Recycled concrete aggregates in climate-neutral structural applications in transport infrastructure

Natalie Williams Portal

ÅForsk Report :18-429

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Abstract

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Closed-loop thinking is paramount concerning the responsible use of concrete as a building material. Residual concrete or demolition concrete waste can be crushed and recycled as aggregates and applied in new concrete or as filler material; the result of this being denoted as Recycled Concrete Aggregates (RCA). A promising market has been identified for re-use aggregates stemming from construction and demolition waste (CDW) in e.g. roads, drainage and other construction projects, but it is projected that the application can also be extended to structural applications.

This project investigated the impact of fractions of RCA on the global structural behavior of reinforced concrete (RC) components in transport infrastructure. Experimental investigations at both the material and structural levels were conducted within this project to gain a comprehensive understanding of the mechanical properties for the developed composite materials. The project brought forth the potential of using RCA in a recycled concrete product in structures which is considered to be a responsible use of resources and an innovative product development compared to the current use of RCA as a "reused material". This project was conducted as a collaborative effort between RISE Research Institutes of Sweden, Chalmers University of Technology, Thomas Concrete Group. Expert support was also provided by the Universidade da Coruña (Spain).

Key words: Concrete, recycled concrete aggregate, recycled aggregate concrete, circularity, construction materials, infrastructure

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Content

Preface

The work presented in this report is related to the ÅForsk financed project 18-429 entitled “Recycled concrete aggregates in climate-neutral structural applications in transport infrastructure” (*Återvunnen betongkross i klimatneutrala konstruktioner inom transportinfrastuktur*). This project took place between October 2018-October 2019 and was coordinated by RISE Research Institutes of Sweden in collaboration with Chalmers University of Technology (Structural Engineering), Thomas Concrete Group (TCG) and Universidade da Coruña (Spain).

The participants in the project have been:

Project leader:	Natalie Williams Portal, RISE
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We want to further thank the following people who have contributed with valuable feedback and assistance:

Diego Carro Lopez, Universidade da Coruña
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Ilias Outras, RISE
Alexander Oliva Rivera, RISE

Borås in November 2019

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1 Introduction

1.1 Project summary

This project investigated the impact of fractions of recycled concrete aggregate (RCA) on the global structural behavior of reinforced concrete (RC) components in transport infrastructure. Experimental investigations at both the material and structural levels were conducted within this project to gain a comprehensive understanding of the mechanical properties for the developed composite materials. The project brought forth the potential of using RCA in a recycled concrete product in structures which is considered to be a responsible use of resources and an innovative product development compared to the current use of RCA as a “reused material”. This project was conducted as a collaborative effort between RISE Research Institutes of Sweden, Chalmers University of Technology, Thomas Concrete Group and Universidade da Coruña (Spain).

1.2 Background

Concrete is known to be the most employed building material in construction. Due to its versatility, it is applied in a wide range of structures and infrastructures, such as residential and commercial buildings, dams, roads, bridges and tunnels. In fact, the majority of bridges are built using concrete in Sweden [1]. This composite material basically consists of a mixture of cement, aggregates and water. The manufacturing of Portland cement, the most commonly used hydraulic cement, is the constituent requiring the highest energy intensity of about 5 GJ of energy per ton of cement; which, in turn, is responsible for the production of significant amounts of CO_2 emissions [2]. In addition, aggregates, which can represent approximately 80 % of the mix volume [3], have a noteworthy impact on the carbon footprint of concrete and also on the environment. The extraction of raw materials in itself, e.g. quarrying of limestone, significantly contributes to air pollution and irreversible damage to the ecology of forests and waterways.

To justify the continued use of concrete as a building material, it is paramount to implement closed-loop thinking; it is to say the environmentally responsible use of natural resources. According to [3], there are three key benefits of using materials more efficiently: 1) to slow down resource depletion at input, 2) to lower pollution at output and 3) to provide a sound growth of worldwide employment. It has been acknowledged that the recycling of construction and demolition waste (CDW) can be an effective method to achieve these benefits. Currently, recycling and re-use of CDW is supported by the European Commission particularly through the Waste Framework Directive [4]. A particular material which can be derived from such recycling is recycled aggregate, defined as aggregate resulting from the processing of inorganic material previously used in construction [5]. More specifically, residual concrete or grated concrete can be crushed and recycled as aggregates and applied in new concrete or as filler material; the result of this being denoted as Recycled Concrete Aggregates (RCA). The modified life-cycle of concrete according to the responsible use of natural resources is schematically illustrated in Figure 1. A promising market has been identified for re-use aggregates stemming from CDW in e.g. roads, drainage and other construction projects [6], but it is thought that the application can be extended to structural applications in transport infrastructure.

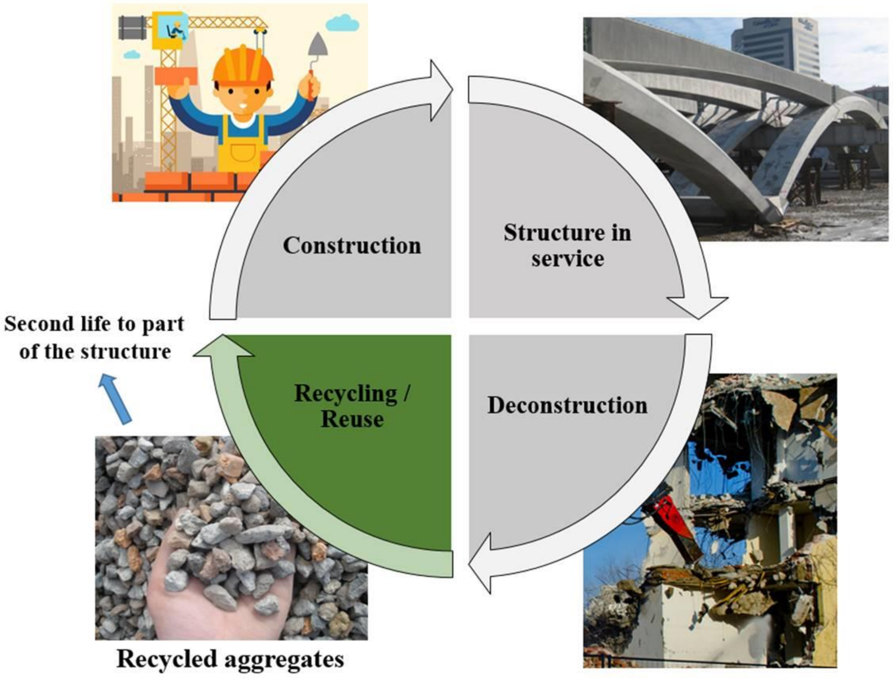

Figure 1 Life cycle of primary and secondary uses of concrete.

Aggregate in Sweden is relatively inexpensive and readily available in terms of raw material sources. Swedish taxes related to natural gravel (1996) and landfill disposal (2000) have however been implemented to attempt to regulate and diversify the materials used for aggregate [7]. Furthermore, there has been recent progress in regards to the legislation behind using recycled aggregates in concrete, yet it also hinders the sole use of RCA. An updated version of SS 137 003 [8] in combination with the main concrete standard SS-EN 206 [9] allows for increased opportunities to incorporate recycled aggregates in concrete. The highest proportions of recycled aggregate which may be used in concrete in relation to a given exposure class is specified in SS 137003 [8]. For instance, the maximum proportion (in mass fraction) of the coarse aggregate (> 4 mm) that may consist of aggregate from recycled residual materials is 50 % wt. for concrete in exposure class X0.

The implementation of RCA derived from crushed concrete waste is already active in the Swedish construction industry, particularly for use in roads and parking areas, which is justified by the fact that such actions help minimize waste disposal and extraction of raw materials all while reducing material costs [10]. A number of recent research and development projects have been conducted in Sweden related to processing methods, quality and applicability of RCA, with a focus on the investigation at the material level, e.g. [11, 12, 13]. These published results indicate benefits, drawbacks and limitations of RCA with respect to the material level, which are of key importance to highlight and refer to within this project. Concerning the structural potential of RCA concrete for applications in transport infrastructure, however, there exists a knowledge gap particularly related to a Swedish context. In the literature, the structural behaviour of RCA concrete, in terms of flexural, shear and seismic behaviour, has been reported to be comparable to concrete with natural aggregate, while being able to fulfil relevant structural code requirements [14, 15, 16, 17]. Exploiting this innovative and promising research area, could not only lead to producing so-called climate neutral transport infrastructure, but could also allow for further product development of RCA from its current use as a “reused material” to a “recycled concrete product”. This project aims to contribute to this field through detailed experimental investigations on both material and structural levels of RCA reinforced concrete, as well as through revealing the environmental impact of the developed materials.

