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Sustainable use of post-demolition concrete as recycled aggregates and cement substitute: Recycling potential in Germany

Antonia Frank, Rebekka Volk, Frank Schultmann

Institute for Industrial Production (IIP),
Karlsruhe Institute of Technology,
Hertzstraße 16, 76187 Karlsruhe, Germany

Summary

Concrete relies heavily on cement as a binder, is versatile and has impressive structural properties. Given the significant carbon emissions of cement, the construction industry should strive to minimise or replace its use in concrete. For this, post-demolition concrete can be used as an aggregate substitute and cement substitute. In 2021, Germany's concrete production peaked at 206 million tons, demonstrating the immense potential to reduce negative environmental impacts by recycling concrete waste. To cut emissions, a circular economy for concrete is essential. Analysis of production data since 1950, the lifetime of concrete structures and waste concrete statistics in Germany will estimate how many tonnes of recycled concrete can replace conventional concrete. Today, approx. 29% of the production nowadays of concrete could be implemented with post-demolition concrete. Reducing primary cement and increasing aggregate substitutes are pivotal for future sustainable concrete production.

1 INTRODUCTION

Concrete is an important building material that is used in many different ways in the construction industry. Concrete stands out with its durability and impresses with its versatility and outstanding visual and physical characteristics. Conventional concrete consists of the basic materials aggregate, cement and water [1]. The aggregate makes up the largest proportion [2]. Concrete has a wide range of applications and is mainly used in bricks and blocks for roofs, walls, prefabricated parts, and products for civil engineering and road construction as well as gardening and landscaping [3, 4].

Cement in concrete, which accounts for 15-20% of the volume, acts as a binding agent and ensures the toughness of the final product [5, 6]. Cement consists mainly of limestone, which is burned at 1450 °C and which leads to immense CO_2 emissions of 580-600 kilogrammes per tonne of produced cement [7–9]. Most of the cement produced in Germany is used for concrete production. Ready-mix concrete accounted for around 54.3% of domestic cement shipments in 2021 [5]. This makes domestic ready-mix concrete producers key customers of the German cement industry.

The production of ready-mix concrete, which is a decisive factor in production, peaked at 55.3 million m^3 in 2020 [10]. 4.1 billion tonnes were produced worldwide in 2023 [11]. In 2022, precast concrete elements summed up to 23.6 million tonnes and 2.2 million m^2 in Germany [12]. At least some of the installed concrete will reach its end-of-life and can turn into secondary resources for concrete production.

Following the Paris Agreement in 2015, sustainability strategies and targets in politics need to be achieved in the coming years – especially regarding climate change mitigation. The targets for reducing CO_2 emissions were set for a maximum temperature increase of 1.5 degrees which was agreed upon and will hopefully be achieved through individual national contributions to reducing GHGs (including CO_2) [13]. Also, the EU has formulated the goal of becoming the first climate-neutral continent by 2050 [14]. This requires immense efforts of the construction industry to meet this target.

Recycling of construction and demolition waste to create cycles of building materials is important to conserve resources, avoid landfilling and reduce CO_2 emissions [15]. Ultimately, this can promote a circular economy in which resources circulate in closed loops and waste generation is reduced. By making circular economy principles an important part of construction projects, their environmental footprint can be improved [16]. Environmental standards and regulations enable processes to be carried out in a regulated manner and are an important complement to fostering a circular economy. In addition, an intensive dialogue and cooperation between construction technology and structural engineering is necessary for a sustainable construction industry [17].

If building materials are not recycled during or directly after dismantling, waste is generated. Between 2017 and 2021, the volume of reclaimed concrete material delivered to waste disposal facilities in Germany totalled 272.72 million tonnes [18]. Reclaimed concrete material that is not sent to such facilities either ends up in recycling or processing plants, in landfills or its whereabouts are not documented. In 2021, almost 3.4 million tonnes of concrete and mixtures containing concrete were sent to landfill in Germany [19]. These quantities can no longer be used as input for a circular economy nor as an aggregate or cement substitute for concrete production.

Incorporating post-demolition concrete into new concrete is an essential step in creating a circular economy. Recycled concrete is a resource-saving concrete, the use of which means that at least some of the post-demolition concrete was reused in new construction. Recycled concrete contributes to the conservation of resources and landfill capacity by being added as a secondary raw material [20].

The following sections outline how to determine the potential of recycled concrete in Germany, future circulation quantities and relevant limitations.

