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THE USE OF GREEN CONCRETE IN GERMANY TO CONSERVE RESOURCES AND THE OPPORTUNITIES FOR DECARBONIZATION ALONG ITS VALUE CHAIN

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Keywords: *resource-saving concrete, decarbonization, CO_2 reduction, recycled aggregates, crushed sand*

ABSTRACT

The building industry is particularly resource-intensive and the urgency to produce concrete in a resource-conserving way is an imperative of the time. Around 40 % of Germany's greenhouse gases are attributable to construction and the use of buildings. These days about 78 % of construction waste is recycled, but due to the existing restrictions in Germany only 12,5 % of the demand for aggregate in concrete is covered by recycled aggregate, so the remaining material loses its value and is removed from the material life-cycle.

The paper presents the results of a testing program and show how, in order to drive decarbonization of concrete, the concrete matrix can be optimized by a significantly expand of the possibilities of using recycled aggregates, as for example replacing natural sand by crushed sands, what currently is not permitted by German Standards.

However, the main potential for saving CO_2 lays in the cement, which is responsible for approximately 93 % of the greenhouse potential of concrete. To reduce the CO_2 emission of concrete significantly a lower clinker content is demanded and a low clinker-cement factor should be aimed for. Other ways to decarbonize include optimizing the fuel matrix, using alternative raw materials, or carbon capture technologies.

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1 Why we need to use green concrete

Finite natural resources form the basis for our daily lives and prosperity. However, not all resources are evenly distributed and available in the world and are becoming increasingly scarce due to unsustainable economic systems, the prosperity of industrialized countries and the constantly increasing demand of emerging and industrialized countries. Orientation to natural material cycles and the careful and efficient use of resources makes it possible to decouple a growing economy from an increasing demand for resources. Raw materials should be recycled as far as possible after extraction, processing and consumption or use. In addition, the use of resources should have as little impact on the environment as possible. In addition to the scarcity of natural resources, climate change also plays an essential role for the future of mankind. The rise in annual mean temperatures is having drastic consequences and must be reduced as quickly as possible. To counter these developments, the 2015 Paris Agreement established that global warming must be limited to well below 2 °C above pre-industrial levels. This target has been criticized for not being sufficient and many demand that global warming should even be limited to 1,5 °C to safely prevent irreversible feedbacks from tipping elements in the Earth system. The climate change and the issue of sustainability and the associated conservation of resources has long been an important topic in in all areas of life. The construction industry is also committed to conserving resources. The construction sector is one of the most resource-intensive economic sectors in the world. Concrete is the most used man-made material due to its wide availability, low price, high compressive strength, durability, fire resistance properties, ductility, sound insulation properties and thermal advantages, to name a few benefits. However, a major disadvantage that must be considered is the large CO_2 emissions resulting from cement production, as well as the large amount of primary material needed for the natural aggregate.

Aggregate comprises about 70 – 80 % by mass of concrete and therefore has great potential to contribute to resource conservation. Construction and demolition waste account for about 50 % of the waste generated in Germany and can be processed into secondary raw materials such as recycled replacing primary raw materials such as sand and gravel. In addition to the recycling of hardened concrete, the recycling of fresh concrete is another important factor contributing to the conservation of concrete resources and has been used in the construction industry in Germany for a long time. The use of recycled aggregate is still not ingrained in the everyday thinking of those involved in construction, and the aspects of deconstruction and recycling need to be considered as early as the design stage of buildings. Another way to promote resource conservation is to extend the normatively regulated application options for recycled aggregates and to permit the use of crushed sand. According to the European standard, recycled concrete can be defined as concrete whose aggregate consists of at least 25 % by mass of recycled material in the form of concrete granulate or mixed demolition granulate. Cement is responsible for 6,9 % of global CO_2 emissions and is therefore an important to reduce man-made global warming. To make the cement industry climate-neutral, clinker-efficient cements and carbon capture technologies in particular play a key role besides many more.

To enable the use of concrete with recycled aggregate in practice while ensuring compliance with load-bearing capacity and serviceability certain fresh and hardened concrete properties must be achieved which are comparable with normal concrete. Over several semesters, both normal concretes and concretes with recycled aggregate were produced and tested at the Building Materials Testing Institute of the Stuttgart University of Applied Sciences. The results will be compiled later. However, it can already be said that RC concrete was able to achieve comparable, if not better results in most studies than normal concrete.

2 The construction industry – globally and in Germany

2.1 Global building energy consumption and energy-related CO_2 emissions from buildings

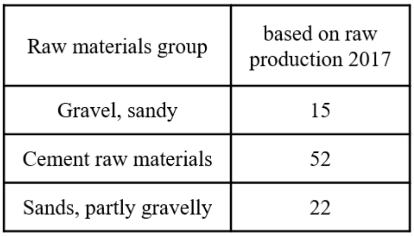
In 2019, buildings accounted for approximately 35 % of global energy consumption and 38 % of global energy-related CO_2 emissions.

Final energy use has increased slightly since 2010. There has been a noticeable change in the shares of fuels as the share of electrical energy is steadily increasing, while the share of coal is decreasing sharply. Renewable energies and natural gas also account for a large share. In 2019, the utilization phases of the buildings were responsible for 9953 Mt of CO_2 emissions, with about 70 % occurring in the provision of electricity and for heating. Another significant role in CO_2 emissions is played by material production, which accounts for 3430 Mt of CO_2. The production of cement and steel accounts for a large proportion of this [1].

2.2 Raw material consumption in Germany

In Germany, approx. 788 million tons of mineral and energetic raw materials are extracted annually, of which 533 million tons are gravel, sand, crushed natural stone and carbonate stone. Accordingly, the construction and cement industries account for around 67,6 % of raw material extraction in Germany**.** In order to be able to estimate the availability of primary raw materials in the future, the statistical range, which is based on the evaluations of the State Office for Geology, Raw Materials and Mining is determined. The table below indicates how many years different primary raw materials required for construction will be available based on the average raw production in the years 2003 to 2007 [2].

Table 1. Statistical range of primary raw materials



Raw materials group	based on raw production 2017
Gravel, sandy	15
Cement raw materials	52
Sands, partly gravelly	22

In sand and gravel mining, there is a conflict of interest with groundwater protection. Meeting the demand for drinking water is prioritized, so shortages can occur locally, especially in urban areas. Especially in cities, the use of secondary raw materials from the anthropogenic stockpile is to be strived for.

2.3 The environmental footprint of the building construction in Germany

To be climate neutral by 2050 greenhouse gas emissions must be reduced by at least 65 % by 2030 compared with 1990 levels. To this end, targets are defined for individual sectors in terms of maximum values of CO_2 equivalents. Buildings may only be responsible for 72 million tons of CO_2 equivalents in 2030 while in 2014 it was still responsible for 119 million tons of CO_2 equivalents [3]. The construction and use of buildings accounts for around 40 % of

Germany's greenhouse gas emissions, or 398 million tons of CO_2 equivalents. At 74,6 % the share from the use and operation of buildings is decisive for the greenhouse gas footprint. The majority of emissions from use and operation are caused by the combustion of fossil fuels for heating and the provision of hot water. Energy-efficient renovation of existing buildings is a particularly good way of reducing energy consumption [4].

