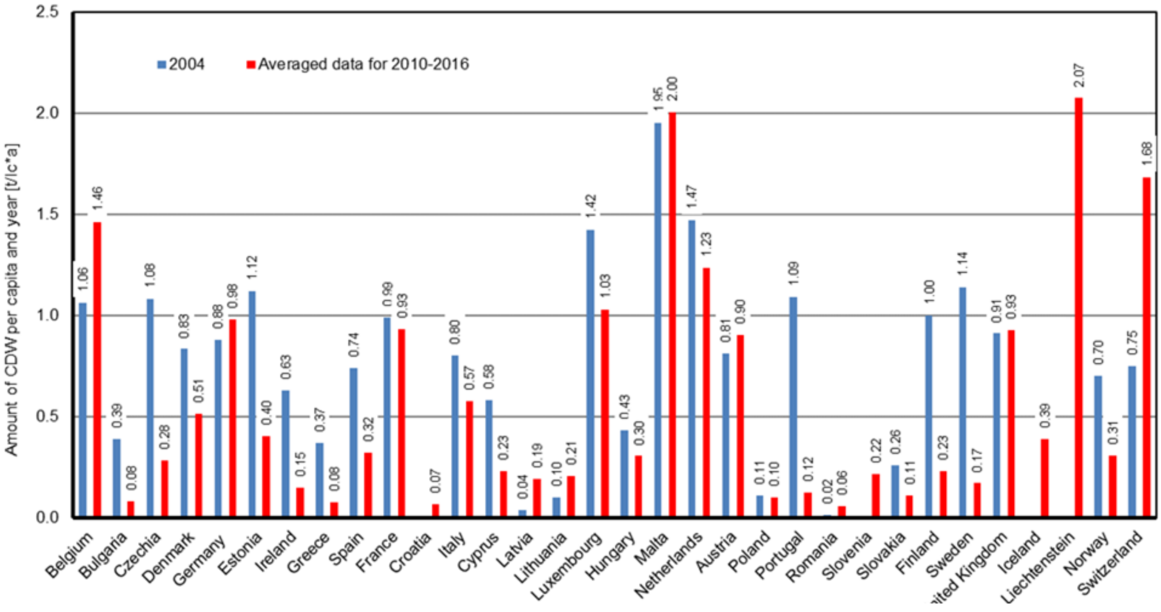


Fig. 7. Amount of CDW per capita in European countries [3]

For the four countries considered here from Fig. 7 follows a minimum amount 0.1 t/C*a for Poland and a maximum amount of 1,12 t/C*a for Germany. In the case of the Czech Republic there are considerable differences between the amounts for 2004 and 2010 - 2016, that cannot be explained. For Poland and Slovenia the amounts are very low. Data from another source than the statistical authority of the European Union are given in Tab. 4. These values confirm a value of 1 t/C*a for the Czech Republic as well as the very low values for Poland.

Tab. 4. Key figures on the generation of construction and demolition waste [6, 7, 8, 9]

		Czech Rep.	Germany	Poland	Slowenia
Inhabitants [Mio]		10,5	84,3	38,2	2,1
Population desity [Inh/km²]		139	236	123	104
Total CDW per year [Mio t]		13,4	90,7	3	1,9
CDW per capita [t/C]		1,28	1,08	0,08	0,95
Recycling [%]		69	85	68	?
Recycling + Backfilling [%]		95	92	91	?

A detailed description of the CDW recycling is given for the Czech Republic [10]. There, the number of recycling centers in operation is given as 80 in total (Fig. 8). From this, the size of the catchment area can be calculated simply as the quotient of the total area of the country and the number of recycling centers. It amounts to 986 km² and is thus twice as high as the catchment area of 580 km² calculated for Germany (Table 5).

Fig. 8. Distribution of recycling centers for CDW in the Czech Republic [10]

Tab. 5. Comparison of data on amount of CWD and processing facilities in the Czech Republic and Germany

	Czech Rep.	**Germany**
Generated CWD [t/a]	13.400.000	90.700.000
Number of recycling centers	80	799
Area of the country [km²]	78.867	357.588
Inhabitants [Mio.]	10,5	83,2
Population density [Inh/km²]	136	232
Average size of the catchment area [km²]	986	448
Average throuput [t/a]	167.500	113.517

In order to overcome the unsatisfactory situation in Poland, a National Waste Management Plan was developed in 2016 [11]. It identifies the following problems in relation to the recycling of construction waste:

With regard to waste from construction, renovation and demolition of buildings and road infrastructure, the problem has been identified consisting in the application of unfair and illegal practices by entities performing C&C work in the field of C&D waste management, including:

- Leaving C&D waste in the place of its generation;
- Provicing C&D waste to unauthorised entities;
- Dumping C&D waste in places not intended for this purpose in order to reduce the costs of management of this waste.

The following measures are intended to achieve improvements:

- Introduction of a system of incentives to promote selective collection of C&D wase;
- Introduction of a system of incentives to promote the use of recycled C&D materials;
- Continuation of carrying out inspections of entities generating waste from construction, renovation and dismantling of buildings and road infrastructure as regards the proper handling of a stream of above-mentioned waste;
- Development of technical infrastructure for selective collection, treatment and reuse of C&D.

2. Overview on demolition and processing techniques and best practice examples

2.1. Demolition techniques

Demolition is carried out by hand held tools, using machines or by blasting. Demolition by hand held tools is usually used for small demolition volumes. Other fields of application are the selective recovery of valuable materials or parts as well as the selective dismantling of hazardous materials or parts. This method is highly labourintensive, slow and expensive. Small vehicles equipped with appropriate tools and operated via a console achieve higher demolition rates.

In mechanical demolition, the most commonly used carrier is the hydraulic excavator. Long-front excavators enable demolition at great heights, currently up to about 40 m (Fig. 9). Demolition tools include demolition and sorting grabs, pulverizers, scrap shears (Fig. 10) and hydraulic breaker. Very high buildings or engineering structures are still often demolished by blasting. The use of the wrecking ball is decreasing.

Fig. 9. Long-front excavator

Fig. 10. Demolition grab (left), scrap shear (right)

The use of demolition robots is becoming increasingly important. Currently, they are mainly used in narrow spaces, high buildings, contaminated areas and when there is a risk of collapse or falling. Their share increased from 2 % in 2005 to 22 % in 2015 [12].

After demolition, pre-sorting usually takes place at the demolition site. Metals, wood, insulating materials and plastics are separated from mineral components (Fig. 11, 12). This can result in economic advantages for the demolition company because the acceptance prices for pre-sorted construction waste are usually lower than those for mixed construction waste. Pre-sorting is usually done mechanically with excavators. Only large-sized parts can be collected and separated.

Fig. 11. Separation of brick from wood

Fig. 12. Separated window frames (left), separated rock wool (right)

Selective deconstruction as a method of recovering sorted material is only carried out under certain conditions. Decisive factors are: The available space at the site of the demolition object, the time available, the labour costs and the possibilities/costs for returning the deconstructed elements.

2.2. Processing techniques

The objective of processing is the production of recycled building materials with defined properties from the secondary raw material “construction and demolition waste”. On the one hand, this concerns the particle size distribution, which must correspond to the requirements for the respective field of application. On the other, the material composition and some physical characteristics must meet certain requirements, especially if the recycled aggregates are to be used in road infrastructures or in concrete construction. The quality of the recycled building material produced depends on the respective starting material and the processing technology used. With a homogeneous starting material, it is possible to produce a high-quality recycled building material with a low level of technological effort. If the starting material is highly heterogeneous, the preparation process must be much more complex in order to achieve this goal. The technology to be chosen for the treatment of construction waste is therefore determined by the characteristics of the raw material and the desired product quality.

Building rubble can be treated in mobile or stationary installations. Their main features are summarized in Tab. 6. From the perspective of technical capabilities, the mobile plants are generally more limited than the stationary plants. Meanwhile, the progress in technology has also provided the availability of mobile devices for screening as well as for air classifying, so that mobile processing can also be used to produce recycled building materials that are classified into fractions and free of light impurities. In stationary plants, a wet sorting can be realized in addition. Mobile plants usually operate at the demolition location. However, it is also possible to create storage areas for construction waste in which mobile plants are used if sufficient building rubble is available. One example is demolition and processing during highway rehabilitation (Fig. 13). Stationary plants are used where the amount of construction waste is high, e.g. in large cities or conurbations. In some cases, stationary plants operate in parallel to the extraction and processing of natural aggregates in quarries.

Fig. 13. Mobile processing plant during crushing of concrete recovered from a highway

Tab. 6. Features of mobile and stationary systems for processing of construction and demolition waste

Mobile systems	Feed quantity up to approx. 250 t/h
	Used for a total quantity of at least approximately 5000 t per demolition site up to sites with large amounts of demolition material, e.g. for example in the case of motorway renewal or the dismantling of industrial plants
	All units grouped on semi-trailers, low-bed trailers or hangers, thus quickly and easily moveable system
	Process technologies from the minimum variant "Pre-screening and crushing" up to variants with additional mobile product screening and air separation possible
	Low effort for the preparation of the installation site, no acquisition of the company premises necessary
	No outlay for approval procedures, provided that the operating time at a site does not exceed a certain limit
	Production of usually only one or two products
	End product quality controllable by the quality of the feed material and the technological effort within limits, quality monitoring required depending on the field of application
	On-site recycling possible
Stationary plants	Capacities up to 1000000 t/year realized
	Used in processing centers in conurbations
	Supply of construction and demolition waste and sale of recycled building materials must be secured in the longer term within the region
	Maximal variants of process technologies possible
	Additional expenses for acquisition and installation of the area of the company
	Considerable expense for approval procedures
	Controllable product quality even in the case of inhomogeneous feed material through targeted acceptance, control, upstream sorting, intermediate storage, multi-stage comminution and downstream sorting Periodic quality control required if recycled materials are supplied to qualified fields of application such as road construction or concrete production
	Broad product sortiment possible

In stationary plants construction waste is received at the recycling plant separately according to types of the construction waste, sizes of the delivered material, degree of mixing or contamination. The delivered material is usually stored on longitudinal stockpiles, whereby at least the input streams of concrete and masonry are stored separately. A more favorable variant is storage in boxes (Fig. 15). When the material is received, the "suitable" box is assigned to the deliverer, thus avoiding additional mixing. Removal from the box can be carried out by an excavator positioned at a higher level. Due to the good view on the material, any foreign material that may be present can be sorted out right at the beginning. The excavator feeds the material directly into the crusher feed chute.

Fig. 14. Separate storage of delivered building rubble concrete and brick rubble in a recycling company and material removal by excavator

The building materials resulting from the processed rubble are stored in outdoor stockpiles and/or boxes (Fig. 17). It is necessary to mark the stored building materials with regard to the type of material, the particle size and any existing external monitoring. The products are usually transported by lorries, which are loaded with wheel loaders. Loading the transport vehicles via conveyor belts is favorable in terms of both energy and time.

Fig. 15. Box storage of recycled building materials and labelling

A simplified scheme of the processing of concrete and masonry crushed material is shown in Fig. 16). The process steps crushing - classification - sorting are passed through (Tab. 7).

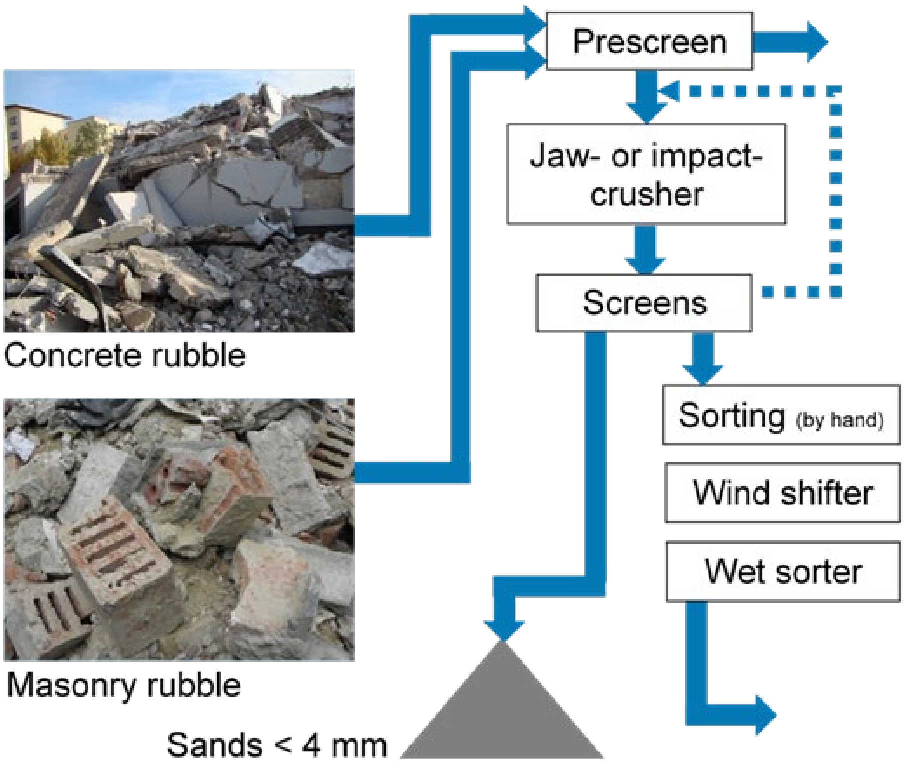


Fig. 16. Scheme of the processing of construction and demolition waste

Tab. 7. Basic operations of CDW processing

Basic operation	**Objectives**
Pre-screening	Separation of soil and/or oversized chunk
Crushing: Using mechanical forces to split up a solid body	Reduction of the largest particle size Production of polydisperse particle mixtures Disintegration of "adhesions", i.e. exposure of the individual components from composites
Classification by screening: Separation of processed granular debris according to geometrical dimensions into different particle size fractions	Limitation of the upper particle size Generation of certain particle size distributions for subsequent recycling Separation of course materials to protect downstream crusher from damages and overloading Separation of fine particles to relieve the load on crushing equipment, to secure against wear and to prevent blockages Preparation for sorting if this is only possible in the case of a narrow particle size range Sorting the material if specific substances are enriched in certain particle size fractions
Sorting: Separating a mixture of materials according to substance types using physical characteristics	Removal of pollutants and impurities Separating mixed construction waste into its mineral components

2.2.1. Pre-screening

The task of pre-screening is, on the one hand, the separation of oversized lumps to prevent damage of the downstream crusher. On the other hand, fine soil components are separated to prevent clogging and wear of the crusher. For the separation of the coarse components very robust rod grates or vibro grates are used (Fig. 17). For the separation of fine soil particles different machines are used. One example are flip-flop screens which are suitable for damp material that tends to clog (Fig. 18).

Fig. 17. Grad for prescreening

Fig. 18. Functionality of a flip-flop and example for the movement of the material [13]

2.2.2. Crushing

The next step in the processing of CDW is crushing. Its task is to produce graded particle size distributions. It is also used to disintegrate composite materials so that they can be sorted after crushing. Jaw and impact crushers which are also used in processing of rocks are mainly used. The input material is fed via a roller grate or a belt. The discharge of the crushed product must be designed in such a way that bulky material does not cause blockages or damage to the discharge belt arranged below the crusher. Jaw crushers can be regarded as a technical implementation of the nutcracker principle. The material falls into the feed opening. The crushing takes place between a fixed and a movable crushing jaw. By the closing of the mouth of the crusher, forces act on the material which it cannot deflect. The material then slides into a deeper position and is stressed again. This process is repeated until the material can pass through the discharge gap. In addition to the material properties, the width of the discharge gap is therefore decisive for the product particle size. The first jaw crusher was developed by Blake in 1858 for rock and ore processing.

Depending on the type of power transmission, different types can be distinguished. The scheme of a single-toggle jaw crusher is shown in Fig. 19. A crusher in action is shown in Fig. 20.

