REPORT

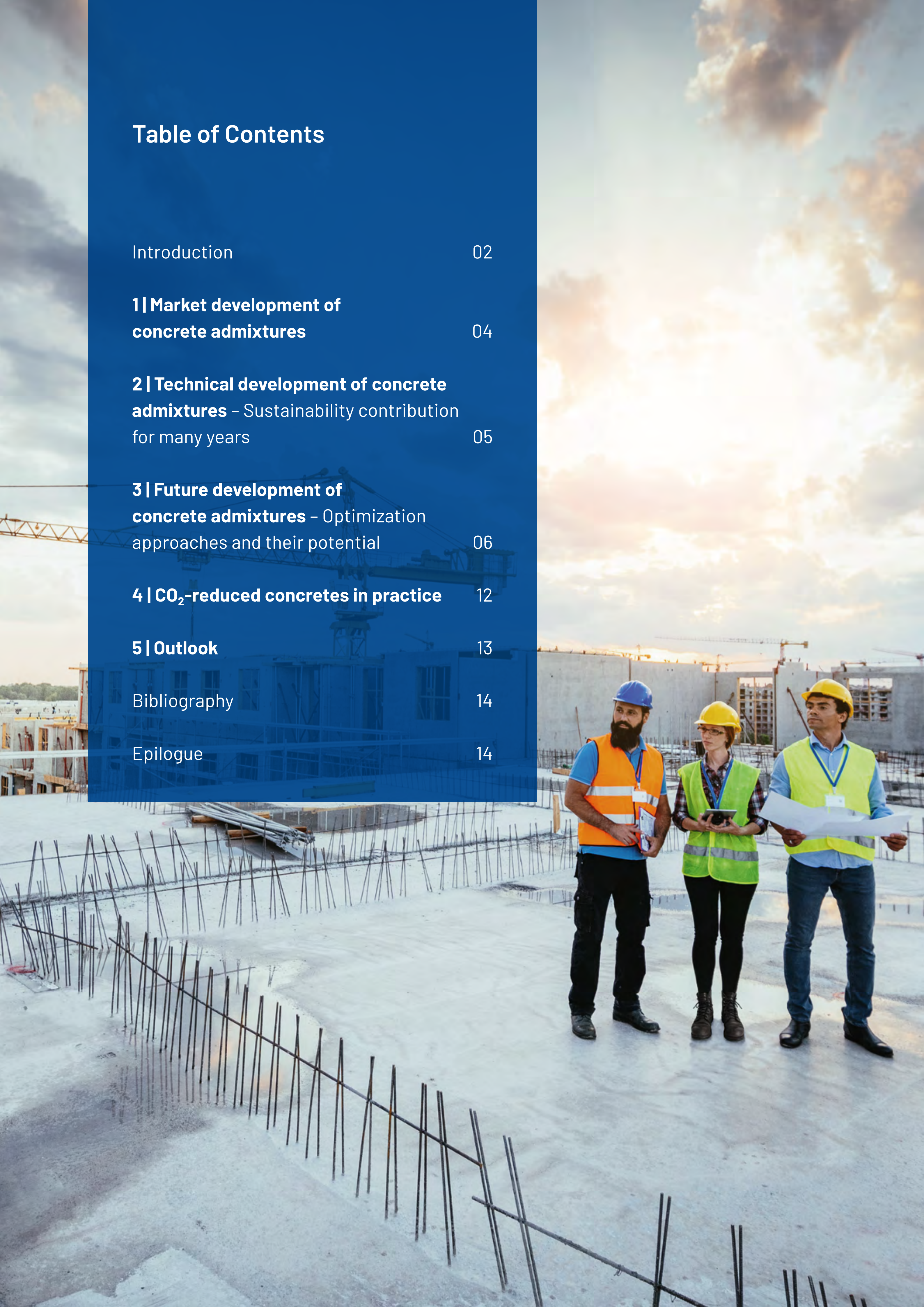
# Contribution of the concrete admixture industry to the decarbonization of the concrete industry

1st edition | May 2024

# Introduction

Concrete is an indispensable part of modern civilization. Its versatility and durability will continue to make it a central element in the further development of our cities and infrastructure in the future. Nevertheless, its future relevance will also depend on how well we succeed in reducing $CO_2$ emissions. It is therefore a task for the entire industry to work together towards the goal of decarbonizing concrete construction.

Modern concrete admixtures are already making an important contribution to more sustainable concrete construction. This report highlights what successes have been achieved so far in reducing $CO_2$ emissions in this way and what further steps are necessary. In the context of a rapidly changing raw material base, it shows how innovative concrete admixtures will enable reliable control of concrete properties and thus make an important contribution to achieving carbon-neutral concrete construction in cooperation with all stakeholders.



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Today's concrete technology is unthinkable without concrete admixtures. Specific concrete admixtures enable the production of high-performance concretes such as self-compacting, high-strength and ultra-high-strength concretes. Today, manufacturers produce concrete admixtures for a wide range of highly specialized applications, from high-rise construction in desert countries to offshore wind farms in the oceans and tunnel projects in the Alps. Concrete admixtures can also be used to improve normal concretes in general building construction and civil engineering.

