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THEMATIC PRIORITY:

RESOURCE AND MATERIALS EFFICIENCY

# Final Conference of SeRaMCo - Precast Concrete in the Circular Economy

March 25th and 26th, 2020
Technische Universität Kaiserslautern

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## Welcome address

I am pleased to welcome you to the international Final Conference of the Interreg NWE project SeRaMCo with the topic „Precast Concrete in the Circular Economy".

SeRaMCo – Secondary Raw Material for Concrete Precast Products – aims at increasing the use of recycled aggregates in a real circular economy.

Eleven European project partners from the academic and industry domains from Belgium, Germany, France, Luxemburg and the Netherlands are involved in the project. It is funded by the EU with 4,3 Mio. Euro. We as Technische Universität Kaiserslautern take pride in being the project Lead Partner.

The project outcomes help to innovate recycling, cement and concrete precast production at the companies who are SeRaMCo project partners and other businesses who learn from us. Equally important is that all partners openly share their research findings, experience and products with students, other researchers, local authorities and industry experts and thereby build a (virtual) community.

I congratulate Prof. Dr. Christian Glock and his team on this conference and wish all participants a fruitful and sustainable collaboration and exchange.

Universitätspräsident
**Helmut J. Schmidt**
Univ.-Prof. Dr. rer. nat. 名誉工学博士[1] (湘南工科大学)[2]

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## Preface

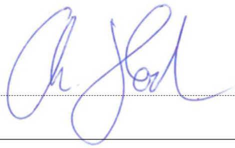
Welcome to the “Final Conference of SeRaMCo: Precast Concrete in the Circular Economy” on March 25th and 26th, 2020 in Kaiserslautern.

About 50 % of primary raw materials in Europe are used in the construction sector where at the same time more than a third of all waste is generated. Given the fact that primary raw materials are limited, we need innovative solutions and ways to preserve the environment.
This is where the project SeRaMCo (= Secondary Raw Materials for Concrete Precast Products) comes into action. Led by the Technical University of Kaiserslautern, Germany and funded by Interreg North-West Europe, 11 universities and business partners from Belgium, France, Luxemburg, the Netherlands and Germany collaborate to raise the material efficiency in the construction sector.

The project’s objective is to reuse recycled construction materials in a real circular economy: recycled sands and aggregates which are obtained after demolition of buildings, are used to produce cement and concrete precast. We expect precast concrete made from recycled aggregates to have a major impact on a future, more sustainable construction industry.

The conference will show the research and hands-on results of the SeRaMCo project. We are honoured to present experienced top-class speakers from industry and research who will report directly from practice and discuss with you. Furthermore, we will have a poster presentation as well as an exhibition of samples in the foyer. A special highlight will be the panel discussion with experts.

I would like to thank the speakers and the SeRaMCo team for their contributions and wish all of us a successful and informative conference! A special thank-you goes to all participants of the conference. May you enjoy the presentations and papers and take home as many ideas as possible for making our future sustainable!



**Christian Glock**
Univ.-Prof. Dr.-Ing.

Department of Civil Engineering
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# Potential and Barriers of Recycled Concrete – View of the Public Authorities

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**Abstract**

The potentials for the use of recycled concrete are as high as the barriers against its use. The perspectives of different authorities involved provide different options to act. The authorities in charge of setting standards are requested to follow up technical development in a more progressive way. Tendering authorities acting as employers for the sake of circular economy and based on acknowledged techniques are supposed to create market demand for recycled concrete. The present contribution describes the status quo and demonstrates options to act and forecasts an enhancement in the use of recycled concrete.

**Keywords**

circular economy, standards, tendering, environment

**Kurzfassung**

Das Nutzungspotential von Recycling-Beton ist ebenso hoch wie die Hindernisse für seine Anwendung. Die Blickwinkel der beteiligten Behörden bringen unterschiedliche Handlungsoptionen mit sich. Die für die Normung zuständigen Behörden sollten sich progressiver an der technischen Entwicklung orientieren. Bauleistungen ausschreibende Behörden als Bauherren sollten auch im Sinne der Kreislaufwirtschaft und auf Basis der anerkannten technischen Entwicklung für mehr Nachfrage nach Recyclingbeton sorgen. In vorliegenden Beitrag werden der Status quo und die Handlungsoptionen aufgezeigt sowie die verstärkte Nutzung von Recycling-Beton prognostiziert.

**Schlüsselwörter**
Kreislaufwirtschaft, Normen, Ausschreibungen, Umwelt

**Résumé**
Les potentiels d'utilisation du béton recyclé sont aussi élevés que les barrières à son usage. Les perspectives des différentes autorités impliquées offrent différentes options pour agir. Les autorités chargées de fixer les normes sont invitées à suivre le développement technique de manière plus progressive. Les pouvoirs adjudicateurs, agissant en tant qu'employeurs au nom de l'économie circulaire et basés sur des techniques reconnues, sont censés créer un marché pour le béton recyclé. La présente contribution décrit le statu quo, suggère des options pour agir et prévoit une augmentation de l'utilisation du béton recyclé.

**Mots-clés**
économie circulaire, standards, environnement

## 1. Introduction

Firstly, a clarification seems useful: The term "recycled concrete" means that demolition material from wrecked structures is being prepared by sorting, crushing and sieving. Afterwards this material is bound to replace natural aggregates from quarries for the production of concrete. This type of concrete is called recycled concrete; in short: R-Concrete. The R is understood in a much wider sense than merely representing “recycled”. It stands for resource saving concrete as other side effects occur such as nature protection as the claiming of quarries will be reduced, shorter transport distances, avoiding landfill. In the past several structures have been completed in recycled concrete in total or partly. However, the potential to apply recycled concrete are 10 to 15 times higher than in the reality.

## 2. Analysis method

First, we should clarify which Public Authorities are meant to be considered and what is their respective role in the whole issue. On one side there are regulating authorities setting rules. On the other side we have the authorities acting as an employer contracting construction activities (see Figure 1).

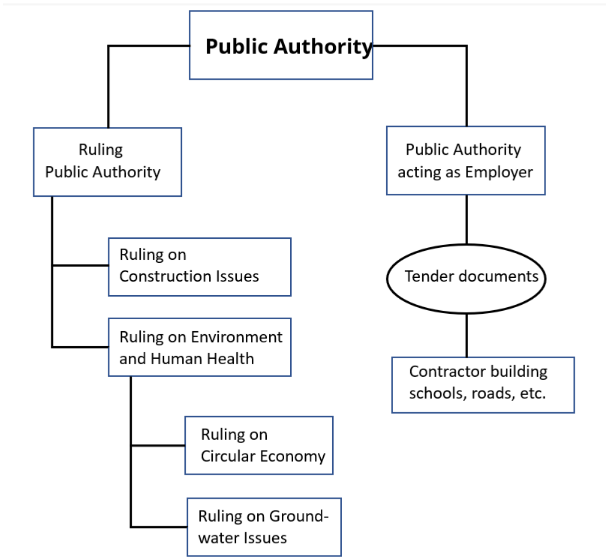


*Figure 1. Different types of public authorities*

## 2.1 The regulating Public Authorities

We may distinguish again two types of regulating authorities: The first is the one in charge of providing rules in the field of construction in terms of quality of construction material. Relevant is the Comité Européen de Normalisation (CEN) which issues the Europe-wide applicable EN-Standards. In the field of recycling material, the “EN 12620 – Aggregates for concrete” [1] has become relevant stipulating parameters regarding the stability and other construction related quality aspects of aggregates.

The second type of authority involved is the one that deals with environmental and health issues. These authorities may set limit values for substances which could become problematic if they exceed certain concentrations in the construction material or if the construction material could release those substances. These authorities define and issue limit values with the objective to protect human health and the environment.
If aggregates are used in an unbound matrix e.g. in road construction as shown in figures 2 to 3 the leachate from precipitation, trickling and resolving dangerous substances could create a problem to groundwater. Therefore, as shown in table 1, in Germany exists a draft ordinance [2] setting environment-motivated limit values for ready-to-go aggregates to be used in road construction or similar purposes.

*Table 1. Limit values for ready-to-go aggregates to be used in road construction or similar purposes according to a draft ordinance [2]*

| Nr. | Parameter | Draft Limit Value (µg/l) |
|---|---|---|
| 1 | Chromium | 150 |
| 2 | Copper | 110 |
| 3 | Vanadium | 120 |
| 4 | PAH | 6 |
| 5 | Sulphates | 600.000 |

The measuring unit µg/l is based on a leachate test using a sample of 1 kg of solids and 2 litres of distilled water. Both are mixed or subject to a cross-flow-test. At the end of the test the solids are filtered out and the remaining water is subjected to a chemical analysis in order to determine to which extend the problematic substances have been resolved from the solids, potentially endangering groundwater.

As the environmental counterpart to the above mentioned EN 12620, the German standard DIN 4226-101 [3] sets limit values for aggregates which are used in concrete. An excerpt of relevant parameters is shown in table 2.

*Table 2. Limit values for ready-to-go aggregates to be used in concrete according to DIN 4226-101 [3] (excerpt only)*

| Nr. | Parameter | Draft Limit Value |
|---|---|---|
| 1 | Chromium | 100 µg/l |
| 2 | Copper | 200 µg/l |
| 3 | Vanadium | n.a. |
| 4 | PAH | 25 mg/kg |
| 5 | Sulphates | 600 mg/l |

In contrary to the limit values shown in table 1 the limit values of table 2 are based on a leachate test run with 100 grams of solid and 1 litre of distilled water. I.e. the dilution factor is 5 times higher and consequently the figures of the limit values in both tables are not correlating, e.g. by a conversion coefficient of 5 [4].

## 2.2 Public authorities acting as employer

E.g. a municipality may contract the construction of a school building, or a road administration may contract the construction of a road. The public sector is the decisive employer for construction projects. Consequently, it is in the hands of the respective authorities to open their tenders for recycling concrete.

## 3. Material flow – status quo versus potential

According to statistics in [5] the author estimates that 99% of aggregates made of demolition waste are being used as bulk material, meaning in layers for road construction or for re-fill purposes as shown in figures 2 to 3.

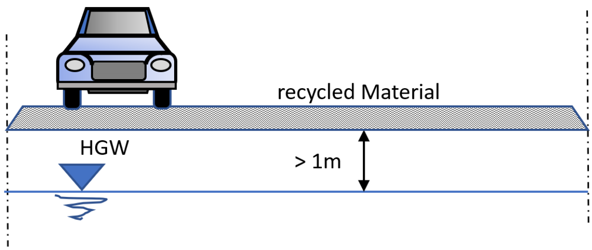


*Figure 2. Simple road construction (country lane)*

For the remaining 1% the following rules are applied: According to German provisions [6] up to 45% of the non-sand aggregate can be replaced by recycled aggregates. If one cubic meter of concrete arbitrarily has a weight of 2.215 kg (figure 4) the quantity of 500 kg of recycled aggregates makes up 22,5% content related to the whole concrete mixture, as the proportions of sand, cement and water remain discounted. In addition, according to German provisions the adding of recycled aggregates is only allowed for concrete up to the class C30/37 and the adding of recycled aggregates is not allowed for pre-stressed concrete. Under these limitations and according to the authors estimation based on [7] and [5] the potential of using recycled aggregates may be increased to up to 15% of all recycled demolition waste. Compared to the above mentioned 1% this would mean a potential 15 times higher than at present, even under the conservative restrictions of German provisions.

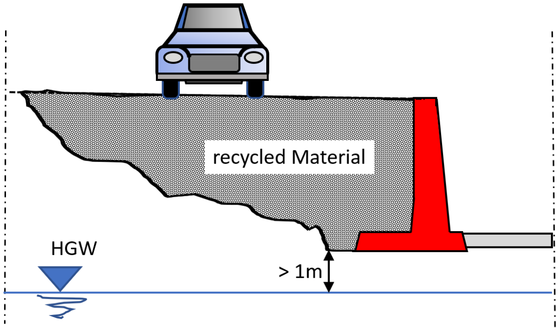


*Figure 3. Refill purpose*

However, meanwhile the SeRaMCo project aims at increasing the recycled part up to even 100% aggregate-replacements including sand-replacement. Many projects have demonstrated the feasibility of more progressive mixtures than prescribed by German provisions.

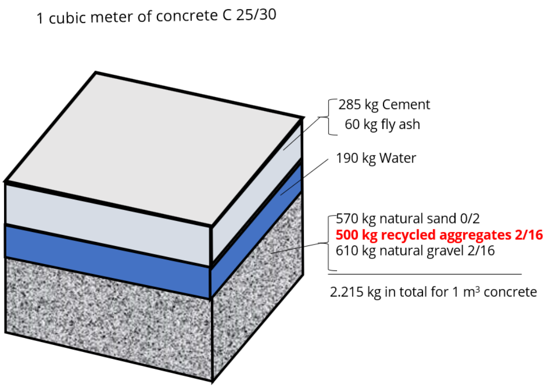


*Figure 4. Composition of recycled concrete*

## 4. The role of public authorities

The actors in the building sector have the tendency to conservative approaches. This might be based on the fact that civil engineering is an empiric science based mainly on empiric approaches. Things which were successful are transported to future generations who copy the successful rules. New approaches or even experiments bear the risk of failure. It may lay in the nature of civil engineering entailing reluctancy to such risks. In general, the actors rather prefer to stay on the safe side. Which is quite understandable as the engineers have to guarantee the quality of their work.

This general approach of conservatism influences both types of public Authorities. On one hand, the regulating authority is very careful in setting new rules for new technologies or methods. It takes long phases of proving experiments, tests and thorough discussions among experts in working groups. On the other hand, the authorities acting as employers are again conservative and very often even do not trust new provisions published by experts, even after being set into force by competent authorities. In case of doubt these authorities stick to the old style and issue respective tender documents. The author himself saw a significant number of tender documents (bills of quantities) excluding the use of recycled aggregates. Investigating the cause, the author found out that the electronic template, the widely used standard bill of quantity (Standardleistungsbuch) does not foresee this item. However, this very template is used by practically all contracting authorities and engineer consultants as a kind of mandatory model when drawing up tender documents.

After the author´s intervention in the competent agency affiliated to the German Federal Ministry for Housing and Building the item “recycling material” was inserted. However, still without significant success. What had happened? – The template unintentionally had been programmed with an “either/or”-function. This means if one clicked on “recycling aggregate” the option “standard aggregate” was not available anymore. As mentioned above, due to the conservative characters involved, the persons or entities in charge had the strong tendency to stay with the standard solution leaving no space for recycled aggregates. Hence, a second intervention was needed with the aim to change the electronic template in to a "both/and"-function. Now it is possible to tender natural aggregates and recycled aggregates alternatively.

## 5. Future Developments and actions needed

The status quo as described above with a ratio of about 1% of recycled demolition waste being used for recycled concrete is not satisfactory. Thus, ways must be established in order to increase this ratio. Besides the appeal to the authorities to show more confidence in their own provisions and to be more open for new developments there are other effects and options for more circular economy in the building sector. Some will appear more or less on their own (5.1 to 5.3). Others have to be developed (5.4) or politically accepted (5.5).

### 5.1 Less road projects

The region of North-west Europe, meaning the region covered by the INTEREG project SeRaMCo, is densely populated and industrialized. This fact will inevitably entail that the construction of new roads may decrease. There is simply no space available for new roads, since apart from living areas other stake holder request space: Nature protection, forest protection, agriculture and water resource areas are a challenge for new traffic infrastructures. The decrease of road construction means less need for bulk mineral material. Thus, more recycled material will be left for use as aggregate in concrete.

## 5.2 Shortage on landfills

To the availability of landfills applies the same as for road construction. In densely populated areas the creation of new landfills is a huge challenge especially due to public resistance. Construction industry complains more and more about shrinking landfill volumes available for waste from construction. This phenomenon is being accompanied by increasing gate fees. However, increasing fees for landfill provide more economical space of manoeuvre for more technical efforts in the recycling industry.

## 5.3 Shortage on natural resources

Besides the reportedly world-wide shortage of sand the reclamation of new quarries and pits in North-west Europe is faced with public and institutional resistance. Thus, existing quarries etc. are becoming more and more precious and operators/owners wish to preserve their sources as long as possible, especially as new licenses are not in sight. Consequently, recycled aggregates will become an important substitute.

## 5.4 Tighter requirements for Groundwater Protection

As demonstrated in figure 1 the Authorities setting rules for the sake of environment are divided again in different sectors in charge of different environmental topics. Looking at the sector in charge of circular economy and at the sector groundwater we discover a conflict. Whilst the first is promoting all kind of actions leading to more recycling the latter is about to tighten the limit values of table 1 in order to further protect groundwater. So far, according to [4] most recycled aggregates meet the limit values of table 1. However, a big debate is going on with the objection to lower these values significantly. If this will become legal fact in the final version of the ordinance, the options to use recycled aggregates as bulk material in projects as shown in figures 2 to 3 will inevitably shrink dramatically. At the moment officiating politicians seem to be inclined to leave circular economy and to be rather in favour for groundwater. This may be motivated by climate change making water a precious resource. In contrary, the water authorities will – at least there are no signs – not touch the values of table 2, which are set for recycled aggregates in concrete. The argumentation is, that concrete can be considered as a stable matrix keeping the problematic substances – if any – away from groundwater. Moreover, concrete structures are regularly covered by roofs, providing shelter from precipitation. This will steer more recycled aggregates into concrete based applications.

### 5.5 Sorting demolition waste by Robots

The selective reclamation of the demolition waste itself plays a decisive role regarding the quality of the aggregates. An important step has to be done on the (de)construction site. If static constraints or space restrictions on-site do not allow for a selective reclamation the separation of the demolition material has to be achieved in a sorting plant. So far, apart from magnetic separation of Fe-metals and removing of disturbing objects done by human resources, no further sophisticated technologies are in common use.

However, the development of new detecting technologies (not based on the light wavelength visible for the human eye) and increased precision of automized grabbing actions made by robots may open new ways. These technologies are widespread in the field of mechanical manufacturing (automotive industry) but not yet applied in demolition waste sorting. Consequently, it seems to be high time that new generations of technical appliances support the attempt of circular economy in the building sector.

## 5.6 An aggregates levy

In the United Kingdom exists a tax on sand, gravel and rock that's either been dug from the ground, dredged from the sea in UK waters or imported. The levy amounts to £2 (about 2,50 €) per ton of sand, gravel or rock. This makes the use of recycled aggregates more competitive. The author estimates that this will provide a significant steering effect in favour of recycled material. The UK approach seems to be worthwhile to be considered for the European Union or at least for some Member States. In order to counter critics saying a levy will make construction more expensive it could politically be decided to use the accumulated money for subsidizing housing project, a field which suffers chronically under a shortage of offers to people seeking affordable dwellings.

## 6. Summary

Some effects, such as shortage on resources and landfills together with tighter restrictions for groundwater protection beyond the thresholds of table 1 will steer more recycled aggregates into concrete-applications. The author estimates that the quantity used at present could be increased by a factor of up to 15 (!). However, this huge increase needs open minded authorities especially when they act as employers contracting building projects. These authorities have the lever to request the use of recycled aggregates from contractors. When contracting public buildings public authorities should ask for recycled concrete and thus act as a model for private investors.

## 7. References


[1] DIN EN 12620: 2008-7, Gesteinskörnung für Beton.

[2] Entwurf – Verordnung zur Einführung einer Ersatzbaustoffverordnung, zur Neufassung der Bundesbodenschutz- und Altlastenverordnung und zur Änderung der Deponieverordnung und der Gewerbeabfallverordnung 2017 – Bundesratsdrucksache DS 566/17

[3] DIN 4226-101: 2017-08 Recyclierte Gesteinskörnungen für Beton nach DIN EN 12620 - Teil 101: Typen und geregelte gefährliche Substanzen.

[4] Institut Fresenius – Probenahme- und Analysenkampagne zur Verifizierung der Auswirkungen der Ersatzbaustoffverordnungen auf den Einsatz von RC-Baustoffen in Baden-Württemberg – Gutachten vom 25.11.2015.

[5] Ministerium für Umwelt Klima und Energiewirtschaft Baden-Württemberg, Abfallbilanz 2018 (2019), chapter 6.

[6] DAfStb-Richtlinie Beton nach DIN EN 206-1 und DIN 1045-2 mit recyclierten Gesteinskörnungen nach DIN EN 12620 (2010-09).

[7] Bundesverband Baustoffe – Steine und Erden e.V., Zahlenspiegel 2017, page 22.

# The Role of Precast in Achieving a Circular Construction: Reduce, Re-use and Recycle

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**Abstract**

Applying circular economy principles to the construction sector is a big challenge for the years to come. There is an urgent need to decouple the environmental impacts from the economic growth if we want to achieve a societal development that is sustainable for the future generations. Precast concrete based solutions have the potential to be the backbone of a circular construction: lean structures with long service life, easy to maintain and repair, reusable and fully recyclable. It is however necessary the implication of all stakeholders in the construction value chain, thus including decision makers and researchers, to allow the transition towards this business model.

**Keywords**

Precast concrete, Circular economy, Durability, Lean construction

**Kurzfassung**

Anwendung der Grundsätze der Kreislaufwirtschaft für den Bausektor ist eine große Herausforderung für die kommenden Jahre. Es ist dringend erforderlich, die Umweltauswirkungen vom Wirtschaftswachstum abzukoppeln, wenn wir eine nachhaltige gesellschaftliche Entwicklung für die künftigen Generationen erreichen wollen. Betonfertigteil-Lösungen haben das Potential die Kreislaufwirtschaft im Bausektor zu ermöglichen: schlanke Konstruktionen mit langer Lebensdauer, einfach zu pflegen und zu reparieren, wiederverwendbar und vollständig recyclebar. Es ist jedoch erforderlich, alle Beteiligten einschließlich Entscheidungsträgern und Forschern in den Prozess einzubinden, um den Übergang in diese Kreislaufwirtschaft zu ermöglichen.

**Schlüsselwörter**
Betonfertigteile, Kreislaufwirtschaft, Dauerhaftigkeit, Schlanke Konstruktionen

**Résumé**
L'application des principes de l'économie circulaire au secteur de la construction est un grand défi pour les années à venir. Il est urgent de dissocier les impacts environnementaux de la croissance économique si nous voulons parvenir à un développement sociétal durable pour les générations futures. Les solutions basées sur le béton préfabriqué ont le potentiel d'être l'épine dorsale d'une construction circulaire : des structures légères avec une longue durée de vie, faciles à entretenir et à réparer, réutilisables et entièrement recyclables. Il est toutefois nécessaire d'impliquer tous les acteurs de la chaîne de valeur de la construction, y compris les preneurs de décision et les chercheurs, pour permettre la transition vers ce modèle opérationnel.

**Mots-clés**
béton préfabriqué, Economie Circulaire, Durabilité, Construction allégée

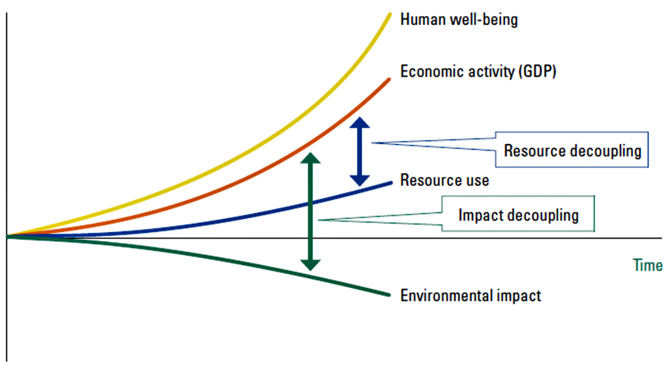
## 1. Introduction

The term "circular economy" is gaining more and more attention on the international level. Most of the time, this term is associated with "avoiding waste" or "recycling"; but it is much more complex. Especially in the field of construction, where the "goods" are built for decades and their value lay mainly in the use phase, a whole life cycle approach should be used, in the same way a sustainable building is assessed. Focussing only on a limited set of aspects may lead to wrong conclusions and finally not achieve the objectives.

## 2. What is circular economy?

The focus of this paper is on the issue of circular economy in the field of construction. Circular economy is a whole life approach of industrial production aimed at securing societal development whilst preserving the environment. It aims at minimising virgin materials inflows and waste outflows using as little energy as possible.

Let's take a step back. Why circular economy principles are so important? The aim of applying its principles is to finally decouple the environmental impacts from the human wellbeing (as shown in Figure 1). In such a way, society can achieve a brighter future whilst preserving and even restoring natural resources.




from: Decoupling Natural Resource Use and Environmental Impacts from Economic Growth
2011 UNEP International Resource Panel Report

*Figure 1. Two aspects of decoupling [1]*

Considering that the economic activity is a good proxy for the well-being of people, two consecutive decoupling are necessary:

- A resource decoupling, which aims at producing more with fewer resources.
- An impact decoupling, which aims at reducing the impact on the environment from the economic activities.

In the field of construction, the durability and efficient design of construction products are important factors to achieve these goals. The lifecycle of buildings and infrastructures is normally measured in decades or hundreds of years, rather than the years or months of most other products, and days or weeks for packaging. Providing structures that can last for hundreds of years with a little need for maintenance and that can be reused for different purposes would reduce the environmental impacts on the long term, leading to a sustainable economy.

## 3. The role of precast concrete

There are several means to minimising inflows (of virgin materials) and outflows (of wastes), as shown in Figure 2:

- repair and maintenance (low energy);
- re-use and redistribution (medium energy);
- recycling (high energy).

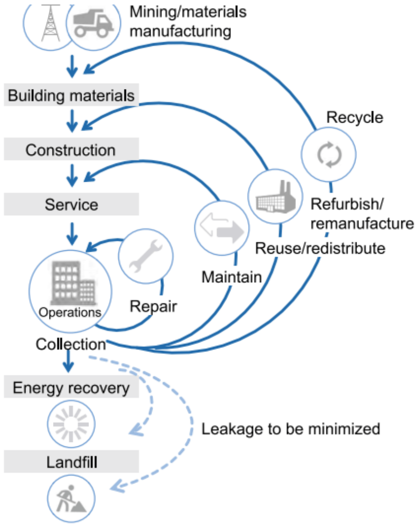



*Figure 2. Technical materials cycle through the economic system [2]*

The objective should be to keep materials within the loop for as long as possible and with the lowest needs for energy. Thanks to the intrinsic properties of concrete and the application of an industrialised manufacturing process, precast concrete products can also be designed to use fewer material for the same function, which is usually referred to as lean construction.

### 3.1 Long service life

One characteristic that is universally recognised to concrete is its durability. When correctly designed and maintained, concrete structures can easily last for 100-150 years; or even longer. Concrete manufactured in a plant can provide even better properties: on one side, quality control ensures that the design of the element is precisely executed. On the other hand, high and very-high strength concrete provide an extremely resistant matrix against the penetration of damaging substances.

### 3.2 Lean construction

The use of high strength concrete can also allow to achieve the same technical characteristics with less material. At the design stage, the optimisation of the concrete and its reinforcement can lead to material saving. Both on site and in the factory, additionally, waste is reduced to a minimum, as precast elements are delivered for direct assembly or with minor site operations.

### 3.3 Maintenance and repair

Maintenance of concrete can be a relatively easy task. There is no need to regularly cover concrete surfaces with preservatives or flame retardants or other kinds of painting. As mineral and inert material, concrete can indeed withstand both normal and accidental conditions without the need of a coating. Repairing operations in case of damage can also be easily performed without the need for a complete demolition.

### 3.4 Re-use and redistribution

Users' needs may change with time, as well as urban planning may relocate certain operations in different areas of the city. A structure which flexible and durable can be re-used for different applications. It is not uncommon to see deep renovation operations where the concrete structure remains whilst the partitioning walls and the facades are changed. In this particular field, using precast (prestressed) elements that allows to have longer spans with very few load bearing elements, provides such flexibility. When designed for disassembly, concrete elements can even be re-used as such in a different place.

### 3.5 Recycling

Concrete can be 100% recycled into secondary aggregates for new functions. Probably their best use is in unbound applications where the remaining binding capacity of the cement improve their properties, thus avoiding the use of stabilisation soil and the use of virgin materials. However, recycled concrete can be used as aggregate for new concrete products with minor technical adjustments. In both cases, this reduce the need for virgin materials!

## 4. What is needed to shift towards a circular economy in construction?

Even if the premises are very positive for precast, this does not mean that the sector has already achieved all the goals. If it is today already technically possible to apply all the principles expressed above, the reality is more complex and further efforts are needed.

First, circularity is not only in the manufacturing of goods, but in the whole design, construction, use and end-of-life stages. For this reason, all actors in the value chain shall play an active role in achieving circular economy in the construction sector and walk all together in the same direction.

Second, the market shall recognise the value of circular construction. Most of the proposed solutions above have indeed higher costs on the short term, even if they are cost-effective on the long; if costs remain the main driver, the shift may be slowed down. Another factor to consider is the difficulty to apply these principles in an efficient manner for refurbishing operations, whereas for new construction it is easier.

Third, legislation shall be set up to encourage the right application of circular economy principles to construction. Simply imposing a minimum content of recycled materials into concrete, for example, would not achieve the objectives. And again, it’s not a matter of manufacturers only, it’s the whole value chain that shall be tackled.

Fourth, research is needed. Technical and scientific background is necessary for a full acceptance of the integration of the principles of the circular economy into construction. Today, topics like the durability of precast elements made with recycled aggregates, dismountable solutions, ultra-high-performance concrete are not completely understood and sometimes the lack of confidence from the market is the real threat.

## 5. Conclusion

The shift towards circular economy in construction is not possible if there is not the full endorsement from all the actors in the value chain. Precast concrete elements have the potential to represent the backbone of a circular construction: lean structures with long service life, easy to maintain and repair, reusable and fully recyclable. With the help of all stakeholders (construction value chain, legislator and administrations, the research community) the shift is possible. BIBM, the federation of the European Precast concrete industry, plays its role in bringing together these actors at the European level with the aim of making the shift possible. And it should take place now.

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# SeRaMCo: Overall Project Management, Communication and Pilot Projects

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**Abstract**

The aim of the SeRaMCo project is to increase the use of construction and demolition wastes (CDW) as secondary raw materials for cement and concrete production in North-West Europe (NWE). CDW consists of components like concrete, bricks, tiles and ceramics (CBTC) that are currently used as backfill materials in road construction in most cases (downcycling). The project works on methods for high-quality recycling of CBTC and the improved use of fines (< 2 mm) from CDW in cement manufacturing. The results shall lead to new cement and concrete mixes and thus to the production of new, innovative concrete precast products (CPP). In the long term a significant increased use of recycled CDW is targeted.

This paper concentrates on the work of TU Kaiserslautern as lead partner of the SeRaMCo project containing overall management of the project in addition to communication and implementation of one of the three prototype buildings.

**Keywords**

recycled aggregates, CDW, project management, communication, pilot projects

**Kurzfassung**

Ziel des Projekts SeRaMCo ist es, die Verwendung von Bau- und Abbruchabfällen (CDW) als sekundäre Rohstoffe für die Produktion von Zement und Beton in Nordwest-Europa (NWE) zu erhöhen. CDW besteht aus Komponenten wie Beton, Ziegeln, Fliesen und Keramik (CBTC), die bisher meistens als Verfüllmaterialien im Straßenbau genutzt werden (sog. „Downcycling“). Das Projekt arbeitet an Methoden für ein qualitativ hochwertiges Recycling von CBTC und die verbesserte Nutzung von Feinstoffen (< 2 mm) aus CDW bei der Zementherstellung. Die Ergebnisse sollen zu neuen Zement- und Betonmischungen und damit zur Herstellung neuer, innovativer Betonfertigteile (CPP) führen. Langfristig wird ein deutlich erhöhter Einsatz von recyceltem CDW angestrebt.

Dieser Beitrag konzentriert sich auf die Arbeit der TU Kaiserslautern als federführender Partner des SeRaMCo-Projekts. Er beinhaltet neben dem Gesamtmanagement des Projekts und der Projekt-Kommunikation auch den Bau eines der drei Prototyp-Projekte.

**Schlüsselwörter**

Rezyklierte Gesteinskörnungen, CDW, Projektmanagement, Kommunikation, Pilotprojekte

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**Résumé**

L‘objectif du projet SeRaMCo est d‘augmenter l‘utilisation des déchets de construction et de démolition comme matières premières secondaires pour la production de ciment et de béton dans le nord-ouest de l‘Europe (NWE). Les déchets de construction et de démolition se composent d’éléments tels que le béton, les briques, les carreaux et la céramique (CBTC) qui sont actuellement utilisés comme matériaux de remblayage dans la construction de routes dans la plupart des cas (downcycling). Le projet travaille sur les méthodes de recyclage de haute qualité du CBTC et l‘utilisation améliorée des particules fines (<2 mm) de déchets de construction et de démolition dans la fabrication du ciment. Les résultats devraient conduire à de nouve-

aux mélanges de ciment et de béton et donc à la production de nouveaux produits préfabriqués en béton innovants. À long terme, une augmentation significative de l'utilisation de déchets de construction et de démolition recyclés est visée.
Cet article se concentre sur le travail de TU Kaiserslautern en tant que partenaire principal du projet SeRaMCo contenant la gestion globale du projet en plus de la communication et de la mise en œuvre de l'un des trois bâtiments prototypes.

**Mots-clés**
agrégats recyclés, déchets de construction et de démolition, gestion de projet, communication, projets pilotes

## 1. Project idea

The project idea of increasing the use of construction and demolition wastes (CDW) as secondary raw materials for cement and concrete production in North-West Europe (NWE) requires a rather interdisciplinary approach. Therefore, proven experts of France, Netherland, Belgium, Luxembourg and Germany have been linked together by the project management team (PMT). The SeRaMCo team consists of six partners from research institutes and five company partners. These project partners simultaneously work together in different working packages (WPs) as shown in figure 1. In the first step of work package T1 (WP T1) the process of recycling of two different types of construction and demolition wastes (from known and unknown sources) should be improved having in mind the goal to produce high, medium and low quality of recycled aggregates and sands. Recycled aggregates (RA) and recycled sands (RS) which are the main outputs of work package T1 (WP T1) are then being used for developing new innovative concrete and cement mixes in work package T2 (WP T2). Finally the new mixes will be tested in the laboratories of university partners and then will be utilized for producing structural and non-structural elements that will be applied in the pilots of the project within work package T3 (WP T3).

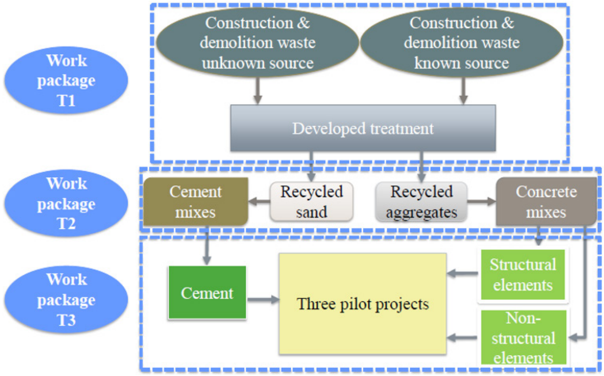


*Figure 1. Project idea*

## 2. Project Management Structure

Managing an interdisciplinary project like SeRaMCo is a demanding challenge. For the success of the project the support of specialists is essential, not only for the specialist functions associated with the technology of the project, but also for project management administration, estimating, planning, purchasing, cost accounting and information handling. The way in which such specialist project administration and management support is provided and organized varies between different companies and projects [1].
The successful management of SeRaMCo project follows a detailed structure covering the complete project period and working packages. SeRaMCo's management structure consists of:

### 2.1. Project management team (PMT)

Project management team (PMT) of Technische Universität Kaiserslautern as project lead partner (LP) with overall coordination. PMT includes project, financial and communication officers at the LP (not externalised), who secure all project and financial management: Reporting, monitoring of progress, risk management and communication issues. Tools comprise e.g. a half-yearly updated budget plan and work plan to monitor and illustrate deviations. PMT informs also steering committee and working groups about the developments and give decision support for them.

### 2.2. Working Groups (WGs)

Three thematic working groups (WGs) that provide a platform for content-wise exchange for the project partners (PPs) and their findings. Each PP is responsible for their regional project implementation according to the work plan and for cooperating in the joint tasks. These are planned and worked out by all PPs in the WGs. WGs correlate with the thematic work packages (WPs) and are coordinated by the WP leaders and the LP. Topics are defined according to work plan and current needs.

### 2.3. Project Steering Committee (SC)

Project steering committee (SC) that consists of one representative per PP (eleven members). It decides jointly about all major issues concerning the project (content-wise and financial progress, risks & quality management, major joint events and products). Input is provided by PMT and WGs. Furthermore, tasks are set to the WGs, especially on project risks and quality management. Meetings are twice a year.