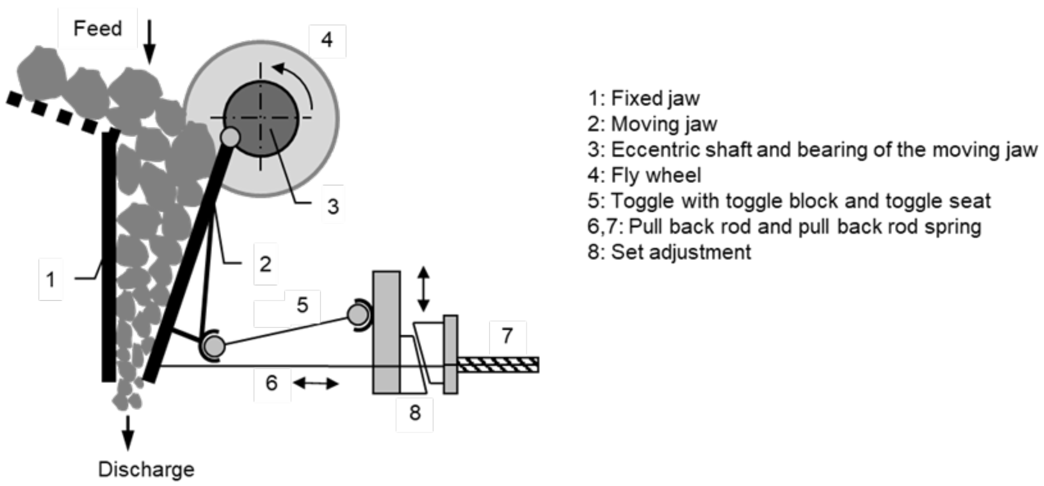


Fig. 19. Schematic of a single-toggle jaw crusher

Fig. 20. Jaw crusher during crushing of building rubble [14]

Impact crushers consist of the housing and the rotor. Both are equipped with impact elements (Fig. 21). The impact bars mounted on the rotor transfer a part of their kinetic energy to the material when they come into contact with it, thereby causing its comminution. Additional stresses are created by the impact of the accelerated material on the impact plates in the crusher housing and the impact of the fragments with each other. Impact crushers can also be equipped with a grinding track for further crushing. In contrast to the jaw crusher, the particle size reduction achieved is less dependent on the geometry of the discharge opening. The decisive factor is the circumferential speed of the rotor.

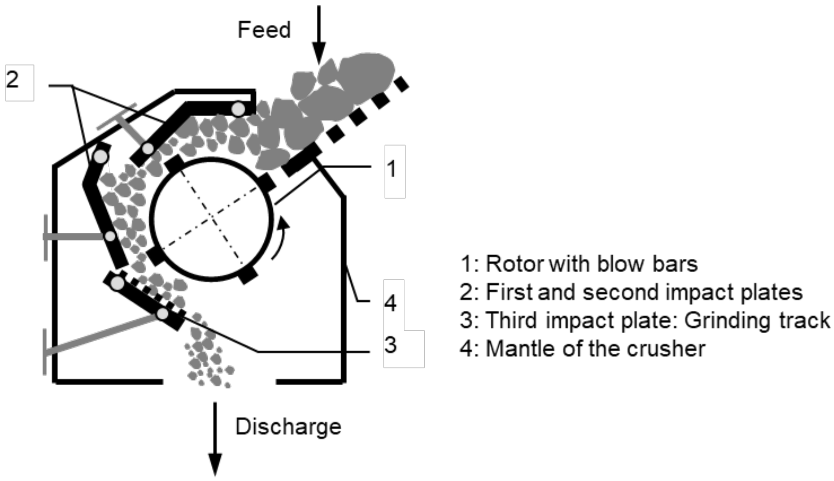


Fig. 22. Schematic of an impact crusher

Fig. 21. Usher during crushing of building rubble [15]

The throughput, the required drive power and the crusher mass increase with increasing size of the feed opening. In the case of stationary crushers, these typical differences can be seen: The jaw crusher is heavier than the impact crusher for the same throughput, but requires less drive power. Mobile crushers require a higher drive power than stationary ones at the same throughput. The crusher mass of mobile plants is larger because additional equipment is required.

Tab. 8. Comparison of the features of jaw and impact crushers

	Jaw crusher	**Impact crusher**
Processible feed material		
Deformation behavior	Brittle material with predominantly elastic behavior such as track ballast, concrete, wall-building materials	Material with predominantly elastic behavior such as concrete, wall-building materials
Resistance	Up to 500 MPa	Up to 300 MPa
Hardness	Hard to very hard material e.g. track ballast	Medium to hard material

Feed size	Flat components up to approx. 1.0 m x 1.0 m of edge length	Flat components up to approx. 1.0 m x 1.0 m of edge length
Susceptibility to foreign matter in the feed material	Asphalt can lead to adhesions. Wood and plastics unproblematic. Exposed or protruding reinforcing steel can hinder discharge.	Asphalt can be crushed, except at high outside temperatures. Wood and plastics unproblematic. Exposed or protruding reinforcing steel can hinder discharge.
Achievable product parameters		
Comminution ratio	10:1	20:1
Product particle size	= function of set width approx. 0 to 150 mm	= function of rotor circumferential speed approx. 0 to 80 mm
Fines content	Low	High
Proportion of oversized particles	Can be high especially in the case of plate-shaped feed material such as pavement slabs or roof tiles, which can get into the end product without being crushed.	Low
Particle shape of the product	Cubic, portions of plate-like to splintery fragments depending on the input material	Cubic
Machine/Plant		
Stress type	Pressure	Impact
Kinematic parameters	Number of strokes 270...400 min-1	Rotor circumferential speed 20...60 m/s
Feeding height	Ramp required	Ramp required
Service life of wear parts	High, about 300,000 t crushed material	Low, 3,000 t as main crusher, 10,000 t as secondary crusher
Environmental impacts	Low dust and noise emission	Noise and dust emissions, spraying with water required
Application recommendations	In two-stage plants: as primary crushers In single-stage plants: for medium requirements on the end product	In two-stage systems: as secondary crusher In single-stage plants: for high demands on the end product

As a result of the comminution, the following particle properties are changed compared to the initial state:

- Size and shape
- Degree of liberation and
- Microstructure of the generated particles.

The particle size changes are most obvious in the processing of construction and demolition waste as well as in rock processing (Fig. 23).

Fig. 23. Feed material concrete rubble (left) and produced recycled aggregates 0/45 mm (right)

Fig. 24 shows screen passing curves of recycled aggregates produced from concrete rubble. The aggregates originate from various processing plants and consist predominantly of concrete and natural stone, which explains the relatively small scattering width with a maximum particle size of 56 mm the coarser range and 32 mm in the finer range.

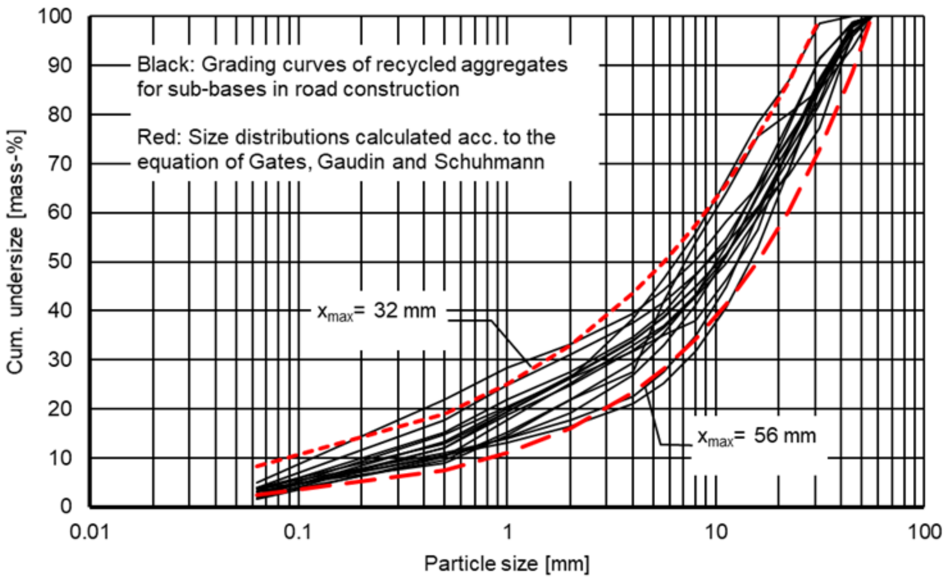


Fig. 24. Screen passing curves of recycled aggregates and calculated Gates Gaudin Schumann distribution functions (Data from quality control protocols)

The changes in the degree of liberation and the microstructure are of secondary importance provided that the recycled aggregates are primarily defined by the particle size distribution. At present, primarily the disintegration of reinforcing steel is of technical and economic importance in the processing of reinforced concrete. A task that has recently come into focus is the processing of concrete with asbestos-containing reinforcement spacers. Here, too, disintegration must be achieved in compliance with all safety regulations in order to avoid having to dispose of the entire material.

2.2.3. Screening

In plants for processing construction and demolition waste, screening is used for the following purposes:

- The separation of coarse components to protect the downstream crushers from overload and damage

- The separation of fine particles to relieve the crushers, to protect against wear and to prevent blockages
- The limitation of the maximum particle size or the production of certain fractions for the subsequent use, e.g. as base course material 0/32 mm or as recycled aggregates 8/16 mm
- The preparation of the sorting, if this is only possible with a narrow range of particle sizes
- The sorting itself, if certain substances are enriched in certain particle fractions.

Throw screening machines are usually used, the screen bottoms of which are vibrated by eccentric drives or unbalanced motors. This allows screening down to the sand range. However, fine grain sizes are strongly influenced by material moisture, which can lead to "blinding" of the screen bottom, to a decrease in throughput and to a deterioration of the separation quality.

2.2.4. Sorting

Selective deconstruction at the demolition site can be regarded as the first sorting stage in the course of preparing construction and demolition waste for recycling. Foreign materials that can be handled with excavators are sorted out and stored separately. In the course of processing, the sorting is integrated into the process flow before or after crushing. With the upstream processes prior to comminution, impurities can be removed manually or mechanically. Mass flow sorting or single particle sorting processes are used for the downstream sorting after comminution. Comminution produces sortable particle sizes and effects the required disintegration of material composites. In contrast to the sorting stages prior to comminution, downstream sorting thus makes it possible to remove impurities that were originally not accessible or impurities that were present as part of a composite.

Sorting of metals

The magnetic sorting is one of the standard methods used to sort out reinforcing steel, small iron parts, etc. The magnetizability of iron, steel or tinplate is used as the sorting characteristic. The required magnetic field is generated by electric or permanent magnets. The effectiveness of the separation depends on the magnetic field strength in the area of the material stream. Further influencing factors are the conveying speed of the material, the bulk height of the material on the conveyor belt and the piece sizes and shapes of the material to be sorted out. Of the two types - overbelt magnet and drum magnet separator - the overbelt magnet is most frequently used in the treatment of construction and demolition waste (Fig. 25).

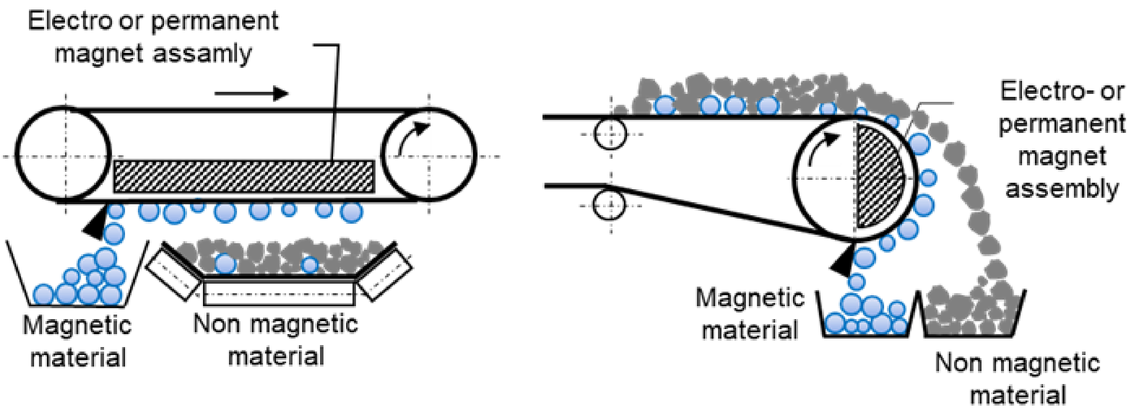


Fig. 25. Schematics of an overbelt magnetic separator (left) and a drum magnetic separator (right)

Eddy current sorting is used to separate non-magnetizable but electrically conductive materials such as stainless steel, aluminum and copper. In eddy current sorting, an alternating magnetic field acts on the material flow. This induces an eddy current in electrically conductive materials, which in turn generates a magnetic field. The latter is directed in the opposite direction to the causal field, so that the conductive materials are rejected.

Sorting of non-metallic materials

The most important characteristic for the sorting of non-metallic components of CDW is the particle density. It ranges from 30 kg/m³ for insulating materials up to 3,000 kg/m³ for certain natural rocks. Before sorting screening usually takes place (Fig. 26). The grain fractions produced depend on the subsequent sorting process.

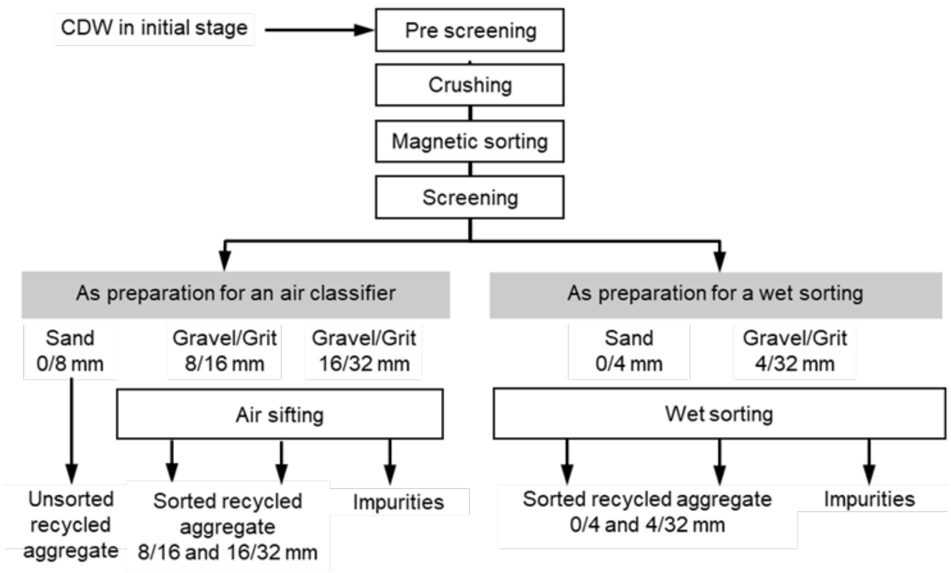


Fig. 26. Placement of the sorting process in the processing sequence of construction and demolition waste

The smallest particle size of the material streams that can be cleaned by air shifting is at best 4 mm, but usually 8 mm or more. So only a portion of 60 to 80 % of a crushed rubble can be cleaned by this method. The wet processes are more robust. Feed particle sizes of a minimum of 4 mm are possible. The particle size ratio can be twice as high as in the dry processes. Sorting of sand fractions is also possible with some wet sorting processes.

Density sorting with air as the fluid medium is carried out in air classifiers (Fig. 27). There are upflow, crossflow and zigzag classifiers, depending on the flow direction of the classifying air. In the case of the frequently used crossflow classifiers, the air flows vertically through the construction and demolition waste stream to be sorted. The light particles are carried by the classifying air, while the heavy particles fall downwards against the air flow. Prerequisites for good separation results are:

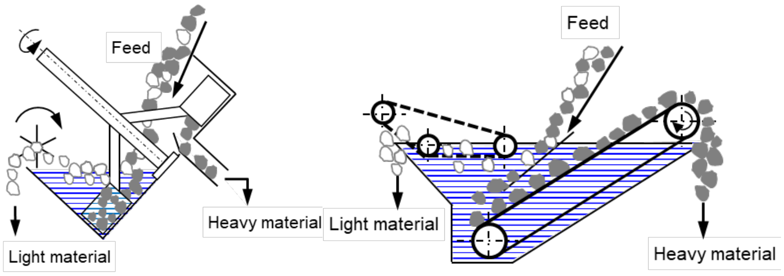
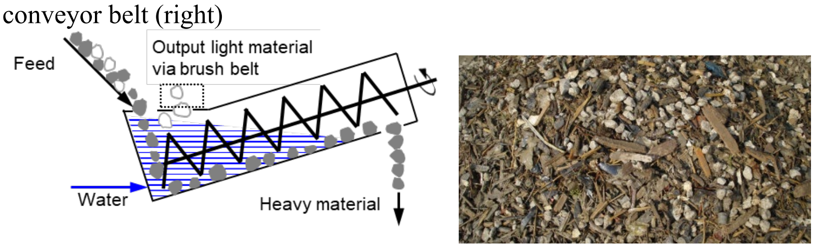
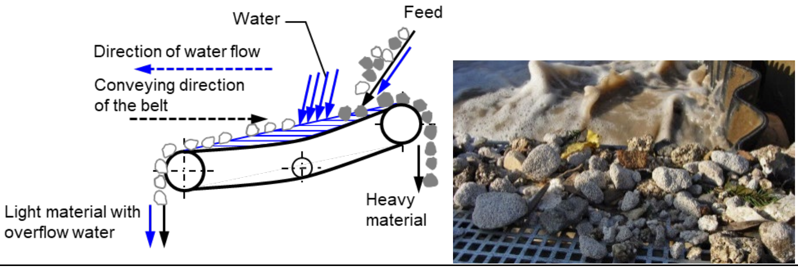
- The material must be present in a sufficiently narrow particle size fraction.
- The particles must be singulated at the latest by where the air stream meets the material.