1.3 Method

To successfully achieve the goal of this project, the following methodology was applied in the project (refer to Figure 2):

- Acquire and process concrete from a demolished structure into RCA.
- Develop concrete mixtures with various fractions of RCA.
- Characterize the mechanical behaviour of concrete with various fractions of RCA on the material level.
- Characterize the global structural behaviour of concrete with various fractions of RCA on the structural level.
- Evaluate the environmental impact of using RCA.

Figure 2 Visual depiction of methodology conducted in this project.

1.4 Limitations

The main limitations of this project are summarized in the following:

- Only one source of mother concrete was investigated in this work, so-to-say the demolished bridge in Gullspång, Sweden. Having a uniform material source helps simplify the characterization and workability of the concrete mixture.
- Only one reference concrete mix was investigated for the purpose of being able to be used in new edge beams.

1.5 Dissemination activities

The following key dissemination activities took place during the course of the project:

- An abstract entitled “Investigating the circularity of a demolished concrete bridge” was submitted to Circular Materials Conference, March 17-18, 2020 https://www.circularmaterialsconference.se/
- An abstract entitled “Analysis of tensile behaviour of recycled aggregate concrete using acoustic emission technique” was submitted to RILEM-SC2020, March 10-14, 2020. https://www.rscc2020.civil.uminho.pt/
- A conference paper entitled “An old bridge transformed into a new one: possible, recommendable?” was presented at IABSE Congress New York, September 4-6, 2019. http://www.iabse.org/IABSE/events/Conferences_files/Newyork2019/Home.aspx?hkey=b2b496ea-3efd-4915-b393-392742491edb
- A series of RAC beams were tested in a bachelor course in February 2019 at Chalmers for educational purposes. The information and analysis of theses beams was spread to a large group of students and teachers.

2 Material acquisition and characterisation

2.1 Material source

The recycled material used in this research was obtained from crushing edge beams from a demolished bridge in Gullspång, Sweden, see Figure 3. The bridge was originally built in 1935, and due to heavy corrosion damages, it was demolished in 2016. The edge beams were initially procured for a research project at Chalmers University of Technology. It was estimated that the concrete had a remaining compressive strength of 30 MPa and smooth reinforcement bars with end hooks, which are typical for the given construction period. The characterisation of this so-called *mother concrete* was also performed in this project.

Edge beams which remained from this initial project were made available for this project to study the potential of transforming the concrete into recycled concrete aggregate (RCA) and thereafter introducing this material into a new concrete, so-called recycled aggregate concrete (RAC). In this project, the main idea was to produce reinforced concrete equivalent to the *mother concrete*, all while incorporating the concept of material circularity.

Figure 3 Bridge in Gullspång, Sweden (a) and removed edge beams (b).

2.1.1 Concrete recycling

The edge beams were processed with a transportable jaw-crusher, shown in Figure 4, that produced a recycled aggregate that included coarse and fine fractions. A magnetic separator was attached to the crusher to recover the majority of the reinforcement for recycling.

Figure 4 Crushing and separation process.

The processed material offered a continuous grain size distribution and it was divided into conventional sand (0/4 mm) and gravel fractions (8/16 and 16/25 mm), as depicted in Figure 5. A low percentage of the crushed material was >25 mm which could undergo further crushing to yield smaller fractions. In this project, only the coarse fraction (>4 mm) of this recycled aggregate was applied, which is the recommended in key EU regulations [18, 4]. The sieving and sorting of the material is shown in Figure 6.

Figure 5 Overview of different fractions recovered from the crushing.

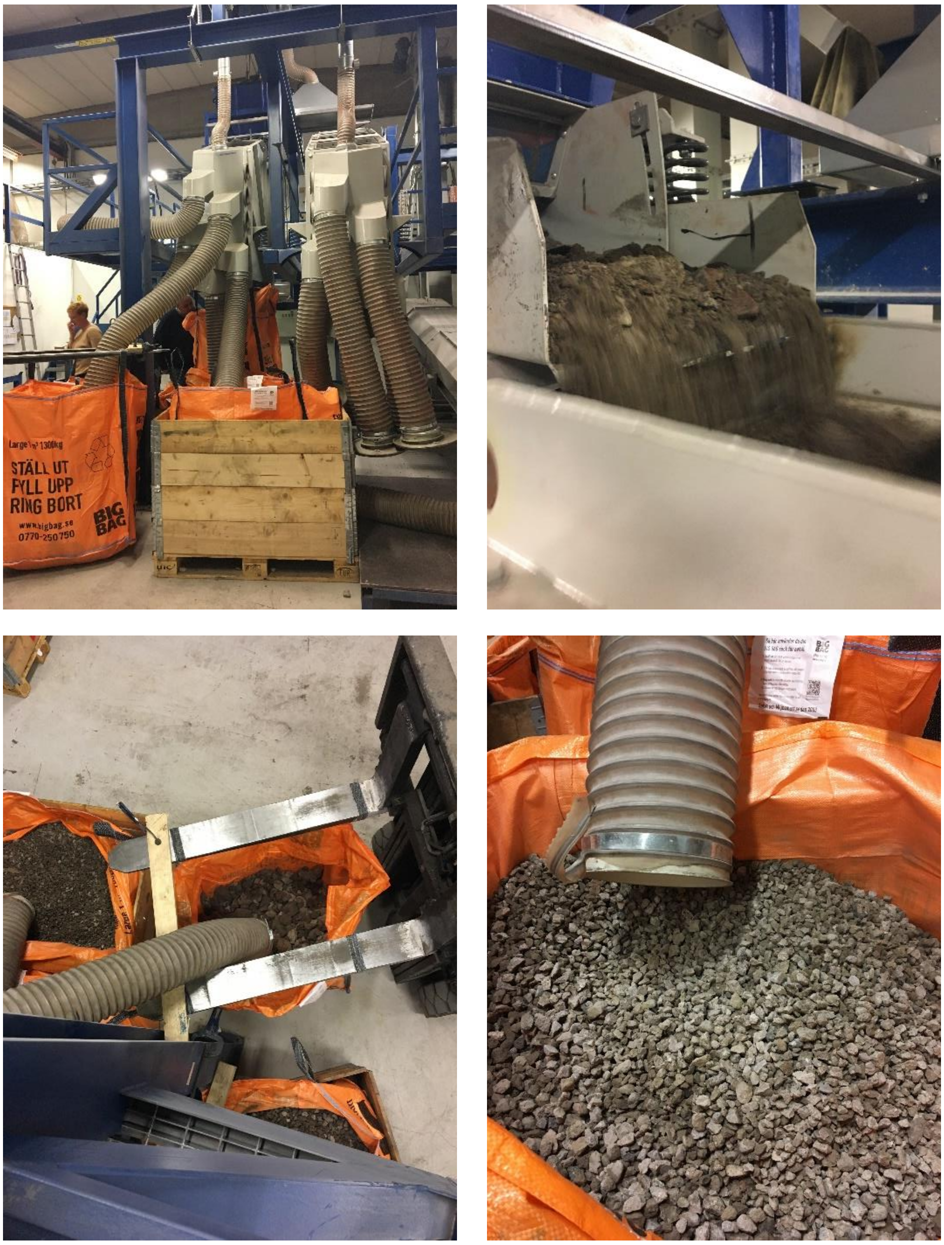

Figure 6 Material sieving and sorting.

2.2 Recycled concrete

2.2.1 Materials

This project analysed the effect of recycled aggregates in concrete with 0 %, 20%, 50% and 100 % of coarse recycled aggregates. The concrete composition also included natural granitic sand (0/4 mm) and gravel (4/16) as base materials. The cement used was a CEM I 42.5 R (compressive strength higher than 42.5 MPa EN 197-1 [19]) very common in Swedish practice. To achieve acceptable workability a naphtalenesulfonate additive was used.

2.2.2 Mix composition

The reference mixture is presented in Table 1. The quantity of cement was of 365 kg per cubic meter, acceptable for aggressive environments. The w/c ratio was of 0.47 and was kept constant for all the coarse aggregate replacement (0%, 20%, 50%, 100%). The procedure to calculate the different mixes was to substitute the volume of the gravel for recycled gravel.

Table 1: Reference mixture composition.

Material	Volume [L]	Specific gravity [-]	Weight [kg/m3]
Cement	119.7	3.05	365.0
Water	171.6	1.00	171.6
Natural Sand (0/4)	355.9	2.65	943.1
Natural Gravel (8/16)	347.7	2.62	911.0
Recycled Gravel (8/16)		2.41	
Additive Glenium 5118	5.2	1.10	3.7
Total	1000.0	-	2394.3

2.2.3 Water adjustment

The natural aggregates presented a reduced value of absorption, 0.5% for the natural gravel and 0.3% for the natural sand. On the contrary, the recycled gravel presented a value of absorption of 4.1%. This measured value is low for recycled aggregates and it was reached as a result of the high quality of the original *mother concrete*.

