CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering

Department of Architectural Engineering

MASTER THESIS

Life cycle assessment of high performance concrete with fine recycled concrete aggregate

LCA analýza vysokopevnostního betonu s jemným betonovým recyklátem

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Název diplomové práce: LCA analýza ysokopevnostního betonu s jemným betonovým recyklátem

Název diplomové práce anglicky: Life cycle assessment of high performance concrete with fine recycled concrete aggregate

Pokyny pro vypracování:
Budou vyrobeny vzorky z vysokohodnotného betonu s jemným betonovým recyklátem různých frakcí. Budou zhodnoceny a porovnány základní mechanické vlastnosti vysokohodnotného betonu. Na závěr budou vyhodnoceny environmentální dopady metodou LCA.

Seznam doporučené literatury:
Pavlu, T.; Fortova, K.; Mariakova, D.; Repka, J.; Vlach, T.; Hajek, P. High-Performance Concrete with Fine Recycled Concrete Aggregate: Experimental Assessment. Struct. Concr., doi:10.1002/suco.202200734.

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Podpis vedoucího práce Podpis vedoucího katedry

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Abstract

This master thesis is focused on the experimental verification of high performance concrete (HPC) with full replacement of its aggregate fractions by recycled concrete aggregate. Mechanical properties such as flexural strength and stress strength and properties of the fresh concrete such as autogenous shrinkage and dynamic modulus of elasticity are examined in this work. LCA method is then used to compare the environmental impact of HPC with recycled concrete aggregate and HPC with natural aggregate.

Key words

high performance concrete, fine recycled concrete aggregate, LCA analysis, mechanical properties, steel fibers, environmental impact assessment

Abstrakt

Tato diplomová práce se zabývá experimentálním ověřením vysokohodnotného betonu, jehož frakce kameniva byly nahrazeny betonovým recyklátem. V rámci práce jsou testovány mechanické vlastnosti jako pevnost v tahu za ohybu a pevnost v tlaku a vlastnosti čerstvého betonu jako autogenní smršťování a dynamický modul pružnosti. Nakonec je pomocí LCA metody porovnán dopad HPC směsí s betonovým recyklátem a HPC s přírodním kamenivem na životní prostředí.

Klíčová slova

vysokohodnotný beton, jemný betonový recyklát, LCA analýza, mechanické vlastnosti, ocelová vlákna, posouzení dopadu na životní prostředí

Sworn statement

I declare that I have written my master thesis completely by myself and I have not used any sources that are not quoted in the bibliography.

Prague, 22.5.2023

Acknowledgements

I would like to thank everyone, who helped me and supported me when I was working on my thesis. Especially I would like to thank my master thesis supervisors Ing. Tereza Pavlů, Ph.D and professor Kyong Ju Kim for showing me the right direction for my work.

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Finally, I woul like to thank my family for the support during my studies.

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1. Introduction

The interest in using recycled materials derived from construction and demolition waste is growing all over the world. Many waste materials have been proven to be successfully utilized in the production of normal concrete and even in HPC (high performance concrete). Number of researches were made about concrete with recycled aggregates, slag or fly ash. It was proven, that recycled aggregate has many advantages in the terms of environmental impacts. We are talking about climate change impacts, ozone layer reduction impacts, soil acidification, fossil fuels consumption etc.

HPC/UHPC (ultra high performance concrete) is material with excellent properties and durability. However, it requires high quality resources like quartz powder, sand, silica fume and high amount of cement. These resources have high environmental footprint and costs. One of the possible ways how to reduce these negative effects is replacing sand or silica powder by secondary raw materials – recycled aggregate.

UHPC and HPC is being used and will be probably used more often every year. Utilization of recycled aggregates in this concrete might therefore help the concrete industry to find more sustainable future. For UHPC and HPC concrete, high quality crushed aggregate is normally used. In this work, recycled aggregate will be used in mixtures. Requirements for satisfying properties of the aggregate are high, therefore it might be challenging to reach properties of sufficient quality for UHPC or HPC concrete. There have only been a few studies dealing with utilization of recycled aggregates in the production of UHPC or HPC.

Generally, recycled aggregates from other UHPC or HPC structures are convenient to use because of their high quality properties. However, UHPC is a relatively new material, therefore not many UHPC structures are being demolished and there is almost no waste containing UHPC. Therefore, this work deals with aggregates derived from conventional concrete.

2. Research

2.1 High performance concrete

UHPC and HPC are types of concrete with exceptional properties. They usually have high compressive strength, toughness, durability, satisfying self-compacting properties, or better water resistance. UHPC and HPC are relatively new and challenging materials used nowadays for special structures like skyscrapers, long spans and slender bridges. These types of concrete are usually made by using more cement, by adding admixtures, and by using finer aggregate.

The requirement for the concrete to be called UHPC is that its compressive strength must exceed 120 MPa. UHPC usually contains fibers, most commonly steel fibers. HPC is concrete with exceptional properties and compressive strength approximately between 55 and 120 MPa. It usually does not contain any fibers.

Because more cement is added, it might look like the usage of HPC/UHPC is less environmentally friendly, because cement production is very energy-consuming. On the other hand, less of this concrete is needed for the same structure, compared to using regular concrete, due to its exceptional properties. The cross-sections are usually much thinner and smaller. And thanks to higher durability, less maintenance is needed. There is also less waste at the end of the life cycle of the structure. Those are the main reasons, why using UHPC or HPC is actually more environmentally friendly than using conventional concrete.

2.1.1 Composition of HPC/UHPC

A regular concrete mixture contains aggregate, cement, water, admixtures, and additions. The difference between HPC/UHPC and regular concrete is in the composition and component´s ratios.

Aggregate

Aggregate has the filling function and it is the main component by weight. The size and shape of the aggregate grains are important indicators of the mixture.

Crushed aggregate is convenient to use because of its angularity. For regular concrete, coarse to fine aggregate fractions are used with the biggest fractions up to 22 mm. For HPC/UHPC, finer aggregate achieves a more homogeneous mixture. The biggest fraction is usually about 16 mm for HPC and 8 mm or smaller for UHPC.

Cement

Cement is the main binder component. A common type of cement is Portland Cement CEM I with a strength class of 42,5 R. For HPC/UHPC more concrete is added to the mixture compared to regular concrete.

Water

Water has two functions in the concrete mixture: it ensures hydration and workability. The hydration process starts after adding water to the concrete mixture. In consequence, concrete starts getting solid and hard. The amount of water in the concrete mixture is determined by a water/cement ratio (w/c). Concrete usually has the water/cement ratio in the ranges 0.4 – 0.7. Concrete with a lower water/cement ratio has better mechanical properties, which is why less water is used for HPC/UHPC. The water/cement ratio for HPC is typically between 0.3-0.4, for UHPC below 0.2. The small amount of water is compensated by adding plasticizers or superplasticizers.

Admixtures and additions

Admixtures and additions are chemical components used in small amounts. Their purpose is to adjust some of the concrete properties such as workability, rate of hardening etc.

Plasticizers and superplasticizers are important admixtures in HPC and UHPC. They compensate for the reduced water/cement ratio by improving workability.

Other admixtures are used for example for slowing down or accelerating the hardening process.

Supplementary cementitious materials are additions, that are not used in regular concrete, but only in HPC/UHPC. These kinds of materials have very small grain sizes – smaller than 0.125 mm and are used to fill the space between coarser grains. Quartz powder, silica fume, or other materials can be used for this purpose.

Fibers

Fibers are used in UHPC or sometimes even in HPC. Fibers increase the strength of the concrete, especially the tensile and flexural strength. Different materials can be used – steel fibers, synthetic fibers, or mineral fibers.

2.2 Recycled aggregate

Natural aggregate, the main component of concrete, is very demanded, and its consumption grows by about 5% annually. It is not only used as a concrete component, but also for backfilling, landscaping, etc. Concrete is the most used construction material, therefore a high amount of construction waste is produced not only during demolitions, but also in precast industry. In the Czech Republic, demolition waste accounts for 30% of total waste production. Recycling of construction and demolition waste produce materials, which can be used again as primary resources. Waste concrete can be recycled, crushed, and used as a primary resource for new concrete.