2.4 Waste generation in Germany

Since 1995, an association of the German building materials industry, the construction industry and the waste disposal industry has been working to promote the circular economy in the construction sector. According to the current monitoring report of January 2021 covering the year 2018, 218,8 million tons of mineral construction waste were generated in Germany. 59,6 % of the mineral construction waste consisted of soil and stones from excavated soil, dredged material and track ballast and 27,3 % is accounted for by the construction waste fraction. About 13,3 million tons of the soil and stones and 46,6 million tons of the construction waste have been recycled. If all recycled quantities are added up, this results in 73,3 million tons of recycled building materials. The demand for aggregate in 2018 was 587,4 million tons. Only 12,5 % of the demand was met with recycled building materials, while most of the demand was met with natural stones and gravels and sands. The average recycling rate of mineral construction waste in Germany is extremely positive at 89,7 %, and the goal of achieving a recycling rate of 70 % of non-hazardous construction and demolition waste by January 2020 was already met in 2018. However, considerable amounts of raw materials are taken out of the original material cycle and thus the value is not preserved, resulting in downcycling [5].

2.5 Life cycle assessment and greenhouse gases

In a research report, the life cycle assessments of concretes with natural and recycled aggregates were compared. In total, a RC concrete C30/37 produced a larger sum of CO_2 equivalents than the normal concrete C30/37. This can be attributed to the increased cement demand. From the research report it can be deduced that approx. 93 % of the greenhouse potential of concrete can be attributed to the cement. The cement industry therefore offers the greatest potential for CO_2 savings in concrete production. In the impact categories acidification, energy resources, the cement production process also dominates the results of the impact estimates with about 90 %. In the impact category gravel extraction and land use, the use of recycled aggregates significantly determines the reduction potential of the impact assessment results [6].

3 Recycled aggregate

In general, recycling means obtaining secondary raw materials from waste by returning primary raw materials to the economic cycle and processing them into new products. Efforts to create closed material cycles have been set in law in Germany to protect people and the environment and to promote a circular economy to conserve natural resources. As already shown, the construction sector in Germany is one of the most resource-intensive sectors of the economy and offers great potential for conserving primary raw materials. The use of recycled aggregate offers the possibility of partial or even complete replacement of natural aggregate and therefore reusing the construction waste without a loss of value.

3.1 Normative bases in Germany

The use of recycled aggregate in concrete is regulated by the guideline of the German Committee for Reinforced Concrete. Four types of recycled aggregate are distinguished in Germany according to the current standard. For use in concrete production, only types 1 and 2 may be used. The difference between the two types lies in the permissible proportions of concrete products and masonry proportions. Type 1 aggregate consists of at least 90 % (wt/wt) of concrete products and natural chippings, while a maximum of 10 % (wt/wt) of masonry may be present while Type 2 may contain up to 30 % (wt/wt) of masonry. The guidline only covers concrete up to strength class C30/37, with restrictions on its use in certain exposure classes and with a maximum permissible proportion of recycled aggregate. In dry environmental conditions, recycled aggregate may be used without further condition. When used in a humid environment, increased requirements are placed on the alkali sensitivity class. Humid environment provides one of the three prerequisites for the harmful alkali-silica reaction. Furthermore, a high effective alkali content in the pore solution of the concrete and an alkali-sensitive aggregate are among the prerequisites. For recycled aggregate, it is either assumed that the origin is known to be able to clearly assign it to a harmless alkali sensitivity class or, if the origin is unknown, it must be assigned to alkali sensitivity class. The permissible proportions of recycled aggregates in relation to the total aggregate vary depending on the exposure class and moisture class as well as the type of the recycled aggregate. A maximum of 45 % of the total aggregate may be replaced by recycled aggregate of type 1 and 35 % of type 2 recycled aggregate [7]. Whether those restrictions are justified, or an extension of the application possibilities would be appreciated will be explained later.

3.2 Extraction and preparation

Ambitious deconstruction with a high degree of selectivity is considered a prerequisite for subsequent utilization as a qualified RC building material in building construction. If conventional processing is used it can only be reused in road construction or other material recycling. The unsuitable and/or polluted parts must be disposed of in landfills.

3.3 Hardened Concrete Recycling

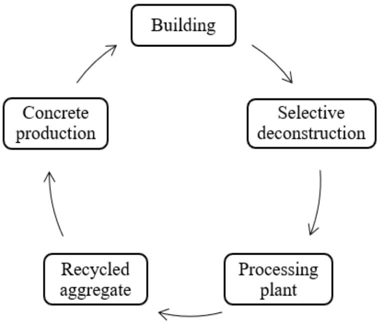


Figure 1. Material cycle of concrete

Already in the design of buildings and with the choice of building materials it is determined whether an economical, sorted and selective deconstruction, as a basic requirement for recycling and to achieve a high quality of the recycled aggregate, will be possible. The construction debris is then processed in processing plants and the unmixed concrete and masonry granules thus obtained are then composed according to the mix calculation and, if necessary, supplemented with crushed primary aggregate. The mixture is then mixed with the other raw materials in the concrete plant, after which the RC concrete is transported to the construction site.

3.3.1 Fresh Concrete Recycling

The recycling of fresh concrete is also an important factor in the conservation of resources in the construction industry and has long been the norm in Germany. In this process, production waste is processed and then fed directly back into the production process. If the entire quantity of concrete supplied is not used on the construction site, the concrete residue that has not yet hardened can be recycled. The remaining fresh concrete is separated into aggregates and cement-containing water, also called gray water. The average amount of concrete left over by the transport plants per day varies considerably. Assuming that 3 % of the concrete production is residual concrete, it can be assumed that about 125 million m^3 of residual concrete is produced annually, from which about 2,9 million t of aggregate can be recovered [8].

3.4 Significant properties

Many properties of the recycled aggregate can be influenced and controlled by an optimized preparation process. High quality can be achieved with the purest possible and most selective reclamation. Of particular importance are porosity/pore size distribution, water absorption, grain strength, modulus of elasticity of the aggregate and the uniformity of properties.

3.4.1 Bulk density

The bulk density is the most important parameter for describing the physical properties of recycled aggregates, since it determines the porosity of the material and influences water absorption. Compared to natural aggregate, the bulk density of recycled aggregate is lower on average. The mean value in the oven-dry state for the natural aggregate was 2,57 kg/dm³, for the recycled aggregate of type 1 – 2,31 kg/dm³ and of type 2 – 2,24 kg/dm³, and for the brick chippings – 1,76 kg/dm³. A decrease in bulk density with increasing brick chippings content can be seen [9].