In general, the aggregates presented variability in moisture due to the open/outdoor storage. This in turn simulates the reality of concrete production in industrial plants. However, this made it necessary to adjust the water content to reduce the quantity of water added to the mixer considering the initial humidity of the aggregate.

3 Experimental results

3.1 Material level

Various mechanical properties were characterized for the *mother concrete*, reference concrete and recycled concrete mixes (20%, 50% and 100%). The mechanical test methods applied were categorized according to *compression* and *tension* depending on the nature of the test, as listed in Table 2. The *compression* properties include compressive strength, ultimate strain, modulus of elasticity and Poisson's ratio, while *tensile* properties comprise tensile strength and fracture energy.

Table 2: Applied mechanical tests and expected outputs at the material level.

Category	Method	Output/results
Compression	Uniaxial compression test	Compressive strength, f_c Modulus of elasticity, E_c Poisson's ratio, v_c
Tension	Uniaxial tensile test	Tensile strength, S_{max} Fracture energy, G_F

Acoustic Emission (AE) measurements were added to both the compression and tension tests to gain knowledge on micro crack initiation and damage development during loading. These results are not presented in detail here and will be published elsewhere.

3.1.1 Uniaxial compression tests

The uniaxial compression tests were conducted using a GCTS servo-hydraulic machine with a stiff load frame (load cell rated up to 1.5 MN and accuracy within 1 %), see Figure 7. The stiffness of the various components of the loading chain in the load frame has been optimized to obtain a high total stiffness. Inductive displacement transducers (range ± 2.50 mm and relative error < 0.6 % for axial deformation and < 1.3 % for circumferential deformation) were used as instrumentation for axial and circumferential deformation measurements. The sensors, the controller and the servo valve are rapidly responding components which prevents the specimen from being crushed after peak stress. Eight cylinders were cast for each mixture with dimensions of Ø100/200 mm. The specimens were demoulded and stored in a climate chamber (RH 65%, 20 °C) until testing at around 28 days. Specimens are denoted according to their replacement amount, i.e. RC = 0%, R20C = 20%, R50C = 50% and R100C = 100%. Three cylinders from the *mother concrete* were cored to undergo the same testing, designated as *Gullspång*.

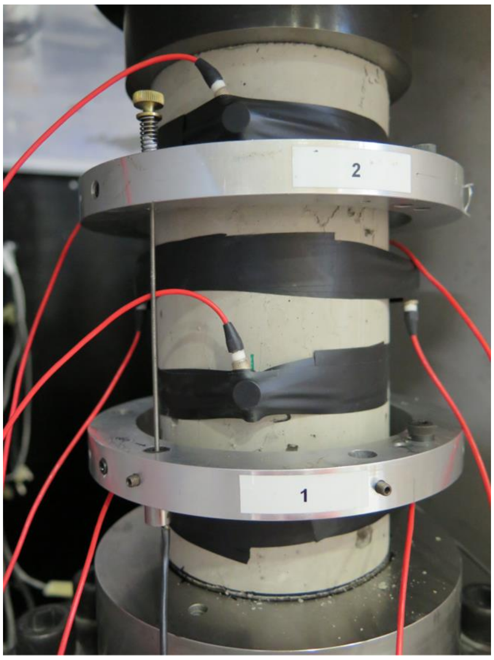

Figure 7 Uniaxial compression test with acoustic emission measurements.

Initially, the compressive strength, f_c, was determined in accordance with EN 12390-3 (2009) [20] to define stress levels for the test cycle used to determine the stabilized secant modulus of elasticity, $E_{c,s}$, according to EN 12390-13 (2013) (Method B) [21]. A limitation of these tests is that only the compressive strength and the secant modulus are obtained, yet one of the benefits of introducing a cyclic load is to minimize the risk of potential settlement of the loading surfaces. The stress-strain relationship in compression was determined for specimens with the same concrete and dimensions. Measurements were performed in accordance with the same aforementioned standards, with the exception that the load was applied using deformation control with a displacement rate of 0.12 mm/min.

The compressive strength, f_c, was defined as the peak stress and the ultimate strain, ε_{cu}, was defined as the corresponding strain. The elastic properties, i.e. modulus of elasticity, E_c, and Poisson's ratio, ν_c, were evaluated as the secant modulus between the lower, σ_l, of 5 MPa and upper stress levels, σ_u, of $f_c/3$. The axial strain, ε_a, was calculated as the ratio of mean axial deformation and gauge length (distance between rings) and strain gauges, while the radial strain, ε_r, was calculated from strain gauge measurements. The volumetric strain, ε_{vol}, corresponded to the summation of axial strain and two times the radial strain. Poisson's ratio, ν, was determined as the ratio of radial to axial strain.

In principle, both methods presented are suitable to determine the compressive properties, i.e. secant modulus and compressive strength of concrete, yet the first one is evaluated according to a standardized method and the other directly from the material's stress-strain curve. Refer to Figure 8 for selected stress-strain results.

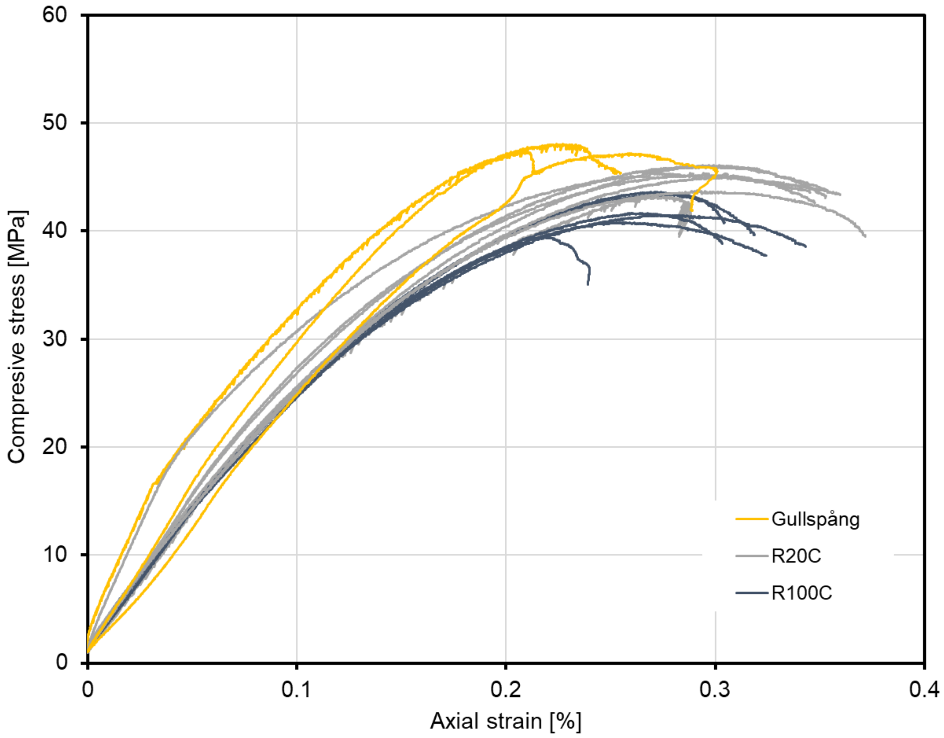

Figure 8 Stress-strain comparison of selected results.

From these selected compression results shown in Figure 8, it can be stated that there is but a minimal loss in compressive strength from the *mother concrete* to the recycled aggregate concrete. Introducing 100% replacement yields a comparable compressive strength to that of the 20% replacement. Additional results from these tests are provided in Appendix A.

3.1.2 Uniaxial tensile tests

The uniaxial tensile tests were conducted at RISE based on RILEM TC 187-SOC (2007) [22] and RILEM TC 162-TDF (2001) [22]. The same testing device as previously specified for the compression tests was used in order to suppress rotations of the load platens that could lead to bending failure, see Figure 9. As well, the device was pre-tensioned with a load of 150 kN and the load cell was rated up to 200 kN. The deformation was applied at a rate of 0.003 mm/min and measured locally over the cylinder notch with three inductive displacement transducers with a gauge length, l_g, of 30 mm. The deformation was calculated as the mean value of the three displacement gauges.

