Energy
National Research Programmes 70 and 71

Synthesis

Sustainable Concrete Structures

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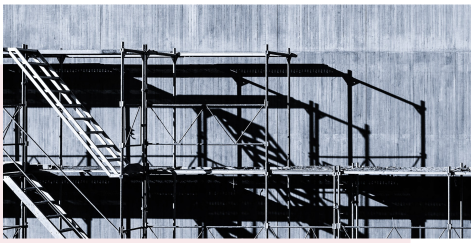
Joint synthesis

1. Sustainable Concrete Structures

Synthesis of the NRP 70 joint project “Low energy concrete”



1.1. Great potential for building materials

1.1.1. Summary

All structures in Switzerland - that is, all buildings, roads, infrastructure constructions and so on - consume over their entire life cycle around 50 % of Switzerland's final energy requirement. They are also responsible for around 30 % of emissions of the greenhouse gas CO_2.

In recent decades, the energy requirements and CO_2 emissions resulting from the use of such structures have fallen sharply. However, the grey energy contained within the structures as well as the CO_2 emissions associated with the construction, renovation and demolition of buildings, remain high. There is great potential for improvement here.

The joint project “Low energy concrete” provides an important basis for transforming the construction industry into a sustainable sector. It primarily focuses on the building material concrete, which is responsible for an especially high amount of grey energy and significant CO_2 emissions. The results of this joint project are summarised and interpreted in this synthesis on “Sustainable Concrete Structures”.

The chief objectives of the joint project were as follows:

1. CO_2 emissions and grey energy are reduced by drastically decreasing the amount of clinker in the cement.
2. Grey energy is reduced by replacing reinforcing and prestressing steel in concrete structures with wood and plastic.
3. The service life of the structures is extended by professional monitoring and adequate renovation measures; this reduces the average annual grey energy and CO_2 emissions.

The research work shows that the CO_2 emissions caused by concrete and concrete structures can be reduced by a factor of 4, while the bound grey energy can be decreased by a factor of

3.

1.2. Core messages

Sustainability

1.2.1. Significant reduction possible

Two core messages can be derived from the research conducted as part of the joint project "Low energy concrete":

1. The grey energy and CO_2 emissions associated with the construction, renovation and demolition of concrete structures in the areas of structural and civil engineering can be reduced by up to one-third without significantly impairing the outstanding material properties of the building material.[1]
2. The professional, continuous monitoring and diagnosis of the condition of a structure helps to avoid unnecessary renovation work and premature replacement measures. Furthermore, permanent monitoring enables the use of innovative – and as yet little tested – building materials and constructions designed to reduce the grey energy and CO_2 emissions associated with the building, renovation and demolition of concrete structures.[2]

Notes and References

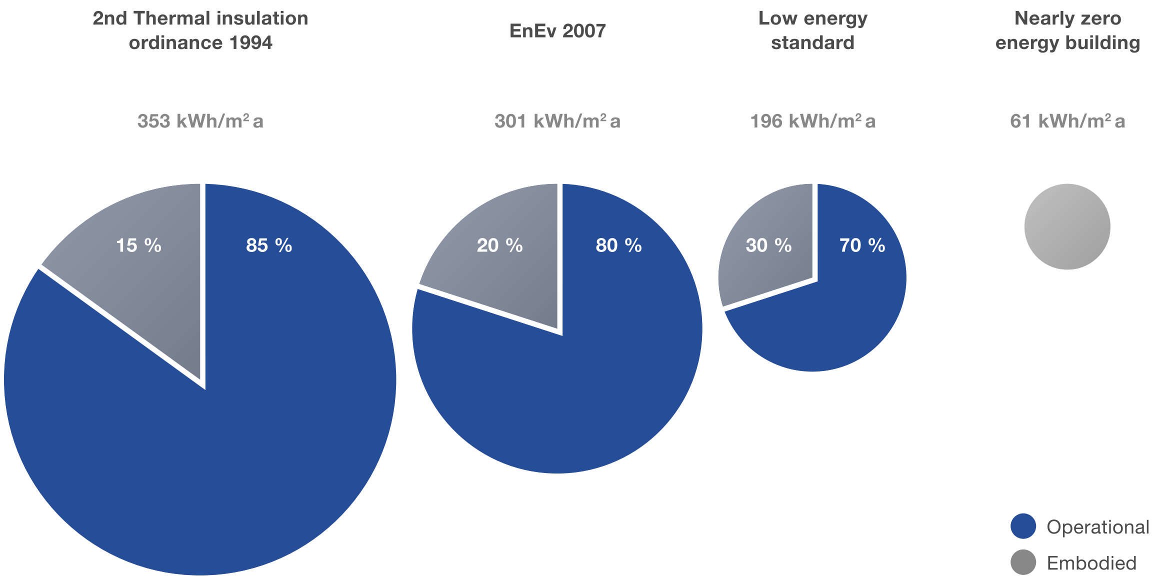
1 Project "Low energy concrete"
2 Project "Monitoring of concrete constructions"

1.3. Concrete – a demanding building material

Concrete binds a great deal of grey energy – and is also an important factor in terms of CO_2 emissions. While the operation of buildings is being steadily optimised with regard to energy consumption and pollutant emissions, there is still considerable potential with respect to the construction, renovation and demolition of concrete structures. Current research results show how this can be exploited.

Building # CO2 / greenhouse gases

1.3.1. Construction and structures as climate sinners



Development of the energy share in the building stock in Germany.*Source: Hegger et al. 2008*

The construction, renovation and operation of Switzerland's existing buildings and infrastructure currently account for around 50 % of final energy consumption and 30 % of CO_2 emissions; four-fifths of these are generated during the operating phase, with one-fifth attributable to the construction, renovation and demolition of the building structures. This ratio will change significantly over the coming years, as a study from Germany shows using the example of the building stock (excluding infrastructure facilities) as an example[1]: During operation, CO_2 emissions and the final energy drawn from the grid will be close to zero, while the corresponding values for construction, renovation and demolition will increase slightly. The reason for this is that the increased energy requirements placed on structures result in additional grey energy and CO_2 emissions. Further information in this regard can be found in the synthesis on "Buildings and Settlements"[2], which was also created as part of the NRP "Energy".

The grey energy and high CO_2 emissions associated with construction, renovation and demolition are 20 % to 30 % attributable to buildings' load-bearing structure[3] – and a large proportion of this is accounted for by concrete structures, including cement-bound mortars. It therefore makes sense to pay special attention to this building material.

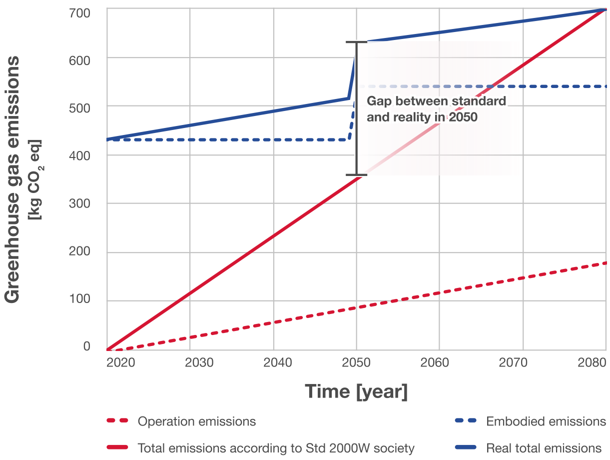
Notes and References

1 Hegger, M., Fuchs, M., Stark, T., Zeumer, M. (2008), Energy Manual: Sustainable Architecture, DETAIL. ed. Institute for International Architecture Documentation / Birkhäuser,

Munich
2 Synthesis on “Buildings and Settlements”
3 SIA (2010), Graue Energie von Gebäuden; SIA information sheet 2032, Swiss Association of Engineers and Architects (SIA), Zurich

CO2 / greenhouse gases

1.3.2. Grey energy and CO_2 emissions generated irregularly



Comparison between operating emissions and embodied emissions for a new building according to the standard of the 2000-Watt Society. *Source: Project "Low energy concrete"*

During the operation of a building, the annual energy requirements and CO_2 emissions remain more or less the same, with a slight upward trend over the years due to increasing aging. There is no such regularity with regard to construction, renovation and demolition; when a building is renovated or demolished is the decision of the owner. It is therefore not possible to establish a rule in this respect.