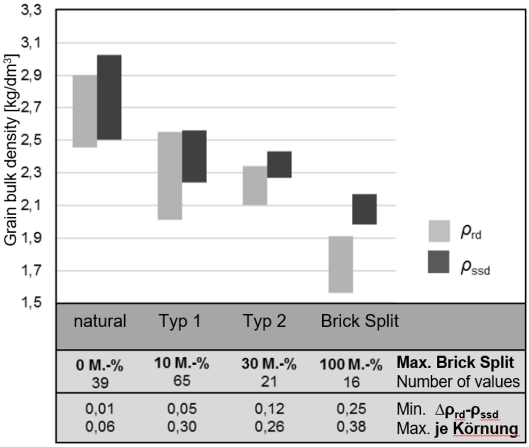


Figure 2. Grain bulk densities of natural and recycled aggregates [9]

3.4.2 Water absorption

Compared to natural aggregate, the recycled aggregate absorbs more water faster. Also, an increasing content of the masonry proportion in the material results in an increased water absorption. As shown in Fig. 3, the natural aggregate absorbs less water than the recycled aggregate both after 10 minutes and after 24 hours. In addition, the spreading width of the natural aggregate is smaller and thus ensures a simplified estimation and calculation of the required addition water. With recycled aggregate, water absorption takes place in two phases. In the first five minutes, a large amount of water is absorbed particularly quickly by the large pores near the surface. Subsequently, the deeper small pores absorb less and slower water [10].

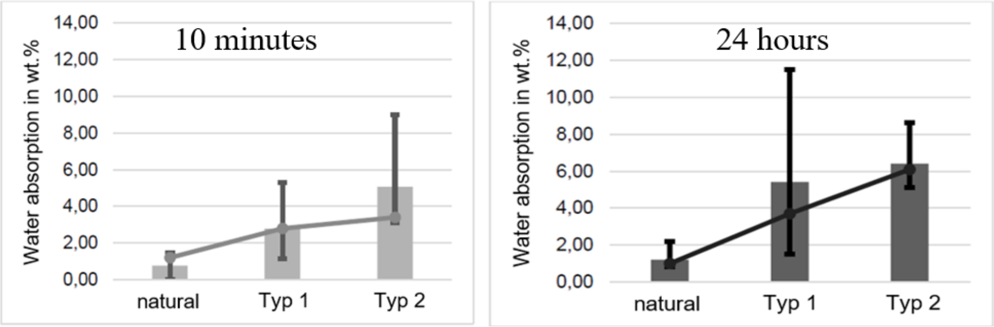


Figure 3. Water absorption after 10 minutes and 24 hours [10]

3.4.3 Grain compressive strength

The grain compressive strength is determined by filling the aggregate into a steel cylinder and compacting it. It is then compressed by a specified height with a compression die and the force required for this is measured. This force corresponds to the grain strength and is given as a pressure value. Tests show that natural aggregates have the highest grain strength, which decreases with increasing brick chippings content [9].

3.5 Crushed sands

Crushed sands have a maximum grain size ≤ 4 mm and are differentiated in 4 Types according to their main constituent. Recycled crushed sands are produced in the crushing process during the preparation of the recycled aggregate and the fraction ≤ 2 mm corresponds to about 20 – 40 % (wt/wt) and the fraction ≤ 4 mm to about 30 – 60 % (wt/wt). According to the current standard, crushed sands may not be used as a main ingredient in concrete production. However, in many research projects on the use of crushed sands in concrete production, the possible uses as a starting material for hydraulic binders, starting material for autoclaved building products, cement production and concrete production are examined.

3.5.1 Use of crushed sands in cement

At the beginning it is necessary to prove the suitability of crushed sands for use in cement. In investigations of the influence of the crushed sands on the compressive strength, the crushed sands were subdivided according to their origin. As a result of the investigations, a decrease in compressive strength with increasing crushed sand content was found for all crushed sand types. A high difference in strength was observed for crushed sands from railway ballast or roof tiles, while it remained very low for crushed sands from masonry rubble. All cements, except the one with 10 % (wt/wt) crushed sands from masonry rubble were able to be assigned to the 52,5 N class. The cement with 10 % (wt/wt) crushed sands from masonry rubble is assigned to class 42,5 R [11].

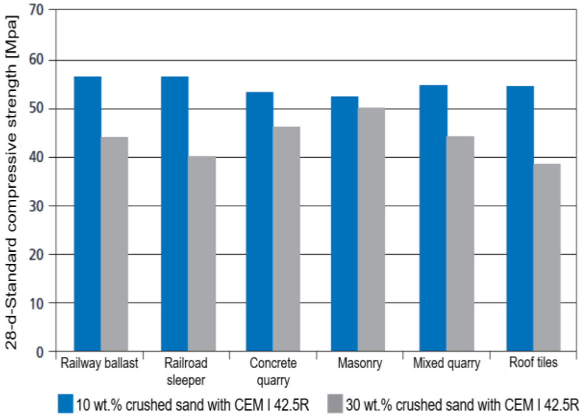


Figure 4. Compressive strength of R cements with 10 / 30 % (wt/wt) crushed sand [11]

3.5.2 Use of crushed sands in concrete

Crushed sands have a decisive influence on the slump and thus the workability of concrete. Without the use of superplasticizer, a steady decrease of the slump ratio with increasing crushed sand content can be observed, as shown in Figure 5 below. Compared to natural sands, crushed sands have a lower bulk density and more pores. These pores lead to a water-absorbing behavior of the crushed sands, which results in a rapid stiffening of the concrete and in a poorer workability [10].

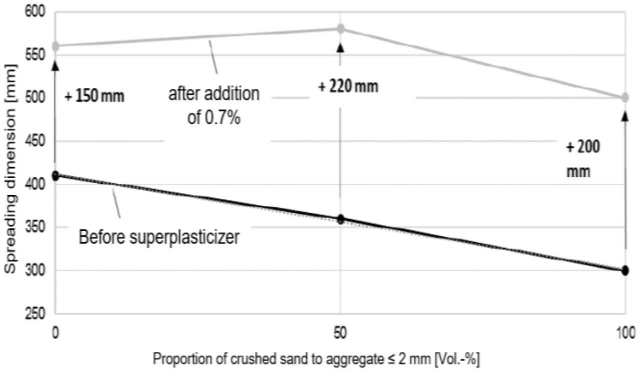


Figure 5. Spreading dimension before and after addition of superplasticizer for different proportions of crushed sand [10]

The influence of crushed sand on the concrete compressive strength after 28 days was also investigated. For a crushed sand content of 0 % the mean value is 49,1 N/mm^2, for 50 % – 49,3 N/mm^2 and for 100 % – 48,7 N/mm^2. The scatter of the mean values corresponds to the test scatter. The target strength could be achieved for all compounds and no negative influence of the crushed sands could be detected [10].