In the 2022/23 annual report of Deutsche Bauchemie [1], the sales figures for concrete admixtures for Germany (+ exports) over the last twenty years were published (see Figure 1). It can be seen that the mark of 200,000 tons was exceeded in 2017 and sales have remained at a high level since then.

Figure 1 shows that plasticizers and superplasticizers are the most frequently used concrete admixtures. The development and optimization of these admixtures is constantly being driven forward. One example is superplasticizers based on polycarboxylate ether (PCE), which make it possible to specifically adjust certain concrete properties and thus further exploit the enormous potential of this high-performance building material.

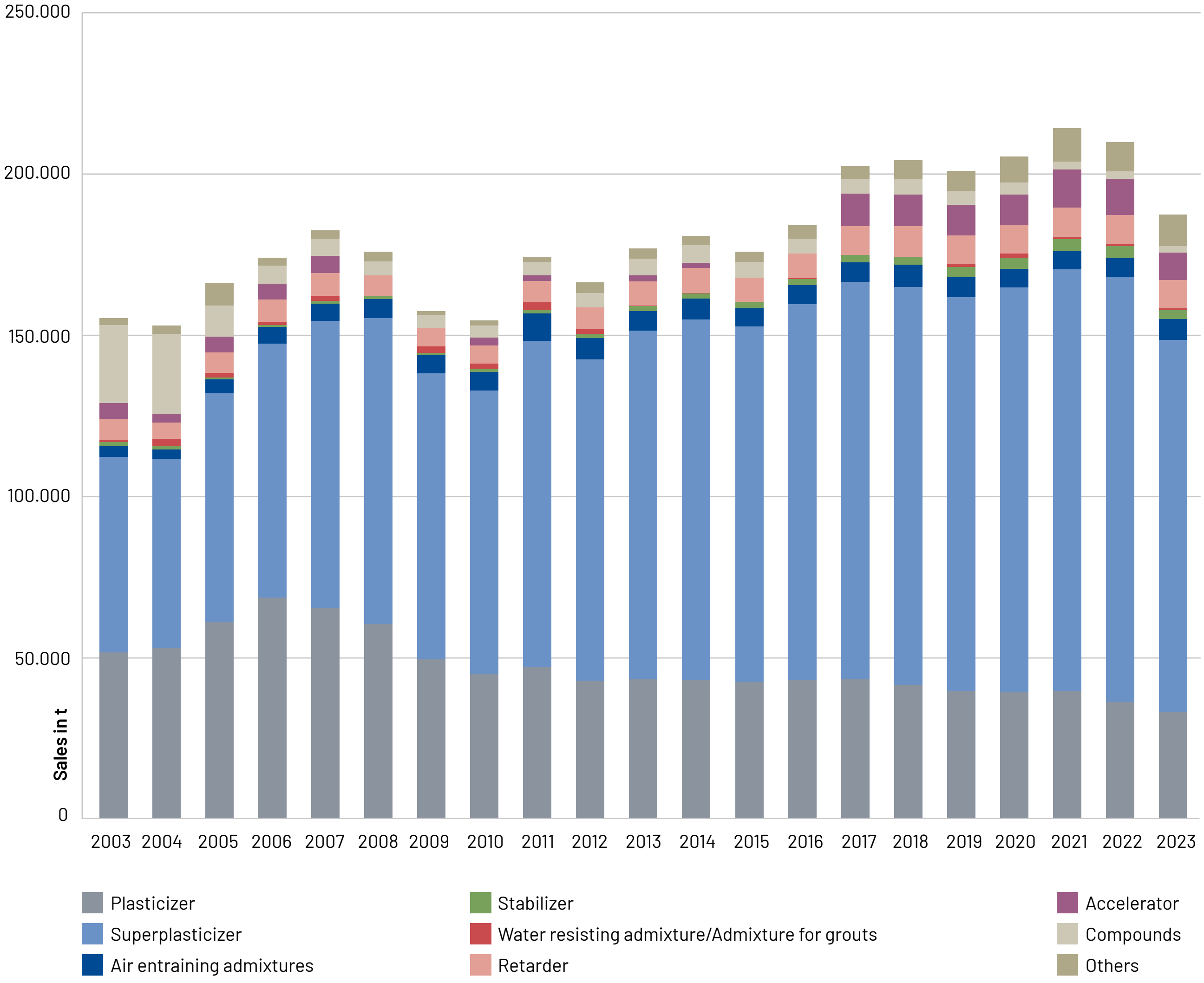

Figure 1 | Sales development of concrete admixtures in Germany + exports

Source: Deutsche Bauchemie e.V.

# 2 | Technical development of concrete admixtures

## Sustainability contribution for many years

The use of concrete admixtures has played a major role in the optimization of concrete mix designs in the concrete industry for many years. On the one hand, this involves economic optimization through binder reduction and, on the other, the optimization of workability.

A reduction in the binder content is associated with a reduction in the total water content of the concrete mix, while the workability of the concrete is maintained. Plasticizers and superplasticizers are particularly relevant here and have been continuously developed and optimized.

Modern superplasticizers make it possible to reduce the water content by an average of approx. 30 kg/$m^3$ of concrete. With a w/c ratio of 0.5, the binder content can be reduced by approx. 60 kg/$m^3$. This considerably improves the carbon footprint by approx. minus 30 to minus 45 kg $CO_2$ per $m^3$ of concrete. With a production volume of 52.2 million $m^3$ in Germany from 2022, this results in significant savings of more than 2.3 million tons of $CO_2$.

