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RiskADAPT Project – Task 4.1 – Low Carbon Structural Adaptation Options regarding precast concrete products – Main opportunities and technical data

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1 INTRODUCTION

One of the main objectives of the European project Riskadapt project is to identify eco-friendly solutions, to offer more resilient alternatives in anticipation of extreme weather conditions.

In this report, five main solutions based on the use of precast concrete products are presented. These solutions offer generally a lower carbon footprint compared to the traditional solutions that are currently used and provide a more conscious resource management.

Cases presented in part 3 used the two following standards:

- EN 15804+A2 (2009): Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products;
- EN 16757 (2022): Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements.

2 5 MAIN OPPORTUNITIES REGARDING LOW CARBON ADAPTATION REGARDING PRECAST CONCRETE PRODUCTS IN LITERATURE

2.1 Low carbon binders

The current state-of-the-art in the cement and binders industry accounts several areas that are gradually optimized to reach a better carbon footprint efficiency.

The first angle is the re-evaluation of the energy used in the industry.
The main thermal energy demand for the clinker production is due to the endothermic reactions of the raw materials that require temperatures of up to 1450°C for the formation of stable clinker phases, and the drying of the raw materials which depends on their moisture content.
The specific fuel energy demand of clinker burning may decrease on average from 3510 MJ/t clinker in 2014 to a level of 3300 to 3400 MJ/t clinker in 2030 and of 3150 to 3250 MJ/t clinker in 2050. In addition to the building of new modern kilns in Asia and Eastern Europe, the technical equipment of older cement kilns in Europe is often replaced every 20 to 30 years and adapted to modern technology.

The electric energy efficiency is also to be considered. The dry processing consists mainly in raw material extraction, raw material preparation and cement grinding. The grinding processes have the most significant impact on the total electric energy demand.
The cement's performance also has an impact on the power consumption, as the higher the cement's strength development, the finer it has to be ground, requiring significantly more energy in the mills. In the burning process, an increase in the thermal efficiency leads to an increase in the energy demand.
The specific electric energy demand of cement production may decrease from 104 kWh/t of cement in 2014 to a level of about 100 kWh/t of cement in 2030 and to 90 to 95 kWh/t cement in 2050 on average, thanks to the technological updates.
Alternative fuels containing biomass present a CO_2 reduction potential, as many alternative fuels exhibit a certain biomass content of which the CO_2 emission factor is accounted zero, and most of them have lower CO_2 emissions than coal or petcoke.

The potential of CO_2 reduction has been estimated for some developing technologies as follows[1]:

- Alternative fuels (including biomass) replacing conventional fossil fuels: biomass content in waste fuels is often considered as CO_2 neutral. Biomass fuels include waste wood, rice husk, saw dust, sewage sludge, animal meal but also pre-treated industrial and domestic wastes as well as waste tyres which contain 20 to 35% of natural rubber.
  - *The direct CO_2 reduction potential is a decrease of 30 to 50 kg CO_2/t of clinker, for a fuel mix including 30% to 40% biomass.*
- Gasification or pre-combustion of alternative fuels: these processes allow for more flexibility on fuel quality with regard to homogeneity, calorific value, moisture content, hazardous contents or sizes.
  - *The direct CO_2 reduction potential is a decrease of 40 to 45 kg CO_2/t of clinker, for a use of alternative fuels of 0.1 to 0.15 t/t of clinker.*

[1] *European Cement Research Academy; Cement Sustainability Initiative, Ed. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead; CSI/ECRA-Technology Papers 2017. Duesseldorf, Geneva, 2017 Available at: https://ecra-online.org/research/technology-papers*

Various technologies are also being developed to optimise the different processes in the cement production:

- Improvement of raw mix burnability: mineralisers in the raw material mix promoting clinker formation can have an important influence on the burning behaviour, by lowering the viscosity of the melt at the same temperature and also lowering the temperature at which the clinker melt begins to form, and the fuel energy demand.
    - *The direct CO_2 reduction potential is a decrease of 4 to 16 kg CO_2/t of clinker.*
- Change from long kilns to preheater/precalciner kilns: Compared to long dry and wet kilns, the preheater technique with 3 to 6 cyclone stages improves the calcining efficiency by drying and preheating the raw material using the kiln exhaust gas.
    - *The direct CO_2 reduction potential is a decrease of 80 to 250 kg CO_2/t of clinker.*
- Additional preheater cyclone stages: the preheater cyclone is designed for heat transfer between hot gases from the burning process and kiln feed. An additional cyclone stage can lead to energy savings by reducing the temperature of the hot gas through heat recovery.
    - *The direct CO_2 reduction potential is a decrease of 7 to 9 kg CO_2/t of clinker.*
- Increase of kiln capacity: as the clinker-specific energy requirement is directly dependent on the dimension of the cement plant, an increase of the kiln capacity is linked to a reduction of specific CO_2 emissions.
    - *The direct CO_2 reduction potential is a decrease of 13 to 18 kg CO_2/t of clinker.*
- Retrofitting mono-channel burner to modern multichannel burner, as the multichannel burner requires lower primary air volume flow.
    - *The direct CO_2 reduction potential is a decrease of 2,2 to 6,5 kg CO_2/t of clinker.*
- Oxygen enrichment technology: oxygen-enriched combustion air in the clinker burning process allows an increase in the energy efficiency, production capacity or substitution of fossil fuels, which avoids CO2 production.
    - *The direct CO_2 reduction potential is a decrease of 9 to 15 kg CO_2/t of clinker.*
- Efficient clinker cooler technology: in cement production the energy of the hot clinker leaving the cement kiln is transferred in the clinker cooler where the clinker enthalpy is used for heating up the combustion air.
    - *The direct CO_2 reduction potential is a decrease of 22 to 26 kg CO_2/t of clinker.*

As a second angle to decreasing the carbon emissions in the cement industry, the clinker content can also be gradually optimized, with the use of alternative materials in the binder composition. The reduction of the clinker content in the cement or in the binder can be achieved with mineral materials:

- Pozzolanas are materials of volcanic origin, clays, shales, or sedimentary rocks with suitable composition, that can be activated by thermal treatment. Pozzolanas contain siliceous or silico-aluminous phases which can react in the cement paste and contribute to strength development. The electric energy demand is slightly lower because of the better grindability of most pozzolanas compared to the replaced clinker, and therefore the thermal energy demand of the binder production decreases with an increase in the pozzolana.
  The early strength of binders that contain pozzolanas depends on the proportion of pozzolana. These materials confer an improved workability, a higher long-term strength, and a better chemical resistance.
  In practice the proportion of pozzolana in technically used binders in Europe is usually in a range of 15 to 35% in mass.