Nevertheless, all sources[1] [2] [3] state annual averages that make reference to standardised service lives for building materials or components and technical installations. These are in turn extrapolated to the target values for an entire building. Using this method – and on the basis of the "2000-Watt Society"[4] concept – the SIA Energy Efficiency Path[5], for example, defines the following target values for the CO_2 emissions of a newly constructed residential building:

- Construction, renovation and demolition: 9.0 kg CO_2/m^2 a
- Facility: 3.0 kg CO_2/m^2 a

These values refer to the energy reference area of the building. However, the 9.0 kg CO_2/m^2 a for construction, renovation and demolition are not distributed linearly. The largest part of the pollution by far occurs during the construction stage. The values then stand at zero for around 30 years – until the first major renovation package is required. As the graphic shows, the problem of CO_2 emissions based on time is strongly underestimated with a linear view. This also applies to grey energy.

Notes and References

1 KBOB, IPB (2016), Ökobilanzen im Baubereich, recommendation 2009/1:2016,

Coordination Conference of Building and Property Bodies of Public Sector Developers (KBOB) and Interest Group of Private, Professional Developers (IPB), Bern and Zurich
2 SIA 2032:2010, Graue Energie von Gebäuden; SIA information sheet 2032, Swiss Association of Engineers and Architects (SIA), Zurich
3 SIA 2014:2017, SIA Energy Efficiency Path, Swiss Association of Engineers and Architects (SIA), Zurich
4 http://www.2000watt.ch
5 SIA 2014:2017, SIA Energy Efficiency Path, Swiss Association of Engineers and Architects (SIA), Zurich

1.3.3. Concrete structures are composite structures

Concrete is the most widely used building material for load-bearing structures of buildings, bridges, retaining structures, tunnels, etc. One cubic metre of fresh concrete consists of around 2,000 kilograms of aggregate (gravel and sand), 300 kilograms of cement and 150 kilograms of water, whereby the recipe is optimised according to the intended use. Furthermore, additives can be added to the concrete to modify specific properties such as porosity, early strength or processability.

After mixing, the fresh concrete is placed in the formwork and compacted. It then hardens due to the hydration of part of the added water. The cement stone binds the aggregate, giving rise to a largely homogenised building material with high compressive strength but low tensile strength. Generally speaking, the target strength is achieved after 28 days.

Concrete structures are not only subjected to compressive stress, however. They also need to be able to absorb bending moments, for example in beam or slab structures. A bending moment is a parallel, equal force couple comprising compression and tensile forces at a certain distance. To allow a concrete structure to absorb the tensile forces, a reinforcement made of steel bars or prestressing steel is inserted on the tensile side of the concrete structure. A concrete structure is therefore a composite structure made up of concrete and steel.

The CO_2 emissions in this composite structure can primarily be attributed to the concrete; the grey energy is accounted for by concrete and reinforcement steel. For a traditional concrete slab with a thickness of 18 centimetres and a customary percentage of reinforcement, the following situation can be observed[1]:

- CO_2 emissions: concrete 75 %, reinforcement 25 %.
- Grey energy: concrete 54 %, reinforcement 46 %.

Measures are therefore required for both the concrete and the reinforcement.

Notes and References

1 KBOB, IPB (2016), Ökobilanzen im Baubereich, recommendation 2009/1:2016, Coordination Conference of Building and Property Bodies of Public Sector Developers (KBOB) and Interest Group of Private, Professional Developers (IPB), Bern and Zurich

1.3.4. Concrete structures also age

Concrete structures are extremely durable and long-lasting. They do age, however. This is particularly true for concrete structures in humid environments with a relative humidity of over 80 %. Here, the alkaline component of the cement stone reacts by absorbing CO_2 from the air to form calcium carbonate and water [$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$]. This reduces the pH value of the cement stone from an average of 12.5 to less than 10. As a result, the original corrosion protection for the reinforcing steel used in the concrete is lost to a large extent. The reinforcement steel thus corrodes – and the associated increase in volume leads to spalling on the concrete surface. This also accelerates the corrosion of the reinforcement.

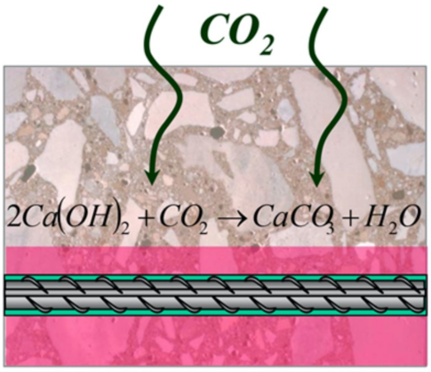
Furthermore, other effects can intensify the corrosion process. These include, for instance, an increased sodium chloride content caused by road salt for traffic structures. Advanced corrosion of the reinforcement leads to an inadmissible reduction in the load-bearing capacity of concrete structures and finally to their collapse.

The speed of corrosion primarily depends on the following factors:

- The concrete moisture close to the surface – 50 % to 70 % is the least favourable range;
- The concrete strength;
- The concrete porosity.

In the case of concrete structures subjected to the effects of the weather – exposed concrete facades, bridges or retaining walls – the concrete must therefore be as dense and strong as possible and is allowed only a few hairline cracks. Corrosion is not usually a problem for dry concrete structures, for example building interiors.

Corrosion caused by carbonation in ordinary reinforced concrete structures; corrosion does not occur if the concrete is not exposed to water, as is the case, for example, indoors. Credits: Francesco Pittau.



Source: Project "Low-clinker cements"

CO2 / greenhouse gases

1.3.5. The death of concrete structures

Concrete structures have a service life – which at some point comes to an end. This does not mean an uncontrolled collapse, as happened, for example, at the Morandi Bridge in Genoa. Instead, this is the point in time when the structure's usability or the required safety margin can no longer be guaranteed. In this case, a radical reinforcement or the replacement of the structure is necessary. Which of the two measures is more suitable depends on the condition of the structure, the environmental and operational impact of the measure and its economic viability.

Since, as a rule, not all parts of a concrete structure reach the end of their service life at the same time, partial reinforcements are common in Switzerland. The country has a long tradition of such partial reinforcement measures. Structures are more likely to be replaced if new usage requirements or legal framework conditions make this necessary.

As is the case with new structures, care must be taken during renovation projects to ensure that grey energy and CO_2 emissions are avoided to the greatest extent possible – and that resources are used sparingly. The key factor here is the point in time at which a renovation project is undertaken: too early is uneconomical, too late can be fatal. Despite extensive experience in this field, there is still considerable potential for improvement in Switzerland, for example in terms of reducing CO_2 emissions and improving durability. The research results of the joint project "Low energy concrete" provide an important basis in this regard.

1.3.6. Focus of synthesis

This synthesis focuses on the results of the joint project “Low energy concrete” and the associated sub-projects “Low-clinker cements”[1], “High-performance concrete”[2], “Hybrid load-bearing structures”[3], “Pre-stressed carbon-fibre concrete”[4] and “Monitoring of concrete constructions”.[5]

A common concern of all research groups was the substantial reduction of grey energy and CO_2 emissions in connection with the construction, renovation and demolition of concrete load-bearing structures. An emphasis was placed on technical feasibility; economic viability and acceptance have not yet been dealt with in depth.

Notes and References

1 Project “Low-clinker cements”
2 Project “High-performance concrete”
3 Project “Hybrid load-bearing structures”
4 Project “Pre-stressed carbon-fibre concrete”
5 Project “Monitoring of concrete constructions”

1.4. Material properties of the concrete

Building materials bind a great deal of grey energy and are responsible for a large proportion of CO_2 emissions. Too little attention has been paid to this fact so far. However, the negative effects can be drastically reduced.

1.4.1. The world leader – and with good reason

Concrete – and especially reinforced concrete – is the most widely used building material in the world. There are good reasons for this:

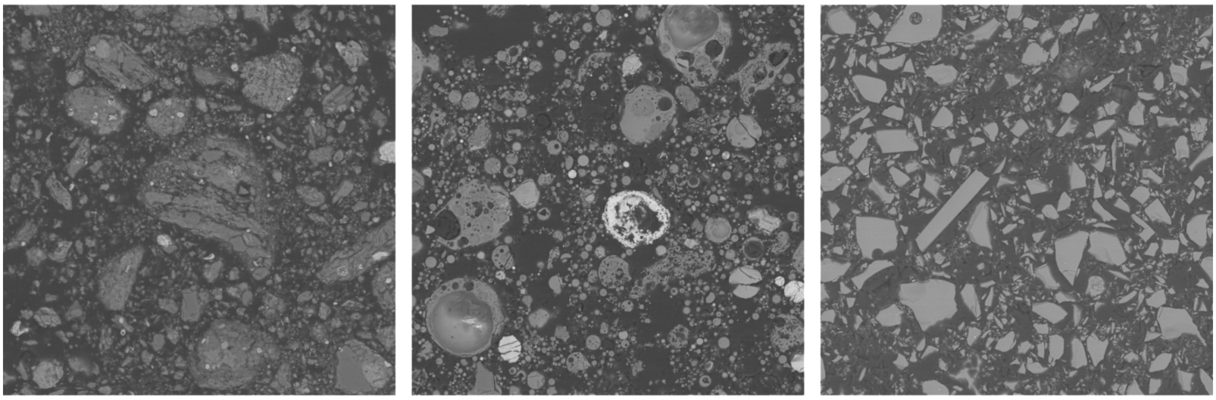
- Its components are relatively easy to produce locally;
- Concrete components can take virtually any shape;
- Processing on site does not necessitate any specialist knowledge;
- Its strength development is excellent;
- It has a low level of porosity;
- The building material is very durable;
- Concrete's material properties can be adjusted in almost any way required with additives;
- The building material is inexpensive.