### 2.4. Advisory Board (AB)

Advisory board that consists of key stakeholders, experts and multipliers from NWE countries. They consult on the project findings and support the establishment and commercialisation of the joint products and technologies at the respective NWE's markets. Special focus has to be drawn to assure the compliance of the products to technical regulations and confirm the quality of the project's results. The advisory board meets four times during the project.

## 3. Project Management Implementation

The project management and structure needs to be monitored consequently and continuously. In the following important management issues of SeRaMCo project are outlined:

### 3.1 Day to day management and coordination

Most important management tool is the project manual for all partners which documents important project information. I.e. progress reporting, internal communication, first level controlling (FLC), etc. It is constantly amended and extended according to the projects' progress. An overview with all project deliverables and responsible partners was generated.

### 3.2 Reporting & first level controlling (FLC)

For reporting purpose, the project management team (PMT) half yearly checks whether the partners' activities and financial reports are delivered in time. Also their inputs are compiled into a consolidated report which is then certified by the lead partner's (LP) first level controller (FLC).

### 3.3 Risk management

The PMT has established a risk management plan to identify, monitor and tackle project risks. This plan contains three risks with information on risk, assessment (probability, impacts, etc.) and proposals to mitigate the risks. In the following is a brief explanation of these risks.

### *3.3.1 Implementing investments*

SeRaMCo includes three investments to apply and promote the methods and precast products in the urban built environment according to the project's investment strategy. Implementation of these investments could be delayed or hindered by following aspects:

- Difficulties with non-compliance with technical regulations
- Delays due to missing building permits
- Difficulties in the previous design process

### *3.3.2 Risk related to the use of recycled aggregates and sands*

Recycled aggregates contain different types and quantities of aggregates, old cement, bricks, masonries, etc. Their composition (chemical and mineralogical) is different than the composition of the classical raw materials (limestone + clay) used for cement and concrete production. These raw materials are blended, burned for clinker manufacture and crushed with additives (calcium sulphate, limestone, slag, etc.) to produce cement. This may lead to the following risks:

- The aggregates may contain reactive silica materials leading to alkali-silica reactions or alkali-carbonate reactions.
- Because of the production variation of recycled aggregates (spatial and temporal), it might be difficult to classify and characterize the sand quality in terms of chemical and mineralogical composition and therefore burning behavior at high temperature.

### *3.3.3 Project outputs cannot be fulfilled in time due to internal project delays*

Many of SeRaMCo's project outputs build on previously conducted project activities. The risk is that a delay in one activity (e.g. in WPT1 or WPT2) will have negative impacts on later activities (WPT2 or WPT3).
This plan is regularly updated according to the current situation of the pro-

ject. The status of the three risks included in the risk log is checked on the basis of available information from progress report, financial controlling tools, work plan, steering committee meetings and advisory board meetings. It is updated twice a year.

### 3.4 Financial management

For financial management a database with the budget plan for a detailed financial monitoring of the project and the expenditure for every PP has been set up. This serves as an internal financial monitoring tool for the financial monitoring reports. There are six monitoring reports as an internal financial monitoring tool. Financial reporting is prepared regularly and the PP inputs are coordinated.

## 4. Project Communication

Concrete precast products from recycled aggregates are technically feasible, eco-friendly, and under ideal preconditions they do not cost more than primary raw materials. This is the basic message of the SeRaMCo project. The main task for SeRaMCo's communication is to inform the actors of the supply chain (enterprises producing either recycling material and/or concrete and cement, public authorities using products in the built environment) about the methods and products developed in the project. The goal is to engage them in implementing a supply chain for replacing the raw materials in pre-cast concrete products with secondary raw materials to finally increase the use of these in the built environment.
As a platform for all communication activities a communication plan that indicates activities, responsibilities and deadlines was developed. It includes smart defined goals, target groups (incl. database), key messages, tactics and tools:

- Start-up activities were developed, like a communication strategy, a project poster and project leaflet.
- Digital activities, like regular updates of the project website that contains a description of goals, objectives, techniques, methods and project news were carried through, 10 quarterly newsletters were written as well as regular weekly posts on Twitter and LinkedIn.
- Regularly information about project outcomes and results were published in scientific and non-scientific articles that appeared in national and international building journals and magazines for the supply-chain-actors (see table 1).
- At least seven presentations of findings were given at key multipliers and high-level conferences.
- Two documentary videos about the recycling process were produced. One video made about the production of recycled aggregates from demolition waste at the premises of the SeRaMCo partner Tradecowall in Belgium. A second video about the production of cement made from recycled aggregates at the cement factory of the SeRaMCo partner Vicat in Créchy, France. A third video about the production of concrete precast products made of secondary raw materials is foreseen within the next weeks at the premises of Prefer in Belgium.
- Three more videos are planned in 2020 about the building and inauguration of the new products at the three different pilot sites
- The execution of the communication plan is monitored by presenting the results in communication progress reports on a half-yearly basis.

Target groups have been defined along the supply chain to be informed during the project duration. They consist of a broad variety of authorities, enterprises, service providers and facilities providing higher education all over North-West-Europe.

The SeRaMCo project has reached a valuable part of the goal. Referring to general public, a goal of 600,000 as target value in the work plan seems very ambitious. But only the number of inhabitants in the pilot cities - without tourists - sum up to a total of 220,000 people. SeRaMCo Communication is constantly working on reaching as many people as possible by issuing newsletters on a regular basis, sharing news on Twitter and LinkedIn as well as writing articles on the project results in national and international journals and on regional and international meetings and conferences. Additional videos, webinars and e-manuals for online-presentation are under development.

Publications about the progress results of the project have been regularly published in magazines for the supply chain actors; i.e. an article has been published in the British "CONCRETE"-magazine: "Recycled sands and aggregates in cement and precast concrete – a step towards a circular economy in the construction sector". The final results of the project will be published as soon as they are completed. Today, more than 30 articles in scientific and non-scientific magazines have already been published.

During the project contact was established with several stakeholders all over NWE (see figure 2) either by presenting project results at conferences and meetings or by offering workshops in the frame of the project. Some were approached by direct dialogue related to connected questions and problems and their advice and information was included into the project work. Thus receiving information about SeRaMCo they were interested to be added to the list of the regularly distributed project newsletter.

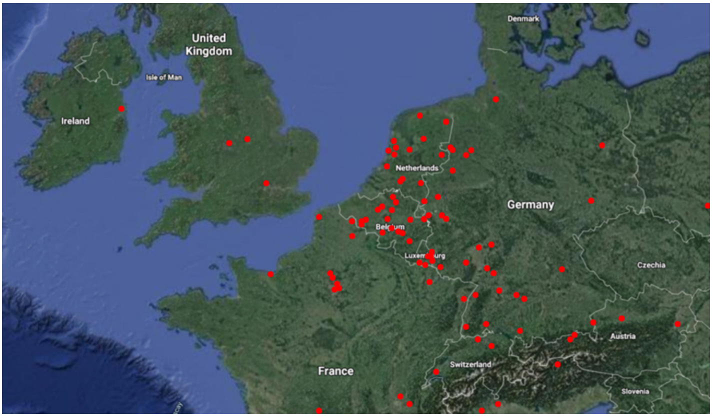


*Figure 2. SeRaMCo stakeholders in the NWE area*

## 5. Investments unication

### 5.1 Investments as a way of communication

The most important challenge for the SeRaMCo team is to spread their results as far as possible, not only beyond the stakeholders and target groups, but in professional and general public. In addition to written information like publications or even social media it is absolutely necessary to have real products as an actual physical outcome of the project. These products can serve as a showcase in public spaces. In case of the SeRaMCo project it is planned, to build three so called "investments" constructions build with finished SeRaMCo products using recycled concrete.
With the cities of Seraing (Belgium), Saarlouis (Germany) and the Direction interdépartementale des Routes EST (Office of Public Roads, France) three public authorities from three different countries joined the SeRaMCo project as sub partners. For a sustainable showcase, it is important that there are public authorities as sub partners in the project. On one hand, to develop a concept, which is really needed and consequently will be used by general public. In this way, the lifetime of the showcase will be increased,

and the impact will be maximized. On the other hand, public authorities can help the project partners with their knowledge about regional regulations and formal requirements in the building process. In the SeRaMCo project the following investments will be built (see figure 3):

- City of Seraing: "Parkour park"
- City of Saarlouis: "Entrance to the fortification"
- Direction interdépartementale des Routes EST: "Highway parking site"

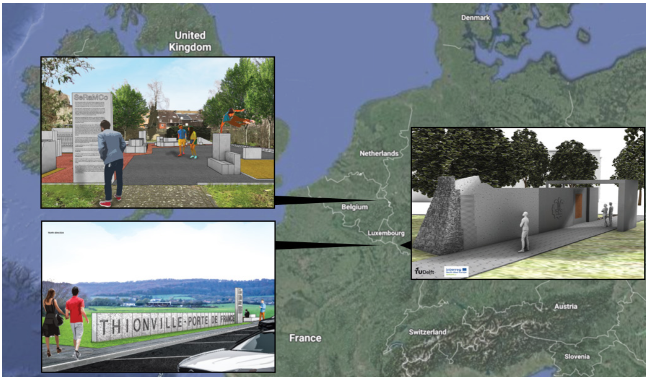


*Figure 3. Investments in SeRaMCo Project*

### 5.2 The City of Saarlouis

The SeRaMCo project's sub partner Saarlouis is a city in Saarland, Germany with about 40,000 people live there. Founded in 1680 the city was designed as a flood fortress: The Saar could be dammed up at the lock bridge to fill the ditches and flood the surrounding area. Impressive elements of the former horn factory, the „Bastion VI" and the Vauban island are just a few buildings from the French and Prussian times that have been preserved and still tell their story today.
Founded as a fortress city by King Ludwig XIV and taken over and expanded

by the Prussians after Napoleon's defeat at Waterloo, the fortress and architectural heritage are not only guiding principles for urban development, but also fundamental, identity-defining features of Saarlouis - for residents and tourists alike. Creating this awareness is a shared task of urban politics and urban planning, tourism promotion, historical research and a rich cultural program.
At the same time, a community oriented towards sustainability requires innovation, courage and the joy of experimentation. Saarlouis was a model city for car sharing projects with e-mobility, private green waste is used as well as landfill gas to generate heat in municipal facilities. Together with a citizens' energy cooperative, it was possible to install photovoltaic systems from several citizens on several buildings without losing the burden urban budget. With the integrated climate protection concept, the city council unanimously voted for the vision of a $CO_2$-free city and sent a strong signal with the permanent appointment of the first climate protection manager in Saarland. The "Stadtwerke Saarlouis" are also a driving force in the development and implementation of sustainable ideas and sustainable supply infrastructure [2].

### 5.3 Investment in the City of Saarlouis

Building an investment as demonstrator for the use of recycled aggregates is very important for the success of the SeRaMCo project. To maximize the lifetime of the investment and concerning to the sustainable aspect of the project the design has to be linked to the location and meet an existing demand.
Considering the city's history, the SeRaMCo team agreed to build a barrier-free "entrance to the fortification" in a public space with high traffic near the "Stadt Garten", a park which is part of former fortification area. The investment will illustrate a longitudinal section of a fortress wall in combination with a portal. Visitors can inform themselves there about both, the fortification and the SeRaMCo project (see figure 4). Different types of concrete surfaces on the precast elements will illustrate the different layers

in the fortification walls. The geometry of the investment will be a scale model. The celling, which will be part of the portal, will be supported by two columns and one wall. On the end of the building there will be a short orthogonal wall build with precast blocks. They symbolize the masonry used for the outer layer.

In particular, the concept of the access portal as a structure made from recycled materials contains a strong connection to the fortress history of Saarlouis. For an example, after the founding of the city the inhabitants of the neighboring “municipality of Wallerfangen” were forcibly relocated to the new city in 1687/88. Most of the buildings in Wallerfangen were demolished in order to obtain building materials for the new houses to be built in Saarlouis. In the end of the 19th century, when the fortress was demolished, essential parts of the fortress were also demolished and reused [2]. This fact will show future visitors they can trust in recycled materials. If the massive fortification buildings in Saarlouis were built using construction and demolition wastes and did not collapse for centuries, why shall we be afraid to use CDW today.

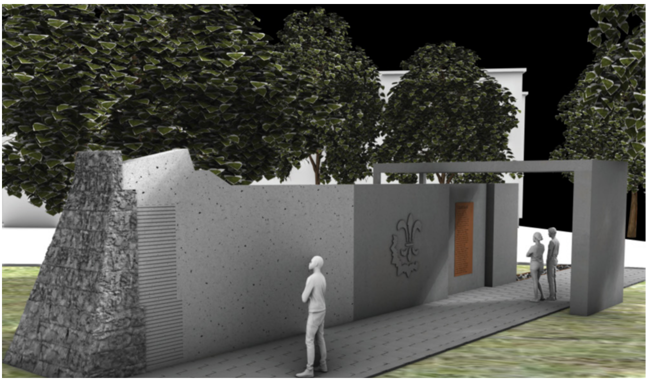

*Figure 4. Investments Saarlouis*

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# Influence of the Wet Process on the Quality of Recycled Aggregates

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**Abstract**

The quality of the recycled aggregates strongly depends on the products treatment, specifically the washing process. The research is focused around the comparison of the classical "dry process" and of the newly implemented "wet process". During this process the aggregates are washed and go through specific screening to remove most of the unwanted floating elements (wood, plaster, etc.) and to reduce the fine content.

First Tradecowall's new aggregates production plant is presented, including its implementation for the SeRaMCo project as well as each of its subcomponents and their function. Then, the results of the laboratory characterisation campaign are analysed.

**Keywords**

concrete, recycled aggregates, aggregates production

**Kurzfassung**

Die Qualität der rezyklierten Gesteinskörnungen ist stark abhängig von Produktbehandlung insbesondere Nassprozess. Im Mittelpunkt dieser Arbeit steht der Vergleich zwischen dem traditionellen Trockenprozess und einem neu eingeführten Nassprozess. Während dieses Prozesses werden die Gesteinskörnungen gewaschen und durchlaufen ein spezielles Screening, um

den Großteil der unerwünschten schwimmenden Elemente (wie Holz, Gips, etc.) zu entfernen und um den Feinanteil zu reduzieren.
Zuerst wird die neue Anlage von Tradecowall zur Produktion von Gesteinskörnungen vorgestellt, einschließlich ihrer Anwendung für SeRaMCo Projekt, sowie ihrer einzelnen Teilkomponenten und deren Funktion. Danach werden die Ergebnisse der Laboruntersuchungen vorgestellt

**Schlüsselwörter**
Beton, rezyklierte Gesteinskörnungen, Gesteinskörnungenproducktion

**Résumé**
La qualité des granulats recyclés dépend en grande partie de la préparation et en particulier du lavage des produits. L’étude est centrée sur la comparaison des propriétés des granulats recyclés issus de la filière classique dite « voie sèche » et ceux issus de la « voie humide ». Le procédé par voie humide implique que les granulats recyclés soient soumis à des opérations de tri spécifiques incluant notamment un lavage afin d’isoler les composants indésirables tel que le plâtre, le bois, etc. Ce procédé permet également de réduire la teneur en particules fines des granulats recyclés produits.
Les nouvelles installations de tri et de lavage mise en place par Tradecowall dans le cadre du projet SeRaMCo sont présentées. Ensuite, les résultats de la campagne de caractérisation sont commentés et analysés.

**Mots-clés**
béton, agrégats recycles, production d’agrégats

## 1. Introduction

Construction and demolition waste (CDW) is one of the heaviest and most voluminous waste streams generated in the EU [1]. Recycling is an increasingly popular method of disposing of CDW that can even provide a sustainable source of aggregates for future concrete production [2, 3]. However, the recycled aggregates are usually of lower quality compared to natural aggregates and are generally considered to be unsuitable for use in structural concrete [4]. Recycled aggregates produced by classical recycling plants usually have lower density, higher water absorption, and lower abrasion resistance than natural aggregates. The recycled aggregates also contain much higher fine content than natural aggregates and often include unwanted elements such as wood, plastic, plaster, etc. All these, as well as the presence of remaining cement paste [5] are responsible for the lower quality of recycled aggregates compared to natural aggregates.
The increasing awareness of the economic and environmental benefits of recycling has led to intensive research activities aimed at a better understanding of the recycled aggregates properties and of the effects they have on the properties of the recycled concrete produced. In order to be able to produce high quality concrete precast products from recycled CDW, techniques to improve the quality of recycled aggregates produced with traditional production processes are investigated. Specifically, the influence of the washing process on the properties of recycled aggregates is studied.

This paper begins by introducing Tradecowall's recycled aggregates production installations and detailing the different components the CDW go through in order to produce high grade recycled aggregates. Then, the paper goes through the installation of the newly designed wet process plant and its specific components are also detailed. Finally, the experimental campaign conducted at ULiège to study the influence the wet process has on the quality of the recycled aggregates is presented. Grain size distribution, fine content, bulk density, particle density, water absorption, unwanted elements composition, resistance to fragmentation have been considered as the defining parameters for recycled aggregates quality.

## 2. Recycled aggregates production

Tradecowall's main objective in the SeRaMCo project is to supply quality recycled materials to partners producing cement and concrete. Two types of installations are being used for the SeRaMCo project: a « dry process » installation and a « wet process » installation, during which the aggregates are cleaned. The dry process installation was already in use before the start of the project. On the other hand, the wet sorting installation had to be set up and required many transformations in order to improve its performance. The final aim of this project is for the dry processed materials to be used by Vicat to produce cement and the wet processed materials by PREFER and Beton-Betz to produce concrete. In Figure 1, the general idea of Tradecowall's role in the SeRaMCo project is exposed.

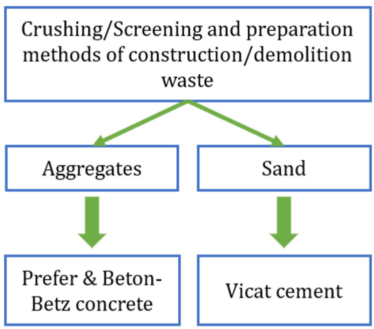


*Figure 1. General idea of Tradecowall's role in the Seramco project.*

In this paper, the influence of the wet process on the properties of the recycled aggregates produced is investigated and therefore, aggregates have been produced using both installations. Theses installations are introduced in the following sections.

## 2.1 Dry process

As previously mentioned, the dry process installation from which the sand for Vicat is produced was already up and running before the SeRaMCo project. The flow sheet for the dry process can be seen in Figure 2. When a building is demolished, its parts must be evacuated and treated somehow. This is when Tradecowall comes in, with its installation capable of producing perfectly good quality of aggregates from CDW.

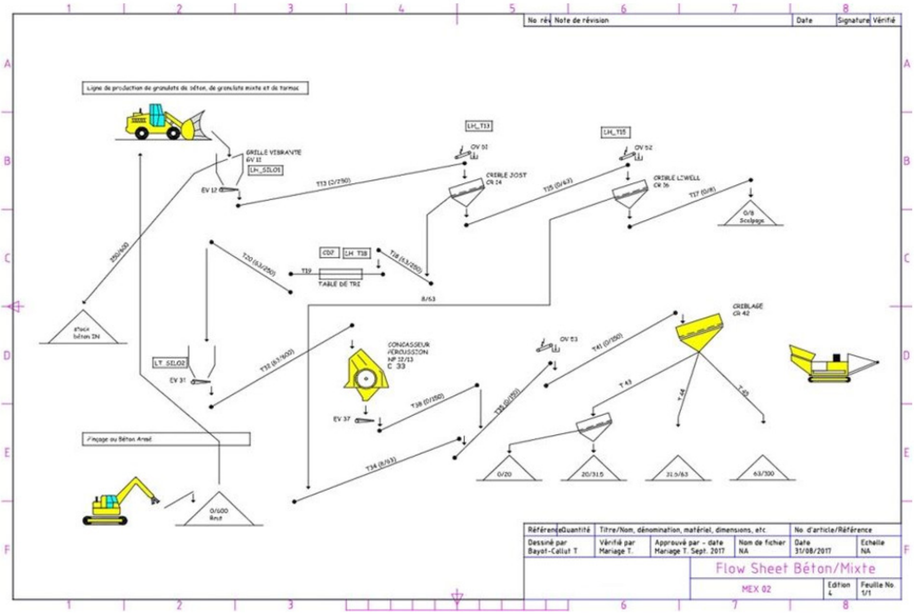


*Figure 2 . Flow sheet of the dry process installation*

The CDW composed of soil and inert waste will go through several types of machineries:

- Crushers: to break down the input product in order to have smaller sized aggregates (figure 3);

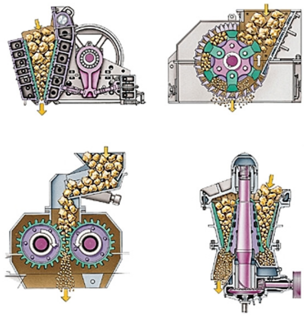

*Figure 3. Crushers*

- Overband magnets: remove metal elements from the product (figure 4);

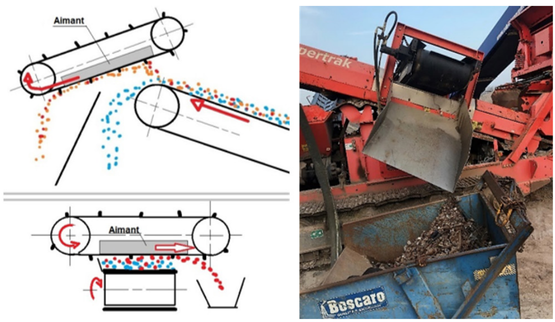


*Figure 4. Overband magnet scheme (left) and in situ picture (right)*

- Mechanical screeners: composed of 2-3 levels of screens, to obtain different particle sizes (figure 5);

*Figure 5. Mechanical screener*

Conveyor belts join these machineries together transporting the load from one step to the next until the final output. Different grain sizes are issued from this process and depending on the input waste, the nature of the aggregates will be different. As shown in the flow process our typical grain size range production are 0/20 mm, 20/31.5 mm, 31.5/63 mm and 63+ mm.

### 2.2 Wet process

The wet process installation had to be done from scratch, starting with the landscaping as shown in Figure 6 where the bases and a concrete slab were laid to support the installation. The installation had then to be transported and set up. Some parts had to be reconditioned, others added to complete and improve the process. Many adjustments had to be made in order to meet the objectives of the SeRaMCo project which is to produce high quality aggregates suitable for precast concrete elements. The University of Liège and TU Delft both tested the quality of the recycled aggregates produced by the wet process installation and their ability to be used in concrete elements. The results of these tests can be seen in section 3.

*Figure 6. Illustration of the different steps of the setup of the installation.*

The wet process installation was up and running in the summer of 2018. A picture of the final setup can be seen in figure 7


*Figure 7. Picture of the final setup of the wet process installation*

After many trials, a final product could be repetitively produced by the end of 2018 and many batches were sent to some of the different project partners (TU Delft, TU Kaiserslautern, University of Lorraine and University of

Liège). The flow sheet of the wet process is shown in figure 8.

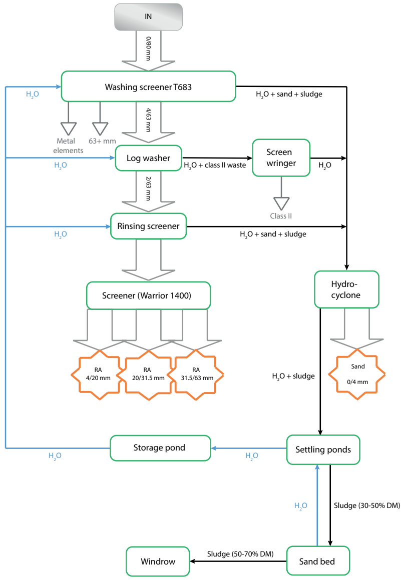


*Figure 8. Flow sheet of the wet process*

This process can be done either on aggregates that have gone through a first crushing and screening process or on the construction's and demolition's raw materials. Like implied in its name, the wet process installation washes the aggregates with water and as can be seen in the flow sheet. The installation has been thought as a closed circuit in order to reduce water consumption.

A few specific machineries compose the wet process compared to the dry process. An overband magnet is also part of the process just as for the dry process which is one of the first step before going through the wet process. After that, the aggregates go through a set of other machineries described below:

- Washing screener (Terex Finlay 683): basically, the same operation as a mechanical screener with an added touch; sprays over the screens for a first wash of the recycled aggregates as shown in figure 9.

*Figure 9. Screen equipped with sprays*

- Log washer (Logwasher 206 Terex Finlay): composed of two rotating shafts equipped with blades. The log washer, working as an Archimedes' screw, is placed in an oblique position for the recycled aggregates to be lifted at the top of the tank. Furthermore, the oblique positioning will enable the removal of part of the floating and drowning elements (see figure 10).

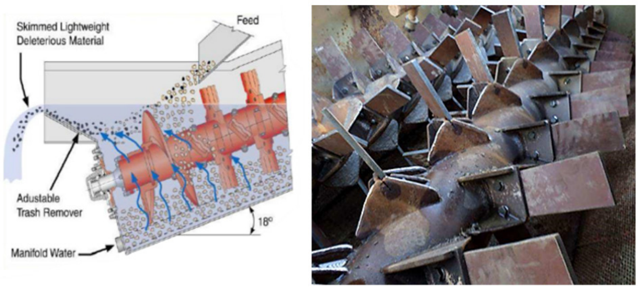


*Figure 10. Scheme (left) and picture of the inside (right) of the log washer*

- Rinsing screener (Mogensen): the aggregates go through a second round of rinsing and screening to obtain a 4/63 mm mixed recycled aggregates (see figure 11).

*Figure 11. Mogensen screener*

- Screener (Warrior 1400): a final screening giving out three final grain size ranges, 4/20 mm, 20/31.5 mm and 31.5/63 mm. Although, in the case of the SeRaMCo project we chose screeners giving out the following grain size range: 4/6 mm, 6/14 mm and 14/20 mm (figure 12).

*Figure 12. Screener Warrior 1400.*

- Screen wringer (Sotrès): this wringer collects the wash water issued from the different steps of the process. Here, elements such as plastic, wood, polystyrene are sorted out to be recycled in the appropriate value chain (figure 13).

*Figure 13. Screen wringer (Sotrès)*

- Hydrocyclone (Sand master Terrex C15): Sludge collected from the different machineries explained just above, flow by gravity into the hydro cyclone which will separate material based on their density. Hence, it will separate the sand, the heavier fraction coming out through the bottom of the hydro cyclone, and the sludge, the lighter fraction coming out through the top as shown in figure 14.

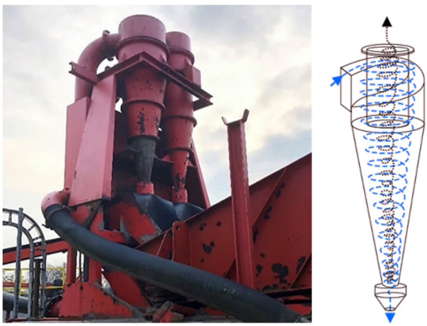

*Figure 14. Hydrocyclone*

The sludge collected from the hydro cyclone is sent to seven containers placed in parallel next to each other serving as tailing ponds to clarify the water with the help of a flocculating agent. At first the containers were simply put next to each other, but they are now buried to ground level. Once the water is cleansed it is stored in another pond to be pumped again when the installation is in use. As for the sludge it is transferred from the containers to a dug-up pool filled with a sand bed spread upon its floor (figure 15). The sand bed will be used as a drainage system in order to dry the sludge as much as possible before being evacuated. As shown in the picture below (figure 15, on the left) a collector of water has been built before putting the sand. This collector and the fact that the pool has a slope across both the width and the length force the water to one corner where it is collected and pumped in the same storage pond as the cleansed water from the tailing ponds.

*Figure 15. Pool for sludge drying (left) and its sand bed (right)*

Many trials were carried out and improvements were continuously brought to the installation to achieve the quality that we now have. Since it is an installation functioning through a wet process, a lot of clogging occurred. But after a lot of hard work and adjustments, the installation was finally a reliably producing recycled aggregates.
As previously said, Tradecowall's major role in the SeRaMCo project was the supply of recycled aggregates for the cement and concrete producers. But before production, these aggregates had to be tested to ensure they were suitable. The following section of this paper will focus on the results obtained by the University of Liège.

## 3. Experimental campaign

In order to assess the effect of washing on the aggregates' properties, washed and unwashed materials coming from the same source have been studied. Two types of aggregates have been considered in this work: concrete aggregates and mixed aggregates. As previously explained, the investigated materials come from Tradecowall's recycling plant. Six batches have been delivered to the University of Liege:

- unwashed concrete aggregates 0/20 (named B-0/20)
- washed concrete aggregates 4/20 (named B-4/20) (Figure 16)
- clean concrete sand 0/4 from the coarse fraction washing (named B-0/4) (Figure 17)
- unwashed mixed aggregates 0/20 (named M-0/20)
- washed mixed aggregates 4/20 (named M-4/20) (Figure 16)
- lean mixed sand 0/4 from the coarse fraction washing (named M-0/4) (Figure 17)

*Figure 16. Washed recycled aggregates (mixed on the left and concrete on the right). Photo from Tradecowall.*

*Figure 17. Washed recycled sands (mixed on the left and concrete on the right). Photo from Tradecowall.*

The experimental campaign consisted in evaluating some of the main properties of the recycled materials. The investigated properties according to the sample are detailed in Table 1. These properties correspond to requirements defined in the standards related to concrete. The aims of this campaign are formulated in the interrogative form as followed:

1. What is the influence of washing aggregates on their technical properties?
2. Do the technical properties of recycled aggregates (washed and unwashed, mixed and concrete) fulfil the requirements defined in the standards related to concrete?
3. What are the main differences between the properties of the recycled aggregates and those from the natural aggregates?

*Table 1. Experimental campaign carried out on the recycled materials.*

| Batches | B-0/20 | | B-4/20 | B-0/4 | M-0/20 | | M-4/20 | M-0/4 |
|---|---|---|---|---|---|---|---|---|
| | 0/20 | 4/20 | | | 0/20 | 4/20 | | |
| Grain size distribution | X | | X | X | X | | X | X |
| Fine content | X | | X | X | X | | X | X |
| Constituents | X | | X | | X | | X | |
| Bulk density | X | | X | X | X | | X | X |
| Particle density | X | X | X | X | X | X | X | X |
| Water absorption | X | X | X | X | X | X | X | X |
| Resistance to fragmentation (LA) | X | | X | | X | | X | |

## 3.1 Results

### *3.1.1 Grain size distribution*

Grain size distribution curves for the different batches of aggregates are visible in Fig. 18. Washing tends to significantly decrease the sandy fraction (0-4 mm in diameter). Washed concrete and mixed aggregates are respectively composed of 4.4% and 12.0% of sands, while unwashed aggregates are characterised by a sandy fraction much more abundant, between 45 and 50% for both types of recycled aggregates (Figure 19).

Figure 18 also compares the experimental grain size distribution curves with standardised curves suggested for aggregates used in concrete for testing. The required maximum and minimum values of the cumulated passing are illustrated according to the norm NBN EN 480-1:2014 [6]. Due to their narrow grain size ranges, the use of washed recycled aggregates in concrete will need the addition of a complementary sandy fraction. As can be seen, both concrete and mixed unwashed aggregates curves are very close to the maximum value accepted by the standards. This is true for fraction ranging from 25 mm to 0.5 mm in diameter. Below 0.5 mm, both unwashed aggregates have values closely above the maximum accepted values by the standard for cumulated passing. This means that the proportion of the fraction 0 to 0.5 mm is a bit too high according to the standard for unwashed aggregates.

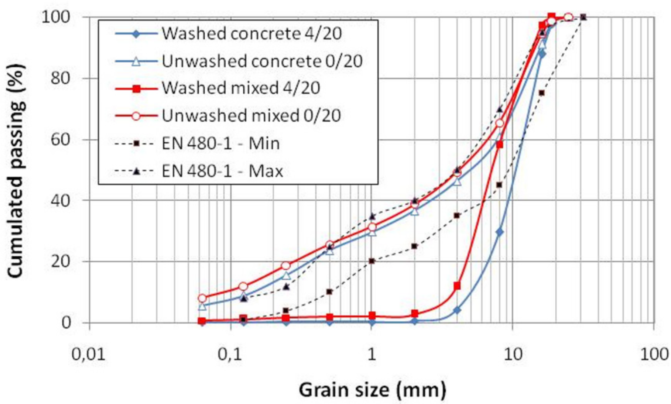


*Figure 18. Grain size distribution of washed and unwashed recycled aggregates (concrete and mixed).*

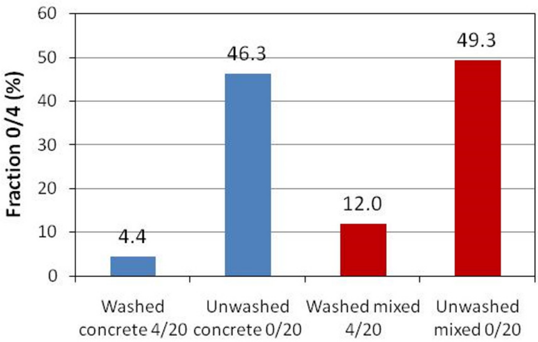


*Figure 19. Proportion of the sandy fraction included into the recycled aggregates (concrete and mixed).*

Another manner to evaluate the quality of the grain size sorting is illustrated in Figure 20. Most of the investigated commercialised natural aggregates have a percentage of aggregates included in the declared grain size range of around 80%. The washed recycled aggregates produced have a higher rate of sorting since the proportion reaches 85 – 90%. It means that more than 85 – 90% of the produced washed aggregates are included between 4 and 20 mm in diameter.

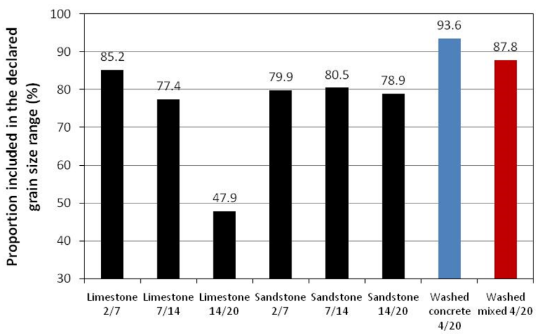


*Figure 20. Percentage of aggregates included in the declared grain size range by the producer. Comparison between natural aggregates and washed recycled products.*

Recycled sands are also investigated in terms of their grain size distribution (cf. Figure. 21). Both recycled sands are well graded sands. Their curve is close to the particle size distribution of crushed calcareous sand. Rhine sand is characterised by a much more uniformly graded curve.

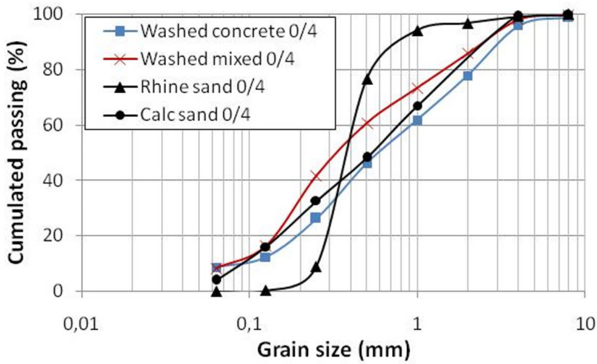


*Figure 21. Grain size distribution of washed sands (mixed and concrete), and commonly used natural sands in concrete (Rhine sand and crushed calcareous sand).*

### *3.1.2 Fine content*

Fine content is one of the most constraining parameters for aggregates used in concrete. Figure 22 shows the fine content for both sources of aggregates, washed and unwashed. Washed aggregates clearly have lower fine content values, below 1%. Unwashed aggregates have fine content of 6% and 8% for concrete and mixed aggregates respectively. National standards prohibit the use of unwashed aggregates due to their too high proportion of fine particles (cf. Table 2). Washed aggregates are accepted in all the investigated NWE countries. Washing can clearly be a suitable method for producing satisfying recycled aggregates in terms of fine content.

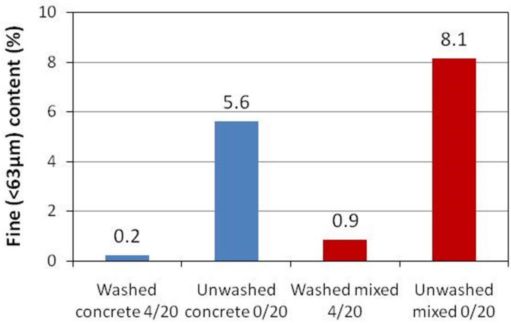


*Figure 22. Fine content of the investigated recycled aggregates.*

*Table 2. Fine content requirements for recycled aggregates (concrete and mixed) related to concrete in NWE national standards.*

| Country | Type | Requirements |
|---|---|---|
| FR | Type 1, 2 & 3 (concrete & mixed agg) | **≤1,5** ($G_C$80/20, $G_C$90/15)<br>**≤11** ($G_A$85) |
| DE | Type 1 & 2 (concrete & mixed agg) | **≤4** |
| LU | | **≤1,5** |
| BE | Type A+ (concrete agg) | **≤1,5** |

Fine content included in the studied recycled sands is higher than fine content characterising crushed limestone (Figure 23). These values are also much higher than the fine content of the Rhine sand.