2 LITERATURE AND STATE OF THE ART

Within the literature, recycling is underscored as a pivotal process in the construction industry, with aspects of resource preservation, waste mitigation and CO_2 reduction [21]. The focus for the future lies in fostering a circular economy, as it will facilitate the attainment of the aforementioned objectives [16, 17, 22, 23].

In general, compliance with legal and technical framework conditions is crucial for the recycling of waste materials produced as aggregates during the demolition of concrete structures. For concrete recycling, there are laws and regulations as well as different standards and guidelines for concrete construction and material recycling [17]. Overall, there is a complex interplay of legal and technical requirements that need to be harmonised with the actual recycling process and the goals of sustainability. Innovative methods and novel approaches are of the utmost importance to drive concrete recycling forward [14]. In addition, infrastructure and logistics still represent a hurdle, as the construction industry has not yet merged extensively with the recycling industry and conventional production processes are still the standard [21].

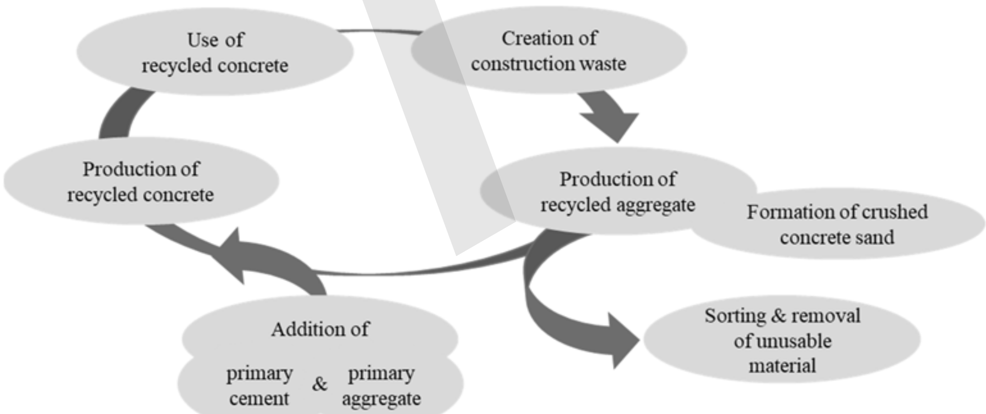

Fig. 1 Circle of (recycled) concrete [based on 20]

The recycled concrete cycle consists of seven steps (Fig. 1): 1. addition of primary cement and primary aggregate, 2. production of recycled concrete, 3. use of recycled concrete, 4. creation of construction waste, 5. production of recycled aggregate, 6. formation of crushed concrete sand and 7. sorting and removal of unusable material (Fig. 1). By mixing the components of concrete and the primary or secondary cement as a binder, recycled aggregate is added to create recycled concrete and ultimately achieve the desired and required properties of the final material [20]. This recycled concrete can then be used in new construction projects and is used in the manufacture of structures, foundations and other building elements [20]. The process of sorting, crushing and processing the rubble after demolition is essential to produce a high-quality and usable aggregate that can be used as a substitute for natural aggregate [17] and cement substitute and crushed concrete sand can be obtained. Further processing of the concrete crushed sand can lead to a Belite cement [24] that can substitute primary cement. Sorting and removal of unusable material is necessary to ensure that only usable and recyclable material remains in the cycle and that material quality remains high.

It is crucial to emphasise that various methodologies already exist for substituting the aggregate in concrete with recycled building material [15, 17]. However, the most environmentally impactful material is cement in concrete, underscoring the imperative to replace it with sustainable and environmentally friendly alternatives in the future [24].

Quantification models for material stocks, urban mining and material inflow and outflow analyses can already be found in the literature. For example, Augiseau and Barles [25] and Deetman et al. [26] deal with building materials and the modelling of the dynamic inventory. Augiseau and Barles [25] review 31 publications, including studies dealing with joint flows and inventories in the construction sector. Deetman et al. [26] developed a model focussing on the global building stock and demand for building materials. Both include different methodological approaches such as static top-down or bottom-up flow analyses, dynamic retrospective or prospective flow analyses using a stock-oriented model and dynamic inflow and outflow stock models. Overall, they provide a useful summary of the different methodological approaches to stock formation.

However, there is currently no approach in the literature to quantify future waste concrete in Germany to estimate the recycling potential for aggregate and cement substitution.

3 METHODOLOGY AND PROCEDURE

To assess the potential for substituting cement and aggregate in concrete via recycling, the presented methodology was developed. For the quantification, comprehensive data collection and analysis were performed focussing on three main areas: concrete production, lifetimes of concrete inventory in building and infrastructure stock and reclaimed concrete material. Historical annual production volumes of concrete, different lifetimes of inventory figures of infrastructure, residential and (non-) residential buildings, as well as waste generation served as input variables of the model.