Thanks to these outstanding properties, it is not possible simply to replace reinforced concrete with another material.

However, reinforced concrete also has disadvantages: the construction, renovation and demolition of concrete structures embodies a lot of grey energy and leads to considerable CO_2 emissions. The big challenge lies in eliminating these disadvantages to the greatest extent possible without compromising the outstanding properties of the building material.

CO2 / greenhouse gases

1.4.2. Cement with less clinker



BSE (back scattered electrons) image of burnt oil shale (BOS), fly ash (FA) and slag embedded in epoxy resin. *Source: ETHZ, Chair of Physical Chemistry of Building Materials*

Cement clinker is the most important component of cement. It is extracted from limestone and marl; the rock is crushed and ground and then converted into clinker by sintering in a rotary or shaft furnace at approximately 1,450 degrees Celsius. This process is energy-intensive and emits a great deal of CO_2.

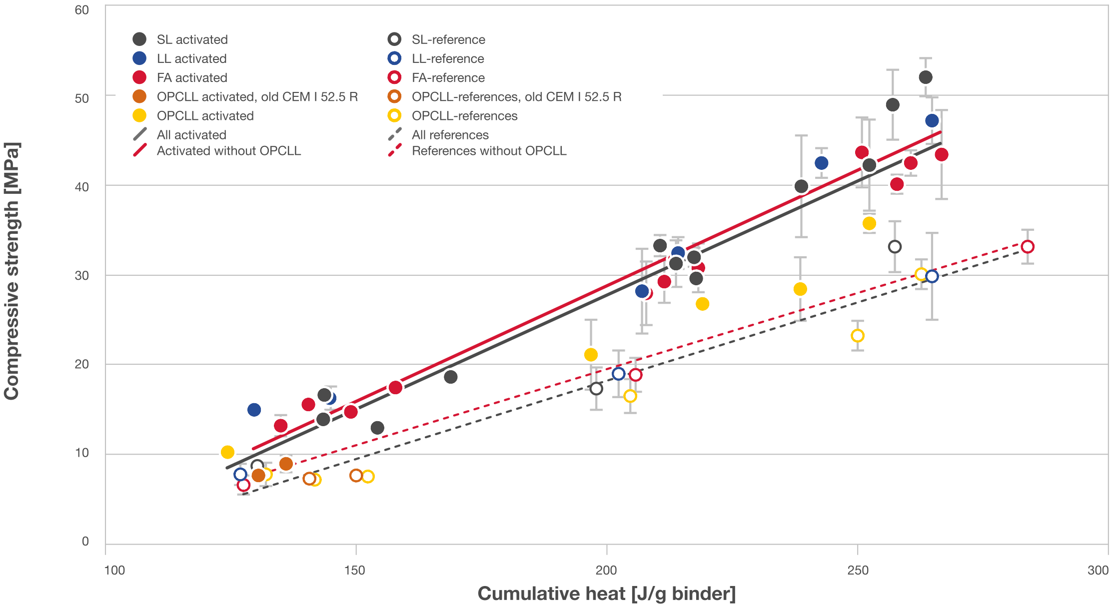
To reduce these disadvantages, a cement was developed as part of the project “Low-clinker cements”[1] that requires up to 65 % less clinker than standard Portland cement (type CEM I). The new cement mixture (type CEM II/C) was mixed with 50 % CEM I as well as limestone powder (filler) and burnt oil shale as additional cement-like components. This new mixture can be produced with the existing production facilities and reduces CO_2 emissions by around half.

The most important material properties are comparable to those of Portland cement, as the development of early strength has been significantly increased by the use of chemical additives. However, there are still uncertainties regarding carbonation and thus the risk of corrosion for steel inserts in very humid environments with a relative humidity of more than 80 %. For the time being, it is therefore recommended to use the new cement primarily inside buildings.

Notes and References

1 Project “Low-clinker cements”

1.4.3. High early strength thanks to chemical additives



Influence of the addition of low concentrated alkali solutions on compressive strength and cumulative heat release after seven days compared to reference mixtures without activators. SL: Mixture with 10 % slag FA: Mixture with 10 % fly ash LL: Mixture with 10 % limestone powder OPCLL: Mixture with 50 % Portland cement and 50 % limestone powder. *Source: Project "Low-clinker cements'*

In the project "Low-clinker cements"[1], the influence of various activators – i.e. "stimulators" such as moderately concentrated alkali solutions, calcium nitrate and gypsum – on the development of early strength was investigated. These additives were tested on one of the new cement mixtures containing 50 % Portland cement as well as 50 % regionally available cement-like additional components such as 20 % limestone powder, 20 % burnt oil shale and 10 % fly ash or slag.

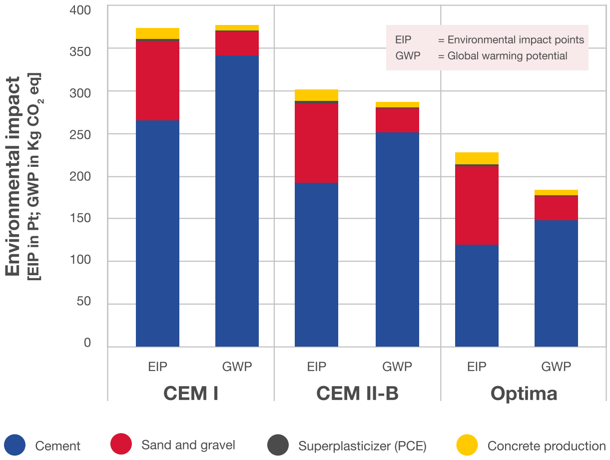
The analyses showed that this mixture performed best when sodium hydroxide and calcium nitrate were added. The 90-day strength increased by 14 % to 120 %. It was also obvious that the increase in strength was clearly thanks to the addition of burnt oil shale. It was likewise demonstrated that the replacement of fly ash and slag with limestone powder does not affect strength development, whereas the mixture comprising 50 % Portland cement and 50 % limestone powder gives rise to considerable strength losses.

Notes and References

1 Project "Low-clinker cements"

CO2 / greenhouse gases

1.4.4. Halving CO_2 emissions



Environmental impact assessment for 1 m^3 of concrete.

In order to quantify the effects of the new cement mixture on CO_2 emissions and grey energy, a life cycle analysis was carried out on two different cement mixtures.[1] The two cements were based on a mixture of Portland cement (CEM II), limestone powder and burnt oil shale. Only 60 % Portland cement was used in one mixture (CEM II-B), while just 35 % was used in the other (OPTIMA). A specially prepared superplasticiser was added to both mixtures in order to improve their early strength and long-term behaviour.

For the life cycle analysis, the ecological scarcity method[2] was applied. This quantifies the environmental impact of a pollutant emission or resource extraction using “environmental impact points (EIP)” based on eco-factors. The global warming potential[3] was also determined using CO_2 equivalents.