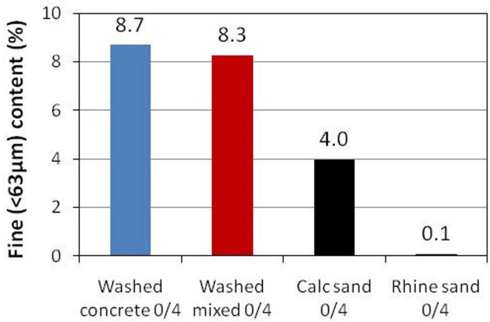


*Figure 23. Fine content of the investigated recycled sands.*

### *3.1.3 Bulk density*

Bulk density of washed recycled sands and aggregates has been measured. Bulk density of washed concrete and washed mixed aggregates 4/20 corresponds to 1.22 and 1.19 g/cm³ respectively. Bulk density of washed concrete and washed mixed sands corresponds to 1.42 and 1.34 g/cm³ respectively.

### *3.1.4 Particle density*

Particle density has been measured with a pycnometer. Due to the high porosity of recycled aggregates, the aggregates saturation has been carried out in a vacuum chamber, forcing water to penetrate the open porosity. In order to compare washed and unwashed coarse aggregates, a sample of granular fraction 4/20 has been taken from both concrete and mixed unwashed aggregates batches (0/20). Figure 14 shows results for the different investigated samples. Recycled coarse concrete aggregates density ranges between 2.3 and 2.5 g/cm³ and recycled coarse mixed aggregates density varies between 2.1 and 2.4 g/cm³. Recycled concrete and mixed sands have particle density corresponding to respectively 2.3 and 2.4 g/cm³.
Measured values are lower than those usually characterizing natural aggregates (particle density of sandstone is 2.6-2.65 g/cm³ and of limestone is 2.65-2.7 g/cm³) but they still verify the standards and requirements in every

investigated NWE country (Table 6). Indeed, minimum particle density of concrete aggregates is defined at 2.0 or 2.2 g/cm³. These values move at 1.7 or 2.0 for mixed aggregates. In every case, the measured values are higher than those required by standards.

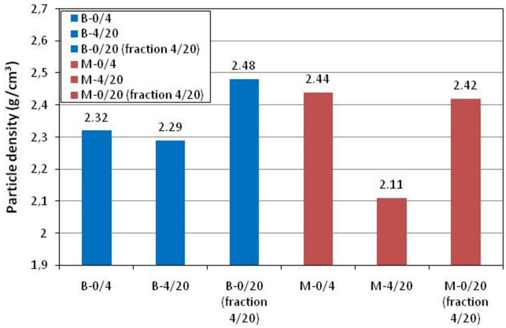


*Figure 24. Particle density of recycled concrete and mixed: washed sands, washed aggregates and unwashed aggregates (fraction 4/20).*

*Table 3. Particle density requirements for recycled aggregates (concrete and mixed) related to concrete in NWE national standards.*

| Country | Type | Requirements |
|---|---|---|
| FR | Type 1 & 2 (concrete agg) | **≥2.0** |
| | Type 3 (mixed agg) | **≥1.7** |
| DE | Type 1 & 2 (concrete & mixed agg) | **≥2.0** |
| LU | | **≥2.0** |
| BE | Type A+ (concrete agg) | **≥2.2** |
| | Type B+ (mixed agg) | **≥1.7** |
| NL | Type A1 (concrete agg) | **≥2.2** |
| | Type A2 & B (concrete & mixed agg) | **≥2.0** |

### *3.1.5 Water absorption*

Water absorption has been measured on both sands and coarse aggregates. General trends show that mixed fractions have higher water absorption than concrete samples. Water absorption of concrete aggregates ranges between 6.0 and 6.3% (Figure 15). This parameter reaches 9.2% in mixed aggregates. Sandy fractions have lower water absorption for both concrete and mixed samples, with respectively 4.9 and 4.8%.
Measured values are lower than the maximum values required in standards from Germany and Belgium (Table 4). Maximum values of water absorption in concrete and mixed aggregates are defined at respectively 10% and 15% in standards from both countries.
However measured values are much higher than those usually characterising natural aggregates. Water absorption usually ranges between 1 and 1.5% in limestone and between 1 and 2% in sandstone.

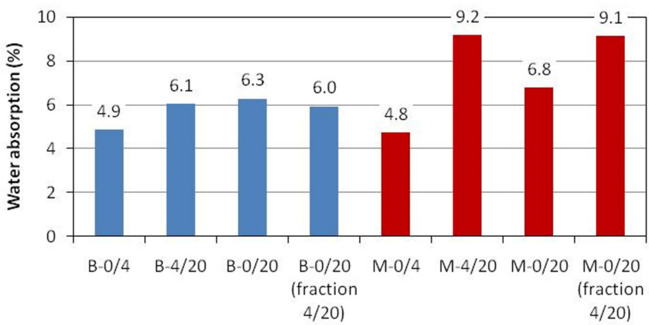


*Figure 25. Water absorption on recycled sands and aggregates (mixed and concrete)*

*Table 4. Water absorption requirements for recycled aggregates (concrete and mixed) related to concrete in NWE national standards.*

| Country | Type | Requirements |
|---|---|---|
| DE | Type 1 (concrete agg) | **≤10** |
| | Type 2 (mixed agg) | **≤15** |
| BE | Type A+ (concrete agg) | **≤10** |
| | Type B+ (mixed agg) | **≤15** |

### *3.1.6 Constituents*

Proportion of the different coarse constituents defined according to the standard EN 933-11 has been measured from washed and unwashed concrete and mixed aggregates. The different constituents are defined in Figure 26 and illustrated in Figure 27. Measured proportion of each constituent is detailed in Table 8. Recycled washed and unwashed concrete aggregates have proportion of Rcu larger than 90% and Rb lower than 10%. Recycled washed and unwashed mixed aggregates have proportion of Rcu larger than 70% and Rb lower than 30%. These compositions are in agreement with most of the national standards (see Table 6 [7]).
No significant differences between washed and unwashed aggregates are observed from non-floating elements. However, floating elements are decreased by washing in both types of recycled aggregates (Figure 18). In most of national standards, floating elements are limited to a maximum of 2 $cm^3/kg$. Unwashed mixed aggregates have higher proportions than the required threshold while washed aggregates have a value lower than 2 $cm^3/kg$.

| Constituent | Description |
|---|---|
| Rc | Concrete, concrete products, mortar<br>Concrete masonry units |
| Ru | Unbound aggregate, natural stone<br>Hydraulically bound aggregate |
| Rb | Clay masonry units (i.e. bricks and tiles)<br>Calcium silicate masonry units<br>Aerated non-floating concrete |
| Ra | Bituminous materials |
| Rg | Glass |
| X | Other: Cohesive (i.e. clay and soil)<br>Miscellaneous: metals (ferrous and non-ferrous),<br>non-floating wood, plastic and rubber<br>Gypsum plaster |

*Figure 26. Non-floating elements of coarse recycled aggregates, according to the standard EN 933-11.*

*Table 5. Measured proportion of constituents of the investigated washed and unwashed samples, according to the standard EN 933-11. FL = floating elements.*

| | **B-4/20** | **B-0/20** | **M-4/20** | **M-0/20** |
|---|---|---|---|---|
| FL ($cm^3/kg$) | 0.51 | 1.25 | 1.58 | 3.10 |
| X (%) | 0.01 | 0.08 | 0.23 | 0.15 |
| Rc (%) | 81.43 | 86.78 | 61.05 | 63.04 |
| Ru (%) | 10.60 | 5.47 | 11.80 | 9.80 |
| Rb (%) | 7.53 | 6.24 | 24.89 | 25.42 |
| Ra (%) | 0.01 | 0.18 | 0.00 | 0.00 |
| Rg (%) | 0.02 | 0.01 | 1.00 | 0.17 |


*Figure 27. Sorting of the different constituents from mixed aggregates.*

*Table 6. Definition of concrete and mixed aggregates according to national standards and requirements in NWE [7].*

| **Country** | **National supplement** | **Other norms and documents** | **Types of recycled aggregates** | **Composition** |
|---|---|---|---|---|
| European norm EN 206:2013 +A1:2016 | | | Type A | $Rc_{90}$, $Rcu_{95}$, $Rb_{10-}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{1-}$ |
| | | | Type B | $Rc_{50}$, $Rcu_{70}$, $Rb_{30-}$, $Ra_{5-}$, $FL_{2-}$, $XRg_{2-}$ |
| France | NF EN 206/CN:2014 | | Type 1 | $Rcu_{95}$, $Rb_{10-}$, $Ra_{1-}$, $FL_{0.2-}$, $XRg_{0.5-}$ |
| | | | Type 2 | $Rcu_{90}$, $Rb_{10-}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{1-}$ |
| | | | Type 3 | $Rcu_{70}$, $Rb_{30-}$, $Ra_{10-}$, $FL_{2-}$, $XRg_{2-}$ |
| Germany | Not published yet | - DIN 4226-101:2017<br>- DAfStb-Guideline | Type 1 | $Rcu_{90}$, $Rb_{10-}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{1-}$ |
| | | | Type 2 | $Rcu_{70}$, $Rb_{30-}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{2-}$ |
| Netherlands | NEN 8005 :2014 | CUR 112 :2014 | Type A1 | Concrete aggregates $Rc_{80}$, $Rcug_{90}$, $Rb_{10-}$, $Ra_{5-}$, $X_{1-}$, $FL_{10-}$ |
| | | | Type A2 | Concrete aggregates $Rc_{80}$, $Rcug_{90}$, $Rb_{10-}$, $Ra_{5-}$, $X_{1-}$, $FL_{10-}$ |
| | | CUR 80 :2014 | Type B | Mixed aggregates $Rc_{45}$, $Rcug_{50}$, $Rb_{50-}$, $Ra_{5-}$, $X_{1-}$, $FL_{10-}$ |
| | | CUR 5 :2014 | Type C | Masonry aggregates $Rb_{85}$, $Ra_{10-}$, $X_{1-}$, $FL_{10-}$ |
| Belgium | NBN B 15-001:2012 | | | $Rc_{90}$, $Rcu_{95}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{0.5-}$ |
| | NBN B 15-001:2018 | | Type A+ | $Rc_{90}$, $Rcu_{95}$, $Ra_{1-}$, $FL_{2-}$, $XRg_{0.5-}$ |
| | | | Type B+ | $Rc_{50}$, $Rcu_{70}$, $Rb_{30-}$, $Ra_{5-}$, $FL_{2-}$, $XRg_{2-}$ |
| Luxembourg | Not published yet | CDC-GRA:2008 | No definition of recycled aggregates | |

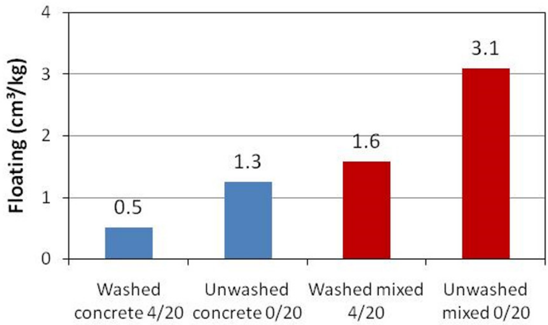


*Figure 28. Floating content in washed and unwashed recycled aggregates (mixed and concrete).*

### *3.1.7 Resistance to fragmentation*

Resistance to fragmentation has been measured through the Los Angeles test. Results show that no significant difference exists between washed and unwashed materials. Concrete aggregates have a Los Angeles coefficient around 34 and 36, and mixed aggregates have values between 42 and 43. Thus, concrete aggregates have a higher resistance to fragmentation than mixed aggregates.

Standards requirements in France, Luxembourg and the Netherlands set a maximum value of 40 for concrete aggregates. This means that measured results agree with these national standards (cf. Table 7). Belgian standards have defined a more demanding maximum value of resistance to fragmentation, fixed at 35. As a result, obtained results are very close to the defined limit in the Belgian standards. For mixed aggregates, the maximum defined value is 50 in France, Belgium and the Netherlands. In Luxembourg, there is no difference in requirements between the types of aggregates. The maximum value for mixed aggregates is thus the same as concrete aggregates and natural aggregates. This limit is defined at 40. Consequently, recycled mixed aggregates have too low resistance to fragmentation compared to the Luxembourgish standards.

For comparison, limestone and sandstone usually have resistance to fragmentation ranging between 15 and 30. Belgian igneous rocks ('porphyre') even have resistance to fragmentation close to 10.

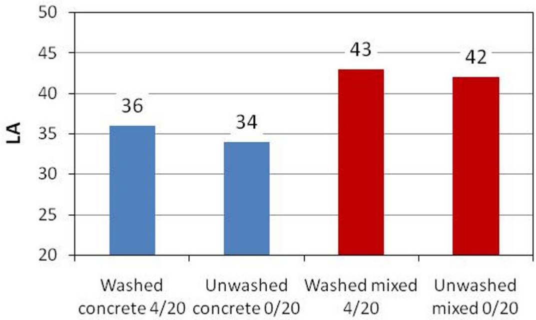


*Figure 29. Los Angeles values for washed and unwashed recycled aggregates (mixed and concrete).*

*Table 7. Resistance to fragmentation (Los Angeles) requirements for recycled aggregates (concrete and mixed) related to concrete in NWE national standards.*

| Country | Type | Requirements |
|---|---|---|
| FR | Type 1 & 2 (concrete agg) | **≤40** |
| | Type 3 (mixed agg) | **≤50** |
| LU | | **≤40** |
| BE | Type A+ (concrete agg) | **≤35** |
| | Type B+ (mixed agg) | **≤50** |
| NL | Type A1 & A2 (concrete agg) | **≤40** |
| | Type B (mixed agg) | **≤50** |

## 4. Conclusions

Washing significantly improves some properties of recycled aggregates. Adding a washing process to a recycling plant allows it to produce clean coarse aggregates respecting the national standards for aggregates use in concrete in every country of the NWE region.
Washing greatly decreases fine content and the weight of floating elements. These parameters are limiting in some of the investigated national standards for using aggregates in concrete. Fine content is the most constraining parameter. Washing brings fine content below the maximum values defined in the investigated national standards.
On the other side, washing has less influence on the following parameters: particle density, water absorption, resistance to fragmentation, proportion of non-floating elements.

## 5. References


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# Use of Mixed Recycled Aggregates for a Sustainable Road Construction

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**Abstract**

A pilot project was recently conducted in Wallonia in order to test the feasibility of increasing the substitution rate of recycled mixed aggregates (RMA) into the base and pavement layers of agricultural roads. Tradecowall and the BRRC took advantage of the renovation of a 500 m long agricultural road to test two different base layer materials, as well as four different concrete pavement compositions incorporating 25% to 90% RMA into two mixes placed with a slip form paver and two roller-compacted concrete mixes. The short-term performances of these pavements incorporating recycled materials were compared to the performances of a reference road concrete composition in terms of compressive strength and durability properties.

**Keywords**

Reallocation road, Recycled mixed aggregates, Sustainable road design

**Kurzfassung**

Vor kurzem wurde in Wallonien ein Pilotprojekt durchgeführt, um die Durchführbarkeit einer Erhöhung des Substitutionsanteils von rezyklierter Gesteinskörnung (RMA) in der Trag- und Deckschicht von Wirtschaftswegen zu testen. Tradecowall und das BRRC haben bei der Erneuerung eines 500 m langen Wirtschaftsweges zwei unterschiedliche Tragschichtmaterialien und vier unterschiedliche Betonbelagzusammensetzungen getestet. Diese enthielten 25% bis 90% an RMA und wurden mittels Gleitschalungsfertiger und zwei Walzbetonmischungen eingebaut. Die Druckfestigkeit als auch die Dauerhaftigkeitseigenschaften der Beläge mit rezyklierten Materialien sind mit denen einer Referenz-Straßenbetonzusammensetzung verglichen worden.

**Schlüsselwörter**
Umgehungsstraße, Rezyklierte Gesteinskörnung, Nachhaltiger Straßenentwurf

**Résumé**
Un projet pilote a récemment été mené en Wallonie afin de tester la possibilité d'augmenter le taux de substitution des granulats recyclés mixtes (GRM) dans les couches de fondation et de revêtement des routes agricoles. Tradecowall et le CRR ont profité de la rénovation d'une route agricole de 500 m de long pour tester deux matériaux de fondation, ainsi que quatre bétons de revêtements différents incorporant de 25% à 90% de GRM. Deux de ces bétons à base de matériaux recyclés sont des bétons routiers placés au slipform, tandis que les deux autres sont des bétons secs compactés au rouleau. Les performances à court terme de ces revêtements ont été comparées aux performances d'un béton routier de référence en termes de résistance à la compression et de propriétés de durabilité.

**Mots-clés**
Route de réaffectation, Agrégats mixtes recycles, Conception de routes durables

## 1. Introduction

In Wallonia (Belgium), the incorporation rate of recycled mixed aggregates into road structures is currently limited to the base and subbase layers. Increasing the substitution rate of this inexpensive and largely available material or allowing its incorporation into other structural layers of the pavements, would reduce the economic cost for local municipalities. It would also increase their sustainability, if the required performances are maintained. In order to demonstrate the practical feasibility of this incorporation, and to determine the optimal substitution rates, the Belgian Road Research Center (BRRC) and the Walloon cooperative union for the treatment of construction waste (TRADECOWALL) recently conducted a pilot project on the agricultural road 'Chemin du Ridias' in Gembloux, Wallonia, which needed to be renovated (Figure 1). This provided an opportunity to test different innovative solutions in base and concrete pavement layers including the use of mixed recycled materials. The final construction took place in the period April – June 2019.

*Figure 1. Former view of the 'Chemin du Ridias' (2016)*

## 2. Description of the pilot section

The experimental site, 500 m long and 3 m wide, was divided into 10 sections of 50 m in length, allowing for testing of two types of base material and five concrete compositions (Figure 2). The first type of base layer, situated in the lower part of the road, is permeable and consists of a mixture of mixed recycled aggregates (0/32 mm) and natural aggregates (32/63 mm). The second type is composed of cement-bound graded mixed recycled aggregates 0/20 mm.

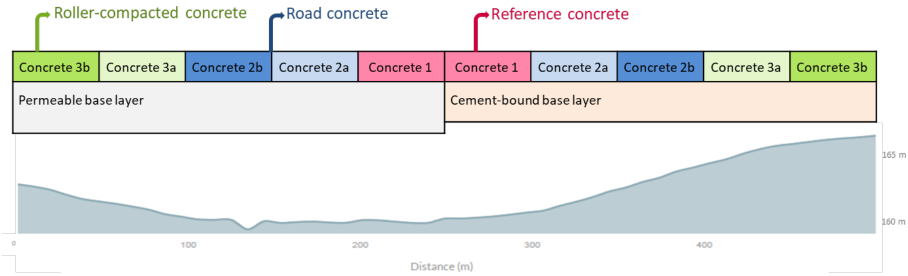


*Figure 2. Overview of test sections for Ridias project with mixed recycled aggregates*

Among the five concrete pavements, one (Concrete 1) is a reference road concrete composition with natural sandstone aggregates while the other four contain mixed recycled aggregates. Two of the experimental mixes (Concrete 2a-2b) consist of 18 cm thick plain jointed concrete pavements put in place with a slipform paver and the two others (Concrete 3a-3b) are roller-compacted concrete (RCC) compositions, providing a lower cost solution, with higher substitution rates.

Before the placement of these new layers, the old pavement, consisting of old and cracked 20 cm-thick concrete slabs, was dismantled. The bearing capacity of the underlying soil revealed to be globally lower than the requirements in the standard tender specifications and even locally too low for the worksite traffic.
After lime treatment, local substitutions with coarse aggregates, and local reinforcement with geogrids, the bearing capacity was increased sufficiently to allow worksite traffic, but the values remained locally quite low. For this reason, the test site can be considered as a worst-case scenario for the local conditions that can be found under agricultural roads in Wallonia.

## 3. Composition and performances of the different mixes

### 3.1. Permeable base layer

The first half of the pilot section contains a low point where water tends to accumulate. For this reason, it was decided to place a permeable base layer in this zone. The final mixture contains 60% in volume of mixed recycled aggregates (0/32 mm) and 40% of natural limestone aggregates (32/63 mm). This ratio was selected based on the grading curves of the materials during the preliminary study, in order to ensure a fines content lower than 7%, which is recommended to ensure a sufficient permeability. This base layer was placed with a thickness of 20 cm.

### 3.2. Cement-bound base layer

The second base layer type is composed of cement-bound graded mixed recycled aggregates 0/20 mm, placed with a thickness of 15 cm. It was decided to comply with the requirements set in the Walloon standard specifications Qualiroutes (§F.4.9.2.3) [1] for base layers in treated "scalping" (from prescreening process of the debris) products, which requires a minimum cement content of 6 %. The laboratory study showed that this cement amount was enough to obtain the performances requirements (compressive strength of 8 MPa on modified Proctor samples after 7 days, resistance to immersion).

The mix was placed with a finisher and compacted with both a roller compactor and a tire compactor. It was protected at the end of the day by a bituminous emulsion and contraction joints were sawn after 24 h. The cores drilled after 90 days showed a high compressive strength, but a relatively large dispersion of results (Table 1).

*Table 1. Compressive strength of the cores drilled from the cement-bound base layer*

| | | | |
|---|---|---|---|
| Individual compressive strength at 90 days (MPa) | 22.2 | 27.7 | 17.6 |
| *Average* | | *22.5* | |

### 3.3. Plain jointed concrete slabs

For the slipform concrete, comparison is made between the reference concrete with natural sandstone aggregates (2/32 mm) and two rich concrete compositions incorporating 25% and 50% in volume of mixed recycled aggregates (4/32 mm). The latter conform to Annex E of NBN EN 206 [2] (> 50 % of concrete, < 30% of masonry bricks) and to the prescriptions for type B+ aggregate according to NBN B15-001 [3]. Cement content was 350 kg/m³, W/C ratio equal to 0.48, and no air entraining-agent was added in the mix. Visually, no difference could be observed between the different mixes during placement and this observation remains true after hardening.

*Figure 3. Regular road concrete composition placed with slipform paver*

Results for fresh and hardened concrete properties for samples prepared on site or at the concrete mixing plant are shown in Table 2 together with the target values and/or the requirements set in the Walloon standard specifications Qualiroutes for low-volume roads (Réseau III), for comparison.

Table 2 suggests that the required compressive strength is easily met, and the water absorption increase is limited for incorporation of up to 25 vol% of the mixed recycled aggregates. All the values for resistance against scaling with freeze-thaw cycles in the presence of de-icing salts are above the estimated target value (the Walloon Qualiroutes specifies a different testing method). This should not lead to consequences for this project because the use of de-icing salts is not foreseen for this agricultural road. For other projects where use of de-icing is planned, the incorporation of air-entraining agents could be considered.

*Table 2. Results of reference and test concrete mixes with mixed recycled aggregates taken on the construction site or at the concrete mixing plant*

| | Reference | | 25 vol% mixed agg. | | 50 vol% mixed agg. | | Target value | *Qualiroutes* Requirement |
|---|---|---|---|---|---|---|---|---|
| | plant | on site | Plant | on site | plant | on site | | |
| Slump (mm) | 55<br>65 | 46<br>35<br>25 | 60<br>30 | 35<br>16<br>40 | 30 | 15<br>17<br>30<br>50 | 25-40 at plant | - |
| Air content (%) | 1.5 | 1.7 | 1.8 | 2.1<br>1.5 | 2 | 3<br>2.4<br>2.5 | - | - |
| Water content (% by heating) | 10.0 | - | 10.7 | - | 10.3 | 9.9[Γ]<br>10.4 | Ref: 8.1<br>25 %: 9.1<br>50 %: 10.1 | - |
| Fresh density (kg/m$^3$) | 2,375 | 2,339 | 2,350 | 2,311<br>2,346 | 2,310 | 2,265<br>2,300<br>2,283 | Ref: 2,386<br>25 %: 2,349<br>50 %: 2,312 | - |
| Rc 7d (MPa) – cubes 15 cm | - | 23.5 | - | 29.4 | - | 30.5 | - | 26.9* |
| Rc 28d (MPa) – cubes 15 cm | - | 40.1 | - | 45.5 | - | 46.8 | - | 39.6* |
| Average water absorption (%) | - | 7.0 | - | 6.4 | - | 7.4 | - | 6.0<br>(if de-icing salts are used) |
| Scaling @ 28 cycles – Slab test** (kg/m2) | - | 9.95 | - | 6.04 | - | 5.58 | (3.00) | - |

[Γ] before adding of 15 l extra water on site
* Re-calculated based on: 50 MPa for cores at 90 d – 46.7 MPa for cubes at 90 d
** Based on CEN/TS 12390-9 and tested on formwork surface

More surprisingly, the reference concrete performs worst of all, which is connected to the higher water content compared to the target value and is also reflected in the high slump values; however, one has to keep in mind that results are based on samples of only one batch for each concrete mix. For this reason, comparison is also made to testing made in the lab before (on 16/4/2019 with cubes of 150 mm side) and on cores (Φ 113 mm – height 100 mm) taken from the pavement itself at an age of 90 days (Figure 4). Figure 4, suggests that the difference between the reference concrete and the concrete mixes with recycled aggregates is less pronounced on the cores, and further comparison is also ongoing regarding water absorption and resistance to scaling tested on cores.

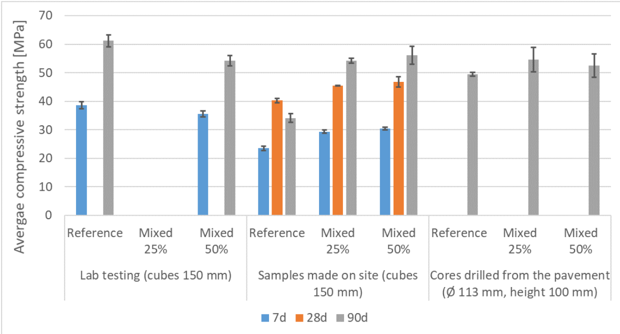


*Figure 4. Comparison of average slipform concrete compressive strength for laboratory samples, samples made on site, and cores drilled from the pavement*

### 3.4. Roller compacted concrete slabs

The two last experimental mixes (Concretes 3a-3b) consist of roller-compacted concrete (RCC) compositions with 70 and 65% in volume (of the total aggregate content) of mixed recycled aggregates respectively (Table 3).

*Table 3. Final composition of roller-compacted concrete compositions used in Ridias*

| | RCC construction site 0/32 | | RCC construction site 0/20 | |
|---|---|---|---|---|
| | % mass | kg/m³ (appr.) | % mass | kg/m³ (appr.) |
| Mixed recycled aggregates 4/32 | 25.9 | 600.25 | - | - |
| Mixed recycled aggregates 0/20 | 25.9 | 600.25 | 47.9 | 1,114.59 |
| Sandstone 2/6 | 7.1 | 165.27 | 10.7 | 247.86 |
| Limestone sand 0/4 | 20.1 | 464.77 | 20.9 | 485.82 |
| CEM III A 42,5 LA | 12.3 | 285 | 12.3 | 285 |
| Water | 8.6 | 198 | 8.3 | 193 |
| Total | | 2,313.8 | | 2,325.9 |
| Volume % recycled materials (without sand) | 70 (89.7) | | 65 (84) | |

In the final execution, the RCC sections were covered with a single chipping surface dressing (with bituminous emulsion) as a lower cost solution and joints were sawn every 4 m (Figure 5).

*Figure 5. Construction of RCC sections, covered with single chipping surface dressing*

The composition and percentages of replacement were fixed following an extensive laboratory study of the mixes [4], where unfortunately several changes also took place in the type of materials used for the final construction site. The final composition of the roller compacted concrete compositions used on site is shown in Table 3 for example. These were designed to follow the recommendations of the Belgian Federation of the Cement Industry (Febelcem) concerning the reference curves of particle size distribution for RCC 0/16 and 0/20 [5] and an average compressive strength of 30 MPa at 90 days.

Finally, similar and first results are also shown in Figure 6 for the RCC mixes used in the pilot project (see Table 3) where samples prepared with Proctor compaction (cf. NBN EN 13286-2) on site are compared to cores drilled from the pavement. Figure 5 suggests that nearly all results meet the proposed objectives (Rc ~ 30 MPa at 90 days).

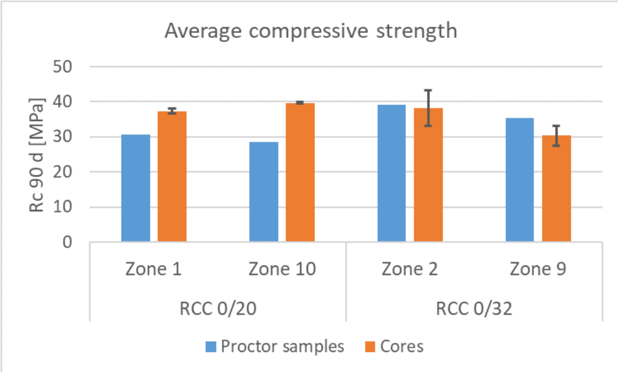


*Figure 6. Comparison of average compressive strength for RCC mixes on samples made on site (Proctor compaction) versus cores drilled from the pavement*

## 4. Conclusions

The Ridias pilot project enabled the field-testing of different pavement materials containing mixed recycled materials, going well beyond what is currently allowed in the Belgian standard tender specifications. Such use of recycled materials reduces the cost of roads for the community (-20 to 30%), while also reducing its environmental impact.

The use of these recycled materials induced little change in the implementation of the mixture on site and still made it possible to obtain satisfactory results in terms of short-term performance. It appeared that the recycled aggregates substitution rate has relatively little influence on the final performance compared to other site factors (real water content, way of execution, etc.). Long-term monitoring, both visually and using non-destructive methods (FWD, Vamos), will confirm the durability of the proposed solutions, despite the initial low soil bearing capacity.

## Acknowledgements

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# SeRaMCo - Development of New Concrete Mixes from Recycled Aggregates from known Resources

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**Abstract**

Within the project SeRaMCo a new approach combining numerical and experimental investigations has been proposed for designing and improving the formulation of recycled concrete. In a first approach, a set of numerical models using the phase field method was developed and implemented for studying the earlier age behavior, the micro cracking ignition and growing, the fracture behavior and the overall load-deformation response of recycled concrete. The developed models enable to gain in-depth insights into the specific behavior of recycled concrete, which has then been used for developing a high strength concrete (HSC) and an open structure concrete (OSC) using 100% of recycled aggregates. Different fractions of the initial recycled aggregate blend were combined for defining the required particle size distribution for the HSC and the OSC. The compression, splitting and flexural strength were then determined, as well as the E-modulus. The HSC and the OSC presented a compressive strength of 58.5 and 5.7 MPa respectively. The HSC also exhibits a higher E-Modulus, density, splitting and flexural strength than the OSC, thanks to better cement hydration and a uniform grain size distribution.

**Keywords**

Recycled Concrete, Phase Field Modeling, Open Structure Concrete, High Strength Concrete

**Kurzfassung**

Im Rahmen des Projekts SeRaMCo wurde ein neuer Ansatz zur Verbindung numerischer und experimenteller Untersuchungen zum Design und zur verbesserten Beschreibung von Recyclingbeton vorgeschlagen. In einem ersten Versuch wurde eine Reihe von numerischen Modellen unter der Verwendung der Phasenfeldmethode entwickelt und implementiert, um das frühe Alterungsverhalten, die Mikrorissinitiierung und das Mikrorisswachstum, das Bruchverhalten und das gesamte Last-Verformungs-Verhalten von Recyclingbeton zu untersuchen. Die entwickelten Modelle ermöglichen es, vertiefte Einblicke in das spezifische Verhalten von Recyclingbeton zu gewinnen, um daraus einen hochfesten Beton (HSC) sowie einen offenporigen Beton (OSC), der zu 100 % aus recycelten Zuschlagsstoffen besteht, zu entwickeln. Verschiedenste Bestandteile der ursprünglichen Mischung aus rezyklierter Gesteinskörnung wurden kombiniert, um die benötigte Korngrößenverteilung für den HSC und OSC zu definieren. Anschließend wurden die Druckfestigkeit, Spaltzugfestigkeit und Biegezugfestigkeit sowie der E-Modul bestimmt. Der HSC und OSC besaßen eine Druckfestigkeit von 58,5 bzw. 5,7 MPa. Der HSC weist auch einen höheren E-Modul, eine Dichte, Spaltzug- und Biegezugfestigkeit als der OSC auf, was auf eine bessere Zementhydratation und eine gleichmäßigere Korngrößenverteilung zurückzuführen ist.

**Schlüsselwörter**

Recyclingbeton, Phasenfeldmethode, Offenporiger Beton, Hochfester Beton

**Résumé**

Dans le cadre du projet SeRaMCo, une nouvelle approche combinant les investigations numériques et expérimentales a été proposée pour concevoir et améliorer la formulation du béton recyclé. Dans une première approche, un ensemble de modèles numériques utilisant la méthode de Phase Field Modeling a été développé et implémenté pour étudier le comportement au jeune âge, la naissance et le développement des microfissures, le comportement post fissuration et de manière générale la réponse contrainte-déformation du béton recyclé. Les modèles développés permettent d'obtenir des informations approfondies sur le comportement spécifique du béton recyclé, ce qui a été exploité pour développer un béton à haute résistance et un béton à structure ouverte faits à base de 100% d'agrégats recyclés. Différentes fractions du mélange initial d'agrégats recyclés ont été combinées pour construire les courbes granulométriques requises pour les bétons à haute résistance et à structure ouverte. Les résistances à la compression, au fendage et à la flexion ont été déterminées, de même que le Module de Young. Le béton à haute résistance et celui à structure ouverte ont respectivement présentés une résistance en compression de 58.5 et 5.7 MPa. Le béton à haute résistance a également présenté un plus grand Module de Young, une plus grande résistance au fendage et à la flexion, et une plus grande densité que le béton à structure ouverte, dû à une meilleure hydratation du liant et à une distribution granulométrique uniforme.

**Mots-clés**
Béton recyclé, modèles de champ de phases, béton poreux, Béton à haute résistance

## 1. Introduction

With recent advances in numerical simulation methods, new studies are now possible, allowing the development of computational models to predict the mechanical performance of concrete made of recycled aggregates [1-4]. In this study, a set of numerical models in the framework of the phase field method [5,6], was developed to evaluate the fracture resistance, and also to get the in-depth insight the early-age behavior of recycled concrete. The phase field model (PFM) makes use of a regularized description of discontinuities through an additional variable and strongly alleviates meshing problems for describing brittle cracking [7]. Furthermore, the PFM can effectively handle the phenomena of crack nucleation, interaction and arbitrary crack morphologies. The technique has proven to be very well suited to the simulation of microcracking in complex heterogeneous materials, such as cement-based materials [6, 8-10]. Recycled aggregates exhibit specific features like a high porosity and water absorption, a high Los Angeles coefficient and a low apparent density generated by the pieces of hardened cement paste bonded on the initial natural aggregates [11-12]. These features induce a large shrinkage and a reduction of the mechanical properties of recycled concrete, which ultimately restrains its application in constructions. Numerous investigations [13-21] show that the properties of recycled concrete are governed by factors like the amount of recycled aggregates, the water to binder ratio and the amount of hardened mortar paste on the recycled aggregates. Using experimental and numerical approaches, this research work is devoted to analyze the performance of recycled concrete.

## 2. Numerical approach

Phase field model has been proven to be a useful tool to study the fracture behaviors in heterogeneous materials. This method is able to model complex, multiple crack fronts, and branching in both 2D/3D without ad-hoc numerical treatments. During SeRaMCo project, a set of numerical models based on phase field method has been developed to evaluate the mechanical performance and durability of recycled concrete. These models allowed to gain an deep inside into the mechanical behavior of recycled concrete and were used to better understand the load-deformation behavior registered during the experimental tests performed on the developed mixes which will be presented in the section 3.

## 2.1. Early age behavior of recycled concrete

The recycled concretes are known to be sensitive to early age cracking triggered by an increased shrinkage deformation in comparison to the one of conventional concrete. The increase in shrinkage behavior is proportional to the amount of recycled aggregates used as a replacement for natural aggregates. Within the SeRaMCo project several computational chemo-thermo-mechanical coupling phase-field models for complex fracture induced by early-age shrinkage and hydration heat in cement-based materials have been developed (and validated by experiment), to gain in-depth insights into these phenomena [22-24].