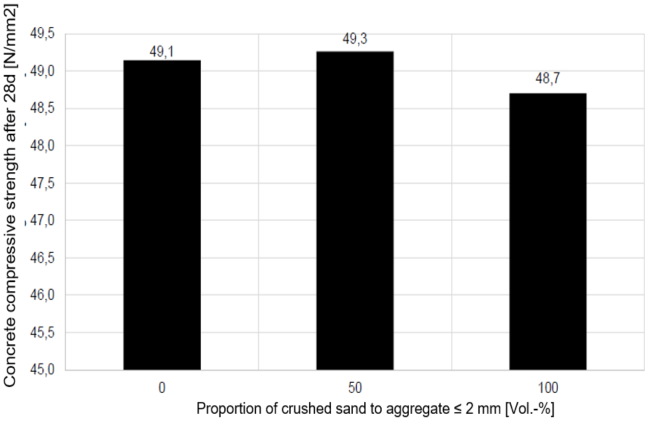


Figure 6. Concrete compressive strength as a function of crushed sand content [10]

3.6 Extension of the application possibilities

3.6.1 Increase of the maximum permissible proportions of recycled aggregate and extension of the permissible strength classes

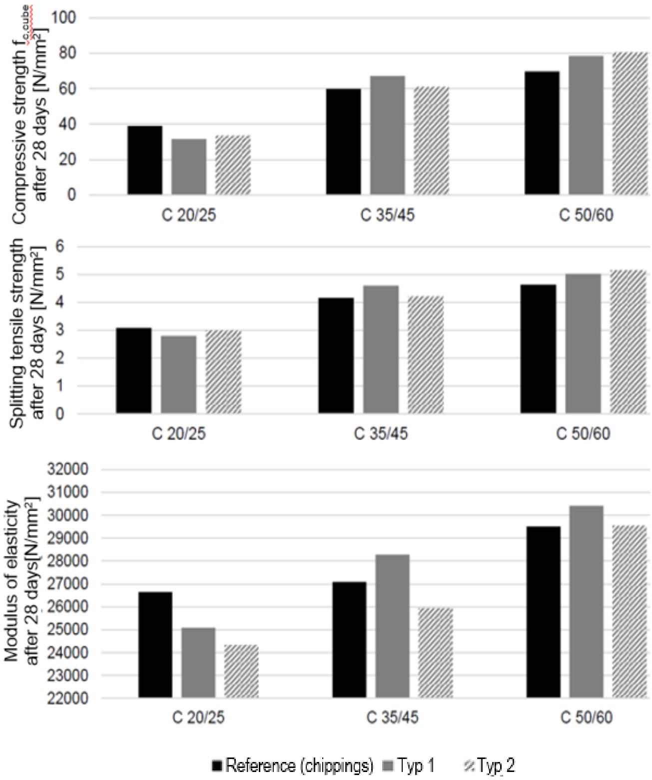


Figure 7. Influence of recycled aggregate on compressive strength, split tensile strength and modulus of elasticity [10]

The BMBF project R-concrete investigated whether the previous restriction up to strength class C30/37 could be lifted and whether an application in the entire normal strength range would be conceivable. In addition, the proportions of recycled aggregate were gradually increased to obtain the optimum mix that would meet all the requirements for fresh and hardened concrete properties. For this purpose, mixes were investigated up to the complete replacement of the natural aggregate.

The conformity criteria for the compressive strength class C30/37 could be met for all mixtures, even when the natural aggregate was completely replaced by recycled aggregate. The average compressive strength of the mixes with type 1 is clearly above the mean value criteria, while the mean value criterion for the strength class C30/37 can only just be met with type 2. In order to investigate the extension of the permissible strength classes three concretes, each with 100% natural aggregate and recycled aggregate of type 1 and 2, were examined. The variants with recycled aggregate of type 1 often exceeded the values of the reference mix with natural aggregate and are thus comparable in the fresh and hardened concrete properties up to strength class C50/60. Mixtures in which type 2 was used performed worse than the reference mix more often, but were able to meet all criteria and can thus also be used [10].

3.6.2 Extension of permissible exposure classes

There are also studies on the extension of the permissible exposure classes which indicate that the currently valid application restrictions in Germany could be extended. At present, recycled aggregate may only be used in dry environments for exposure class XC1. In humid environments, use is restricted to exposure classes X0, XC1 to XC4, XF1, XF3 and XA1. According to the tests, concretes with 100 % recycled aggregate of type 1 can be used in exposure classes XD1/XS1 and XD2/XS2. If type 2 is used, the application is only possible in exposure class XD1/XS1, according to these results. So far, the use of recycled aggregate is not allowed in environmental conditions with chlorides. According to investigations, concretes with 100 % recycled aggregate of type 1 as well as type 2 can be used in the exposure classes XF1 and XF3, where currently only 35 % of type 1 and 25 % of type 2 are permitted [10].

3.6.3 Expanding the range of applications for crushed sands

The use of crushed sands in cement and concrete production has already been discussed. In summary, it can be said that the use of crushed sands results in an increased demand for superplasticizer to achieve the desired target consistency and to ensure workability. A negative influence on the concrete compressive strength when using crushed sands could not be determined within the scope of investigations. However, attention should be paid to the origin of the materials.

4 Cement

The largest share of CO_2 emissions in concrete production can be attributed to the production of cement. On the one hand, this is due to the burning process. In order to burn the clinker from the starting material limestone, high burning temperatures of 1450 °C are required. In order to reach the burning temperature, a high fuel consumption is required, which results in energy-related fuel emissions that cause about one third of the total emissions in cement production. Secondly, CO_2 is released during the chemical reaction of deacidification of the limestone during burning. These raw material-related emissions account for around two-thirds of the total emissions in cement production. Around 4,4 billion tons of cement were produced worldwide in 2020, 56,2 % of which in China and only 5,9 % in Germany. The CO_2 intensity in

2020 was 0,59 tCO_2/t of cement. To achieve climate neutrality by 2050, this must be reduced to 0,45 tCO_2/t of cement by 2030 [12].

4.1 Climate neutrality by 2050

In order not to produce any further CO2 emissions by 2050 in accordance with the "Green Deal" of the European Commission from 2019, far-reaching steps must be taken. The goal of the "Green Deal" to be climate neutral by 2050 was tightened by the climate protection law of Germany from 2021 and climate neutrality is to be achieved already in 2045.
"The European Cement Association" (CEMBUREAU) defines how climate neutrality of the cement and concrete value chain can be achieved in Europe by 2050.

