Infrastructure

Science topic n°1

Can concrete **be green?**

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Université Gustave Eiffel

CAN CONCRETE BE GREEN?

Consumption of concrete currently stands at three tonnes per person per year, making it the world's most used manufactured material, and this figure continues to rise, fuelled by emerging countries. It behaves like liquid rock at ambient temperatures, making it uniquely straightforward to use and therefore difficult to replace. In France more than 80% of our buildings are made of concrete.

Its generalized use is not without impacts, for example on CO_2 emissions, mainly due to the manufacture of cement, or the production of mineral wastes after deconstruction.
In this context, it is urgent to explore possible ways of producing green concrete. First, IFSTTAR is working on re-using demolition concrete as aggregates, developing ways of treating the concrete that trap the CO_2 in order to improve the quality of the aggregates and the total life cycle emissions of the material. For the more distant future, IFSTTAR is also working on materials that can replace Portland cement, which is the "glue" used in present-day concrete.
Before these new cements and concretes can be used on an industrial scale they must be tested and accepted by the construction sector and demonstrate that they are compatible with modern construction techniques.

> **"In this context, it is urgent to explore possible ways of producing green concrete."**

▲ Demolition by pliers

Pictures: Yves Soulabaille / Genier Deforge and Ifsttar

1 CONCRETE. AN ESSENTIAL MATERIAL, WHICH CONTINUES TO ADAPT TO THE TIMES

By Henri Van Damme
and updated by Jean-Michel Torrenti,
Director - MAST[1] Department

It is hard to imagine France without concrete…

France has an enormous intertwined road system made up of some 7,000 km of motorways, 12,000 km of main roads and a network of secondary roads that totals not far from 1 million km. In addition, the high speed rail network is almost 2,000 km long and the conventional rail network is over 15,000 km. This infrastructure coexists thanks to 230,000 road bridges and 50,000 rail bridges. It needs more than 50,000 retaining walls and makes more direct connections due to almost 1,000 km of tunnels. Furthermore, as 10% of our energy is from hydro schemes and 80% is from nuclear power plants, we also have over a thousand dams of all sizes and some sixty nuclear reactors. And the drainage system for our waste water, which is almost entirely underground, is as dense as the surface infrastructure. This huge set of assets is essential for the country to run smoothly. Apart from the roads, this system relies mainly on concrete and steel (which are closely linked). Removing concrete from our country would instantly return us to the pre-industrial age.

The characteristics of concrete

Concrete is a genuine artificial rock, and incomparably easy to use. It consists of a mixture of stones (known technically as “aggregate”), sand, a glue (cement) and water. To begin with it is liquid enough to take on any form and hardens spontaneously in a reasonable amount of time, even under water without needing to be either heated or cooled. This ease of use explains its ever-increasing importance at a global level. Currently, every inhabitant of the planet uses almost 1 m^3 per year. As a result of the development of emerging countries, this consumption is likely to double between now and 2050.