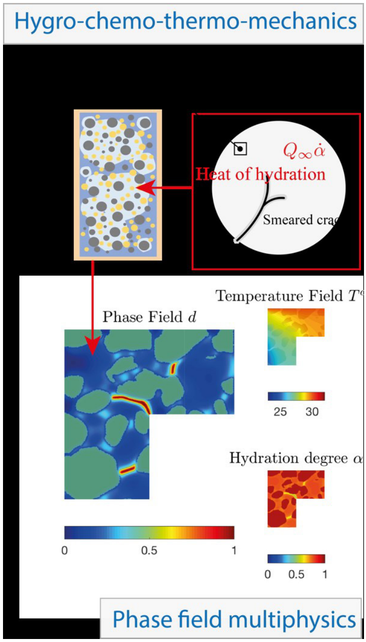



*Figure 1. Simulation of the early-age behaviors of recycled concrete by using a phase field model. A high risk of cracking is noted [22, 23]*

The proposed model efficiently simulates the heat of hydration, thermal transfer, material strength's development thanks to age effects, as well as the creeping phenomena of the early-age concrete. Thus, the risk of cracking is examined by means of the phase field method, see Figure 1.

The obtained results show the critical shrinkage properties of recycled concrete. A high risk of cracking is also captured. The major damage cause is noted due to the autogenous/drying shrinkage. The important effects of creeps at the early age, for instance, transient thermal creep and basic creep are also demonstrated.

## 2.2. Modeling of fracture behavior in recycled concrete by using a new strain split to model unilateral contact within the phase field method

The fracture behavior of cement-based materials (brittle fracture) is known to be different in compression and traction. A new orthogonal split of strain tensor into compressive and tensile parts has been developed and implemented within the phase field model to describe such difference. The proposed model can efficiently mimic unilateral contact condition with which any existing cracks and any crack propagation have to comply. A comparison of the fracture responses predicted by the present model and experimental observation is provided in Figure 2, demonstrating its accuracy and efficiency.

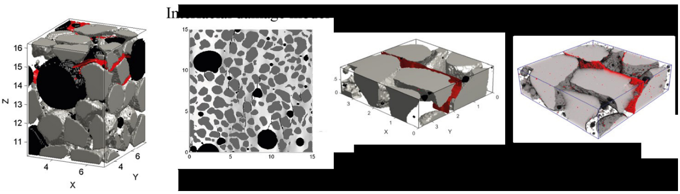



*Figure 2. Modeling of fracture behavior in cement-based materials [9]*

The new formulation is also able to simulate the fracture behavior of any arbitrary initial anisotropic behavior. Hence, this proposed numerical model allows us to predict the complex cracking problem at different scales, ranging from microscopic to macroscopic scales. That will identify the important factors controlling the material performance, which need to be considered in the mix design, see Figure 3.

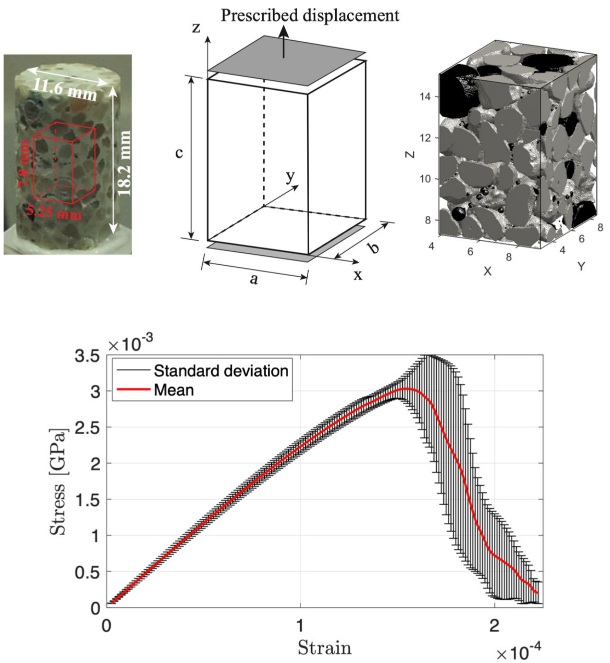



*Figure 3. Numerical evaluation of the fracture performance of cement-based materials at microscopic scale for various grain size distribution of aggregates. The out-put can be used to estimate the concrete class with a given aggregates characterization.*

### 2.3. Modelling of interfacial crack propagation in strongly heterogeneous materials by using phase field method

Mechanisms of the interfacial transition zone is often considered as one of the most important factors that governs the performance of recycled concrete [25-26]. However, taking into account interfacial effects is not a trivial task in the numerical model, due to its complexity in geometry, length scale and especially its non-homogeneous materials in nature, in this study, a new interfacial cracking model in the phase field framework is proposed [26]. A dimensional-reduced model based on a rigorous asymptotic analysis is adapted to derive the null thickness imperfect interface models from an original configuration containing thin interphase. Then, the idea of mixing the bulk and interfacial energy within the phase field framework is used to describe the material degradation both on the interface and in the bulk. The new model is able to consider the complex interfaces with arbitrary geometry and properties, see Figure 4.

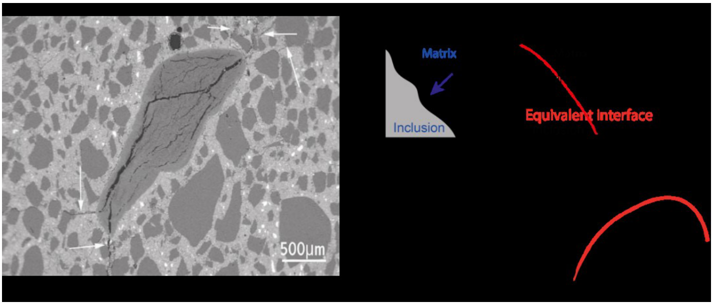



*Figure 4. Modelling of interfacial crack propagation in strongly heterogeneous materials by using phase field method. The proposed model can be used to improve the mechanical strength by optimizing the interfacial transition zone. The red line of loading curve shows the expected mechanical performance after performing the interfacial designing.*

We apply the present model to study the interfacial cracking in recycled concretes and to understand the effects of interfacial transition zone on the global behavior of recycled concrete material. The new model predicts very well the complex cracking phenomena on interfaces such as initiation, delamination, coalescence, and deflection. This demonstrated the performance of the present computational framework. The developed numerical models constitute a promising tool to optimize the mechanical performance of recycled concrete as well as of cement-based materials in general by enhancing the interface's characterization.

## 3. Experimental approach

### 3.1. Recycled concrete formulations

In the framework of the development of new recycled concretes, two mixes using 100% of recycled aggregates were composed. These used recycled aggregates are of known origin and come from a concrete precast element producer. Indeed, the recycled aggregate are produced on their site by crushing elements e.g. failing the self-control criteria of the producer or remaining on stock. The mixes developed out of these aggregates are the High-Strength Concrete (HSC) and the Open Structure Concrete (OSC) mixes. The recipes of the new mixes were chosen based on existent mixtures of a precast concrete producer for guaranteeing an easy transfer to an industrial application. Hence, for the new mixes, a similar rheology with the existent mixtures of the partnership was targeted to formulate mixes with the same production process using existing technical equipment. In the same light, materials with similar prices were chosen for maintaining the same economic competitiveness as the existent mixtures.

#### *3.1.1. High-Strength Concrete mix (HSC mix)*

For the developed High Strength Concrete (HSC) mix, a blend of complementary fractions of recycled aggregates of known origin was chosen from the initial 0/63 fraction resulting out of the crushing process. The initial granulometry is represented in Figure 5. The raw aggregates have been sieved to different granulometric fractions. The refusals of sieves 1, 2, 4, 8 and 16 mm have been separated for reconstructing the particle size distribution of the aggregates used for the high strength concrete. Hence, for the coarse aggregates, the fraction 4/8 was obtained by mixing the refusals of sieve 4 mm with the refusals of sieve 8 mm in the proportion 1:1 in terms of weight. The 0.25/2 sand was obtained by removing the very fine particles from the raw fine aggregates. The final granulometry is ensuring a uniform distribution, with a maximum grain size of 8 mm and a minimum grain size of 0.25 mm. These blends presented the best grain size distribution for reducing segregation and for having an optimized workability of fresh concrete. The coarse aggregates were used in saturated dry surface conditions.

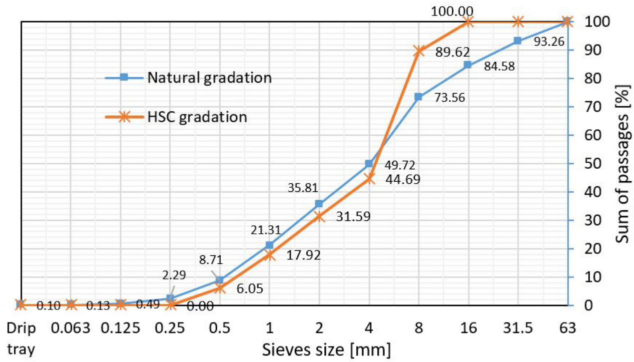



*Figure 5. Granulometry of the initial and of the reconstructed HSC aggregates*

The used cement was a recycled cement including 10% of recycled fines provided by the project partner VICAT in France. In addition to the recycled cement, calcium carbonate ($CaCO_3$) has been added in the proportions 1:3 with respect to the cement weight. The proportions of additives were mainly defined based on the existent recipe and on the expected concrete strength. The quantity of micro-silica and superplasticizer was respectively 2% and 3% in terms of weight of the binder. The binder to aggregate ratio was 1:3.6 and the water to binder ratio w/b 0.35. Table 1 shows the detailed recipe.

With regard to the mixing procedure, the aggregates and the total binder (cement + fillers) were first dry mixed for 30 seconds. Then, a half of the free water was added during 30 seconds and the whole was then mixed for 60 additional seconds. After the first 120 seconds of mixing, the remaining half of the free water as well as the superplasticizer were added during another

30 seconds. Following that, the whole was mixed for 60 seconds, then the edges were scraped, and the whole mixed again for 120 seconds, resulting in a total mixing time of 5 min 30 seconds.

*Table 1. High Strength Concrete (HSC) mix*

| **Description** | | **[kg/m³]** |
|---|---|---|
| | Fraction 4/8 mm | 1037.4 |
| | Fraction 0.25/2 mm | 558.6 |
| Binder | Filler | 131.9 |
| | Cement R42.5 | 307.8 |
| Additives | Superplasticizer | 13.2 |
| | Micro-silica | 8.8 |
| Water to binder ratio (w/b) | | 0.35 |

### *3.1.2. Open Structure Concrete mix (OSC mix)*

For the open structure concrete (OSC) mix, a coarse blend was chosen from the initial fraction 0/63 resulting from the crushing process. This coarse blend presents a maximum grain size of 16 mm and a minimum grain size of 4 mm. The fraction 4/16 was obtained by mixing the refusals of sieves 16, 4 and 8 mm in respective proportions of 20%, 60% and 20% in terms of weight. The fine particles with grain sizes less than 4 mm were purposely reduced for ensuring a high and connected porosity in the final concrete mixture. The same recycled cement was also used with an additional calcium carbonate filler in the proportion 1:3 in terms of weight. Moreover, 2% of micro-silica was also added. The binder to aggregate ratio was 1:2.9 and the water to binder ratio w/b 0.35. The detailed composition of the open structure concrete is presented in Table 2. The mix process was the same as for the HSC mix.

*Table 2. Open structure concrete mix*

Table 2. Open structure concrete mix

| **Description** | | **[kg/m³]** |
|---|---|---|
| Aggregates | Fraction 4/16 mm | 1417.3 |
| | Fraction 0/2 mm | 82.7 |
| Binder | Filler | 154.3 |
| | R42.5 | 360.0 |
| Additives | Micro-silica | 10.3 |
| Water to binder ratio (w/b) | | 0.35 |

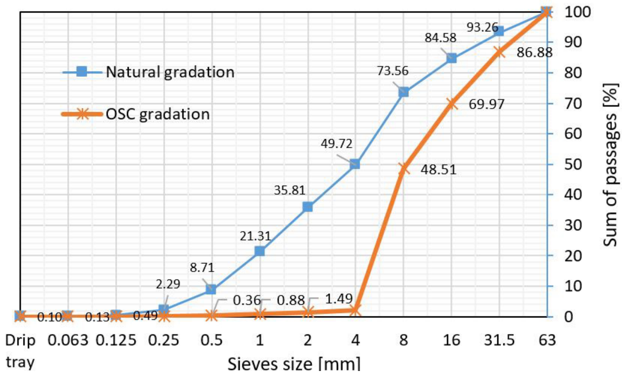
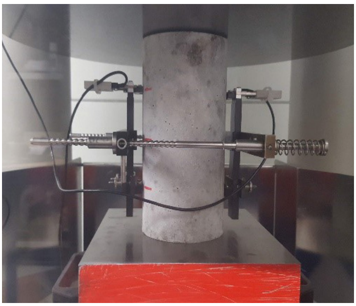



*Figure 6. Granulometry of the initial and of the reconstructed OSC aggregates*

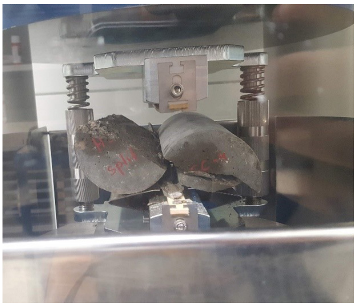
The used superplasticizer ACE 456 is based on polycarboxylate ether polymers. It acts as cement hydration accelerator by exposing more surfaces of the cement particles for reaction with water. The fast and complete hydration of the cement particles enables to reach higher strengths at an earlier age. Moreover, the most advantageous aspect of the used superplasticizer is the improvement of rheological aspects of fresh concrete, especially in concrete mixtures with a low water to binder ratio. The micro-silica used is a common pozzolan made of fines particles of silicon dioxide (SiO2) solved into water before adding into fresh concrete. The particles of micro-silica support a good hydration process by wide spreading the particles of cement. In addition, they reduce the porosity in the final mix by acting as fine aggregates in the blend. Indeed, the small grains of micro-silica fill the space between cement grains in a phenomenon that is referred to as particle packing. Moreover, micro-silica is very active in a chemical aspect. As the hydration of cement results, among other effects, in the release of calcium hydroxide, micro-silica reacts with it and creates an additional binding material called calcium silicate hydrate.

### 3.2. Experimental tests and results

Experimental tests have been conducted for determining the mechanical performances of the developed recycled concrete. These experimental tests were conducted respecting the European norms: EN 12390-3: 2009 for the compressive strength, EN 12390-5: 2009 for the flexural strength, EN 12390-6: 2009 for the tensile splitting strength and EN 12390-13: 2009 for the secant modulus of elasticity in compression.



*Compression test on HSC*



*Tensile splitting test on HSC*

*OPC concrete*

*Figure 7. High strength and open structure concrete*

The results of the experimental tests after 28 days of hardening are presented in Table 3. The compressive strength of the HSC was 58.5 MPa and the one of the OSC 5.7 MPa respectively. The low compressive strength of the

OSC is due to the high porosity and the low density (1600 kg/m³), whereas the relative high compressive strength of the HSC is due to a better hydration and a more important density of roughly 2300 kg/m³. Concerning the tensile splitting strength, a mean value of 18.7 MPa at 28 days was found for the HSC.

*Table 3. Mechanical properties of the developed recycled concrete*

| | | **High strength concrete** (At 28 days) | **Open structure concrete** (At 28 days) |
|---|---|---|---|
| **Compressive strength [MPa]** | Mean value | 58.5 | 5.7 |
| | (Standard deviation) | (3.9) | (0.4) |
| **E-Modulus [MPa]** | Mean value | 29 500 | 1500 |
| | (Standard deviation) | (3000) | (160) |
| **Splitting tests [MPa]** | Mean value | 18.7 | - |
| | (Standard deviation) | (2.6) | - |
| **Flexural strength [MPa]** | Mean value | 10.1 | 2.3 |
| | (Standard deviation) | (0.7) | (0) |

The shrinkage tests presented in Figure 8 are still in progress for assessing the fracture resistance and control the earlier-age behaviour of both the HSC and the OSC.

*Figure 8. Shrinkage tests on High Strength Concrete HSC and Open Structures Concrete OSC*

### 3.3. Future applications

As for an application, in common agreement with the partner Contern - Lëtzebuerger Beton, the developed self-compacting concrete will be used for manufacturing a set of products like platform edge for railway track, public bench, Maxiblocs and precast demountable timber concrete slab system (see Figure 9).

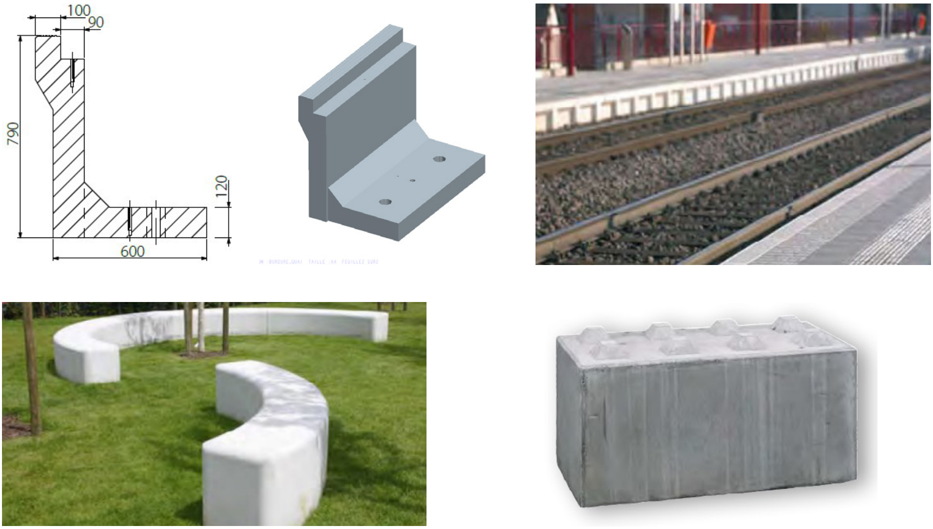



*Figure 9. Application of self-compacting concrete (Product catalog of Conter - Lëtzebuerger Beton)*

## 4. Conclusion

Within this research work a set of numerical models have been developed based on the phase field method to evaluate the mechanical performance and durability of recycled concrete. Different phase field models retraced the early age behavior of recycled concrete, showing the cracking behavior triggered by an increased shrinkage deformation of recycled concrete compared to conventional concrete and helped to gain in-depth insights into these phenomena. In addition, a new model is also developed to study the effects of interfacial transition zone on the global behavior of recycled concrete. These models allowed to understand the load-deformation behavior registered during the experimental tests. Following the numerical simulation, two mixes using 100% of recycled aggregates were developed and devoted for high strength and open structure concrete. Different fractions of the raw recycled aggregates were combined for constructing a uniform granulometry for the HSC and the OSC respectively. Compressive, splitting, flexural and E-modulus tests were conducted for characterizing the mechanical performance of the mixes. The HSC presented a satisfactory strength development at 28 days while the OSC exhibited a relative low strength. Finally, the reduction of both the E-Modulus and the flexural strength of the OSC with respect to the HSC demonstrated the influence of the granulometry on the mechanical performance of recycled concrete.

## Acknowledgements

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# Concrete Containing Recycled Aggregates – Development of New Mixes and the Challenges one has to face

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**Abstract**

The production of concrete from recycled aggregates has received increasing attention in recent years. The part of the SeRaMCo project presented here also deals with the development of concretes from recycled aggregates. Recycled aggregates have different properties than natural aggregates, which must be considered accordingly in the concrete development. The concretes should be used primarily to produce precast concrete elements. A total of four concrete mixtures for different applications have been developed. These are a concrete mixture to produce load-bearing components, one to produce paving stones, a rammed concrete and another one for the production of non-reinforced components with the additional use of saltwater.

**Keywords**

recycled aggregates, concrete technology, pavement, concrete precast production

**Kurzfassung**

Die Herstellung von Beton aus rezyklierter Gesteinskörnung erfährt in den letzten Jahren zunehmend an Aufmerksamkeit. Der hier dargestellte Teil des Projekts SeRaMCo befasst sich ebenfalls mit der Entwicklung von Betonen aus rezyklierten Gesteinskörnungen. Rezyklierte Gesteinskörnung weist andere Eigenschaften als natürliche Gesteinskörnung, was bei der Be-

tonentwicklung entsprechend berücksichtigt werden muss. Die Betone sollen in erster Linie für die Herstellung von Betonfertigteilen genutzt werden. Insgesamt wurden vier Betonzusammen-setzungen für unterschiedliche Anwendungen entwickelt. Dabei handelt es sich um eine Betonzusammensetzung zur Herstellung tragender Bauteile, eine für die Herstellung von Pflastersteinen, ein Stampfbeton und eine weitere zur Herstellung unbewehrter Bauteile unter zusätzlicher Verwendung von Salzwasser.

**Schlüsselwörter**
Rezyklierte Gesteinskörnungen, Betontechnologie, Pflasterstein, Betonfertigteilproduktion

**Résumé**
La production de béton à partir de granulats recyclés fait l‘objet d‘une attention croissante ces dernières années. La partie du projet SeRaMCo présentée ici porte sur le développement de bétons à partir d‘agrégats recyclés. Les agrégats recyclés ont des propriétés différentes des granulats naturels, ce qui doit être pris en compte dans le développement du béton. Les bétons doivent être utilisés principalement pour la production d‘éléments préfabriqués. Au total, quatre mélanges de béton ont été mis au point pour différentes applications. Un premier mélange de béton est destiné à la production d‘éléments porteurs, un mélange pour la production de pavés, un mélange de béton pilonné et un mélange pour la production d‘éléments non renforcés avec l‘utilisation supplémentaire d‘eau salée.

**Mots-clés**
agrégats recyclé, technologie du béton, pavés, production de béton préfabriqué

## 1. Introduction

The idea of using recycled aggregates to produce concrete is not new, but in times of rising discussions about reducing $CO_2$-emissions and saving resources it gains new attention. The building industry is one of the most resource intensive branches and the one with the highest waste generation. In Germany alone about 202 Mio t of mineral construction and demolition waste were generated [1]. According to the recycling management act wastes should be recycled as high quality as possible. Still today, most of the construction and demolition wastes are reused. For example, in Germany about 89% were reused within 2014 [1], most of it for road construction and landfilling. However, this is not a high-quality recycling according to the recycling management act. It´s more a kind of downcycling.
The project SeRaMCo aims to contribute for a high-quality recycling of recycled aggregates by using them to produce concrete precast products. Within one of the work packages, new concrete mixes containing different kinds of aggregates should be developed.

## 2. Development of concrete mixes containing recycled aggregates

The aim of WPT2 of SeRaMCo was the development of new concrete mixtures to produce structural elements and for non-structural elements each. Due to the fact, that in the beginning of the project the resulting precast products weren´t defined more precisely, a flexible mixture was needed, that can be used for different products. It was decided not to design a special mixture, but to design a basic mixture and to test the influence of w/c ratio and aggregates on the resulting properties. The mixture for the non-structural elements was defined more precisely. One of the products for the pilot projects in the end of the project is a pavement and it was decided to develop a specialized mixture for this product because they are produced in a different process compared with other precast products. Other non-structural products might be produced with the same mixture that will be used for the structural elements.

Due to the fact, that different products should be designed, new ideas for products came up during the project, which make it necessary to work with more specialized mixtures. Therefore, in addition to the initially two concrete mixtures, two further mixtures were tested. The first one was a rammed concrete, which is close to the mixture for the production of pavement blocks and the second one was not really a mixture for one special product, but more the idea to use salt water for the production of unreinforced concrete.

For all developed mixtures in this project part, recycled aggregates from unknown origin were used, what leads to some special challenges. These aggregates normally originate from different deconstruction sites and cannot be assigned clearly. They can contain a large amount of different materials like concrete of different qualities and strength classes, bricks, tiles and gypsum. Furthermore, these materials are contained in a different composition. As a result, recycled aggregates show different properties than natural aggregates and these properties vary from batch to batch because of the varying material composition. This is a challenge, not to be underestimated for concrete technology. Especially properties like density, strength and durability show a greater variety. All these factors have an influence of the workability and the resulting properties of the concrete. Recycled aggregates show a markedly higher water absorption than natural aggregates. This has great influence on the water demand of the concrete and the resulting consistency.

## 2.1 Test setup

### *2.1.1 Materials*

For the tests in this project part two different kinds of recycled aggregates were used. The first one (crushed concrete) were aggregates consisting mostly from crushed concrete. It contained only a very small amount of other materials like bricks or ceramics. According to EN 206 it can be classified more or less as Type A material [2]. Only the maximum amount of asphalt couldn´t be maintained in all cases. The second kind of aggregates (mixed aggregates) are aggregates containing higher amounts of different materials. The main material still is crushed concrete, but it also contains higher amounts of bricks and ceramics. According to the EN 206 it can be classified as Type B material [2]. The material composition can be seen in detail in Table 1.

All aggregates were split up into different fractions. There were three fractions of each kind of aggregates 2-6 mm, 6-14 mm and 14-22 mm. The smaller fraction from 0-2 mm wasn´t used. For this fraction a natural sand was used.

In addition to the recycled aggregates, in one test series for the concrete for structural elements two cements containing recycled sands, which were developed by another project partner, were used. The first cement was a CEM I 52.5 N and the other one was a CEM II 42.5 N A-LL. For the other tests a standard CEM I 42.5 N was used.

*Table 1: Average mass proportions for the defined material classes in the determined charges of aggregates*

| constituent | proportion [M.-%] | | | |
|---|---|---|---|---|
| | crushed concrete charge 1 | crushed concrete charge 2 | mixed aggregates charge 1 | mixed aggregates charge 2 |
| Rc + Ru | 93 | 96 | 71 | 74 |
| Rb | 3 | 3 | 24 | 24 |
| Ra | 4 | 2 | 4 | 2 |
| X + Rg | 0 | 0 | 1 | 3 |
| Fl | 0 | 0 | 0 | 0 |

$R_c$: concrete, concrete products, mortar, bricks made from concrete
$R_u$: unbound aggregates, natural aggregates, hydraulic bounded aggregates
$R_b$: Brick masonry blocks (non-porous), clinker, stoneware, sand-lime bricks, various bricks and roof tiles, pumice concrete (lightweight concrete), non-floating aerated concrete
$R_a$: bituminous materials, asphalt
$R_g$: glass
X: Other materials: cohesive materials (i.e. clay and soil), various other materials: metals (ferrous and non-ferrous), non-floating wood, plastic, rubber, plaster

### 2.1.2 Concrete for structural elements

Due to the fact, that the products weren´t known in the beginning of the project, it was important to develop a mixture, which is as flexible as possible. A large number of different products should be able to be realized with it. So the idea was not to develop one specialized mixture but to test what is possible within a defined frame. Differences in workability and performance will be seen and can be estimated.
Basis for these tests was to develop a mixture matching a concrete strength class of C 30/37. It was started with the standard CEM I 42.5 N and two different w/c ratios 0.55 and 0.45 were chosen. Later the tests were repeated with the CEM II 42.5 A-LL and the CEM I 52.5. Additionally, in test series 2 the grain size distribution was optimized. In test series one it was worked with a coarse to medium grained grain size distribution.
To see the influence of the different factors, fresh concrete properties like density, consistency and air content as well as the properties of the hardened concrete like compressive strength and tensile splitting strength were estimated.

### 2.1.3 Pavement

The development of concrete mixtures for pavements is a special challenge. On industrial scale, they are produced with a process that is very different from the production of other prefabricated products. Not only the mixture and the raw materials have a big influence on the resulting product, but also the production process itself. Normally it is worked with earth-moist concretes, which will be demolded directly after production, so that in addition a high early age strength is needed. A resulting paving block will have to fulfill the standards of EN 1338 [3]. Development of a suitable mixture only under laboratory conditions is almost impossible. Only the first tests can be done in lab. The final optimization must be done directly in production line. In lab, it was started with the determination of a well graded grain composition with a suitable cement amount and an optimum water content. This was done analogous to the determination of the proctor density. After that it was determined if the mixture is able to fulfill the requirements. The focus was initially on the strength properties.

### *2.1.4 Rammed concrete*

Rammed concrete is as well as the concrete for the pavements an earth moist concrete. It should be suitable for external components by use of a minimum content of cement. As starting point a mixture with a minimum cement content of 300 kg/m³ was developed and adjusted to a consistency class C1. Then tests with different compaction factors were carried out. A mechanical compaction to 90% and to 80% were tested to determine the influence of the compaction degree on the compressive strength. The test setup is shown in Figure 1.

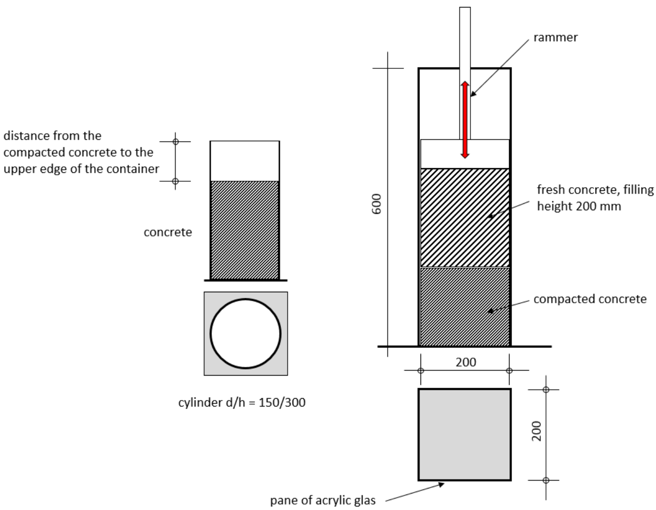


*Figure 1. Test setup [4]*

### *2.1.5 Salty concrete*

Another idea, which came up during the project, was to use seawater instead of freshwater to produce unreinforced concrete. Due to the lack of information in this field it wasn´t started directly with concreting. The first tests were carried out only with mortar. It was tested a mixture with a maximum aggregate size of 16 mm and a w/c ratio of 0.5. As cement, ordinary Portland cement (OPC) was used and artificial seawater as water. Then different tests were carried out. On the fresh mortar setting point and consistency and on the hardened mortar prisms the compressive strength after 2, 28, 56 and 90 days were tested.

## 2.2 Results

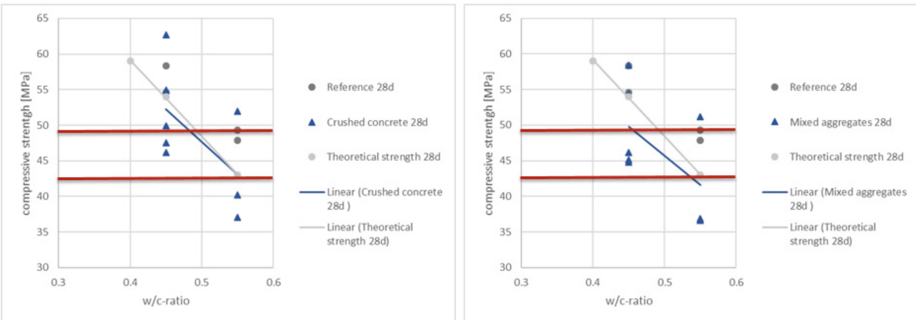


*Figure 2. Compressive strength of concrete mixes of test series 1 after 28 days. Crushed concrete on the right and mixed aggregates on the left.*

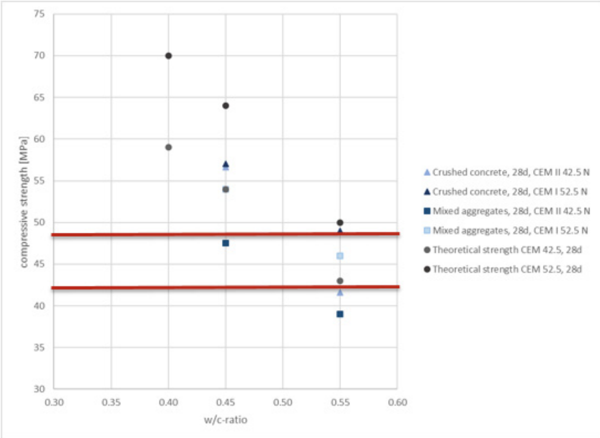


*Figure 3. Compressive strength of the concrete mixtures of test series 2 after 28 days*

The results for the use of recycled aggregates look promisingly although some of the results for the compressive strength are lower than with natural aggregates. The loss in compressive strength is bigger for the concrete containing mixed aggregates than for crushed concrete. But it could also be seen that the curve of the ratio of compressive strength to w/c ratio runs more or less parallel to the standard WALZ curve. The results also showed that it is possible to reach the targeted strength class of C 30/37 with a sufficient margin if the w/c ratio will be lowered to the direction of 0.45. The other possibility might be to use a cement of a higher strength class.

The investigations on the concrete for pavements showed that there are different influences that must be considered. Not only the mixture and the raw materials have an influence, but also the compacting factor as well as the compacting time show an influence. One important factor is the mixing ratio of cement to aggregates. In the tests it was found that a mixing ratio of 1:5 of cement: aggregates might be a suitable mixture for the use of crushed concrete aggregates. With this ratio it seems to be possible to reach the required tensile splitting strength of 3.6 MPa when using 100% coarse crushed concrete aggregates (see Figure 4).

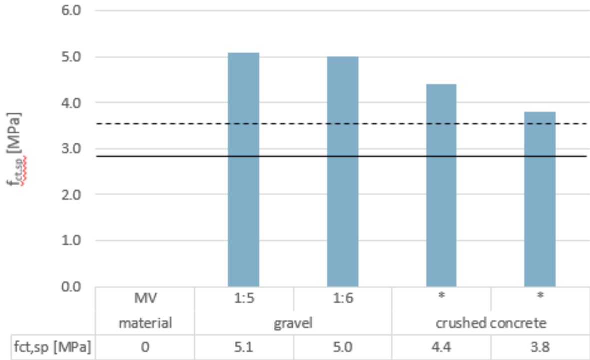


*Figure 4. Tensile splitting strength of concrete paving blocks 150 x 150 x 80 mm made from gravel concrete and concrete containing recycled aggregates depending on the ratio MV (proportion of cement : aggregates) of 1:5 or 1:6 [4] (* Due to the lower grain densities, the mixtures containing recycled aggregates have different mixing ratios in mass proportions)*

For the rammed concrete the best way for treatment was determined and the following procedure has proven successful for practical implementation [5]:

1. Optimisation can be carried out, for example, for adjusting the colour shade using test cubes, which can also be used to determine the compressive strength.
2. In a second step, the properties that can actually be achieved shall be investigated on sample specimens whose production shall correspond as closely as possible to the intended manufacturing process. The actual strength can be checked by the layer height and finally confirmed by testing drill cores.
3. The production processes under site conditions, in particular mixing and compaction technology, shall be discussed with the contractor prior to commencement of construction.
4. The colour shade and structure of the test wall are specified and must be achieved unerringly by the manufacturer.

5. The specified composition of the rammed concrete must be adjusted during use on site, if necessary, if the consistency or compactability deviates from the desired targets under site conditions.
6. The manufacturer must work through a „qualification catalogue" (cf. exposed concrete), whereby desired and excluded criteria must be clearly formulated by the client. Examples here are the overall impression of the surface with smooth and porous parts, desired colour shades, flatness of the individual layers, etc ...

For the test with the saltwater it can be said that the mortar tests showed no differences to tests with normal water. To get further information it will be needed to make further tests concerning the durability.

## 3. Conclusion

The tests showed that there are many possibilities for the use of recycled aggregates to produce concrete. The use of aggregates from unknown resources leads to some special challenges, which must be considered, but with an optimized mixture design, a lot of different product seem to be possible. Nevertheless, there are still a lot of questions that must be clarified in further tests to find optimum mixtures to produce good products. Especially the durability of the concretes containing recycled aggregates from unknown resources must be tested.

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# Development of New Cement Mixes from Fine Recycled Aggregates

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**Abstract**

The incorporation of Fine Recycled Aggregates (FRA) into concrete can affect its fresh and hardened properties. Another way of their valorization consists of their use as alternative resources in Cement Raw Meals (CRMs). The mineralogical characterization of a wide panel of recycled materials shows the presence of calcium carbonates and tectosilicates as major phases. Their quantities vary widely depending on the origin of the recycled aggregates, the category of Construction and Demolition Waste (CDWs) and the method of treatment. During the SeRaMCo project, eight recycled FRA were analyzed. These FRA were incorporated into laboratory cement raw meals replacing conventional materials (especially marl) and clinkers were synthesized. At the same time, two industrial cement batches incorporating 5 and 14% of recycled aggregates in their raw meals were produced and confirmed the feasibility of this way of valorization. However, the analysis of the cement raw meal fineness and composition shows that the high quartz and feldspars content and the hardness of these minerals could reduce the raw meal reactivity at high temperature and increase the kiln energy consumption. Therefore, incorporation rates of FRAs in CRMs of 5% are recommended in order to avoid difficulties related to the recycled aggregates supply chain, its chemical variability and the cement plant quarry specificities (limestone resources, etc.).