Synergetic effects of combinations of calcined clays and ground limestone as supplementary cementitious material have also been demonstrated.
Other pozzolanic reacting materials are identified that are only relevant on a local scale: rice husk ash, palm oil ash, burnt shale.
The CO_2 footprint of natural pozzolana is estimated between 30 and 60 kg eq CO_2/t, and between 139 and 239 CO_2/t for calcined pozzolana.

- *The direct CO_2 reduction potential is:*
  - ✓ *a decrease of up to 90 kg CO_2/t of cement for natural pozzolana, with an input of natural pozzolanas of up to 0.35 t/t of cement,*
  - ✓ *a decrease of up to 73 kg CO_2/t of cement for a use of calcined clay without limestone up to 0,35 t/t of cement,*
  - ✓ *and a decrease of up to 180 kg CO_2/t of cement for a use of calcined clay combined with limestone of up to 0,50 t/t of cement.*

- The use of limestone in binder is an efficient method to reduce the clinker/binder ratio and leads to a better workability of the concrete. However, it does not contribute to the strength formation of the hardening paste, and the amount of limestone is decisive for the resistance of the hardened paste to acids and sulphates and its freeze-thaw-resistance.
  Synergetic effects of optimised combinations of calcined clays and ground limestone as supplementary cementitious material have also been demonstrated, as the co-addition allows a clinker reduction of up to 50% maintaining similar performance to existing binders.
  The CO_2 footprint of limestone is estimated between 30 and 60 kg eq CO_2/t, depending on the fineness.

There are other unstandardized possibilities offered by calcium silicates, that are based on globally available raw materials (limestone and quartz). Low lime calcium-silicates can be burnt at lower temperatures than Portland cement clinker (about 250 °C lower), and the active carbonation of the silicates via CO_2 rich atmosphere at ambient gas pressures, during the concrete curing, serves as an effective CO_2 sink. This technology has to be used near CO_2 emitters using carbon capture and utilization technologies and seems suitable for precast plants. Another approach consists in intergrinding autoclaved non-hydraulic CHS-precursors with unreactive silica-rich substrates to generate a core-shell product with a hydraulically active rim. The CO_2 saving potential is induced using a filler core instead of complete clinker particles. These new methods are currently under development.

The cement industry produced EPDs for the main current cements, as showed in the table 1 (French case).

Cements	GHG emissions (kg CO_2 eq / t)	% of clinker (in this EPD)	% of other secondary constituents	Main secondary constituents
CEM I	827	98.2%	1.8%	
CEM II/A-L or CEM II/LL	714	85.7%	14.3%	Limestone
CEM II/A-S or CEM II/A-M or CEM II/A-V	696	84.5%	15.5%	Blast furnace slag or Fly ash or Calcareous and pozzolana compounds
CEM II/B-L	602	70.9%	29.1%	Limestone
CEM III/A	565	54.8%	45.2%	Blast furnace slag
CEM III/A-PM or CEM III/A-ES	389	35.3%	64.7%	Blast furnace slag
CEM III/B	339	29.8%	70.2%	Blast furnace slag
CEM III/C	225	15.4%	84.6%	Blast furnace slag
CEM V/A (S-V)	518	55.3%	44.7%	Blast furnace slag and Fly ash

Table 1. Greenhouse gas emissions and main composition of the main current cements in France

The third angle is the use of CO_2 capture and storage technologies that are currently under development. There are various CO_2 capture technologies, and some appear to be more appropriate for a potential application at cement kilns than others. Most of these technologies are at a pilot stage or ongoing research activities:

- Post-combustion technologies, which are end-of-pipe measures that do not require fundamental changes in the clinker burning process, and can be applicable at new kilns and for retrofits at existing cement kilns,
- Calcium looping process, with a modified version that would be integrated in the preheater of a rotary cement kiln,
- Oxyfuel technology, with the use of oxygen instead of air in the cement kiln firing that would result in a comparatively pure CO_2 stream, which could be supplied to the transport and storage infrastructure with less effort for purification,
- CO_2 capture by photosynthesis (with algae) or photo-catalytic reduction of CO_2.

2.2 Industrial by-products as part of concrete composition

The decrease of clinker content can also be achieved with industrial by-products:

- Granulated blast furnace slag (GBFS): the molten iron slag is a by-product of the pig-iron production process. The product granulated blast furnace slag (GBFS) shows latent hydraulic behaviour, and its hydraulicity is activated by calcium hydroxide that is formed by the hydration of clinker. Binders containing GBFS exhibit generally a lower early strength when ground to the same fineness and a lower heat of hydration, but they also show higher long-term strength and particularly improved chemical resistance.

  As it is estimated in France since 2022 that there is an allocation of 1.4% from the cast iron production, the CO_2 footprint of GGBS is estimated in France to 100 kg eq CO_2/t, and to 83 kg eq CO_2/t for ground granulated GGBFS.