The aim is to produce accurate estimates and forecasts to enable informed decisions regarding the use of cement substitute and aggregate substitute from post-demolition concrete for the production of new concrete. The developed procedure of the quantification model is shown in Fig. 2.

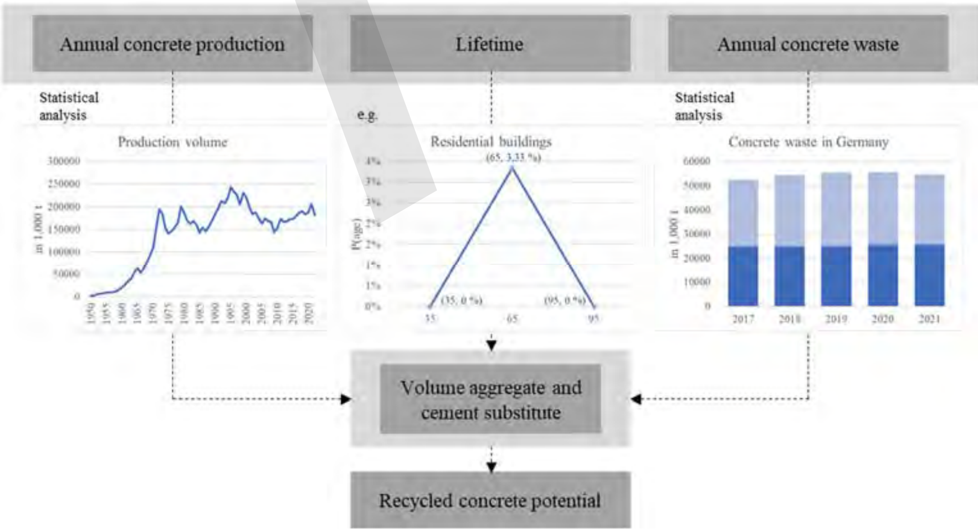

Fig. 2 Procedure of the quantification model

As part of the production analysis, annual statistical data from 1950 onwards was used to determine the volume of concrete production in Germany. This includes examining various production categories and carefully analysing the statistics of the Federal Statistical Office from 1950 to 2018 [3] to create a reliable basis for projecting the volume of concrete production up to 2040. In addition, data from [12] was used as a comparative value. If values in key categories were unavailable in individual years, an estimate was set to the previous year's production volume. Expected lifetimes of concrete structures from the literature were used to estimate when these structures will be demolished or replaced.

The analysis of the reclaimed concrete material included an in-depth study of all waste streams containing concrete and the corresponding disposal routes, including landfills and other disposal facilities. The Federal Statistical Office (Destatis) [18] provides data that correlates different types of waste and disposal methods.

In an ongoing research project (URBAN) funded by the German Federal Ministry of Economic Affairs and Climate Action, the aim is to replace approx. 30% of the primary cement in concrete with a cement substitute from post-demolition concrete and, likewise, to entirely replace the aggregate in concrete with recycled aggregate.

4 RESULTS

The production data from the Federal Statistical Office [3] and the FBF Betondienst Gesellschaft für Information, Werbung, Qualitätssicherung und Normung mbH [12] are broken down into different categories. While [12] divides the total volume into eight categories (see Table 1), the Federal Statistical Office [3] provides a more detailed breakdown (see Table 2). The data from [3] covers the years 1950 to 2018 and while [12] provides annual production volumes only for more recent years from 2009 to 2022.

Table 1 Concrete production categories according to [12]

Category
Structural prefabricated parts
Bricks and blocks
Chimney fittings
Road, gardening and landscaping construction
Concrete pipes
Prefabricated buildings made from precast concrete elements
Other prefabricated parts
Ready-mix concrete

Table 2 Concrete production categories according to [3]

Category
Building blocks and bricks
Roof tiles, sidewalk tiles, paving slabs, concrete paving stones, etc.
Concrete products for building construction
Concrete blocks
Concrete roof tiles
Prefabricated concrete parts
Concrete products for civil engineering and road
Concrete products for other purposes
Ready-mix concrete
Other products

The production volume from 2009 to 2022 is shown in Fig. 3 with a clear peak in 2021 with more than 206 million tonnes [13]. Ready-mixed concrete accounts for the largest share here with around 66% of the total volume.

This is followed by structural precast elements with 10% and components for road construction, gardening and landscaping with 11%. A linear increase in volume in recent years can also be observed (see red dots).