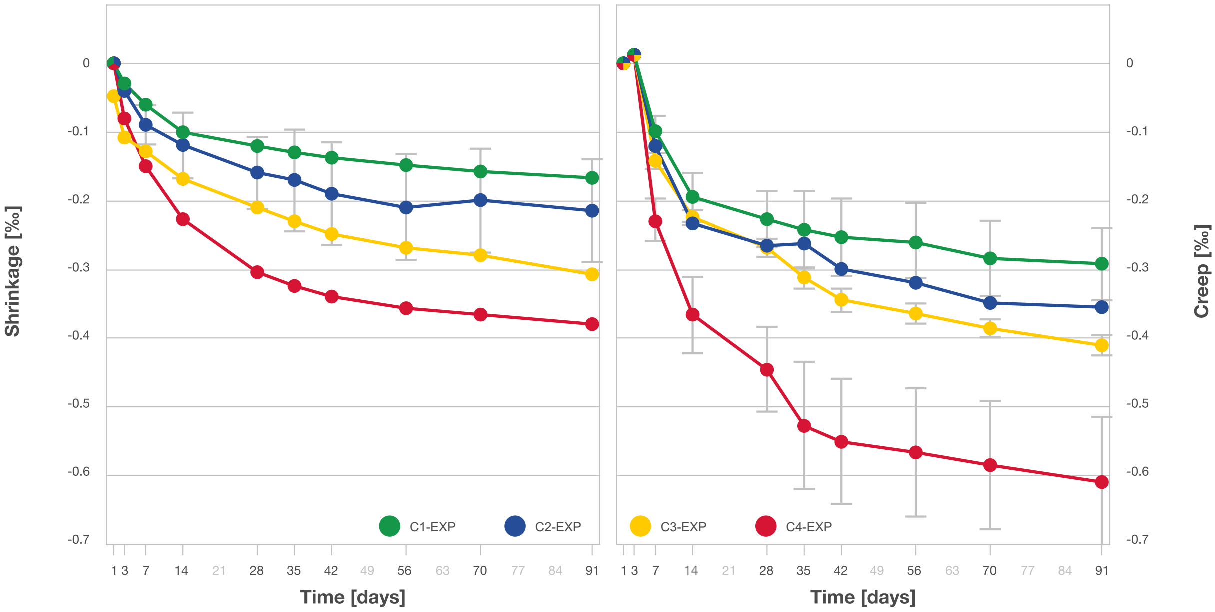
Both analyses show that the new cement mixtures lead to a 40 % reduction in the environmental impact of finished concrete and a 50 % decline in global greenhouse potential. These substantial improvements in terms of grey energy and CO_2 emissions are achieved without any major impact on the material properties of the concrete.

Notes and References

1 Project “Low energy concrete”
2 FOEN (2013), Swiss Eco-Factors 2013 according to the Ecological Scarcity Method, Federal Office for the Environment, Ittigen
3 [https://www.unfccc.int

CO2 / greenhouse gases

1.4.5. Sustainable high-performance cements



Shrinkage rate (left) and creep rate (right). For creep rate measurements, the load was increased to correspond to 20 % of compressive strength after three, seven and 28 days. C1 is an industrial self-compacting high-performance cement as it is currently used in the Swiss precast concrete industry. C2, C3 and C4 correspond to the newly developed cement mixture. *Source: Project "High-performance concrete'*

To prevent corrosion in concrete elements prestressed in the prestressing bed, carbon-fibre-reinforced polymers are increasingly being used instead of prestressing steel. In order to reduce production costs and to make rapid stripping possible, self-compacting high-performance cements are used. In this process, high values for grey energy and CO_2 emissions are recorded.

To remedy this situation, a high-performance cement with a very low carbonate content was developed as part of the project "High-performance concrete"[1]. Up to 70 % of Portland cement was replaced by metakaolin, microsilica and limestone powder and the water/cement ratio was reduced to 17 %. Self-compaction was ensured with the greatly increased addition of superplasticisers. With this more environmentally friendly cement mixture, a concrete compressive strength of 80 MPa and a bond tensile strength between the concrete and the sand-coated carbon-fibre-reinforced polymers of 20 MPa were achieved. These values correspond to the strength of standard high-performance cements.

In addition, FEM calculations and tests showed that the new cement mixture has a significantly lower creep and shrinkage rate than conventional high-performance cements. This results in significantly lower prestressing losses and thus lower costs – while at the same time halving grey energy and CO_2 emissions.

Notes and References
1 Project “High-performance concrete”

1.5. Concrete structures without steel

The production and transportation of reinforcing and prestressing steel for concrete structures require a lot of energy. However, there are innovative ways for building concrete structures without steel.

1.5.1. Steel as an energy guzzler

Concrete has excellent compressive strength – but very limited tensile strength. In traditional concrete structures such as foundations, walls, columns, beams and ceilings, reinforcing or prestressing steel must therefore be installed to absorb the tensile forces that are experienced.

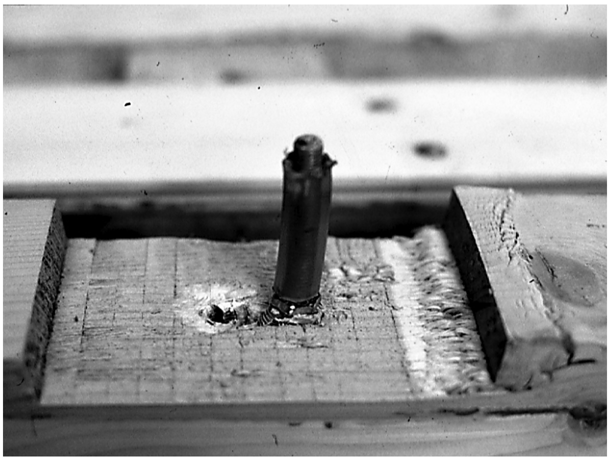
The production of steel – especially high-quality reinforcing and prestressing steel – is extremely energy-intensive. Furthermore, the steel reinforcement has to be transported from the steelworks over relatively long distances to the steel traders and from there to construction sites throughout the country – this requires additional energy. The reinforcing and prestressing steel therefore contains a considerable amount of grey energy when it arrives at the construction site. In the case of reinforcing steel, for example, this equates to 3.55 crude oil equivalents/kg (without transport). By comparison: air-dried, planed domestic coniferous wood contains just 0.69 crude oil equivalents/kg.[1] From an ecological point of view, it therefore makes sense to minimise or completely eliminate the steel contained in concrete structures.

Notes and References

1 KBOB, IPB (2016), Ökobilanzen im Baubereich, recommendation 2009/1:2016, Coordination Conference of Building and Property Bodies of Public Sector Developers (KBOB) and Interest Group of Private, Professional Developers (IPB), Bern and Zurich

Wood

1.5.2. Wood instead of steel



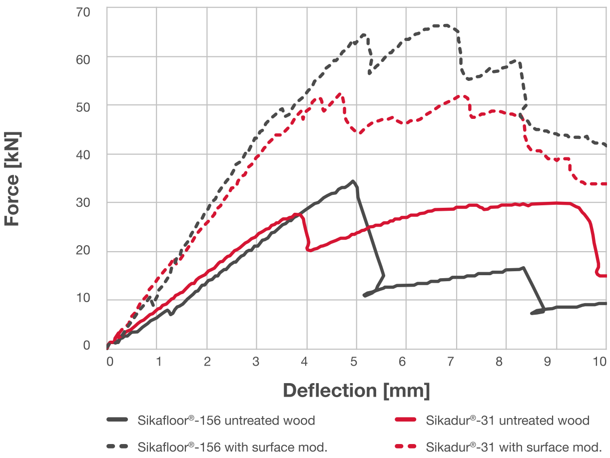
The project “Hybrid load-bearing structures”[1] pursued an innovative approach for avoiding steel reinforcement in concrete ceilings. The basic principle of the approach is to replace the underlying reinforcement with a layer of beech laminated veneer lumber. This absorbs the tensile forces on the underside of the ceiling and acts as formwork during construction. A relatively thin layer of concrete is applied to this beech laminated veneer lumber, which takes on the compressive forces on the upper side; wood and concrete must, however, be firmly connected to each other.

This technique has already been used for several years during the renovation of historic buildings. Such hybrid ceilings have numerous advantages over conventional wooden ceilings. These include, for example, better footfall sound insulation, greater fire resistance and shorter construction times. But there are also disadvantages: in order to ensure a slip-free bond between wood and concrete, a large number of strong metal dowels are required. This leads to local stress peaks and corrosion risks. In addition, the hybrid ceilings commonly used today are only suitable for one-way ceiling panels with continuous beams as supports. This significant disadvantage restricts the architectural design possibilities and prevents the solution’s widespread use.

Notes and References

1 Project “Low-clinker cements”

1.5.3. Gluing instead of dowelling



4-point deflection tests of wood-concrete composite specimens with Sikafloor®-156 and Sikadur®-31 coatings, with and without wood surface treatment. The graph shows the reference curves of 10 measurements. *Source: Project "Hybrid load-bearing structures"*

In order to eliminate the need for problematic metal dowels in hybrid wood-concrete composite ceilings[1], an innovative adhesive bond was developed as part of the project "Hybrid load-bearing structures".[2] This technique is based on hydrophobing the wooden surface using standard polysilanes to prevent the adhesive from penetrating into the wood and an epoxy-based adhesive. This adhesive layer also prevents free pore water from the concrete penetrating into the beech veneer.