This path to maintaining workability while maximizing water reduction is being intensively pursued by the admixture industry. It forms an essential basis for the future minimization of the carbon footprint together with the use of new and future generations of cements with a further reduced clinker content.

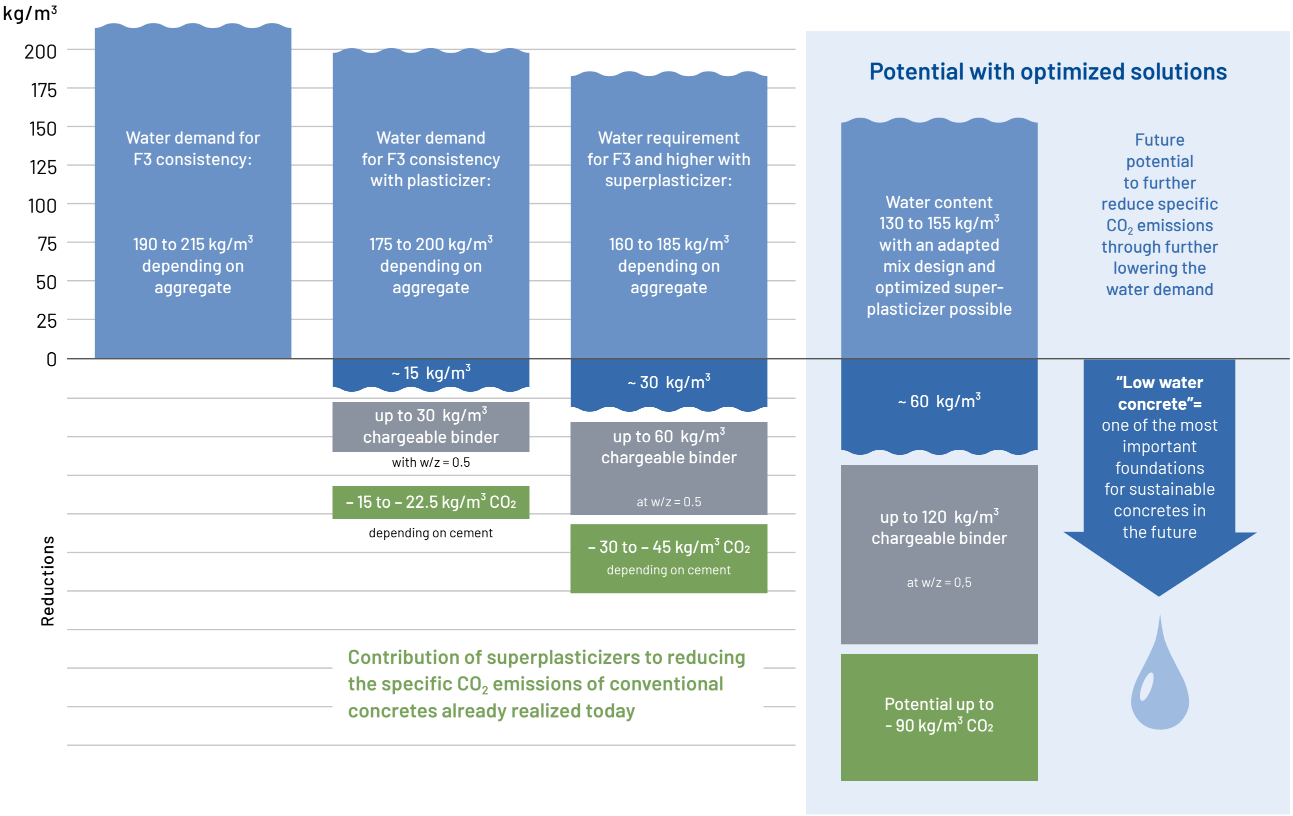

Figure 2 | Future potential to further cut specific $CO_2$ emissions by further reducing water demand

The cement industry in Germany has always focused on carbon-neutral and resource-efficient concrete construction. The specific $CO_2$ emissions of the manufacturing process have been reduced from 742 kg/t of cement in 1990 to currently around 566 kg/t of cement [2]. Based on the approximately 52.2 million $m^3$ of ready-mixed concrete in 2022, this results in $CO_2$ savings of around 2.8 million tons per year. The specific $CO_2$ emissions were significantly lowered reducing the absolute and fossil energy input in cement production and increasingly producing clinker-efficient cements with several main components. According to Figure 3, these $CO_2$-efficient cements already accounted for around 75 % of domestic shipments in Germany in the current reporting year 2022. The use of clinker-efficient cements continues to be an important component of decarbonization and resource-efficiency in concrete construction. In Germany, mainly unburned limestone and/or granulated blast furnace slag are used as additional cement components. In order to achieve carbon neutrality in concrete construction, the content of other main constituents in the new generation of clinker-efficient cements, such as CEM II/C-M and CEM VI cements, is increased to around 50 % and 65 % respectively. This is achieved through a combination of limestone and/or recycled concrete fines as well as granulated blast furnace slag, pozzolans or calcined clays in ternary or quaternary systems. The aim of future cements, especially the so-called CEM X cements, is to maximize the content of unburnt limestone or recycled concrete fines while maintaining cement performance. Such cements can contain up to 80 % of other main constituents besides clinker.