- *The direct CO_2 reduction potential is a decrease of up to 100 kg CO_2/t of clinker for a 10 to 15% replacement of raw materials by GBFS, and up to 390 kg CO_2/t of cement for a use of GBFS of 0.7 t/t of cement.*

- Fly ash (FA) is obtained by the electrostatic or mechanical precipitation of dust-like particles from the flue gases from furnaces fired with pulverised coal. Since the reaction of pozzolanic material is slower than that of clinker, binders containing fly ash typically show a lower early strength compared to ordinary Portland cement at similar fineness. They also exhibit a lower water demand, an improved workability, a higher long-term strength and - depending on the application - a better durability such as an increased resistance against sulphate attack.
  The CO_2 footprint of fly ash is estimated to 354 kg eq CO_2/t.
  - *The direct CO_2 reduction potential is a decrease of up to 90 kg CO_2/t of cement for a use of fly ash of 0.25 to 0.35 t/t of cement.*

- Silica fume, a by-product in the production of silicon and ferro-silicon alloys, is a very effective pozzolanic material because of its extreme fineness and its high silica content, but its worldwide availability is limited.
  The CO_2 footprint of silica fume is estimated to 47.5 kg eq CO_2/t.

The availability of these materials is limited, as they are already being used for conventional cement production for reduction of the clinker to cement ratio. The high sensitivity to different water contents makes alkali-activated binders difficult to use in ordinary concrete applications, as concrete aggregates are often wet to different extents. The properties of alkali-activated binders strongly depend on the starting material properties, their chemical composition, temperature, and moisture. Additional operational safety also has to be assured while working with alkaline activators on a building site. All these constraints make the precast concrete industry an interesting candidate to incorporate these binders in its concrete products.

There are also non standardized industrial by-products that are identified and under research:

- conversion steelworks slag, obtained during the refining of steel cast iron in converters, and that are mainly used in earthworks,
- cupola slag,
- foundry fine particles,
- paper mill sludge ashes,
- biomass boiler ashes,
- crushed glass.

2.3 Recycled aggregates derived from Construction and Demolition Waste

Today, the concrete waste resulting from deconstruction is mainly recycled into backfill, recycled coarse aggregates for road works, or even in quarry filling.

Standards are evolving towards a higher content in recycled aggregates in structural concrete, as the European concrete standard sets a foundation on which several European country norms are based to aim higher results. In France, for example, it is allowed to use up to 60% of recycled aggregates in structural concrete, depending on the exposure class. However, additional constraints have to be taken into account regarding for example the fire reaction of the concrete containing a certain proportion of recycled aggregates.

Recycled aggregates can also be derived from other industrial fields, as many materials can be diverted from waste to concrete:

- plant-based aggregates: hemp, flax, miscanthus, cork, rapeseed, bamboo,
- aggregates from other industrial sectors: slag aggregates, foundry sands, rubber aggregates, used or recycled textile aggregates,
- aggregates from other sources: aggregates from agricultural land or excavated soil, bottom ash aggregates, marine and river sediment aggregates.

Several European projects have been conducted these last years, with the participation of the BIBM, among them VEEP, RE4 and SeRaMCo projects.

In the VEEP project[2] (Cost effective recycling of Construction and Demolition Waste (CDW) in high added Value Energy Efficient Prefabricated concrete components for massive retrofitting of our built environment), several technologies have been developed or optimized to produce materials with an important amount of recycled C&D waste.

This project brought together several European academics and industrials, between 2016 and 2021, and developed different technologies focused on the circular economy in the construction field.
It resorts to the ADR (Advanced Drying Recovery) technology, which was previously developed by the previous European projects C2CA and HISER. This technology is based on a mechanical sorting system for wet crushed concrete, which directly recovers the coarse fraction of wet aggregates from demolition work. Kinetic energy is used to break the wet bonds between the fine fractions and the gravel. 3 separate fractions are produced: 4-12 mm ready to be used, 1-4 mm including wood or plastic impurities, and fines of 0-1 mm. The VEEP project developed a mobile version which can be directly used on the demolition sites, with a processing rate of 50t/h.

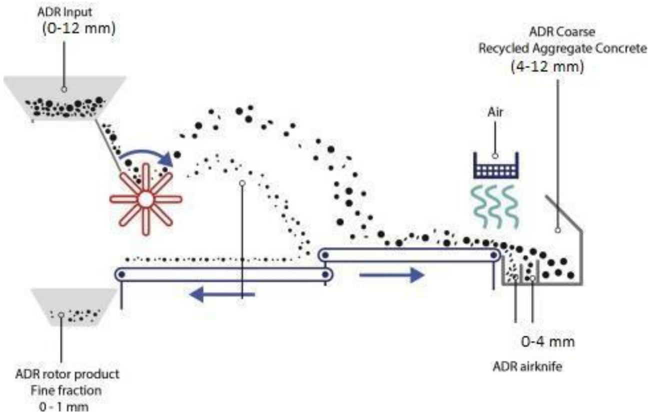

Figure 1. ADR technology

Combined to the mobile ADR technology, the HAS (Heating Air-classification System) technology has been developed to have a better sorting of the finer aggregates (less than 4 mm). These aggregates are integrated into the upper part of a vertical chamber with an ascending flow of hot air. The fine aggregates (0.125-4 mm) fall downwards and the ultrafine particles (< 0.125 mm) are transported to the adjacent compartment. Impurities such as wood or plastic are burnt in the hot air zone reaching a temperature of 600°C. This technology allows simultaneous separation and drying of aggregates, with a processing rate of 3t/h.