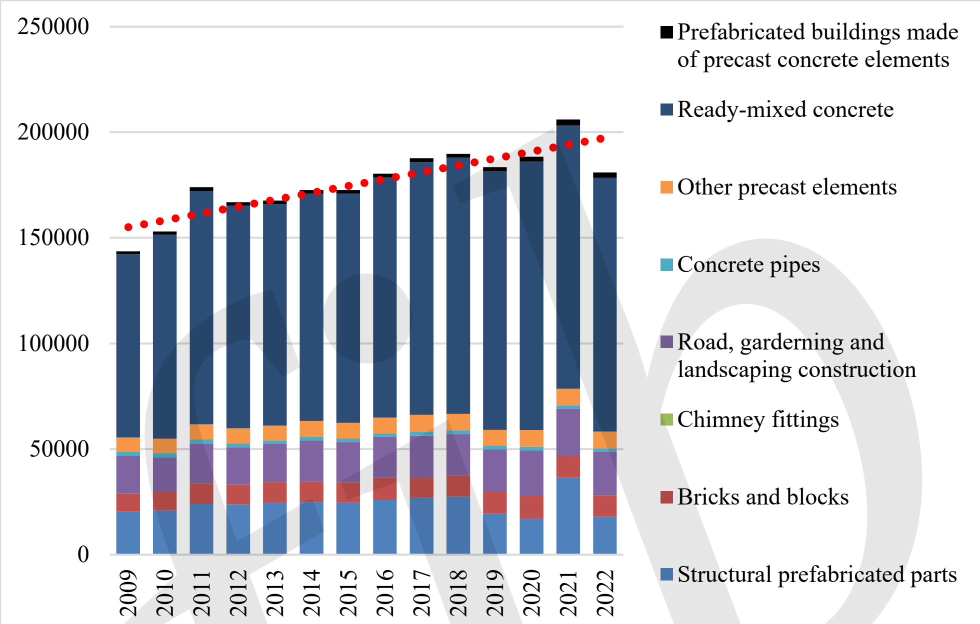

Fig. 3 Concrete production volume (in 1,000 tonnes) of concrete components and products in Germany from 2009 to 2022 and the trend (red dots) [12]

Information in the literature on the different lifetimes of individual structures is available and provides important insights [27–30]. By analysing the different lifetimes, it was possible to identify trends in the lifetime of concrete structures that have significant implications for future infrastructure planning and maintenance. For example, the expected lifetime of 65 years was used for residential buildings. Based on the year 1957, 4.5 to 4.9 million tonnes of concrete waste would have been generated in 2022 from buildings with a lifetime of 65 years.

To quantify and compare the volume of waste with projections from production combined with expected lifetimes, statistics were sought to analyse waste that contains concrete or identifies it as the main material. In Germany, this is documented by the Federal Statistical Office [18]. Four waste identification codes were identified that include concrete as a waste material. The waste identification codes and their definitions are shown in Table 3.

Table 3 Waste categories containing concrete in Germany [18]

Waste identification code	Category
101314	Concrete waste and concrete sludge
170101	Concrete
170106	Mixture of separated fractions of concrete
170107	Mixture of concrete, bricks, etc. (without 170106)

The volume of waste in these four categories stagnated in recent years at around 55 million. tonnes. In Fig. 4 the volume of waste generated as reclaimed concrete material is presented for the years 2017 to 2021 and stood at 54.7 million tonnes in 2021 [18]. This volume is theoretically available annually for the production of recycled concrete in Germany. Assuming that 30% of the cement is replaced by a cement substitute made from post-demolition concrete, and 100% of the aggregate in concrete (approximately 74% of one tonne concrete) is replaced as well with the aggregate substitute, then approx. 29% of the production nowadays of concrete could be implemented with post-demolition concrete. If recycled concrete is produced and both the aggregate and the cement substitute are used, 79% of the recycled concrete consists of post-demolition material. Conventional cement in concrete production emits 112.4 CO_2 per tonne of concrete. By saving 30% of primary cement, ideally, 11.5 kilogrammes of CO_2 can be saved per tonne of recycled concrete produced. With the concrete waste generated in 2021, 2.1 million tonnes of CO_2 could have been saved in 2022 by replacing 30% of the primary cement with cement substitute. At the same time, 46.1 million tonnes of primary aggregate could be saved by using the remaining concrete waste, which would save valuable resources.