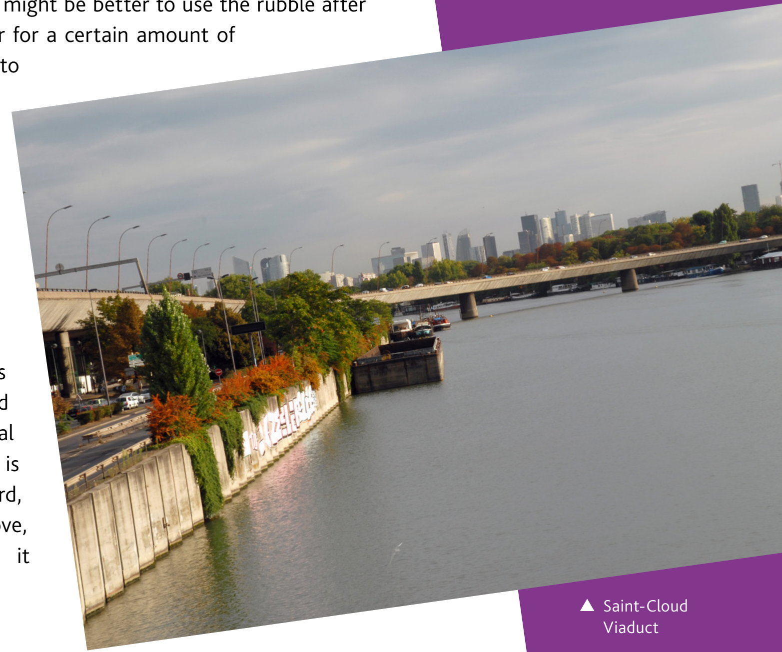
Some limits

There are nevertheless some limits to this universal use. First, the manufacture of today's cement (known as Portland cement) which involves a high temperature reaction between clay and calcareous rocks creates non-negligible amounts of CO_2 (5 to 7 % of global emissions[2]). Second, the aggregates, which form the skeleton of the concrete, are non-equitably distributed and a resource which is far from inexhaustible. Finally, using recycled aggregates in situ in the context of reconstruction is also beneficial from the point of view of CO_2 emissions point of view.

The need to optimise use

Recycling deconstructed concrete may therefore be something we should consider.

Reusing aggregate and the smaller particles obtained by crushing construction concrete waste is less simple than it seems. The strength of concrete depends, to a very high degree and according to precise laws, on how the particles of different sizes are stacked. Any change in the size, shape or simply the roughness of the particles changes the stacking structure and strength of the concrete. Understanding and controlling these changes in order nevertheless to obtain concrete that is as strong as first generation concrete is an initial topic on which IFSTTAR's researchers are engaged. But rather than directly recycling aggregates, sand and potentially cement in order to make new fresh concrete, it might be better to use the rubble after leaving it exposed to the air for a certain amount of time or by subjecting them to an accelerated carbonation treatment. In this way, CO_2 is reabsorbed by the cement which is re-carbonated. The rubble hardens at the same time forming much better quality aggregate. This technique represents a clear improvement, both as regards CO_2 emissions and the conservation of natural resources. The principle is appealing and straightforward, but, as was the case above, more complicated than it seems.



▲ Saint-Cloud Viaduct

1. MAST: Department Materials and Structures of Ifsttar
2. Which is both a little and a great deal as no other material which is as easy to use and that is available in such quantities would have such a low impact.

Picture: Ifsttar

Article Update: november 2018

2 THE SEARCH FOR NEW SUBSTITUTE MATERIALS FOR CEMENT

By Nicolas Roussel,
Senior Researcher - MAST[1] Department, FM2D[2] Laboratory

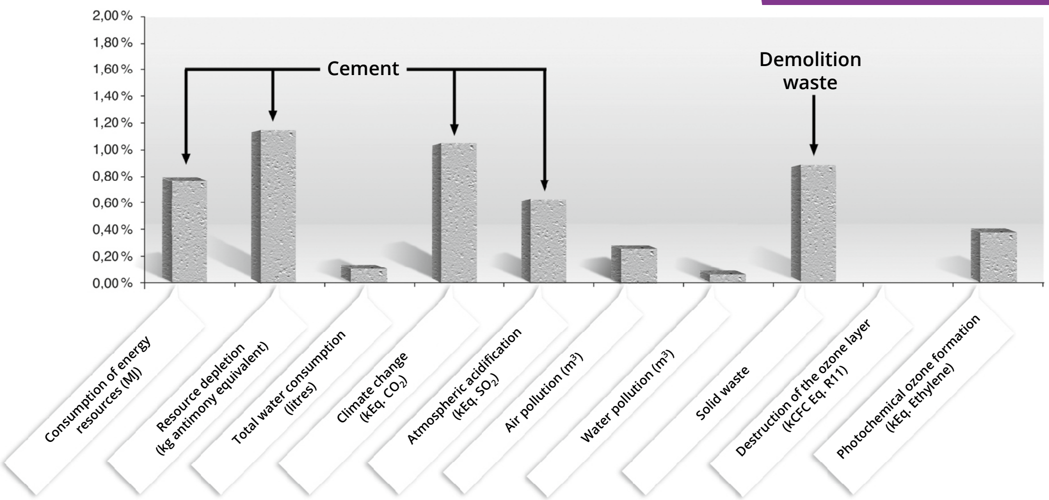
The goals of reducing greenhouse gas emissions and increasing the contribution of renewable energies are political and legislative responses to the concerns of civil society about the environmental impacts of human activities.
These goals have a general impact on our future development but also, more specifically, on the way in which we construct our buildings and infrastructure. In France, most engineering structures and buildings are made out of concrete. At a global level, our annual consumption of 3 tonnes of concrete per person makes it the most consumed manufactured material.
This is justified by the low energy cost and hence the low economic cost of concrete manufacture. The fact that its constituents are available all over the planet's surface also partly explains this success. However, as far as sustainable development is concerned, this situation with regard to manufacture and consumption means that the relationship between concrete and the environment constitutes a major issue.