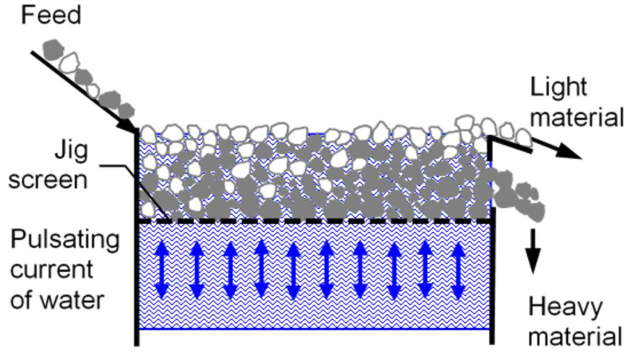
Flat lightweight materials such as paper, plastic folis, and insulation fragments are discharged. Wood is also usually discharged, if it is not present as a very compact fragment.

For wet density sorting different operating principles are used (Tab. 9). Wet sorting based at differences of the material densities too. The separation density is (slightly) higher compared to the wind shifting. The sorters are used for the removal of low-density contaminants. With the exception of aerated concrete and other low-density building materials, it is not possible to separate them according to mineral building material types.

Fig. 27. Air shifter for separation of lightweight materials, cleaned heavy material separated lightweight (left), lightweight materials (right)

Tab. 9. Schemes of wet sorting devices

Swim-sink sorting Tank filled with water or a so called a “autogenous slurry” with densities of 1200 to 1400 kg/m3. Materials with higher densities sink, with lower densities swim. Thus lightweight mate-rials can separate out. The fresh water supply is limited to the water discharged with the material	 Wheel separator (left) and a light material separator with a heavy material conveyor belt (right)  Light material separator with screw discharge and separated material
Film layer sorting The heavy and the light materials are transport-ted in different direc-tions	

Sorting by jigging Fluidization of the material bed by a pulsating water upflow, Acceleration of the lighter particles in the direction of the flow, settling of the heavier particles sink against the direction of the flow	

2.3. Advanced sorting

Sensor-based sorting machines began to be used in the waste management about 30 years ago and have since then become established in the sorting of end-of-life plastics, waste paper and waste glass. In the sorting of construction waste, they have been used only very sporadically up to now.

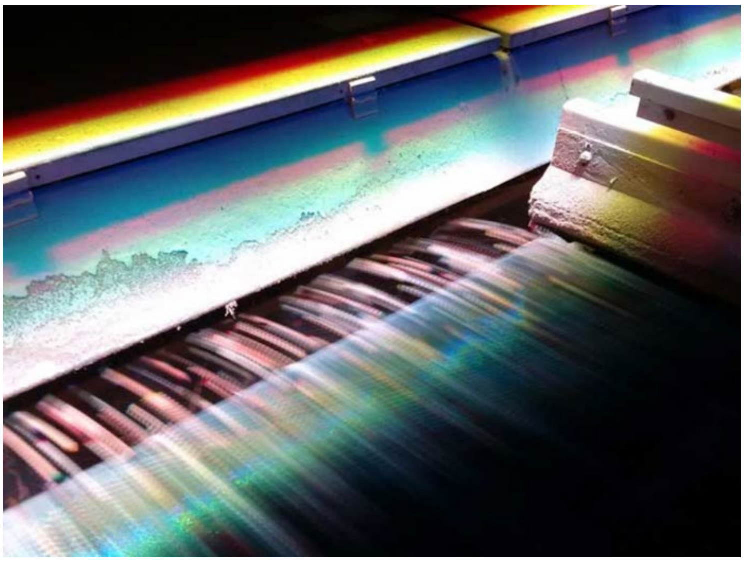


Fig. 28. Sensor-based sorting device for separation of brick and concrete in action in a recycling plant [16]

The newest development is the sorting by "heavy pickers" (Fig. 29). The entire sorting device consists of a conveyor belt, one or more sensors, the process computer, the actual picker, to which 4 drop boxes are assigned. The components of the building rubble are transported on the flat conveyor belt and pass the sensors individually. Impurities or recyclables and their position on the belt are detected. This information is transmitted to the sorting gripper which picks up the materials and drops them into the box provided for the respective type of material. The performance parameters specified by the manufacturer for the sorting of construction waste are a maximum sorting speed of 33 objects per minute with a maximum mass of the objects of 30 kg and dimensions up to 1500 mm x 500 mm x 300 mm.

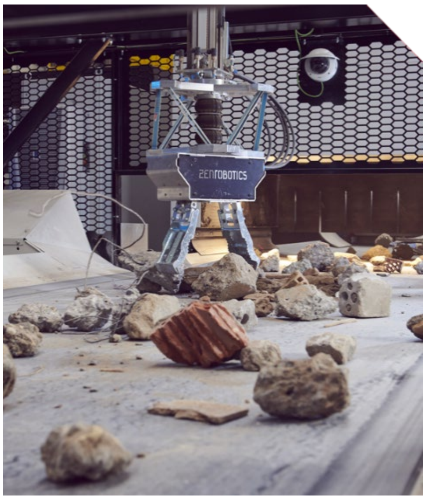


Fig. 29. Heavy picker sorting construction and demolition waste [17]

Tab. 10. Technical parameters [17]

HEAVY PICKER			
Technical specifications:			
Robot Arms	1, 2 or 3	Discharge Chutes	Up to 4 per Arm
Sensor Units	1	Max. Object Weight	30 kg (66 lb)
Gripper Type	Mechanical Gripper	Max. Object Size	1500 mm x 500 mm x 300 mm (60’ x 20’ x 12’)
Max. Speed per Arm	2300 Picks per Hour*	No. of Recognized Fractions	Unlimited
Sorting Belt Speed	0.1 – 0.6 m/s (20-118 fpm)	Installed Power (1 robot)	10 kW (13.4 hp)
Unit Length	6125 mm – 1372 5 mm (20’ 1” – 45’)	Air Consumption (HP1/HP2/HP3)	Pressure of air supply: 7 bar (100 psi) 60/120/180 l/min (2/4/6 CFM)
Unit Weight	4700 kg – 11300 kg (10400 lb – 25000 lb)	Noise Level	<80 bB(A)

*) actual picking speed dependent on material feed

One "picker" can perform up to 2300 picks per hour. The order of magnitude of the feasible throughput can be estimated if the following assumptions are made:

- Feed material: 30 kg fragments
- Impurities to be sorted out: 20 mass %.
- Hourly contaminant discharge: 2300 picks/hour * 30 kg = 69000 kg/h = 69 t/hour

This results in a calculated total throughput of 345 t/h. For up-stream sorting arranged before the crusher, this throughput is quite interesting. Heavy pickers have already found their way into practice in several cases (Fig. 30).

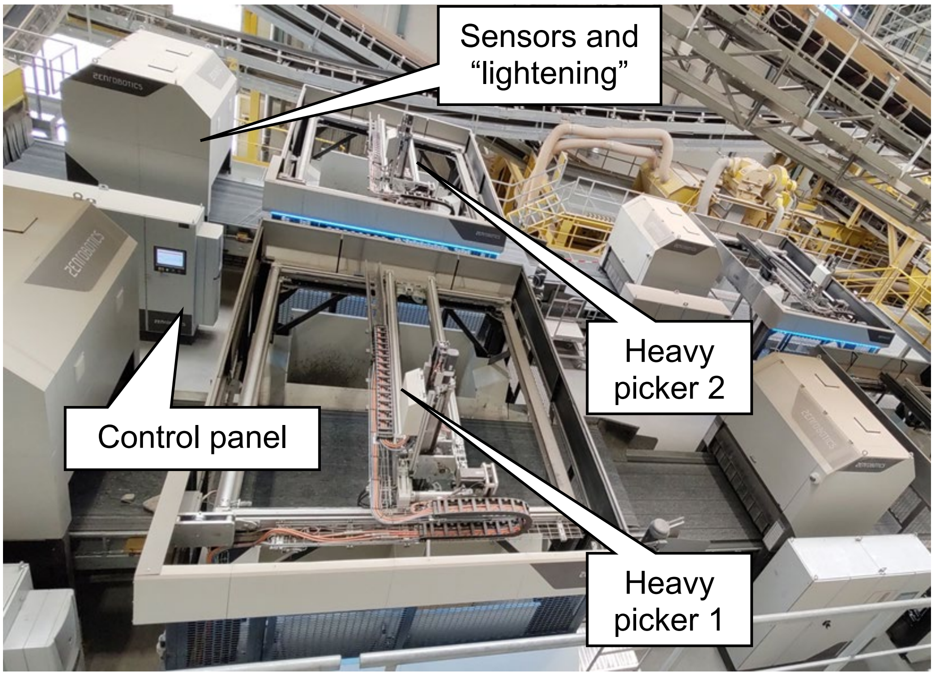


Fig. 30. Heavy picker in a construction and demolition waste recycling plant

3. Requirements on source materials and end products

3.1. State of the art - applications of processed CDW

Industrially produced recycled building materials from demolished concrete or masonry consist mainly of concrete, natural aggregates, bricks and mortar. The sum of these components ranges between 80 and 100 mass-%. They have a comparatively wide range of applications between “Using (only) the volume” of the recycled materials for filling cavities etc. and “Using their mechanical properties” for layers in road construction or as aggregates in concrete.

In earthworks and road construction, the possible fields of application depend on the components of the recycled aggregates (Tab. 11, Fig. 31). If the recycled building material consists of the material groups concrete, natural stone, sand and gravel, there are no restrictions on use, provided that the construction and environmental parameters are observed. Dense ceramic products are also recyclable as long as they do not dominate. Wall building materials with lower strengths and fine components can be problematic for the reuse.

Tab. 11. Possibilities of recovery for recycled building materials in road construction and earthworks depending on the material composition

MATERIAL / FIELD OF APPLICATION	Aggregates of crushed natural rock	Sand, gravel	Aggregates of crushed concrete	Aggregates of dense clay bricks	Calcium silica bricks, soft clay bricks, plasters, lightweight materials etc.	Material groups as left with > 15 mass%, < 0.063 mm
Superstructure of streets, pathways and squares						
Unbound base courses in road construction	+	+	+	⌖	-	-
Surface cources without binder	+	+	+	+/-	-	-
Subgrade of paving surfaces and flagstones	+	+	+	+/-	-	-
Unbound aggregate shoulders	+	+	+	+	⌖	+/-
Temporary site roads	+	+	+	+	+/-	+/-
Hydraulic bound layers						
Hydraulically bound base course	+	+	+	+	-	-
Concrete base layers	+	+	+	+	-	-
Concrete surface layers	+	+	+	-	-	-
Earthworks						
Earthworks	+	+	+	+	+/-	+/-

LEGEND:	
Utilization possible	+
Co-utilization possible	⌖
Utilization limited possible	+/-
Utilization not possible	-

Base courses and frost protection layers of road constructions are the preferred fields of application. The use of recycled concrete aggregates from road pavements for these layers has been successfully implemented since over 20 years. As measurements at old layers show the bearing capacity increased over the service life, while the water permeability decreased. Possible reason could be the carbonation of the concrete constituents and the associated structural compaction.

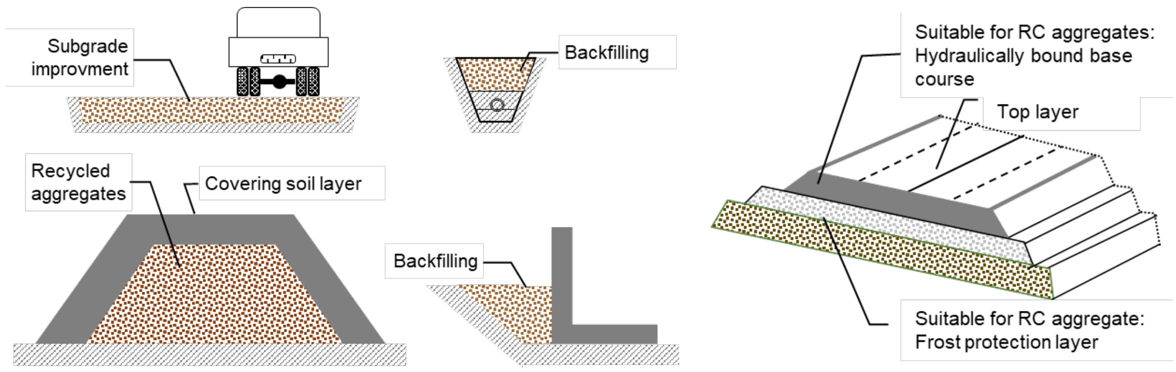


Fig. 31. Examples for the use of recycled aggregates in geotechnical applications (left) and in in road construction (right)

For the production of concrete recycled building materials, which consist mainly of the material groups natural aggregates, concrete and less than 30 mass-% of brick, can be widely used. The amounts of asphalt, mineral-bound wall building materials and impurities are strictly limited. Further requirements regard the some chemical and physical parameters (Tab. 12).

Tab. 12. Requirements on recycled aggregates for concrete production [18, 19, 20]

	Requirement	
	Type1: Concrete recycled aggregate	Type 2: Mixed recycled aggregate
Constituents of recycled aggregates > 4 mm	[mass-%]	
Concrete, masonry blocs of concrete, hydraulically bound aggregates Rc	Rc + Ru ≥ 90	Rc + Ru ≥ 70
Solid rock, gravel Ru		
Clay bricks, calcium slilca bricks, not foalting aerated autoclaved concrete Rb	≤ 10	≤ 30
Asphalt granulate Ra	≤ 1	≤ 1
Glass Rg	Rg + X ≤ 2	
Other materials: binding materials such as clay and soil Various other materials: (ferrous and non-ferrous) metals, non-floating wood, plastic, rubber, plaster X		
Floating material [cm³/kg] FL	≤ 2	≤ 2
Chemical constituents	[mass-%]	
Acid soluble chlorid	≤ 0.04	
Acid soluble sulfate	≤ 0.8	
Water soluble sulfate	≤ 0.2	
Densities and water absorption	[kg/m³], [mass %]	
Particle density OvenDry	≥ 2,000 ± 150	≥ 2,000 ± 150
Water absorption after 10 min	≤ 10	≤ 15
Freeze-thaw resistance, amount of chippins < 2 mm [mass-%]	< 4	

From recycled aggregates that meet these requirements, a maximum of 45 vol.-% of type 1 or 35 vol.-% of type 2 may be used for the production of concretes up to compressive strength class C30/37 [21]. The use of recycled sand for concrete production has not been allowed so far. A revision of the standard, in which the conditions for the use of recycled sand are specified, is in preparation. To ensure durability, concretes with recycled aggregates are used in exposure classes with weak to moderate effects from moisture and/or frost as well as from chemical influences.

Concretes with recycled aggregates are predestined for use in the construction of residential buildings (Fig. 32), social and commercial buildings as well as the production of precast concrete elements and concrete products. Concretes with recycled aggregates are less suitable for industrial or agricultural buildings and civil engineering works.