[2] http://veep-project.eu/

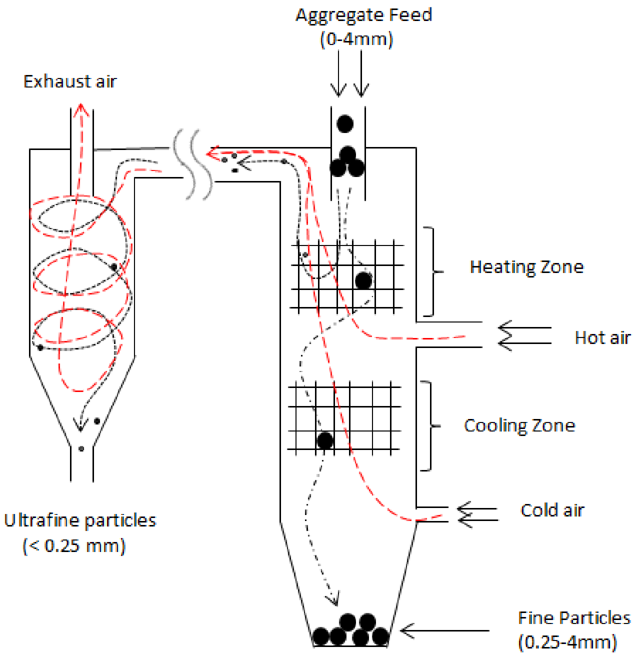

Figure 2. HAS technology

An LCA and LCC study on these processes compared 4 different systems: BAU WP (Business-As-Usual Wet Process) system, ADR-S (stationary) system, ADR-M (mobile) system, A&H (ADR & HAS) system. For the functional unit, considering that each system delivers different products, each product system was expanded to ensure the comparability, and the functions for the comparison are: EOL (end-of-life) concrete treatment, coarse aggregate for concrete production, fine aggregate for concrete production, cementitious material for concrete production. The results of the study show that the most advantageous technological solutions are recycling on-site and producing high-value secondary products with the ADR-M or A&H system.

A new insulation technology has also been developed, using the glass and glass wool from demolition sites, with a sorting and crushing system for these materials followed by a low-cost synthesis of soluble glass (cost reduction estimated at 60%). A sustained chemical reaction makes it possible to obtain a hydrophobic recycled silica aerogel in the form of granules or layers with thermal insulation properties, with a drying process that consumes little energy (LTSCD, Low Temperature Supercritical Drying). For an equivalent performance, aerogel would represent 15% of the thickness of conventional insulation and would be significantly less expensive than a "new" material due to its manufacturing process.
Two concrete panel prototypes were developed, with an incorporation of 75% weight of CDW (construction and demolition waste) aggregates, and a replacement of 5% of the cement by CDW ultrafines:

- PCE1 for structural application in new construction (2 concrete panels with insulation in the middle, with a maximum thickness of 26 cm).
- PCE2 for refurbishment application (a panel with insulation, to be installed on an existing wall, with a maximum thickness of 13 cm).

Figure 3. PCE 1 and PCE 2

An LCA and LCC analyses have been conducted to determine the energy, carbon, and investment payback periods for buildings renovated with the PCE2 system in the climatic context of three EU member States: Spain, the Netherlands, and Sweden. Three technological systems were considered: the BAU (Business-As-Usual) traditional wall, the BAU traditional wall retrofitted with PCE2-a (a 30 mm aerogel insulation for the Spanish case), and with a PCE2-b (a 70 mm aerogel insulation for the Dutch and Swedish case). The functional unit is based on retaining the heating and cooling comfort for 1 m^2 floor area through passive building façades, and active heating and cooling systems for 1 year based on the climate conditions. The results show that the energy payback periods were of 17.6 years (Dutch climate) to 20.45 years (Spanish climate). Meanwhile, the carbon payback periods for the three cases were 8.58 years (Swedish climate) to 23.33 years (Spanish climate). However, the financial payback periods revealed that payback was unlikely to be achieved within the lifetime of a building (only the Swedish case reached a payback period within 100 years, with a result of 83.59 years). The impacts of material circularity on the payback period of PCE2 were also evaluated. The influence of recycling was quantified using secondary raw materials in the embodiment phase. However, the results show that using secondary materials in the PCE2 system only slightly reduces the payback periods. However, reusing the PCE2 can noticeably shorten the energy and carbon payback periods to 4.11–5.99 years and 3.03–10.82 years, respectively, for all cases. Regarding cost, reusing the PCE2 reduced the payback period of the Swedish case to 29.30 years, and those of the Dutch and Spanish cases to 42.97 years and 85.68 years, respectively.
On a production scale, it is stated that the panel shouldn't cost more than 90 €/m^2.

The RE4 project[3] (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) aimed, between 2016 and 2020, to develop prefabricated construction elements using a high rate of deconstruction materials easily assembled and dismantled with solutions for renovation and new construction.
Two main structural systems have been developed:

- a frame precast system, based on precast columns and beams with shear walls, designed to be fully dismantled and reused,
- a panelised precast system, with load-bearing sandwich panels on the perimeter with cross walls, and a reduced number of elements to put on site.

[3] http://www.re4.eu/

For the non-load-bearing concrete sandwich panels, the steel reinforcement in the outer layer has been replaced by two layers of carbon textile reinforcement and the conventional concrete by high performance concrete, which reduces the thickness of the layer by half.

Another solution that has been developed is production of concrete extruded tiles composed of 85% of recycled sand, as a coating for a ventilated or isolated existing façade.

Several prefabricated concrete products have been developed with a significant rate of recycled aggregates, and some of them with a reuse potential (see table 2).

RE4 elements	Typology	Recycled materials	Reuse potential
Wall panel	Structural	50%	✓
Beam (L-section)	Structural	50%	✓
Beam (square section)	Structural	50%	✓
Column	Structural	50%	✓
Solid floor slab	Structural	50%	✓
Sandwich panel	Non- structural	50%	✓
Sandwich panel	Structural	50%	✗
Block wall	Non- structural	75%	✗
Extruded tiles	Non- structural	85%	✓
Hollow core slabs	Structural	50%	✗
Stairs	Structural	50%	✓

Table 2. Precast concrete elements developed in the RE4 project

4 demonstrators, in 4 different countries and climates have been built using these elements to show the feasibility of these solutions: Spain and Northern Ireland for new construction, Italy and Tawain for refurbishment solutions.
An LCA and LCC study has been conducted on the concrete-based façade solutions developed in the project. In this case, the square meter of an RE4 panel is compared to a commercial product with the same structural and thermal performance. In this analysis the conventional concrete elements are assumed to be demolished and disposed after 50 years of service life whereas the RE4 concrete products are considered as designed to be disassembled and reused in another product system with a total service life of 100 years. The RE4 solutions present improvements over the conventional ones concerning global warming potential, fossil embodied energy and costs.
Within this project, a single indicator LCSA aims to combine environmental, costs and social analysis.