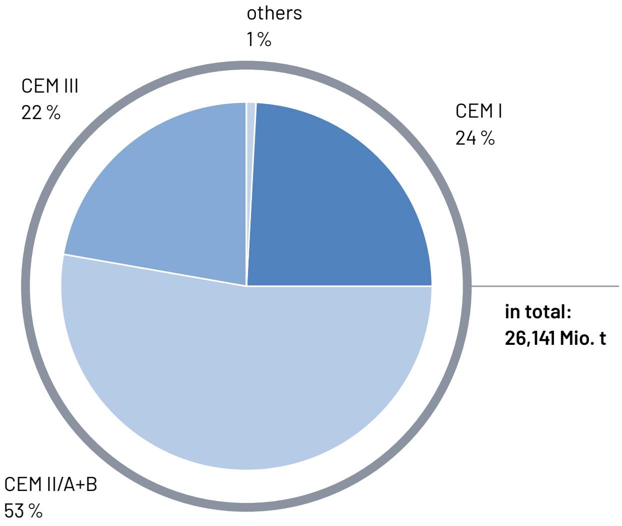

Figure 3 | Domestic shipping by VDZ association members in 2022 [2]

# 3 | Future development of concrete admixtures

## Optimization approaches and their potential

In principle, there are five ways to decarbonize concrete:

- Use of renewable energy,
- Reduction of the clinker content of cement through additional main components or the use of alternative binders,
- Reduction in the proportion of clinker per cubic meter of concrete,
- Carbon compensation and Carbon capture
- as well as other measures such as the use of recycled aggregates or $CO_2$ storage in concrete.

Cement additives and concrete admixtures can make the following contribution to the decarbonization of concrete:

**Optimization of cement production**
Cement additives can be used to optimize the performance of cement with a low clinker content. They improve production processes, reduce the energy required for grinding and increase clinker efficiency and the performance of the binder.

**Clinker replacement**
The content of other main constituents in the cement can be increased by using natural pozzolans and calcined clays. At the same time, the amount of conventional other main constituents, such as granulated blast furnace slag, fly ash and unburnt limestone, can be maximized without compromising workability, strength and durability.

**Clinker-efficient concrete**
In order to reduce the clinker content per cubic meter of concrete, the total amount of water is significantly lowered and additions such as filer aggregates are made, maintaining workability, strength and durability.

**Other approaches**
Alternative raw materials such as recycled material and previously unusable aggregates are used to maintain workability, strength and durability.

The manufacturers of concrete admixtures see opportunities to achieve this objective in the following areas or effect groups:

- Superplasticizer
- Hardening accelerator
- Stabilizer/viscosity
- Concrete admixtures to optimize the service life of concrete components
- Geopolymer concrete
- Additives for the cement industry
- Recycling

## 1. Superplasticizer

Innovative superplasticizer concepts offer the greatest potential for controlling workability, concrete rheology, working time and consistency. A total of five different options can be distinguished.

There are two ways to reduce the clinker content in concrete: Firstly, cement that has already been reduced in clinker content can be used. Secondly, a significant proportion of the cement can be replaced by aggregates or other additions.

In Germany, 52 million m$^3$ of ready-mixed concrete is processed every year. By lowering the minimum cement content from currently approx. 280 kg/m$^3$ to 200 kg/m$^3$ and using additions and new, innovative superplasticizer concepts to maintain workability while reducing the total water content, up to 50 kg of $CO_2$ can be saved per cubic metre of concrete. Even if only 60 % to 70 % of the ready-mixed concrete volume is used (e.g. exposure classes XC1 and XC2), a saving of 1.6 million to 1.85 million tons of CO2 per year can be achieved.

The graph below shows the effects of reducing the minimum cement content while maintaining the maximum w/c ratio (example for exposure classes XC4, XF1, XA1).