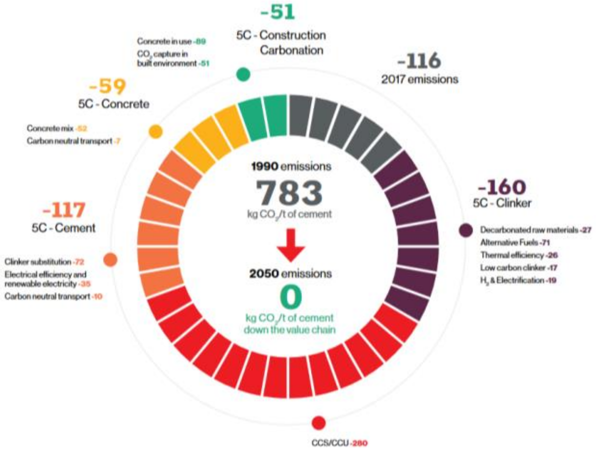


Figure 8. CEMBUREAU Roadmap [13]

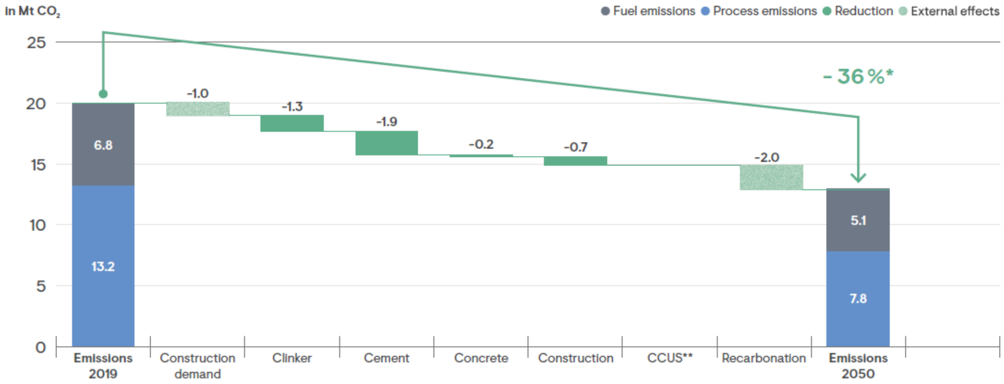
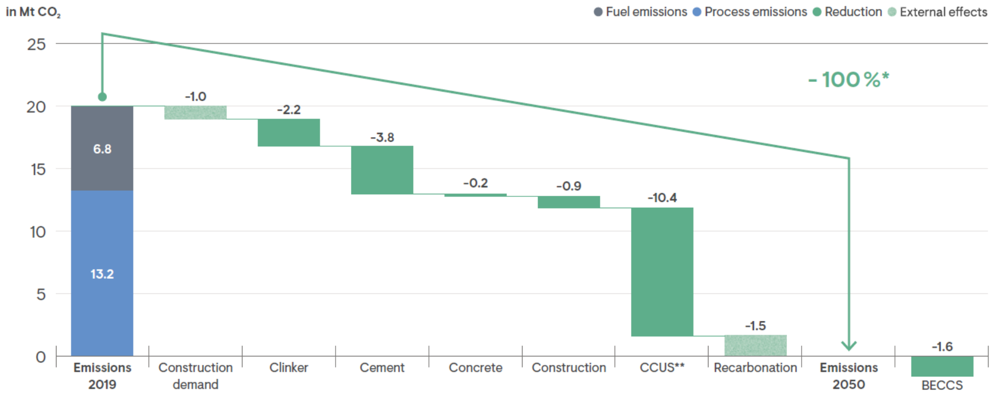


Figure 9. Ambitious reference scenario – CO_2 reduction by 2050 [14]

The German cement industry of the association of German cement manufacturers (VDZ) has been investigating how climate neutrality can be achieved and presents the steps to achieve the decarbonization of cement and concrete in its roadmap. In the CO_2 roadmap it is assumed that greenhouse gas neutrality must be achieved by 2050. The VDZ distinguishes between the ambitious reference scenario and the climate neutrality scenario.

The ambitious reference scenario is based on currently available CO_2 reduction technologies. Increased thermal efficiency, the use of alternative fuels containing biomass, the use of clinker-reduced CEM II/C cement and further developments in concrete construction all contribute to CO_2 reduction. With the ambitious reference scenario, a reduction of 36 % of emissions from 2019 to 2050 can be achieved but climate neutrality will not be achieved.

The climate neutrality scenario is, for example, based on the use of break-through technologies, CEM VI cements, assumes the use of hydrogen, further efficiency improvements, and innovations in the production and application of concrete. In this scenario, climate neutrality is achieved by 2050 by exhausting all available CO_2 reduction options along the value chain and taking external effects such as a decline in construction demand into account.



* Thereof about 88 % reduction through measures along the value chain. Remaining emissions are reduced by a decreasing construction demand as well as the contribution of recarbonation.

** CCUS: Carbon Capture technologies aiming at reducing CO_2 emissions in the atmosphere through CO_2 storage (CCS) and appropriate procedures for CO_2 utilisation (CCU).

Source: VDZ

Figure 10. Scenario climate neutrality – CO_2 reduction by 2050 [14]

4.2 CO_2 reduction possibilities along the value chain of Cement and Concrete

4.2.1 Clinker

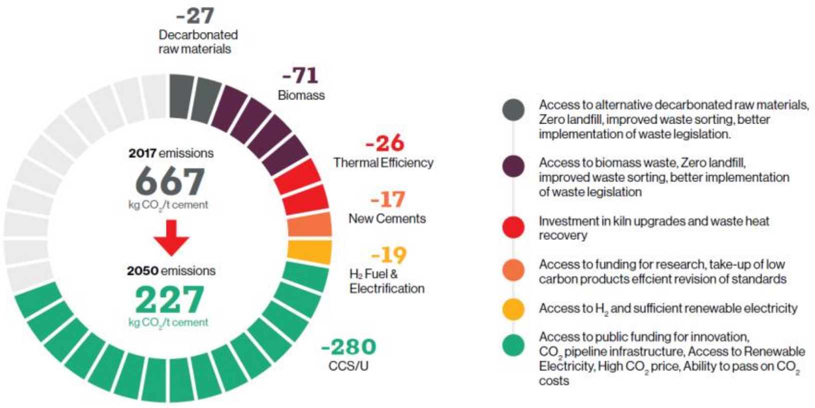


Figure 11. Opportunities to achieve CO_2 reduction for clinker [13]

In order to reduce emissions from the deacidification of limestone, which belong to the category of raw material-related emissions and account for approximately two-thirds of direct CO_2 emissions from cement production, the use of alternative raw materials for cement clinker production is an option. Alternative raw materials that are currently already being used include for example sewage sludge, calcium-containing and already deacidified alternative raw materials (blast furnace slag, crushed concrete sands, carbide sludge, aerated concrete powder) or hard coal and lignite fly ash. Calcium-containing and already deacidified alternative resources reduce CO_2 emissions but must not impair the performance and environmental compatibility of the clinker. CEMBUREAU sees an opportunity to save up to 3,5 % CO_2 by 2030 and up to 8 % by 2050 by using alternative raw materials such as recycled crushed sands from construction waste or industrial waste from other sectors such as metal processing or coal-fired power plants [13]. It should be noted here, however, that availability will decrease over time as a switch to renewable energy occurs, resulting in less waste. Various research projects are also underway to find other alternative raw materials, with the use of mineral residues such as ground crushed sands, which are produced during the manufacture of recycled aggregates, playing a particularly important role. Potential new feedstocks include for example waste incineration ashes, aluminum slag and red mud, plastics containing glass fibers or Brick chips.