The SeRaMCo project[4] (SEcondary Raw Materials for COncrete precast products), conducted between 2017 and 2020, aimed to study the replacement of primary raw materials with the high-quality recycled materials from the construction & demolition waste (CDW) in the production of cement and concrete products. An assessment of the environmental impacts of recycled aggregates has also been conducted, with the manufacture of 1 m³ of concrete class C30/37 as a functional unit, using recycled aggregates or natural aggregates. It is shown that the "water usage" indicator is inversely proportional to the recycled aggregates substitution rate in the concrete mix. Surprisingly, the "global warming" impact is higher when recycled aggregates substitution is higher, but it is mainly because in this case concrete with high substitution of natural aggregates by recycled aggregates required more cement to achieve the C30/37 strength class. This is mainly linked to the quality of the recycled aggregates that are used for a certain mechanical performance.

[4] https://vb.nweurope.eu/projects/project-search/seramco-secondary-raw-materials-for-concrete-precast-products/

Some ways to reduce the environmental impact of the recycled aggregates are suggested as follows:

- the use of renewable energy in this process,
- reduction of waste landfill and generation from the recycling process,
- recycling the sludge from the recycling process,
- the impacts can be mitigated when boundaries of the recycling process are modified and when the allocation procedures of these impacts with by-products of the recycling process are reconsidered,
- the CO_2 uptake of cement-based material could be up to 0,05 tCO_2/ton of material. Considering this assumption, waste and global warming indicators can vary considerably,
- the importance of considering the delivery distances of natural and recycled aggregates, as a study conducted by the Cerema (the french center for studies and expertise on risks, environment, mobility, and urban planning) shows that recycled aggregates are more advantageous than natural aggregates for distances lower than 50 km.

2.4 Reuse of concrete elements

The reuse of construction and demolition materials is theoretically a more sustainable solution in terms of material recovery. It is today mostly assigned to non-structural and low-density materials.
These last years, several projects in Europe have experimented the reuse of structural and concrete components.

The European project ReCreate was launched in 2021, aiming to propose a reproducible deconstruction model for the reuse of prefabricated concrete elements. A first demonstrator in Sweden was constructed with a metal structure and concrete elements (façade walls, hollow core slabs, concrete slab) from different sources. This building was also designed to be demountable. It stated that this pilot has a 92% lower carbon footprint in the production phase compared with a new construction[5].

Figure 4. First pilot of the ReCreate project

For the Swiss project Re:Crete, researchers recreated a footbridge in the form of a pre-stressed arch from concrete blocks cut from the walls of demolition site. The footbridge is made up of 25 concrete blocks, 20 cm thick, over a 10 m span. These blocks are drilled and connected in post tension, with cement mortar joints. The guardrail system having also been manufactured from reused elements.

[5] https://recreate-project.eu/recreate-exhibitions/h22-pilot/

Figure 5. The footbridge of the Re:Crete project

The Dutch project “Super circular estate” has experimented the deconstruction of a high-rise building of 100 housing units, in the form “3D modules” ready to be reassembled for a new construction.
In the last image in the figure below, the supporting structure of the 2 buildings on the left comes from the “3D modules” dismantled from the building appearing in the first two images of the same figure, while the structure of the 3rd building on the right is made of recycled aggregates from the same building. All the partition walls come from walls cut out of the building. The facade elements also come from the reuse or recycling of elements from the deconstructed building.

Figure 6. Deconstruction of the high rise building and construction of the pilots.

Most concrete elements that were developed in the RE4 and VEEP projects were designed to be dismountable and reusable.

A thesis that was submitted in 2023 in France about the reuse in the construction sector, and which presents a comparative LCA of a beam, made of virgin materials, recycled materials, or a deconstructed and reused beam. It is stated that the reuse scenario is suitable or equivalent in most indicators, with lower greenhouse gas emissions by 30% comparatively with the virgin materials scenario and 25% with the recycled materials scenario. The photochemical ozone formation indicator was higher in the reuse scenario as it requires a heavier deconstruction protocol.[6]

In the latest French energetic and environmental regulation published in 2022, components that are reused in a new building project are considered to have a null carbon footprint. This measure aims to encourage the use of second-hand products.

Implementation of reuse technics are highly dependent on generally non-standardized specifications, design rules and regulations valid in the place of use.

2.5 Structural design

The structural design can combine the previous 4 aspects, in addition to a specific attention to the different elements and parts of the construction.

A direct reduction of CO_2 emissions in concrete can also be evaluated.
The use of high or ultra-high-performance concrete (UHPC) present a potential CO_2 reduction related to the functional unit of the concrete construction element. Although these concretes contain increased cement contents per ton or per m³, the amount of concrete in construction units such as columns or bridge elements can decrease significantly. The cement used until today for UHPC is in most cases Portland cement, and the potential of CO_2 reduction of UPHC is expected to grow with the combination of clinker-efficient cements. These concretes are also expected to last longer than normal concrete and can be even more considered as CO_2 efficient if considering the whole life cycle of a construction work or element.

Several examples have been presented in the French national project “BHP 2000”[7] (High Strength Concrete), as for a given functional unit, improvements have been presented in terms of costs, quantity of materials used and the environmental impact. Each example shows optimization regarding the material used, by upgrading the class resistance of concrete, adding reinforcements, or introducing alternative binders.