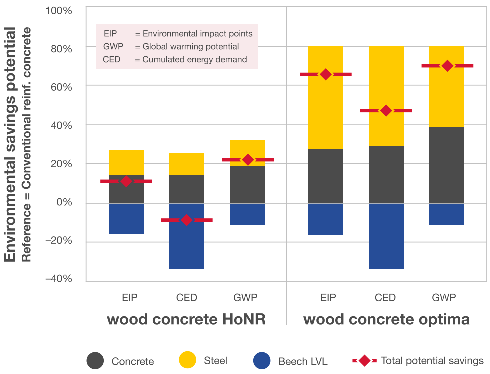
As part of the project "Hybrid load-bearing structures", in order to better understand and optimise the load-bearing behaviour in the joint between beech veneer and concrete, numerous tests were performed on pre-treated and non-pre-treated beech wood at a scale of 1:1 using two different adhesives. These showed that the two adhesives lead to comparable load-bearing behaviour, while the differences between the samples with pre-treated and non-pre-treated wooden surfaces are considerable. Moreover, pre-treatment contributes to stronger chemical and mechanical interlocking. Pull-out tests showed that the fracture between the wood and concrete is brittle, as the bonded connection with epoxy resin does not contribute to ductile fracture behaviour. For practical application, however, ductile fracture behaviour would be of great benefit.

Notes and References

1 Wood instead of steel
2 Project "Hybrid load-bearing structures"

Wood # CO2 / greenhouse gases

1.5.4. 70 percent less CO_2 emissions



Environmental impact assessment for 1 m² of a wood-concrete composite ceiling in the House of Natural Resources (HoNR) and with the new OPTIMA high-performance cement containing 40 % clinker. The reference is a conventional reinforced concrete ceiling with 100 % Portland cement. *Source: Project "Low energy concrete"*

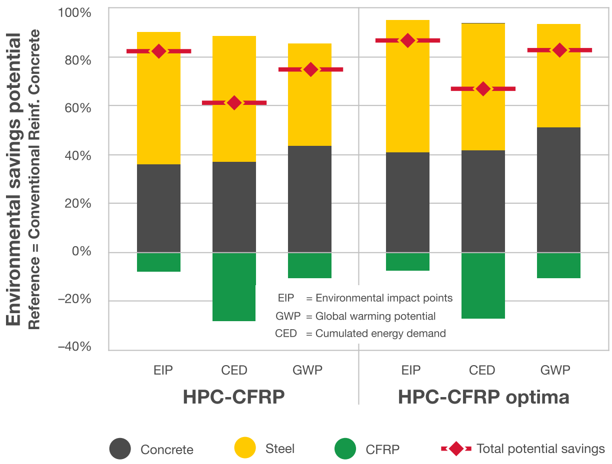
The further development of the wood-concrete composite ceiling as part of the project "Hybrid load-bearing structures"[1] gave rise to astonishing results: life cycle analyses show that using OPTIMA high-performance cement containing only 40 % Portland cement can reduce the cumulative energy demand (CED) by around 50 % and CO_2 emissions by around 70 % compared to a conventional reinforced concrete ceiling. The environmental impact points (EIP) as per the ecological scarcity method are also reduced by around 60 %.

The same research team implemented and tested the first wood-concrete composite ceilings as far back as 2014 as part of the "House of Natural Resources (HonR)"[2] demonstration object at the ETH Zurich Hönggerberg campus. Here, beech laminated veneer lumber with a thickness of 40 mm was used as formwork and lower reinforcement. In the overlay, which had a thickness of 120 millimetres to 160 millimetres, some reinforcement steel was used and the shear connection between the wood and concrete was ensured by means of interlocking with notches milled into the wood. In view of the still relatively high steel content of this construction, the environmentally relevant savings are significantly lower. The further development of this technology within the framework of the NRP "Energy" thus brought about substantial improvements.

Notes and References

1 Project "Hybrid load-bearing structures"
2 https://honr.ethz.ch

1.5.5. Carbon-fibre-reinforced polymers instead of steel



Environmental impact assessment for 1 m² of carbon-fibre pre-stressed high-performance concrete with OPTIMA high-performance cement and 40 % clinker content. The reference is conventional reinforced concrete with 100 % Portland cement.
Source: Project "Low energy concrete'

Another way to banish steel entirely from concrete structures is to replace the reinforcing and prestressing steel with carbon-fibre-reinforced polymers. This technique has been used successfully for several years, especially for concrete elements prestressed in prestressing beds and for the reinforcement of existing concrete structures. Until now, however, little attention has been paid to environmentally relevant aspects.

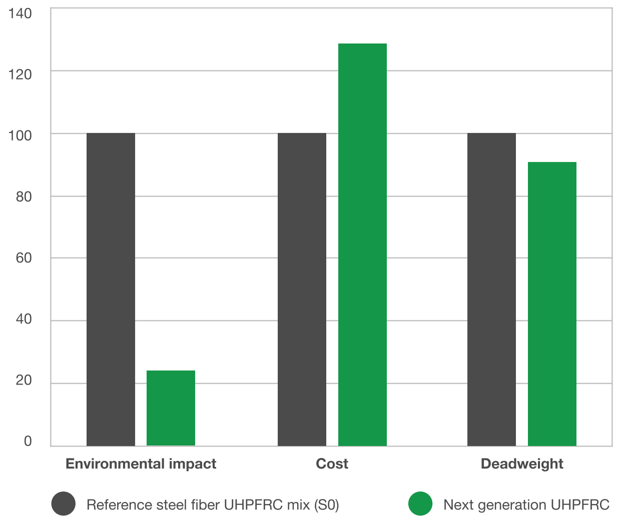
To close this gap, a new generation of carbon-fibre prestressed beams was developed as part of the project "Pre-stressed carbon-fibre concrete".[1] Ultra-high-strength carbon fibres were used in the tendons and the newly developed cement mixtures[2] were used in which up to 60 % of the Portland cement is replaced by limestone powder and metakaolin. Extensive large-scale laboratory tests have shown that this new construction technique – relative to conventional solutions – leads to higher load capacities, lower deflections and smaller crack widths.

Alongside the mechanical advantages, the newly developed carbon-fibre pre-stressed concrete beams achieve major environmentally relevant improvements: compared to a conventionally reinforced concrete beam, the new construction technique and the use of the OPTIMA cement mixture reduce grey energy by around 70 % and CO_2 emissions by approximately 80 %.

Notes and References

1 Project "Pre-stressed carbon-fibre concrete"
2 Cement with less clinker

1.5.6. Polyethylene fibres instead of steel



Comparison of environmental impact, price and net weight of the newly developed ultra-high-performance fibre concrete and a conventional steel fibre concrete. *Source: Project "High-performance concrete"*

For special applications, concrete structures are not reinforced with bar steel or tendons, but rather with homogeneously and undirectionally distributed steel fibres (length approximately 35 millimetres, diameter approximately 0.6 millimetres, quantity approximately 25-35 kg/m^3 of concrete). At present, steel fibre concrete is mainly used for highly stressed floor coverings, as shotcrete for tunnel construction and for prefabricated elements.

As part of the project "High-performance concrete"[1], an ultra-high-performance fibre concrete was developed. Here, the steel fibres are completely replaced by high-quality polyethylene fibres and a high-performance cement is used in which 50 % of the clinker is substituted by limestone powder. This polyethylene fibre-reinforced concrete has a similar elastic limit stress to steel fibre-reinforced concrete and meets the requirements of the type UA according to the SIA information sheet 2052.[2] This new concrete has already proved its worth during the renovation of the bridge slab of the Chillon Viaduct and is becoming increasingly popular in Switzerland.

Compared to steel fibre-reinforced concrete, however, polyethylene fibre-reinforced concrete has about 75 % less grey energy and is approximately 10 % less dense. However, current market prices are around 30 % higher.

Notes and References

1 Project "High-performance concrete"
2 SIA (2016), Ultra-Hochleistungs-Faserbeton (UHFB) – Baustoffe, Bemessung und Ausführung, SIA information sheet 2052:2016, Swiss Association of Engineers and Architects (SIA), Zurich

1.6. Optimal preservation strategy

If concrete structures are used for longer, their average grey energy and CO_2 emissions per year are reduced. This requires special processes and building materials.