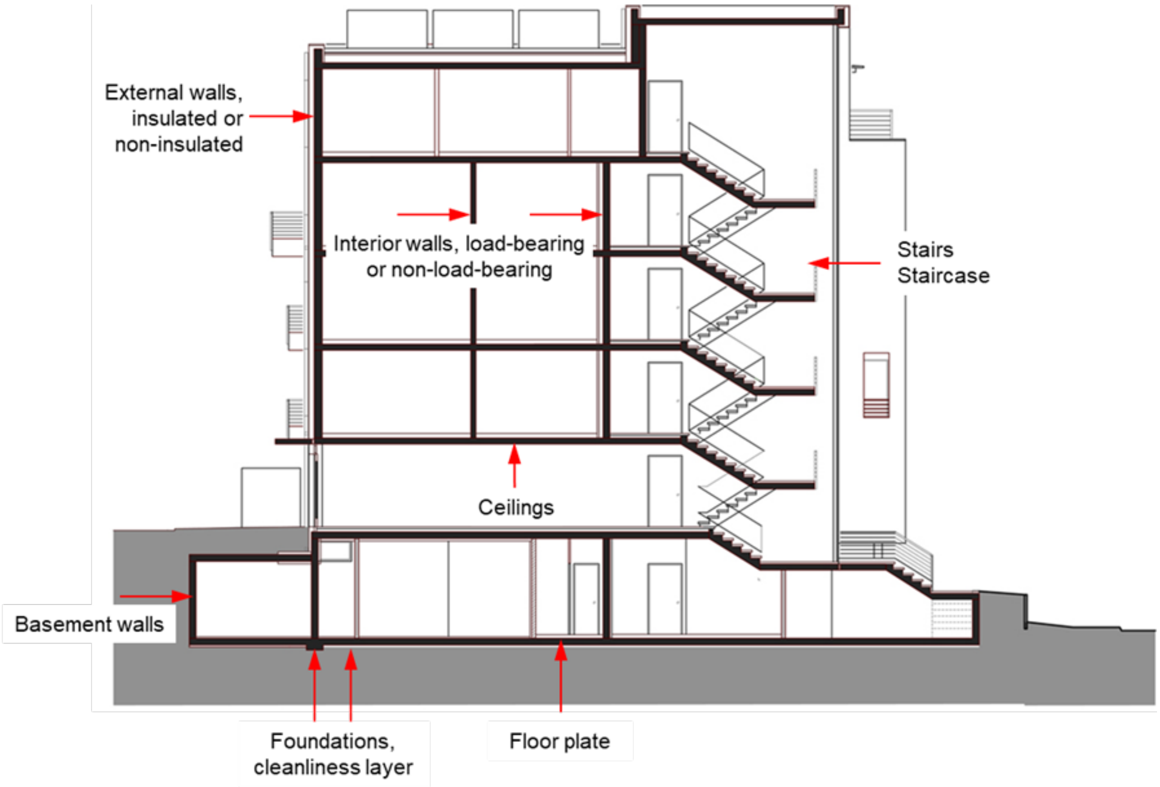


Fig. 32. Example of building components manufacturable out of concrete with recycled aggregates (Image source: Stefan Poggel, Poggel Architekten)

In contrast to natural aggregates, which must meet only certain construction engineering requirements dictated by the area of application, recycled aggregates are subject to additional environmental requirements in order to prevent possible pollutant loads from the recycled materials in the soil or the groundwater. These requirements diverge:

- If the recycled aggregates are used for concrete production, they are firmly embedded in a hardened cement paste matrix. This prevents the elution of pollutants. The environmental requirements are therefore moderate, while the structural requirements are high in order to ensure a sufficient quality of the concretes.
- If the recycled aggregates are used as backfill materials, the environmental requirements are high because pollutants can be washed out. The structural requirements are relativly low.

The durability of concretes with recycled aggregates is influenced by more factors than that of concretes made from natural aggregates. Although their effects have been described, they are not yet sufficiently quantified. The recycling of concretes is therefore based on the pragmatic approach of ensuring sufficient durability by composition requirements and by limiting the use to the strength class C30/37, and moderate exposure and moisture classes.

Recycled construction materials are subject to a strict quality control. Excerpts from the quality protocols for recyclates to be used for road construction or concrete production are included in the appendix.

From around 2015, the use of recycled aggregates for concrete production increases in Germany. The following experiences were made:

- No or low impact on consistency and compressive strength, modulus of elasticity slightly lower
- Advantage of concrete with recycled aggregates: Better surface quality.

There are two “hotspots” of application of R-concretes in Germany: The urban areas around Stuttgart and Berlin. Examples are shown in Fig. 33 to 35.

Fig. 33. Weighing house with columns made of high strength concrete with 100 % RC-aggregates, built 2016

Fig. 34. Entrance area of a new school building Kirchheim unter Teck near Stuttgart 2020 [22]

Placing of the R-concrete

Diaphragm wall

Supporting structure

Fig. 35. New construction of a research and laboratory building of the Charité, Berlin 2014 [23]

In the properties of concretes with recycled aggregates, an initial visible advantage is now crystallizing. The absorption behavior of the recycled material noticeably reduces the number of blowholes and water runs on the surface of the concrete components. As a result, RC concrete is recommended for use as exposed concrete, a finding that was already available in Switzerland a good 15 years ago (Fig. 36).

Fig. 36. New school building in Zurich in 2005 (Image source: Hansruedi Eberhard, Eberhard Bau AG Oberglatt) and in Berlin in 2020 (Image source: Friedemann Steinhausen)

Even before concrete recycling became the focus of research and practice, structures were built in the Netherlands and Belgium using recycled aggregates. Several hydraulic structures erected around 1990 in the Netherlands and in Belgium, which are still in use today, provide exemplary proof of the durability of concretes with recycled aggregates. In the Netherlands in the 1980s and 1990s, a number of hydraulic structures with a share of recycled concrete of 20 to 30 mass-% were built. They are still in use today.

The practical suitability of concretes with recycled aggregates is particularly impressively demonstrated by a structure in the port of Antwerp: There in 1987, all of the coarse aggregates from the demolition of a lock, which was in operation for 30 years, were used for the construction of a new lock (Fig. 37). During the dismantling of the old lock, a total amount of reinforced concrete of 80,000 m^3 or 180,000 tons was produced. This concrete was used to produce concrete with coarse recycled aggregates and natural sand of B 35 quality [24], which was used in a „second generation lock". These lock was in operation for 30 years again, before it was replaced by a larger lock.

Fig. 37. View of the Berend-recht lock in the port of Antwerp built with recycled coarse aggregates (Image source: Jeroen Vrijders, Belgian Building Research Institute)

3.2. CDW as future secondary raw material

3.2.1. Use in the cement production

The cement production consists of the following steps: Raw material extraction and processing, cement clinker burning in the rotary kiln and grinding the clinker with the addition of certain components. During the thermal treatment in the rotary kiln, the formation of CO_2 from the raw material is unavoidable, because only as a result of the specific chemical composition with a high proportion of calcium oxide a hydraulic binder is formed which also hardens under water. This binder is the basis for the production of concretes with the needed performance and durability. After the thermal treatment, gypsum and "additional cementitious materials" are added to the clinker. The power plant by-products raw gas desulfurization gypsum and fly ash are frequently used for this addition. These by-products are already in scarce today and will no longer be available in the future as a result of the restructuring of power generation. Replacement with secondary products derived from certain construction wastes lends itself.

Secondary gypsum from construction and demolition waste

Gypsum contained in construction waste is a problem in many application areas. In geotechnical applications, it can be leached and enter the groundwater. When recycled materials are used in concrete, it can affect the durability, among other things. In addition, natural gypsum deposits are limited. This has given impetus to the development and the application of recycling processes for "End of Life Gypsum".

Recycling of gypsum waste, which must be dry, takes place in facilities designed specifically for this purpose. It starts with a visual inspection of the incoming waste after the unloading of the transport truck. A second, batch-wise quality control follows before the material is fed in the recycling device. The first step of processing is the coarse crushing with a three-roll crusher with helically designed crushing tools. Subsequently, the metallic components and other impurities are sorted out. This is followed by a multiple secondary comminution that allows selective fragmentation of the components gypsum and cardboard, based on the fact that the comminution behavior of gypsum and cardboard is very different. Crushing is followed by screening the crushed product, during which the cardboard, which is present in coarse flakes, is separated. The screen undersize consists of gypsum particles up to a size of about 10 mm. The products of the processing are the powdery to fine-grained gypsum fractions (90 to 95 mass-%) and the fractions of cardboard flakes (5 to 10 mass-%) (Fig. 38). The recovered gypsum is used for new plasterboards. It can be also used as cement setting regulator.

So far, there are 4 locations in Germany where gypsum recycling plants operate. They are located in Saxony, North Rhine-Westphalia, Rhineland-Palatinate and Baden-Württemberg [25]. Their capacity

Fig. 38. Products of the processing of gypsum plasterboard: Gypsum grains (left) and cardboard flakes (right)

utilization is not satisfactory. Considerable amounts of gypsum waste are still being disposed of as the cheaper alternative.

Pozzolanic additives from brick rubble

The chemical composition of bricks is near the composition of fly ash of power plants (Fig. 39). Therefore, it can be concluded that they could be suitable as additional cementitious material for the substitution of fly ash. This idea has been pursued for years. Now it is once again in the focus of many research projects.

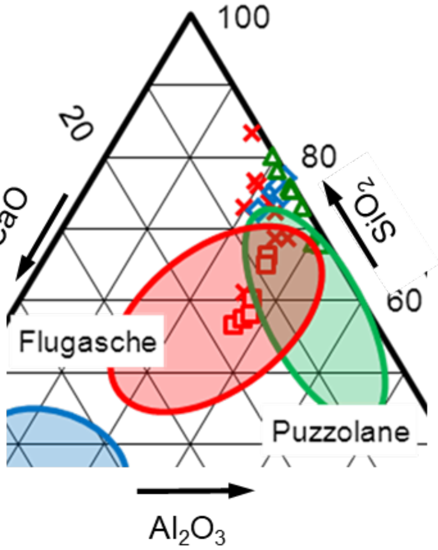


Fig. 39. Comparison of the chemical composition (mass-%) of different pure clay bricks with composition of fly ash and natural pozzolans in the triplot SiO_2-CaO-Al_2O_3 [26]

For a summary of the in the literature published results the measured strengths of brick containing mortar were related to the strength of the pure cement mortar and shown as a function of the substituted content (Fig. 40). This results in the expected decrease in strength in line with an increasing proportion of brick powder. But the majority of the values lies above the linear “dilution curve”. This means that a filler effect can be assumed, which has a positive influence on the strength. In the case of substituted proportions of up to 15 %, some powders play a role in the strength formation.

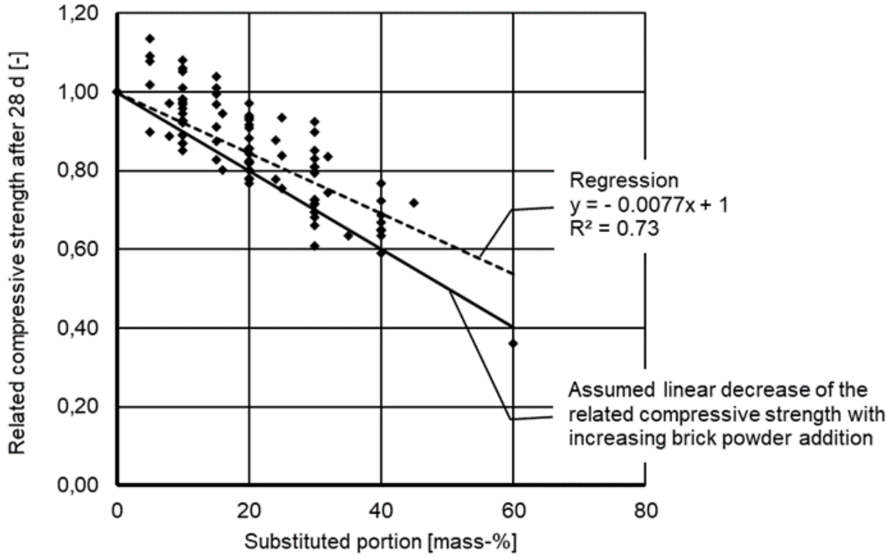


Fig. 40. Related compressive strength of cements blended with brick powders [26]

In broadly based investigations with different types of bricks (Fig. 41), it could be proven that the brick meals participate in the strength formation. The prerequisite is a sufficient fineness.

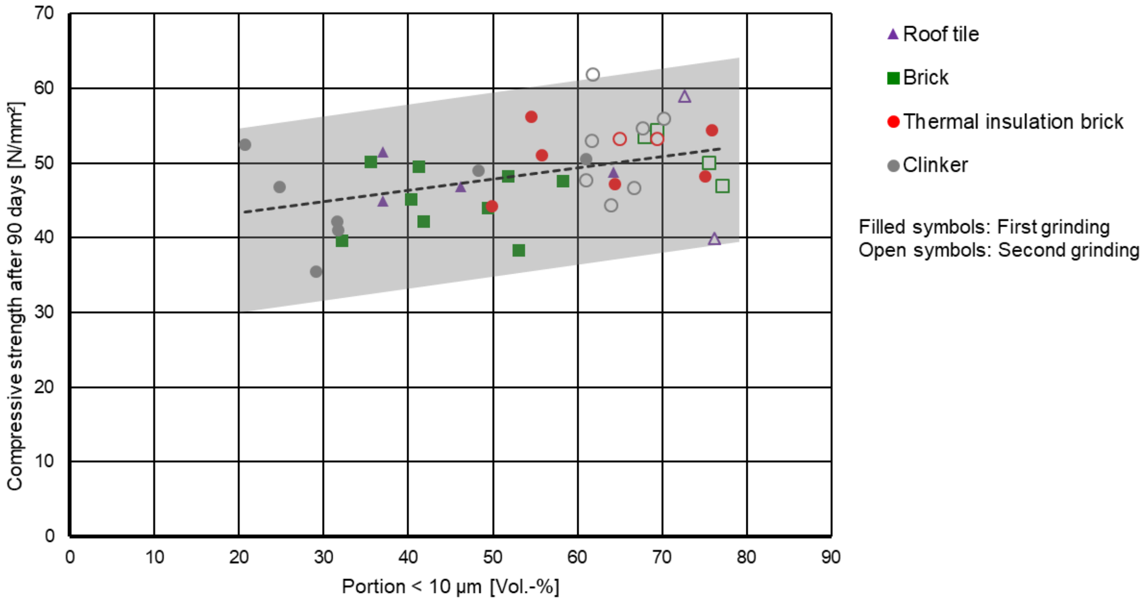


Fig. 41. Compressive strength (after 90 days) of cement mortars containing brick powder dependent on the percentage of particles < 10 µm, strength of used Portland Cement 64,3 N/mm² [26]

Further research – especially to the recovery of pure brick particles from mixtures and an effective grinding to particle sizes < 10 µm – with so far unusual methods and devices – are in progress and showed first positive results.

3.2.2. Replacement of natural raw materials

Masonry rubble as secondary raw material for lightweight aggregates

Lightweight aggregates are mineral aggregates with a particle density < 2000 kg/m³. They are either of natural origin, if produced from volcanic rocks such as pumice, or are produced industrially from expandable clays. In Germany, the availability of natural lightweight aggregates is declining. The quantity of lightweight concrete blocks, produced from them, has fallen from almost 10 million t in the 1970s to less than 1 million t in 2015 [27].

Masonry rubble is an alternative raw material for the production of lightweight aggregates. It usually occurs as a mixture of different wall construction materials such as bricks, sand-lime bricks, lightweight and aerated concrete as well as mortar and plaster. Even when walls consisting of only one type of building material are demolished, at least mortar occurs as a minor component.

The heterogeneity means that masonry rubble is limited in its application. The large differences between the physical properties such as porosity, strength and frost resistance of the individual constituents mean that utilization must be based on the constituent that has the least favorable properties. This limits its use to low levels such as for backfilling shafts or voids on construction sites or for construction and profiling at landfills. In the case of high sulfate contents, the use may not be permissible even for these simple applications for ground water protection reasons. Unlaunched intermediate deposits in a gravel pit cannot be ruled out (Fig. 42).