A two-span 21,5m long meter bridge has been designed with traditional concrete, and with high performance prestressed concrete and a lower thickness (about half the thickness of the traditional bridge).

Figure 7. Picture of the 21.5 m long bridge

[6] Source : https://pastel.hal.science/tel-04011357

[7] This project has been conducted from 1995 to 2003: https://irex.asso.fr/projets/projets-nationaux-termines/bhp-2000-1995-2003/

	Traditional prestressed concrete deck B35 (C35/45)		High performance prestressed concrete deck B80 (C80/95)	
	quantity	*GWP (kgCO₂eq)*	*quantity*	*GWP (kgCO₂eq)*
Average thickness (m)	0.75	/	0.37	/
Concrete volume (m^3)	390	105 300	188	63 920
Rebars (t)	39	44 460	39	44 460
Prestressed steel (t)	12	13 680	8	9 120
Weight (deck) (t)	975	/	520	/
GWP subtotal	/	163 440	/	117 500

Table 3. Characteristics of prestressed solution

The global warming potential of the HPC bridge is significantly lower than the traditional one, by about 28%.

Another design of bridge, 150 m high, with a total length of 189 m and piers dimensions of 10x15 m, was designed with 4 different materials solutions:

- B40 (C40/50) with a pier reinforcement of 1%, with a wall thickness of 1 m,
- B40 (C40/50) with a pier reinforcement of 2.5%, with a wall thickness of 0.68 m,
- B80 (C80/95) with a pier reinforcement of 1%, with a wall a thickness of 0.8 m,
- B80 (C80/95) with a pier reinforcement of 2.5%, with a wall thickness of 0.48 m.

	B40 1%		B40 2,5%		B80 1%		B80 2,5%	
	Quantity	GWP ($kgCO_2eq$)	Quantity	GWP ($kgCO_2eq$)	Quantity	GWP ($kgCO_2eq$)	Quantity	GWP ($kgCO_2eq$)
Concrete (m^3)	3450	1 069 500	2411	747 410	2808	954 720	1731	588 540
Rebars (t)	269.1	306 774	470,2	536 028	219	249 660	337,5	384 750
GWP subtotal	/	1 376 274	/	1 283 438	/	1 204 380	/	973 290
Variation vs B40 1%	/	/	/	-6.7%	/	-12.5%	/	-29.3%
Variation vs B40 2.5%	/	7.2%	/	/	/	-6.2%	/	-24.2%

Table 4. Characteristics of each solution (B40/B80)

The materials costs evolutions, for the project that was set in the late 1990s/early 2000s, are as follows: variation of costs vs B40 1%: +3% for B40 2.5%, +15% for B80 1% and -5% for B80 2.5.

There is unfortunately no data available including the costs of the whole construction project, but only the material costs.
We notice a significant evolution with the use of the B80 2.5%, with an optimization in the class resistance of concrete and in the percentage of steel reinforcement, as the latter allows a significant reduction in concrete quantity, which reduces the carbon footprint and the overall material costs.

The last design of bridge excerpted is a 189 m long bridge, where 2 solutions were developed: a resistance class of B40 (C40/C50) with traditional concrete, and a B80 (C80/C95) with high performance concrete that contains silica fume (FS).

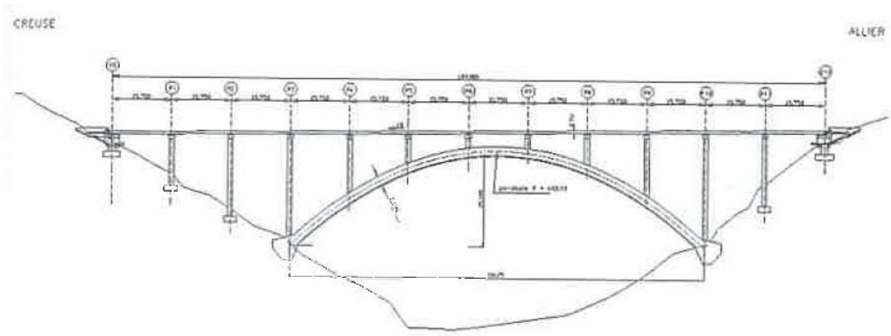

Figure 8. Sketch of the bridge

Properties	Common values
Span of the arch	100 m
Max height	25 m
Total length	189 m
Distribution of the piles	every 15.75 m
Deck width	11 m

Table 5. Common characteristics for the 2 solutions

	B40	B80 SF
Maximal thickness (m)	0.641	0.5
Piles section (m*m)	1.1 * 1.35	1.1 * 1.0
Dimension of the arch profile (m*m)	1.2 * 2.0	1.1 * 1.8
Core thickness (m)	0.4	0.25
Maximal traction (MPa)	3.16	4.93
Maximal compression (MPa)	19.3	23.1

Table 6. Geometric characteristics for each solution (B40/B80SF)

In the table 6, we notice a reduction in many sections: piles, thickness, arch profiles, etc., and an improvement in mechanical resistance.
The table below presents the quantities of materials for each part of the bridges, for both types of concrete used.

	B40		B80 SF		Variation of B80 SF / B40		
Components	**Quantity**	**GWP ($kgCO_2eq$)**	**Quantity**	**GWP ($kgCO_2eq$)**	**Quantity**	**Costs**	**GWP**
Piles							
Concrete (m^3)	572	177320	424	142040	-26%	19%	-4.1%
Ribbed rebars (t)	55	62700	55	62700	0%	0%	10.2%
Plain rebars (t)	5.3	6042	4.24	4834	-20%	-20%	0.0%
GWP subtotal	/	246062	/	209574	/	/	-14.8%
arch							
Concrete (m^3)	595	184450	420	140700	-29%	13%	-23.7%
Ribbed rebars (t)	42	47880	42	47880	0%	0%	0.0%
Plain rebars (t)	6.93	7900	6.93	7900	0%	0%	0.0%
GWP subtotal	/	240230	/	196480	/	/	-18.2%
deck							
Concrete (m^3)	624	193440	554	185590	-11%	42%	-4.1%
Ribbed rebars (t)	59	67260	65	74100	10%	10%	10.2%
Plain rebars (t)	5.54	6316	5.54	6316	0%	0%	0.0%
GWP subtotal	/	267016	/	266006	/	/	-0.4%

Table 7. Material quantity and carbon footprint for each solution

The overall costs variation is estimated to 7.2% including the deck, and 2% without the deck.
The overall carbon footprint (for the concrete and rebars) variation is estimated to -16% including the deck, and -11% without the deck.