**Keywords**
Recycled aggregates; Cement raw meal; Clinker; Burnability; Mineralogical characterization.

**Kurzfassung**
Die Einarbeitung von feinen recycelten Zuschlagstoffen (FRA) in Beton kann seine Frisch- und Erhärtungseigenschaften beeinflussen. Eine weitere Möglichkeit ihrer Verwertung besteht in ihrer Verwendung als alternative Ressourcen in Zementrohmehlen (CRM). Die mineralogische Charakterisierung vielfältiger recycelter Materialien zeigt das Vorhandensein von Kalziumkarbonaten und Gerüstsilikaten als Hauptphasen. Ihre Mengen variieren stark in Abhängigkeit der Herkunft der rezyklierten Zuschlagsstoffe, der Kategorie der Bau- und Abbruchabfälle (CDWs) und der Behandlungsmethode. Während des SeRaMCo-Projekts wurden acht rezyklierte FRAs analysiert. Diese FRAs wurden in das Zementrohmehl integriert und ersetzten die herkömmlichen Materialien (insbesondere Mergel), darüber hinaus wurden Klinker synthetisiert. Gleichzeitig wurden zwei industrielle Zement mit 5 % bzw. 14 % rezyklierter Zuschlagsstoffe im Zement produziert, was die Machbarkeit für eine alternative Verwertung bestätigt. Die Analyse des Zementrohmels und der Zusammensetzung zeigt, dass der hohe Anteil an Quarz und Feldspat sowie die Härte dieser Materialien die Rohmehlreaktivität bei hohen Temperaturen verringern und den Energieverbrauch des Brennofens erhöhen können. Daher wird eine Beimischungsrate der FRAs ins CRM von 5 % empfohlen, um Schwierigkeiten im Zusammenhang mit der Lieferung von rezyklierten Zuschlagsstoffen, der chemischen Variabilität und den Besonderheiten des Zementwerks (Kalksteinressourcen) zu vermeiden.

**Schlüsselwörter**
rezyklierte Zuschlagsstoffe, Zementrohmehl, Klinker, Brennbarkeit, Mineralogische Charakterisierung

**Résumé**

La substitution des sables naturels par des sables recyclés dans les bétons est souvent problématique, car les propriétés à l'état frais et durci des nouveaux composites sont très généralement altérées. Une autre voie de valorisation de ces matériaux consiste à les utiliser comme matériaux alternatifs dans le cru cimentier. La caractérisation minéralogique de nombreux sables recyclés a montré qu'ils contiennent majoritairement du carbonate de calcium et des tectosilicates. Les quantités de ces phases varient en fonction de l'origine des déchets et du mode de traitement. Dans le cadre du projet SeRaMCo, huit sables recyclés ont été analysés. Au laboratoire, ces sables ont été incorporés dans un cru cimentier en remplacement des matériaux classiques (notamment la marne) et des clinkers ont été synthétisés. Parallèlement, deux essais à échelle industrielle, réalisés avec certains de ces matériaux à des taux d'incorporation de 5 et 14%, ont montré la faisabilité effective de la solution. Cependant, l'analyse de la finesse des crus incorporant les sables recyclés révèle que ces derniers peuvent contenir des grains de quartz et de feldspaths non finement broyés, ce qui grève le bilan énergétique du four rotatif lors de la cuisson. Il en résulte que les sables de béton recyclé peuvent être valorisés sans difficulté dans le cru cimentier, mais qu'un taux d'incorporation de l'ordre de 5% évite des problèmes liés à l'approvisionnement des granulats recyclés, à leur variabilité chimique et aux spécificités de la carrière de la cimenterie.

**Mots-clés**

granulats recyclés, farine brute de ciment, clinker, combustibilité, caractérisation minéralogique

## 1. Introduction

Recycled aggregates are generated by treatments of construction and demolition waste (CDWs). This treatment consists mainly of crushing and impurities removal (steel bars, woods, plastics, etc.) [1]. They are composite materials containing natural aggregates, mortars, ceramics and some impurities. The amount of these components depends mainly on the origin of natural aggregates, the original composition of concrete, waste treatment, etc.

Calcite and quartz are the main minerals found in these materials [2,3]. They come from natural aggregates and the carbonation of the hydrated cement paste. Other tectosilicates and/or phyllosilicates may also be present as minor or major phases (feldspars, clays, micas, etc.). Hydrated cement paste is also observed, mainly, in the finest fractions of these materials.

The use of finest fractions of these materials were tested in concrete mix design as partial and/or total replacement of natural aggregates [4]. It was shown that the fresh and hardened properties of final products were slightly or highly affected depending on the replacement rate. This was due mainly to the presence of high amounts of porous hydrated cement paste in these fractions of recycled aggregates which increases their water absorption [2,4].

The fine recycled aggregates (FRA) were also used as alternative raw materials for cement production [5–9]. They were incorporated in cement raw meals (CRMs) as replacement of siliceous conventional materials for cement production (mainly clays and/or marls). The incorporation rates of these materials in CRMs can reach in very particular cases 100% [7]. This huge variability is mainly due to their mineralogical composition and the cement type produced.

During SeRaMCo project, mineralogical compositions of FRA from different origins were used in order to discuss their incorporation rates in CRMs. Laboratory and industrial productions of clinkers were performed in order to confirm the feasibility of recycled aggregates incorporation as well as the quality of the cement produced.

## 2. Laboratory studies

### 2.1 Materials and methods

"Tradecowall" (T) in Belgium, "VICAT" (V) and "Agrégats du Centre" (N) in France supplied the recycled materials. These samples were obtained from Recycled Concrete Aggregates (RCA) and Mixed Aggregates (MA) which contain RCA but also ceramics, bricks, soil and impurities (asphalt, plaster, wood, plastic, etc.).

Calcium carbonate contents of these materials were determined by the calcimeter method (NF P94-048) while tectosilicates (mainly quartz and feldspars) were estimated by the insoluble residue method after dissolution in acid (EN 196-2). These two methods require hydrochloric acid and simple laboratory equipment only. These mineralogical compositions were confirmed by X-ray diffraction analysis and X-ray fluorescence.

Laboratory CRMs were prepared using a mixture of classical raw materials (limestone, marl, bauxite, foundry sand and iron ore) used in cement plant and recycled aggregates. For the incorporation of recycled aggregates, criteria linking the chemical composition of the CRMs and the final clinker composition need to be respected (Eq 1-7) [10–12]. These criteria were adjusted in order to calculate the incorporation rate of recycled aggregates.

$$0.97 < LSF = \frac{CaO + 0.75 \times MgO}{1.18 \times Al_2O_3 + 0.65 \times Fe_2O_3 + 2.8 \times SiO_2} < 0.99 \quad (1)$$

$$2.4 < SM = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} < 2.6 \quad (2)$$

$$1.5 < AM = \frac{Al_2O_3}{Fe_2O_3} < 1.8 \quad (3)$$

$$Liq.\,1450°C = 3.00 \times Al_2O_3 + 2.25 \times Fe_2O_3 + MgO + K_2O + Na_2O > 25\% \quad (4)$$

$$MgO < 3.0\% \quad (5)$$

$$SO_3 < 1.0\% \quad (6)$$

$$K_2O + 0.658 \times Na_2O < 1.2\% \quad (7)$$

## 2.2. Results and discussion

### *2.2.1. Chemical variability of FRAs and their incorporation rates in CRMs*

#### *2.2.1.1. Mineralogical composition of recycled materials*

Mineralogical compositions show that calcite (9-38%) and insoluble phases (quartz and feldspars principally) are the main phases in the samples with very variable quantities (Table 1). Remaining phases (Others), which are not determined by hydrochloric acid treatments, were identified by XRD analyzes or visual observations as hydrated cement paste, impurities (woods, plastics, etc.), clays, etc. Calcite is provided by natural aggregates or by the carbonation of the hardened cement paste while tectosilicates (quartz and feldspars) mainly come from natural aggregates or some impurities (ceramics, bricks and clays).

*Table 1. Mineralogical composition of the recycled aggregates estimated by hydrochloric acid treatments*

| | RCA-T | RCA-V | MA1-T | MA2-T | MA3-T | MA-V | MA1-N | MA2-N |
|---|---|---|---|---|---|---|---|---|
| Calcite (wt. %) | 32.1 | 38.2 | 16.9 | 18.0 | 20.0 | 29.5 | 9.2 | 11.5 |
| Insoluble residue (wt. %) | 38.7 | 35.5 | 58.2 | 52.3 | 52.5 | 45.3 | 65.8 | 67.4 |
| Others (wt. %) | 29.2 | 26.3 | 24.9 | 29.7 | 27.5 | 25.2 | 25.0 | 21.1 |

It is noteworthy from the results that MAs contain more tectosilicates than RCAs (and this is the opposite for calcite). This is due to the presence of impurities as ceramics, bricks and clays in this category.
Complementary XRD and XRF analyzes showed some particularities:

- Only recycled aggregates received from Belgium (Tradecowall) contain dolomite while aggregates from France (Agrégats du Centre) have the highest feldspars content;
- Few quantities of portlandite can be observed in RCA from France (VICAT) since it is a construction waste (Ready Mixed Concrete's drum returns), which is not yet carbonated.

#### *2.1.1.2. CRMs optimizations*

The maximum calculated incorporation rates of recycled aggregates are varying between 11% and 21% (Table 2). RCAs are more incorporated than MAs mainly due to their higher calcite contents. In fact, since OPC contains more CaO than SiO2, materials containing a high calcium oxide content are more incorporated in cement raw meal (Figure 1). The incorporation of FRAs is replacing both marl and foundry sand except for materials from "Agrégats du Centre". This is due to the high alkali content brought by feldspars, which limits the incorporation of these materials. Therefore, the lack of silicon content (logically brought by FRAs in this case) is compensated by the use of foundry sand.

*Table 2. Results of the optimization of raw meal with and without incorporation of the recycled aggregates*

| | Ref | RCA-T | RCA-V | MA1-T | MA2-T | MA3-T | MA-V | MA1-N | MA2-N |
|---|---|---|---|---|---|---|---|---|---|
| Max FRA rate (%) | 0.00 | 21.70 | 19.99 | 13.89 | 16.92 | 16.06 | 16.50 | 11.45 | 11.55 |
| LSF (%) | 97.44 | 97.97 | 97.00 | 97.21 | 97.51 | 97.13 | 97.00 | 97.00 | 97.03 |
| SM | 2.40 | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 | 2.40 | 2.40 |
| AM | 1.80 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| Liq. 1450°C (%) | 27.6 | 26.0 | 25.1 | 25.4 | 25.7 | 25.5 | 25.3 | 27.1 | 27.1 |

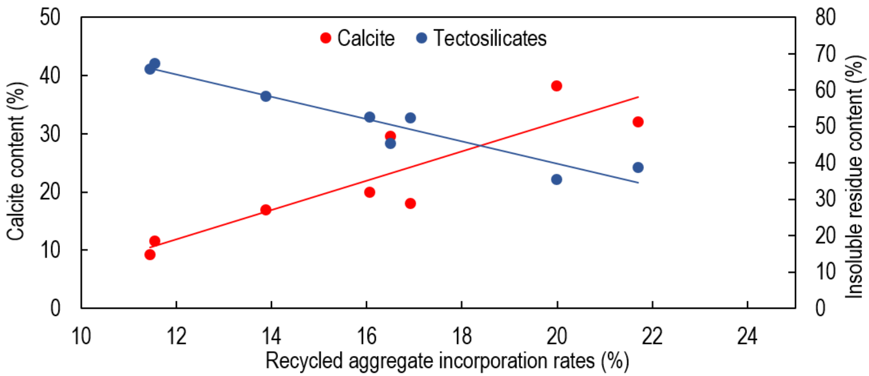



*Figure 1. Relationship between incorporation rates of recycled aggregates in a cement raw meal and mineralogical composition (calcite and tectosilicates contents)*

These incorporation rates are calculated for an ordinary Portland cement clinker and with classical materials from one cement plant quarry. The type of cement produced and/or the cement plant quarry composition (limestone content, etc.) could also highly affect these incorporation rates. Therefore, a lower incorporation rate seems to be realistic and easily feasible for most of the cement type produced and cement plant [13].

### *2.1.1.3. Tectosilicates fineness and burnability of CRMs*

Previous incorporation rates were calculated on a maximum rate basis. However, a particular attention has to be paid concerning the tectosilicates fineness (quartz and feldspars) and their contents in raw meal. Indeed, the presence of quartz and/or feldspars as rough particles (higher than 44 μm particles) can highly impact the burnability process of CRMs in a kiln and therefore the energy needed for the clinkerisation process will be increased [14–16].

Figure 2 shows the calculated contents of particles (quartz and feldspars) higher than 40 μm obtained after sieving, XRD analysis and Rietveld refinement of the different raw materials. It is noteworthy that CRMs incorporating recycled aggregates contain high and variable quartz and feldspars proportions, which can affect the burnability. In laboratory conditions, the CRMs burnability and the final clinker mineralogy (alite, belite) are not significantly modified by the incorporation of recycled aggregates (after chemical calculations). Industrial trials confirm the cement quality but reveal the possible mineralogical impact of recycled aggregates on the kiln consumption.

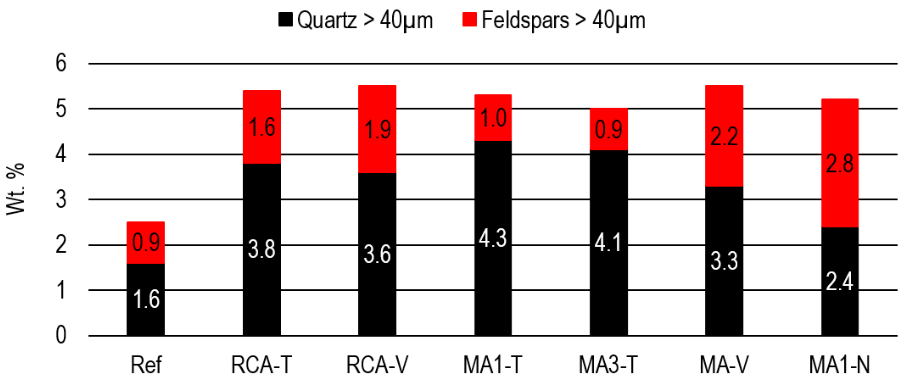
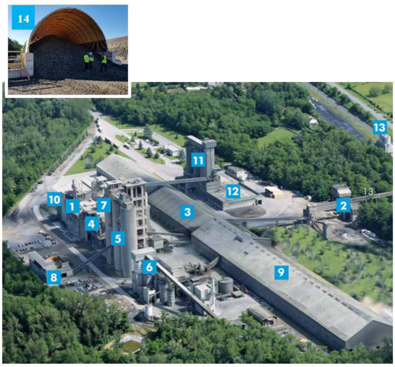



*Figure 2. Quartz and feldspars contents in CRMs (particles higher than 40μm)*

## 3. Industrial production

### 3.1. Industrial trails

The production of clinker was carried out at the VICAT cement factory in Créchy located near Vichy (France). This plant was chosen for its layout and equipment, with a platform for receiving alternative raw materials, a linear prehomogenization hall and a clinker storage tunnel, allowing tests to be carried out with a limited quantity of materials and to isolate the production tested (Figure 3).




1. Control room
2. The conveyor belt from the quarry
3. Prehomogenization hall
4. The raw crusher Polysius (output 120 T/h)
5. Homogenization silos
6. The coal crusher
7. The Polysius rotary kiln
8. Alternative fuels
9. Clinker storage hall
10. The Polysius cement crusher
11. Cement silos and bulk delivery
12. Palletization
13. Bulk cement shipments by train
14. Tunnel for storing clinker

*Figure 3. Aerial view of the Créchy cement plant. (© VICAT)*

This plant has an average capacity of 425 kt of clinker / year. It is equipped with a Polysius rotary kiln (75 m long, 4.40 m in diameter) preceded by a four-stage Dopol dry heat exchanger without precalciner. This kiln is 80% powered with alternative fuels (wood waste, used oils, tires, dried urban sludge, etc.).

### *3.1.2. Characterization methods*

The chemical composition of the cements was obtained by X-ray fluorescence on a fusion bead. The mineralogical composition was determined by X-ray diffraction after indexing on the Diffrac.EVA ® software and quantification by Rietveld refinement using the Topas ® software. The density was measured using a helium pycnometer (Micrometrics - AccuPyc II 1340). The tests for obtaining the generic properties of cements on pastes and / or on mortars were carried out according to standard EN 196. The fineness (d10, d50 and d90) of the cements was controlled using laser diffraction analysis (Helos®).

### *3.1.3. Cement production*

After crushing the clinkers, the grinding of the cements was carried out using a ball mill of 3 meters length and 0.9 meter internal diameter, consisting of two chambers of respectively 1 and 2 meters length, and equipped with a 3rd generation O-Sepa dynamic separator. Its output flow is 500 kg/h. The clinkers produced were used to make cements of different grades (CEM-II / A LL for test 1 and CEM-I for test 2).

## 3.2 Test procedure

A first test was carried out in September 2018. 730 tons of fine recycled aggregates (FRA) were transported to Créchy and stored at the cement plant in order to carry out a pre-homogenization stockpile of 5,137 tons (i.e. 14.2% of the total mass of the stockpile). The materials came from two platforms - one of which is a partner of the SeRaMCo project (Tradecowall; 150 tons) - mainly processing building demolition waste (2.9% of the stockpile for one, FRA 1; 11.3% of the stockpile for the other, FRA 2). These FRAs have high contents of silicon oxide and calcium oxide (Table 3), in agreement with their mineralogical composition (quartz and calcite).

A second test was carried out in July 2019. 271 tons of FRA (FRA 3) were transported to Créchy and stored at the cement plant in order to carry out a pre-homogenization stockpile of 5,231 tons (i.e. 5,2% of the total mass of the stockpile). The 5% rate is equivalent to a yearly consumption of approx. 50,000 tons of FRA for an average European cement plant, which seems to be an achievable figure to reach with local CDWs. The materials came from Tradecowall, partner of the SeRaMCo project. These FRAs have high contents of silicon oxide and calcium oxide, in agreement with their mineralogical composition (quartz and calcite).
This second test used slightly different conditions compared to the first one, as a secondary burner was implemented in addition to the main burner to inject fuels into the kiln.

*Table 3. Water content and chemical composition of FRA, in mass percentage.*

| | $H_2O$ | LOI | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $K_2O$ | $Na_2O$ | $SO_3$ | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FRA 1 | 9.1 | 17.5 | 47.2 | 5.4 | 2.1 | 22.7 | 2.0 | 1.1 | 0.5 | 0.8 | 0.03 |
| FRA 2 | 10.7 | 6.9 | 64.7 | 9.2 | 2.2 | 9.7 | 0.9 | 3.3 | 1.2 | 1.1 | 0.02 |
| FRA 3 | 11.8 | 12.9 | 49.0 | 7.1 | 3.5 | 13.7 | 1.1 | 1.3 | 0.4 | 1.6 | 0.05 |

The traditional raw materials of the factory (Table 4) are mainly local materials; the major constituents (98% of the raw mixture) are limestone, marl, foundry sand and excavated soils from public works. The minor constituents - or correctors - (2% of the raw mixture), of external origin, are bauxite, iron oxides.

*Table 4. Average composition of „classic" raw mix and „recycled" raw mixes, in mass percentage.*

| | Limestone | Marl | Foundry sands | Excavated soils | Correctors | RA |
|---|---|---|---|---|---|---|
| "Classic" raw mix | 51 | 36 | 6 | 5 | 2 | - |
| "Recycled" raw mix 1 | 84 | - | - | - | 2 | 14 |
| "Recycled" raw mix 2 | 56 | 33 | 3.5 | 0.5 | 2 | 5 |

Given the mineralogical composition of FRAs, in particular their high silica content (including quartz), the formulation strategy of the raw mixture has led to the complete replacement of marl, excavated soils and foundry sands. As a result, the raw mix contained only limestone, bauxite, iron oxide and FRA (Table 4). The lower amount of FRA ("Recycled" raw mix 2) allows the use of the usual resources.

### 3.3. Monitoring and controls

The chemistry of the raw mix was checked every two hours. The burning parameters for "recycled" raw materials, i.e. lime saturation factor "LSF", silicic module "MS" and alumino-ferric module "MA" have values very comparable to that of „classic" raw mix (Figure 4).

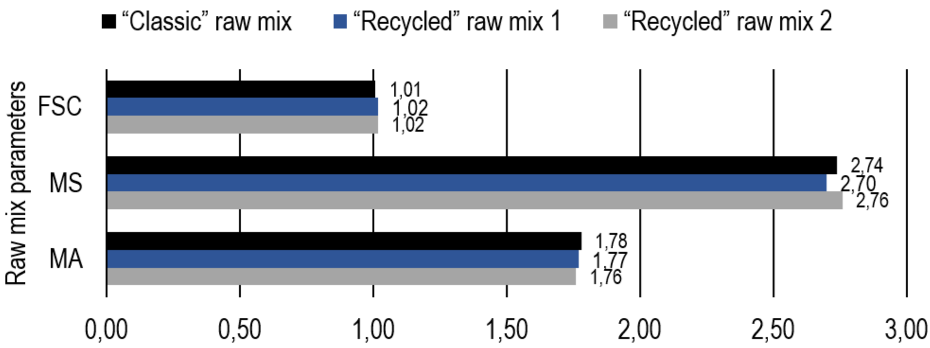



*Figure 4. Parameters of the raw mixes measured during the making of the heaps. For the "recycled" raw mix, average value of 23 measures. For the "classic" raw mix, average for the second half of 2018 (910 measures)*

Some burning parameters are presented (Table 5). The burning of the "recycled" raw mix 1 was more difficult than burning a classic raw mix or the recycled raw mix 2. It required an increase of about 20% in thermal consumption in order to maintain the quality of the clinker, regularly checked (free lime, alite content, etc.).

*Table 5. Burning parameters recorded during production (average of the 2nd half of 2018 for the "classic" raw mix).*

| | Clinker output (tpd*) | Clinker downgrading rate (%) | Energy balance (Thm/tck**) |
|---|---|---|---|
| "Classic" raw mix | 1065 | 4.5 | 980 |
| "Recycled" raw mix 1 | 1065 | 10 | 1178 |
| "Recycled" raw mix 2 | 1065 | - | 980 |

* Tons per day
** Therms per ton of clinker

During all the tests, the quality of the clinker (reactivity, mineralogical composition, etc.) was evaluated periodically (Figure 5). The mineralogical composition of the „recycled“ clinker corresponds to that of the usual productions of the factory. These results corroborate the parameters of the raw mixes.

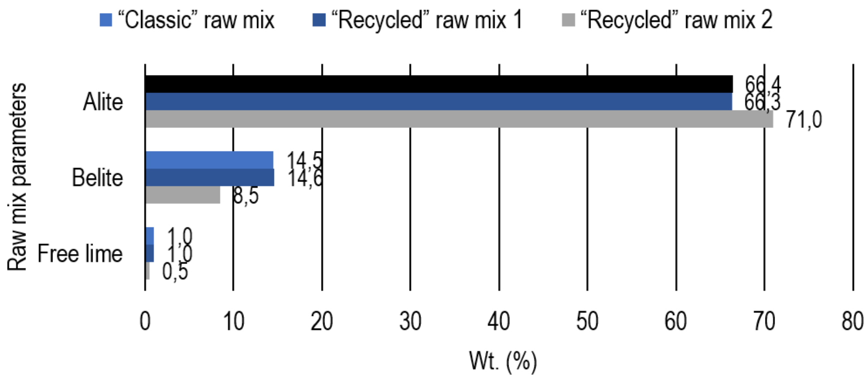



*Figure 5. Analysis of clinkers during industrial production. Average of 13 measures for the "recycled" clinker, average of production during the second semester for the "classic" clinker (394 measures)*

### 3.4 Cement characterization

Table 6 presents the generic properties of all the cements produced. The characteristics and performance of „recycled“ products compared to those of a control cement show no major difference and their performance is consistent. However, the mineralogical and chemical composition of clinkers and cements (fillers rate, etc.) presents slight differences, which can explain the hydration heat and the mechanical performances.

*Table 6. Generic properties of « recycled » and reference cements.*

| | CEM-II/A LL Ref | CEM-II/A LL Rec | CEM-I Ref | CEM-I Rec |
|---|---|---|---|---|
| Density ($g/cm^3$) | 3.07 | 3.13 | 3.17 | 3.16 |
| Blaine Specific Surface (BSS. $cm^2/g$) | 4488 | 4111 | 4187 | 3885 |
| $d_{10}$ / $d_{50}$ / $d_{90}$ (µm) | 1.22 / 9.11 / 27.38 | 1.38 / 9.75 / 27.32 | 0.98 / 9.07 / 29.66 | 1.60 / 10.54 / 26.90 |
| Water demand (water/cement ratio) | 0.35 | 0.35 | 0.30 | 0.35 |
| Setting time (min) | 330 | 245 | 233 | 267 |
| Heat released at 7 days on mortar (J/g) | 289 | 305 | 325 | 351 |
| Compressive strength at 28 days on mortar (MPa) | 52 | 57 | 62 | 61 |
| %$Na_2O$ | 0.21 | 0.23 | 0.22 | 0.22 |
| %MgO | 1.30 | 1.14 | 1.47 | 1.53 |
| %$Al_2O_3$ | 4.19 | 4.33 | 4.85 | 4.95 |
| %$SiO_2$ | 17.39 | 17.79 | 20.66 | 20.77 |
| %$P_2O_5$ | 0.22 | 0.25 | 0.25 | 0.21 |
| %$SO_3$ | 2.96 | 2.71 | 3.12 | 3.15 |
| %$K_2O$ | 0.83 | 0.66 | 0.97 | 0.89 |
| %CaO | 60.54 | 60.76 | 62.65 | 62.80 |
| %$TiO_2$ | 0.15 | 0.14 | 0.16 | 0.18 |
| %MnO | 0.10 | 0.09 | 0.12 | 0.13 |
| %$Fe_2O_3$ | 2.52 | 2.75 | 3.16 | 3.06 |
| %SrO | 0.08 | 0.07 | 0.09 | 0.10 |
| LOI at 1000 °C | 8.45 | 7.21 | 1.52 | 1.67 |

## 4. Conclusion

During the SeRaMCo project, various fine recycled concrete aggregates and mixed aggregates were used as raw material for cement production.
Mineralogical analysis shows that carbonates (calcite) and tectosilicates (quartz and feldspars) are the main phases in these materials. However, their quantities vary widely in function of the categories and the origin of the FRA. An analysis of CRMs particles higher than 40 µm showed that the ones with recycled aggregates contain higher quartz and feldspars contents. The incorporation rates of these materials in CRMs were optimized

using ordinary Portland cement criteria. They vary between 11 and 21% depending on the chemistry of the recycled sands and on the chemistry of the natural resources. Laboratory and industrial synthesis of clinker confirm the quality of the cement produced but the raw meal can be harder to burn. Low incorporation rates (around 5%) could allow using thousands of tons of recycled aggregates per year per cement plant and seems to be more realistic in order to avoid high quartz and feldspars contents and not to compete with other alternative or natural resources used in cement plants (foundry sands, excavated soils, marls, etc.).

## Acknowledgements

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# Principal Outputs of RECYBETON. A French National R&D Project on Complete Recycling of Concretes


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**Abstract**

France produces more than 20 Mt/year of demolished pure concrete, generally used in road works or embankments. This flow should increase soon while less new roads will be built. Additionally, more than 50 Mt of mixed demolition materials containing a good part of concrete or natural rock are available. Therefore, it is necessary to make the best use of this accessible material to preserve the natural resource and to avoid landfill of waste material.

Based on this reality, a National Project, partially sponsored by the French Ministry of Ecology, was set up in 2012 and finalized in 2018, gathering 47 partners among whom representatives of all construction stakeholders.

The main outputs of the project, which has produced a scientific book (English and French versions), a guide of recommendations, proposals to adapt standards and regulations, and experimental constructions, including a car park, a bridge, buildings and industrial constructions, are presented.



**Keywords**

recycled aggregate, recycled cement, recycled concrete



**Kurzfassung**

Frankreich produziert mehr als 20 Mt/Jahr reinen Abbruchbeton, der im Allgemeinen bei Straßenbauarbeiten oder Böschungen verwendet wird. Die

verbleibende Menge sollte zunehmen, wenn weniger neue Straßen gebaut werden. Zusätzlich sind mehr als 50 Mt gemischte Abbruchmaterialien mit einem guten Anteil an Beton oder Naturstein verfügbar. Daher ist es notwendig, diese zugänglichen Materialien bestmöglich zu nutzen, um die natürlichen Ressourcen zu schonen und die Deponierung von Abfallmaterial zu vermeiden.
Ausgehend von dieser Tatsache wurde 2012 ein nationales Projekt ins Leben gerufen, das teilweise vom französischen Ökologieministerium gesponsert und 2018 abgeschlossen wurde. Dabei kamen 47 Partner zusammen, darunter Vertreter aller Stakeholder des Bausektors.
Die wichtigsten Ergebnisse des Projekts, ein wissenschaftliches Buch (englische und französische Version), einen Leitfaden mit Empfehlungen, Vorschläge zur Anpassung von Normen und Vorschriften sowie experimentelle Konstruktionen, darunter ein Parkplatz, eine Brücke, Gebäude und Industriebauten, werden vorgestellt.

**Schlüsselwörter**
rezyklierte Gesteinskörnung, R- Zement, R-Beton

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**Résumé**
Plus de 20 Mt/an de béton pur issu des démolitions sont produites en France, généralement utilisées dans des travaux routiers ou des remblais. Ce débit devrait augmenter prochainement tandis que moins de nouvelles routes seront construites. De plus, plus de 50 Mt de matériaux de démolition mixtes contenant une bonne partie de béton ou de roche naturelle sont aussi disponibles. Par conséquent, il est nécessaire d'utiliser au mieux ce matériau accessible pour préserver la ressource naturelle et éviter la mise en décharge des déchets.
Partant de cette réalité, un Projet National, partiellement parrainé par le Ministère français de l'Écologie, a été mis en place en 2012 et terminé en 2018, regroupant 47 partenaires représentant tous les acteurs de la construction.
Les principaux résultats du projet, qui a produit un livre scientifique (versi-

ons anglaise et française), un guide de recommandations, des propositions d'adaptation des normes et réglementations, et des chantiers expérimentaux, dont un parking, un pont, des bâtiments et des constructions industrielles, sont présentés.

**Mots-clés**
granulat recyclé, ciment recyclé, béton recyclé

## 1. Introduction

After two years of preparation, important actors of the French construction community launched in 2012 a national project on Complete Recycling of Concrete, called RECYBETON [1]. The stakes were multiple: I) preservation of the natural aggregate sources; II) increasing flow of construction & demolition materials; III) suppression of all landfill; IV) decreasing the transportation distances and V) catching-up of the concrete sector into the circular economy. This paper summarizes the work done by more than 100 researchers and practitioners in 7 years.

## 2. Main outputs

### 2.1. Material processing

The project aimed to develop the use of recycled concrete aggregate (RA), coarse and fine, into new concrete with replacement rates higher than those currently accepted by the standards. RA are generally used “as obtained” through the process of crushing, sieving and sorting. Compared to natural aggregates, RA displays low density and high porosity to be considered when batching fresh recycled concrete (RAC). Otherwise, the process of recycled concrete production does not differ from the one of natural aggrega-

te concrete (NAC). A review of the available techniques to perform selection (sorting the undesirable particles in a mixed demolition material), detection (on-line identification of the presence of such a phase) or fracturation (de-bonding the cement matrix from the original natural aggregates) was done. The possibility of using fine RA as a supplementary cementitious material or as a constituent of cement was also investigated. When grounded with the clinker (to make a blended cement) or added to the concrete, the product performs as a filler with a tendency to degrade the fresh concrete slump retention (the use of a set retarder resolves this problem).
As raw material, recycled sand was incorporated to the meal of an industrial cement kiln at a replacement rate of 15%, producing an optimal clinker. This process is currently allowed by the cement standard EN 197-1, so the only obstacle for cement factories is the availability of a consistent, close and large enough source of recycled fine aggregate. The corresponding cement, equivalent to CEM I, was produced in a pilot cement mill with good performances.

### 2.2. Recycled materials and structures

The impact of the incorporation of RA into concrete was investigated. The effect is minor on strength (only noticeable at high replacement rate), but deformability properties evolve towards more strains in RAC. The flexural fatigue strength is also affected (more scatter in the results).
The behavior of structural elements is in line with material properties: higher deflections in beams, higher buckling risk for columns, shear resistance and the bond steel-RAC depending on RAC tensile strength. However, no significant increase of crack width was observed.
In terms of durability, the incorporation of RA increases the total porosity of concrete, leading to an easier transport of gas, water and alien species through RAC. Despite this, carbonation is only affected in the lower strength range of the mixes. For freeze-thaw, the risk depends on the original natural aggregate of RA, which can be frost-sensitive.

### 2.3. Sustainable development

As potential national resource in RA, 18 Mt of pure concrete was identified, to which a bigger amount of mixed concrete and untreated NA have to be added. Currently, these materials are employed in road works and embankments, but they can also be used to make concrete. In terms of Life Cycle Analysis, the positive points are saving of non-renewable resource and avoidance of landfill. With respect to the Carbon footprint, there are two key aspects to be considered: the transportation distances, which can be shorter for RA than for NA, and the cement content of RAC, which tends to increase for large replacement rates. Finally, leaching of RA or RAC does not seem to release significant amount of pollutants when exposed to water.

### 2.4. Dissemination

To disseminate these outputs, two intermediary seminars were organized and a series of final conferences in different regions of France are now in progress. A scientific book has been written, with a French version published in 2018 [2] and the English version published in 2019 [3]. A guide of recommendations has also been edited [4] and proposals for standards and regulation to extend the range of possible uses of RAC are ready. Finally, six different experimental sites (a car park, a small bridge, an archive room, short walls and sidewalk in an industrial premise, a slab in an office, a slab with cement made with clinker containing recycled sand), considering different RA rates, were carried out showing the feasibility of recycling concrete into concrete.

## 3. Conclusion

After 7 years of collective work, the French construction community has increased its awareness about recycling concrete into concrete. Most technical problems were addressed, and none of them appears to be a roadblock. The National Project RECYBETON has produced all the necessary tools allowing the use of this potential resource in concrete, hoping that a gradual change in the current practices will happen to reach this important goal.


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# 10 Innovative Concrete Precast Products

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**Abstract**

With every product made, material and energy is used. The result however is not only the product we aimed for. Typically, it also involved emissions, pollution and waste. An increasing amount of material sources is becoming more and more scarce. One major effort to reduce the use of primary materials is recycling. The Interreg NWE/SeRaMCo project provided the scope to research and design new intelligible applications for prefab concrete products with recycled Construction and Demolition Waste (CDW). This paper reviews the design and research process for innovative concrete products developed by TU Delft, to contribute to the aim of increasing the European and global market potential for the re-use of CDW. The search for innovative products based on recycled concrete however brought also the insight that recycling alone is not sufficient to compensate for the negative impacts on the environment generated by production in general. This notion initiated the search for concrete products that possess more functions or features than just the originally aimed single function, in order to restore or repair the intrinsic damage caused by the production process. This approach could be applicable for other kinds of products mankind makes, and as such this SeRaMCo project and the chosen approach of TU Delft can be seen as a pioneer project in developing a new vision on production in general.

**Keywords**

Innovative concrete products, Intrinsic damage, Recycled Concrete, CDW

**Kurzfassung**

Bei jeder Herstellung eines Produkts werden Material und Energie verbraucht. Das Ergebnis ist jedoch nicht nur das angestrebte Produkt. Es ist typischerweise auch mit Emissionen, Verschmutzung und Abfall verbunden. Die Rohstoffquellen werden nach und nach immer weniger. Um den Verbrauch an Primärstoffen einzudämmern, ist Recycling die maßgebliche Lösung. Das Interreg NWE/SeRaMCo Projekt ermöglichte eine Plattform für die Forschung und das Design von sinnvollen Anwendungen für Betonfertigteile mit rezyklierten Bauabfällen (CDW). Dieses Paper gibt einen Überblick über das Design und den Forschungsprozess zu den von der TU Delft entwickelten innovativen Betonprodukten, um damit zum Ziel beizutragen, das Europäische und globale Marktpotential von wiederverwertbaren Bauabfällen (CDW) zu erhöhen. Die Suche nach innovativen Produkten auf der Basis von rezykliertem Beton brachte jedoch auch die Einsicht, dass Recycling allein nicht ausreicht, um die negativen Umwelteinflüsse, die bei der Produktion entstehen, auszugleichen. Diese Erkenntnis veranlasste die Suche nach Betonprodukten, die mehr Funktionen und Eigenschaften besitzen als nur die ursprünglich angestrebte Funktion, um damit den beim Produktionsprozess entstandenen Schaden wieder zu beheben. Dieser Ansatz könnte auch für andere Arten von Produkten, die von Menschenhand hergestellt werden, anwendbar sein und als solches kann dieses SeRaMCo Projekt und der von TU Delft gewählte Ansatz als ein Pionier-Projekt gesehen werden, eine neue Vision der Produktion im Allgemeinen zu entwickeln.