1.6.1. Savings through prolonged use

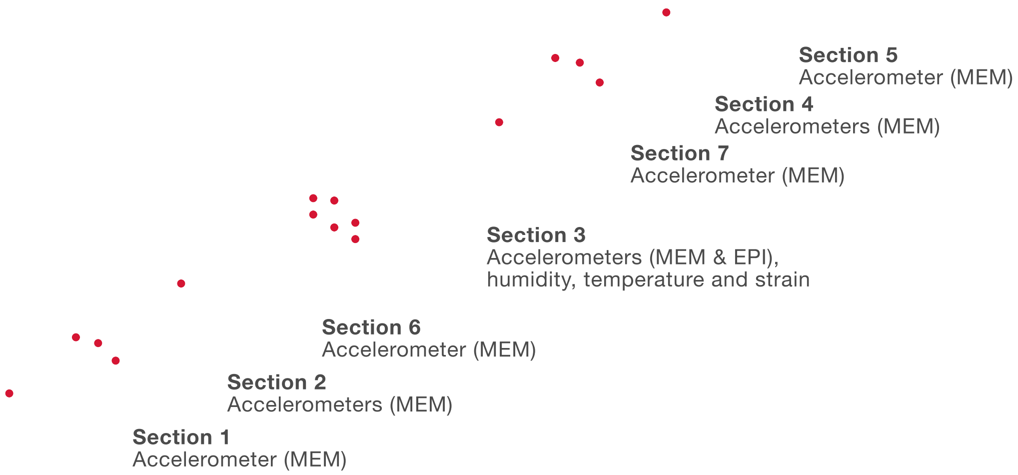
In principle, the greatest savings can be made for structures if they are used for as long as possible and are not replaced by a new structure as soon as the first complaints about aging emerge – even if a replacement would have certain advantages over the ageing structure. Not only money, but also grey energy and CO_2 emissions are saved through the waiting approach.

The principle of “saving through prolonged use” primarily applies to infrastructure such as water and sewerage systems, electricity grids, railway lines, roads, bridges and tunnels, which have relatively low operating costs and low emissions. Of course, it is only the costs and emissions that emanate from the structures themselves that are saved and not those related to their use.

The situation in buildings is somewhat different: poorly insulated buildings with outdated and fossil-fuelled building technology are known to have high CO_2 emissions and continuously rising operating costs. An overall analysis is therefore required for buildings in which the expenditure for the operation, energy renovation and demolition of the existing building stock is compared with that of constructing new buildings.

An optimal strategy is required to ensure that infrastructure installations can be used for longer periods of time. The basis for this is formed by the current condition of the structure, a forecast of the development of its condition over time together with well-founded ideas on possible immediate and long-term measures.

1.6.2. New basis for a clean diagnosis



Instrumentation of half a bridge section of the Chillon Viaduct. *Source: Project "Monitoring of concrete constructions"*

When it comes to the renovation or renewal of infrastructure constructions, comprehensive and reliable diagnoses are key. Responsibility here lies with the authorities at a federal, cantonal and municipal level – and increasingly also with private organisations, for example within the framework of public-private partnerships.

In the past, diagnoses were made on the basis of inspections and visual checks. Today, however, the processes are far more complicated and demanding. For example, high-tech measurement methods, thinking devices (IoT), drones as well as a great deal of computer science and many communication technologies are used.

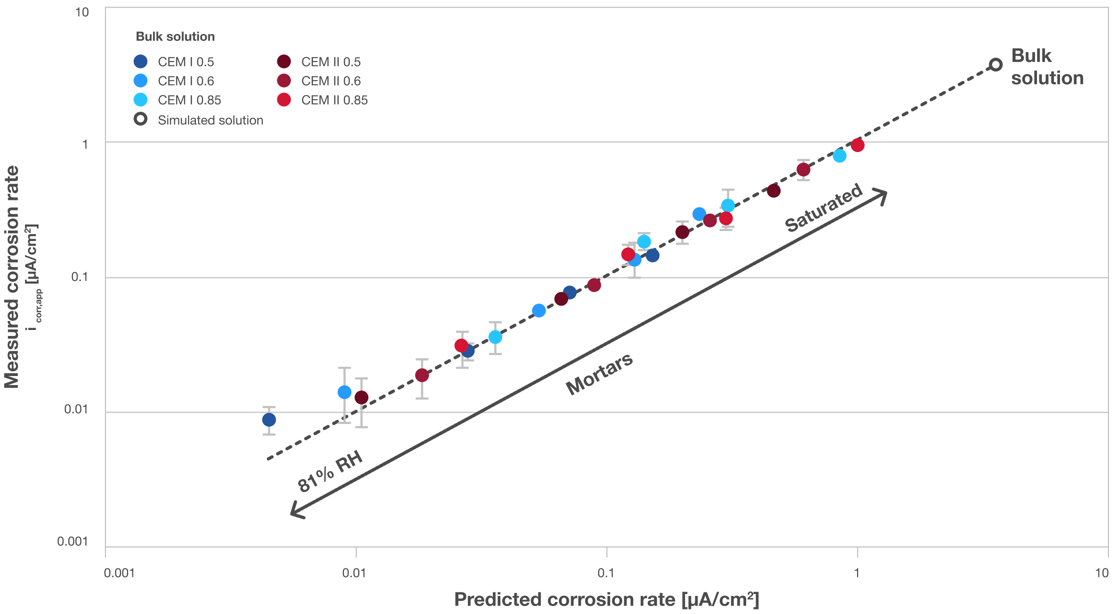
As part of the project "Monitoring of concrete constructions"[1], a comprehensive monitoring system was developed and tested in practice during the comprehensive renovation of the Chillon Viaduct, which was built between 1966 and 1969. The impressive road bridge is 2,100 metres long which – as a prestressed continuous girder – passes over 23 sections each spanning between 42 metres and 108 metres. The increasing problems with alkali-silica reactions (ASR) on the concrete and the associated damage to the carriageway slab made extensive renovation necessary.

A measuring system with four strain gauges, 11 acceleration gauges, one temperature gauge and one humidity gauge was installed on one of the sections prior to the start of the renovation work. This allowed countless dynamic loads, strains and stiffness values as well as climate data to be measured and transmitted online to the evaluation team at ETH Zurich.

Notes and References

1 Project "Monitoring of concrete constructions"

1.6.3. Analysis of material samples



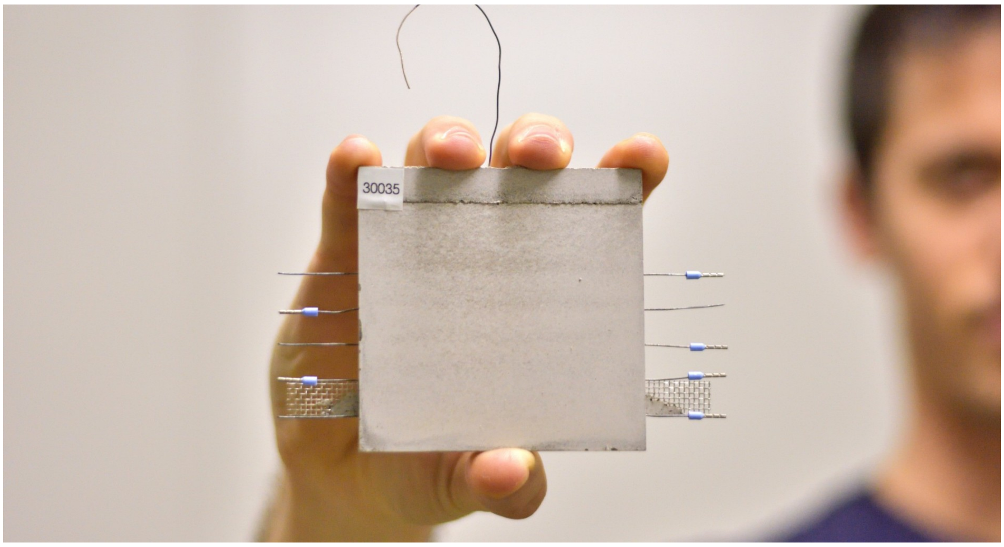
Corrosion curve of steel in porous media. The diagram shows how the measured corrosion rates can be reliably predicted using the proposed theoretical model. Marker = average values, whisker plot = standard deviations. *Source: Project "Monitoring of concrete constructions"*

In order to interpret correctly the damage to the Chillon Viaduct's carriageway and to take the appropriate renovation measures, countless material samples were taken from the bridge for laboratory testing. This was necessary because the usual methods for measuring corrosion on concrete-cast reinforcing steel – such as ohmic resistance measurement or cathodic corrosion control – do not provide reliable results.