3 LOW CARBON STRUCTURAL ADAPTATION OPTIONS

As part of the task 4.1 in the Riskadapt project, 10 types of solutions from the precast concrete industry have been detailed in terms of material composition and performance, with data regarding the life cycle assessment (LCA), and grouped in two main categories: infrastructure (rebuilt or replacement for a service life of 100 years for the new elements) and building (rebuilt or replacement for a service life of 50 years for the new elements).
The material composition presented represent an average of the current practices, regarding the intended application.
The technical characteristics presented are mean values based on the material and the application according to the Eurocode 2.
For each of these 2 categories, 2 main environmental product declarations (EPDs) have been produced, with a main distinction regarding the design (width and heigh) and the class resistance.
These EPDs are based on technical hypothesis and mean values regarding the practices in the precast concrete industry in France.

3.1 Case 1: infrastructures - Concrete elements with conventional compressive strength (30 MPa) and a medium reduction of carbon footprint:

The first case applies to regular infrastructure (bridges), that have a life expectancy of 100 years, and a conventional compressive strength of 30 MPa. The concrete is composed of regular cement (CEM I or CEM II) and mineral additions, and sand and coarse aggregates (100% natural).

The reduction of the carbon footprint is mainly based on adding mineral additions (limestone for example), which enhances the mechanical performance while lowering the amount of cement used, in addition to an optimised design.

The related configured EPD, "fdes_Poutre en beton precontraint - 1m lineaire - traditionnel C30 – 90 cm-30 cm", presents an average of the data collected from the different precast concrete products industry practices in France, in terms of materials used, distances, factory processes, etc. This EPD presents a prestressed precast concrete beam with a thickness of 30 cm and a width of 90 cm and 100 kg/m^3 of steel. As an example, this product presents a global warming potential (GWP) of 123 $kgCO_2eq$ per linear meter.

3.2 Case 2: infrastructures - Concrete elements with conventional compressive strength (30 MPa) and a medium reduction of carbon footprint and a content of recycled aggregates:

This case applies to regular infrastructure (bridges) with a conventional compressive strength of 30 MPa. The concrete is composed of regular cement and mineral additions, sand, and coarse aggregates (80% natural and 20% recycled).

In addition to the characteristics of previous case, 20% of the natural coarse aggregates have been replaced by recycled aggregates. There is no significant gain in terms of carbon footprint when using recycled aggregates. The main emissive parameters are the distance between the extraction site and the supplier if there is, and between the supplier and the concrete or precast concrete products factory, and the processes of crushing and screening, which roughly have an equivalent impact as the distances and the processes involved in natural aggregates' extraction and delivery.

The variation in the GWP with the use of recycled aggregates is had to tell as it depends on various parameters.
The SeRaMCo project showed that the use of recycled aggregates is more ecologically profitable than the use of natural aggregates, in terms of carbon emissions, if the delivery distance exceeds 50 km. And this estimate doesn't consider the CO_2 uptake of the recycled aggregates, which also lowers the carbon emissions. The same project also shows that the substitution of natural aggregates by a high proportion of recycled aggregates can lead to a higher cement density to achieve a certain resistance class.
However, the EPDs produced by the french national union of aggregate producers (UNPG) in 2017 show a GWP that is slightly lower for recycled aggregates (1.5 $kgCO_2eq/t$) than for the natural aggregates (2.75 $kgCO_2eq/t$ and 2.6 $kgCO_2eq/t$).

3.3 Case 3: infrastructures - Concrete elements with conventional compressive strength (30 MPa) and a high reduction of carbon footprint:

This case applies to regular infrastructure (bridges) with a conventional compressive strength of 30 MPa. The concrete is composed of a CEM III cement that has a lower content in clinker, and mineral additions, and sand and coarse aggregates (100% natural).

A CEM I cement contains at least 95% of clinker, which is the main carbon emitter in the cement composition, and a CEM III cement contains 5 to 64% of clinker and the rest being mainly composed of blast furnace slag.

The cement EPDs produced by the French syndicate of cement shows a global warming potential of 752 $kgCO_2eq/t$ for CEM I cement, and between 199 and 467 $kgCO_2eq/t$ for CEM III cement (depending on the composition of the CEM III cement).
Based on the EPD presented in the chapter 3.1, and with an estimation that the GWP of a CEM III cement is approximately 30% lower that the GWP of a CEM I cement, and that the cement GWP represents approximately 70% of the GWP of a beam compared to the other components, the GWP of the beam containing CEM III cement can be evaluated to 98 $kgCO_2eq$ per linear meter.

3.4 Case 4: infrastructures - Concrete elements with high compressive strength (60 MPa) and a medium reduction of carbon footprint:

This case applies to regular infrastructure (bridges) with a higher compressive strength of 60 MPa. The concrete is composed of regular cement (CEM I or CEM II) and mineral additions, a plasticizer, sand, and coarse aggregates (100% natural).
The reduction of the carbon footprint is mainly based on adding mineral additions (limestone or silica fume for example), which enhances the mechanical performance while lowering the amount of cement used, in addition to an optimised design compared to the previous cases.