Using recycled aggregate for concrete has some inconveniences. One of the issues is determining the concrete´s properties with this aggregate. Usually, we don´t know the origin of the recycled aggregate and the environment of the specific concrete element, that was used (crushed) to concrete aggregate. Therefore, we also don´t know the exact properties of the recycled aggregate and which impurities or chemicals it might contain. These circumstances might affect the final concrete properties in ways that are hard to predict. Without the exact properties of the recycled aggregate, it is difficult to determine the concrete properties.

2.2.1 Drivers for the deployment of recycled aggregate in concrete

CO_2 emissions

Production of natural aggregate requires a lot of energy connected to the high CO_2 emissions.

Waste landfilling

Instead of ending up in landfills, materials can be reused. This also cuts landfilling costs that would otherwise appear if storing waste at the landfill.

Scarcity of raw materials

Aggregates are the largest components of concrete. Demand and production of aggregate are rapidly increasing. Crushed rock and river sand or gravel are used the most. Increasing extraction might lead to serious problems.

Costs

Nowadays, getting recycled aggregate is cheaper than using natural raw aggregate.

2.2.2 Recycling process

The way of parental concrete recycling is important for the properties of the future recycled aggregate. The recycling process takes place in a recycling plant. Concrete rubble from different demolition sites is transported to these plants. In the rubble, different types of concrete might be mixed. Therefore, the properties of the recycled aggregate might differ a lot. It would be very difficult to separate the concrete types because even at one demolition site, concrete elements have different origins, properties, components and have been exposed to different environments.

There are numerous recycling techniques being used in the recycling plants. Mechanical methods like jaw, impact, or rotor crushing might be used. Methods differ in the duration of crushing, number of crushing cycles, etc. Some methods use an increased number of steps to remove the paste from the recycled concrete aggregates. Still, more steps result in higher energy consumption and a higher amount of particles smaller than 0.063 mm, which is not desired.

During the recycling process it is desirable to remove pollutants. Metals can be removed using magnets, and light materials like polymers can be removed by water flotation. Screens are used to separate coarse and fine materials.

Storage of the concrete recycled aggregate should be inside. Outside storage should be avoided because it causes carbonatation of the outer layers of fRCA piles.

2.2.3 Fine recycled concrete aggregate

Fine recycled concrete aggregate (fRCA) is aggregate with grain size smaller than 4 mm. It originates from multiple crushing of the concrete rubble. The fRCA is currently used in low-grade applications as a substitute material for natural aggregate, it is not commonly used for load-bearing structures. Only a few studies deal with the utilization of fRCA for structural concrete. These studies mainly focus on testing specimens that are made with fRCA from laboratory crushed mortars and concretes, therefore, prepared with material that is different from the actual recycled concrete from real structures.

Although the use of fRCA in structural concrete was reported to have a positive environmental impact, studies have indicated several issues when using fRCA regarding fresh and hardened properties of new concrete. For example, high water absorption of fRCA may lower concrete workability, or it can be contaminated by chlorides and sulfates, which may significantly impact the durability of the new concrete.

Water absorption (WA) and density of aggregates are the key parameters in concrete mix design. To determine the water absorption of fRCA no single method is generally accepted, and therefore various test methods are used to determine water absorption of fRCA. The water absorption testing of fRCA is very complicated due to fluctuating fRCA properties. The WA determination methods are generally based on saturating and drying the aggregate. For fRCA, a much longer time for saturation is needed than for regular concrete. Also, it is very difficult to dry every small particle uniformly. Result might be extrapolated from different method results. fRCA generally has higher WA and lower density than natural fine aggregate due to higher content of open pores and rougher surfaces. For comparison, the reported WA values for fRCA vary between 4.28 and 13.1% with an average of 8.4%, WA of natural fine aggregate varies between 0.15 and 4.1% with an average of 1.1%. Higher WA increases the water/cement ratio needed for the mixture, which might cause some of the concrete properties to get worse. The moisture state is another property of the fRCA that should be considered when designing the concrete mix. fRCA might already contain some moisture, this state would decrease the WA rate.

To sum up, fRCA contains more fine particles with significantly higher WA capacity, and the particle size distribution differs from natural fine aggregate (Figure 1). The shape of fRCA particles is rounder, and the surface are rougher. The surface texture and particle shape of fRCA depend largely on the parent concrete composition, the recycling technique, and the number of crushing cycles. Impurities such as various chemicals or particles of wood, steel, polymers, glass, or plant fibers might significantly impact the concrete's properties.

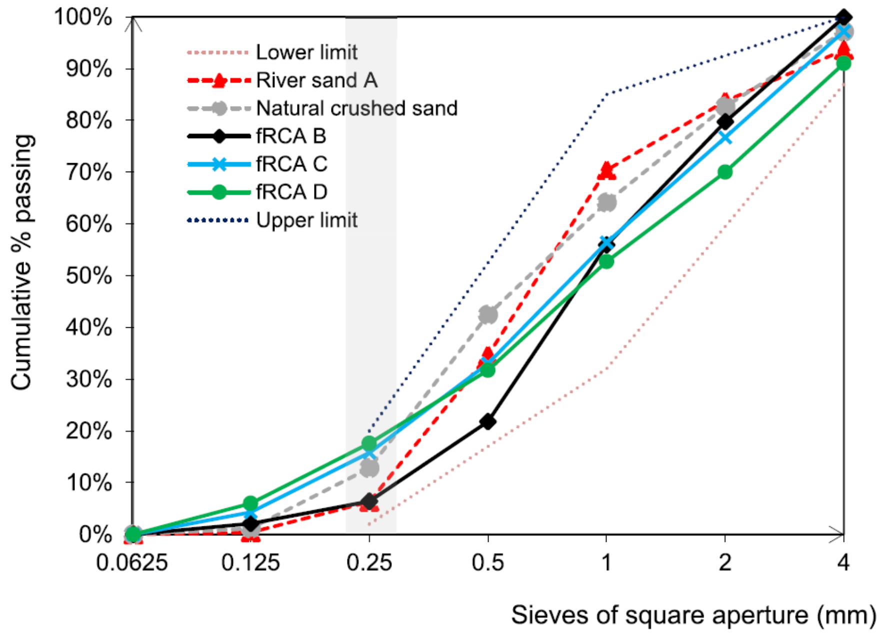

Figure 1 - Particle size distributions of a river sand (A), natural crushed sand and fRCA obtained by rotor crushing (B) and two different fRCA obtained by jaw crushing (C, D)

2.2.4 Properties of concretes containing fRCA

Aggregate properties such as particle size distribution, particle texture and shape, porosity, and initial water saturation have a huge impact on the properties of the concrete. As mentioned, fRCA has much higher WA than natural aggregate. High WA might cause worse workability of the concrete. A higher water/cement ratio caused by higher WA also tends to have an impact on mechanical properties.

The compressive strength of concrete with fRCA is usually lower, but not always. It depends on the replacement level and which fractions are being replaced. Some studies found a strength increase of the concrete with fRCA compared to reference concrete. fRCA can have a positive impact like this thanks to its filler effect – thanks to the higher ratio of small particles it can make the concrete mix more compact and denser. Another reason could be its internal curing ability – water initially absorbed in the pores is available during the late stages of the hydration process.

According to recent studies, the elastic modulus is decreased quite rapidly when fRCA is used, even if the substitution is low (<30%). However, superplasticizers can compensate for this decrease of the elastic modulus.

Shrinkage and creep also tend to be higher, but again, not always. It depends on many factors, and in some cases, shrinkage could decrease with the usage of fRCA.

The durability of the concrete is influenced by its permeability, which is higher when fRCA is used. Higher water and oxygen permeability negatively affects the durability of the concrete.