The CEMBUREAU sets a target of using 60 % alternative fuels with 30 % biomass by 2030 and to increase the amount to 90 % alternative fuels with 50 % biomass by 2050 [13] to reduce the Fuel-related emissions. Here, two effects have a positive impact on CO_2 reduction. On the one hand, CO_2 is saved by avoiding the use of fossil fuels. On the other hand, emissions due to waste incineration or methane emissions from landfills are reduced. To obtain the energy to burn and process the raw material into clinker, electricity, alternative fuels (used tires, waste oil, animal meal, recycled fractions from commercial and municipal waste, and sewage sludge), and fossil fuels (lignite and hard coal) are used. Over time, the share of fossil fuels has decreased, the share of alternative fuels has increased and the share of electricity has changed only slightly. With the conversion to renewable energies, a reduction of emissions can be achieved in the cement industry, as well.

According to the CEMBUREAU, 26 $kgCO_2/t$ of cement can be saved by optimizing thermal efficiency. Thus, an improvement of 4 % is to be achieved by 2030 and 14 % by 2050 [13]. The thermal energy is mainly required for the clinker burning process and is the usual parameter for assessing the fuel energy consumption in cement production. Savings potentials are offered here by the choice of plant type and the condition and operating mode of the plant. In addition, the thermal energy demand is influenced by the kiln capacity, the raw materials as well as the fuels and their shares in the energy input.

In 2020, the average demand for electrical energy in Germany was 109,4 kWh/t cement, in 1997, the value was 103,9 kWh/t of cement. The maximum value was reached in 2019 [14]. About half of the electrical energy required for cement grinding. Accordingly, it is recommended to use efficient types of mills. Despite innovations or pre-grinding, however, the average demand for electrical energy has increased in recent years. This is due, among other things, to the demand for cement with higher strength. This has to be ground finer and therefore requires more electrical energy. In addition, the use of alternative raw materials in clinker production may require a higher degree of grinding. Environmental protection measures, for example to reduce dust emissions, also require electrical energy. Measures to optimize thermal energy utilization also have a negative impact on electrical energy efficiency, since systems must be operated which, for example, use the waste heat for drying.

4.2.2 Cement

The CEMBUREAU considers a low clinker content to be the main way of reducing CO_2 emissions from cements. In Europe, the clinker share was 77 % in 2017, higher than that of Germany. It is to be reduced to 65 % by 2050. In 2020, the clinker-cement factor was about 70 % in Germany [13]. The cement production is increasing during the past years which can be explained by the increased construction activity. Accordingly, clinker production has also increased, but less than cement production due to the decreasing clinker-cement factor. In recent years there has been a steady and marked decline in the share of CEM I, while CEM II / A+B is gaining in importance. The CEM II with a clinker content of 65 – 94 % has up to 30 % less clinker content compared to the CEM I with 95 – 100 % clinker content and thus emits less CO_2 [14].

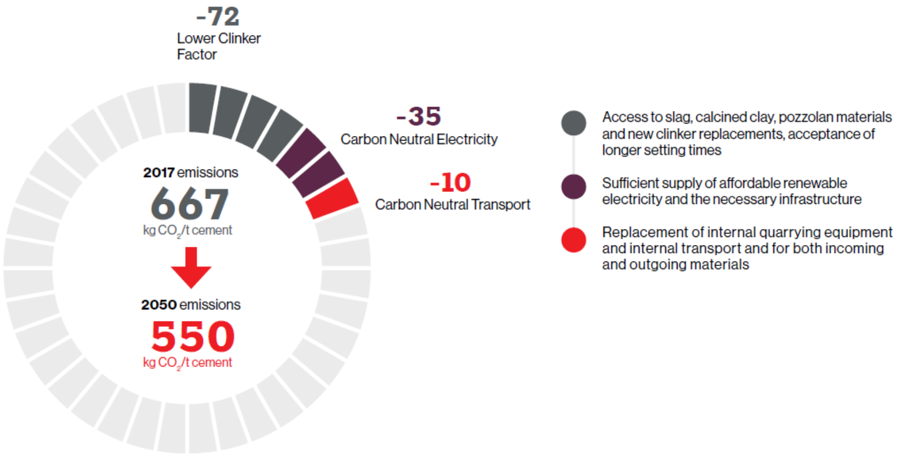


Figure 12. Opportunities to achieve CO_2 reductions for Cement [13]

Depending on the type of cement, other main constituents besides the clinker are either ground together with the clinker or separated and then added. The composition defines different performance characteristics and delimits the possible areas of application. Currently, mainly reactive and inert composite materials are used as alternative main cement constituents besides the Portland cement clinker. Blastfurnace slags have a significant role as alternative main cement constituents. Blastfurnace slags are produced as an industrial by-product during pig iron production by granulation. The availability of granulated blastfurnace slag depends to a large extent on the demand for steel and represents the close interlinking of cross-sector, industrial value chains. Fly ash as a further alternative main cement constituent consists of combustion residues of pulverized coal and is produced during the separation of dust-like particles from flue gases of combustion plants in thermal power stations. Currently, research is also being carried out on the use of calcined clays. Calcined clays play an important role against the background of the future availability of blastfurnace slags and fly ash. Naturally occurring clay mixtures offer the possibility of developing pozzolanic properties after calcination. These occurring clay mixtures are available worldwide in sufficient quantity and quality, and by using them, previously largely unused mineral secondary raw materials from the stone and earth industry can be utilized. Crushed sands are also a research topic for clinker reduction. Crushed sands are among the calcium-containing and already deacidified alternative raw materials.

4.2.3 Concrete

In the case of concrete, CO_2 can be saved during transport. CEMBUREAU assumes that by 2050 all concrete will be transported by zero-emission vehicles. In this way, it should be possible to save only about 1 % of the emissions per ton of cement in 2017. The improved concrete mix has a more important role to play, with a potential saving of about 7,8 % of the 2017 emissions per ton of cement. According to CEMBUREAU, the combination of digitalization, improved concrete mix and new additives should reduce cement by 5 % by 2030 and by 15 % by 2050 [13].