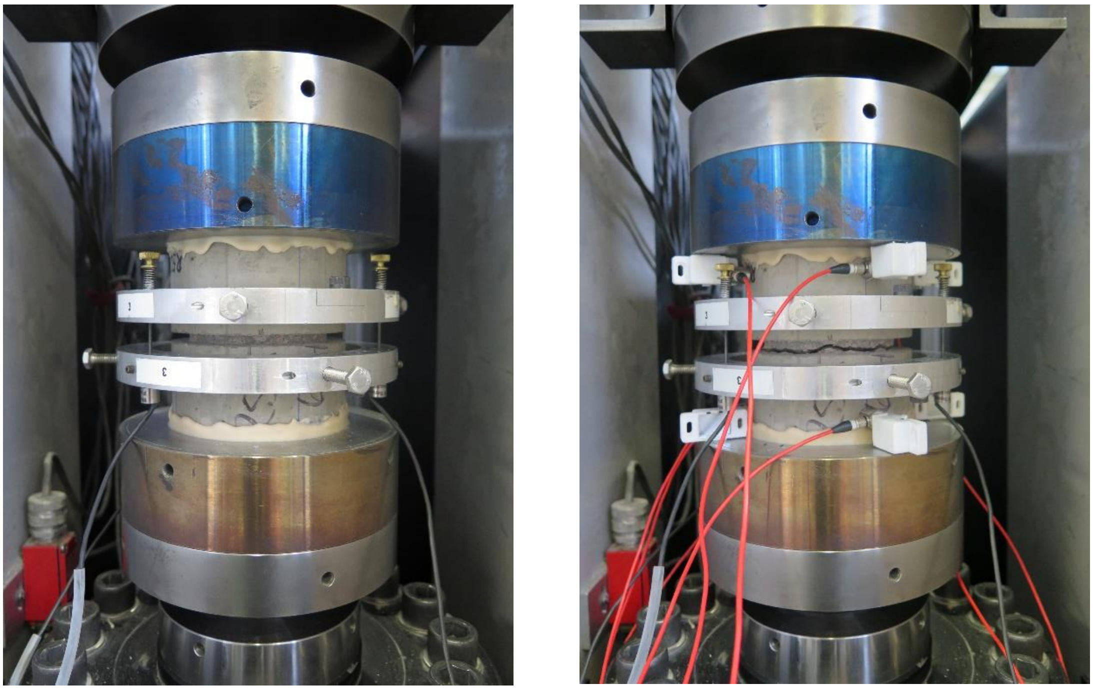
(a) (b)

Figure 9 Uniaxial tensile test: pre-loading setup (a) and with acoustic emission during testing (b)

Eight cylinders were cast for each mixture with dimensions of Ø100/100 mm, as per Figure 10. Specimens are denoted according to their replacement amount, i.e. RT = 0%, R20T = 20%, R50T = 50% and R100T = 100%. The specimens were demoulded and stored in a climate chamber (RH 65%, 20 °C) until testing at around 28 days. The specimen ends were planed and a notch with depth of 15 mm and width of 3 mm was cut in the middle of each specimen prior to testing. Four cylinders from the *mother concrete* were cored to undergo the same testing, designated as *Gullspång*.

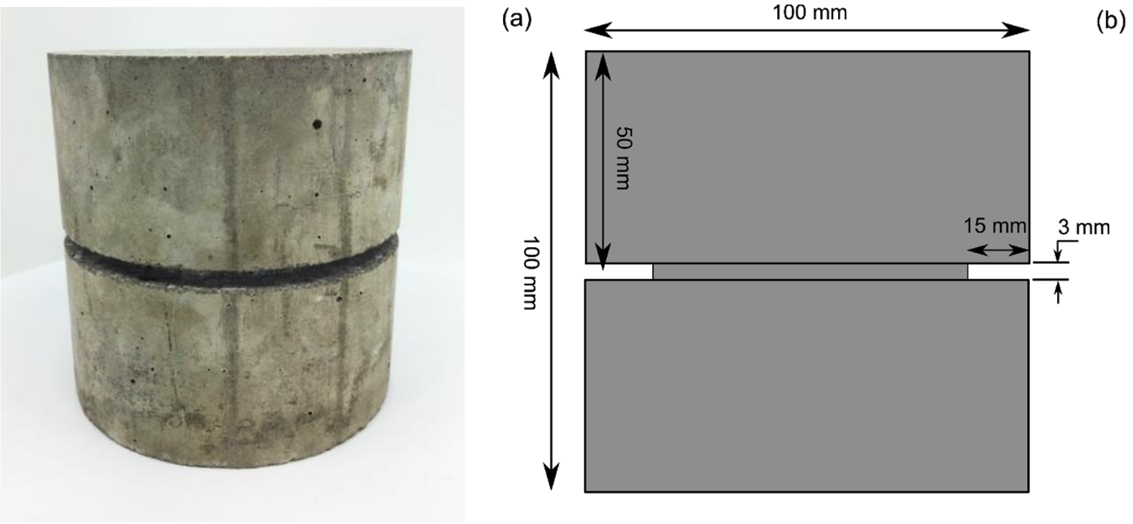

Figure 10 Uniaxial tensile test specimen with notch.

The stress-displacement curve shown in Figure 11 was used to derive the softening behaviour of the concrete material according to equations provisioned in RILEM TC 187-SOC (2007) [22]. The tensile stress, σ, was derived by dividing the load by the effective cross-section, A_{eff}, at the notch. The tensile strength, f_t, is defined as the peak stress and deformation at peak stress, δ_{tu}, which takes place at the onset of macro cracking. The crack opening w, in the post-peak regime, was calculated by subtracting the elastic deformation, δ_e, from the measured deformation, δ. Since the notch obstructed the direct measurement of the modulus of elasticity in tension, the ratio E/l_g was replaced by the elastic stiffness, K, which was evaluated directly from the tensile stress-deformation curve. The fracture energy G_F was thereafter calculated from the area under the stress-crack opening relationship.

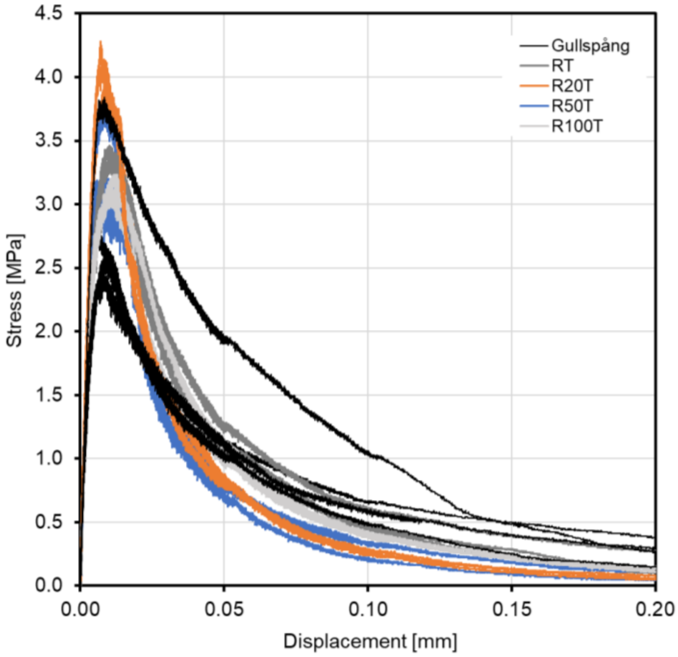

Figure 11 Stress-displacement comparison.

Selected results pertaining to the different concrete mixes are summarized in Table 3, more specifically, the tensile strength and fracture energy are presented. It can be generally stated that the variation between the average values for the replacement mixes is minimal, such that the tensile strength ranges between 3.13-4.09 MPa and the fracture energy ranges between 124-175 Nm/m². In this case, it appears as if the 20% replacement has a slightly superior tensile behaviour. The highest variation in results was noted for the *mother concrete*, which was suspected due to the inherent difference in aggregate size (large river stones were found in the specimens). Additional graphical results pertaining to these tests are presented in Appendix B.

Table 3: Selected results for uniaxial tensile tests.

Concrete mix	Specimen ID	Tensile strength, S_{max} [MPa]	Fracture energy, G_F [Nm/m^2]
Gullspång (mother concrete)	16B100	2.94	232
	17B1	2.42	230
	17G100	2.57	153
	18B200	3.79	306
	Average (Std dev)	2.93 (0.53)	230 (54)
Reference, 0% replacement	RT-1	3.01	157
	RT-3	3.36	157
	RT-4	3.43	212
	Average (Std dev)	3.27 (0.18)	175 (26)
Recycled aggregate concrete , 20% replacement	R20T-1	3.91	132
	R20T-2	4.24	136
	R20T-3	4.11	126
	Average (Std dev)	4.09 (0.13)	131 (4)
Recycled aggregate concrete, 50% replacement	R50T-1	3.08	131
	R50T-2	3.19	105
	R50T-3	3.70	137
	Average (Std dev)	3.33 (0.27)	124 (14)
Recycled aggregate concrete, 100% replacement	R100T-1	3.06	146
	R100T-2	3.12	145
	R100T-3	3.21	155
	Average (Std dev)	3.13 (0.06)	149 (5)

3.2 Structural level

The *mother concrete* once transformed in recycled aggregates was included in concrete to produce new reinforced beams having dimensions of 250 x 300 x 2000 mm. These new elements presented a ductile structural configuration with failure by steel. They reproduced the original beams although complying with the modern standards of reinforcement depth and minimum reinforcement.