Fig. 42. Masonry rubble deposited in a gravel pit

One recycling solution with potential for unsorted, gypsum-containing masonry rubble, including the fine fractions, is the production of lightweight aggregates [28]. These are expanded granules that are produced in a thermal process similar to expanded clays or slates. The mixtures to be recycled are precrushed, ground, doped with an expanding agent and granulated. During the subsequent thermal treatment, the granules expand and obtain their stability through sintering. These lightweight aggregates are comparable to products made from natural clays. The produced expanded aggregates from masonry rubble have the following characteristics:

- Particle densities from 600 to 1.000 kg/m³
- Grain strength up to 10 N/mm²
- Thermal conductivity below 0,135 W/mK
- Compliance with all environmental parameters.

The process does not require any natural raw materials. Gypsum contained in construction waste is thermally decomposed and can be recovered as flue gas desulfurization gypsum. Against the background of the shortage of primary and secondary raw materials for gypsum production, this is an additional interesting aspect.

The feasibility of this recycling idea was demonstrated in experimental studies on a semi-industrial scale. Lightweight granules were produced in quantities of several cubic meters [29]. They were processed into lightweight concrete blocks on an industrial plant in exchange for pumice (Fig. 43).

Fig. 43. Lightweight aggregate produced in a rotary kiln and processed into lightweight concrete blocks [12]

Excavated soil as secondary raw material for gravel and sand

Excavated soil represents the largest share of total construction waste. According to the actual regulations in Germany, it is classified as construction and demolition waste, although it is not a product that becomes waste at the end of its life. Compared to concrete rubble, for example, which results from a defined product, its composition depends on the geology and the history of the place where it is generated. There are extremes ranging from completely unpolluted to anthropogenically polluted soils to soil-building rubble mixtures. The excavated material can consist of loose or solid rock. Anthropogenically contaminated soils and soil-building rubble mixtures are typical for construction projects in urban agglomerations. The non-uniformity of the source material means that only a small quantity of 10 % usable for construction purposes is recovered from the 130.3 million tons of excavated soil generated in Germany. Most of the excavated soil is used for backfilling or is landfilled.

Recently has more attention been paid to soil processing. One example is a plant in the Stuttgart area. It is equipped with a pre-screening unit, several wet screens, a log washer, hydro cyclones and a water treatment. The first step of processing is the dry oversize screening followed by the separation of the sand fractions by wet screening. In the log washer the middle fraction is cleaned from the cohesive components. Besides the light impurities floating on the surface of the slurry in the log washer are separated out. The cleaned material is screened. The screen underflows with fine particles generated during pre-screening and after the log washing are passed over hydro cyclones to separate the sands. The washing water is cleaned in several steps and circulated.

Analyses of the processed products show that coarse and fine aggregates with a high proportion of natural aggregates are generated (Fig. 44). Both the coarse aggregates from the log washer and the sands from the hydro cyclones have qualities that allow their use in concrete production.

Log washer | Input material | Products

Fig. 44. Log washer, input material and products from the whole cleaning process

In the process, loam/silt is produced during the wet cleaning. Its utilization is necessary in the interest of economic efficiency. It can be used as raw material in the production of bricks or of cement clinker. This is due to its high degree of fineness and its more uniform composition compared to the starting material. As a limiting factor, the pollutant contents must be taken into account.

3.3. State of the art - recycling of window frames

The main types of window frames are such from unplasticized PVC, from aluminum and from wood. The market shares in 2018 were [30]:

- Window frames from PVC: 57,7 %
- Window frames from Aluminium: 18,1 %
- Window frames from wood: 15 %.

In addition, there are window frames from the combinations PVC/metal and wood/metal. Windows consist of the glass pane and the frame, as well as other elements such as seals, handles and fittings. Many of the individual components can be recycled if they are separated. This is achieved through multi-stage processing.

Upstream of the processing a take-back system must exist in order to collect the highest possible proportion of the used windows. Take-back systems and processing technologies exist for windows with PVC and aluminum frames. Wooden windows, on the other hand, are often collected as part of mixed construction and demolition waste.

Wooden frames windows

Windows with wooden frames have the longest tradition of use compared other types. So, the windows that exist in the inventory are very different and therefore difficult to recycle effectively. Sometimes the will be take back by recovery yards and offered for sale (Fig. 45).

Fig. 45. Old windows for sale (Image source: Kleinanzeigen)

A remanufacturing and refurbishment however usually refers to special, unusual or “antique” windows. To refurbish “normal windows of wood” so that they subsequently meet the thermal insulation requirements is very cost-intensive or impossible from the technical point of view. According to the UBA's waste wood balance [31], wooden window frames are a component of mixed construction and demolition waste. They amount to 449,100 tons per year and about 38 % of the volume of total waste wood. The majority of the waste wood is thermally treated or burned in combustion plants for power generation. Only a very small proportion of 0.01 % of the total waste wood volume is used for particleboard production, but this does not have to be waste wood from the construction industry.

Forstwirtschaft	Forestry	711 kt
Holzverarbeitende Industrie	Wood processing industry	2755 kt
Verpackungsabfälle	Packing waste	895 kt
Bau- und Abbruchabfälle	Construction and demolition waste	4491 kt
Holz aus Siedlungsabfällen	Wood from municipal waste	719 kt
Sperrmüll	Bulky waste	998 kt
Holz an gemischten Siedlungsabfällen	Wood in mixed municipal waste	605 kt

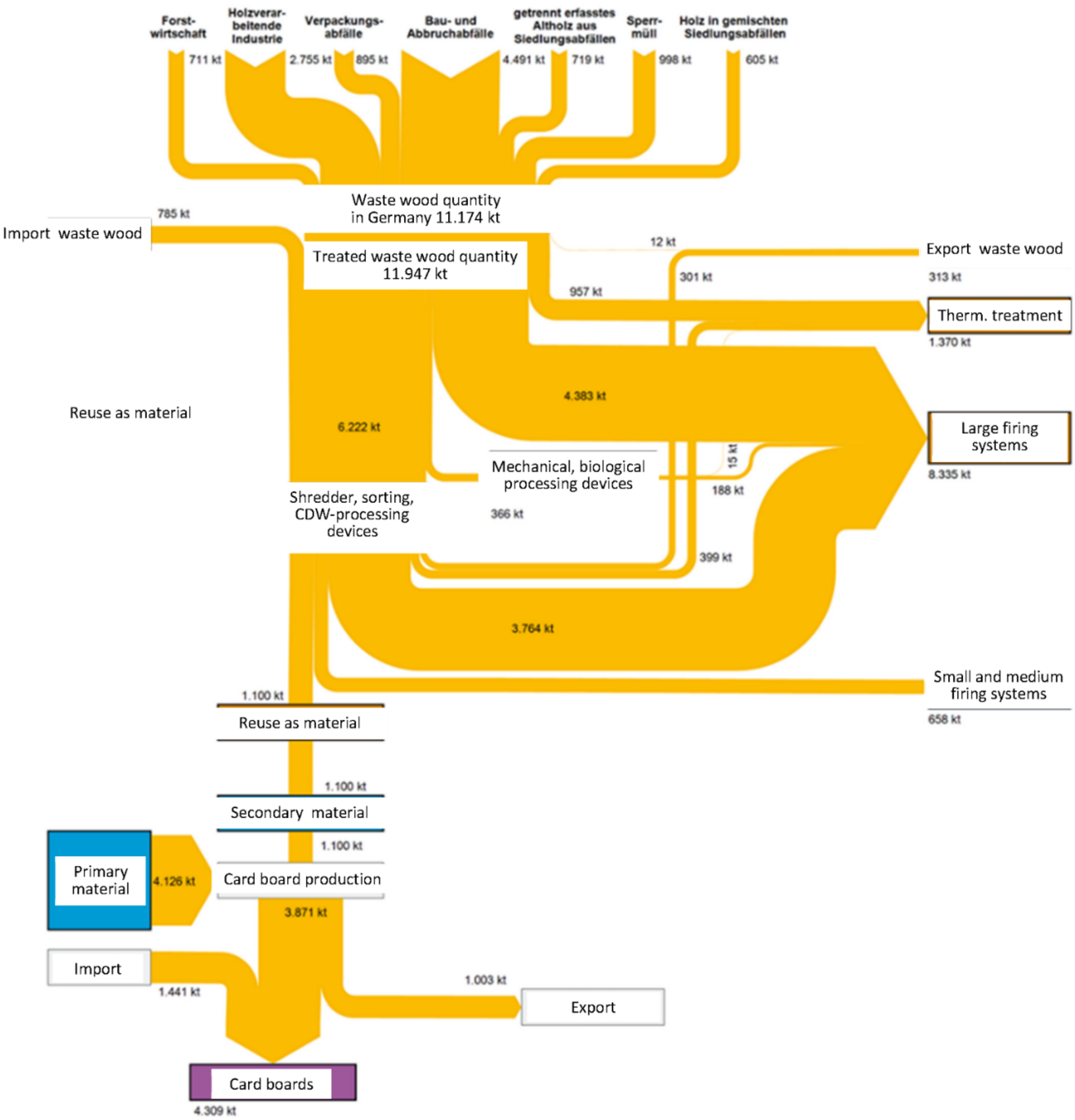


Fig. 46. Mass balance of waste wood [30]

For PVC windows, shutters and doors the take-back is organized in Germany by Rewindo [31]. The amount of PVC profiles returned any in 2019 was 33.300 t. Two routes are provided for delivery:

- Larger quantities can be delivered to the 10 “Recycling partners” of Rewindo in Germany.
- For small quantities up to 10 windows a network of regional collection points exists, of which there are a large number spread across Germany.

Processing takes place in a plant that has been in operation since 1993. In France and in the United Kingdom there are two other plants from the same company. The processing starts with the delivery, the pre-sorting of the delivered material by an excavator and the first shredding (Fig. 47, 48).

Fig. 47. Delivery of used PVC window frames, shutters and doors [32]

Fig. 48. Feeding the material into the first shredder [32]

A scheme of the following steps of processing is shown in the Fig. 49. After pre-sorting of the delivered material, the material is processed in several steps where most of these steps are for sorting. At the end of the process, the material will be regranulated. In this step the material passes through an extruder and undergoes melting. It leaves the extruder through a screen that retains foreign particles > 200 µm. After this multi-stage processing, the re-granulate can be used for the production of PVC profiles again.

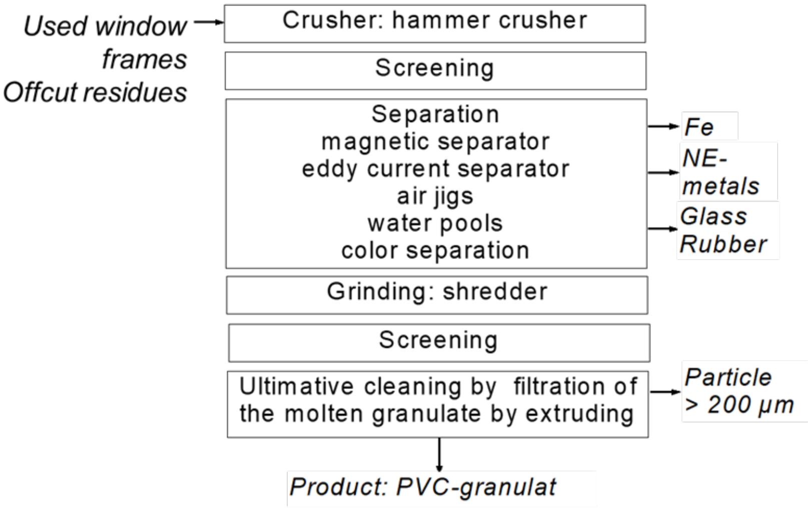


Fig. 49. Scheme of preparation of Eol PVC profiles

Fig. 50. Processed PVC from window frames [33]

For aluminum window frames the take-back system AIUIF [34] exists. In 2011, 125.00 t of waste were accepted and processed. The processing consists of crushing, screening and sorting to remove foreign materials. The Fig. 51 shows an example of the aluminum scrap processing sequence. Two sorting stages are run through.

- X-ray sorting is used to separate foreign metals or alloys. This sorting is based on the differences in the "atomic density" of different metals, which is detected by means of X-ray sensors.
- Non-ferrous metal separators are used to separate plastics and glass.

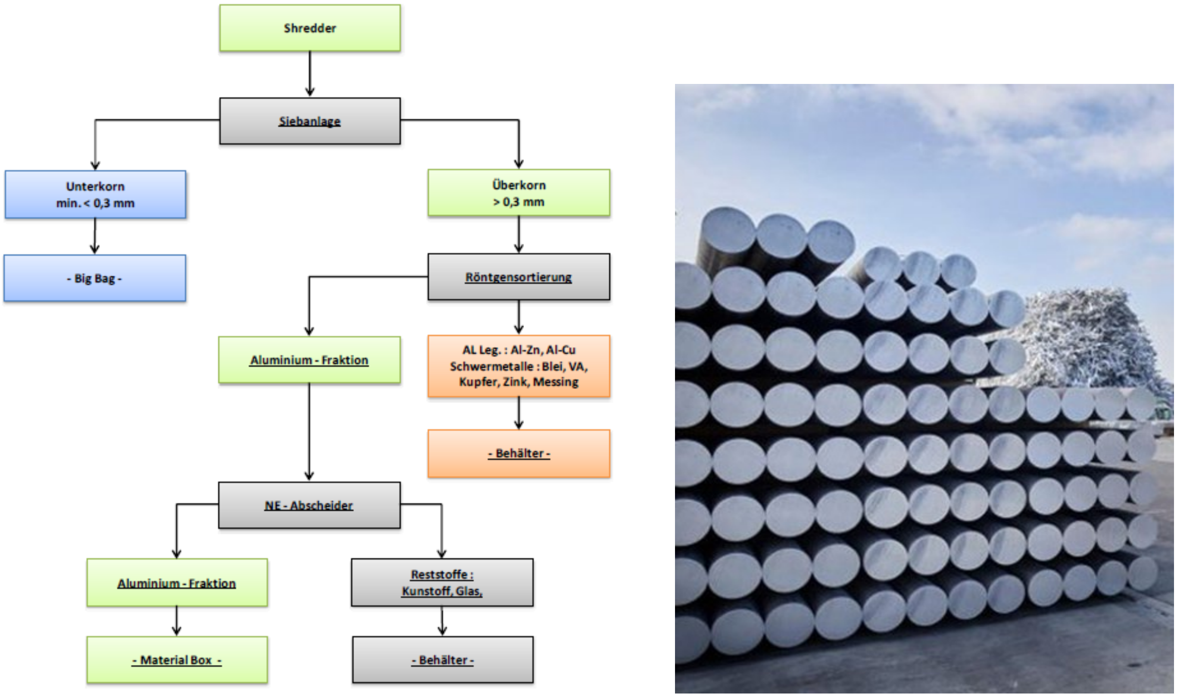


Fig. 51. Scheme of processing aluminum scrap and press billets from secondary aluminum [35]

The unmixed aluminum scrap is delivered to foundries then, which produce so-called "extrusion billets" from it [36]. From these, construction profiles can be produced again by means of extrusion. The production of primary aluminum from bauxite is known to be very energy-intensive. The recycling of aluminum scrap has a significantly lower energy consumption, amounting to only 5 % in relation to the production of primary aluminum.

4. Contribution of CDW recycling to energy saving

Consideration of the energy consumption required for the production of secondary building materials from construction waste has been very rare to date. In the available life cycle assessments, subjective factors such as transport distances are often included. In contrast, objective factors such as the energy required for processing or the possible savings from the repeated use of the energy already input into the primary product are missing. Causes include a lack of knowledge and data. In the following, possible energy saving potentials for the most important types of construction waste are presented.

4.1. Recycling of asphalt

Asphalt is a composite construction material consisting of the binder bitumen and coarse and fine aggregates, including fillers and possibly other additives. The binder bitumen is produced from crude oil by vacuum distillation. It is a low-volatility, dark-colored mixture consisting of chain- or ring-shaped hydrocarbons of various sizes. The aggregates used in asphalt ensure the load-bearing capacity of the construction material by forming a mineral framework. The aggregates must be weather-resistant, impact-resistant, compression-resistant and polish-resistant. During asphalt production, they are heated to temperatures of up to about 300 °C, which must not lead to any changes.