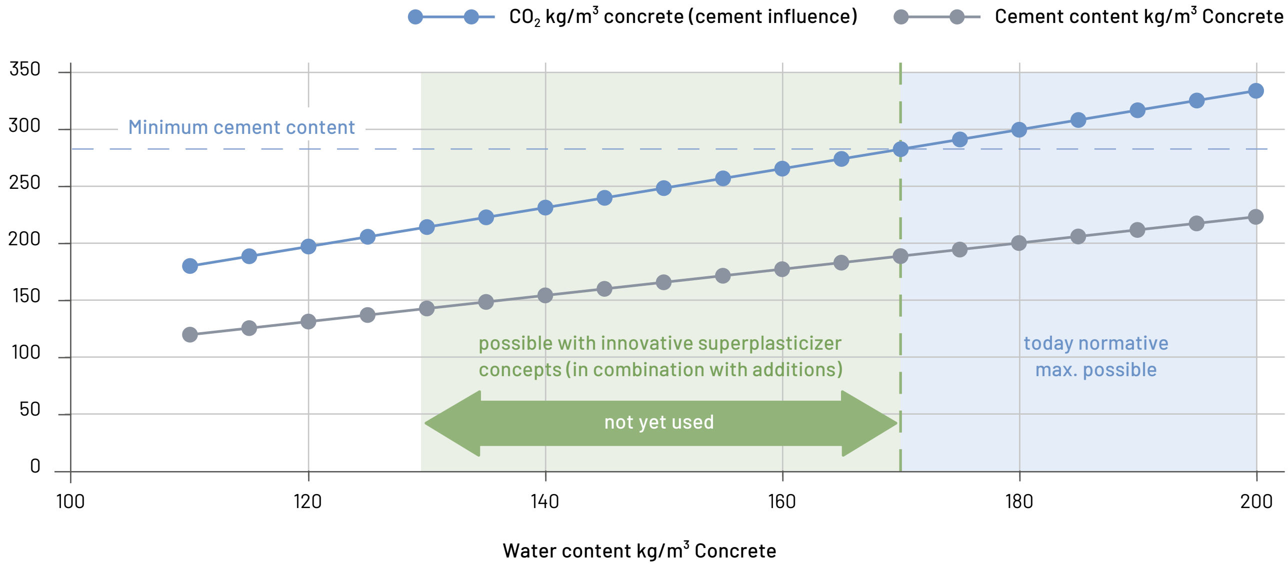

Figure 4 | Reduction of $CO_2$ emissions through savings in the amount of water added and in the clinker and cement content (example for the three exposure classes XC4, XF1 and XA 1)

Alternatively, proof of the same performance of concrete (performance test) could be enabled in order to reach a comparable optimization potential. Another important basis for the decarbonization of concrete construction is the use of CEM II/C and CEM VI or CEM X cements. In order to guarantee the durability properties of concrete, it is necessary to tighten the maximum w/c values and reduce the water content. In future, compliance with the requirements for the w/c ratio while maintaining workability can only be achieved together with suitable and efficient superplasticizer technologies.

In general, calcined clays, natural pozzolans and concrete powder have a larger specific surface area than, for example, granulated blast furnace slag, which results in a higher water demand. The cement industry is in a position to counter this problem with modern grinding and classifying technology, although the demands on superplasticizer technology will continue to increase.

The interaction between cement and concrete admixtures, especially with low water contents, is becoming ever more important. The concrete admixture industry already offers innovative superplasticizer technologies for controlling processing properties such as fresh concrete consistency and rheology and is continuously developing these further.

## 2. Hardening accelerator

Modern hardening accelerators particularly increase the early strength of the concrete without negatively affecting the strength at later ages. They are therefore particularly suitable for the production of concrete products and precast elements. When using clinker-efficient cements with significantly reduced specific $CO_2$ emissions, they can be used to achieve the strength level for stripping or lifting at the same time or even earlier. By completely replacing the approximately 6.4 million tons of CEM I Portland cement [2] produced in 2022 with CEM II/A cements, around 0.72 million tons of $CO_2$ could have been saved. Approx. 0.15 million tons of $CO_2$ emissions per year must be estimated for the corresponding quantity of accelerator. This still results in a total saving of 0.57 million tons of $CO_2$ emissions.

The next step is to establish Portland composite cements of the type CEM II/B or selectively CEM II/C with a clinker content of at least 65 or 50 wt.%. The control of early strength by means of hardening accelerators is becoming increasingly important. It should be noted that the $CO_2$ input of hardening accelerators within the total carbon footprint of concrete is significantly lower than the $CO_2$ savings potential from clinker reduction. In a typical precast mix design, switching from CEM I to CEM II/A can save around 30 kg of $CO_2$ per $m^3$ of concrete. If blast furnace cement CEM III is used, it is even 130 kg $CO_2$ per $m^3$ of concrete. The overall balance is extremely positive, as the usual dosing quantities of a hardening accelerator of between 2.0 and 4.0 % by weight of cement only have a carbon footprint of approx. 5 kg/$m^3$ to 15 kg/$m^3$.