2.3 LCA (Life cycle assessment)

LCA analysis may be used as a tool for the environmental impact assessment of HPC structures. In this thesis, I will compare the environmental impacts of different HPC mixtures containing natural aggregate and fRCA using LCA analysis.

In the construction industry, LCA is used as a decision-making tool to assess environmental impacts by quantifying environmental loads through the life cycle of a structure, including manufacturing and fabrication of construction materials, construction, operation and maintenance, and demolition and disposal.

2.3.1 LCA principles and procedures

LCA is a standardized multi-stage methodology used by scientists and engineers to evaluate and assess the environmental impact of a product or a product system during its entire life cycle. All the product life cycle phases are considered in the LCA – from materials, energy and transportation needed for manufacturing the product to maintenance, recycling, and elimination (demolition). Technical standards ISO 14040 and 14044 deal with LCA topics. LCA structure is determined by the mentioned standards and has 4 phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment (Life cycle impact assessment – LCIA)
4. Interpretation of results

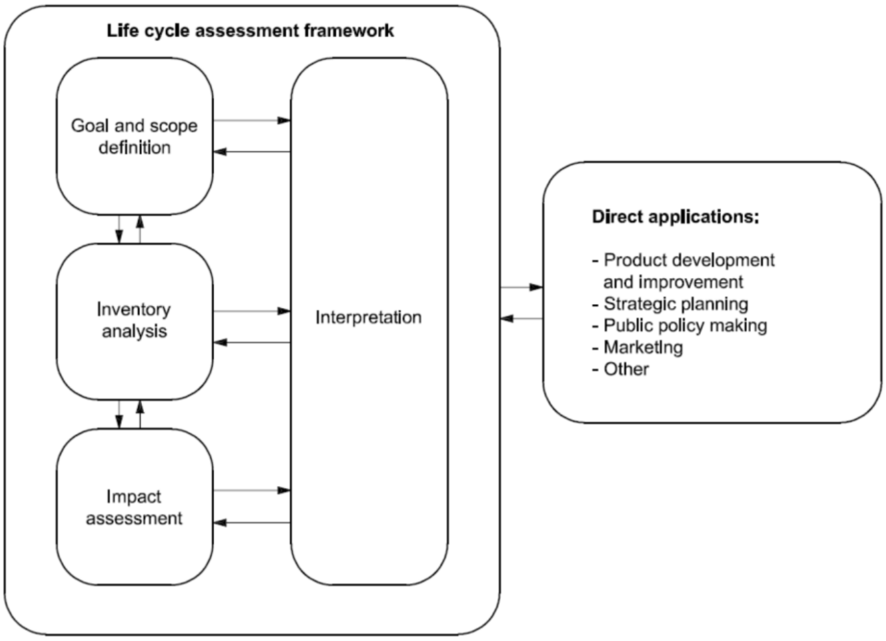

Figure 2 – Phases of LCA

2.3.1.1 Goal and scope definition

In the first phase, the overall purpose of the study, scope, system boundaries and chosen functional unit are determined. It is decided, which inputs and outputs are considered in the study (scope).

System boundaries define the life cycle approach depending on which parts of the life cycle we want to cover. Common system boundaries are:

1. Cradle to gate: includes only the production stage, and does not include the operation and end-of-life stage of the product.
2. Cradle to grave: includes all stages from production through the stages of transportation and use of the product to its disposal.
3. Cradle to cradle: includes all the mentioned stages plus the recycling stage. This model creates a loop, where recycled materials from the final stage are used for the initial stage of the new product.

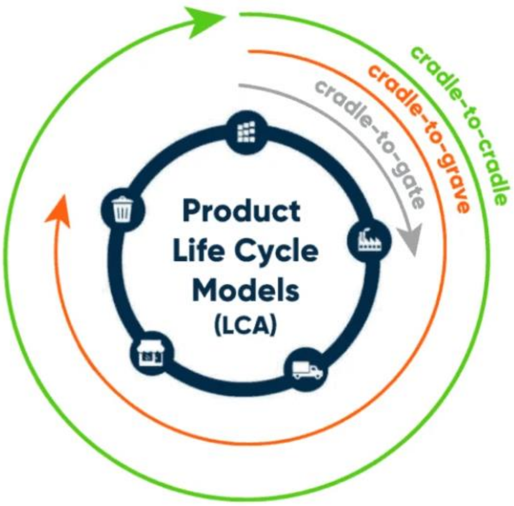

Figure 3 – Common system boundaries in LCA

Every product or product system has a function, but its performance is usually not the same. Thanks to the determined functional unit we can compare individual products. A functional unit is the quantified description of the performance of the product or product system.

2.3.1.2 Inventory analysis

The second phase, also called life cycle inventory phase, looks at the environmental inputs and outputs of a production system. It is necessary to find all the processes included in the system and quantify them. Individual processes in the product systems are modeled as flows. Flows contain data like amounts of materials, energy, fuels, water, and emissions. The inventory analysis phase involves collecting the data necessary to meet the goals of the defined study. Usually, a lot of data is needed for LCA, which is commonly taken from the online databases. A lot of the data for the LCA is already available, but usually additional data are required. Additional data can be obtained directly from the companies involved in the production or sometimes industry average can be used.

2.3.1.3 Impact assessment (LCIA)

LCIA phase is the third phase of LCA, which evaluates how significant the impacts are. In this phase, impact categories are defined, and the potential environmental impacts are calculated and evaluated according to the chosen evaluation method. The impact categories are defined based on our goals. The most common impact categories are global warming potential, human toxicity, ecotoxicity, acidification and eutrophication. The life cycle inventory is sorted and assigned to these impact categories. And finally, results for each category are calculated using data from the inventory analysis phase.

2.3.1.4 Interpretation of results

The last phase is an interpretation of the results. The results are the amounts of materials, substances and energy that interact with the environment. According to the type of environmental impact, we distinguish different impact categories and get results for them. The results are summarized and discussed as a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definitions.

3. THE EXPERIMENTAL PART

3.1 The aim of the work

In this part of the work, the experimental examination of the HPC samples containing fRCA is described. The aim of the work is to test the compressive and flexural strength of the samples with fRCA and compare the results with the samples with natural aggregate. Shrinkage and dynamic modulus of elasticity values were also measured in the experimental part.

3.2 Materials and Mixtures

The materials used for HPC samples preparation were cement, natural aggregate – technical quartz sand and technical quartz powder, fRCA, silica fume, steel fibers, superplasticizer, and water.

fRCA was taken from a recycling plant. It was crushed in a jaw crusher to get smaller particles and sieved to get fractions. One crushing process was used to get the fractions that were needed. The concrete mixtures contained three types of fRCA - fraction 0.000/0.063 mm, 0.125/0.5 mm, and 0.5/1.0 mm.

Figure 4 - Materials used in the HPC mixtures - different fractions of natural aggregate, cement, silica fume and superplasticizer

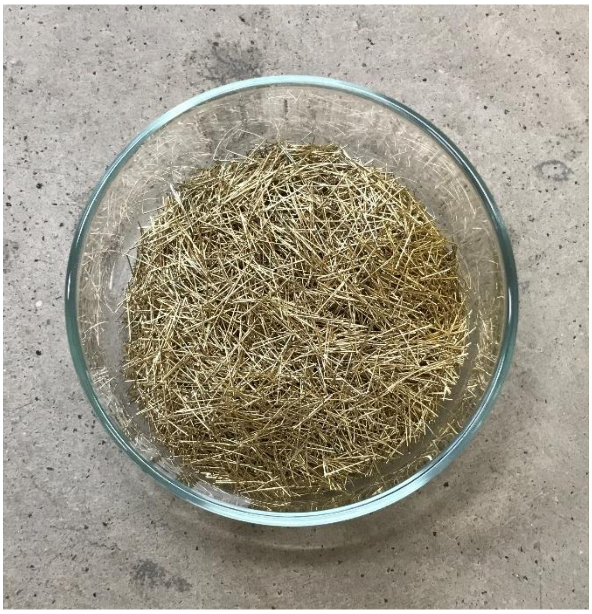
Figure 5 - All the samples contained steel fibers

In this work, 4 different mixtures were made and tested. The first mixture was a reference mixture (HPC_REF), only natural aggregate was used for this mixture. The other 3 mixtures (HPC_1, HPC_2, HPC_3) all contained fRCA, but different fractions. The reference mixture and mixtures with fRCA were made according to the same concrete recipe, only the different fractions of the natural aggregate were substituted for fRCA. See Tables 1 – 4 for the recipes of each mixture.