As part of the project "Monitoring of concrete constructions"[1], a new method was developed for measuring steel corrosion in carbonised mortar. The test system is a small mortar sample (8 x 8 x 0.6 cm) provided with a reference electrode, five electrodes made from normal steel wire and a counter electrode made from stainless steel. The thin mortar sample allows complete carbonation within one week at an ambient humidity of 57 % with a 4 % CO_2 content. The electrical resistance, corrosion potential and corrosion rate of the steel as well as oxygen diffusion and oxygen consumption are measured. Using this data, the carbonation-induced corrosion can be investigated – especially its dynamics. Here, a linear correlation between the corrosion rate and the water content was determined for each sample. The developed model is based on two parameters: the pore structure of the mortar and the ambient humidity.

Using this approach, it was possible to quantify reliably the influence of the different concrete mixtures on the corrosion of the reinforcing steel. This confirmed that types of concrete in which there is a substantial replacement of Portland cement with other binders (CEM II) do not give rise to a significantly higher corrosion rate than those with the usual mixtures (CEM I). On the other hand, the analyses also revealed that the addition of activating or accelerating additives significantly increases susceptibility to corrosion – in proportion to the dosage.

Image of the small concrete sample. The absence of cracks and shrink holes in the surface of the sample is noteworthy.



Source: Project "Monitoring of concrete constructions"

Notes and References

1 Project "Monitoring of concrete constructions"

1.6.4. From diagnosis to treatment

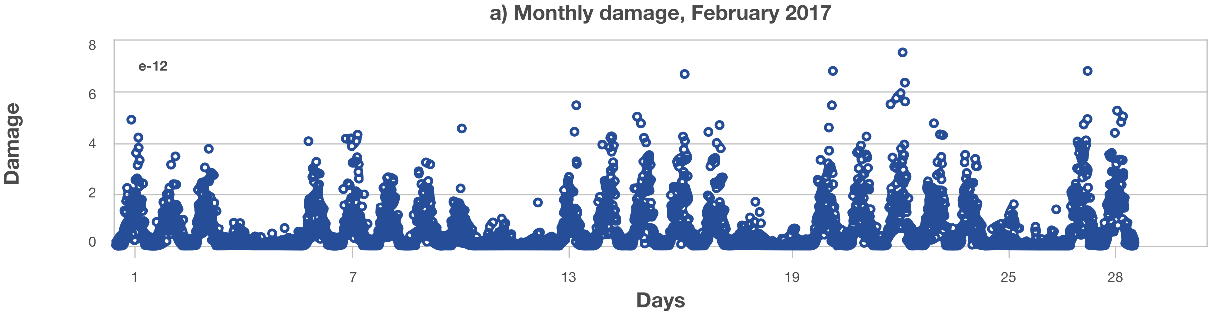
To diagnose the current condition of the Chillon Viaduct, countless measurements were carried out on the structure as well as in laboratory tests.[1] They clearly showed that the damaged areas on the upper side of the bridge had to be eliminated over a large area and that a new surface layer was then required. This 40-mm-thick surface layer was constructed using the ultra-high-performance fibre-reinforced concrete with polyethylene fibres[2] that had been newly developed as part of the project "Monitoring of concrete constructions". As this new concrete is also highly watertight over the long term, there was no need for conventional waterproofing. This resulted in substantial time and cost savings. Grey energy was also saved and CO_2 emissions were reduced relative to conventional steel fibre concrete.[3]

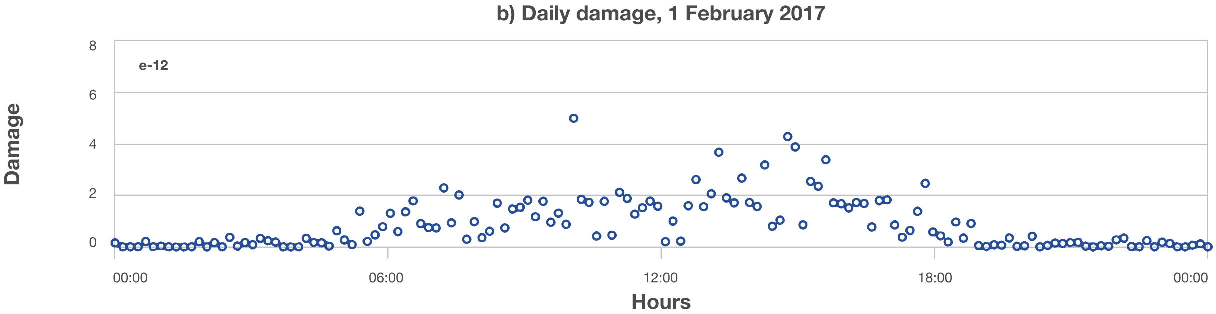
In the meantime, the newly developed measurement and test concepts as well as the new ultra-high-performance fibre concrete have also been used in other structures and further analysed. For example, during the renovation of the Buna Railway Bridge in Croatia and the conversion of Haus Du Pont, an eight-storey building dating back to 1913 in the heart of Zurich, where the floor slabs were reinforced with a 4-cm-thick layer of the new ultra-high-performance fibre concrete.

Notes and References

1 Project "Monitoring of concrete constructions"
2 Polyethylene fibres instead of steel
3 Polyethylene fibres instead of steel

1.6.5. The follow-up inspection





Detail of the damage accumulation for the longitudinal strain gauge: for a) month and b) day. This illustrates that the strain on work days and at rush hours is more pronounced. *Source: Project "Monitoring of concrete constructions'*

The building materials and processes developed as part of the joint project "Low energy concrete" have opened up unimagined potential for saving grey energy and reducing CO_2 emissions in theory and in practice. However – especially where these research results have been applied in concrete construction projects on a large scale – the expected long-term behaviour still has to be proven.

For this purpose, the measurement systems installed on the structures are essential. At the Chillon Viaduct, a first series of measurements was recorded and subsequently evaluated in the period from mid-May to the end of June 2017, i.e. after completion of the renovation work. The evaluations were still in progress upon the project's completion in spring 2018. Initial results are already available, however. These include, for example, the results from the acceleration measurements and the frequencies derived from them. They allow a statement to be made about the "healthy" condition of the bridge and any possible damage. Based on the strain measurements, it was possible to derive the cumulated loads. This is an important parameter for describing actual load-bearing behaviour under real conditions. These measurements revealed plausible bridge behaviour – the stresses in the warm months of the year, on work days and during the day were greater than during other periods.

In May 2018, comparable measuring equipment was installed at another bridge section – with the aim of being able to quantify the long-term behaviour of the renovation measures and their impact on the entire bridge structure on the basis of specially defined indicators. The results are not yet available.

Estimation of the accumulated stresses or damage using the longitudinal strain gauges (blue) and the transverse strain gauges (red).

Source: Project "Monitoring of concrete constructions"

1.7. Need for action

1.7.1. Need for action in the areas of research and development

Some of the research conducted as part of the joint project "Low energy concrete" is basic research with a low degree of technological maturity. Further research and development efforts are therefore required.

For example, the activator developed in the laboratory to improve the processability and early strength of low-clinker concrete – the superplasticiser – must be upscaled and made marketable by construction chemicals companies.[1] The accelerated carbonation of low-clinker concrete relative to normal Portland cement concrete must also be further investigated and controlled[2] [3] so that these sustainable concrete varieties can also be used at a relative humidity of over 80 % without the risk of corrosion.

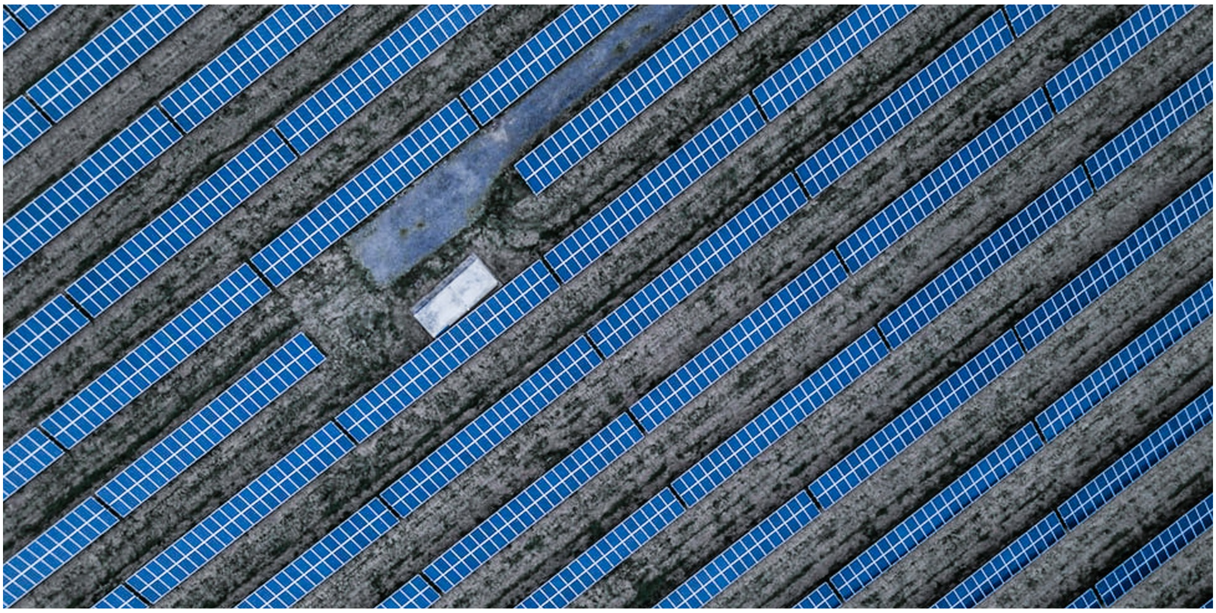
In the case of wood-concrete composite ceilings[4], the shear transmission between the beech board and the overlay must be made more ductile using an adhesive. With fibre prestressed beams[5], it is essential to increase the shear strength between the polyethylene fibre tendons and the concrete.