4.2.4 Construction

It should be emphasized here that, according to the CEMBUREAU, 72 % of the CO_2 emissions of buildings are emitted by their energy consumption over their lifetime [13]. Concrete should be used efficiently and differentiated according to the requirements, but always under the condition that the load-bearing capacity and serviceability of the structures and components are not limited. In particular, an intelligent and optimized load-bearing system can lead to a reduction in the amount of concrete used. In order to avoid the additional emission of CO_2 through the production of "new" concrete, concrete recycling in the sense of a circular economy is an option. In order to make optimum use of the concrete used, component or concrete core activation can be used. In combination with renewable energy sources, special heating or cooling can be achieved by supplying energy only when renewable electricity is available in surplus.

4.2.5 Carbonation

From the point of view of concrete technology, carbonation is to be regarded negatively, since corrosion of the reinforcement occurs when the carbonation front reaches the reinforcement in the simultaneous presence of oxygen and water. In terms of reducing CO_2 emissions by the construction industry, carbonation is positive. When CO_2 from the ambient air enters the concrete and reacts with the hydration products in the hardened cement paste, part of the process emissions during cement production can be compensated over the lifetime of the concrete components as well as after demolition. According to CEMBUREAU, 23 % of the process emissions are recarbonated back into the concrete. This corresponds to about 8 % of the total CO_2 emissions during cement production [13]. This is subdivided into 20 % during the use phase, 2 % at the end of life and 1 % during the recycling of the concrete [14]. The use phase largely determines how much CO_2 is absorbed. In principle, it can be assumed that an interior component with lower strength has a greater absorption capacity than an exterior component with high-strength concrete. If the surfaces of the concrete components are treated, this also influences the CO_2 absorption. At the end of life, recarbonation is determined by the treatment, recycling or disposal measures taken. In order to be able to bind more CO_2 through recarbonation, the concrete should be crushed, which greatly increases the surface area accessible to carbon dioxide. In addition, after demolition, the crushed concrete should be stored for as long as possible unbound and as dry as possible in contact with the outside air. However, especially in urban areas, storage areas are severely limited and are rebuilt as quickly as possible after demolition.

4.2.6 Carbon capture technologies

CEMBUREAU sees an opportunity to reduce CO_2 emissions by 42 % by 2050 through the use of different carbon capture technologies (CCUS). The climate neutrality of the cement industry by 2050 will not be achievable without the use of CCUS. However, currently the technology is not advanced enough to apply these technologies and a major research effort is still needed. The European Cement Research Academy has already been researching technologies since 2007 to counteract the unavoidable CO_2 emissions of the cement industry, which also occur when all possibilities of CO_2 reduction have been exhausted. A distinction must be made between the concepts of CO_2 utilization (CCU) and its storage (CCS). In CCS, the goal is to geologically or mineralogically sequester an emitted amount of CO_2 over the long term. The Global CCS Institute stated in its 2018 report that over 300 billion tons of CO_2 can already be stored in Europe. With this amount of CO_2 storage, it would be possible to reach the 2 °C target more than twice [15].

5 Laboratory results

The laboratory results from the Building Materials Testing Institute of the Stuttgart University of Applied Sciences from the winter semester 14/15 to the summer semester 2019 and the summer semester 2022 were evaluated. The concretes with recycled aggregate are subsequently called RC concretes and those with natural aggregate are called normal concretes. In order to obtain comparable values, the classification is made in four categories. All concretes with CEMI are assigned to category 1, and all with CEMII cements to category 2. A distinction is made between normal concrete (KN1 or KN2) and RC concrete (KR1 and KR2).

The results of the fresh concrete test are not decisive, since the adjustment of the fresh concrete bulk density, the air content, the degree of compaction and the degree of spread can easily be regulated by the composition as well as additives and admixtures and the processing. The evaluations of the hardened concrete tests should provide information on whether RC concretes achieved comparable, better or worse results than normal concretes.

5.1 Compressive strength

The compressive strength is the main parameter of concrete, according to which it is classified into compressive strength classes. It is significantly influenced by the porosity of the concrete. Other factors are the material composition, the properties of the raw materials, the production, the specimen shape and the storage. In direct comparison, the compressive strength of RC concrete is higher than that of normal concrete. Thus, from the results, RC concretes can achieve the targeted compressive strength unerringly and even perform better than normal concrete. All concretes, except for one, achieve the target compressive strength.

5.2 Modulus of elasticity

The modulus of elasticity (E-Modul) is a material-specific parameter for elastic deformation under load. It is particularly important for deflections and restraint stresses.

In category 1, the modulus of elasticity of RC concretes is significantly lower than that of normal concretes, while the modulus of elasticity of normal concretes in category 2 is slightly lower than that of RC concretes in category 2.

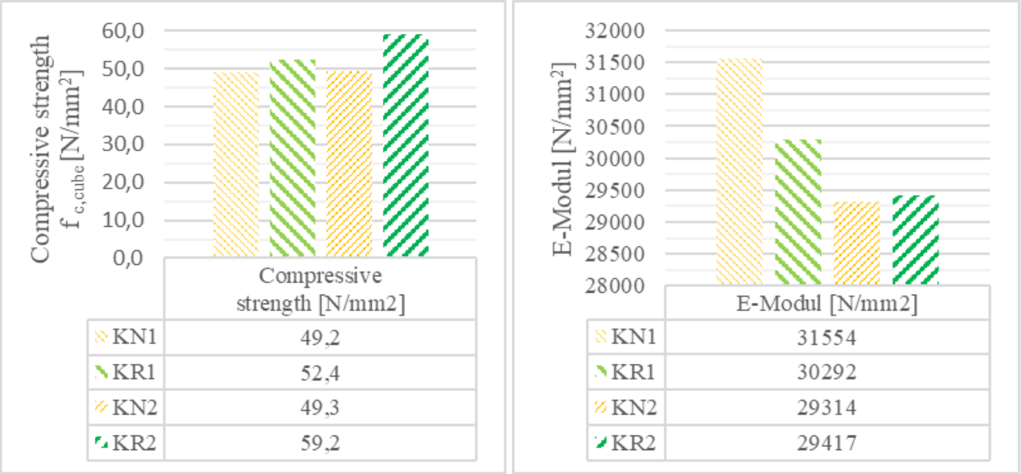


Figure 13. Compressive strength [N/mm^2] and E-Modul [N/mm^2]

5.3 Water penetration depth

The water penetration resistance is largely determined by the impermeability of the hardened cement paste. The capillary pore space should be as small as possible, which can be controlled by a small w/c ratio. If water penetrates deep into the concrete, substances such as chlorides can be transported into the concrete, resulting in increased frost sensitivity and possible spalling. In addition, reinforcement corrosion can occur if the water penetration depth is greater than the concrete cover. As shown water penetrates RC concretes less deeply than normal concretes. Water penetration depth can be reduced by storing in water instead of in air. If water penetrates less deeply, fewer pollutants can be transported into the concrete, the risk of reinforcement corrosion decreases and durability is positively influenced.