Environmental impacts of the use of materials

Figure 1 takes a reinforced concrete beam from an apartment block as an element that represents a concrete structure. The different environmental impact data have been normalised with respect to those of a European citizen in 1995. This shows that the production of cement and the demolition of concrete constitute the principal environmental impacts of this functional system.
It is possible to foresee some of the ways in which cement will change as a result of the implementation of policies to reduce environmental impacts.

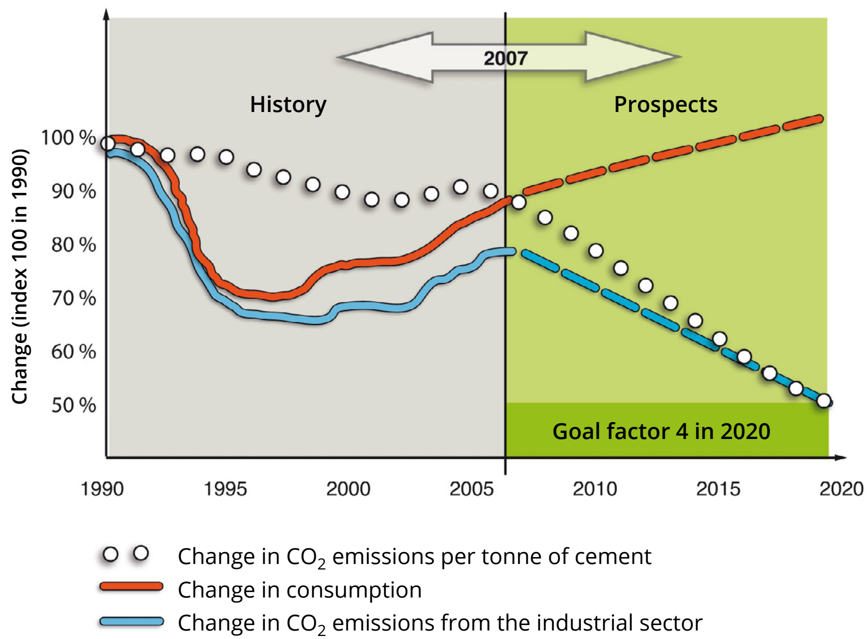
Using new technologies to limit harmful impacts

The CO_2 emissions are mainly due to the kilning and decarbonation of limestone that is required to produce conventional cement. IFSTTAR has shown recently that today's industry, taking account of its growth and potential technical developments, could produce cementitious materials that meet the criteria for CO_2 emission reductions that have been set for the intermediate stage of 2020 (see Fig. 2).
However, current technology will not be able to reach the criteria fixed for 2050. While the next 10 years will be dominated by "technological development", a "technical revolution" therefore seems inevitable in the longer term.



▲ Figure 1. Standardised environmental impacts, compared to those of a European citizen, for a reinforced concrete beam for collective housing (Ifsttar).

THE SEARCH FOR NEW SUBSTITUTE MATERIALS FOR CEMENT (END)



▲ Figure 2. Change in the impact of climate change per tonne of cement. History and prospects (Ifsttar).

A revolution: replacing cement with new binders

Much of IFSTTAR's research focuses on the technological development that is necessary in the short term. This involves reducing the amount of conventional cement in concrete mix designs. Some ways of achieving this include more systematic use of blended cements, the use of other industrial wastes and the substitution of cement with large proportions of one or more mineral additions such as blast furnace slag, fly ash or other industrial wastes.

In the longer term, the "technological revolution" could be brought about by the use of alternative binders such as geopolymers or sulpho-aluminous clinkers[3]. These materials have very low environmental impacts and could therefore replace conventional Portland cement. The knowledge and expertise required to deal with such topics within IFSTTAR are now mature.

Ultimately, our Institute will generate knowledge which will do away with concerns about the use of these materials by demonstrating their compatibility with modern construction processes and by a quantitative evaluation of their environmental impact throughout their life cycle (production, placement and deconstruction).