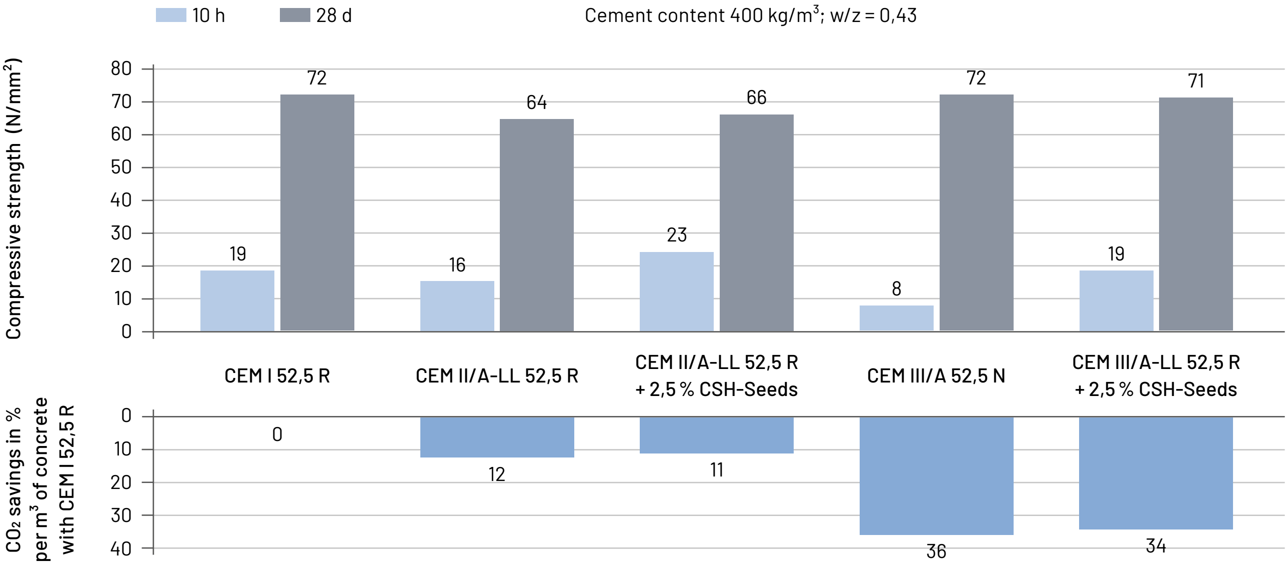

Figure 5 | Potential $CO_2$ savings through the use of CEM II/A or CEM III/A cements in combination with hardening accelerators

The ready-mixed concrete industry mainly uses clinker-efficient CEM II and, depending on availability, CEM III cements. The use of hardening accelerators therefore has a different relevance in the ready-mixed concrete industry than in the concrete products and precast concrete industry. Optimization potential in ready-mixed concrete mainly concerns the acceleration of construction progress, especially at cooler temperatures (winter concreting). For example, the freeze resistance, the accessibility or load-bearing capacity of components, the stripping strength and the time at which concrete floors can be surface-treated (sanding/smoothing) can be achieved significantly earlier. Practical examples show that even highly clinker-reduced CEM III/B cements, which have no measurable compressive strength values after one day at a production and storage temperature of 10 °C, achieve strengths comparable to the unaccelerated system at 20 °C with suitable setting accelerators.

Faster construction progress on ready-mixed concrete construction sites and early stripping or lifting in the precast concrete industry primarily reduce the operating hours of heat treatment. Energy consumption and emissions are reduced, thus minimizing the ecological footprint. The use of hardening accelerators in combination with clinker-efficient cements therefore contributes to the climate neutrality and resource efficiency of a more sustainable concrete industry. Innovative hardening accelerators can maintain early strength despite lowering the temperature of hot concrete, the temperature in heating chambers or the temperature of formwork heating.

The possible annual savings in $CO_2$ in the ready-mixed concrete and precast and construction chemicals industries described above can certainly be achieved in a period of five to ten years, which is the time required for a complete switch from CEM I to CEM II/A-LL cements, for example. These savings can therefore be realized in the medium term. For a further decarbonization of concrete construction, it is thus necessary that the unavoidable $CO_2$ produced during the clinker burning process is captured and stored or used so that it remains permanently bound.

## 3. Stabilizer/Viscosity modifier

Stabilizers/viscosity modifiers are substances that lead to a thickening effect or at least to an increase in viscosity in cementitious systems. Celluloses, starches or other viscosity-modifying substances are often used. Areas of application include underwater concrete, bored pile concrete, concrete mixes that tend to bleed, as well as stable filler and mortar mixes.

These concrete admixtures ensure maximum robustness and safety in concrete production, even with extremely reduced binder contents. The use of stabilizers in conjunction with highly effective superplasticizers makes it possible to maximize $CO_2$ reduction. Concrete mix designs with a low fines content generally offer a particularly high $CO_2$ saving potential. The reason for this is that the fines content contains less cement. Relatively inexpensive limestone powder is often used as filler. The limestone powder must meet a minimum quality and must not be contaminated with clay minerals, for example, as this would lead to increased adsorption of the superplasticizer and significantly poorer workability. This minimum quality means that limestone powder often has to be transported over long distances, which is associated with both transport-related $CO_2$ emissions and considerable costs.

With a suitable stabilizer, additions – such as limestone powder – can be avoided or significantly reduced. Stable, robust and consistent concrete types with reduced fines and glue content can thus be produced. The use of stabilizers will also be worthwhile from an economic point of view, especially if $CO_2$ certificate prices continue to rise.

One of the most common areas of application for stabilizers is self-compacting concrete (SCC). This type of concrete must achieve high flowability without instability (sedimentation) and without bleeding. In Germany, a relatively high slump is required according to the DAfStb SCC guideline [4]. In other European countries such as the Netherlands or Denmark, SCC is much more popular due to lower minimum consistency requirements and many precast plants use this technology.

It is a major challenge to completely prevent bleeding and instability, especially in SCC mix designs with low content of fines. Powdered stabilizers are often used to meet these requirements at a high consistency level. For some time now, liquid stabilizers/viscosity modifiers have also been available on the market, which can be used to produce stable self-compacting concretes with low proportions of fines.

## 4. Concrete admixtures to improve the durability of concrete and extend the service life of concrete components

Air-entraining admixtures and hollow microspheres can help to improve the durability of concrete under frost attack with or without de-icing agents. Spherical micro-air voids stabilized by the addition of hollow microspheres or Air-entraining admixtures provide expansion spaces for freezing water in hardened concrete. With a sufficient quantity and correspondingly small distance between these air voids, the water freezes without building up relevant compressive stresses that would damage the concrete. This can significantly improve the durability of concrete components under attack.