HPC_REF mixture is a reference mixture, which contained only natural aggregate. The biggest grain size was 1.2 mm.

Table 1 - HPC_REF mixture recipe

Component	**Quantity [kg/ton]**
Cement CEM I 42,5R	308.1
Technical quartz sand 0.1/0.6	261.0
Technical quartz sand 0.6/1.2	174.0
Technical quartz powder ST 6	101.9
Elkem microsilica 940 U-S	34.0
Fibers	36.2
Superplasticizer	8.6
Water	76.1
TOTAL	**1000.0**

In **HPC_1** mixture, technical quartz sand 0.1/0.6 was substituted by fRCA fractions 0.125/0.25 and 0.25/0.5.

Table 2 - HPC_1 mixture recipe

Component	**Quantity [kg/ton]**
Cement CEM I 42,5R	305.3
fRCA 0.125/0.5	**258.6**
Technical quartz sand 0.6/1.2	172.4
Technical quartz powder ST 6	101.0
Elkem microsilica 940 U-S	33.7
Fibers	35.9
Superplasticizer	8.5
Water	84.4
TOTAL	**1000.0**

Figure 6 – fRCA fractions 0.125/0.25 and 0.25/0.5

In **HPC_2** mixture, technical quartz sand 0.6/1.2 was substituted by fRCA fraction 0.5/1.0. This means, that the coarsest fraction of the natural aggregate was substituted in this mixture. The biggest grain size of this mixture is 1.0 mm.

Table 3 - HPC_2 mixture recipe

Component	**Quantity [kg/ton]**
Cement CEM I 42,5R	304.0
Technical quartz sand 0.1/0.6	257.5
fRCA 0.5/1.0	**171.7**
Technical quartz powder ST 6	100.6
Elkem microsilica 940 U-S	33.5
Fibers	35.8
Superplasticizer	8.5
Water	88.5
TOTAL	**1000.0**

Figure 7 – fRCA fraction 0.5/1.0

In **HPC_3** mixture, technical quartz powder was substituted by fRCA fraction 0.000/0.063. This means, that the finest fraction of the natural aggregate was substituted in this mixture.

Table 4 - HPC_3 mixture recipe

Cement CEM I 42,5R	303.0
Technical quartz sand 0.1/.,6	256.7
Technical quartz sand 0.6/1.2	171.1
fRCA 0.000/0.063	**100.3**
Elkem microsilica 940 U-S	33.4
Fibers	35.7
Superplasticizer	8.5
Water	91.4
TOTAL	**1000.0**

Figure 8 – fRCA fraction 0.000/0.063

3.3 Preparation of the samples

Together, 48 sample beams were prepared – 12 samples from each mixture. The dimensions of the beams were 160 × 40 × 40 mm.

The consistency of the reference mixture was favorable. Because water absorption of fRCA is higher than water absorption of natural aggregate, mixtures with fRCA were too dense and water addition was necessary. After adding 100 g, 150 g and 185 g of water to the mixtures HPC_1, HPC_2 and HPC_3, respectively, the consistency of the mixtures with fRCA was favorable, too. In the Tables 2 - 4, the addition of extra water is already included.

Figure 9 - Set of 12 beam samples in the forms – reference mixture HPC_REF

Figure 10 - Set of 12 beam samples all made from one mixture – HPC_3

3.4 Testing

HPC mixtures were tested by several methods. Flexural strength and compressive strength were tested by a destructive method. Shrinkage was measured for the first 3 days after mixing in a shrinkage measuring cone device. Dynamic modulus of elasticity was also measured for the first 3 days after mixing with a Vikasonic device.

3.4.1 Flexural strength tests

Samples from each mixture were tested for flexural strength by three-point bending at the age of 3, 7, 14 and 28 days. Another alternative testing type would have been four-point bending. At each age, 3 samples were tested.

Before the tests were executed, the samples were stored in water. After taking out of the water, the samples were let to dry for a couple of minutes. When they were dry, their weight and dimensions were measured. Then, the samples were placed in a hydraulic press and the test was ready to start. Testing was controlled by a PC program. The required data like weight, sample width, type of the sample and type of testing were entered in the PC program. Speed of testing was set to 50 N/s, peak 3 kN.

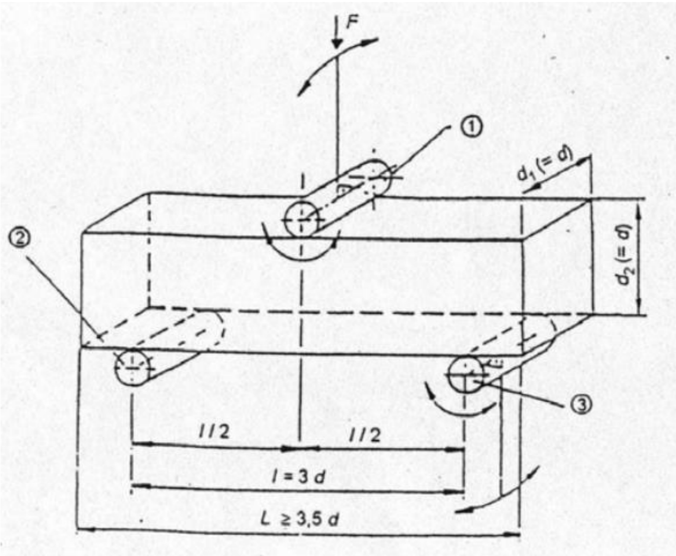

Figure 11 - Flexural strength testing scheme

The result of this test is the highest force registered during testing. Most of the times, the appearance of the first crack was not followed by a collapse immediately. The sample was able to carry more load, while the crack was getting wider. The sample was loaded until the collapse was registered. This occured only due to the fibers presence. In case of a sample with no fibers, collapse and the highest force would be registered in the moment right after the first crack appeared.

The highest registered force was used to calculate the flexural bending strength:

$$f_{cf} = \frac{3.F.l}{2.d_1.d_2^2}$$

Where:

f_{cf} is the flexural strength [MPa]

F is the highest force registered during testing [N]

l is the distance between supports [mm]

d_1 is the horizontal dimension of the sample´s cross section [mm]

d_2 is the vertical dimension of the sample´s cross section [mm]

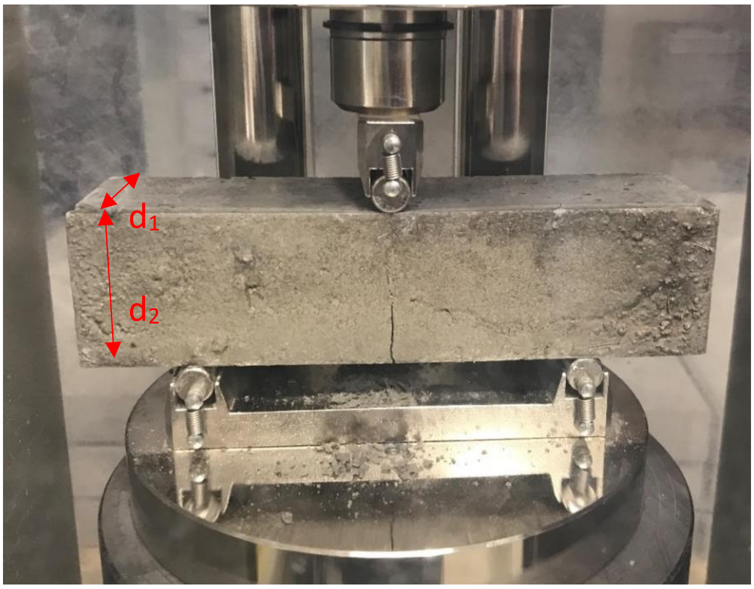

Figure 12 - The moment when the first crack appeared – the maximum force was not yet registered