Beams with incremental percentages of coarse aggregate replacement were cast: 20%, 50% & 100% and 0% as reference. A total of 12 beams were cast, so-to-say three of each mixture. All beams were tested under two-point loading (four-point bending) at Chalmers University of Technology, as per Figure 13, when the concrete had attained 28 days of curing in the laboratory environment. Digital Image Correlation (DIC) was incorporated in the experimental setup to be able to capture the strains and crack development on the speckled area during testing. AE and fiber optics were also included for comparison purposes. These data will however be published elsewhere.

Figure 12 Casting process of beams.

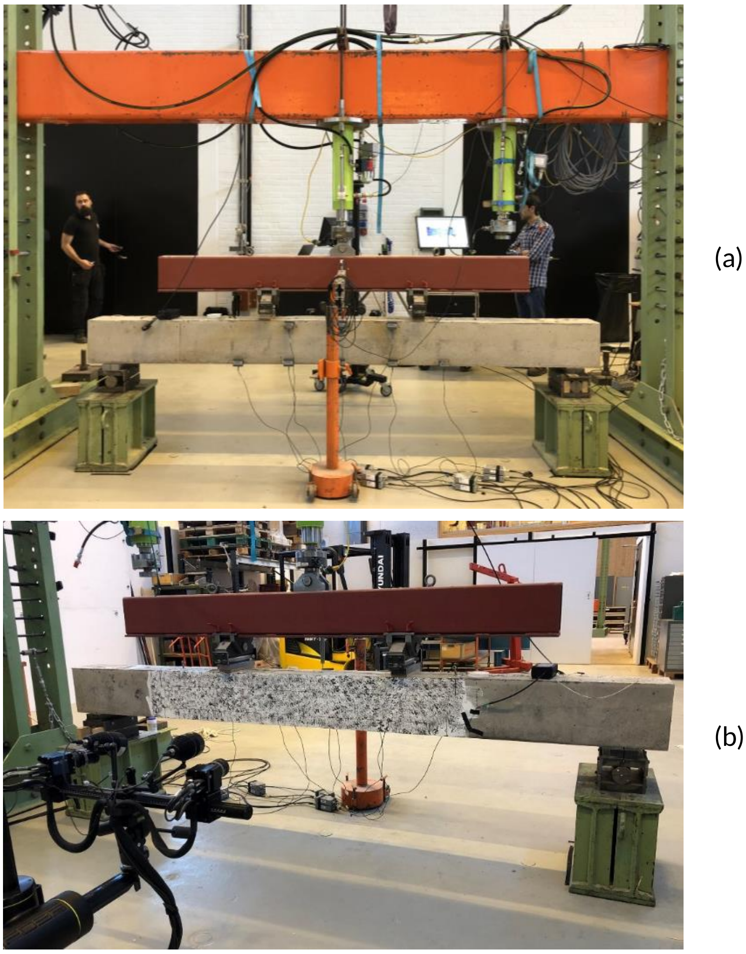

Figure 13 Two point loading test setup for beams (a) with digital image correlation system (b)

The load capacity of the tested beams was similar with a total load around 140 kN. Figure 14 and Figure 15 present selected results of force vs displacement for 20% and 100% replacement, respectively. The beams with 20% of replacement presented identical behaviour than those of 0% of replacement. However, the beams with 50% and 100% of replacement presented higher deformation and also a different cracking pattern. It can be observed that the distance between cracks is shorter in the case of 100% of replacement. This also could affect durability of the concrete itself or also to the reinforcement corrosion, which needs to be further investigated. More detailed analysis will be published elsewhere.

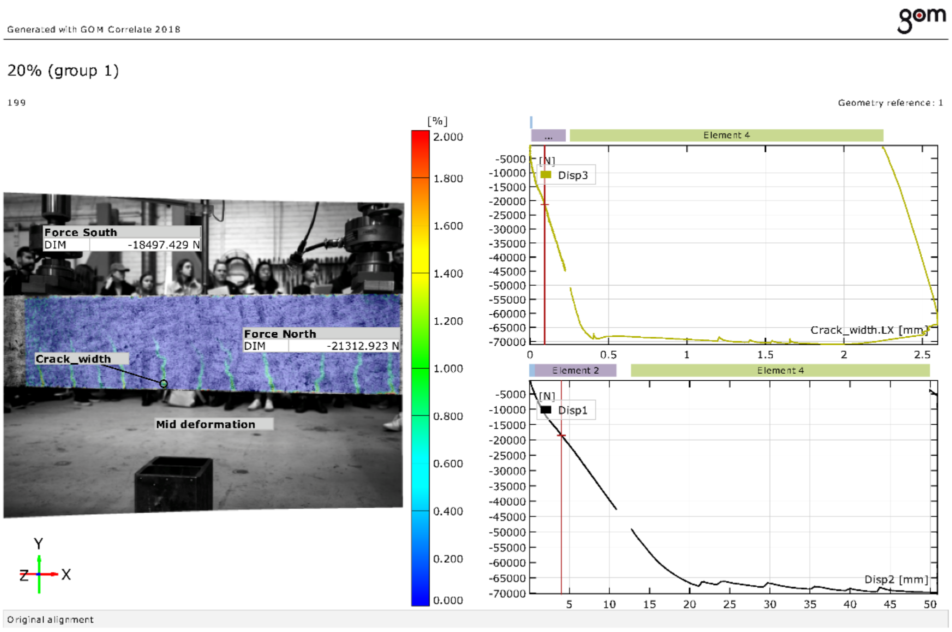

Figure 14 Result summary of two-point loading test of beam with 20% replacement.

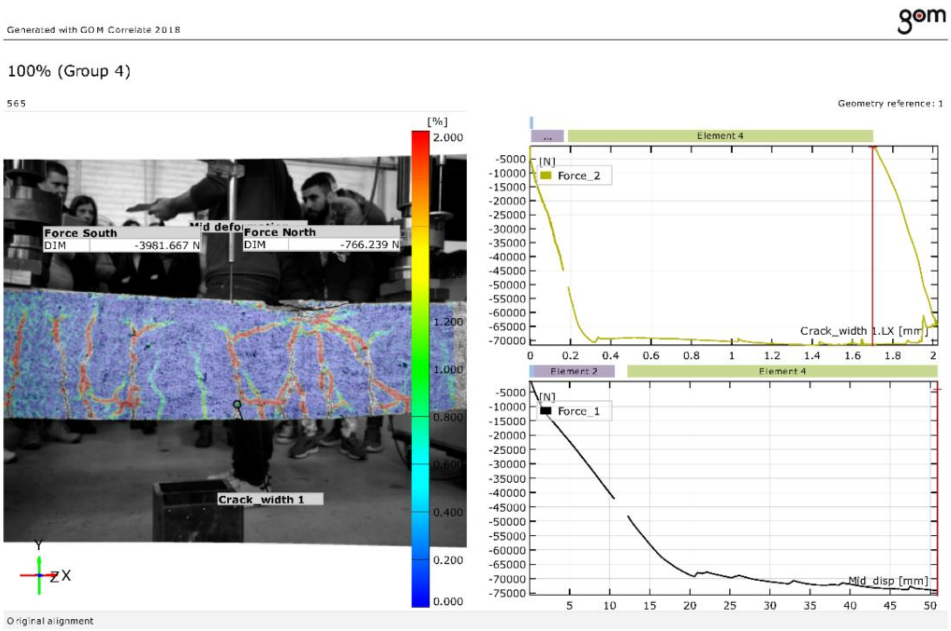

Figure 15 Result summary of two-point loading test of beam with 100% replacement.

4 Life Cycle Analysis (LCA)

The analysis is built upon a scenario of replacing concrete edge beams for an existing bridge structure, see Figure 16. The production of the edge beams will consider the in-situ casting of beams containing different fractions of RCA as the coarse aggregate in comparison with in-situ casting of beams with 100% primary raw materials (i.e., extracted from natural pits or by rock blasting). The two scenarios have been labelled as "1" and "2", respectively. The software that was used for the analysis is SimaPro and the Ecoinvent database or relevant literature were applied for input data.