1. MAST: Department Materials and Structures of Ifsttar
2. FM2D: Mix-design, Microstructure, Modelling and Durability of Building Materials Laboratory
3. Sulpho-aluminous cements are marked out by the absence of some chemical phases that are characteristic of Portland cement. Sulpho-aluminous clinker contains less lime and silica but more hydrated calcium sulphate (gypsum) and non-hydrated calcium sulphate (anhydrite). It is therefore responsible for a reduction in CO_2 emissions of about 40% during its manufacture, due to the use of a raw meal with a lower limestone content and kilning temperature.

Further readings

G. Habert, N. Roussel, Comment concevoir un béton ayant un faible impact environnemental ? Annales du BTP, 4 (2008), 12-16.

G. Habert, N. Roussel, Study of two concrete mix-design strategies to reach carbon mitigation objectives, Cement & Concrete Composites, 31 (2009), 397–402.

3 THE PHYSICS OF MATERIALS FOR LOW ENVIRONMENTAL IMPACT CEMENTS

By Hela Bessaies-Bey,
Researcher in the physico-chemistry of materials - MAST[1] Department, CPDM[2] Laboratory

Our society relies essentially on the use of concrete for construction. It is becoming vital to limit its harmful environmental impacts. The challenge lies in the manufacture of cement, which is a significant source of CO_2. Cement is a binder which, like glue, sticks the ingredients of the concrete together. IFSTTAR researchers are working to ensure that the introduction of low environmental impact cements does not degrade the fundamental properties of concrete.

Low environmental impact cements

The production of low environmental impact cement is a major challenge for today's society. To some extent it can be solved by removing a part of the clinker (the main component of cement) from the mixture. One of the most promising options is to replace it with by-products from other industries (slag, silica fume, glass waste, agricultural waste, etc.) or natural minerals (limestone, clay, bauxite, etc.). This area of research has been the subject of many scientific publications[a, b] and a gradual change in the standards.

However, some questions remain about the effect of these materials on concrete flow (rheology). They are mainly related to the diversity of the products and their proportioning[c]. The behaviour of these new cements in the fresh state (i.e. before the cement sets) has a significant impact on the different stages of concrete placement (mixing, pumping, formwork, etc.). An uncontrolled behaviour of concrete at the fresh state can considerably impact its performances at the hardened state (mechanical strength and durability).

Behaviour under close surveillance

The flow of a cement paste (rheological behaviour[d]) is dictated by the physical properties of the aggregate particles (size distribution, shape, specific surface area, density, etc.), the physico-chemical interactions between the particles which are influenced by the packing density (the fraction volume that is filled by solid particles). These parameters must therefore be taken into account and may be modified when the clinker is substituted, even partially, by another product.

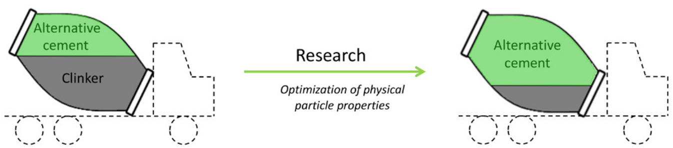
Research thus makes it possible to identify and classify the physico-chemical phenomena that are modified by the use of mineral additions. The findings allows for the development of new ways to control the fresh behaviour of these alternative cements.

Materials with ever-increasing performance

The physical properties identified by the study (shape, size distribution, packing density and specific surface area) allow the producers of industrial by-products or natural minerals to improve the performance of their materials. By improving the way the particles are crushed, filtered or separated, it is possible to make their use in cement much more attractive.

This work allows for the optimization of the choice of new binders and the quantity required to produce a more environmentally-friendly concrete. New perspectives are being opened up for green concrete.