The related configured EPD, "fdes_Poutre en beton precontraint - 1m lineaire - optimise C60 – 60 cm-20 cm" presents an average of the data collected from the different precast concrete products industry practices in France. This EPD presents a prestressed precast concrete beam with a lowered section with a thickness of 20 cm and a width of 60 cm, and with a higher density of steel 180 kg/m^3 of steel. The volume of used concrete is decreased, even though the steel density is higher. This product presents a global warming potential of 73 $kgCO_2eq$ per linear meter.

3.5 Case 5: infrastructures - Concrete elements with high compressive strength (60 MPa) and a high reduction of carbon footprint:

This case applies to regular infrastructure (bridges) with a higher compressive strength of 60 MPa. The concrete is composed of a CEM III cement and mineral additions, a plasticizer, and sand and natural coarse aggregates.

Based on the EPD presented in the chapter 3.4, and with an estimation that the GWP of a CEM III cement is approximately 30% lower that the GWP of a CEM I cement, and that the cement GWP represents approximately 70% of the GWP of a beam compared to the other components, the GWP of the beam containing CEM III cement can be evaluated to 58 kgCO_2eq per linear meter.

3.6 Case 6: buildings - Concrete elements with conventional compressive strength (30 MPa) and a medium reduction of carbon footprint:

The first case applies to buildings superstructure, with a life expectancy of 50 years, and a conventional compressive strength of 30 MPa. The concrete is composed of regular cement (CEM I or CEM II) and mineral additions, and sand and coarse aggregates (100% natural).

The related configured EPD, "fdes_Poteau en beton arme - 1m lineaire - Poteau batiment traditionnel C30 – 50 cm-50 cm", presents an average of the data collected from the different precast concrete products industry practices in France, in terms of materials used, distances, factory processes, etc. This EPD presents a prestressed precast concrete beam or pole with a thickness of 50 cm and a width of 50 cm and 50 kg/m^3 of steel. This product presents a global warming potential of 87 kgCO_2eq per linear meter.

3.7 Case 7: buildings - Concrete elements with conventional compressive strength (30 MPa) and a medium reduction of carbon footprint and a content of recycled aggregates:

This case applies to buildings superstructure, with a life expectancy of 50 years, and a conventional compressive strength of 30 MPa. The concrete is composed of regular cement and mineral additions, sand, and coarse aggregates (80% natural and 20% recycled).

In addition to the characteristics of previous case, 20% of the natural coarse aggregates have been replaced by recycled aggregates. There is no significant gain in terms of carbon footprint when using recycled aggregates. The main emissive parameters are the distance between the extraction site and the supplier if there is, and between the supplier and the concrete or precast concrete products factory, and the processes of crushing and screening, which roughly have an equivalent impact as the distances and the processes involved in natural aggregates' extraction and delivery.

3.8 Case 8: buildings - Concrete elements with conventional compressive strength (30 MPa) and a high reduction of carbon footprint:

This case applies to buildings superstructure, with a life expectancy of 50 years, and a conventional compressive strength of 30 MPa. The concrete is composed of a CEM III cement with a lower content in clinker, and mineral additions, and sand and coarse aggregates (100% natural).

The cement EPDs produced by the French syndicate of cement shows a carbon footprint of 752 kgCO_2eq/t for CEM I cement, and between 199 and 467 kgCO_2eq/t for CEM III cement (depending on the composition of the CEM III cement).
Based on the EPD presented in the chapter 3.6, and with an estimation that the GWP of a CEM III cement is approximately 30% lower that the GWP of a CEM I cement, and that the cement GWP represents approximately 70% of the GWP of a beam compared to the other components, the GWP of the beam containing CEM III cement can be evaluated to 69 kgCO_2eq per linear meter.

3.9 Case 9: buildings - Concrete elements with high compressive strength (60 MPa) and a medium reduction of carbon footprint:

This case applies to buildings superstructure, with a life expectancy of 50 years, and a higher compressive strength of 60 MPa. The concrete is composed of regular cement (CEM I or CEM II) and mineral additions, a plasticizer, sand, and coarse aggregates (100% natural).

The related configured EPD "fdes_Poteau en beton arme - 1m lineaire --Poteau batiment optimisé C60 – 40 cm-40 cm" presents an average of the data collected from the different precast concrete products industry practices in France. This EPD presents a prestressed precast concrete beam with a lowered section with a thickness of 40 cm and a width of 40 cm, and with a higher density of steel 100 kg/m^3 of steel. The volume of used concrete is decreased, even though the steel density is higher. This product presents a global warming potential of 73 kgCO_2eq per linear meter.

3.10 Case 10: buildings - Concrete elements with high compressive strength (60 MPa) and a high reduction of carbon footprint:

This case applies to buildings superstructure, with a life expectancy of 50 years, and a higher compressive strength of 60 MPa. The concrete is composed of a CEM III cement (and mineral additions, a plasticizer, sand, and coarse aggregates (100% natural).

Based on the EPD presented in the chapter 3.1, and with an estimation that the GWP of a CEM III cement is approximately 30% lower that the GWP of a CEM I cement, and that the cement GWP represents approximately 70% of the GWP of a beam compared to the other components, the GWP of the beam containing CEM III cement can be evaluated to 58 kgCO_2eq per linear meter.

4 CONCLUSION

This report highlights 5 types of sustainable practices concerning precast concrete that will tend to be more common in the years to come due to the necessity of climate change adaptation. The optimization of the cement and the binders, the use of alternative materials and industrial materials in the binder and/or concrete composition, the use of recycled aggregates in concrete and structural concrete, the reuse of concrete elements, and a global reasoning on the design of the construction works by combining the different practices cited before and reducing the quantity of materials used for the same functional unit.

Among the adaptation options analysed and because of reuse technics are highly dependent on generally non-standardized specifications, design rules and regulations valid in the place of use, data collected shows use of low carbon binders combined with optimized structural design leads to highly significant decrease of CO_2 footprint.