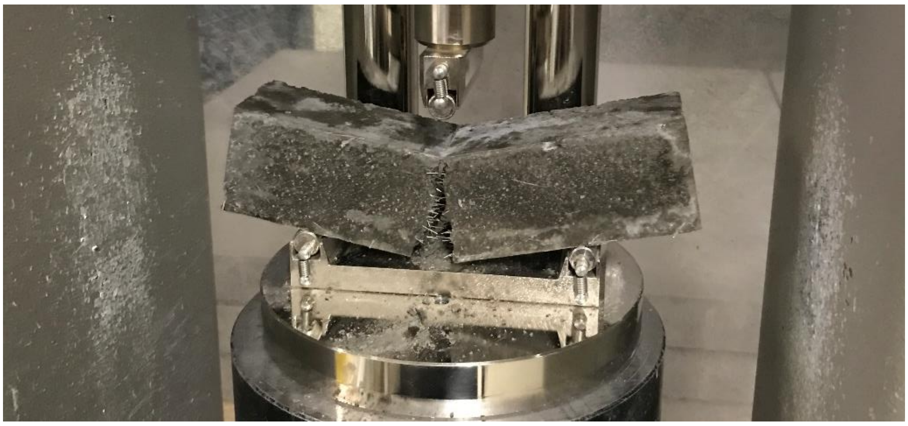

Figure 13 - The sample after the collapse

3.4.2 Compressive strength tests

Samples of each mixture were tested for a compressive strength at the age of 3, 7, 14 and 28 days. Samples were tested by using destructive method with a hydraulic press. Compressive strength tests were carried out immediately after flexural strength tests. Samples from the flexural tests, that were broken in halves, were used for this test. At each age, 6 samples were tested. Testing surface was 40 × 40 mm.

Testing was again controlled by PC program, required data were entered in the PC program and testing was ready to start. Speed of testing was set to 2400 N/s, peak 35 kN.

The test was completed when the sample broke. The highest force was recorded at the moment of the collapse. The highest recorded force was used to calculate the compressive strength:

$$f_{cc} = \frac{F}{A_c}$$

Where:

f_{cc} is the compressive strength [MPa]

F is the highest force registered during testing [N]

A_c is the surface of the sample on which the compressive strength is applied [mm^2]

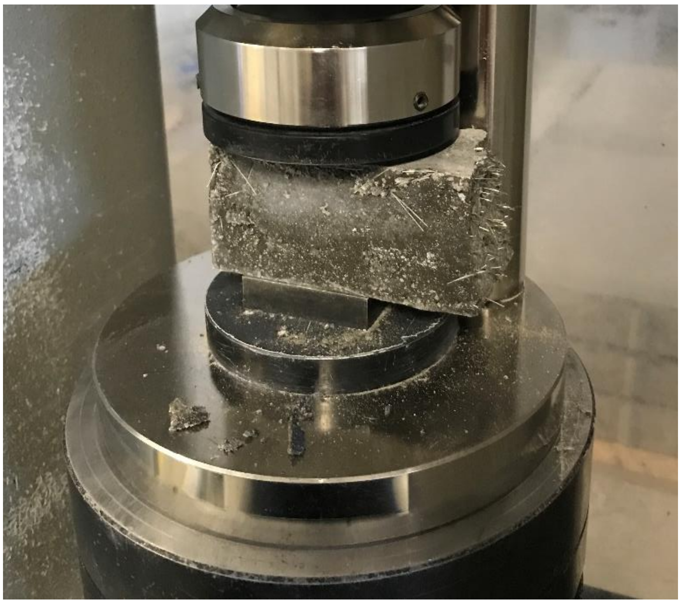

Figure 14 - Sample ready for the compressive strength test

Figure 15 - Broken sample after the compressive strength test

3.4.3 Shrinkage tests

Shrinkage was measured during the first 3 days after making the mixture. Shrinkage measuring cone device was used for this measurement. This device can measure early shrinkage and expansion of fluid materials. Shrinkage of the material is registered contactless and accurately by a laser beam.

The measurement procedure begins with filling the fluid material into the cone-shaped specimen container. The container is placed under the laser unit. The position of the laser unit is adjusted. Sensor is placed in the mixture for temperature measurement. The measurement is started in a PC program. The measurement data are digitized and stored in the PC program.

Figure 16 - Shrinkage measuring cone device

3.4.4 Dynamic modulus of elasticity tests

The development of dynamic modulus of elasticity was measured during the first 3 days after making the mixture. Vikasonic device was used for this measurement. Vicasonic device uses ultrasonic waves for continuously monitoring the material properties.

Fresh material is placed between two ultrasonic transducers. The ultrasound signal is generated by a signal source, is then transmitted through the material, and detected by the second transducer. The time the signal needs to go through the sample to the receiver is measured to calculate the velocity of the signal. During the hardening of the sample transit times are continuously measured. Due to the consistency change of the sample this results in different wave velocities.

Also, the Youngs modulus in GPa and the signal strength in dB is calculated and recorded. Additionally, the temperature inside the specimen is measured with a type K thermocouple and recorded in °C. The measurement is done continuously, and the measurement data are recorded digitally to a USB stick. No PC is required during testing. Recorded data can be easily imported to the Excel worksheet or to other programs.

Figure 17 - Vikasonic device

3.5 Results and discussion

Destructive tests to determine the flexural and compressive strength were carried out. Additionally, shrinkage and dynamic modulus of elasticity was measured with the shrinkage measuring cone device and Vikasonic device, respectively. The following chapters describe and discuss the results of all tests that were carried out.

3.5.1 Flexural strength

Flexural strength of the samples was tested by the three-point bending test. Behavior of the samples during this test was significantly influenced by the steel fibers. Due to the presence of the fibers, samples did not collapse right after the the first crack appeared. Most of the times, the first crack appeared relatively early after loading started. Then, with the increasing load, the crack was getting wider until the sample collapsed. The Table 5 shows all maximum recorded flexural strengths of the samples.

Table 5 – The maximum recorded flexural strengths

Age [days]	Sample number	HPC_REF Strength [MPa]	HPC_1 Strength [MPa]	HPC_2 Strength [MPa]	HPC_3 Strength [MPa]
3	1	17.81	15.45	18.65	13.51
	2	18.58	10.53	21.41	11.4
	3	19.51	14.42	14.95	11.14
7	4	16.72	18.54	15.18	14.92
	5	18.96	9.88	16.58	17.99
	6	19.9	9.28	19.16	11.62
14	7	24.39	17.83	21.86	14.53
	8	27.15	13.12	26.31	17.72
	9	19.13	16.67	20.86	14.58
28	10	21.53	15.36	23.67	30.2
	11	23.87	15.78	24.69	28.35
	12	32.6	21.35	22.05	27.13

Figure 18 shows average values of flexural strength at the age of 3, 7, 14 and 28 days of different mixtures.