**Schlüsselwörter**

Innovative Betonprodukte, Wesentlicher Schaden, Rezyklierter Beton, CDW

**Résumé**

Résumé Pour chaque produit fabriqué, on utilise des matériaux et de l'énergie. Le résultat n'est cependant pas seulement le produit que nous visons. En général, il s'agit aussi d'émissions, de pollution et de déchets. De plus en plus de matières premières se raréfient. Le recyclage est l'une des principales mesures visant à réduire leur utilisation. Le projet Interreg NWE/SeRaMCo a permis de rechercher et de concevoir de nouvelles applications intelligibles pour les produits en béton préfabriqué avec des déchets de construction et de démolition (CDW) recyclés. La présente publication examine le processus de conception et de recherche pour des produits en béton innovants. Ces procédés, développés par l'Université Technique de Delft, contribuent à l'objectif d'augmenter le potentiel du marché européen et mondial pour la réutilisation des déchets de construction et de démolition. La recherche de produits innovants à base de béton recyclé a toutefois permis de comprendre que le recyclage ne suffit pas à lui seul à compenser les impacts négatifs sur l'environnement générés par les modes de production actuels. Cette notion a lancé la recherche de produits en béton qui possèdent plus de fonctions ou de caractéristiques que la seule fonction visée à l'origine, afin de restaurer ou de réparer les dommages intrinsèques causés par le processus de production. Cette approche pourrait s'appliquer à d'autres types de produits fabriqués par l'homme et, à ce titre, ce projet SeRaMCo et l'approche choisie par l'Université Technique de Delft peuvent être considérés comme un projet pionnier dans le développement d'une nouvelle vision des modes de production.

**Mots-clés**

produits bétons innovants, dommage intrinsèque, béton recycle, déchets de construction et démolition

## 1. Background

This document is part of the SeRaMCo/INTERREG research project that aims to replace primary raw materials with high-quality materials from construction and demolition waste (CDW) in cement and concrete precast products (CPP's) for the North-West European (NWE) market.
As the result of a design and experimenting process, TU Delft developed 10 innovative concrete products ranging from immediately deployable to visionary. The reason to define product concepts to be developed into CPP business cases contributes to the larger SeRaMCo goal: increasing the use of secondary raw materials in prefabricated concrete production. On the one hand, by proposing and realizing alternatives with secondary materials for recognizable prefabricated concrete products, helping to gain trust in the successful use of secondary materials, and on the other hand by developing innovative, even visionary applications with CDW. Showcasing these applications to the NWE public and concrete industry will open up the discussion on re-use and end- of life concrete.
A sub goal is to establish a market niche for CPP's, leading to economic advantages for CPP producers and generating new jobs in the construction sector. One of the expected outputs is a range of CPP's from up to 100% recycled aggregates, comparable to conventional products both in terms of costs and quality, and ready for commercialization in NWE.

## 2. Method & design principles

The key challenge is to define sustainable applications that contribute to a closed cycle of raw materials and simultaneously address other global environmental issues. From the industrial revolution on, mankind has taken from material resources without proper reflection on the environmental effects. A seemingly nearly irreversible path was taken, that takes its toll on finite resources consumed and emissions produced along the way. As a result, scarcity and induced climate change [1] are facts and we struggle globally to stop this. For now, we can merely slow down the tremendous impact we have as a global society on natural reserves and life, and it has already proven to be a complex task.

In our own field of prefabricated concrete construction, limiting the use of primary resources will be one of the first steps. With the production of cement and concrete having significant environmental impact on a global scale [2], we need to take responsibility as an industry, from designer to producer, beyond the direct feasibility of merely using secondary resources. The impact of using all available CDW in the Netherlands in concrete illustrates the fact: concrete and mixed aggregate from all available construction and demolition waste, would cover roughly up to 20% of aggregates for the demand for new concrete, assuming the collection and processing of CDW is optimized [3].

Thus, we need to take responsibility for the damaging impact that production and use in general has caused and will cause. Our common task and moral obligation is that our designs need to repair the intrinsic damage caused on both the earth's resources and her inhabitants, during their production and during their lifetime. This principle should in fact apply to everything we produce and use.

## 2.1 Architectural design principles for SeRaMCo CPP's

To repair the aforementioned (environmental) damage the production and use of all CPP's cause, is an ambitious design task. Therefore, TU Delft identified clear goals and design principles to support the concept development process. The strategies are commonly used in state-of-the-art design and adapted from approaches like the 3R Strategy, Circular Economy design, and Stewart Brand's building layers.

### A. Design to reduce

Optimize the use of concrete and reduce the production volume of concrete. Use concrete applications for a longer period, optimize its product life.
Use less, reduce consumption.

**B. Design to reuse**
Facilitate the possibility to upgrade, maintain, deconstruct and disassemble, aim for a qualitative, timeless design and a responsible surplus to opt for adaptation later.

**C. Design to recycle**
Maximize the use of available and usable CDW in prefabricated concrete products. For a realistic adoption of secondary raw materials in precast concrete production, producers are dependent on a continuous high-quality supply of clean aggregates; furthermore, the product's ability to be recycled is essential.

**D. Relevant design**
The concepts must be relevant in a global context and cannot cater to merely one function: in order to repair what was damaged in previous years and during production, aiming for multi-functionality and multi-efficiency are integral parts of the design strategy. Apply the concrete products with multiple functions.

**E. Material specific design**
Embracing and using the specific technical and architectural properties of concrete with CBTC (Concrete, Bricks, Tile and Ceramic).

**F. Context-sensitive design**
Address local (NWE) market demands. Apply locally available material to reduce transport costs and emissions while keeping urgent global necessities in mind. Specify CPP properties on local use and context.

## 3. Process

The efforts that TU Delft performed regarding Work Package T3 is roughly divided in three consecutive phases and approached by a combination of research and design in studios.

**1) Global focus and experimenting (March 2017 – March 2018)**

Alongside research, discussions, design development and brainstorm sessions amongst academics, with input from our partners in the professional industry, in this first phase an experimental design workshop and studio 'Making' [4] was set up to support these efforts with practical experiments and input from a team of students. This workshop enabled our researchers, design tutors, master students and experts from the Dutch concrete industry to exchange knowledge and developments and to design together, thus creating and testing experimental designs all based on the use of secondary raw materials. The brief for the design studio was to investigate the potential for secondary raw materials by completely free experimental designs. The result was a broad spectrum of over 24 inspirational ideas for concept ideas, not necessarily all realistic yet, but inspiring enough to potentially be developed into realistic product proposals. In the process of developing innovative CPP concepts, 2 main theses are defined:

- if it is possible to create concrete with secondary raw materials in the same quality as traditional concrete with primary raw materials, we can make everything that is already currently available on the market.
- if the properties of concrete made with secondary raw materials potentially deviate from traditional concrete, then those properties could possibly provide an advantage for new innovative products to be developed.

These two theses manifest the two extremes in a spectrum of concepts, varying from immediately deployable products to visionary products.


*Figure 1. Concept proposals find a place on a spectrum from immediately deployable products to visionary concepts and anything in between.*

**2) Product development (March 2018 – September 2019)**
The 24 presented concept ideas were narrowed down to 12 proposals by the representatives of all SeRaMCo project partners, in a democratic vote during the Delft meeting on July 5th and 6th 2018. A detailed evaluation on the 12 proposals was done within the consortium, to harvest detailed feedback based on the total expertise of the consortium. The evaluation [5] offered TU Delft the opportunity to work on the proposals in more detail, while our SeRaMCo partners started developing appropriate concrete mixes needed for these 10 foreseen products. TU Delft organized several meetings with partners during which the product concepts were further developed. At the project partner meeting of May 6th/7th 2019, TU Delft presented 10 products for final evaluation in order for the preparations for production to commence.

**3) Pilot projects and products (September 2019 – September 2020)**
The product proposals will be developed and produced in collaboration and with the help of the project partners into realistic prototypes. Some of them will be showcased in one of the 3 pilot projects that will serve as lighthouse projects.

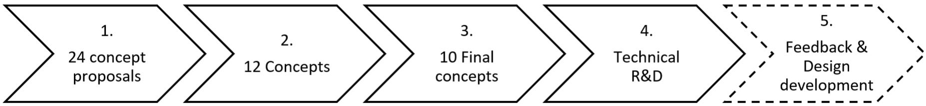


*Figure 2. Project development process SeRaMCo CPP's – TU Delft (2018)*

## 4. Results

The following list presents the 10 final product designs that TU Delft and involved partners developed into prototypes for the SeRaMCo project. With these products, TU Delft is stressing the need to take responsibility for the (environmental) impact that the production and use of precast concrete causes, even when raw materials are recycled. Our common task and moral obligation should transcend using secondary raw materials. As a result, SeRaMCo precast products should minimize the impact both on the earth's resources and her inhabitants, in production, use and at end-of-life. In other words, SeRaMCo building products should contribute positively to the environmental challenges we face, complementary to what they are made for in the first place, and beyond sheer recycling. The descriptions for each product serve as a justification of the designed element by providing background information on the purpose and functionality of the product. More detailed descriptions, product visualization, dimension drawings, product specifications and supplementary information can be found for each prototype in the 10 innovative SeRaMCo products report [6].

### 4.1 Hollow Core Floor Slab

A hollow core slab is a precast slab of pre-stressed or reinforced concrete, and typically used in the construction of floors and roofs in residential and office buildings. This type of precast element is popular in North West Europe for over decades because of its installation speed and material efficiency. An example: more than one third of all Dutch precast concrete is produced for commercial and residential buildings, consisting mostly of floors and walls. [7] Thus, a standard and widely used element such as a hollow core slab composed with recycled aggregate, has great potential to introduce secondary raw materials to the precast market.

### 4.2 Urban SeRaMCo Elements

A series of pavement and street guidance elements for the public realm, compose an informal introduction to the topic of secondary raw materials in concrete. The modular elements composed with recycled aggregates, fit within a modular grid and thus promote two straightforward strategies for circularity: by recycling raw materials and the ability to reuse. Flooded inner cities caused by peak rainfall due to climate change are no longer an uncommon phenomenon in North Western Europe [8]. Thus, one of the focal points in current city development is to make the urban context more water resilient using measures like permeable pavement. A factor of openness of 2,5% allows for both the permeability and effective element strength [9]. For the SeRaMCo project, TU Delft has designed a modular pavement with 4 different sizes, ranging from 11x11 to 44x44 cm with designed slots of minimal 2,5% of the surface of the pavement, that simultaneously give the pavement a visual character. The modularity allows for a combination with the designed collision blocks and traffic guidance elements. These elements serve as safeguarding elements against motorized traffic (large) or as marking elements (small) indicating routes in pedestrian areas. In landscaped contexts these elements can be a visual nuisance. With a market share of 40%, precast concrete pavement and bricks take on a significant part of prefabricated concrete products in the Netherlands. The pavement series have a great potential to introduce secondary raw materials to the public [7].

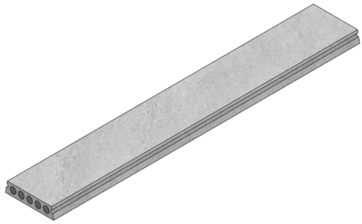

Figure 3. Recycled concrete Hollow Core Slab

Figure 4. Urban SeRaMCo Elements

### 4.3 Sound Absorbing L-Wall

A retaining wall is used to prevent soil from passing from a higher to a lower level. Typical applications include overpasses along a high way, the realization of different levels in landscaping and the different levels of platform and rails in stations.

The obvious advantage of precast L-walls lies in the speed of installation and cost-effectiveness of the solution. The element surfaces that are visible and in contact with the atmosphere, are areas that can be exploited by adding a functionality to the surface. An additional porous concrete layer, thickness of 60 – 100 mm, based on C. Whealy's porous absorber calculator [10], will serve as a sound absorbing measure. A previous study has shown that a void ratio of 25% is optimal to provide sound absorbing conditions in a high traffic situation [11]. The thickness of the porous layer is dependent on the type of traffic (heavy or light) that is the source of the noise pollution, generally heavy traffic noise is absorbed better by a thicker layer.

### 4.4 Green Concrete Facade Cladding

The SeRaMCo Green Concrete Façade Cladding or 'multi-façade' presents the potential of façades as a water buffer. The cladding panel is design not merely as a rainwater device, emphasis is put on the multi- functionality of the façade: combining features such as improving biodiversity, reduction of air and acoustic pollution, and promotion of human well-being. ‘Living wall’ systems are mostly suited for modular façade panels, containing plant pockets or porous surfaces with integrated water systems and substrates [12]. The multi-façade solution is specifically made for buildings with a water retaining roof (temporary rainwater buffer). Currently the water from these roofs is left mostly unused, the multi-façade uses the dripping water to water the substrate layer and consequently the plants. A permeable concrete top layer divides the water evenly over the façade, giving all the plants water over time. To avoid technical complexities and reduce maintenance it is chosen to design a passive façade element, which has a water retaining substrate in the panel that reduces the need of watering the plants.

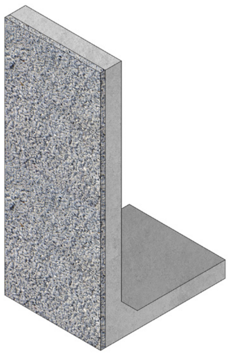

*Figure 5. Sound absorbing L wall*

*Figure 6. Green Concrete Facade Cladding*

## 4.5 Salty Concrete

To think of alternatives for (scarce) fresh water, concrete production with salt water is worthwhile. With concrete being the most-used construction material worldwide with a responsibility of almost 2% of the global water withdraws [13] building concrete elements with salt water can have a big impact. Studies have shown that using salt water in concrete without reinforcement is possible and even in some aspects beneficial for concrete [14, 15]. A spectrum of possible applications open up, when reinforcement is no longer a requirement, which is the case for armor blocks for coastal protection: the SeRaMCo Coastal Protection Block. A significant part of the North-West European region is located within 100 km distance of the sea. With most large cities situated near coastal area's the potential of salt water use in concrete is even greater.

**4.6 Rammed Concrete**

The high absorptive character of fine recycled aggregates makes it difficult to replace sand in concrete, as it influences the workability of fresh concrete. As a result, it ends up in other uses or worse: landfill, instead of retaining its material value in a similar purpose. Compressing fine fraction into building components simultaneously retains value and uses the un-hydrated cement in the material (approximately 10% by weight) to stabilize the shape. If the free cement in the fine aggregates is not enough to secure the structural integrity of the building blocks, additional binders are added. SeRaMCo suggests to use the fine aggregates from CDW according to the relation between demolition locations and use destination, in two principle ways:

- When the destination is either not known or not in the proximity of the source, modular compressed building blocks of manageable size will be made, to be used in a later instance or to be transported to a distant location.
- When the destination is in the near proximity of or similar to the demolition location, rammed building components will be made on the spot. In this case geometry and dimension are not dependent on factors as transport and standardization.

*Figure 7. Salty concrete coastal element*

*Figure 8. Rammed Concrete brick*

### 4.7 Energy Sound Barrier

The need for sound reflecting measures along a high way in the vicinity of urbanized areas coincides with the same areas producing and consuming heat. Today the majority of sound-absorbing walls just reflect sound, and their potential to be activated into multi-functional elements is ignored. The Energy Sound Barrier combines the mass that is needed to shield of noise with a sound absorbing layer on the surface, and with an additional system that absorbs and stores heat and cold. Inclined precast concrete elements absorb both noise and solar radiation that is either fed directly into an urban grid to provide heat or cold into a soil heat exchanger to provide cold to the buildings located behind the barrier. The heating network concept is comparable to the solar supported heat supply system in Crailsheim [16], however in this case the SeRaMCo Energy Sound Barrier gathers the thermal heat itself instead of the solar collectors.

### 4.8 Foam concrete Insulated Wall

The Foam concrete insulated wall is characterized by a double wall build-up with insulating anchors, a layer of insulating foamed concrete and a cavity that is filled with in-situ concrete to achieve a monolithic structure. The insulating foam concrete intentionally deviates from the structural concrete, to enhance time efficiency and functionality during the production and use phase. However, what has to be tested out, if foam concrete can be removed with the same technique used for low density materials such as plastics and wood during the recycling process of this element. With a thermal conductivity of approximately 0,035 – 0,04 (W/mK) for expanded poly styrene (EPS) in the traditional insulated wall, the insulated layer with foam concrete ($\lambda$ with a density of 400 kg/m³ 0,075 (W/mK)) needs to exhibit twice the thickness to compensate for a higher thermal conductivity. Lower density foam concrete is commercially available and could lead to a higher thermal insulation [17,18].

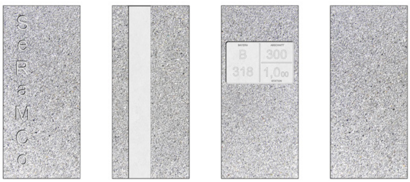

*Figure 9. Energy Sound barrier*

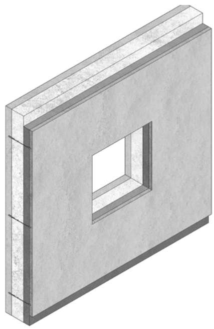

*Figure 10. Foam concrete insulated wall*

### 4.9 Cooling Wall

Due to increasing activity in cities, temperature in city centers may increase up to 5,3 °C compared to rural areas during the daytime [19]. This phenomenon is called the Urban Heat Island Effect. Combined with global warming, it results in a growing demand for cooling installations worldwide. To avoid using even more energy to do so, alternative ways are needed to cool our cities when it is warm outside. With the help of surface water, ambient outside temperatures can be reduced up to 5 °C, as was the case during the

World Expo ’92 in Sevilla [20]. Exterior cooling walls, using the principle of evaporation with irrigated recycled mixed aggregate in a gabion structure are a SeRaMCo translation. Passive cooling relies on the atmosphere, the sky and the earth in order to achieve temperature moderation [21]. These walls store water and release it for cooling in the city, when needed, via porous recycled aggregate. Evaporation of water at elevated temperature provides a cooling effect and simultaneously increases the relative humidity [22]. On an urban scale it works along the same principle as on a human scale: as the body heats up, a sweating mechanism is activated and air flowing along the skin induces the moisture to evaporate and cool down the body. Similarly, the cooling wall will “sweat” via an irrigation system, which is stored during heavy rainfall. As water drips down the gabion wall filled with CDW aggregate, wind flows that are induced by smart orientation accelerate the evaporative effect and thus bring down local air temperature to a comfortably cool atmosphere during the warmest times of day. Studies show that brick wall surface temperatures can be lower than ambient temperatures by 5 – 7 degrees [23, 24]. It is expected that the use of unbound mixed concrete will have similar effects and might perform even better, due to a higher surface being exposed to air and thus activated to evaporate.

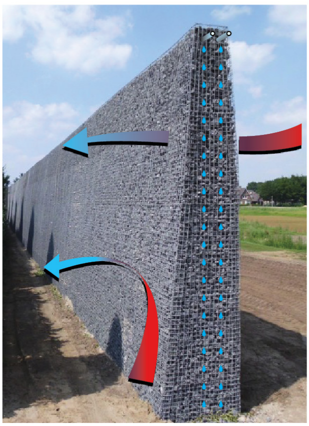

*Figure 11. Cooling wall*

## 4.10 Energy Bench

The SeRaMCo energy bench embodies the exploration of the role of concrete in renewable energy development. While there is an abundance of renewable energy sources, such as solar-, wind or gravitational power, the larger challenge is to find ways of storing the intermittent supply of these resources.

The SeRaMCo energy bench mainly represents the function of concrete being a medium of thermal energy. Thermal energy is an important form of energy storage for solar power conversion, but residual industrial heat is also a possible energy source when provided with an appropriate storage system. Regarding the ease of production, relative low cost, high heat capacity and high thermal mass, concrete is an ideal thermal energy storage (TES) agent [25]. In principle, thermal mass heat storage by sensible heat transfer is based on the specific heat of material and temperature variation. Thermal energy is stored in a solid or liquid medium. Simply by charging this medium by increasing its temperature, energy can be drawn from the material when discharging by lowering its temperature. SeRaMCo/ TU Delft represent the possibility of concrete as a medium of thermal energy in the so called 'energy bench'. In this case, the bench can directly showcase how the stored energy can be transmitted to usable energy in the form of electricity to charge a phone or light a LED-bulb. A critical asset to be able to transfer thermal energy stored in the bench into electrical energy, is to add a so-called Peltier element. This element consists of two metal plates at a small distance from each other, which when being exposed to different temperatures from each other, produce an electrical current. In the design the concrete bench that stores the thermal energy that derives heat from the sun during the day in the material itself. While the heat retention of concrete is much higher than that of air, two metal plates (one touching the air, one touching concrete) will continuously differ in temperature, so an electrical current will emerge throughout the day.

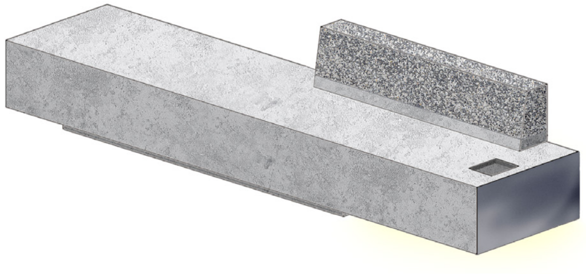

*Figure 12. Energy bench design*

## 5. Future perspective

In the scope of the Interreg/SeRaMCo project, 10 products have been developed ranging from immediately deployable to innovative products. Whilst most of the presented concepts have been optimized in conjunction with the specific project partners in terms of dimensioning, production and testing, the energy bench and Energy Sound barrier proved to be more complicated to develop into a 'working' prototype since it requires expertise outside of the scope of this project. Currently TU Delft is in contact with the Electrical Engineering department for further development of the products. The planned schedule for realization is projected to June 2020. Further optimizations should be undertaken to improve the performance of each individual SeRaMCo product.

According to the scope and research objectives of the project, the consortium of project partners did not perform further advanced investigation into potentially deviating properties of concrete products made with secondary raw materials in such way that those properties could possibly provide an advantage for new innovative products to be developed. Therefore, further research into the performance of new mixes with recycled concrete will be needed in order to determine whether the use of recycled concrete from

CDW could lead to new, yet unknown CPP's and new applications.

The largest gain however lies in combining multiple features and properties in any element, beyond the aimed primary function of it. Buildings and structures can thus be developed to 'net-plus' constructions by applying concrete elements with multiple functions, amongst other applications. Global climate and environmental related issues like loss of biodiversity, urban heat island effect (UHI) and the annoyance of sound and fine-dust are having a negative influence on people's health and health related costs. Incorporating properties to CPP's and other products that reduce or eliminate the negative effects of UHI, sound and fine dust, and support the restoration of biodiversity would have a positive effect on reducing climate change and health issues. A same type of argumentation is applicable to issues like energy harvesting and energy storing. The presented Energy Bench as designed by TU Delft is an example of using the material properties of concrete to store and help generating electrical energy. In general, the material properties of concrete that can play a role in combating negative effects of production and climate related issues has been the central focus of TU Delft's efforts along this SeRaMCo project. As stated, this is merely a beginning and deserves further research and development.

There is a great way to go!

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# SeRaMCo
# Recycled Concrete in the Precast Concrete Industry

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**Abstract**

Given the growing scarcity of raw materials and the consumption of materials becoming more and more important for the production of concrete, the SeRaMCo project aims to promote the use of recycled aggregates and recycled cement in precast concrete. Concretes facing the outside environment must be durable over time. To do so, different concrete recipes must be studied, tested for their durability and strength. Then, at industrial scale, the precast concrete elements will be produced for various pilot projects including street pavements which are produced with earth-moist concrete.

**Keywords**

Recycled aggregates, recycled cement, concrete mixes, durability, pavement, concrete precast industry

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**Kurzfassung**

Da die Rohstoffknappheit zunimmt und der Materialverbrauch zur Betonherstellung immer wichtiger wird, will das SeRaMCo-Projekt die Verwendung von rezyklierten Zuschlagsstoffen und rezykliertem Zement in Fertigteilen fördern. Betone, die der äußeren Umgebung ausgesetzt sind, müssen eine hohe Dauerhaftigkeit aufweisen. Um dies zu erreichen, wurden verschiedene Betonzusammensetzungen studiert und im Hinblick auf Dauerhaftigkeit und Festigkeit getestet. Anschließend sollen die Fertigteile im industriellem Maßstab für unterschiedliche Pilotprojekte hergestellt werden, darunter

Straßenbeläge, die aus erdfeuchten Beton hergestellt werden.

**Schlüsselwörter**
Rezyklierte Gesteinskörnung, Rezyklierter Zement, Betonmischungen, Dauerhaftigkeit, Straßenbelag, Fertigteilindustrie

**Résumé**
La raréfaction des matières premières grandissante et la consommation des matières étant de plus en plus importante pour la production de béton, le projet SeRaMCo a pour but de promouvoir l'utilisation de granulats recyclés et de ciment recyclés dans les bétons préfabriqués. Les bétons faisant face à l'environnement extérieure doivent être durables dans le temps. Pour se faire, différentes recettes béton doivent être étudiées, testées au niveau de leur durabilité et résistance. Ensuite, en milieu industriel, les éléments en béton préfabriqués seront produits pour différents projets pilotes dont la production de pavé de rue avec du béton sec.

**Mots-clés**
Agrégats recycles, ciment recyclés, recettes béton, durabilité, pavé en béton, industrie du béton préfabriqué

## 1. Introduction

The purpose of the SeRaMCo project is to provide high-quality recycled aggregates (Type A and B according to EN 12630) and recycled cement. The development of new concrete mixes will allow the use of recycled aggregates and cement to produce concrete precast products (CPP). Theses concrete precast products will be tested and shown in different pilot projects in Belgium, France and Germany.

The current standards for precast concrete product EN 13369 and for ready-mixed concrete EN 206 allow the producer to use up to 50% of recycled aggregates based on the class of exposure, types of concrete, type of aggregates used and concrete strength. The origin of the recycled aggregates (known origin or unknown origin) is also taken into account in this standard. The aggregates form known origin allow the producer to use more recycled aggregates.

All the CPPs in the pilot project will be exposed to outside conditions and according to EN 13369 and EN 206, a maximum of 30% of recycled aggregates from known origin are allowed in the concrete. One aim of the SeRaMCo project is to use higher percentages of recycled aggregates without compromising the durability of the concrete. The use of recycled sand is not allowed by current concrete standards.

In the SeRaMCo project, PREFER is in charge of producing innovative concrete precast prototypes (developed by TU Delft), and of producing the concrete precast elements for the Parkour Park in the city of Seraing in Belgium and paving blocks for the city of Saarlouis in Germany.

## 2. Concrete mixes

The development of concrete mixes for structural and non-structural elements is the purpose of the Work Package T2. Self-compacting concrete, dry concrete, open concrete, rammed concrete, high- and low-strength concrete and salty concrete are the concrete mixes selected to be developed with the recycled raw material. The concrete mixes are designed by University of Kaiserslautern (dry concrete, rammed concrete, low strength concrete and the salty concrete) and Luxembourg University (self-compacting concrete, open concrete and high-strength concrete).

For the pilot project, PREFER needs the dry concrete for paving blocks and the high-low strength concrete for CPPs. For this type of product, the durability is more important than for the prototype product which will more show-case concrete precast products. Several concrete mixes have been studied by the universities, but it has been decided to produce some concrete in the lab.

### 2.1 Concrete mixes for concrete precast product in outside conditions

The elements in the pilot project are in outside conditions and according to EN 206-1 and EN 13369, the exposition classes of the concrete are XC4, XD2, XF4 (Environment class EE4 for Belgium regulations). There is no standard product for the element in the pilot project (see Figure 1). For the EN 206-1 and EN 13369, the national annexes are NBN B15-001 and NBN B21-600.

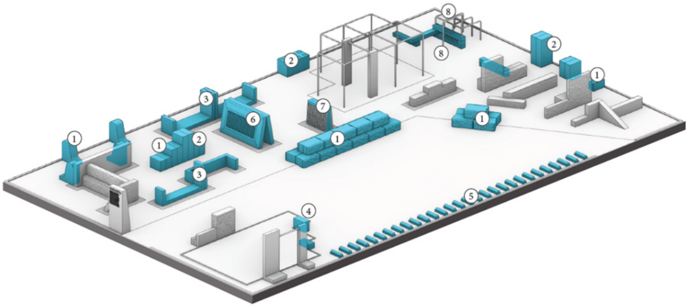

*Figure 1. Draft design of the parkour park in Seraing, Belgium*

The exposition classes involve requirements on the concrete mixes:

- according to EN 206-1 and EN 13369, the requirements are:
- Ratio Water/Cement (W/C) <= 0,45;
- Cement Quantity = min 340 kg/m³;
- Strength on the concrete C35/45 =>
  $F_{mean}$ (cube 150 x 150 x 150mm) = 50-55 MPa.

- according to the national annex NBN B15-001 NBN B21-600, there is an extra requirement:
- Water absorption
  - Max aggregate size > 16 mm: <= 5,5%;
  - 16 mm >= Max aggregate size > 8 mm: <=6,5%;
  - 8 mm >= Max aggregate size > 4 mm: <= 7,5%.

### 2.1 Concrete mixes

The following mixes have been designed after the first test series made by University of Kaiserslautern. The grading curves a similar and we decided to choose a water on cement ratio of 0,5 and 0,45 which are most used in the precast industry.

For the crushed concrete aggregates (Type A EN 12630), it was decided to produce 2 mixes (Mix 1-cement 400 kg – W/C=0,45, Mix 2-cement 360 kg – W/C = 0,50) with 68% of recycled aggregates including sand.
For the mixed aggregates (Type A EN 12630), it was decided to produce 2 mixes (Mix 3-cement 400 kg – W/C=0,45, Mix 4-cement 360 kg – W/C=0,50) with 66% of recycled aggregates and 1 mix (Mix 5-cement 34 kg – W/C = 0,50) with 47% of recycled aggregates. The mix 5 is designed for hollow core slabs. The soaking water is the additional water needed to saturate the recycled aggregates. Indeed, the water absorption of the recycled aggregates is higher (between 3% and 6% in this case) than of natural aggregates (< 1%). This additional water is needed to have enough workability of the concrete and is not taken into account in the calculation of the water on cement ratio (W/C).

| | | Crushed concrete aggregates (Type A - EN12620) | | Mixed aggregates (Type B - EN12620) | | |
|---|---|---|---|---|---|---|
| | | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 |
| Water | [kg] | 180 | 180 | 180 | 180 | 170 |
| Soaking water | [kg] | 48 | 49 | 53 | 54 | 39 |
| **Cement CEM I 52,5 N** | [kg] | 400 | 360 | 400 | 360 | 340 |
| **W/C ( water on cement Ratio)** | [-] | 0,45 | 0,5 | 0,45 | 0,5 | 0,5 |
| Sand 0/2 | [kg] | 525 | 535 | 525 | 535 | 920 |
| RA aggregates 2/6 - Tradecowall | [kg] | 441 | 450 | 402 | 410 | 829 |
| RA aggregates 6/14 - Tradecowall | [kg] | 473 | 482 | 433 | 441 | 0 |
| RA aggregates 14/20 - Tradecowall | [kg] | 189 | 193 | 173 | 176 | 0 |
| Superplastizer | [%] | 1% | 1% | 1% | 1% | 1% |
| **% of Recycled aggregates** | [-] | **100%** | **100%** | **100%** | **100%** | **100%** |
| **% of Recycled aggregates including Sand** | [-] | **68%** | **68%** | **66%** | **66%** | **47%** |

*Figure 2. Concrete mixes*

### *2.1.2 Results*

In figure 3 the results regarding the fresh and hard concrete of the concrete mixes show that the requirements in §2.1 are almost achieved expect for the water absorption. The compressive strength is between 45 MPa and 65 MPA and the water absorption is between 6,3 % and 8,9%. The water absorption is directly linked to the durability of the concrete. In concrete mixes with normal aggregates, the water absorption obtained must be between 4,5 and 6% and the compressive strength between 60 MPa and 90 MPA. The influence of the recycled aggregates shows that it decreases the compressive strength and increases the water absorption.

| | | Crushed concrete aggregates (Type A - EN12620) | | | Mixed aggregates (Type B - EN12620) | | |
|---|---|---|---|---|---|---|---|
| | | Mix 1 - Trial n°1 | Mix 1 - Trial n°2 | Mix 2 | Mix 3 | Mix 4 | Mix 5 |
| **Cement CEM I 52,5 N** | [kg] | 400 | 400 | 360 | 400 | 360 | 340 |
| **W/C ( water on cement Ratio)** | [-] | 0,45 | 0,45 | 0,5 | 0,45 | 0,5 | 0,5 |
| **% of Recycled aggregates including Sand** | [-] | **68%** | **68%** | **68%** | **66%** | **66%** | **66%** |
| **Fresh concrete** | | | | | | | |
| **W/C mesured ( water on cement Ratio)** | [-] | 0,47 | 0,44 | 0,47 | 0,46 | 0,49 | 0,46 |
| Slump test (Abrams cones) EN12350-2 | [-] | S1 (4 cm) | S2 (7 cm) | S2 (7 cm) | S1 - (1 cm ) | S3 - (11 cm) | S1 (1 cm) |
| Fresh raw density | [kg/m³] | 2271 | 2269 | 2231 | 2186 | 2236 | 2172 |
| **Hard concrete** | | | | | | | |
| Compressive Strength at 1 days | [MPA] | 29,3 | 24,6 | 20,8 | *13,6** | 18,2 | 17,9 |
| Compressive Strength at 7 days | [MPA] | 45,2 | 58,1 | 44,7 | *23,6** | 39,0 | 38,4 |
| **Compressive Strength at 28 days** | [MPA] | 57,5 | 63,3 | 50,4 | ***38,2**** | 52,1 | 48,5 |
| Tensile splitting Strength at 28 days | [MPA] | 4,3 | 4,3 | 4,0 | *2,5** | 3,6 | 3,6 |
| **Water absorption** | [%] | 7,5 | 6,3 | 8,4 | **8,8** | 8,9 | 8,1 |
| Hard dry raw density | [kg/m³] | 2149 | 2191 | 2108 | 2092 | 2058 | 2105 |
| ***Strength results on Mix 3 are not relevent** | | | | | | | |

*Figure 3. Results regarding fresh and hard concrete*

The compressive strength at 28 days is related to the water absorption shown in figure 4. To obtain a water absorption of 6% or 5,5 %, a compressive strength of 70 to 80 MPa must be achieved with 70% of recycled aggregates.

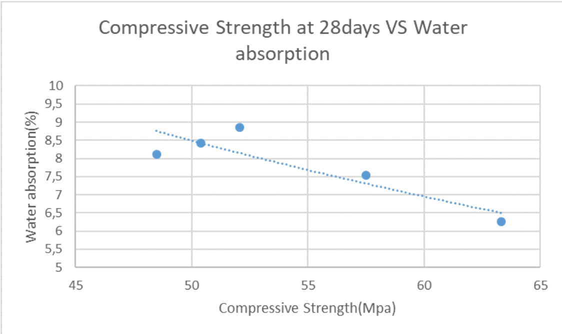


*Figure 3. Results regarding fresh and hard concrete*

Another solution to obtain lower water absorption ratios and ensure the durability of the concrete is to reduce the amount of recycled aggregates. This next step was planned together with University of Kaiserslautern and PREFER for concrete with crushed concrete and mixed aggregates.
The purpose is to have the optimal mix of concrete with a guarantee regarding the concrete durability and using the highest rate of recycled aggregates. Afterwards, this concrete mix will be used at industrial scale to produce the concrete precast products for the pilot project.

### 2.2 Concrete mixes for paving blocks

The design of the dry concrete mix (or earth-moist concrete mix) for the paving blocks in laboratory is challenging because the lab scale and the industrial scale are very different. In the industrial process, the dry concrete is placed in a mould and a hydraulic machine applies a pressure and a vibration on the concrete. After that, the paving blocks are direct demoulded and go to maturation chamber. A hydraulic press allows to produce industrially about 100 to 200 m² of paving blocks per hour. This process is very difficult to implement at laboratory level.

The dry concrete mix studied for the pavement block needs to match all requirements defined in the product standard (EN1338) and University of Kaiserslautern was responsible for the design of the mix. The results in laboratory show that the tensile strength is fulfilled with the design mix. However, the difficulty is to obtain the same conditions in the laboratory that exist at industrial scale.