For the calculation of the future waste volume, it is important to consider different scenarios of how the processes in a complex system such as the built environment, in the waste industry and future politics will take place in the coming years. To do this, it is necessary to consider changes in the market, new regulations and requirements in advance so that potential changes can be recognised at an early stage.

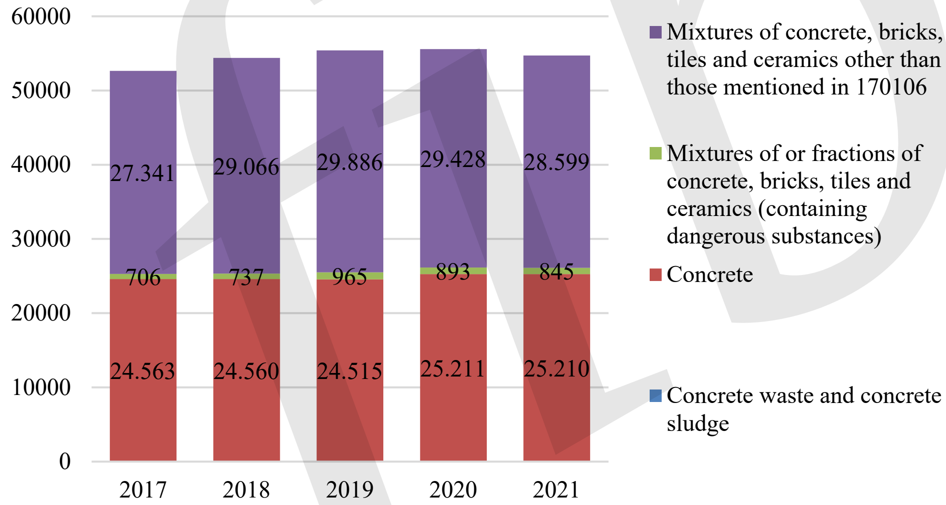

Fig. 4 Concrete waste volume (in 1,000 tonnes) in Germany in the years 2017 to 2021 [18]

5 LIMITATIONS OF THE ANALYSIS

Assessing current production volumes and adjusting production data poses challenges due to gaps or inconsistencies. Gaps are filled with estimates based on the available historical data. However, accurately forecasting production for coming decades is hindered by factors like rising housing demand and evolving construction methods and the trend towards renovation rather than demolition. In this context, it is important to consider the effects on the lifetime of concrete structures and components. Here, the development of scenarios will be essential to take various developments into account.

In addition, waste statistics can only shed light on what is captured, leaving the question of what happened to the quantities that do not end up in landfills and waste facilities unanswered. Thus, for future research, it is essential to collect or estimate data on the quantities that never reach waste disposal or recycling facilities. The need for comprehensive waste management strategies must be emphasised and the handling of waste should be evaluated from various points of view. Furthermore, it is crucial for the deconstruction of concrete structures that the materials removed are not labelled as 'waste' during the process. The material remains valuable and the importance and acceptance of the secondary material are diminished when labelled as waste.

Moreover, other aspects are important, such as the development of new technologies for the processing of crushed concrete sand to cement, the economic and ecological effects of cement substitution, and the acceptance and feasibility of such measures in the construction industry. These aspects contribute to the comprehensive assessment of the potential for substituting primary cement in concrete and are of great relevance for future decisions in the field of sustainable construction.

In the end, it must be assumed that the volume of concrete waste cannot be utilised as a 100% substitute for aggregate and cement for the production of recycled concrete, as there may be potential losses or other constraints. Moreover, we do not consider processing, transport or other technical restrictions of a full recycling of post-demolition concrete in our analysis.

6 CONCLUSION

Moving towards circular concrete production is an essential step for a more sustainable construction industry in the future. Opportunities for improvement exist, for example, through financial incentives and support programmes that could increase the recycling of concrete and in particular the cementitious crushed concrete sand. The development of new technologies and processes for the preparation and use of recycled concrete could address potential concerns about the quality and durability of the building material.

A sensible and sustainable circular economy can be created with the help of the quantified recycling potential via the production quantity, the lifetime of various concrete structures and the handling of recycled concrete. By using recycled aggregate and cement substitutes, the annual volume of waste can be reduced and the use of primary cement can be minimised. Resources can be conserved and CO_2 emissions can be reduced.

Overall, the identified potential contributes to closing knowledge gaps and provides a solid basis for the creation of policies and measures to promote a more sustainable concrete industry and construction sector. Based on the results of the analysis of the production, inventory and waste side, a comprehensive concept can be developed that covers concrete and cement recycling in Germany and includes the modelling of different scenarios of how the market will change and which trends will develop.

Acknowledgements

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