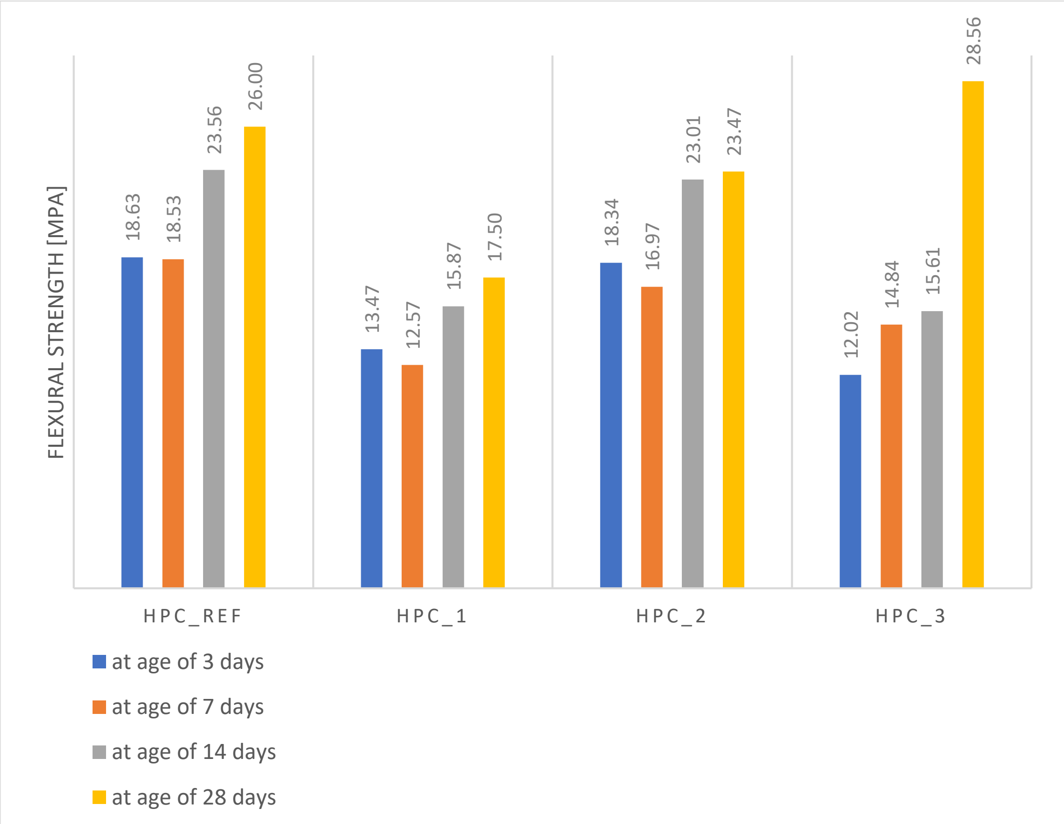

Figure 18 - Average flexural strengths at the age of 3, 7, 14 and 28 days of different mixtures

The values of flexural strength do not grow very steadily, and they show some abnormalities - in the case of three mixtures, the strength at the age of 7 days is lower than the strength at the age of 3 days. Abnormalities can be caused by the random distribution of the fibers. The position of the fibers has a significant impact on the flexural strength test results.

3.5.2 Compressive strength

As typical for concrete, compressive strength grows with age. Table 6 show the maximum recorded compressive strengths of the samples made from each mixture.

Table 6 - The maximum recorded compressive strengths

Age [days]	Sample number	HPC_REF Strength [MPa]		HPC_1 Strength [MPa]	
3	1	98.16	98.19	75.19	79.33
	2	96.12	102.80	79.79	81.55
	3	104.63	105.07	81.65	77.73
7	4	108.59	111.95	97.56	96.03
	5	117.33	114.53	95.61	93.42
	6	113.78	114.95	96.19	97.44
14	7	124.02	126.55	112.04	119.74
	8	133.50	132.97	109.08	111.43
	9	120.65	132.41	115.39	109.34
28	10	145.29	142.95	119.45	121.24
	11	147.33	142.42	131.31	124.33
	12	137.88	146.16	123.98	121.92

Age [days]	Sample number	HPC_2 Strength [MPa]		HPC_3 Strength [MPa]	
3	1	85.72	91.46	76.80	75.95
	2	91.20	86.90	72.37	71.94
	3	89.17	87.53	71.63	72.86
7	4	107.55	107.98	86.72	88.01
	5	101.39	104.92	89.83	93.73
	6	103.82	106.03	84.77	89.14
14	7	126.23	120.52	98.29	106.56
	8	118.68	117.97	100.72	105.90
	9	127.15	124.77	101.43	100.36
28	10	139.23	121.80	119.51	116.52
	11	143.33	148.01	119.80	112.07
	12	128.75	125.81	111.92	111.85

Figure 19 shows average values of compressive strength at the age of 3, 7, 14 and 28 days of different mixtures.

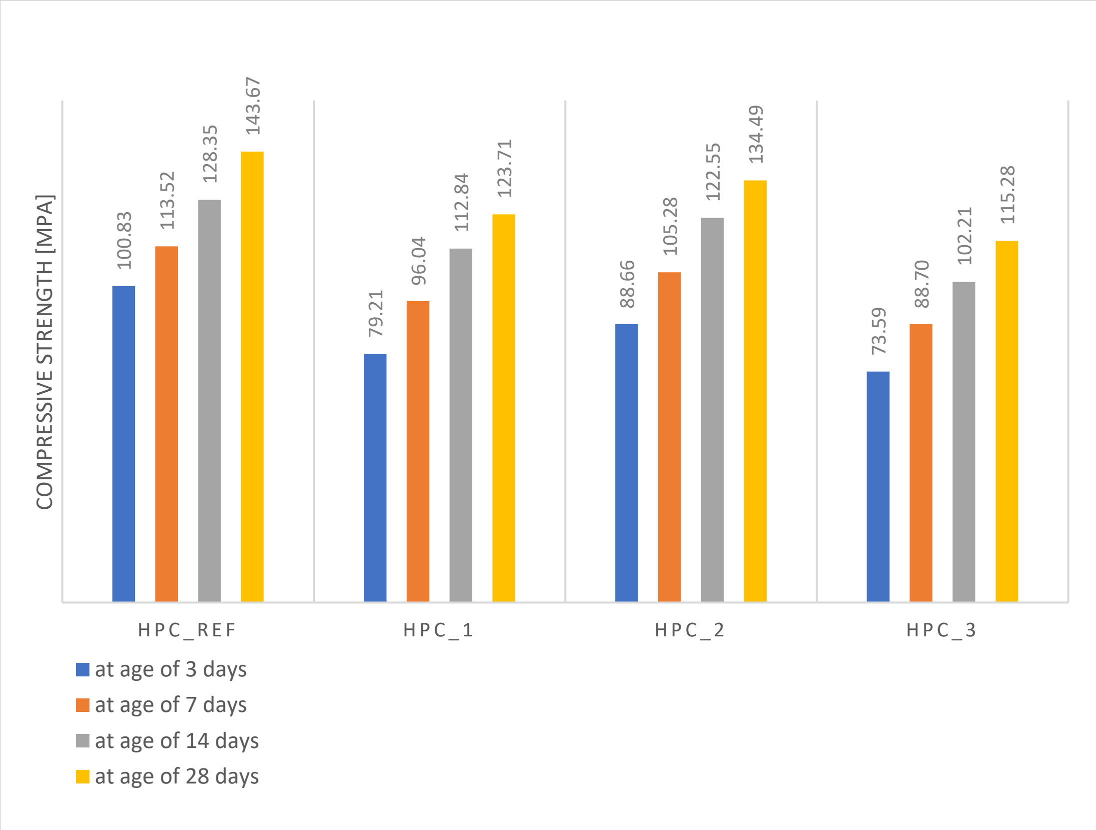

Figure 19 - Average compressive strengths at the age of 3, 7, 14 and 28 days of different mixtures

The values of compressive strength of all mixtures steadily grow in time, which corresponds with the expectation. The reference mixture shows the best results, meaning that substituting the natural aggregate for recycled concrete aggregate always negatively impacted the compressive strength. However, the results were satisfying – after 28 days, mixtures HPC_1, HPC_2 and HPC_3 had a compressive strength of 86.1%, 93.6% and 80.2%, respectively, compared to the reference mixture (considered as 100%) – Figure 20. HPC_2, the mixture with the coarsest fraction replacement (0.5/1.0 mm), showed the best results. On the contrary, HPC_3 mixture, the mixture with the finest fraction replacement (0.000/0.063 mm), showed the poorest results.