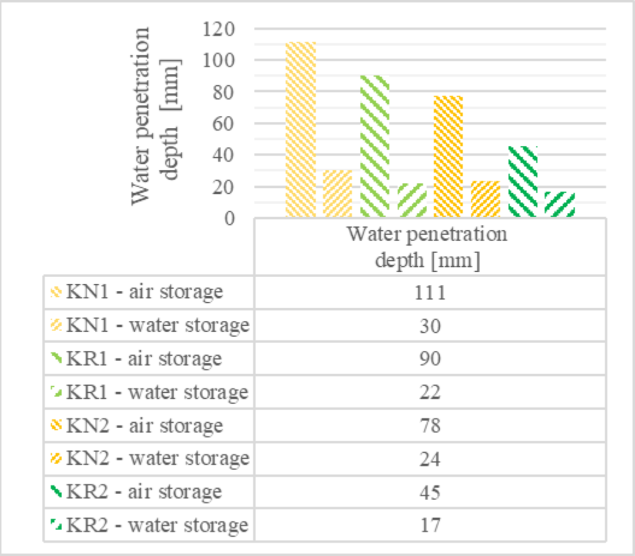


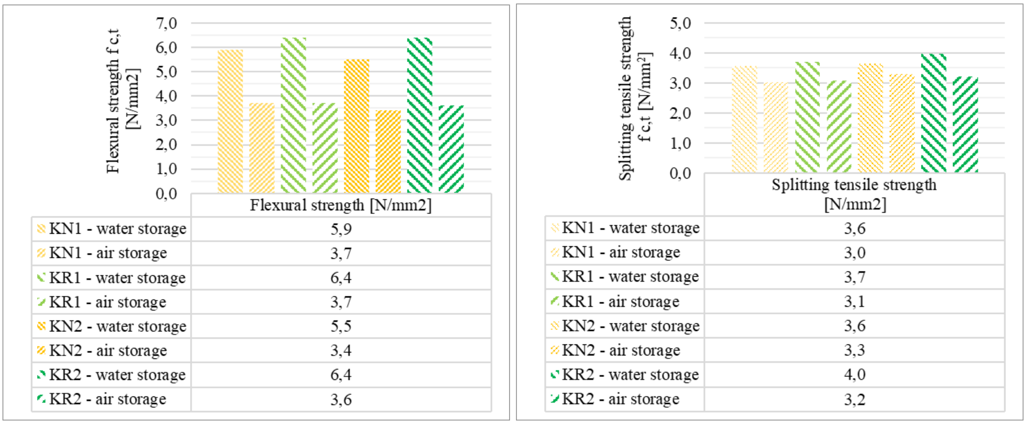
Figure 14. Water penetration depth [mm]

5.4 Flexural strength

The flexural tensile strength of RC concrete is higher than that of normal concrete in direct comparison when stored in water.
It can be concluded from the results that RC concrete behaves at least the same, if not better, than normal concrete when subjected to a moment. In category 1, when stored in air, the same flexural tensile strength could be obtained for the RC concretes as for the normal concretes. In category 2, a higher flexural strength could be determined for the RC concrete than for the normal concrete.

5.5 Splitting tensile strength

The splitting tensile strength is also considered as an indirect determination of the aggregate tensile strength, because due to the tensile stresses perpendicular to the compressive stress, fracture occurs when the cohesion of the aggregate is exceeded. For specimens stored in water, the splitting tensile strength of the RC concretes is higher than normal concretes. In category 1, the splitting tensile strength when stored in air is greater for the RC concretes than the normal concretes. In category 2, the RC concretes showed lower splitting tensile strength than the normal concretes.



	Flexural strength [N/mm2]
KN1 - water storage	5,9
KN1 - air storage	3,7
KR1 - water storage	6,4
KR1 - air storage	3,7
KN2 - water storage	5,5
KN2 - air storage	3,4
KR2 - water storage	6,4
KR2 - air storage	3,6

	Splitting tensile strength [N/mm2]
KN1 - water storage	3,6
KN1 - air storage	3,0
KR1 - water storage	3,7
KR1 - air storage	3,1
KN2 - water storage	3,6
KN2 - air storage	3,3
KR2 - water storage	4,0
KR2 - air storage	3,2

Figure 15. Flexural strength [N/mm^2] and splitting tensile strength [N/mm^2]

6 Conclusion

The urgency to produce concrete in a resource-saving way has long been given. The construction industry is particularly resource-intensive and a large part of the waste generated in Germany results from construction and demolition waste. Landfill space is limited, and the use of recycled aggregates offers great potential to replace natural resources such as sand and gravel with secondary raw materials and to establish closed material cycles.

The currently permitted proportion of recycled aggregate used in concrete production should be significantly increased in the future. The extension of the permissible exposure classes as well as the extension of the permissible strength classes are also desirable and technically possible. Currently, the use of crushed sands, which are produced in large quantities during the processing of the construction waste, is not permitted in concrete production. The exclusion of this fraction should be reconsidered in order to preserve natural sand. At the same time, an economically and ecologically optimum concrete mix should be aimed for when using crushed sands to avoid greater CO_2 emissions due to the increased cement demand.

The largest share of the greenhouse potential of concrete can be attributed to cement and cement is responsible for 6,9 % of global CO_2 emissions. Far-reaching measures are needed to reduce CO_2 emissions from concrete and cement production and for the value chain to be climate neutral by 2050. In the future, fewer fossil fuels and more alternative fuels will have to be used to reduce fuel-related CO_2 emissions. A reduction in emissions can also be achieved by switching to renewable energy sources. Optimization in the fuel matrix and an increase in thermal and electrical energy efficiency should be strived for. The greenhouse potential of cement depends to a large extent on the clinker content and therefore is an important factor in the reduction of CO_2 emissions. The aim must be to replace the clinker with alternative main cement constituents such as crushed sands. Carbon capture technologies are of particular importance, as it will not be possible to make the cement industry greenhouse gas neutral without them. These must be further researched, tested and expanded.

In order to ensure compliance with the ultimate and serviceability limit states as well as workability and durability, RC concrete must have comparable properties to normal concrete. In the case of differences, such as the increased water absorption of recycled aggregate due to the absorption behavior, the properties of recycled aggregates must be precisely known, controllable and proven by research with numerical values in order to ensure reliable concrete production. In the tests of compressive strength, water penetration depth and flexural strength, RC concrete performs better than normal concrete. The modulus of elasticity of RC concretes measured at the Building Materials Testing Institute of the Stuttgart University of Applied Sciences is partly lower than that of normal concretes, which is only partially in agreement with the statements made in the literature. In order to identify the cause of this and obtain further data, further research will be required in order to be able to guarantee a purposeful production of green concrete.

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