Only when these challenges have been met in a practical and economical manner will the new materials and structures be able to enter the market on a large scale.

Notes and References

1 Project "Low-clinker cements"
2 Project "Low-clinker cements"
3 Analysis of material samples
4 Project "Hybrid load-bearing structures"
5 Project "Pre-stressed carbon-fibre concrete"

1.7.2. Need for action in practice



Despite the still low degree of technological maturity of the building materials, constructions and processes developed as part of the joint project “Low energy concrete”, there is already a need for action in practice. Focus here needs to be placed on the following three areas:

Pilot and demonstration objects
If you can prove on a 1:1 scale that an innovation works, it is more likely to be accepted by builders, architects, engineers and contractors. This also applies to sustainable construction and all innovative measures aimed at reducing grey energy and CO_2 emissions. For a rapid transfer of the research results from the joint project “Low energy concrete”, pilot and demonstration objects are therefore required.[1]

Structural maintenance
The replacement or far-reaching conversion of existing structures requires an enormous amount of grey energy and leads to considerable CO_2 emissions. Corresponding measures must therefore be examined professionally with respect to their necessity and appropriateness and their implementation should be put back for as long as possible. For optimal decisions to be taken, the current condition and further development of the structure must be reliably known; visual inspections and taking some concrete drill cores are not enough.[2]

Knowledge and skills
Architects, engineers and contractors only apply new building materials, constructions and processes if they know them and feel that they are able to implement them correctly. In other words: without the relevant knowledge and skills, innovative measures aimed at reducing grey energy and CO_2 emissions are only applied very hesitantly. There is therefore an urgent need for the provision of information and training.[3]

Notes and References

1 Project "Low energy concrete"
2 Project "Monitoring of concrete constructions"
3 Project "Low energy concrete"

1.8. Building owners are called on to take action

1.8.1. The relevant stakeholders

With regard to the practical application of the new findings from the research work conducted as part of the joint project "Low energy concrete", the following main stakeholders are decisive:

Building owners
The building materials and technologies used in construction processes are primarily decided upon by the building owners – i.e. private individuals, organisations and businesses as well as the public sector. Generally speaking, decisions are made on the basis of recommendations from architects and engineers.

Planners and entrepreneurs
The architects, engineers and contractors commissioned by the building owners are just as important. This is because they have to trust the new building materials, constructions and processes and use them in their construction projects.

Associations
The professional associations are important in connection with the provision of information and further training to their members and the creation of the association's own standards.

The recommendations of the joint synthesis "Sustainable Concrete Structures" are therefore primarily aimed at these three stakeholder groups.

Building owners

1.8.2. Support demonstration projects!

NEST, the modular research and innovation building from the Swiss Federal Laboratories for Materials Science (Empa) and the Swiss Federal Institute of Aquatic Science and Technology (Eawag). *Source: Roman Keller*

The owners of buildings and infrastructure installations support the use of low-clinker concrete and concrete structures without steel inserts and share their experiences.

In the case of new buildings, conversions or renovations, building owners promote the use of building materials, constructions and processes that give rise to as little grey energy and CO_2 emissions as possible. In doing so, they make a substantial contribution to the sustainability of their buildings. They report on these demonstration objects and the experiences gained; in this way, they promote the rapid transfer of research results into practice.

Building owners

1.8.3. Professional building diagnosis is essential!

The owners of buildings and infrastructure installations are convinced of the added value provided by a professional building diagnosis and place their trust in it.

Structures can be used longer if they are carefully maintained. “Carefully” does not mean implementing the maximum in terms of maintenance, but rather what is necessary at the right time. To meet this requirement, periodic checks and professional diagnoses based on these inspections are required. This knowledge allows building owners to save a lot of money as they avoid excessive renovation and premature replacement measures.

Building owners

1.8.4. Economical renovation instead of demolition!

The owners of buildings and infrastructure installations examine comprehensively the necessity and appropriateness of the two options - maintenance or replacement - and, in cases of doubt, decide in favour of economical renovation.

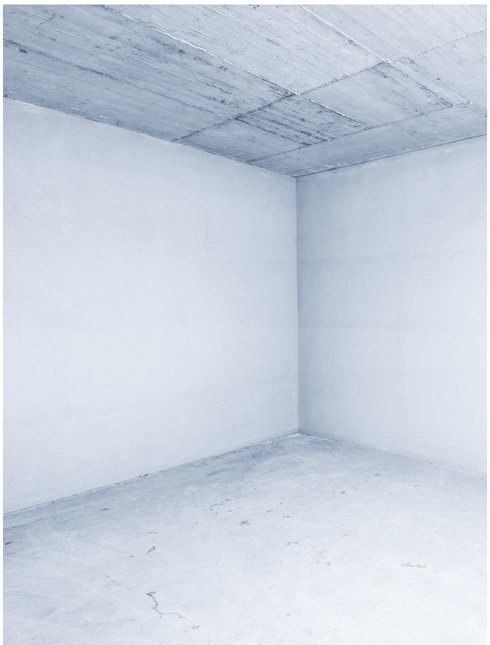
For sustainable building owners, potentially higher yields and the demodulation of buildings are no longer sufficient reasons for demolition and replacement measures. A holistic analysis quickly shows that the replacement option is associated with an above-average amount of grey energy and CO_2 emissions, whereas the renovation option performs much better – especially if the building materials, constructions and processes developed in the joint project “Low energy concrete” are applied.[1]

Notes and References

1 Synthesis on “Buildings and Settlements”

Building owners

1.8.5. Use low-clinker concrete inside buildings!



Architects and engineers are convinced by low-clinker concrete and use it in dry environments whenever possible – especially inside buildings.

As a rule, it is the civil engineers who specify the concrete formula to the contractor. However, the contractor can reject this suggestion and offer an alternative or pass on this responsibility to the building owner by means of a warning notice. As the person with overall responsibility for the building, the architect can also oppose innovative solutions. It is therefore crucial that planners and entrepreneurs trust innovative solutions, train themselves accordingly and summon up the courage to apply them.

Building owners

1.8.6. Use sustainable building materials for renovation!

Architects and engineers know the outstanding properties of the new ultra-high-performance fibre concrete with polyethylene fibres and use it whenever appropriate.

The ultra-high-performance fibre concrete with polyethylene fibres is market-ready and has already been used successfully several times. It combines all the advantages of conventional steel fibre concrete and, when OPTIMA cement is used, is characterised by around 70 % less grey energy and 80 % lower CO_2 emissions. The additional price of around 30 % relative to steel fibre concrete is compensated for in part by the 300 kilogram lower density. Architects and engineers are aware of these advantages and primarily use this building material for the renovation of floor slabs and carriageway slabs as well as for the production of highly stressed floor coverings and prefabricated concrete elements in tunnels and outdoors.

Associations and NGOs

1.8.7. Promote the provision of information and further training!

Professional associations inform their members about grey energy and CO_2 emissions during the construction, renovation and demolition of buildings and infrastructure installations – and provide them with further training in this area. If necessary, they commence standardisation work at an early stage.

Professional associations are obliged to keep their members up to date in terms of the latest knowledge and architectural developments. It is therefore primarily up to them to offer information and further training on issues relating to grey energy and CO_2 emissions as well as on new technical solutions for the construction, renovation and demolition of buildings and infrastructure installations. Professional associations, that are also active in the field of setting standards, must meet the need for standardisation which has been identified at an early stage.