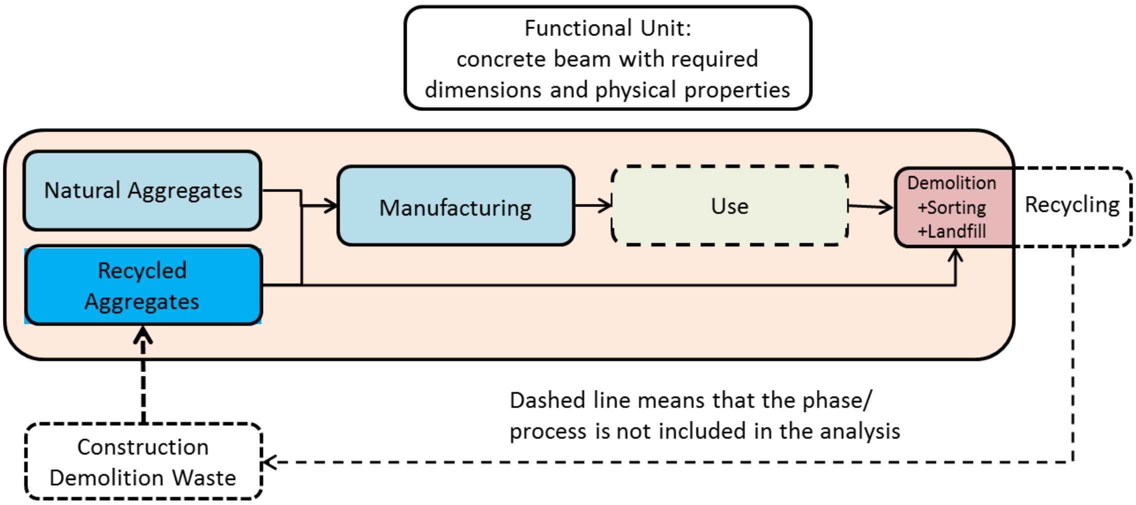

Figure 16 System boundaries for the LCA.

The main difference between Scenario 1 and Scenario 2 is that in the latter one, part of the material used to produce the beam comes from older beams that must be replaced in an existing infrastructure, typically a bridge. The beams which have lost their load-bearing capacity are crushed and some amount of the resulting material (generally denoted as Construction and Demolition Waste (CDW) is used in situ (i.e. at the same location of the infrastructure) to produce new beams. In Scenario 1, production of RCA takes place in a dedicated facility far from the location of the infrastructure, while a small-scale recycling plant is installed and operated locally in Scenario 2. There may be differences in the production control of the concrete in the two scenarios, with consequences for the quality of the produced material. The Use phase of the concrete beam is neglected, which entails that no significant environmental impacts (detrimental or beneficial) are expected to be generated during the service life of the beam. In the End of Life models of both Scenario 1 and Scenario 2, after demolition and sorting which should be done in any case, part of the CDW is disposed by transporting it to a landfill, while the rest is recovered for the production of the new beams. The recycling process is deliberately kept outside the End of Life side of the system boundary, as dictated by the "cut off" or "recycling content" approach to LCA modelling of systems with recycling [20]. This method is considered more conservative than alternatives proposed in the literature such as, e.g. the "avoided burden" approach which "loans out" some environmental positive impact from the new life of the recycled material. , In the "cut off" approach, some amount of secondary raw material is directly included in the manufacturing phase (see Figure 16). Continuous lines indicate included processes or system boundaries, while dashed lines represent processes which are not modelled since they are considered outside the boundaries of the investigated system. The impact of recycling processes is included in the manufacturing phase instead of the end of life, but only the emissions and energy consumptions due to the recycling processes are considered (i.e. no material input from waste produced by the life cycles of other products).

Selected results calculated using the CML-IA baseline V3.05 method are presented in Figure 17. From these presented results, it can be observed that for the majority of the environmental indicators, a concrete beam with 100% natural aggregate has a higher impact than a concrete beam that would contain 100% or 50% recycled aggregate. Further analysis is however required to determine the sensitivity of given variables (e.g. transportation distances, scenario for production, efficiency of recycling etc.) to the results.

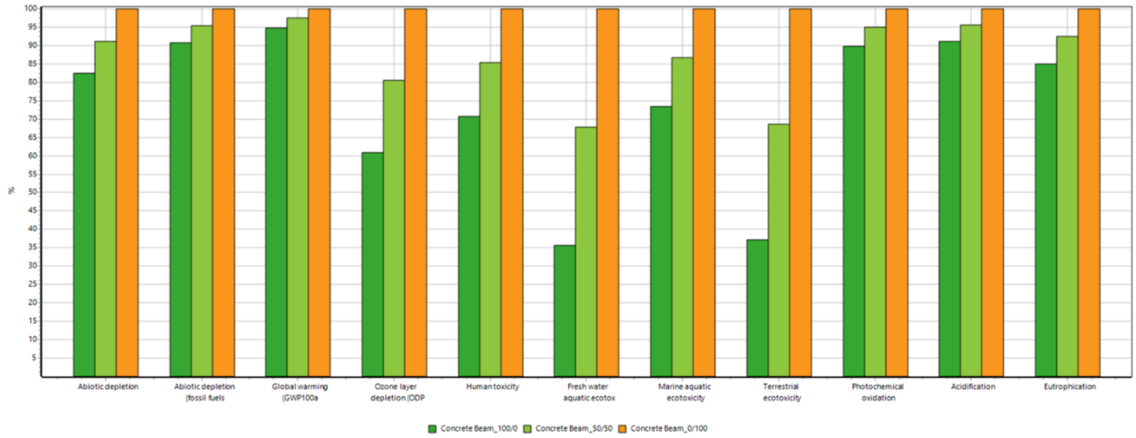

Figure 17 Comparison of environmental impact for different ratio recycled/natural aggregates.

5 Conclusions

In this project, we have reached the following conclusions:

- Making use of recycled concrete aggregates is a relevant trend that should be considered to achieve higher sustainability and material circularity in the construction industry.
- It is recommended to reuse concrete material from old constructions locally to produce e.g. new constructions/structural components using the recycled aggregates. This minimizes environmental impact via transportation.
- Recycling concrete from a single source appears to enhance the quality of recycled aggregate concrete and minimize uncertainty.
- The recycled aggregate concrete produced in this project presented a limited reduction of compressive and tensile strength.
- The beams produced with the recycled aggregate concrete presented acceptable quality even for replacement up to 100%.