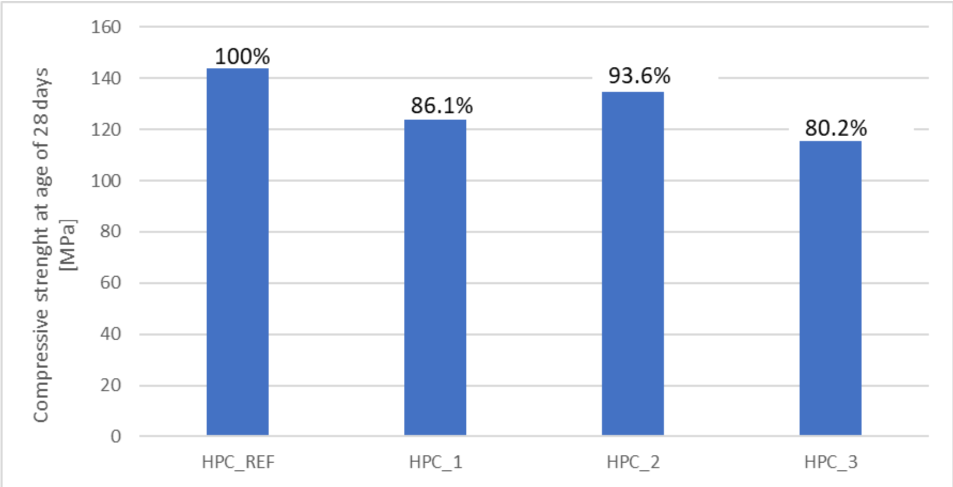

Figure 20 – Compressive strength comparison at the age of 28 days

3.5.3 Shrinkage

Autogenous shrinkage is one of the critical properties of fresh HPC. It is typical for HPC due to the reduced water/cement ratio and internal moisture. The Figure 21 shows the shrinking progress of all four mixtures during the first three days after making the mixture.

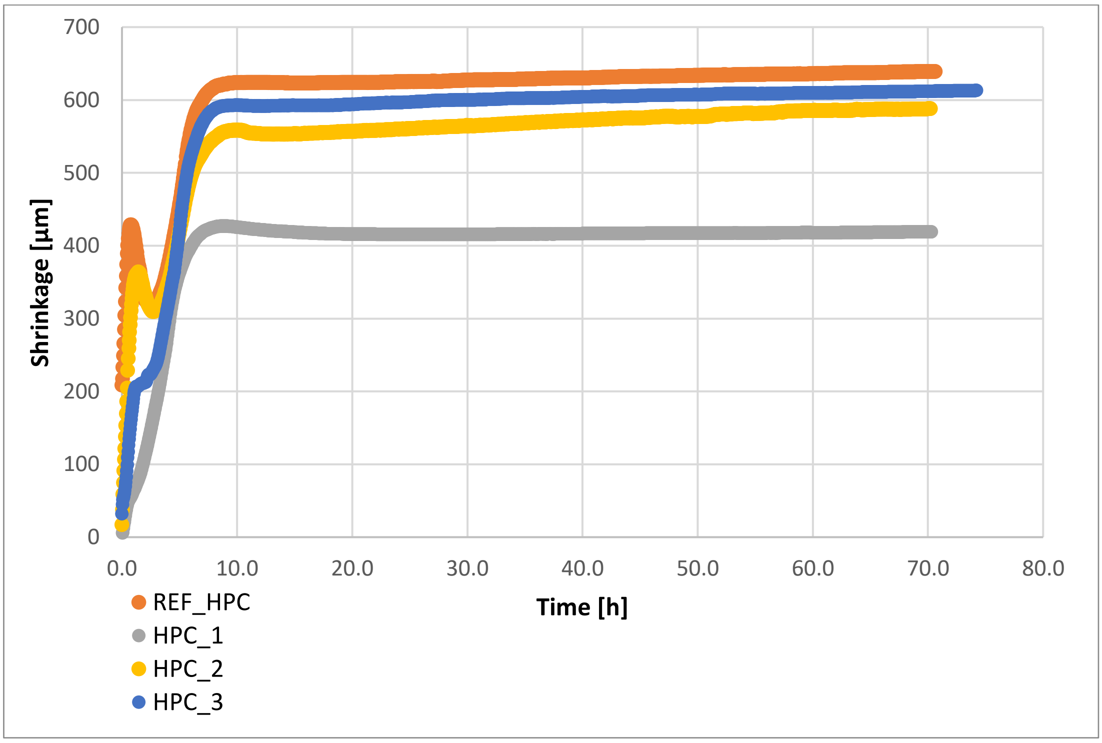

Figure 21 – Shrinkage development of each mixture

In the Figure 21 we can see that the replacement of natural aggregate by fRCA led to the decrease of autogenous shrinkage. All the three mixtures containing fRCA shrank less than the reference mixture. The highest decrease was observed for the mixture HPC_1 (fraction 0.125/0.5 replacement). The decrease in shrinkage is probably caused by internal curing – fRCA absorbed water initially and was releasing it during hydration process.

3.5.4 Dynamic modulus of elasticity

Dynamic modulus of elasticity was one of the properties recorded by Vicasonic device. Figure 22 shows the development of the dynamic modulus of elasticity during the first three days after making the mixture.

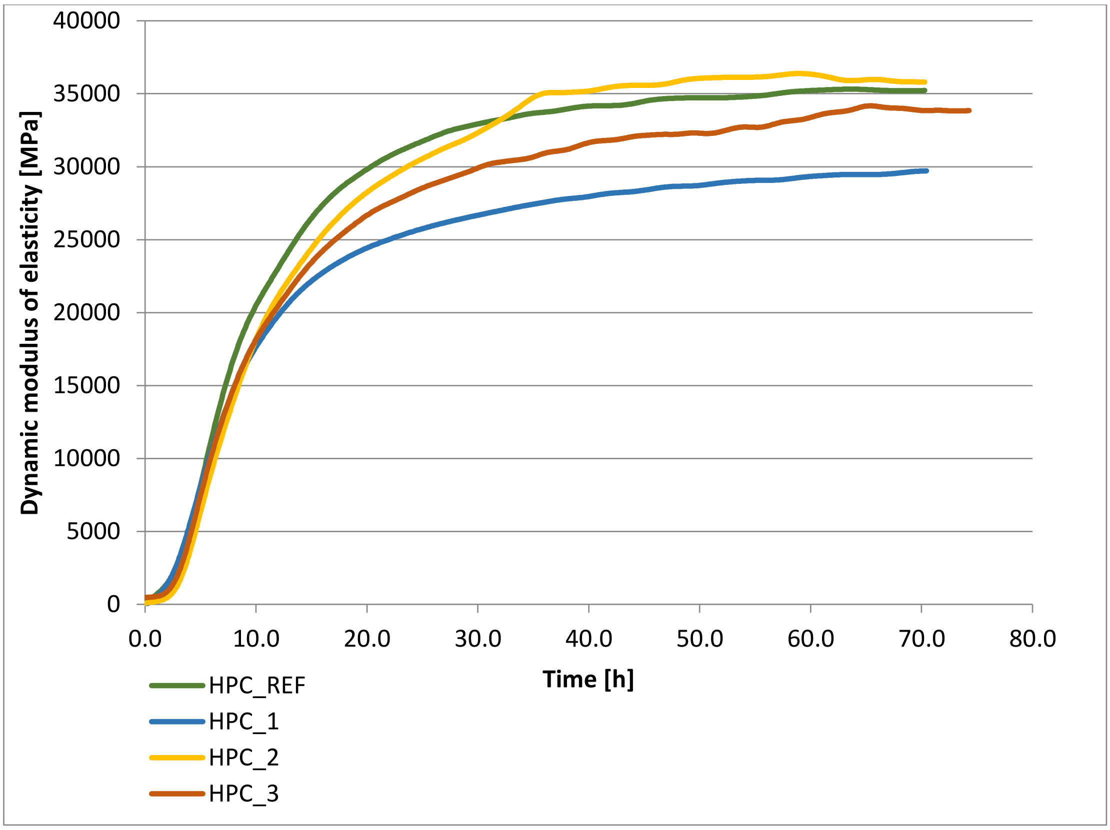

Figure 22 – Dynamic modulus of elasticity development

In general, mixtures with recycled aggregate tend to show a decrease of modulus of elasticity. However, in this work the HPC_2 mixture resulted to have higher dynamic modulus of elasticity. The lines in the graph were smoothened out by averaging values, that are close to each other. Because the concrete mixtures solidified after approximately 4 hours, the result might not be accurate during the first 4 hours.