The main requirements according to the product standards for paving blocks are:

- Water absorption < 6% (annex E - EN 1338) or/ and freeze – thaw cycle < 1,5 kg/m2 (annex D – EN 1338);
- Tensile splitting strength > 3,6 MPa (annex F – EN 1338);

## 3. Paving blocks production

Before producing the paving blocks with the recycled aggregates and cement, set-up tests need to be carried out with normal concrete and to optimize the machine settings.

### 3.1 Set-up tests

Different mixes have been carried out with different proportions of aggregate, sand, cement and amount of water. The concrete is based on a mix of crushed limestone 2/6, crushed limestone 0/2 - 0/4, natural Rhin sand, CEM III 42,5 N LA and water. The machine settings are quite complex with modifications of pre-vibration, final vibration, time of filling, etc.
The first optimum mix for a good direct demoulding and a good aesthetic appearance is :

- Crushed limestone 2/6: 450 kg;
- Crushed limestone 0/2 - 0/4: 1150 kg;
- Sand 0/2: 250 kg;
- Cement: 300 kg;
- W/C = 0,5 – 0,6.

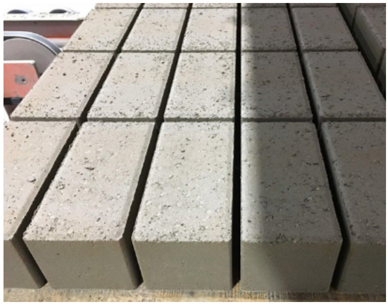

*Figure 5. Paving blocks in natural concrete 21x11x10mm*

If the amount of coarse aggregates (crushed limestone 2/6) is over 800 kg, the top surface is too rough. The aspect of the top surface is linked to the freeze – thaw cycle and to the water absorption and then to the durability of the concrete.

Tensile strength has been carried out on the first optimum mix and the value was below 3,6 MPa. Then, the amount of cement needs to be adapted to achieve the target of 3,6 MPa.

### 3.2 Paving blocks production

After small adaptations of the concrete mixes, the final mix for the pavement is:

- Crushed concrete aggregates 2/6 (Tradecowall): 600 kg;
- Natural crushed limestone 0/2 - 0/4: 600 kg;
- Natural sand 0/2: 600 kg;
- Recycled Cement CEM I 52,5 N (Vicat): 300 kg;
- W/C = 0,5 – 0,6.

The amount of crushed concrete aggregates is 33% of the whole amount of aggregates including sand.
Paving blocks 22x11x7 cm and 11x11x7 cm have been produced with recycled aggregate 2/6 from Tradecowall and with natural crushed limestone

2/6 to see the influence of the recycled material on the properties of the pavement.

*Figure 6. Paving blocks with recycled aggregates after demoulding*

*Figure 7. Paving blocks with recycled aggregates after demoulding*

### 3.3 Test on paving blocks

Paving blocks have been sampled to provide various tests as the tensile strength, the water absorption and freeze-thaw tests.

The first results of tensile strength are shown in table 1 but more samples will be tested at University of Liège to confirm those results.

*Table 1. Results of tensile strength*

| Paving blocks | Amount of recycled aggregates | Hard density [kg/m³] | Tensile splitting strength [MPA] |
|---|---|---|---|
| Natural | 0% | 2350 | 4,79 |
| Recycled | 33% | 2205 | 3,08 |

The hard density of the concrete is lower with recycled aggregates and the tensile splitting strength is also about 30% lower. According to EN1338, the tensile splitting strength is fulfilled (>3,6 MPa) with the natural concrete and closed with the recycled concrete. The 33% of recycled aggregates have an important influence on the hard density and the strength of the concrete.

The paving blocks (3000 pc of 11x11x7 cm and 4000 pc of 22x11x7 cm) will be sent to the pilot project at Saarlouis in Germany and to Seraing in Belgium. The pavements will not be used for road pavement.

## 4. Conclusion

A lot of possibilities exist with recycled aggregate and cement to achieve a sufficient compressive and tensile strength. The difficulty is to ensure the durability of the concrete put in outside conditions. However, concrete for interiors represents the easiest opportunity in a limited market. Durability tests need to be realized on further concrete mixes.

In a circular economy, all industrial producers do not need to use 100% of recycled aggregates. The rate will depend on the availability of the raw material and the transport costs. The situation will be different from big cities to country sides and between countries. The SeRaMCo project is a first step to promote the reuse of recycled raw material.

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# Precast Walls and Slabs produced with Recycled Concrete

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**Abstract**

Although norms and standards as wells sound ecological impacts exist, little contribution is found toady in Germany with respect to structural concrete using recycled aggregates and crushed sand. Beton-Betz, a member of Sy-spro-Quality Group, is a main partner of the European fund project SeRaM-Co. Based on certain crushing technologies and related concrete mix design all information was obtained to start the application of a building permit in order to realize a first building project.

Long term aspects and the assembly stage deformations of the precast constructions were considered.

**Keywords**

Recycled concrete, load bearing structures, building permit

**Kurzfassung**

Trotz normativer Grundlagen und ökologischer Anreize wird Recyclingbeton in Deutschland noch immer nur in geringem Umfang eingesetzt. Sy-spro-Mitglied Beton-Betz ist Partner im EU-Projekt SeRaMCo und startete ein Referenzprojekt. Spezielle Grundlage zur Brechtechnik und Betontechnologie wurden benötigt, um eine Bauzulassung zu beantragen. Dabei spielten auch die Gebrauchstauglichkeit der geplanten Betonfertigteile und deren Bauzustand eine Rolle.

**Schlüsselwörter**
Recyclingbeton, Tragwerke, Baugenehmigung

**Résumé**
Bien que des normes et standards ainsi que des impacts écologiques sains existent, peu de contributions sont trouvées aujourd'hui en Allemagne en ce qui concerne le béton de structure utilisant des granulats recyclés et du sable concassé. Beton-Betz, membre du groupe Syspro-Quality, est l'un des principaux partenaires du projet de fonds européen SeRaMCo. Sur la base de certaines technologies de concassage et de la conception du mélange de béton connexe, toutes les informations ont été obtenues pour commencer la demande d'un permis de construire afin de réaliser un premier projet de construction.
Les aspects à long terme et les déformations au stade de l'assemblage des constructions préfabriquées ont été pris en compte.

**Mots-clés**
béton recyclé, structures porteuses de charge, permis de construire

## 1. Introduction

Recycled concrete (R-concrete) is still being produced only to a small extent for load-bearing components, although respective building codes exist for quite a long time, and ecological incentives are given. Precast concrete plants have not yet adapted their product range to this portfolio. Accordingly, this article provides an overview of the challenges faced by German precast plants in the implementation of R-concrete and describes how recycled concrete may be used in structural elements.

## 2. Market development

Already in the year 2000, the artist Friedensreich Hundertwasser created the „Waldspirale“ in Darmstadt - a promising building with R-concrete. It contained only a quite low proportion of recycled aggregates. Further projects in the following years had, with a few exceptions, a volume of less than 1,000 m³, which did not noticeably increase the share of R-concrete in Germany. Major projects that have become public between 2016 and 2018 are Humboldt University Research building in Berlin, District building in Ludwigsburg, Leonardo-da-Vinci-Gymnasium in Berlin-Buckow and Technical Town Hall in Tübingen. This reticence of the parties involved is quite different in some of our neighboring countries. There, the awareness of the material and the trust in it are much more clearly pronounced. In Switzerland, for example, the use of recycled concrete is no longer labelled separately. A share of at least 15% in public works shall contribute to the use of recycled concrete in building construction, even with content of broken masonry. Current funding measures, for example for the EU funded project „Secondary Raw Materials for Concrete Precast Products“ (SeRaMCo), represent the starting point here and offer a knowledge platform of international exchange with the aim of carrying out further reference buildings. Within the SeRaMCo project, SysPro member Beton-Betz is one of the main partners who focuses on obtaining the necessary building permits for load-bearing components in Germany.

## 3. Crushing technology

In the SeRaMCo project, best practice is an essential point. In a first step, Beton-Betz decided to focus on its own concrete residues, which are usually either generated in the production process or result from misalignments from clients changes in the planning stage. Collected over years, more than 2,000 tons were produced here. This quantity would yield over 2,000 m³ of R-concrete after recycling. A challenge! For the practical application, Beton-Betz gathered the appropriate know-how via SeRaMCo. The first focus was on crushing technology. SeRaMCo adapted specifications for gentle processes and economic procedures, and the latter have been used as a basis when awarding the contract for crushing work. Concrete remains from our own production can therefore be reused with a mobile jaw crusher and a treatment plant with three decks for the 0/2, 2/16 and 16/50 mm fractions. The sand and grain fractions thus obtained are stored on the company premises and can be integrated into the production process.

*Figure 1. Mobile crushing unit used at Beton-Betz*

The main hurdles in breaking/crushing are dust and noise; therefore, early coordination with the monitoring authority (for industrial plants in accordance with the Federal Emission Control Act) is mandatory. After all, the process takes about two weeks including the pre-crushing and extraction of steel parts with approx. 30 tons/hour, which is significantly slower than the crushing process itself with over 300 tons/hour. This effort is not uneconomical.

The real result was not surprising either: the approximately 2,000 tons of material resulted in about 50% of the total of crushed sand.

*Figure 2. Overview of the grain fractions obtained after processing*

## 4. Normative principals for R-concrete and properties

The Directive of the German Committee for Reinforced Concrete (DAfStb) „Concrete according to DIN EN 206-1 and DIN 1045-2 with recycled coarse aggregate in accordance with DIN EN 12620“ applies to the pure use of recycled coarse aggregate > 2 mm. Two types (i.e. 1 and 2) up to a grade of C30/37 are included. As to Beton-Betz, the resulting aggregate may be classified in type 1 according to the DAfStb Directive. Type 1 must have at least 90% concrete, mortar, concrete bricks and a maximum of 10% masonry bricks, limestone bricks, porous concrete. Furthermore, the alkali directive has to be considered.

Within the scope of the class WF according to alkali directive concretes up to exposure class XC4 and XF1 as well as concretes with high water penetration resistance in accordance with DIN 1045-2, section 5.5.3, may be used. This makes it available for the usual floor and wall components of residential and commercial construction, provided that the proportion of the surcharge is limited to 35 vol.%. As the origin of the recycled aggregate is known, the aggregate contained in the old concrete can clearly be assigned to a harmless alkali sensitivity class. The manufacturer must prove to the user the safe origin regarding the alkali sensitivity class and document it in writing. This shall be verified by the relevant building authorities.

The proof of conformity must be based on the so-called system 2+ in compliance with the requirements set out in Table U.1 of DIN 1045-2: 2008-08 for all aggregate groups used. Therefore, an external supervision for aggregate properties must be settled.

**a) Coarse aggregates**

For the natural aggregates the use of aggregates in accordance with DIN EN 12620, is fundamentally required. The material composition of the recycled aggregates > 2 mm must comply with the requirements of Table 1 of DIN EN 12620:2008-07, Section 5.8.

According to Table 2 in Section 5.8, there are some essential properties to be checked, e.g. grain shape, shell content, fine parts of coarse aggregate and tolerance of bulk density.

As to 3/16 mm the tests on bulk density yielded 2.36 kg/dm³ found what is below the natural material at 2.56 kg/dm³ for 2/8 and 2.64 kg/dm³ for 8/16. The test subjected to frost resistance according to DIN 1367-1 showed the classification into category F4.

**b) Fines**

The testing of the properties of the fines is carried out analogously to DIN EN 12620 for coarse aggregates. The bulk grain density was set at 2.30 kg/dm³ which is well below the natural material at 2.63 kg/dm³. As the German standards to do not include testing of frost and de-icing salt resistance a foreign lab must be consulted to obtain those properties according to Swiss standard SIA 262/1: 2013, i.e. SN 505 262/1, app. C. The reduction was similar to a. m. values in the region of 10%.

**c) Concrete properties, concrete technology, supervision**

The tests according to the DAfStb Directive, in addition to those of DIN EN 206-1 and those of DIN 1045-2 referred to properties of fresh and hardened concrete. As to series production, a special productional concept was required, namely the determination of the added water depending on the

moisture of the aggregate, taking into account the water absorption in relation to the desired water cement value.
Also, the following is in addition to normal concrete production:

- Extended initial tests with changes in consistency, increase of the consistency value according to the dosing chart, moisture content of the coarse aggregate (core moisture and surface moisture)
- Production control per production week with regard to bulk density, water content, water absorption, air content and compression.

The following further tests are recommended by the expert as part of the extended initial research: Tensile splitting strength according to DIN EN 12390-6, Modulus of elasticity according to DIN EN 12390-13, Concrete to detect the frost resistance of the recycled coarse and Water penetration depth according to DIN EN 12390-8.
The important properties of the R-concrete according to the DAfStb directive, correspond essentially to those of normal concrete. If crushed sand is additionally used, then the processability requires an increased cement content. Even with a small proportion of fines, the concrete properties deviate from the normative numerical values, in particular the modulus of elasticity as well as creeping and shrinking effects. The following trend has been observed for early age strength at 3 days, which is important for precast members (in this case C25/30): Normal concrete (initial mix, w/z = 0.58, 280 kg cement): ßc,cube,3d = 34.5 MPa. This value was also obtained for R-concrete without crushed sand: R-concrete (additionally 10% crushed sand , w/z = 0.60, 310 kg cement): ßc,cube,3d = 21.2 MPa
Reducing the crushing sand to 5% resulted in a 3-day strength that was only 10% below the strength of the normal concrete. The 28-day strength was then 40.1 MPa and was thus just under 10% below the normal concrete (initial mix) with 44.5 MPa. For the water penetration depth, the R-concrete had a depth of penetration about 10% lower due to the increased fine parts.
Note: Due to the increased water demand for the fines (30% coarse plus fines) the cement quantity was increased by 30 kilograms to maintain the

water-cement ratio. This may be bypassed if an innovative concept is adopted, e.g. additional cement replacement can be bypassed by coal fly ash and limestone flour as well as use of modern plasticizers. This avoids a negative impact on the life cycle assessment. The E-modulus is reduced from 32,000 MPa for normal concrete (initial mix) to 29,100 MPa. According to EC2, the design value is Ecm = 31,000 MPa; the initial mix thus barely reaches the strength class C30/37 with Ecm = 33,000 MPa, wherein the R-concrete as C16/20 is assigned. The structural planner has to take this influence into account. In this case, there also may be larger values for the props after assembly floor slabs.

**d) Long term and service stage performance**

Accordingly, Beton-Betz performed various tests on structural members to verify load-deflection behavior, creep and shrinkage. In autumn 2017, floor slabs components were made of recycled concrete (30% crushed gravel and 10 % crushed sand) and subjected to climatic loading on the Beton-Betz storage site to show the shrinkage influences. After the second winter, there were no significant differences to normal concrete at the bottom of the slab panel.

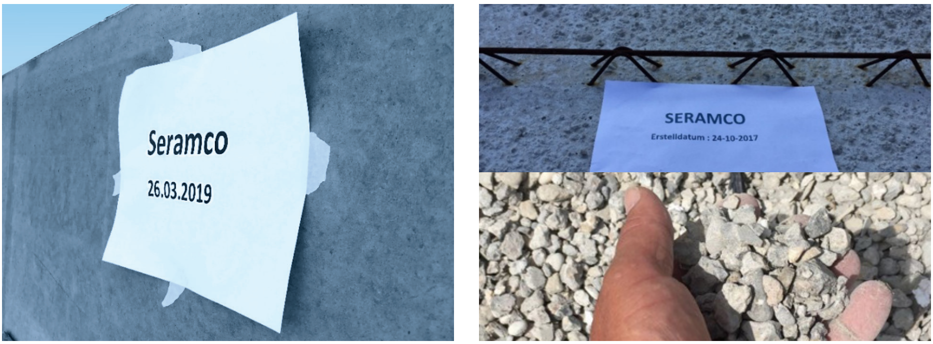


*Figure 3. No cracks at bottom of slab (left), Crushed gravel including plastic residues from embedded items (top), Proper roughness (bond) of concrete layers (bottom)*

However, an important task for future series production is to control the aggregates after recycling with regard to the residues from small rebar or wires. Also, the crushing process will shredder e-pipes and spacers and other built-in parts, which might float upwards when compacting the fresh concrete. Simplified creeping tests were started in spring of 2019. Tests were performed by using floor panel components, i.e. 18 cm thick hollow core slabs (double wall with 7 cm shells without core concrete). In order to show a comparison normal concrete C25/30 and R-concrete specimen 30% coarse plus 10% crushed sand have been investigated. Various preloads were carried out with steel coils and after that a 5 kN load as a long term test was applied in April of 2019. As a result of this permanent load, a steel tension stress of 250 MPa was generated, i.e. about the full load level was reached. The computational concrete compressive stress was 8 MPa. Due to the lower E-module and the lower tensile strength, an initial deflection of 22 mm was measured, which is significantly above normal concrete (12 mm). After 15 weeks, the deformations for both slab types had doubled.

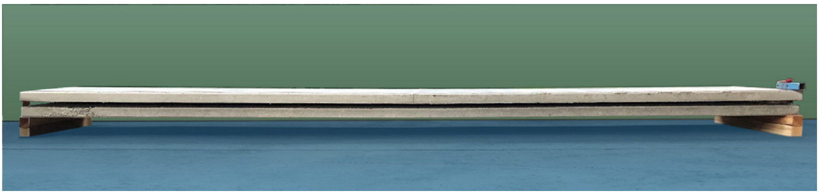

*Figure 4. Test setup as a single span (5,4 m)*


*Figure 5. Deflection at mid-span after 7 weeks*

There is therefore no relevant effect on creep in comparison to normal concrete.
However, the structural design must determine the proper deflection according to EC2, what means in the cracked stage, by using the actual material properties, which will be higher than with normal concrete.

## 5. Building permit

The building authority in Tübingen is responsible for the supply area of Beton-Betz, and has already approved some projects with R-concrete. In addition to the usual documents such as execution drawings and structural calculations, expert approvals were required about the concrete technology and the EC2 design, although the first project concerns a simple residential building. In that case, exterior and interior walls with 20 cm thickness and 18 cm thick slabs are to be used. Concrete components produced using recycled aggregates in accordance with the DafStb Directive may be dimensioned following EC2, i.e. DIN EN 1992 1. The design of the limit state of load-bearing capacity, the design rules for the anchoring lengths and the limitation of deformations are essential.

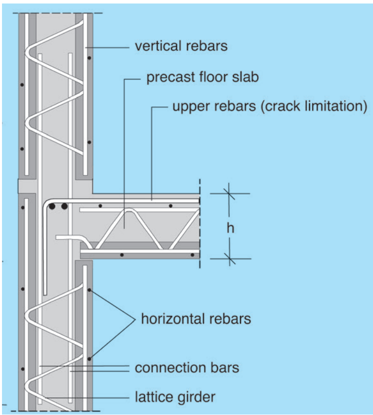


*Figure 6. Wall Section and support of slabs*

**a)** The load-bearing capacity according to section 6.1 of EC2 is not considerably different to normal concrete as the strength properties do not differ significantly
from normal concrete.

**b)** The anchorage lengths respectively the overlaps according to 9.2.1.4 and 9.2.15 of EC2 are of minor importance as the rebars are cut to dimensions and no laps occur within the precast members. Furthermore, the anchorage at supports is limited to the in-situ part of the structures, which is not cast with recycled aggregates. As to the assembly stage of floor slabs, additional props at the support are sufficient to meet the bond properties of R-concrete.

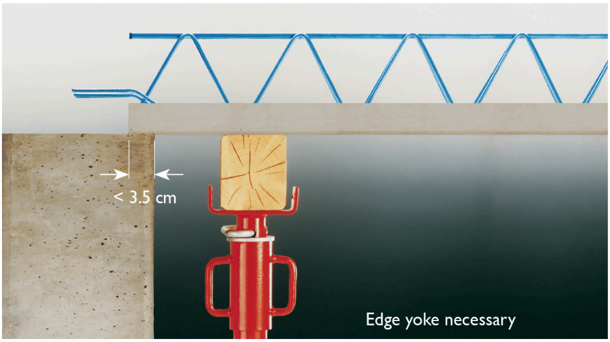


*Figure 7. Additional props at slab support*

**c)** The limitation of deformations relates to the floor slabs (deflections with direct calculation according to section 7.4.3 of EC2). The recalculation of the component test shows an agreement with this calculation method. The coefficient of crack distribution according to equation 7.19, which describes the cracked and uncracked parts of the member, is therefore essential for calculating deflections. The tested slab unit with R-concrete (10% crushed sand) shows cracked range about 40% larger due to the lower tensile strength. The E-modulus is also 10% lower, the double deflection is therefore represented by the theoretical approach according to EC2. Accordingly, the deflection for the reference project reaches 20% higher values. However, the precast floor slabs have a 30% lower deflection than in-situ concrete slabs, so that an upgrade of slab thickness, concrete grade or reinforcements are not required.

However, the design of the assembly stage requires special attention if lattice girder top bar diameters above 10 mm are used. In this case, the assembly stage deflection plays a role. This deflection is limited to 1 cm according to building approvals, whereby the E-modulus of the early age concrete is used. Lying on the safe side, until approval tests are available, the support spans resp props are limited to 80% of normal concrete in this special case.

## 6. Conclusion

In the preparation of a reference project, it was shown that the prefab concrete factory has only little efforts on application of structural members designed with recycled aggregates.
After further reference projects and verification about the service stage design, a general building permit is advantageous to include a comprised testing and supervision procedure which will reduce the additional costs. Environmental aspects of innovative concrete formulations for cement replacement can also be integrated, as R-concrete production is already associated with special aspects. In compliance with the above-mentioned topics, the decision on R-concrete does not have to be made early during the planning phase. There is sufficient time to draw the attention of the parties to the conditions. At present, the costs are not likely to be significantly higher than those of normal concrete. Even with increased costs, the environmental benefits are obvious. In addition to the protection of gravel storage and landfill capacities, transport routes are reduced.

# Recycling End-Of-Life Concrete: An Attempt towards Circular Economy in the Residential Sector

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**Abstract**

The ever-increasing interest on sustainable circular economy practices has urged the need to recycle end-of-life (EoL) concrete into materials that can be used as substitutes for raw materials. This paper demonstrates the feasibility of such practices considering EoL concrete and concrete bricks (masonry) from the Grand-Est (French northeast region) residential sector as a case study. To do so, stock and flows of concrete and concrete bricks were quantified in this sector. These flows are then recycled into recycled concrete aggregates concrete (RA). Then, the ability of these RA to substitute raw materials was quantified in this region. Finally, barriers towards achieving such circular economy practices were listed.

**Keywords**

Concrete, recycling, circular economy, recycled concrete aggregates

**Kurzfassung**

Das ständig wachsende Interesse an nachhaltiger Kreislaufwirtschaftspraktiken hat die Notwendigkeit der Wiederverwertung von Betonabfällen zu Materialien, die als Ersatz für Rohstoffe verwendet werden können, deutlich gemacht. Dieser Aufsatz demonstriert die Machbarkeit solcher Praktiken unter Berücksichtigung von EoL-Beton und Betonmauersteinen aus dem Grand-Est (Nordostregion von Frankreich) - Wohnungssektor als Fallstudie. Dazu wurden die Bestände und Ströme von Beton und Betonmauersteinen in diesem Sektor quantifiziert. Diese Ströme werden dann zu Recycling-Betonzuschlagstoffen (RA) rezykliert. Anschließend wurde die Fähigkeit dieser rezyklierten Materialien, natürliche Materialien zu ersetzen, in dieser Region quantifiziert. Schließlich wurden die Hindernisse für das Erreichen solcher Kreislaufwirtschaftspraktiken aufgeführt.

**Schlüsselwörter**
Beton, Recycling, Kreislaufwirtschaft, rezyklierte Gesteinskörnung aus Beton

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**Résumé**
L'intérêt grandissant d'appliquer les principes d'économie circulaire pour les matériaux a nécessité l'urgence de développer des méthodologies innovantes pour gérer le béton en fin de vie et sa capacité à se substituer aux matériaux naturels. Cet article démontre la faisabilité de ces pratiques pour le cas du béton résidentiel dans la région Grand-Est (Région nord-est de France). Dans cette optique, le stock général, ainsi que les flux annuels du béton et du bloc béton (parpaing) de cette région ont été quantifiés. Ces flux de matériaux en fin de vie sont ensuite transformés en granulats de béton recyclés. Ultérieurement, la capacité de ces matériaux recyclés à se substituer aux matériaux naturels a été quantifiée. L'article résume aussi les différents verrous à l'implémentation de ce genre de pratique d'économie circulaire dans le secteur résidentiel français.

**Mots-clés**
béton, recyclage, économie circulaire, granulats de béton recyclé

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## 1. Introduction

Concrete is the most used material on earth after water. This material's formulation is constantly changing from traditional concrete to 3D printing.

However, its end-of-life (EoL) seems to be ignored. Concrete was doomed to landfill at its EoL until the advent of recycling it into concrete. Since, several studies show the effectiveness of recycling concrete wastes into aggregates and fines [1]. Aggregates are thus obtained by recycling concrete wastes, and they are used as natural aggregates substitution in granular base. These recycled aggregates are known in the literature as recycled concrete aggregates concrete (RA). RA are expected to contribute to solve the problem of natural resources depletion.

The state-of-art is providing a good knowledge of substitution rates of natural aggregates with RA in concrete according to its use phase [2]. This will allow the introduction of circular economy practices and reduce natural materials use. Circular economy practices are in fact leading the way to cradle-to-cradle as sustainable concept to deal with resource depletion and increase the reuse of materials [3]. Besides, reuse of such materials is proven to be environmentally friendly in major cases [4]. From the other hand, several studies deal with quantifying material use and consumption in many sectors. These papers are mainly based on material flow analysis [5]. The literature also quantifies deposit, stock and flows of concrete and concrete based materials.

However, the research's barrier lies in combining material quantifying methods and circular economy practices for the concrete and concrete based materials. In order to deal with this research gap, the objective of this paper is to quantify the concrete in the residential northeast region of France (Grand-Est region). Then, an introduction to circular economy practices based on this stock is presented. To do so, we used in this paper a material flow analysis to quantify all stock and flows of concrete in the residential sector of Grand-Est French region. Then, a framework for achieving circular economy of concrete in this sector is presented. Afterwards, we end up with a series of barriers towards achieving such circular economy practice in the residential sector.

## 2. Analysis method

### 2.1. Material Flow Analysis

The methodology provided in this paper is based on material flow analysis (MFA). It is a well-known concept used for inventory management, stock and flow accounting. It is a bottom-up approach that was used for several systems and processes. In the literature, MFA was used to quantify concrete and concrete based materials in Ireland [6], Norway [7] and the United States [8].

### 2.2. Concrete in the Grand-Est residential sector

We relied on the relevance tree for methodology selection developed by Wu et al. in [9] to quantify concrete of the residential sector in the Grand-Est region. Thus, a classifier of national French data was used in this paper. It regroups data into the following:

- Dwelling type 1: the residential stock was classified into individual and collective stock.
- Dwelling type 2: the dwelling type 1 stock was classified into primary residences, occasional residences, second homes and vacant properties. For the sake of simplicity, we consider here after only primary residences, since they represent 87% of the total residential stock in the Grand-Est region.
- Construction period: the residential segmented stock was sorted into 6 main construction periods; before 1919, from 1919 to 1945, from 1945 to 1970, from 1971 to 1990, from 1991 to 2005 and from 2006 to 2013.
- Concrete rate in the residential stock: Concrete rate contains both single (concrete from construction & demolition flows) and concrete bricks (perpend) rates. We rely mainly on surface area data of the residential stock and the average concrete rate per residence in

each construction period and architecture type (stone, brick, concrete or wood architecture). Table 1 resumes the average concrete weight per square meter in each architecture type for each construction period.

*Table 1. Concrete rate in the Grand-Est residential sector by architecture and construction period types [10] [11]*

| Collective residences | | | Individual residences | | |
|---|---|---|---|---|---|
| Construction period | Architecture type | Concrete (kg/m²) | Construction period | Architecture type | Concrete (kg/m²) |
| Before 1919 | stone dwelling | 0 | Before 1919 | dwelling | 0 |
| Before 1919 | brick dwelling | 0 | 1919-1945 | dwelling | 0 |
| 1919-1945 | stone dwelling | 0 | 1946-1970 | dwelling | 601.1 |
| 1919-1945 | brick dwelling | 1577.9 | 1971-1990 | concrete dwelling | 1024.3 |
| 1946-1790 | dwelling | 1950 | 1971-1990 | brick dwelling | 698.6 |
| 1971-1990 | dwelling | 1628.3 | 1991-2005 | concrete dwelling | 1325.9 |
| 1991-2005 | concrete dwelling | 1966.1 | 1991-2005 | brick dwelling | 1188.5 |
| 1991-2005 | brick dwelling | 1810 | 1991-2005 | wood dwelling | 630.4 |
| 2006-2013 | concrete dwelling | 1966.1 | 2006-2013 | concrete dwelling | 1325.9 |
| 2006-2013 | brick dwelling | 1810 | 2006-2013 | brick dwelling | 1188.5 |
| | | | 2006-2013 | wood | 630.4 |

Consequently, one could generate the in-use stock in the Grand-Est region over the six main periods. Afterwards, French residential market uncertainties and annual residential replacement stock were integrated in order to calculate the annual flow of concrete generated by the replacement stock of residential residences. In last French national institute of statistics and economic studies, data about French annual replacement showed an average replacement rate 2% of the French residential stock, with market uncertainties of 15.4% and 10.7% for collective and individual dwellings, respectively.

### 2.3. End-of-Life of concrete

At its EoL, concrete is sorted on-site or sent to sorting facilities. In France, 88% of this material is sent to recycling facilities to be crushed into RA, whereas the 12% left is sent to landfill. Hazardous or contaminated concrete wastes were excluded from this study. Besides, we rely in this paper on French national reports [10] [11] that outline the mastery of French sorting and logistic processes of construction and demolition wastes. Next, the results of the MFA applied to the Grand-Est residential concrete are presented. Then, locks towards applying circular economy practices for this material in the residential sector are assessed.

## 3. Result and discussion

The total deposit of concrete from construction and demolition wastes from the Grand-Est residential sector was recorded. Thus, more than 196 million tons of concrete were injected in the Grand-Est residential sector in the period before 1919 until late 2013. During the six main periods, this total stock was repartitioned equally between the collective and individual primary residences: 98 million tons and 97 million tons were injected respectively in the collective and individual residences.

### 3.1. Concrete in the inert stock of the residential sector

Inert materials in the residential sector came mainly from stone, concrete, concrete bricks, solid brick, hollow brick, tiles, mortar, mineral plaster, glass, sand and asphalt. When dealing with the total embodied concrete stock in the Grand-Est residential stock, concrete and concrete bricks represent 80% and 43% of the total inert stock embodied in collective and residential stocks, respectively. This inert stock is non-dangerous.

### 3.2. Comparison with other French regions

In order to compare the generated results of concrete wastes annual production with other French regions, we assume that same architecture types and materials were used in the other thirteen French regions

(FR-GES: Grand-Est, FR-OCC: Occitanie, FR-PDL: Pays-de-la-Loire, FR-PACA: Provence-Alpes-Côte d'Azur, FR-ARA: Auvergne-Rhone-Alpes, FR-BFC: Bourgogne-Franche-Comté, FR-IDF: Ile-de-France, FR-CVL: Centre-Val-de-Loire, FR-HDF: Hauts-de-France, FR-NAQ: Nouvelle-Aquitaine, FR-BRE: Bretagne, FR-COR: Corsica, FR-NOR: Normandie). Figure 1 and 2 present these results, where total embodied concrete (Figure 1) and concrete bricks (Figure 2)) flows were generated for the 13 French regions during the six main periods.

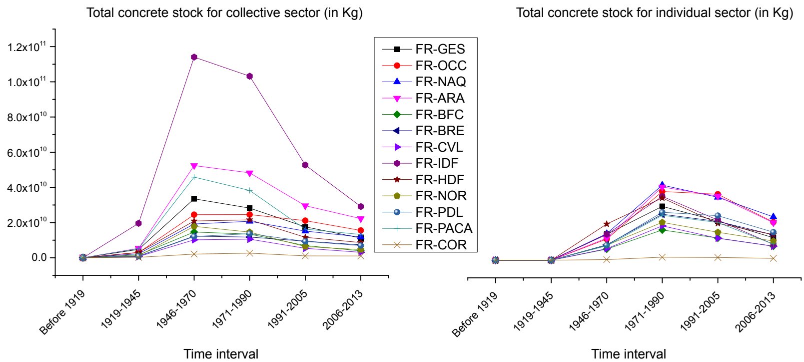


*Figure 1. Chronological concrete flows generated in French regions from collective (left figure) and individual (right figure) dwellings*

As shown in these figures, one could use an MFA for concrete and concrete bricks to assess their average consumption in collective and individual residences per French region. Grand-Est region consumption of concrete and concrete bricks in both dwelling types is on the average rate when compared to other regions' consumption. The upper bound is the Paris region (FR-IDF) and the lower one is Corsica island.

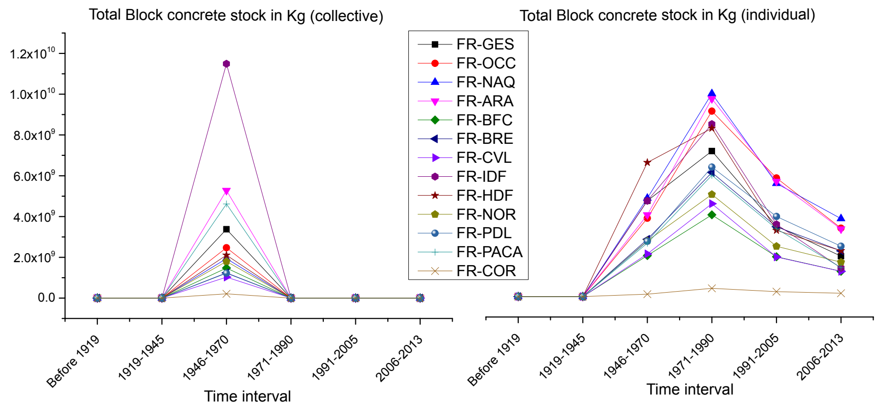


*Figure 2. Chronological concrete bricks (perpend) flows generated in French regions from collective (left figure) and individual (right figure) dwellings*

### 3.3. Towards circular economy practices in the Grand-Est residential sector

Given concrete and concrete bricks regional stock and considering the recyclability of these materials, their annual flows and EoL management can be calculated. Thus, an average of 1.9 million tons of concrete is generated annually from replacement stock, with uncertainties of 0.3 tons and 0.2 tons for collective and individual residences, respectively. Afterwards, the annual recycled concrete is up to 3.4 million tons, generated equally from collective and individual primary residences in the Grand-Est region. The rest is sent to landfill.

Concrete is then sorted and send to recycling facilities when it can be recycled into RA. They have proven to be efficient when used in new concrete as a substitute to natural aggregates. Besides, their environmental impact can compete the natural aggregate's one [4]. As a result, one could rely on this to generate the potential substitution of natural aggregates by RA generated from concrete and concrete bricks. The recent UNICEM report showed that 32.8 million tons of natural aggregates were extracted from the Grand-Est region in 2017. Thanks to the recycling of concrete and concrete bricks from the same region's residential stock, a reduction of 11% of extraction of natural aggregates can be avoided and replaced by RA. This rate can increase up to 19% on the same region if we include other inert materials embodied in the residential sector. The residential sector and its inert materials could enhance the development of RA industry and reduce natural resource depletion in regions. Such practices lead to the development of circular economy in the residential sector. However, several barriers remain in order to move towards a sustainable circular economy. Next section summarizes these barriers.

### 3.4. Barriers towards recycling end-of-life concrete

Recycling concrete is a major step towards achieving circular economy in the residential sector. The following barriers entail improving this sustainable process. These locks are clustered into technological, standard, econological and social. Table 2 resumes these locks. These barriers as well as unraveled opportunities towards achieving circular economy in the residential sector materials are detailed in our last paper [12].

*Table 2. Major locks that entail the use of recycled aggregates [12].*

| Locks | Description |
|---|---|
| Technological | • Better management of on-site sorting. |
| Standard | • Less overdesign in the residential sector<br>• Towards a better inclusion of RA and recycled concrete sand in current standards. |
| Social | • Better broadcast of recycled aggregate concrete use |
| Econological | • Better added-value recycling scenario of residential concrete and concrete bricks. |

## 4. Conclusion

The feasibility of circular economy practices of residential concrete has been studied. The model proposed in this paper can quantify stock and annual flows of concrete and concrete bricks. These materials came from residential buildings in the French Grand-Est region in the period before 1919 until late 2013. A comparison of regional concrete consumption in the French residential stock was performed. This concrete's wastes are then able to be recycled into concrete for the same sector. Reduction of resources depletion as circular economy practice was presented. Afterwards, barriers towards achieving sustainable circular economy were listed.