In terms of its material properties, asphalt offers favorable conditions for recycling In simple terms, it can be regarded as a composite of aggregates and the thermoviscous binder bitumen. The latter can be reactivated by heating, which is not possible with other binders, such as cement paste in concrete. Reactivation takes place by heating the reclaimed asphalt. This makes the binder malleable again, similar to a thermoplastic. The mix can then be placed and compacted again, usually mixed with fresh mix. After cooling, the asphalt is in a solid, serviceable form (Fig. 52).

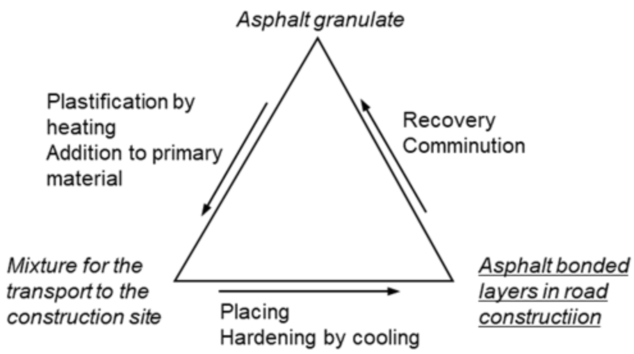


Fig. 52. Simplified material cycle for asphalt

For more than 30 years, reclaimed asphalt has been used in the form of granules for the production of new asphalt, with recycling rates stagnating at around 20 %. From a technical point of view, significantly higher addition rates of up to approx. 60 % would be possible in asphalt base and binder courses. If these recycling opportunities were exploited, energy savings could result.

The strongest influence would be a reduction in the amount of bitumen required. Its energy content is made up of the energy content known as "feedstock energy" in the amount of 40,000 MJ/t, which could be released by incineration, and the energy requirement of binder production, which, according to literature data, ranges between 1,304 MJ/t and 4,710 MJ/t [37, 38, 39, 40]. Even with low substitution rates, this energy demand could be reduced. Additional savings result from the mining and construction waste are presented.

4.2. Recycling of concrete

In the simplest case, concrete is produced from the raw materials cement, aggregates and water. The cement stone is formed from the cement and the added water, which, as a hardening product, causes the aggregate to bond to form a stable solid.

By far the most energy-intensive component of concrete is the cement. Numerous investigations have been undertaken to separate the cement paste from the concrete and then to produce a hydraulic binder from it again. If no Portland cement was used, the second step is to separate the Portland cement component from the "supplementary cementitious materials" such as granulated blast furnace slag, fly ash or rock flour used as filler.

For both process steps - the separation of the cement paste from the coarse and fine aggregates and the elimination of the "supplementary cementitious materials" - there are currently no technologies available, although numerous and in part extensive research projects have been carried out. Only if limestone was used as aggregate for the production of the concrete, the concrete is suitable as a raw material component for the renewed production of Portland cement clinker. However, there are then neither energy advantages nor are lower CO_2 emissions possible.

4.3. Recycling of clay brick

Bricks are the building materials that are used after the thermal process of manufacture. Unlike the mineral-bound building material concrete, they are not a composite. Bricks acquire their load-bearing capacity through sintering processes which take place during the thermal treatment of the brick blanks in the tunnel kiln. In order to produce load-bearing walls from them, however, the bricks must be processed together with mortar to form the "macro-composite" masonry.

4.3.1. Recovery of pure brick recyclates

The recovery of unmixed brick recyclates is possible in the selective demolition of brick masonry, but it is costly. Conventional demolition dominates. This produces mixtures of plaster, mortar and brick. Subsequent sorting can produce single-variety brick aggregates. For coarse grain sizes, automatic sorting processes are suitable in addition to manual picking, which is still the dominant method. In the latter, the construction debris particles are sampled piece by piece and classified into recyclable material or impurities. The impurities are discharged by means of compressed air. According to literature [41], the specific energy requirement for sensor sorting is 1 to 3 kWh/t or 3.6 to 10.8 MJ/t, whereby the upper limit is more likely to apply to the comparatively heavy particles of construction waste sorting.

For fine grain sizes, processes based on the magnetic susceptibility of the brick particles are being tested [42, 43]. The energy consumption of these processes, which are state of the art in the processing of certain ores or glass sands, is low.

4.3.2. Recycling of brick recyclates

When recycling brick waste in thermal processes, energy savings are possible compared to comparable primary building materials. Examples are a partial raw material substitution in brick production [44] or the production of lightweight aggregates using masonry rubble instead of clay [45]. In both cases, hydroxylation, in which the chemically bound water is expelled from the structure of the clay, has already been carried out during the preceding brick production. The energy required for this does not have to be expended a second time. It can be concluded from this that savings of thermal energy for the firing process are possible.

5. Overview of the regulatory framework for RC building materials in Germany

5.1. The German regulatory system in the context of the European framework

The German regulatory framework aligns with the broader European legal context, emphasizing environmental protection, waste handling, and material safety. The European Union (EU) aims to shift towards a circular economy, minimizing waste and enhancing resource efficiency. This strategy, reflected in the **Circular Economy Action Plan** [46], advocates for increased adoption of recycled materials, especially within construction, and promotes business models that prioritize circular practices.

In general, the **European Waste Framework Directive** [47] applies, which requires preparation for reuse or recycling of waste via the waste hierarchy. Waste may only be used for energy recovery or disposed of if reuse or recycling are impossible.

The **Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulation** [48] addresses the production and use of chemical substances in the EU. It applies to all chemicals, including those used in construction materials. REACH aims to manage and control the risks associated with these substances, impacting the use and handling of recycled materials containing chemicals.

The **Ecodesign Directive** [49] sets eco-design requirements for energy-related products to improve their environmental performance. It indirectly influences the construction sector by encouraging the use of more sustainable and energy-efficient materials and products.

The **European Construction Products Regulation (EU-CPR)** [50] sets out harmonised rules for the marketing of construction products in the European Economic Area (EEA). This regulation doesn't specifically focus on recycled building products but ensures that any construction material placed on the market, including recycled materials, meet essential requirements, including those related to safety, health, and environmental protection.

Requirements are laid out in Harmonised Technical Specifications. Products that have undergone testing and meet all applicable requirements according to **Harmonised Standards** are affixed with the **CE-marking**. A route to the CE-marking for building products not or not fully covered by a harmonised standard is the **European Assessment Document** (EAD) [51].

Supplementing these directives and ordinances are numerous guidelines, delivery conditions, and regulations that further detail and specify the obligations and standards. The **European Commission's CP-DS database** provides a comprehensive overview of these regulations, aiding in navigating the intricate European legal framework concerning recycled building materials [52].

5.2. German level

The German legal framework on recycled building materials often aligns and integrates with EU directives and regulations. National and state level laws within Germany complement and adapt to European directives, ensuring coherence and compliance with EU standards.

Building products made from recycled materials (RC products) are held to similar structural and environmental standards outlined in **technical regulations** as products made from primary raw materials. Those falling under waste law might require **additional environmental** and process engineering measures to ensure safe and sustainable recycling practices. The **distinction between waste and non-waste** depends on whether the materials represent an economic burden without clear prospects for legal and environmentally friendly use. Materials intended for reuse in identical structures or as material resources for identical construction products may not be considered waste.

5.2.1. Technical regulations

Building regulations in Germany, outlined in the **Building Codes of its 16 federal states**, govern the use of construction materials and techniques in building construction. Based on the **Model Building Code (Musterbauordnung, MBO)** [53], these state-specific codes may vary while defining general construction requirements [54].

The EU CPR, integrated into German law by the **Building Products Act (Bauproduktengesetz, BauPG)** [55], holds precedence over national and state level laws. Construction products meeting European standards may be used, as long as they meet specified performance criteria. [50, 53]

Technical Building Rules, derived from a common model (Muster-Verwaltungsvorschrift Technische Baubestimmungen 2021/1) [56], further detail the requirements set by the Building Codes. Supplemented by standards, Technical Guidelines, and contractual conditions, these rules are typically recommendations rather than binding unless referenced by laws or contracts.

Deviations from Technical Building Rules are possible, demanding **fitness verifications** by accredited testing laboratories in cases where no recognized technical rules exist. Fitness verifications are issued for construction products or construction techniques, either as a National Test Certificate or Approval, or Project Related Test Certificate or Approval for singular construction projects [53]. The specific requirements for these verifications are stipulated by individual state Building Codes.

5.2.1. Environmental regulations

The **Waste Management Act (KrWG)** serves as a pivotal legislation governing waste management, stipulating proper and damage-free recycling of waste materials [57]. The KrWG emphasizes their proper separation, recycling, and non-hazardous waste treatment while prioritizing the avoidance of pollutant accumulation in recycling cycles [57].

The **Substitute Building Material Ordinance (EBV – Ersatzbaustoffverordnung)** governs the use of substitute building materials, including recycled materials, in technical structures [58]. In conjunction with the **Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV - Bundes-Bodenschutz- und Altlastenverordnung)** [59], the EBV establishes legally binding regulations for the production and installation of these materials, ensuring compliance with national standards.

The **Waste Wood Ordinance (Altholzverordnung – AltHolzV)** [60] governs the use and recycling of waste wood.

Environmental standards set by the EU-CPR are complemented by additional rules primarily from chemical legislation, such as the REACH-Regulation and the **Persistent Organic Pollutant Regulation** (POP-Regulation) [61]. The European **Biocidal Products Regulation** [62] controls biocide approval, usage, and labeling in construction products.

Further restrictions arise from the German **Chemicals Ban Regulations** (Chemikalien-Verbotsverordnung - ChemVerbotsV) [63], enforcing stringent limits on harmful substances. Products containing substances listed in Annex XIV of REACH fall under the German **Hazardous Substances Ordinance** (Gefahrstoffverordnung, GefStoffV) [64] requiring their avoidance or minimization.

Numerous other guidelines and regulations complement these ordinances. In case of contradicting statements, the strictest limit value must always be applied [65].

RC products can reach the **end of their waste status** and be managed as non-waste [57]. To achieve this, these products must undergo a reclamation process, emerging in a state suitable for specific purposes with an established market demand and meet all necessary technical and legal standards for their intended use.

5.2.2. Requirements based on further legal provisions

If construction contracts are awarded by **Contracting Regulations for Construction Works** (Vergabe- und Vertragsordnung für Bauleistungen – VOB) [66] the services must often be provided in accordance with recognised technical standards and legal and official regulations. RC building products must therefore comply with the generally recognized rules of technology valid at the time of acceptance, even if, for example, the use of RC building materials is explicitly permitted in the construction specifications [67]. This way, the use of RC materials on the basis of fitness verifications or EADs may be prohibited.

The **Commercial Waste Ordinance** (Gewerbeabfallverordnung – GewAbfV) [68] outlines requirements for the separation and proper disposal of waste generated by commercial activities. Stakeholders may be required to document and report on their waste management practices, including efforts related to recycling and the use of recycled materials. There is additional ordinances regulating the use of RC materials for backfilling and landfilling, and documentation and notification obligations [69].

5.3. Process of quality assurance procedure according to waste law

The quality assurance process serves as a critical mechanism to ascertain that the construction products employed conform to both environmental and construction prerequisites. The formulation of the process is contingent upon the intended application context, distinguishing between building construction and road and civil engineering, and further contingent upon the specific construction product and its constituent materials.

In general, a distinction must be made between the **quality assurance procedures** undertaken **pre-construction** and **during construction**. The former involves assessments and protocols implemented before the start of construction activities, while the latter entails ongoing monitoring and compliance measures throughout the construction process.

5.3.1. Quality assurance by the manufacturer or pre-construction

Depending on the systems of assessment and verification of constancy of performance of the construction product, various actors are involved in the quality assurance of RC construction products before construction is carried out (see Annex V EU CPR; §5 EBV) [50, 58]. Criteria for quality assurance are the manufacturer's **proof of suitability**, the **manufacturer's factory production control** and **testing of samples taken at the factory**, **external monitoring** by a notified testing laboratory and the **certification** of processes and products.

Quality assurance commences with a **delivery inspection** at the manufacturing plant, primarily focusing on environmental properties. The process involves examining the material composition and origin of the waste through visual inspection and scrutiny of delivery notes, in accordance with regulations such as NachwV, KrWG, and EBV. If required, compliance with maximum pollutant levels can be verified through a declaration analysis.

Subsequent to the delivery inspection, the materials undergo processing through a state of the art procedure. The validity of both the company and the employed procedure constitutes components of the manufacturer's or recycling company's **certificate of suitability**, granted by an officially recognized testing entity. Additionally, the testing entity routinely evaluates the manufacturer's **internal production control processes.**

In addition to the **determination of the product-type on the basis of type testing**, further tests of the environmental and structural properties of the manufactured RC product may be required on a regular basis, partly by the factory's own inspection department and partly by external testing bodies.

At the end of the process, there is a quality-assured RC building product that guarantees compliance with defined limit values for environmental and structural parameters. Its suitability is assured by a declaration relating to the area of application and identified by a **quality marking**.

5.3.2. Quality assurance during construction:

During construction, the building contractor must carry out checks of the manufacturer's verifications and certificates. He must ensure that the RC construction products are suitable for the intended use and comply with the contractual provisions. The contractor is also required to monitor whether the construction products are installed correctly and in accordance with the regulations. The client (building owner) has a control function [69].

5.4. Regulations by material group

Environmental and technical regulations are interdependent, particularly concerning designated purposes and material classifications. The manifestation of environmental hazards is depending on the specific technical procedures employed and the designated application area of the RC material within the construction matrix. Consequently, regulatory frameworks are delineated with specificity according to material group classifications.

5.4.1. Mineral RC materials

The regulations applying for the use of mineral RC materials are depending on whether it is used in concrete construction or road, path and earthworks. They may only be used if they do not have any harmful effects on the environment. The corresponding limit values and specifications are based on the REACH-Regulation and **Hazardous Substances Ordinance (Technische Regeln für Gefahrstoffe – TRGS)** [70] and are further detailed in standards and legal regulations, such as EBV and BBodschV. The content of harmful substances is analysed in the eluate or solids. The limit values of the different analysis methods are not comparable. Regularly observed pollutant concentrations are e.g. chloride, sulphate, arsenic, lead and polycyclic aromatic hydrocarbons (PAHs). The pollutant limit values for a mixture are deemed to have been met if the individual fractions comply with the limit values [71, 72, 59].

Technical construction requirements exist with regard to material parameters for raw materials and mixtures. Depending on the area of use, RC mixtures also require a certain material composition that limits the proportion of RC raw materials contained. The specifications are intended to ensure that the RC mixtures can fulfil the required material parameters. Typical parameters for raw materials are, for example, grain shape, grain bulk density, water absorption, freeze-thaw resistance and/or resistance to abrasion. For mixtures, regulations may stipulate that they must have a certain grading curve for grain composition, bulk density, compressive strength, degree of compaction and/or void/air void content.

The provisions for RC aggregates are laid down in European standards, such as the EU product standard DIN EN 12620 [73], while most standards for mixtures have not yet been harmonised at European level.

a) Use in concrete in building construction

Which and to what proportion RC aggregates can be used depends on the type and duration of the intended use, the chemical effects on the structure/component, the type of concrete, construction and construction methods and, if necessary, other boundary conditions. Additionally to European standards, by German national standards moisture exposure has to be taken into consideration [74].

In principle, the RC aggregates are divided into types according to their composition [71]. Type 1 and Type 2 are suitable for processing in RC concrete. Their composition limit values can be found in table 13.

Tab. 13. Composition of RC aggregates for RC concrete by type [71]

Component	Constituents	Type 1	Type 2
		% by mass	
Rc	Concrete, concrete products, mortar, masonry blocks of concrete	Rc + Ru ≤ 90	Rc + Ru ≤ 70
Ru	Unbound aggregate, natural stone, hydraulically bound aggregate		
Rb	Non porous brick wall stones, sand-lime/ clinker bricks, stoneware, pumice/non-floating aerated concrete, various masonry and roof tiles	< 10	< 30
Ra	Bituminous materials, asphalt	< 1	< 1
Rg	Glass	X + Rg < 1	X + Rg < 2
X	Other materials: Cohesive materials (i.e. clay and soil material), various other materials: metals (iron and non-ferrous metals), non-floating wood, plastic, rubber, plaster		
FL	Floating material in volume	< 2	< 2

The relevant standard (**DIN 1045-2: Concrete, reinforced and prestressed concrete structures - Part 2: Concrete**) [75] for RC concrete made from RC aggregates has recently been revised and the use of recycled aggregates has been newly regulated. It integrates relevant European and German standards and guidelines.