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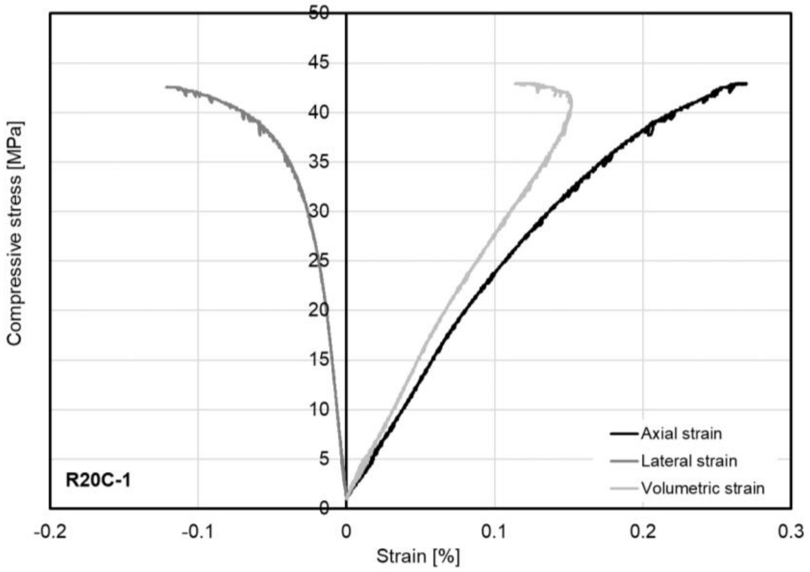
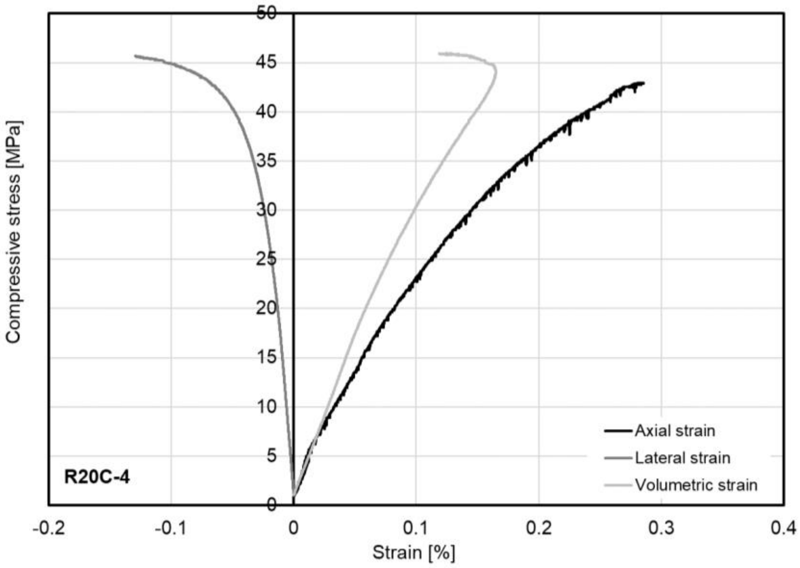
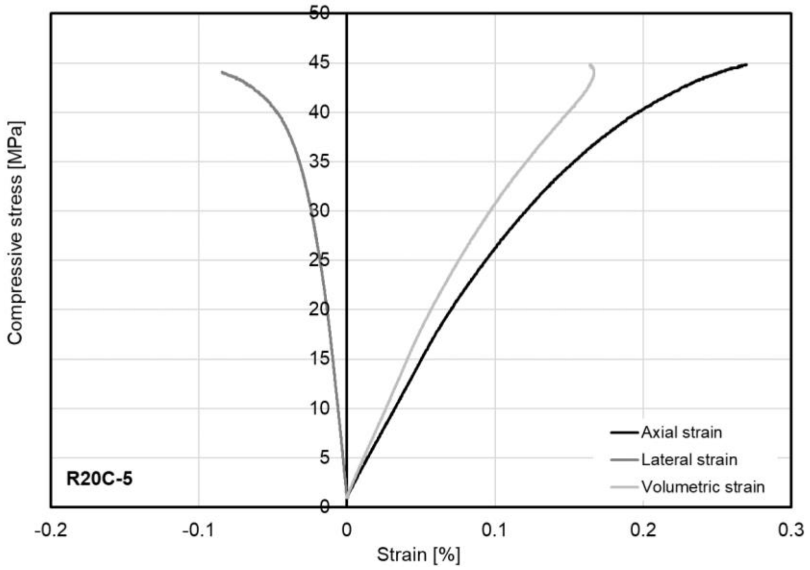
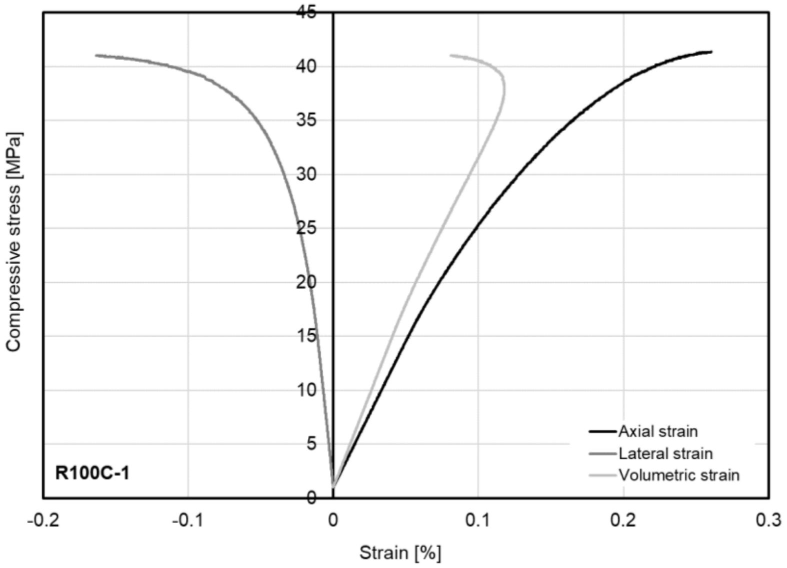
Appendix A

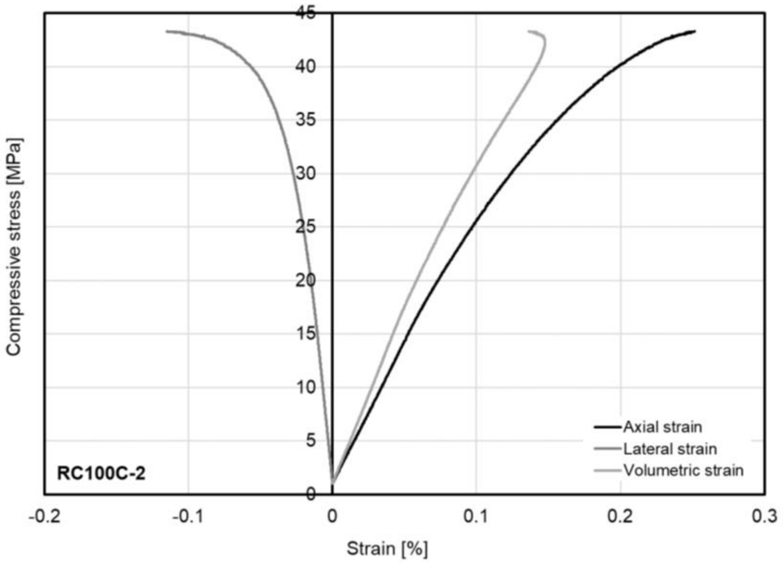
Selected uniaxial compression test results for 20% and 100% replacement.

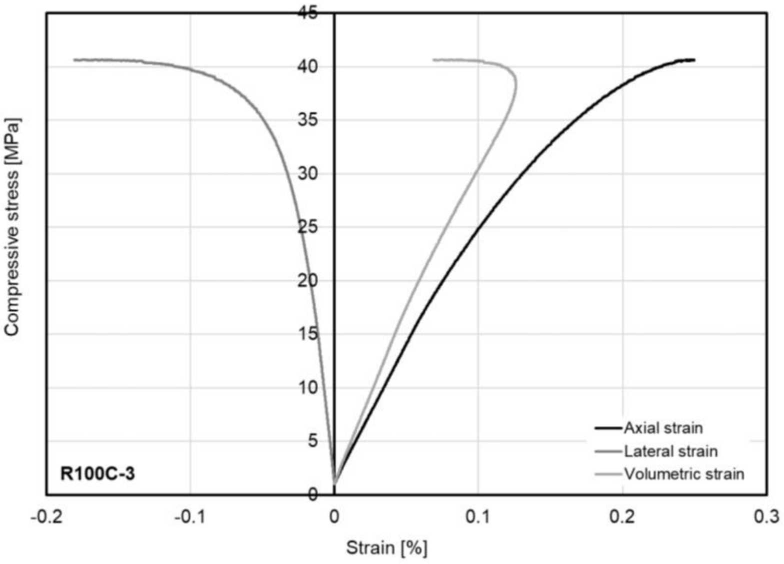

R20C-1
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
50
-0.2
-0.1
0
0.1
0.2
0.3
Axial strain
Lateral strain
Volumetric strain

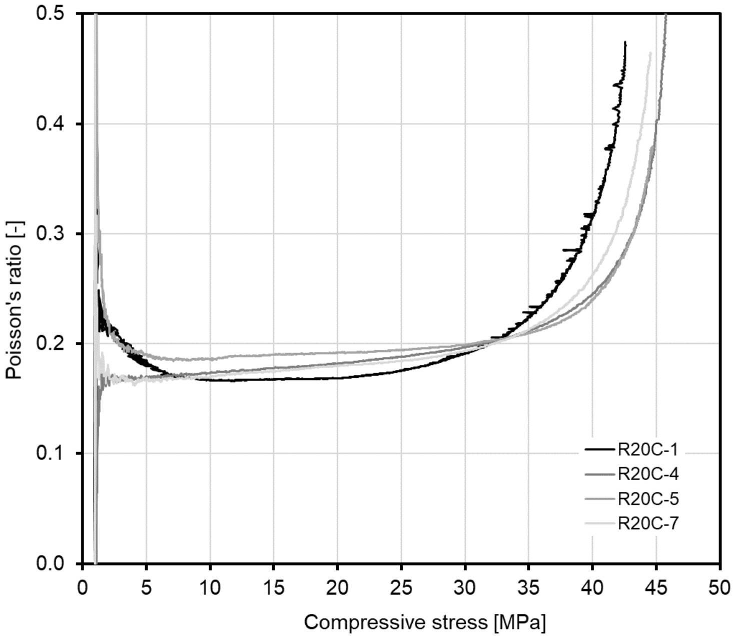

R20C-4
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
50
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Axial strain
Lateral strain
Volumetric strain


R20C-5
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
50
-0.2
-0.1
0
0.1
0.2
0.3
Axial strain
Lateral strain
Volumetric strain