▲ Poured concrete in construction



◄ Decreasing clinker amount in low environmental impacts cements

1. MAST: Department Materials and Structures of Ifsttar
2. CPDM: Division for Material Physicochemistry

Further readings

a. *M. C.G. Juenger, R. Siddique, Recent advances in understanding the role of supplementary cementitious materials in concrete, Cement and Concrete Research 78 (2015) 71–80.*
b. *B. Lothenbach, K. Scrivener, R.D. Hooton, Supplementary cementitious materials, Cement and Concrete Research 41 (2011) 1244–1256.*
c. *R.J. Flatt, N. Roussel, C.R. Cheeseman, Concrete: An eco material that needs to be improved, Journal of the European Ceramic Society, 32 (2012) 2787-2798.*
d. *N. Roussel, A. Lemaitre, R.J. Flatt, P. Coussot, Steady state flow of cement suspensions: A micromechanical state of the art, Cem. Concr. Res. 40 (2010) 77–84.*

Pictures: Ifsttar and Epictura

Article Update: november 2018

4 EXPLORING THE POSSIBILITIES OF AGGREGATE

*By **Jean-Michel Torrenti**,*
Director - MAST[1] Department

Aggregate is the main constituent of concrete, accounting for approximately two-thirds of its mass. However, demand for aggregate is extremely high in large urban areas. For example, Paris and its inner suburbs consume 13 million tonnes of aggregate every year (the UNPG White Book) and this requirement will increase in future years. It has been estimated that this figure will increase by 5 million tonnes per year (DRIEE Ile-de-France) as a result of the Grand Paris project. This comes at a time when the Paris Region is already short of resources and imports almost half the aggregate it consumes. Concrete accounts for 42% of total aggregate consumption. It therefore follows that using less aggregate to manufacture concrete will be an important issue in the future. Below we will describe a few ways of achieving this that are being explored by research at IFSTTAR.

Recycling concrete in concrete

While demand for aggregates is increasing, the volume of waste generated by deconstruction is increasing and will become very large in the years to come. Approximately a third of this waste consists of cementitious materials but little use is made of them to remanufacture concrete. However, the environmental cost of this waste is increasing which justifies the research which has been carried out to show that its environmental impact can be reduced by recycling. This explains why, as early as 2008, IFSTTAR began to conduct research in partnership with the profession with a view to optimising the mix design of concrete with recycled aggregate (more information about Duc-Tung Dao's thesis is available in No 122 of the journal Routes). Research in this area is continuing, in particular since 2012 in the framework of a national project known as RECYBETON (RECYclage complet des BETONs – Complete Recycling of Concrete – www.pnrecybeton.fr). The goal of this project, which brings together industry and research centres including IFSTTAR, is to increase the re-use of materials obtained from demolition concrete in new concrete.

Supplementing the national Recybéton project, ECOREB (ECOconstruction par le REcyclage du Béton – Ecoconstruction through the recycling of concrete)) is an ANR project which sets out to develop new tools, drawing on our existing knowledge about conventional concretes. The aim is to quantify the amount of water required by recycled aggregate from concrete and to characterise the quality of paste-aggregate interfaces. The project also aims to provide a tool for predicting the strength of recycled concrete, in particular how it responds to endogenous stresses (shrinkage, heat of hydration, etc.) and external stresses (mechanical loads, snow, etc.).

Also worthy of mention is the ANR CRAC project (Carbonated Recycled Aggregates for Concrete), which deals with the capture of CO_2 by the aggregate from recycled concrete and the national FastCarb project, which is studying the accelerated recarbonation of recycled concrete aggregates. The process in question improves the physical and mechanical characteristics of these aggregate and optimises the CO_2 balance of the concretes. The combined outcome of these research projects aims to promote the recycling of concrete and thereby conserve natural resources of aggregates.

Contacts: Bogdan Cazacliu (process), Thierry Sedran (mix design), Assia Teguer (ECOREB)

The use of excavated aggregates: the LTF (Lyon Tunnel Ferroviaire) tunnel

The planned rail link between Lyon and Turin, of which the company LTF is the promoter, will include two tunnels with a combined length of 65 km. Digging these will produce 18.8 million m^3 of spoil. In the interests of sustainable development, almost a quarter of the spoil should be recycled as aggregate for the concrete lining of the tunnels. Apart from its economic advantages, this solution avoids the creation of new quarries and limits the amount of spoil and aggregate that is transported by road.

However, the spoil has a sulphate content that is between 10 and 20 times higher than that recommended by current standards, and this may cause the concrete to deteriorate as a result of the formation of expansive products such as ettringite and thaumasite[2]. Consequently, IFSTTAR's Materials and Structures Department is participating in a research partnership with LTF, the cement manufacturers HOLCIM and VICAT and LERM. The goal is to improve our understanding of the behaviour of the sulphates in the aggregate and develop new concrete mix designs that are appropriate for these aggregates in order to avoid deterioration problems arising from environmental conditions.