A maximum proportion of 45 % by volume of type 1 aggregates may be used, for type 2 aggregates the maximum proportion is 35 % by volume. The minimum proportion of recycled aggregates which may be used is 20 % by volume. Table 14 shows which proportions may be used regarding the circumstances of construction.

Tab. 14. Composition of RC aggregates for RC concrete by type [71]

Area of use		Type of RC aggregate	
		Type 1	Type 2
Moisture exposure	Chemical exposure	% by volume	
W0	Carbonation XC1	≤ 45	≤ 35
WF	No risk of corrosion X0		
	Carbonation XC1 to XC 4	≤ 45	≤ 35
	Frost attack without De-icing agents and XF1 and XF 3		
	Concrete with high water resistance		
	Chemical attack XA1	≤ 25	≤ 25
WA	XD1 and XD2 XS1 and XS2 XF2 and XF4	≤ 30	≤ 20

Aggregates of types 3 and 4 can be used in RC concrete in statically non-load-bearing applications in road and path construction, such as back support concrete. RC aggregates of type 3 have a proportion of at least 80 % by mass brick and mixed granules, while RC aggregates of type 4 have an increased proportion of up to 20 % by mass asphalt granulates [71]. The use of RC concrete with types 3 and 4 aggregates is not standardized according to DIN 1045 [75].

b) Excavated soil and technical structures

For RC materials used in concrete road surfaces, base courses with hydraulic binders, in asphalt construction, unbound road and path construction and earthworks within technical structures, the standardised German requirements of the **Substitute Building Materials Ordinance (Ersatzbaustoffverordnung - EBV)** apply. RC raw materials are categorised into different classes depending on origin of the waste, recycling processes used and the maximum pollutant values they contain. A distinction is made between concrete, brick and mixed granulates as well as unbound recyclates from processed soil, stone and dredged material waste with up to 10 or 50 % by volume of foreign mineral components and track ballast waste (see Tab. 15).

Tab. 15. Composition of RC aggregates for RC concrete by type [72]

Material group	Classes
RC - building material	RC-1, RC-2, RC-3
Brick material	ZM
Excavated soil	BM-0, BM-0*, BM-F0*, BM-F1, BM-F2, BM-F3
Dredged material waste	BG-0, BG-0*, BG-F0*, BG-F1, BG-F2, BG-F3
track ballast	GS-0, GS-1, GS-2, GS-3

The main criteria for the use of so called mineral substitute building materials (MEB) is the location in relation to water protection areas. The basic premise that the concentration of pollutants in the leachate from the RC construction material must not exceed certain maximum pollutant levels when it enters the groundwater [76]. MEB may therefore only be installed at a certain distance from the highest expected groundwater level, which must be at least 0.6 m or more [72]. Their use is not permitted in zone I water and medicinal spring protection areas [72]. In rural road construction only concrete, brick and mixed granulates of the lowest pollutant class RC-1 may be used [77]. If RC raw materials from processed soil, stone and dredged material waste are to be used for earthworks outside technical structures, they must comply with the maximum pollutant values in accordance with the BBodSchV [59]. Soil material and dredged material assigned to the lowest pollutant class BM-0 and BG-0 respectively may be treated like material from primary resources [59].

RC material from processed soil, stone and dredged material waste that is to be used in unbound mixtures must be tested for more and sometimes different pollutant values than the concrete, brick and mixed granulates as well as unbound granulates from processed track ballast waste. In addition, the pollutant content must be analysed in both the solid and the eluate, whereas otherwise the solid analysis is usually omitted [72].

Extended notification obligations apply if MEBs are to be installed in technical structures. If more than 250 m³ of RC building material of class RC-3 is to be used or if it is to be used in protected areas the construction project must be notified in advance. The competent authority will record these notifiable MEB in a substitute building materials register [72].

b) Asphalt construction:

Asphalt may only be re-used as asphalt granulates. Milled waste from bitumen mixtures is usually already in granular form and, if suitable, can be directly processed into RC asphalt. Broken waste is often in the form of coarse clods that must first be shredded in a recycling plant. Materials are suitable for further processing if the asphalt granules themselves, the aggregates and the bitumen are suitable. There must be almost no foreign substances such as concrete, bricks, soil, metals and plastics [78].

Technical requirements depend on the area of use (i.e. bound superstructure layers, unbound superstructure layers, substructure or earthworks) and the construction technique used (i.e. hot construction, cold construction, in conjunction with hydraulic binding agents, unbound installation), but also the kind of construction project (i.e. federal highways, roads, sidewalks, rural paths, flight operations areas etc.) In general, asphalt granulates should, if possible, be further processed into RC asphalt, which has a comparable recipe and function to their previous use [79]. When reused in hot construction, rejuvenators or softer binders can be used to reactivate the binder. The use of asphalt granulates is only permitted without tar/pitch-containing components [80].

5.4.2. Plastics

The recycling of construction plastics faces a significant hurdle due to contamination by various foreign substances and impurities. These include additives aimed at enhancing plastic properties, now prohibited and requiring removal from the material cycle. Contamination from harmful substances can occur during different phases such as assembly, use, or dismantling [81]. Substances can be subject to restriction (Annex XVII REACH [48]), authorisation (Annex XIV REACH [48]) or information requirements (SVHC-list REACH [48]) or further handling requirements (POP-regulation [61]; GefStoffV [64]).

Important substances to look out for include **cadmium and lead stabilisers**, which are banned in the EU. An exception applies to certain PVC products made from recycled rigid PVC [81].

The use of **short-chain phthalates** as plasticisers is prohibited. Removing them from the recycling process is problematic and hardly practicable [82]. The use of **higher molecular weight phthalates** in children's toys is restricted [48]. Processing **glass fiber plastics** must adhere to Technical Rules for Hazardous Substances (Technische Regeln für Gefahrstoffe-TRGS [70]) to mitigate risks of respirable dust during sanding.

Numerous flame retardants, such as **short-chain chlorinated paraffins** or **brominated flame retardants** have EU-wide bans or stringent limits for recycling, which poses obstacles to recycling of XPS and EPS insulation boards [82].

Additional limitations exist for **biocides and pigments** [83].

Plastic polymers are subject to oxidative degradation. This can lead to a deterioration of the material properties with increasing product life. Reprocessing of plastics does not restore the original material properties; on the contrary, each reprocessing step of plastics leads to a **decrease in long-term properties** in particular, e.g. the creep behaviour under internal [82]. Increased use of recyclates can also impair optical properties (e.g. gloss or transparency) [84, 85].

Many **harmonised standards** already contain explicit provisions for products that are not made from virgin material (e.g. DIN EN 13598 [86], DIN EN 1852-1 [87]); for other areas of application, the use of RC plastics is not permitted according to the standard (DIN EN 1555-2 [88]).

5.4.3. Wood

Due to potential pollutant problems and a lack of warranty, the reuse of construction timber in the construction industry is only used in small private building projects [89], except for chips obtained from waste wood, which are primarily used in the middle layer of chipboard.

The **Waste Wood Ordinance** [60] categorizes wood residues into four waste wood categories based on processing type and potential foreign substance presence. Recycling for wood-based materials is allowed up to category II; category III requires varnish or coating removal by specialized companies. The presumption principle guides this, where construction waste wood is usually assumed to have increased contamination, relegating it to higher categories unless exceptions arise.

Limit values target pollutants which mainly come from use of wood preservatives. Contaminated waste needs recycling or disposal methods that destroy or transform the pollutants irreversibly [61, 63, 89, 90].

The technical standards applicable to construction products made of recycled wood also align with those for wood from primary sources. The European harmonised standards for design, construction and safety requirements are summarised in Eurocode 5 [91].

5.4.4. Metal

In the construction industry, construction steel is of particular interest as an RC construction product in terms of quantity. In Germany, almost half of the steel is produced from scrap, mainly by melting down old metal. A reduction in quality is not to be feared [92]. The harmonised European standards for the design and construction of steel structures and steel components are contained in Eurocode 3 (https://www.eurocode-online.de/de/eurocode-inhalte/eurocode-3) [93]. They deal with requirements for the serviceability, load-bearing capacity, durability and fire resistance of steel structures.

For products made from certain metal residues, limits have been set at European level to ensure compliance with environmental standards that guarantee the **end of waste status**. These regulations also contain processing and material-specific criteria as well as requirements for an operational quality assurance system for producers and suppliers. Regulations have currently been issued for iron and steel scrap and aluminium scrap [94] and copper scrap [95]. Criteria include absence of impurities, contaminants and foreign materials.

5.4.1. Exemplary process chain

The quality assurance of RC aggregates for use in concrete construction is presented as an example; specifically, a standard concrete for concrete structures is to be used as RC concrete of compressive strength class ≤ C30/37 and moisture/exposure classes WO/X0, XC1 or WF/X0.

RC concrete with recycled aggregates type 1 (concrete chippings) or type 2 (building chippings) in accordance with No. 5.2.3.4 para. 2-5 DIN 1045-2, 2023 [21]. The maximum proportion of recycled aggregates >2 mm, based on the total aggregates, must not exceed 25 % by volume. Recycled aggregates ≤2 mm of type 1 (concrete chippings) may be used if they originate from the production of coarse recycled aggregates of type 1 (concrete chippings); the proportion of fine recycled aggregates in relation to the proportion of coarse recycled aggregates must not be greater than the proportion of total fine aggregates in relation to the proportion of total coarse aggregates.

RC concrete with recycled aggregates type 1 (concrete chippings) in accordance with Annex E No. E.3.2.2 Tab. E.5 DIN 1045-2, 2023 [21]. The maximum proportion of recycled aggregates >2 mm, based on the total aggregates, must not exceed 45 % by volume. Of these, a maximum of 20 % by volume of the replaceable recycled aggregates may be ≤2 mm. These fine recycled aggregates must come from the same production as the coarse recycled aggregates used.

RC concrete with recycled aggregates type 2 (building chippings) in accordance with Annex E No. E.3.2.2 Table E.5 DIN 1045-2, 2023 [21]. The maximum proportion of recycled aggregates >2 mm, based on the total aggregates, must not exceed 35 % by volume.

In accordance with DIN EN 12620 [73], the possible aggregates are subject to the 2+ quality assurance system for assessing and verifying the constancy of performance of the EU CPR with regard to their structural properties. System 2+ requires the manufacturer to carry out determination of the product-type on the basis of type testing with a test certificate, factory production control and testing of samples taken at the factory in accordance with the prescribed test plan. The notified certification body for the factory production control must first carry out an initial inspection of the manufacturing plant and of factory production control and then continuously survey, assess and evaluate these on an ongoing basis. After the inspection, the conformity of the production control is certified for this specific manufactury.

The manufacturer must then confirm the conformity of the aggregates with the performance specified in its declaration of performance by means of CE marking. The manufacturer may then market the RC construction product throughout the EU.

5.5. Conclusion

High environmental standards ensure the safe use of RC building products, but the existing regulations introduce a multitude of requirements at various at various levels, posing challenges. This complexity creates a dilemma between environmental protection through the avoidance of pollutants and environmental protection through circularity when using RC building products. Efforts to facilitate the adoption of RC building materials include informal decision support tools like the one from the INTEGRAL research project (https://integral-info.webspace.tu-dresden.de/) [96] and the online handbook on substitute building materials from REMEX GmbH (https://meb-services.de/handbuch) [97]. Even if the developments could be even broader and more dynamic, the recycling of mineral construction waste is well established in Germany, at least in road construction. But there are still potentials to foster recycling in the building sector.

Appendix: Examples of test reports

Extract from a test report of a RC building material for road construction

Probenahme

Die Probenahme erfolgte am 09.12.2020 durch einen Laboranten der IFTA GmbH vom Vorratshaufwerk an der o. g. Aufbereitungsanlage, welches zum Zeitpunkt der Probenahme ca. 8.000 Tonnen umfasste.

Entnommen wurde eine repräsentative Sammelprobe von ca. 60 kg des betreffenden RC-Materials; zusätzlich wurden für die Laboruntersuchungen jeweils ca. 15 kg Splitt 8/16 und Schotter 35/45 mm vor Ort ausgesiebt.

Untersuchungsergebnisse

Die Untersuchungsergebnisse sind nachfolgend aufgeführt.

Stoffliche Zusammensetzung der Körnungen > 4 mm [TL Gestein StB 04/18, Anhang B]

Stoffgruppe	Anteil [M.-%]	Grenzwert [M.-%]
Beton, Betonprodukte, Mauersteine aus Beton, hydr. geb. Gesteinsk.	40,5	---
Festgestein, Kies	22,9	---
Schlacke (Hochofen-, Stahlwerks- und Metallhüttenschlacke)	2,6	---
Klinker, Ziegel und Steinzeug	11,8	≤ 30
Kalksandstein, Mörtel und ähnliche Stoffe	1,2	≤ 5
Mineralische Leicht- und Dämmbaustoffe wie Poren- und Bimsbeton	0,6	≤ 1
Asphaltgranulat	18,9	≤ 30
Glas	0,2	≤ 5
Nicht schwimmende Fremdstoffe, wie Gummi, Kunststoffe etc.	---	≤ 0,2
Gipshaltige Baustoffe	0,1	≤ 0,5
Eisen- und nichteisenhaltige Metalle	1,2	≤ 2
Schwimmendes Material	---	---

Korngrößenverteilung [DIN EN 933-1]

Siehe tabellarische und graphische Darstellung in Anlage 1. Wie hieraus zu ersehen ist, verläuft die Sieblinie innerhalb des nach TL SoB-StB 04 für Schottertragschichten 0/45 mm vorgegebenen Bereiches.

Bruchflächigkeit [DIN EN 933-5]

Die Körnungen > 4 mm enthalten 0,4 M.-% vollständig gerundete Körner. Laut TL Gestein-StB 04/18 sind im Schottertragschichtmaterial bis zu 3 M.-% an vollständig gerundetem Korn (Kategorie $C_{90/3}$) zulässig.

Widerstand gegen Frost-Tau-Beanspruchung [DIN EN 1367-1]

Im Rahmen der vierteljährlichen Fremdüberwachungsprüfung nicht erforderlich.

Raumbeständigkeit [DIN EN 1367-3]

Prüfkörnung [mm]	Absplitterungen im Kochversuch [M.-%]		Differenzschlagzertrümmerungswert [M.-%]	
	Ergebnis	Grenzwert	Ergebnis	Grenzwert
Schotter 35 - 45	0,5	1	Im Rahmen der vierteljährlichen Fremdüberwachungsprüfung nicht erforderlich	
Splitt 8 - 16	0,6	1		

Trockenrohdichte [DIN EN 1097-6 Anhang A]

Die Trockenrohdichte des Korngemisches 0/45 mm beträgt 2,599 Mg/m³. Sie stellt einen Kennwert, kein Qualitätskriterium dar.

Kornformkennzahl [DIN EN 933-4]

Der Anteil an Körnern mit einem Verhältnis von Länge zu Dicke größer 3 : 1 beträgt in den Kornklassen über 4 mm 7,0 M.-%. Laut TL Gestein-StB 04/18 sind in Schottertragschichten bis zu 50 M.-% (Kategorie SI_{50}) zulässig.

Reinheit und schädliche Bestandteile [DIN 52099]

Die Probe ist weitestgehend frei von Fremdstoffen. Organische Verunreinigungen waren mit dem Natronlaugeverfahren nicht nachweisbar.

Widerstand gegen Zertrümmerung [DIN 52115 T2; DIN EN 1097-2 Abs. 6]
Im Rahmen der vierteljährlichen Fremdüberwachungsprüfung nicht erforderlich.

Wasserwirtschaftliche Merkmale

Die Bestimmung der wasserwirtschaftlichen Merkmale erfolgte hinsichtlich der in den Tabellen 5a (Eluatanalysen) und 5b (Feststoffanalysen) des Gem. Runderlasses MWMEV/MUNLV (NRW) vom 09.10.2001 vorgegebenen Parameter.
Die Analysenergebnisse sind in der Anlage 2 aufgeführt und den Grenzwerten des vorgenannten Gemeinsamen Runderlasses für RCL I und RCL II gegenübergestellt.