## Acknowledgements

This work is supported by the SeRaMCo-Interreg Research Fund.


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# Reducing the Environmental Impacts of Recycled Aggregates Concrete

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**Abstract**

This paper aims to assess the environmental impacts of recycled aggregates concrete (RAC) in comparison with concrete with natural aggregates (NA). In order to mitigate the environmental impacts of recycled aggregates (RA) and those of RAC, alternatives are presented and studied; i) optimizing the recycling process and ii) considering the $CO_2$ uptake of RA. Then, the effect of the $CO_2$ uptake on the ecological profitability distance of RA is investigated.

**Keywords**

recycled aggregates, environmental impact, $CO_2$ uptake, concrete

**Kurzfassung**

Dieser Aufsatz zielt darauf ab, die Umweltauswirkungen von Beton mit rezyklierten Gesteinskörnungen (RAC) im Vergleich zu Beton mit natürlichen Gesteinskörnungen (NA) zu vergleichen. Um die Umweltauswirkungen von rezyklierten Gesteinskörnungen (RA) und die von RAC zu mindern, werden Alternativen vorgestellt und untersucht: i) Optimierung des Recyclingprozesses und ii) Berücksichtigung der $CO_2$-Aufnahme von RA. Anschließend wird die Auswirkung der $CO_2$-Aufnahme auf den ökologischen Wirtschaftlichkeitsabstand von RA untersucht.

**Schlüsselwörter**
Rezyklierte Gesteinskörnung, Umweltauswirkungen, $CO_2$ Aufnahme, Beton

**Résumé**
L'objectif de cet article est d'évaluer les impacts environnementaux du béton aux granulats recyclé en comparaison avec un béton aux granulats naturels. Ainsi, dans une démarche de réduction des impacts environnementaux de ces granulats recyclés, des alternatives sont présentées et étudiées ; i) optimiser le processus du recyclage du béton, ii) considérer l'effet de l'absorption du $CO_2$ par les granulats recyclés. Ensuite, l'effet de cette absorption sur la distance de rentabilité écologique a été évalué.

**Mots-clés**
granulats de béton recyclé, impact environnemental, absorption du $CO_2$, béton

## 1. Introduction

There is no deny that recycled concrete aggregates (RA) are playing an important role in reducing natural resource depletion. Utilization of RA in concrete decreases its durability and mechanical properties. Yet we can compensate this decrease of properties by the increase of cement content, but it increases the environmental impacts of the recycled aggregates concrete (RAC). We have addressed in our previous paper [1] the environmental impacts of RAC and how it is ecologically effective to use RA if the NA procurement distance exceeds 50 km. This paper investigates other alternatives to reduce the environmental impacts of RA and those of recycled concrete. The alternatives are: i) optimize the recycling process of RA production, and ii) consider the $CO_2$ uptake of RA. Then, the effect of the $CO_2$ uptake on the ecological profitability distance of RA is investigated.

## 2. Life cycle assessment of RA: from concrete to recycled aggregates

### 2.1. System description and boundaries

For the purpose of this study, a functional unit of "manufacture 1 m³ of concrete class C30/37" was considered. The studied concrete is supposed to have a compressive strength of 30 MPa at 28 days. When introducing RA in the concrete mix, different water cement ratios were considered in order to maintain the suitable compressive strength. The formulas of the studied concrete mixes with different water and cement contents are detailed in our previous paper [1]. Boundaries fixed in this paper are limited to the production of the concrete constituents, their transport and the production of recycled concrete. The boundaries and processes included in this paper are presented in Figure 1.

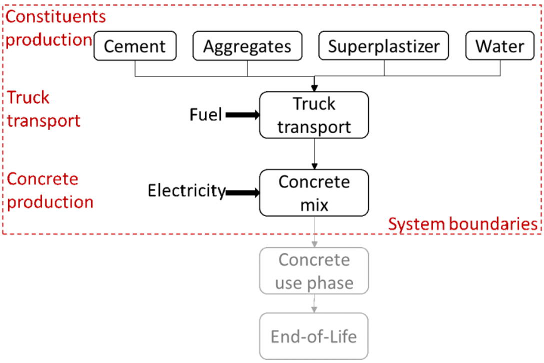


*Figure 1. Boundaries of the studied system*

Afterwards, Simapro program and Ecoinvent 2.2 (2010) database were used to perform the environmental analysis of the studied system. Input data collected from literature as well as from recycling platform were used [2]. Besides, we rely on the Mat France V2.05 method based on the standard NF P01-010 to evaluate the different categories of impacts [3].
The production process of recycled aggregates was also assessed in this

paper. Figure 2 displays the process of recycled aggregates production. As showed in this figure, wastes from end-of-life concrete are transported to recycling facilities. Afterwards, concrete blocks are crushed, grinded and separated from ferrous wastes in the overband step. These steps can also be preceded by visual inspection in order to sort undesired wastes. Lightweight materials are sorted in the flotation and washing steps. Then, a second grinding to reduce concrete agglomerate and a sieving process are required to get final recycled aggregates. RA are then stored. As for wastes collected from the recycling process (W1 and W2), they are either transported to specific plant (for ferrous wastes) or landfilled (for other wastes).

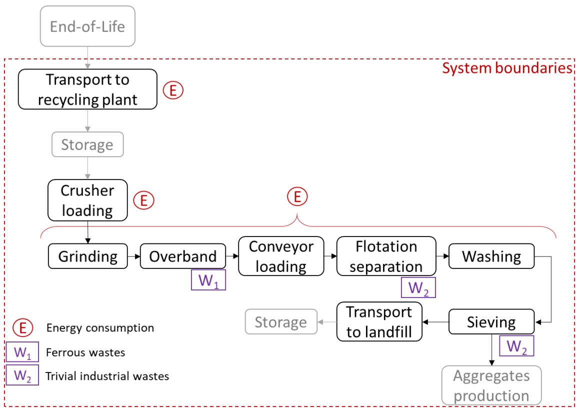


*Figure 2. Recycled aggregates production process and the system boundaries selected in this paper*

For the sake of this study, three recycled aggregates concrete were tested: RA_1, RA_2 and RA_3. The former are Rcu70 with bituminous materials, the second are at least Rcu95 and stem from concrete blocks with different origins. The latter are high quality aggregates [1]. Afterwards, distances used in this LCA are presented in Table 1. As presented in this table, cement distance corresponds to the average distances between concrete and cement plants in the Paris' region.

*Table 1. Distances considered in this paper*

| Material | Distance (Km) |
|---|---|
| Cement | 24 |
| NA | 22 |
| RA | 15 |

## 2.2. LCA results

Results were generated for the functional unit of concrete with the three considered recycled aggregates concrete (RA_1, RA_2 and RA_3) and with different RA content (0, 20, 50 and 100 %). The environmental impacts were compared to those of conventional C30/37 concrete with NA and RA. Figure 3 summarizes these results. Histograms are the contribution of the studied concrete formulas in the total of each studied indicator. As showed in this figure, 'waste' is the most sensitive indicator to the presence of RA in the concrete mix. 'Water usage' indicator is inversely proportional to the RA substitution rate in the concrete mix. The higher the substitution rate, the lower the water usage. This is mainly due to the high share of water usage in NA production compared to RA [1]. Afterwards, 'global warming' impact is higher when RA substitution is higher as well. Indeed, while the recycling process of the three RA is the same in the three platforms considered in this paper [1], concrete with high substitution of NA by RA requires more cement to achieve the C30 strength. This additional cement increases negatively the global warming indicator, which implied that the intensity of this indicator in recycled concrete is more related to cement production.

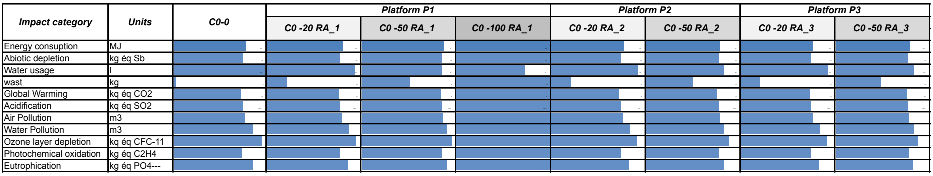


*Figure 3. Environmental impacts of 1 m3 of C30 concrete with 0, 20, 50 and 100% NA substitution by RA_1 and 0, 20 and 50% substitution of NA by RA_2 and RA_3. C0_0 is the reference (conventional) concrete*

However, different alternatives can improve the environmental impacts of recycled concrete aggregates and thus of recycled concrete. Next section discusses this matter.

## 3. Ways to reduce the environmental impacts of recycled concrete

There are several ways to reduce the environmental impacts of RA. Reducing these impacts can be achieved by optimizing the recycling process of construction & demolition wastes and by considering the $CO_2$ uptake of RA. Then, the effect of the $CO_2$ uptake on the ecological profitability distance of RA is investigated.

### 3.1. Optimization of the recycling process of RA production

Previous results showed that the production process of RA have in general greater impacts than NA. However, these impacts could be mitigated if the recycling process is optimized. Indeed, one could optimize the energy use of the recycling process. This could be also achieved by using renewable energy in this process. Another way of reducing the environmental impact of RA is to reduce waste landfill and generation from the recycling process. This waste impact category is one of the highest for RA impact categories. While different types of wastes (hazardous, non-hazardous, inert, radioactive) are

regrouped in this impact category, results show that inert waste constitute 99% of the total wastes quantified from the recycling process of RA.
Besides, the current paper does not consider any recovering scenario for these wastes, which lead to their landfill. Thus, considering a recycling scenario for these inert wastes could significantly decrease the total environmental impacts of RA. Studies that harvest this way showed that the environmental impacts of RA decrease when sludge from the recycling process is recycled. Other studies showed similar mitigated impacts 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 [1] [4].

### 3.2. $CO_2$ uptake of RA

The carbonation and $CO_2$ uptake of RA and recycled concrete have gained interest as a way of reducing the environmental impacts of concrete. Jang et al. in [5] estimated that the $CO_2$ uptake of cement-based material could be up to 0.05 ton $CO_2$/ton material. Thus, when considering this assumption, waste and global warming indicators are reshaped as presented in Figure 4, where impacts of RA and NA are presented without (left figure) and with (right figure) the consideration of Carbone dioxide uptake. For the sake of this study, trivial industrial wastes from Figure 2 were also recovered.

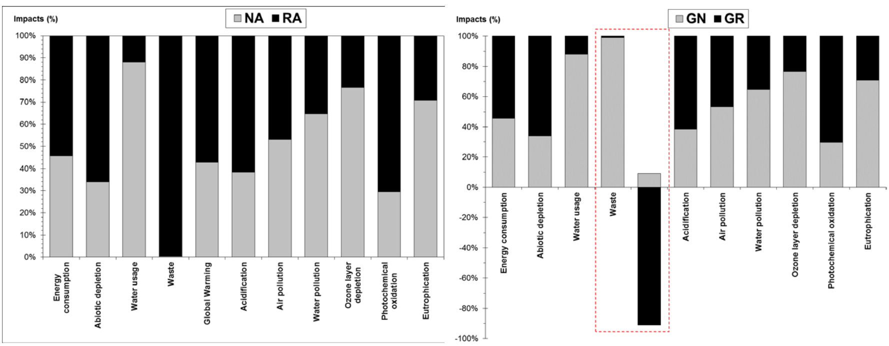


*Figure 4. Environmental impacts from the production of one ton of NA and RA with (right figure) and without (left) considering the valorization of wastes and the uptake of $CO_2$*

Afterwards, the uptake of CO2 also affects the ecological profitability distance. Thus, when considering this uptake, it will be always ecologically profitable to use RA instead of NA.

### 3.3. Optimal distance of RA and NA delivery

Previous studies showed that without considering the delivery distance, the environmental impacts of RA based concrete are higher than conventional concrete [1]. It is then necessary to consider the delivery distances to assess the environmental impacts of RA and NA. Our last paper deals with this issue and calculated the ecological profitability distance for the studied recycled aggregates for the Paris region [1]. Figure 5 resumes these results, where the routing distances of NA were varied from 22 to 250 km, whereas the RA distance was fixed. As a result, the NA use is more ecologically profitable for small delivery distances such as 22 km. However, after a mean distance of 50 km, the use of RA is more advantageous from an environmental point of view.

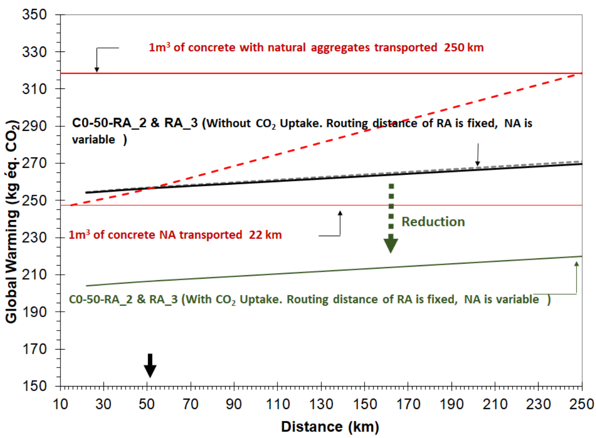


*Figure 5. Ecological profitability distance for RA containing 50% of RA_1, 2 or 3*

These previous statements were made without considering the uptake of $CO_2$ by RA. In case of this uptake consideration, the green curve in Figure 5 shows that it is always ecologically profitable to use RA in concrete.

## 4. Conclusion

This paper compares the environmental impacts of RA and NA. The environmental impacts of concrete with RA were also assessed. Then, alternatives for reducing the environmental impacts of RA were presented in this paper; i) optimizing the recycling process, ii) considering the carbonation and $CO_2$ uptake. Then, the effect of the $CO_2$ uptake on the ecological profitability distance of RA is investigated. The following recommendations can be drawn in order to mitigate the environmental impacts of RA:

- Optimizing the energy consumption of the recycling process of RA helps decrease this indicator for recycled aggregates and thus for recycled concrete.
- Valorization alternatives for the RA by-product recycling process could significantly decrease the waste impact indicator of RA.
- Delivery distances of RA and NA are parameters that influence the environmental impacts of RA and thus of concrete. It is then necessary to consider the ecologically profitable distance for aggregates. As presented in this paper, it is more ecologically profitable to use RA rather than NA in the Paris' region when the delivery distance of NA exceeds 50 km.
- When considering the carbonation effect of RA and concrete, optimal delivery distance of NA become obsolete and RA significantly reduce the environmental impacts of recycled concrete.

To summarize, these alternatives could reduce the environmental impacts of recycled concrete aggregates and thus of recycled concrete. They are however closely linked to the studied system and its boundaries. It is then necessary to conduct a project-by-project analysis in order to select the most optimal alternative or set of alternatives to mitigate the environmental impacts of recycled aggregates.

## Acknowledgements

This work is supported by the SeRaMCo-Interreg Research Fund.

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# SeRaMCo
# Circular Business Models - a Stepwise Approach


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**Abstract**

Higher efficiency of raw building materials increases the sustainability of construction projects.  With sand and aggregates becoming scarcer in certain regions of North-West Europe, their replacement by recycled construction and demolition waste (CDW) is a way out of this dilemma, coupled with benefits for the environment. However, innovative circular business models are needed to make the uptake of the related new technologies lucrative for construction businesses.

Our two short-term business models suppose that the origin of CDW is known, that it is homogeneous and available on-site. This is the case firstly for very big construction projects in European urban environments where old buildings and sites are mostly replaced by constructions of similar size and big quantities of CDW can be processed for reuse in new concrete to mix on-site. In our second business model the remains from concrete precast production are reused in the production process. For the mid-term, we propose a business model where all stakeholders and sites are all geographically close, and their demand and supply are reconciled.

For the long-term, we envisage that a fully integrated business model prevails which is supported by tax or state incentives, favourable regulations and digital tools against the background of scarce raw materials and heftier climate change.

**Keywords**
Circular Business Models, Material Efficiency, Recycled Construction and Demolition Waste, Recycled Concrete, Concrete Precast

**Kurzfassung**
Eine höhere Rohstoffeffizienz erhöht die Nachhaltigkeit von Bauprojekten. Da Sand und Zuschlagstoffe in bestimmten Regionen Nordwesteuropas immer knapper werden, ist ihr Ersatz durch rezyklierte Bau- und Abbruchabfälle (CDW) ein Ausweg aus diesem Dilemma, verbunden mit Vorteilen für die Umwelt. Allerdings sind innovative, zirkuläre Geschäftsmodelle erforderlich, um die Einführung der damit verbundenen neuen Technologien für die Bauunternehmen lukrativ zu machen.
Unsere beiden kurzfristig umsetzbaren Geschäftsmodelle setzen voraus, dass die Herkunft der Bauabfälle bekannt ist, dass sie homogen und vor Ort verfügbar sind. Dies ist erstens bei sehr großen Bauprojekten in europäischen Städten der Fall, bei denen alte Gebäude und Standorte meist durch Bauten ähnlicher Größe ersetzt werden und große Mengen an Bauabfällen in neuem Ortbeton wiederverwertet werden können. In unserem zweiten Geschäftsmodell werden die Reste und Fehlprodukte aus der Betonfertigteilproduktion im Produktionsprozess wiederverwendet. Mittelfristig schlagen wir ein Geschäftsmodell vor, bei dem alle Beteiligten und Standorte geografisch nahe beieinander liegen und Nachfrage und Angebot miteinander in Einklang gebracht werden.
Langfristig sehen wir ein vollständig integriertes Geschäftsmodell vor, das sich mit Hilfe steuerlicher oder staatlicher Anreize, entsprechender Normen und Gesetze und digitaler Werkzeuge vor dem Hintergrund knapper Rohstoffe und heftigeren Klimawandels durchsetzt.

**Schlüsselwörter**
Geschäftsmodelle für die Kreislaufwirtschaft, Materialeffizienz, rezyklierte Bau- und Abbruchabfälle, Recycling-Beton, Betonfertigteile

**Résumé**
Une meilleure efficacité des matériaux de construction augmente la durabilité des projets de construction. Le sable et les agrégats se faisant de plus en plus rares dans certaines régions du nord-ouest de l'Europe, leur remplacement par des déchets de construction et de démolition recyclés est un moyen durable de sortir de ce dilemme. Ce procédé s'avère bénéfique pour l'environnement. Toutefois, des modèles opérationnels circulaires innovants sont nécessaires pour rendre l'adoption de nouvelles technologies avantageuse pour les entreprises du bâtiment.
Nos deux modèles opérationnels à court terme supposent que l'origine des déchets de construction et de démolition soit connue, qu'ils soient homogènes et disponibles sur place. C'est d'abord le cas dans de très grands projets de construction situés en environnement urbain. Les anciens bâtiments et sites sont, pour la plupart, remplacés par des constructions de taille similaire. De plus de grandes quantités de déchets de construction peuvent être traitées pour être réutilisées dans un nouveau béton mélangé sur site. Dans notre deuxième modèle opérationnel, les restes de la production de béton préfabriqué sont réutilisés dans le processus de production. Sur le moyen terme, nous proposons un modèle opérationnel dans lequel toutes les parties prenantes et tous les sites sont géographiquement proches, et où l'offre et la demande sont conciliées.
À long terme, nous envisageons un modèle opérationnel totalement intégré, soutenu par des mesures fiscales ou des aides de l'État, des réglementations favorables et des outils numériques, dans un contexte de pénurie de matières premières et de changement climatique plus marqué.

**Mots-clés**
Modèles opérationnels circulaires, efficacité des matériaux, déchets de construction et de démolition recyclés, béton recyclé, béton préfabriqué

## 1. Introduction

Economic growth makes the construction sector flourish. However, the building sector is the most resource-intensive industry. It uses half of all primary raw materials extracted leading to a huge irreversible negative impact on our environment and scarcity of primary raw materials. Hence, there is an urgent need for innovative business models and circular thinking.

The EU-funded INTERREG project SeRaMCo (Secondary Raw Materials for Concrete Precast Products) aims at reducing the use of primary raw materials in construction projects, and thereby protecting natural resources in North-West Europe. SeRaMCo shall bring higher resource-efficiency to mineral construction materials and in this way contribute to a future circular economy where materials are used again and again.
Mineral construction and demolition waste being composed of mixed rubble of concrete, bricks, tiles and ceramics shall substitute primary raw materials, i.e. sands and gravels, to a large extent. In an emerging market SeRaMCo shall showcase that innovative concrete precast products (CPPs) incorporating recycled aggregates are technically feasible, safe, eco-friendly and in sum do not cost more than those manufactured with primary raw materials. What does this imply for the business environment of recyclers, cement and CPP producers, and contractors in construction projects? How has the business environment to evolve in order to fit with SeRaMCo-like practices of CDW reuse in CPPs? We choose a stepwise approach over time including business models and a SWOT analysis (Strengths-Weaknesses-Opportunities and Threats) for the short and mid-term. In addition, we define enabling conditions for their implementation such as the geographical proximity of business partners, knowledge about the origin of CDW, and the relation of supply to demand of secondary raw materials.

## 2. Status quo

### 2.1. Circular CPPs - an emerging market

In 2015, the European precast industry generated more than €24 billion of revenue [1]. These figures - since they are usually coupled with the economic trends - will have surpassed in the last years. Should circular CPPs take 5% of the market share they would represent a total of more than €1,2 billion per year. With a market share of 20% revenues of €4,8 billion could be generated annually.

Yet, a break-through of new circular products and processes into the construction market has still not happened at a larger economic scale due to the relatively low price of primary raw materials and products, persistent norms and habits, inadequate pricing of environmental use, and a lack of environmental laws and regulations.

Governments can accelerate the transition to a circular economy by giving incentives to businesses to invest into promising new technologies and by including sustainability requirements for secondary raw materials in their public tenders. Without these measurements, a drastically reduced use of primary raw materials will be difficult to achieve within the next years.

In our current economic system, the prevalent business practice and models focus on economic short-term profitability alone, and do not consider environmental or social impacts. The construction sector in North-West Europe operates in a particularly competitive and challenging yet conservative environment with many stakeholders involved in the value chain which makes more complex innovative processes difficult to implement, especially when they are not financially supported.

### 2.2. The stakeholders' view

Circular business models shall enable the business partners in the value chain to successfully commercialize SeRaMCo's research results. In other words, to make a lucrative business out of CPPs made from recycled CDW.

Environmental gains and social benefits should also result from their implementation.
The SeRaMCo project partners and, more broadly spoken, the diverse stakeholders in the construction industry look at this challenge from different perspectives:

**Recycling companies** want the cost of processing CDW to be lower than the sum of the price they can charge when accepting CDW added by its output value as a commodity for the construction industry; In particular, why should they invest into high-quality recycling if down-cycling for road construction is already a profitable business and the demand for this type of output material remains stable?
**CPP, cement and concrete producers** compare the price of secondary raw materials with the one of natural sands and aggregates, their availability, their quality and the impact they have on their production processes in terms of product quality, energy consumption, $CO_2$ emissions etc. Do their clients request circular or green products?
**Construction companies** consider calls for tenders with regard to requirements for recycled materials and products, the norms and standards they have to comply with and the quality they have to deliver taking into account time and budget constraints.

However, although the current business conditions do not seem to provide immediate market opportunities, we must anticipate tighter environmental regulations and scarcity of primary raw materials. Higher prices for commodities, requirements for sustainable, environment-friendly products and a waste-free circular value chain will result from this trend. Moreover, higher demand will decrease the costs for producing circular CPPs over time.
Having the right technologies and circular business models in place will prove as a competitive advantage and enable the transition.

## 3. Short-Term Business Models

This section sketches business models for CDW recycling and CPP production which we believe could be viable for innovative recycling and CPP businesses immediately. Regarding CDW recycling, we propose a business model where CDW from the demolition of the previous construction is used on-site for the new construction. With regard to CPP production, we suggest a business model where concrete waste from the own production, i.e. production remains, and failures are crushed and incorporated as secondary raw material in the production line.
Both approaches have the advantage that **the origin of CDW is known, homogeneous and available on-site.**

### 3.1. On-site CDW recycling

So far in Europe, there have been big construction projects such as the NATO site in Brussels [2] or the Tottenham FC stadium in London [3] where mineral CDW generated through the demolition of previous constructions has been reused as secondary raw materials in new constructions.
The underlying **circular business model** for these best practices can be described as follows:

| Value proposition | Customer and key partners |
|---|---|
| In very big construction projects in European urban environments old buildings and sites are mostly replaced by constructions of similar size. Big quantities of CDW resulting from the dismantling and selected demolition of the previous construction can be reused if a mobile crusher, washing equipment and a concrete plant | The builder and the main contractor have to be convinced to opt for this innovative approach. The recycler, cement and concrete producers are key partners and have to work seamlessly together and find original solutions. |

are installed on-site or very nearby.
The transport of heavy CDW, and sand and gravels from quarries through the city for concrete production is in this way drastically reduced.

| **Main technologies and processes** | **Revenues mechanisms** |
| --- | --- |
| Technologies for selected demolition, performant mobile crushers and washing equipment.<br>Concrete plants on-site which do not harm the city environment. | Price for removal and transport of mineral waste; Price of primary sands and aggregates and their transport replaced by secondary materials generated from CDW.<br>Additional incentives provided by the city to promote the reuse of CDW (optional). |

| **Material streams processed** | **Typical investment** |
| --- | --- |
| Mineral CDW from the construction site | To be estimated |

| **Main risks** | **Sample projects** |
| --- | --- |
| The mindset of the contractor and all stakeholders involved; The quality of the mineral CDW, especially the risk of hazardous substances in the recovered material; The smooth coordination of a more complex project; The alignment of demand and supply of secondary raw materials; The need for high capacity of mate- | NATO site in Brussels (2007): recycled aggregates were used for slabs of parking areas [2];<br>Tottenham FC stadium in London (2018) [3];<br>WTC in Brussels (2019) [4]. |

rial stock on-site.

**SWOT analysis:**

| Strengths | Weaknesses |
| --- | --- |
| High material-efficiency; Sands and gravel from natural environment conserved; Landfill is avoided; $CO_2$ emissions caused by transport of bulky raw materials are drastically reduced. | High quantity of $CO_2$ emissions by cement production are not affected; Noise and dust generated in an urban environment. |

| Opportunities | Threats |
| --- | --- |
| The material loop for mineral CDW is closed.<br>The introduction of new technologies is spearheaded; Awareness is raised and new business opportunities for all partners involved are created. | The economic viability; Certification and norms in place; To obtain insurances for the new construction might be more complicated. |

In conclusion, if the builder and the contractor opt for recycling of CDW on the construction site, economies of scale with regard to sand and gravel consumption can be obtained. Currently available technologies for the mobile upcycling of CDW and its use in concrete production have not yet reached major market shares which might keep the production costs higher than those using primary raw materials. State incentives would therefore make sense to encourage innovation and uptake of these new technologies until they reach a critical market acceptance.

### 3.2. Re-use of precast concrete remains

In the short-term, a first step to higher material-efficiency is to incorporate production failures and remains as secondary raw material in a company's own production of concrete precast. This approach has the advantage that the **origin of concrete waste is known**, is rather **homogeneous** and is **available directly on the production site**.

The underlying **circular business model** can be described as follows:

| Value proposition | Customers and key partners |
|---|---|
| Roughly 5% of the concrete used during CPP production ends up as waste. This is due to production failures and remains. This concrete waste is homogeneous and of known origin since it is generated at the production site.<br>If the CPP producer invests into a crusher and sieves (s)he could easily feed crushed concrete in a limited percentage into his/her CPP production. Since this type of aggregates does not present more than 5%, current norms and regulations are respected.<br>The CPP producer benefits from two advantages: the need for primary aggregates is reduced by up to 5%, and the costs for landfill of his production remains are avoided. | Only internal processes are changed, so no upward or downward change in the supply chain results from the re-use of own concrete waste. |

| Main technologies and processes | Revenues mechanisms |
|---|---|
| Smart crusher which recovers the sand, gravel from concrete. | Reduction of costs for primary raw materials by 5%; Reduction of costs for landfill by 5%.<br>Reduction of transport costs from quarry by 5% each. |

| Material streams processed | Typical investment |
|---|---|
| Concrete waste made of broken, damaged or wrongly produced CPPs, from concrete remains etc.<br>Since the material value of sand, gravel and cement is fully recovered, the incorporation of these secondary materials can be done in a flexible way according to their availability. | Investment into new equipment (smart crusher);<br>Additional space for operations and storage needed.<br>Regular maintenance of equipment.<br>On-site manpower needed. |

| Main risks | Sample projects |
|---|---|
| Certification and norms might be an issue if the substitution rate exceeds a certain percentage or the high quantity of fines have an impact on durability or concrete strength.<br>Market acceptance of CPPs containing recycled concrete; | Beton-Betz [5] |

**SWOT analysis:**

| Strengths | Weaknesses |
|---|---|
| 5% of landfill is avoided.<br>5% less sand and gravel are needed which reduces the costs of sand and gravel excavation and transport by 5%. | One-time investment into a (mobile) crusher and sieves is needed; Noise and dust will result from the crushing process. Some more space is needed for this operation and the storage of secondary aggregates.<br>Manpower who supervises the production of secondary aggregates, and maintenance of the machines will also add some additional costs. |

| Opportunities | Threats |
|---|---|
| Since public procurement increasingly requires higher resource-efficiency and more sustainable production, the re-use of own concrete waste might be a positive aspect in tendering which goes beyond the pure economic concerns.<br>In tenders where the circular yet safe use of raw materials matters, showing a circular approach within the limits of current norms, regulations and practices might turn into a competitive advantage for the CPP producer and contractor alike. | As long as the cost for primary raw materials from quarries is low, quarries exist in the close neighbourhood, and landfill with concrete remains is cheap, from a pure economic point of view, the investment into new equipment proves to be more expensive than buying primary aggregates.<br>More incentives or scarcity of primary resources leading to higher prices could make this business more profitable. |

## 4. Mid-Term Business Models

Within 5 years from now, we can expect that awareness for the needs of a circular economy will have grown in Europe and businesses will have started to make a shift in their strategies to a more circular use of raw materials. The rising scarcity of sands and aggregates in Europe leading to higher prices of raw materials will have further forced them to rethink their production in a more circular way. Innovative trendsetters will have proven the feasibility of alternative, circular value chains also in the construction industry.

At the same time, legislators will have pushed the reuse of products, components and materials in the construction industry, especially when the ecological footprint can be drastically limited through a major reduction of $CO_2$ emissions and/or raw material use. Financial institutions will be more willing to finance investments into companies enabling a circular economy such as CDW recycling, and governments will provide incentives to foster the uptake of their products. Certification of products using secondary raw materials will become easier and faster thereby encouraging businesses.

Last, digital tools, data banks and virtual marketplaces will become available that forecast the quantity and quality of CDW available at a certain time and allow for matching supply and demand.

Recyclers, cement and (precast) concrete producers will have experienced their successful cooperation in pilot projects and start to closely cooperate in order to close the value chain.

Depending on the region and their needs, these developments will happen at different speed. Regions with scarcer availability of raw materials such as Flanders and the Netherlands will probably be the most advanced in this transition to a circular economy.

Urban areas, especially those (re-)constructed almost entirely after second world war such as the city of Berlin will produce huge quantities of building material and demolition waste when most of their buildings will reach their end of life.

In the light of this situation, we propose a **circular business model** which is derived from the construction project of the Institute of Life Sciences of Humboldt University Berlin [6]. The main conditions for this model are geographical proximity in the sense that the **CDW stems from a demolition site which is close to both the recycling facility, the cement and the CPP production.** This setting is more likely to be found around urban areas and cities.

Recycling facilities and (precast) concrete production plants closely cooperate and recycled CDW smoothly feeds CPP production plants:

| Value proposition | Customers and key partners |
|---|---|
| Demolition which precedes new constructions in European cities generates enormous quantities of CDW which are difficult to recycle and re-use on-site because of missing space.<br>Specialized CDW recycling facilities which produce secondary raw materials for nearby (precast) concrete plants can reduce the traffic of heavy materials on highly frequented urban roads. CDW is carried to the recycling centre and its output material used for the production of CPPs which are taken back on the way to the construction site. Since the combined recycling and manufacturing plant is in the vicinity of the city, transport distances will be much lower than nowadays. | The builder and the contractor are key customers who need to be willing to use secondary raw materials and to change processes in the construction project accordingly.<br>The recycling plant and the CPP producer must be involved early in the demolition and construction project in order to schedule supply of recycled aggregates and CPPs according to the demand on the construction site.<br>Recycler and CPP producer must align their production processes so to deliver products in time.<br>The key partners must sort out the ownership of materials before the project starts. Different solutions can be envisaged, such as the recycler only providing service or the recycler buying/selling CDW. |

| Main technologies and processes | Revenues mechanisms |
| --- | --- |
| Crushing and washing equipment which allows high throughput of materials in the recycling process.<br>Digital tools, data banks and virtual marketplaces that forecast the quantity and quality of CDW available at a certain time and allow for matching supply and demand. | The builder pays for the transport and processing of demolition waste, and for the CPPs produced and delivered. They spare money for the primary raw material replaced, its transport from the quarries.<br>Ideally, the builder is rewarded by additional state incentives per ton of CDW re-used.<br>The recycling company is paid input and an output gate fees per ton of material processed. The fees vary depending on the quality of CDW received.<br>The CPP producer buys recycled aggregates form the recycler at the same rate as primary sand and gravel. |

| Material streams processed | Typical investment |
| --- | --- |
| Concrete, bricks, tiles and ceramics selectively demolished at demolition sites in the near-by cities. | Investment into powerful CDW crushing and washing equipment.<br>Investment into silos for storage of secondary raw materials.<br>Investment into digital tools to control supply and demand of CDW and secondary raw materials and to schedule transport.<br>State incentives/structural funds shared among all stakeholders in- |

| | |
|---|---|
| | volved: builder, contractor, recycler and CPP producer. |

| Main risks | Typical investment |
|---|---|
| Hazardous materials have to be identified and sorted out before demolition on the demolition site.<br>Certification and norms might be an issue if the substitution rate exceeds a certain percentage.<br>Market acceptance of CPPs containing recycled CDW.<br>The trend goes to the dismantling of buildings. Demolition is considered to be the last choice. | Construction of Institute of Life Sciences of Humboldt University Berlin [6] |

**SWOT analysis:**

| Strengths | Weaknesses |
|---|---|
| Landfill is avoided and the material loop for mineral CDW is closed.<br>Sand and gravel extraction from quarries and their transport is avoided. | Matching supply and demand may prove difficult and hamper construction projects.<br>The performance of recycling facilities if not substantially modernised. |

| Opportunities | Threats |
|---|---|
| Since public procurement increasingly requires higher resource-efficiency and more circular approaches in new construction projects, the production and use of secondary | The low price and abundant availability of primary raw materials in some regions of North-West Europe.<br>The low price of recycled aggregates in some regions. |

raw materials might provide a competitive advantage for the builder, contractor, recycler and CPP producer alike.

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In conclusion, the trend to a circular economy will also play in favour of the CDW recycling business which will be able to meet the rising demand for secondary raw materials in the construction industry supposing that major investments are made.
Big cities will be the first to implement the change, and in consequence, CDW recycling and CPP production plants will closely cooperate to timely deliver CPPs made from recycled CDW to big construction projects. However, major structural investments into cutting-edge recycling technologies but also innovation regarding CDW material audits are a prerequisite to make this major shift in the use of mineral construction materials happen. Public procurement will play a decisive role in creating demand for material circularity in the European construction industry. Additional state incentives for all business partners involved should foster the take-up of this innovation.

## 5. Long-Term Vision

Around 2030, the mindset and willingness to change practices for a more circular economy will have reached all levels of society, and politicians and businesses will have adopted circular thinking. Sustainability criteria will have been translated into accountable financial measurements for businesses which means that CPP and cement producers will be inclined to adopt those circular business models to increase their profitability.
As for the use of secondary raw materials in the construction business, we estimate that the business model developed for 2025 will still apply but be implemented at a much larger scale. We forecast that **integrated recycling and concrete precast production facilities** will be located in the vicinities

of all cities in North-West Europe. Buildings will get an inventory as material banks, in-depth demolition audits will be performed routinely, which will allow to determine the quality of CDW as secondary raw material. Consequently, **secondary raw materials of diverse quality and origin** will be identified and classified. These will be traded in **virtual marketplaces** according to supply and demand. Since primary raw materials will have become much scarcer and structural state incentives will support the circular economy, recycling will be a flourishing business also in the construction sector. Beside the business model described in the last section, other business models - tailor-made to the specific local conditions - will be invented. Non-European countries with high growth rates such as China, India and Brazil which will have had a tremendous construction output over the last decade will investigate the potential to adopt business models developed in Europe.

## Acknowledgements

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