However, the recycling of tunnelling spoil must not be conducted to the detriment of the other characteristics and durability a structure of this type requires. In addition to this research, a comprehensive predictive performance assessment of the durability of the selected concrete mix designs will be carried out on the basis of the recognised durability indicators given in the AFGC guide « Conception des bétons pour une durée de vie donnée des ouvrages » (Design of concrete for structures with a given service life).

Contact: Loic Divet

Video (FR)

▲ Sustainability of bio-sourced materials

Picture: Thomas Rault et Ifsttar

Article Update: november 2018

1/2›

EXPLORING THE POSSIBILITIES OF AGGREGATE (END)

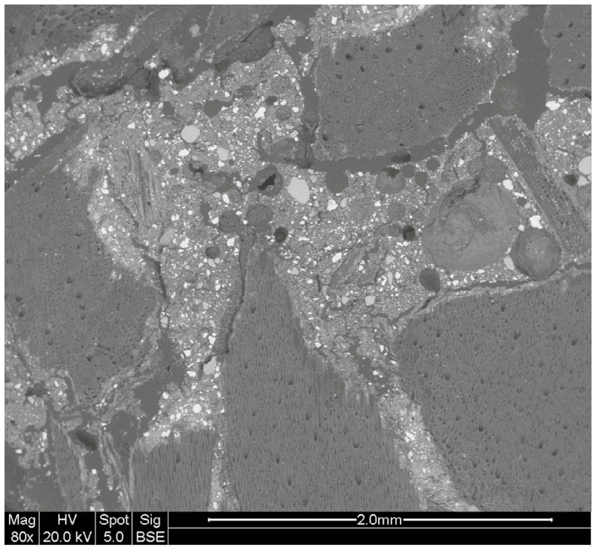
Bio-based materials

In order to reduce the environmental impact of construction materials and improve the energy efficiency of buldings, the use of vegetal aggregates is recommanded. Vegetal aggregates, which are mainly sourced from agriculture, are coated with lime based mineral binders to form insulating materials, known as "vegetal concretes".

Using these materials reduces a building's overall environmental footprint and is of value in many respects, improving thermal and acoustic performance and reducing the weight of the construction. They also store CO_2 throughout their service life. However, there are many outstanding obstacles that restrict the development of this type of ecomaterial. More knowledge about their ageing is needed, since the first constructions using these materials only date back to 1985-90.

This explains why IFSTTAR is conducting research on their durability. This is mainly concerned with the change in their properties according to their conditions of use. For a two-year period, specimens of hemp concrete were subjected to several phases of accelerated ageing in the laboratory. Their mechanical, thermal, acoustic and moisture regulating properties were characterized and correlated to their chemical composition and microstructure. These new insights have made it possible to demonstrate the stable performance of these vegetal concretes in environments that are representative of their actual conditions of use.

Contact: Sandrine Marceau



◀ Microstructure of hemp concrete under the scanning electron microscope

Consult

▲ consult on https://reflexscience.univ-gustave-eiffel.fr

1. MAST: Department Materials and Structures of Ifsttar
2. Ettringite and thaumasite are two mineral compounds which are created when certain phases of the hydrated cement are attacked by sulphates. Ettringite can expand and cause the concrete to crack. Thaumasite causes a reduction in the mechanical strength of the concrete by consuming hydrated calcium silicates. The conditions under which these compounds are formed depend both on the design of the concrete and the environmental conditions.

Further readings

Delannoy, S. Marceau, P. Glé, E. Gourlay, M. Guéguen-Minerbe, D. Diafi, I. Nour, S. Amziane, F. Farcas, Influence of binder on the multiscale properties of hemp concretes, European Journal of Environmental and Civil Engineering (2018) doi.org/10.1080/19648189.2018.1457571.

Pictures: Ifsttar

Article Update: november 2018

5 CAPTURING CO_2 WITHIN THE MATERIAL

By Mickaël Thiéry
and updated by Jean-Michel Torrenti,
Director - MAST[1] Department

Every kilogramme of cement produced in a cement factory generates an average of between 0.6 and 0.7 grammes of CO_2. In view of the enormous amounts of cement that are produced worldwide, the cement industry is responsible for between 5 and 7% of anthropic CO_2 emissions. Almost half of these emissions are due to the chemical nature of the cement's principal ingredient, clinker, which is obtained by decarbonating limestone[2].