Zusammenfassende Beurteilung

Der durch die untersuchte Probe - Körnungsgemisch 0/45 mm - repräsentierte RC-Baustoff entspricht den Technischen Lieferbedingungen für Baustoffgemische und Böden zur Herstellung von Schichten ohne Bindemittel im Straßenbau (TL SoB-StB 04), den Gütebestimmungen, Klasse I nach RAL-RG 501/1 für ungebundene Frostschutz- und Schottertragschichten sowie den Anforderungen der Technischen Lieferbedingungen für Gesteinskörnungen im Straßenbau (TL Gestein-StB 04/18) Anhang A.

Das vorgenannte Material erfüllt hinsichtlich seiner wasserwirtschaftlichen Merkmale (siehe Ergebnistabelle in Anlage 2) die Anforderungen des Gemeinsamen Runderlasses MWMEV/MUNLV (NRW) vom 09.10.2001 an RCL- Material I. Die Verwendungsbedingungen für dieses Material sind im Gemeinsamen Runderlass MUNLV/MWMEV (NRW) in Anlage 1 (siehe Anlage 3 zu diesem Prüfzeugnis) geregelt.

Gegen eine Verwendung gemäß ZTV SoB-StB 04 des durch die Probe repräsentierten, aus aufbereiteten Altbaustoffen hergestellten Körnungsgemisches 0/45 mm in Frostschutz- und Schottertragschichten von Straßen der Belastungsklassen Bk 0,3 bis 100 bestehen - stets gleichbleibende Qualität vorausgesetzt - bei Berücksichtigung der Anlage 3 hinsichtlich aller geprüften Eigenschaften keine Bedenken.

Wasserwirtschaftliche Merkmale von RC - Material gemäß den Tabellen 5a u. 5b des Gemeinsamen RdErl. d. Ministeriums für Wirtschaft u. Mittelstand, Energie und Verkehr [VI A 3 - 32-40/45] und des Ministeriums für Umwelt u. Naturschutz, Landwirtschaft und Verbraucherschutz [IV - 3 - 953-26308] sowie [IV - 8- 1573-30052] vom 09.10.2001.

Projekt Nr.:	2012051	Entnahmedatum:	09.12.2020
Probenbezeichnung:	RC-Material 0/45 mm		
Anlagenstandort:	Im Karrenberg, Dortmund		

		Analysen - ergebnisse	Grenzwerte	
			RCL I	RCL II
Eluatanalyse				
pH-Wert [1]		11,1	7 - 12,5	7 - 12,5
elektr. Leitfähigkeit	µS/cm	1.470	2.000	3.000
Chlorid	mg/l	3,5	40	150
Sulfat	mg/l	101	150	600
PAK (EPA)	µg/l	----	5 [2]	[3]
Phenolindex	µg/l	< 5	50	100
Blei	µg/l	< 1	40	100
Cadmium	µg/l	< 0,3	5	5
Chrom VI	µg/l	< 30	30	50
Kupfer	µg/l	3,3	100	200
Nickel	µg/l	< 1	30	100
Zink	µg/l	< 10	200	400
Feststoffanalyse				
EOX	mg/kg	1,1	3	5
PAK (EPA)	mg/kg	8,8	15 [4]	75 [5]

Erläuterungen:

1) kein Grenzwert

2) nur einzuhalten, wenn Feststoffwert > 15 und < 20 mg/kg

3) zur Erfahrungssammlung zu bestimmen

4) Überschreitung bis 20 mg/kg zulässig, wenn Eluatwert < 5 µg/l

5) Überschreitung bis 100 mg/kg zulässig

Extract from a test report of concrete chippings for concrete production

2 Prüfergebnisse

2.1 Kornzusammensetzung, Gehalt an Feinanteilen (DIN EN 933-1, Waschen und Trockensiebung)

2.1.1 Grobe Gesteinskörnungen

Korngruppe		2/16						
Sieb-Öffnungsweite	mm	0,063	1	2	8	16	22,4	31,5
Siebdurchgang	M.-%	1,5	5	10	53	96	100	100
Anforderung	M.-%	0-1,5	0-5	0-15	25-70	90-99 *)	98-100	100
Typischer Durchgang	M.-%				50			
Toleranz	M.-%				± 17,5			

Kategorie Kornzusammensetzung: G_C90/15; G_T17,5 Kategorie Feinanteile: $f_{1,5}$

*) Der Siebdurchgang durch D darf unter Umständen auch mehr als 99 M.-% betragen, in diesen Fällen muss der Hersteller die typische Kornzusammensetzung aufzeichnen und angeben (DIN EN 12620, Tabelle 2, Fußnote c).

2.2 Kornform von groben Gesteinskörnungen

2.2.1 Kornformkennzahl (DIN EN 933-4)

Korngruppe	Kornklasse	Kornformkennzahl *SI* M.-%	Kategorie
2/16	4/16	9	SI_{15}

2.3 Kornrohdichte und Wasseraufnahme (DIN EN 1097-6, Abschnitte 8 und 9)

Korngruppe	Scheinbare Rohdichte ρ_a Mg/m³	Rohdichte auf ofentrockener Basis ρ_{rd} Mg/m³	Rohdichte auf wassergesättigter und oberflächentrockener Basis ρ_{ssd} Mg/m³	Wasseraufnahme WA_{24} M.-%
2/16	2,62	2,33	2,44	4,8
Soll		≥ 2,00		
Vom Hersteller deklarierter Mittelwert		2,40		
Schwankungsbreite		± 0,15		

2.4 Wasseraufnahme nach 10 Minuten (DAfStb-Richtlinie, Anhang B)

Korngruppe	Wasseraufnahme *W* M.-%	Soll M.-%
2/16	3,4	≤ 10

2.5 Schüttdichte (DIN EN 1097-3)

Korngruppe	Einzelwerte Schüttdichte ρ_b Mg/m³			Mittelwert Schüttdichte ρ_b Mg/m³	Hohlraumgehalt *v* Vol.-%
2/16	1,30	1,30	1,30	1,30	44

2.6 Dauerhaftigkeit

2.6.1 Frost-Tau-Widerstand (DIN EN 1367-1)

Korngruppe	Prozentualer Massenverlust *F* M.-%	Kategorie
2/16	3,7	F_4

2.7 Stoffliche Kennzeichnung (DIN EN 933-11)

Bestandteile im Anteil > 4 mm		Ist	Soll	Kategorie
Beton, Betonprodukte, Mörtel, Mauersteine aus Beton (Rc) Ungebundene Gesteinskörnung, Naturstein, hydraulisch gebund. Gesteinskörnung (Ru)	M.-%	97,9	≥ 90	Rcu_{90}
Mauerziegel (d. h. Mauersteine und Ziegel), Kalksandsteine, nicht schwimmender Porenbeton (Rb)	M.-%	1,0	≤ 10	Rb_{10-}
Bitumenhaltige Materialien (*Ra*)	M.-%	0,7	≤ 1	Ra_{1-}
Sonstige Materialien: Bindige Materialien (d. h. Ton und Boden), verschiedene sonstige Materialien: Metalle (Eisen- und Nichteisenmetalle), nicht schwimmendes Holz, Kunststoff, Gummi, Gips (X) Glas (Rg)	M.-%	0,4	≤ 1	XRg_{1-}
Schwimmendes Material (FL)	cm³/kg	0,4	≤ 2	FL_{2-}

2.8 Chloride

2.8.1 Wasserlösliche Chloridionen (DIN EN 1744-1, Abschnitt 7)

Korngruppe	Chloridgehalt C M.-%	Soll M.-%
2/16	0,0023	≤ 0,04

2.8.2 Säurelösliche Chloridionen (DIN EN 1744-1, Abschnitt 7)

Korngruppe	Chloridgehalt C M.-%	Soll M.-%
2/16	0,0330	≤ 0,04

2.9 Schwefelhaltige Bestandteile

2.9.1 Säurelösliches Sulfat (DIN EN 1744-1, Abschnitt 12)

Korngruppe	Säurelöslicher Sulfatgehalt SO_3 M.-%	Kategorie
2/16	0,320	$AS_{0,8}$

2.9.2 Wasserlösliches Sulfat (DIN EN 1744-1, Abschnitt 15.3)

Korngruppe	Wasserlöslicher Sulfatgehalt SO_3 M.-%	Kategorie
2/16	0,0910	$SS_{0,2}$

2.9.3 Gesamt-Schwefel (DIN EN 1744-1, Abschnitt 11.1)

Korngruppe	Gesamtschwefelgehalt S M.-%	Soll M.-%
2/16	0,280	≤ 1

2.10 Andere Bestandteile

2.10.1 Leichtgewichtige organische Verunreinigungen (DIN EN 1744-1, Abschnitt 14.2)

Korngruppe	Leichtgewichtige Bestandteile m_{LPC} M.-%	Soll M.-%
2/16	< 0,01	≤ 0,1

2.11 Bewertung der Inhaltsstoffe rezyklierter Gesteinskörnungen (geregelte gefährliche Substanzen) (DIN 4226-101, Tabelle 2)

Eigenschaft / Parameter		Ist	Höchstwerte
Eluat			
pH-Wert	-	11,9	12,5 [a]
Elektrische Leitfähigkeit	µS/cm	1558	3000 [a]
Chlorid	mg/l	2,7	150
Sulfat	mg/l	9,9	600
Arsen	µg/l	< 1,0	50
Blei	µg/l	< 1,0	100
Cadmium	µg/l	< 0,10	5
Chrom gesamt	µg/l	5,7	100
Kupfer	µg/l	1,1	200
Nickel	µg/l	< 1,0	100
Quecksilber	µg/l	< 0,1	2
Zink	µg/l	38	400
Phenolindex	µg/l	< 10	100
Feststoff			
Mineralölkohlenwasserstoffe (C_{10} – C_{40})	mg/kg	< 50	1000 [b]
PAK nach EPA	mg/kg	--	25
EOX	mg/kg	< 0,5	10
PCB	mg/kg	--	1

[a] Kein Ausschlusskriterium

[b] Überschreitungen, die auf Asphaltanteile zurückzuführen sind, stellen kein Ausschlusskriterium dar.

Extract from a test report of construction chippings for concrete production

2 Prüfergebnisse

2.1 Kornzusammensetzung, Gehalt an Feinanteilen (DIN EN 933-1, Waschen und Trockensiebung)

2.1.1 Grobe Gesteinskörnungen

Korngruppe		2/16						
Sieb-Öffnungsweite	mm	0,063	1	2	8	16	22,4	31,5
Siebdurchgang	M.-%	1,5	5	8	48	96	100	100
Anforderung	M.-%	0-1,5	0-5	0-15	25-70	90-99 *)	98-100	100
Typischer Durchgang	M.-%				50			
Toleranz	M.-%				± 17,5			

Kategorie Kornzusammensetzung: G_C90/15; G_T17,5 Kategorie Feinanteile: $f_{1,5}$

*) Der Siebdurchgang durch D darf unter Umständen auch mehr als 99 M.-% betragen, in diesen Fällen muss der Hersteller die typische Kornzusammensetzung aufzeichnen und angeben (DIN EN 12620, Tabelle 2, Fußnote c).

2.2 Kornform von groben Gesteinskörnungen

2.2.1 Kornformkennzahl (DIN EN 933-4)

Korngruppe	Kornklasse	Kornformkennzahl *SI* M.-%	Kategorie
2/16	4/16	12	SI_{15}

2.3 Kornrohdichte und Wasseraufnahme (DIN EN 1097-6, Abschnitte 8 und 9)

Korngruppe	Scheinbare Rohdichte ρ_a Mg/m³	Rohdichte auf ofentrockener Basis ρ_{rd} Mg/m³	Rohdichte auf wassergesättigter und oberflächentrockener Basis ρ_{ssd} Mg/m³	Wasseraufnahme WA_{24} M.-%
2/16	2,58	2,17	2,33	7,2
Soll		≥ 2,00		
Vom Hersteller deklarierter Mittelwert		2,30		
Schwankungsbreite		± 0,15		

2.4 Wasseraufnahme nach 10 Minuten (DAfStb-Richtlinie, Anhang B)

Korngruppe	Wasseraufnahme W M.-%	Soll M.-%
2/16	4,6	≤ 15

2.5 Schüttdichte (DIN EN 1097-3)

Korngruppe	Einzelwerte Schüttdichte ρ_b Mg/m³			Mittelwert Schüttdichte ρ_b Mg/m³	Hohlraumgehalt v Vol.-%
2/16	1,27	1,27	1,27	1,27	42

2.6 Dauerhaftigkeit

2.6.1 Frost-Tau-Widerstand (DIN EN 1367-1)

Korngruppe	Prozentualer Massenverlust F M.-%	Kategorie
2/16	3,3	F_4

2.7 Stoffliche Kennzeichnung (DIN EN 933-11)

Bestandteile im Anteil > 4 mm		Ist	Soll	Kategorie
Beton, Betonprodukte, Mörtel, Mauersteine aus Beton (Rc) Ungebundene Gesteinskörnung, Naturstein, hydraulisch gebund. Gesteinskörnung (Ru)	M.-%	81,4	≥ 70	Rcu_{70}
Mauerziegel (d. h. Mauersteine und Ziegel), Kalksandsteine, nicht schwimmender Porenbeton (Rb)	M.-%	16,8	≤ 30	Rb_{30-}
Bitumenhaltige Materialien (*Ra*)	M.-%	1,0	≤ 1	Ra_{1-}
Sonstige Materialien: Bindige Materialien (d. h. Ton und Boden), verschiedene sonstige Materialien: Metalle (Eisen- und Nichteisenmetalle), nicht schwimmendes Holz, Kunststoff, Gummi, Gips (X) Glas (Rg)	M.-%	0,8	≤ 2	XRg_{2-}
Schwimmendes Material (FL)	cm³/kg	0,8	≤ 2	FL_{2-}

2.8 Chloride

2.8.1 **Wasserlösliche Chloridionen** (DIN EN 1744-1, Abschnitt 7)

Korngruppe	Chloridgehalt *C* M.-%	Soll M.-%
2/16	0,0104	≤ 0,04

2.8.2 **Säurelösliche Chloridionen** (DIN EN 1744-1, Abschnitt 7)

Korngruppe	Chloridgehalt *C* M.-%	Soll M.-%
2/16	0,0240	≤ 0,04

2.9 Schwefelhaltige Bestandteile

2.9.1 **Säurelösliches Sulfat** (DIN EN 1744-1, Abschnitt 12)

Korngruppe	Säurelöslicher Sulfatgehalt SO_3 M.-%	Kategorie
2/16	0,280	$AS_{0,8}$

2.9.2 **Wasserlösliches Sulfat** (DIN EN 1744-1, Abschnitt 15.3)

Korngruppe	Wasserlöslicher Sulfatgehalt SO_3 M.-%	Kategorie
2/16	0,0756	$SS_{0,2}$

2.9.3 **Gesamt-Schwefel** (DIN EN 1744-1, Abschnitt 11.1)

Korngruppe	Gesamtschwefelgehalt *S* M.-%	Soll M.-%
2/16	0,180	≤ 1

2.11 Bewertung der Inhaltsstoffe rezyklierter Gesteinskörnungen (geregelte gefährliche Substanzen) (DIN 4226-101, Tabelle 2)

Eigenschaft / Parameter		Ist	Höchstwerte
Eluat			
pH-Wert	-	11,8	12,5 [a]
Elektrische Leitfähigkeit	µS/cm	1287	3000 [a]
Chlorid	mg/l	10,9	150
Sulfat	mg/l	57,7	600
Arsen	µg/l	< 1,0	50
Blei	µg/l	< 1,0	100
Cadmium	µg/l	< 0,10	5
Chrom gesamt	µg/l	14	100
Kupfer	µg/l	3,1	200
Nickel	µg/l	1,2	100
Quecksilber	µg/l	< 0,1	2
Zink	µg/l	52	400
Phenolindex	µg/l	< 10	100
Feststoff			
Mineralölkohlenwasserstoffe ($C_{10} - C_{40}$)	mg/kg	< 50	1000 [b]
PAK nach EPA	mg/kg	--	25
EOX	mg/kg	< 0,5	10
PCB	mg/kg	--	1

[a] Kein Ausschlusskriterium

[b] Überschreitungen, die auf Asphaltanteile zurückzuführen sind, stellen kein Ausschlusskriterium dar.

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