Other concrete admixtures for extending the service life of reinforced concrete components include water-repellent and water-resisting admixtures, corrosion inhibitors and passivators as well as superabsorbers, shrinkage reducers and encapsulated, calcium carbonate-forming bacteria/spores. The latter three are intended to reduce the formation of cracks due to chemical shrinkage or drying shrinkage or to support the self-sealing of concrete after cracking, thereby reducing the penetration of corrosion-causing substances. Corrosion inhibitors or passivators are also added to concrete during its production and extend the time until depassivation of the steel reinforcement in hardened concrete, thus delaying the onset of reinforcement corrosion. Corrosion begins as soon as the active substances in the hardened concrete are consumed by corrosion-causing substances. They therefore support a covering of the steel reinforcement designed for the service life of the structure. This requires a well-cured concrete with low permeability, which is achieved by a reduced water content and the use of clinker-efficient cement.

## 5. Additives for the cement industry

Cement additives play a crucial role in cement production. They are added to the production grinding process to improve grindability, strength, workability and other properties. The use of cement additives offers solutions for the production of clinker-efficient cements in particular and has become standard practice. In addition to reducing the energy required for grinding, the grinding fineness can be specifically optimized through the use of cement additives, which leads to an increase in the performance of the cements and subsequently enables a further reduction in the clinker content while maintaining the same cement performance. Another focus is on the strength development of cements. Both early and final strength can be increased through the use of special additives. These additives influence the hydration process of the cement, promote the formation of calcium silicate hydrates (CSH) and support the formation of a denser and more durable concrete matrix. They can also optimize the water demand of the cements and improve the processing properties of the concrete.

Cement additives therefore contribute to decarbonization as they support the further optimization of cements. In this context, cement optimization means that the full performance spectrum of clinker and cement is exploited by maximizing the use of other main components and thus reducing the amount of clinker. These processes hold considerable potential for further reducing $CO_2$ emissions.

## 6. Recycling

In the future, recycled materials will play a greater role in the construction industry for several reasons. They are widely available, conserve natural resources (even when used proportionately in new buildings), can make a significant contribution to reducing $CO_2$ emissions and at the same time generate less disposal and waste. They are therefore an optimal solution for sustainability requirements.

However, recycled materials have special requirements for concrete admixtures. What all recycled materials have had in common so far is that they have an increased water demand and also have a higher demand for superplasticizers. However, this problem can be successfully solved with specialized and high-performance superplasticizer systems.

The desired new properties include high robustness against fluctuating properties of the concrete raw materials and against challenging raw material components such as clay minerals. It is important that these properties are fulfilled in addition to the previous requirements for consistency retention and water reduction. In addition, the new superplasticizers should be produced in an environmentally friendly way and have a low carbon footprint.

Several research projects are currently focusing on the complete processing of concrete. The aim is to produce a reactive, cement-like material from the cement paste matrix in addition to the aggregate. The concretes produced with these raw materials must also be competitive with concretes available on the market.

By using customized admixtures and additives, it is already possible to achieve identical workability and strength development with lower binder and clinker contents with these new raw material components.

In addition to superplasticizers, there will also be additional demand for hardening accelerators. This is because most recycled concretes, which also contain recycled reactive material for cement clinker substitution, for example, will have a lower strength development. In order to bring these concretes into a competitive position, accelerator systems are required that guarantee at least a similar strength development as conventional concretes.

The use of recycled materials and the development of new, special admixtures for recycled concretes are still in the early stages in some cases. Although there are flagship projects, the widespread use of RC concretes or even RC binders has not yet taken place.

An important basis for maximizing the use of RC materials is also the preparation, provision and flexibilization of regulations, provided that the safety of the systems has been proven beforehand. Part 6 of the EN 197 series of cement standards, which specifies the use of recycled building materials as the main component of cement, is an example of such a normative development.

# 4 | $CO_2$-reduced concretes in practice

The introduction and establishment of $CO_2$-optimized concretes is based on intensive cooperation between all stakeholders in construction, the entire value chain of clients, architects, planners, the raw materials industry, concrete manufacturers, concrete technologists and contractors. Key success factors include the early involvement of consulting concrete technologists as well as laboratory- and 1:1-scale-tests. There is now experience with $CO_2$-optimized concretes from a number of projects. Examples include the EDGE East Side Berlin project and a new museum building in Detmold.

In the EDGE East Side Berlin project, an extremely $CO_2$-reduced concrete was used as an in-situ concrete supplement on prefabricated reinforced concrete slabs. This concrete sets new standards in terms of $CO_2$ equivalent while ensuring high strength and durability. This concept was successfully implemented by using an innovative binder concept (based on CEM X) and significantly reducing the added water content, while maintaining workability thanks to innovative superplasticizer concepts. The resulting concrete has a $CO_2$ equivalent of only around 138 kg/$m^3$ and is therefore well below the industry average for C 40/50 of 299 kg/$m^3$ $CO_2$ equivalent (interpolated according to [3]).

The project demonstrated that innovative concrete admixtures and clinker-efficient cements can be used to produce and safely cast $CO_2$-optimized concrete even under extreme conditions such as high concrete temperatures and pumping distances of more than 250 m and up to 140 m in height. The successful implementation was made possible by the smooth cooperation of all those involved in the construction and the innovative spirit of the investors, clients and the contractor.