The carbonation of concrete

Hydrates are formed when water is mixed with cement, and these are what give concrete its strength. Atmospheric CO_2, even though it is present in very small quantities (0.038%), causes slow irreversible carbonation[3] of these hydrates. Over geological timescales, carbonation is thus capable of chemically trapping some of the CO_2 that is emitted at the cement factory when the limestone is calcinated. Carbonation nevertheless has various consequences depending on whether it occurs when the concrete is in service or after demolition.

IFSTTAR has been working for many years on the carbonation of in-service concrete in the case of reinforced concrete structures. Atmospheric CO_2 diffuses within the porosity of the concrete and dissolves, forming acids on contact with the interstitial solution. The main consequence of this is to lower the pH of the medium and corrode the reinforcing steel. IFSTTAR has developed models to predict lifetime in relation to corrosion risk. These can be used during concrete mix design or when dimensioning structures, etc.

Video (FR)

▲ How can concrete be recycled?

◄ Storage place for demolition concrete

▲ Example pathologies (spalling) of reinforced concrete due to reinforcement corrosion induced by carbonation.

Pictures: Ifsttar

Article Update: november 2018

CAPTURING CO_2 WITHIN THE MATERIAL (END)

A godsend for improving the carbon balance of concrete

Although carbonation has adverse impacts on the durability of reinforced concrete structures, the process can be beneficial as far as the concrete itself is concerned. In the case of members that contain no reinforcement, carbonation can help to capture CO_2 and improve the carbon balance of the concrete. IFSTTAR has been working on the positive aspects of carbonation in work that has been funded by the National Research Agency (ANR) – the CRAC project (Carbonation of Recycled Aggregates of Concrete) which ended in 2013 and which was awarded the Eugène Freyssinet Prize in 2011.

Concrete has a natural ability to capture CO_2, but in a structural member in a building the reaction takes place on a very small surface area and is therefore extremely slow. However, when concrete is crushed during demolition, the surface area that interacts with the atmosphere increases and the reaction that traps CO_2 takes place more quickly.

Since 2018, the national FastCarb project has been studying ways to further accelerate this CO_2 recovery, in order to recover about 20% of the CO_2 initially released during the manufacture of a given concrete, i.e. 40 to 60 kg of CO_2 per m^3 of concrete. In collaboration with many partners, IFSTTAR is studying how the process can be optimised. The project will also provide an industrial-level demonstration and applications on sites using recycled aggregates.

The use of demolition concrete aggregate

Carbonation also has another advantage: it improves the microstructural and mechanical properties of the concrete. Consequently, when CO_2 capture has been optimised, the recycled aggregate is of better quality and can be used to manufacture more concrete. This is an undeniable benefit in view of the large number of buildings in France that are reaching the end of their service life and which will have to be destroyed. IFSTTAR is therefore working on the use of carbonation to improve the properties of demolition concrete aggregate with a view to recycling it to remanufacture concrete.

Consult

Accelerated re-carbonation of concrete

Further readings

M. Thiéry et al., Comment intégrer quantitativement la carbonatation atmosphérique dans le bilan carbon des bétons ? Conférence GC'2009 organisée par l'AFGC, 18 et 19 mars 2009, Paris.

M. Thiéry et al., Carbonation Kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials, Cement & Concrete Research, 2013.

J.M. Torrenti, Carbonatation accélérée de granulats de béton recyclé : le projet FastCarb, conférence Nomad 2018, Liège.

1. MAST: Department Materials and Structures of Ifsttar
2. Limestone ($CaCO_3$) is, with clay, the raw material from which clinker is made. The manufacture of clinker requires the limestone to be decarbonated at around 900°C in a kiln in the cement factory ($CaCO_3 \rightarrow CaO + CO_2$). Its manufacture therefore produces CO_2 chemically, to which is added the CO_2 that is generated by the combustion required to heat the kiln.
3. Carbonation involves the transformation of the hydrates in the cement into limestone (calcium carbonate $CaCO_3$) due to the chemical action of atmospheric CO_2.

Picture: Ifsttar

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