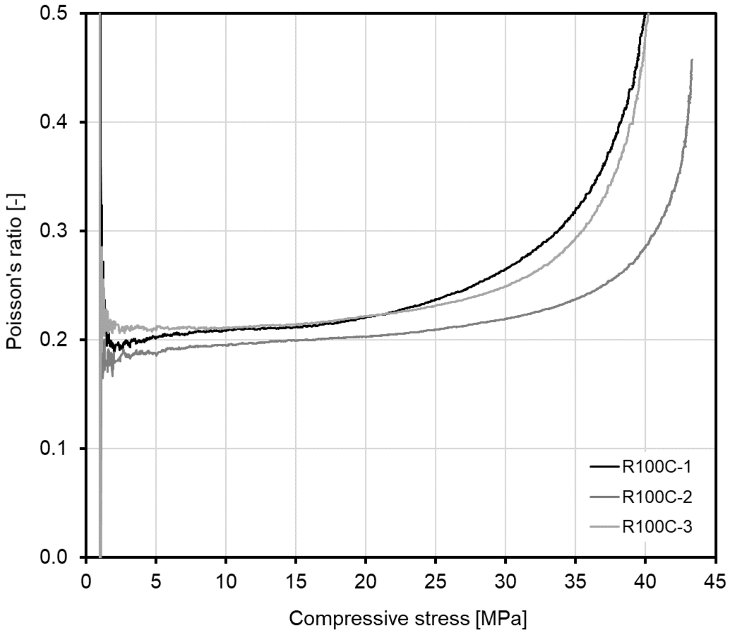

R100C-1
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
-0.2
-0.1
0
0.1
0.2
0.3
Axial strain
Lateral strain
Volumetric strain


RC100C-2
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
-0.2
-0.1
0
0.1
0.2
0.3
Axial strain
Lateral strain
Volumetric strain


R100C-3
Compressive stress [MPa]
Strain [%]
0
5
10
15
20
25
30
35
40
45
-0.2
-0.1
0
0.1
0.2
0.3
Axial strain
Lateral strain
Volumetric strain



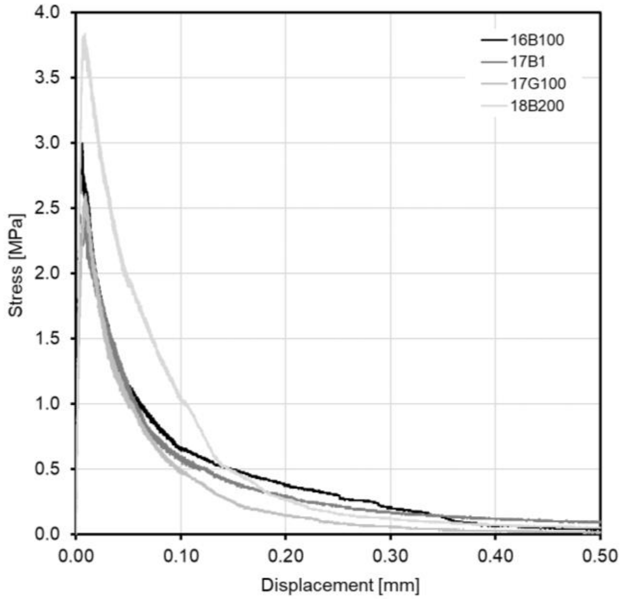
0.5
0.4
0.3
0.2
0.1
0.0
Poisson's ratio [-]
0
5
10
15
20
25
30
35
40
45
50
Compressive stress [MPa]
R20C-1
R20C-4
R20C-5
R20C-7

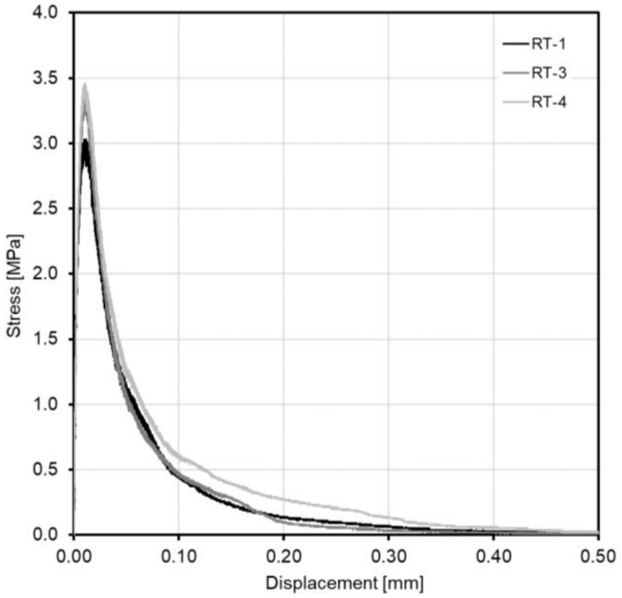


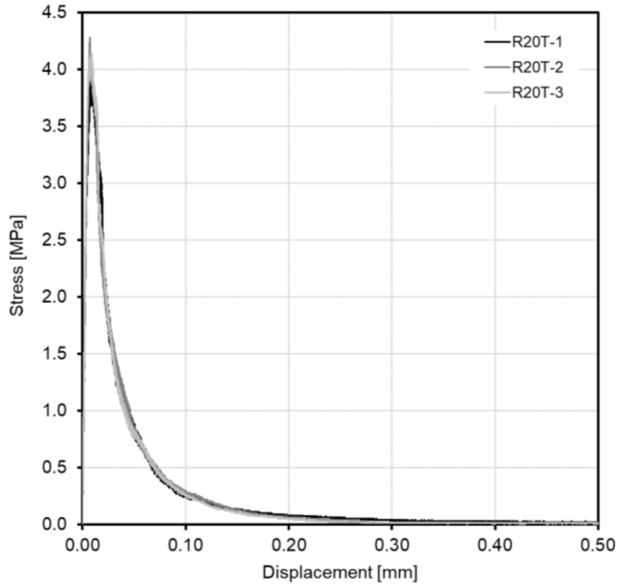
0.5
0.4
0.3
0.2
0.1
0.0
Poisson's ratio [-]
0
5
10
15
20
25
30
35
40
45
Compressive stress [MPa]
R100C-1
R100C-2
R100C-3

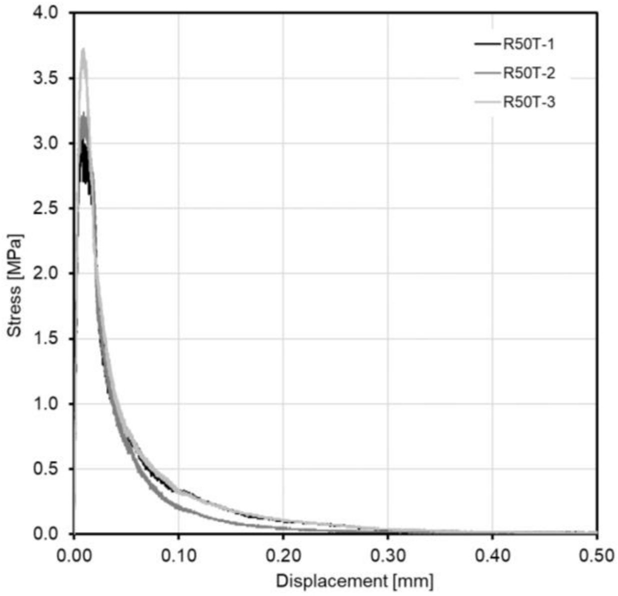
Appendix B

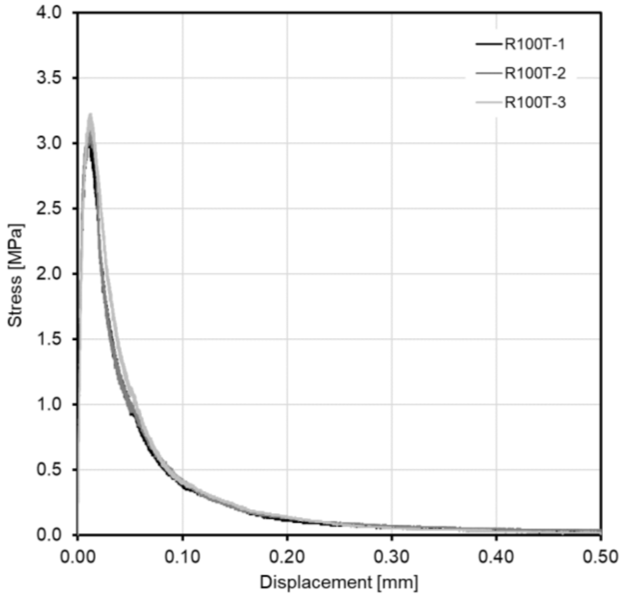
Selected uniaxial tensile test results for Gullspång, 0%, 20%, 50% and 100% replacement


16B100
17B1
17G100
18B200
Stress [MPa]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.10
0.20
0.30
0.40
0.50
Displacement [mm]


RT-1
RT-3
RT-4
Stress [MPa]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.10
0.20
0.30
0.40
0.50
Displacement [mm]


R20T-1
R20T-2
R20T-3
Stress [MPa]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.10
0.20
0.30
0.40
0.50
Displacement [mm]


R50T-1
R50T-2
R50T-3
Stress [MPa]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.10
0.20
0.30
0.40
0.50
Displacement [mm]


R100T-1
R100T-2
R100T-3
Stress [MPa]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.10
0.20
0.30
0.40
0.50
Displacement [mm]