Another example is the new construction of an entrance and exhibition building at the Detmold Open-Air Museum. The $CO_2$-optimized concrete was designed outside of the concrete standard DIN 1045-2 [5] (the German national adoption of EN 206), whereby the minimum cement content was undercut. Its use was made possible through approval in individual cases. It is clear that modernization of the normative boundary conditions is an important basis for the further establishment of $CO_2$-optimized concretes. This is also a prerequisite for advancing the decarbonization of the most important building material of our time, concrete, and fully exploiting optimization potential.

**Example of cement-free concrete (geopolymer)**
The name geopolymer was coined by the chemist Joseph Davidovits in the 1970s. The polymer structures produced by this binder are non-crystalline (amorphous) Si-O-Al frameworks. According to Davidovits, metakaolin and alkaline activators are required for this application. In addition to metakaolin, other latent hydraulic or pozzolanic secondary raw materials such as ground granulated blast furnace slag, fly ash or trass fines can also be used as binders.

These raw materials require a chemical activator to harden. By using these activators, concrete strength classes of up to C 50/60 can be achieved. In order to bring about good workability, new superplasticizers are also required. Both activators and superplasticizers are described in the currently only cement-free DIBt approval[1].

The setting behavior and the resulting bonding structures of the geopolymer differ significantly from cementitious binders, which has a number of advantages for the concrete produced from it. The geopolymer is highly resistant to chemical attack, meaning that the requirements of exposure class XA3 can be met without additional coatings.

The concrete also has a high heat resistance and is particularly suitable for the production of bulky components due to its low hydration heat development.

By using this concrete, $CO_2$ emissions can be reduced by up to 75 %. This concrete has already been used for paving stones, prefabricated parts, pipes and also as ready-mixed concrete for inverts.

The latest example of this is the USB4 building construction project in Norderstedt with a concrete volume of 3,000 $m^3$, in which cement was completely dispensed with. Another well-known example is the cement-free pipes from the NextBeton Group, which do not require an additional coating thanks to the concrete's approved exposure class XA3.

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1 | General building authority approval (DIBt), approval number Z-3.15-2157 "Wagners EFC Binder" (2019)

# 5 | Outlook

As has been shown, low-clinker cements in ready-mix concrete have already been achieving savings of around 2.8 million tons of $CO_2$ emissions annually for years. In the medium term, the optimization of

- ready-mix concrete with the help of innovative superplasticizer concepts, a further 1.6 to 1.85 million tonnes of $CO_2$ and
- replacing CEM I with CEM II for precast elements would also save a further 0.63 million tons of $CO_2$ emissions per year.

To further reduce $CO_2$ emissions in concrete construction, we propose the following aspects for discussion:

- Adaptation, modernization and flexibilization of the cement, concrete and concrete admixture standard to enable maximum $CO_2$ savings.

- Improved interaction between all parties involved: Clients – planners – concrete technologists – contractors – etc. is required as a basis for achieving the objectives.

- The fresh concrete characteristics of the future – with maximum possible water savings – will differ from the current situation. This means that a change in the processes (processing/casting, etc.) on the construction site is necessary.

- Modernization of concrete production through sensor technology and computer-aided systems as a basis for maximum $CO_2$ savings and quality assurance of more challenging concrete concepts. This can be supported by digitizing the concrete industry from production in the plant to the construction site.

- A perspective change of the admixture systems to flexible, controllable, "intelligent" multi-component systems. This requires an expansion of the storage and dosing equipment for concrete admixtures in concrete plants.

- Greater variability of the binder systems and their targeted application according to the requirements/exposure of the concrete. This also requires an expansion of the storage and dosing equipment for cements and additions.

- In the medium term, the following developments are expected for binders and other main cement constituents:
  - Elimination of fly ash by 2038,
  - Furnace slag 2.0,
  - Greater use of recycled binders,
  - Use of natural pozzolans and calcined clays,
  - Development of new binders.

- Optimization of admixture and binder systems for modular construction

The development outlined above will lead to an ever-increasing specialization and differentiation of concrete admixtures in terms of concrete raw material components (cement, other main cement components, recycled material, regional – possibly more challenging/demanding sand and aggregate qualities) in order to achieve a high level of target reliability in the production and robustness of the concretes.

It remains for us to note that for a total decarbonization of concrete construction, it will be necessary for the unavoidable carbon dioxide produced during the clinker burning process to be captured and stored or used so that it is permanently bound and does not enter the atmosphere at a later date.

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# Epilogue

This report "Contribution of the concrete admixtures industry to the decarbonization of concrete industry" was prepared by Working Group 2.1 "Concrete Admixtures and the Environment" of Deutsche Bauchemie e.V. and discussed and approved by Expert Committee 2 "Concrete Technology". It serves to provide information for all members and for the technically interested public.

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# Imprint

1st edition, May 2024
Deadline: May 2024

312-IS-E-2025

**Design**
Annette Schindler Grafikdesign
grafikdesign-schindler.de

**Picture credits**
Cover picture: istockphoto.com
Page 3: istockphoto.com
Page 10: istockphoto.com

**ISBN** 978-3-944138-84-8 (PDF version)

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