4 LCA

The LCA method was used to analyze and compare the potential environmental impacts of different HPC mixtures. LCA was performed in four main phases: goal and scope definition, inventory analysis, life cycle impact assessment (LCIA), and interpretation of results (see chapter 2.3). The method follows ČSN EN ISO 14040, ČSN EN ISO 14044, and ČSN EN 15804.

4.1 Goal and scope definition

The initial step in this analysis is to determine the goal and scope that provide the overall purpose and limits of the research. The work aims to compare the environmental impact of 3 concrete mixtures containing different fractions of fRCA and the reference mixture containing only natural aggregate. All 4 mixtures have similar recipes – they contain the same amount of cement, silica fume, fibers, and superplasticizer. The only composition difference is in the type of aggregate and the amount of water. Mixture HPC_REF contains only natural aggregate. Different fractions of natural aggregate were replaced in the mixtures HPC_1, HPC_2 and HPC_3. Also, HPC_1, HPC_2 and HPC_3 mixtures contain more water than the reference mixture to acquire required workability. Table 7 shows clearly the amounts of all types of aggregates, as well as water and cement. Types of aggregate and amounts of water were the only differences in the composition of each mixture.

Table 7 - Amounts of cement, water, and aggregates in mixtures

Component	Unit	Mixture			
		HPC_REF	**HPC_1**	**HPC_2**	**HPC_3**
Cement	**[kg/ton]**	308.1	305.3	304.0	303.0
Mixing water + additional water	**[kg/ton]**	76.1	76.1+8.3	76.1+1.,4	76.1+15.3
w/c ratio		0.25	0.27	0.29	0.30
Technical quartz sand 0.1/0.6 mm	**[kg/ton]**	261.0	0.0	257.5	256.7
Technical quartz sand 0.6/1.2 mm	**[kg/ton]**	174.0	172.4	0.0	171.1
Technical quartz powder ST 6	**[kg/ton]**	101.9	101.0	100.6	0.0
Sum of natural aggregates	**[kg/ton]**	**536.9**	**273.5**	**358.1**	**427.8**
fRCA 0.125/0.5 mm	**[kg/ton]**	0.0	258.6	0.0	0.0
fRCA 0.5/1.0 mm	**[kg/ton]**	0.0	0.0	171.7	0.0
fRCA 0.000/0.063 mm	**[kg/ton]**	0.0	0.0	0.0	100.3
Sum of fRCAs	**[kg/ton]**	**0.0**	**258.6**	**171.7**	**100.3**

Another thing that must be done in the first phase is determination of system boundaries. The system boundaries of the LCA in this work were set as cradle to gate. Cradle to gate system boundaries means, that the construction, use and end-of-life phase is not considered in the model. Only the production stage was considered in the LCA. Production stage normally includes production of raw materials, in the case of concrete with recycled aggregate it includes manipulation with the rubble, crushing, magnetic separation of the metals and aggregate separation, then transport and preparation of the concrete mixture. However, some processes were the same or similar for each mixture, so they could be omitted from the model. Transport of the concrete mixture was considered similar for each mixture; therefore, it was omitted in the model. For the same reason, the preparation process of the mixtures is also omitted except for additional energy that was required for the HPC_3 mixture. The mixture HPC_3 required extra electricity compared to other mixtures. The reason for that is the presence of fine fRCA. fRCA with grain size 0.000/0.063 mm was hard to obtain from the recycled concrete and the process of gaining this fraction required additional crushing. Crushing was carried out in the UCEEB laboratory by a jaw crusher with a 2.2 kW power. Service life of all mixtures are not considered in the model, it is considered the same.

Thus, the processes that are included in the model are connected to the materials used in the concrete mixtures. The model covers the processes like extraction of the raw materials, their transport and manipulation,, magnetic separation of the metals and aggregate separation and other processes connected to the final component production.

Another important issue is the choice of functional unit. Functional unit was set as one column element with determined height and cross section capable of bearing a specific load. When determining a specific element as the functional unit, we can easily take the compressive strength into consideration.

The process of the assessment is following. The column must be able to carry a specific load, in this case, the load was considered 5 000 kN. The cross section was optimized for each mixture according to the compressive strength. Therefore, cross section area of the column made from mixture with higher compressive strength was smaller. With this procedure, each column required different volume of concrete. Different volumes of the columns reflected the different compressive strengths of each mixture.

Table 8 shows the calculation of required cross section areas of each column. Then, column dimensions, volumes and weights are calculated. The density of all mixtures was assumed to be 2500 kg/m^3. Columns are considered to have square cross section. Dimension "a" is the length of the cross-section side. The height of the column was considered constant – 2.5 m.

Table 8 - Calculation of required column dimensions

COLUMN REQUIRED CROSS SECTION AREA

	HPC_REF	HPC_1	HPC_2	HPC_3
F [N]	5 000 000	5 000 000	5 000 000	5 000 000
f_c [MPa]	143.7	123.7	134.5	115.3
A_{req} [mm^2]	34802.0	40417.1	37177.5	43372.7

COLUMN DIMENSIONS AND WEIGHTS

a [mm]	186.6	201.0	192.8	208.3
h [mm]	2500.0	2500.0	2500.0	2500.0
Column volume [m^3]	0.087	0.101	0.093	0.108
Column weight [kg]	217.5	252.6	232.4	271.1

In the Table 9, amounts of materials required for one column of each mixture are calculated. Natural aggregates were added up to a sum as well as fRCAs.

Table 9 - Amounts of materials required for one column of each mixture

MATERIAL REQUIRED FOR EACH COLUMN

	HPC_REF	HPC_1	HPC_2	HPC_3
Cement [kg]	67.0	77.1	70.6	82.1
Technical quartz sand [kg]	94.6	43.5	59.8	116.0
Technical quartz powder [kg]	22.2	25.5	23.4	0.0
fRCA [kg]	0.0	65.3	39.9	27.2
Elkem microsilica 940 U-S [kg]	7.4	8.5	7.8	9.1
Fibres [kg]	7.9	9.1	8.3	9.7
Superplasticizer [kg]	1.9	2.1	2.0	2.3
Water [kg]	16.6	21.3	20.6	24.8

4.2 Inventory analysis and LCIA

With the knowledge of amounts of all materials used for each column, environmental footprint of each column was. Environmental data were taken from the Environmental footprint 3.0 database. This database includes environmental footprint data for the materials, that were used in the concrete mixtures. Environmental data are related to 1 kg for all the materials and for 1 kwh for electricity. In the Table 10, category results of the inventory analysis for each column were compared.

Table 10 – LCIA results

Impact category indicators	**HPC_REF**	**HPC_1**	**HPC_2**	**HPC_3**
Acidification [Mole of H+ eq.]	0.130	0.148	0.136	0.163
Climate Change - total [kg CO2 eq.]	71.40	79.84	73.86	86.26
Ecotoxicity, freshwater - total [CTUe]	836.71	958.74	881.96	1037.17
Eutrophication, freshwater [kg P eq.]	0.000769	0.00088	0.00081	0.0009401
Eutrophication, marine [kg N eq.]	0.042	0.048	0.044	0.051
Human toxicity, cancer - total [CTUh]	1.08E-08	1.2E-08	1.12E-08	1.277E-08
Ionising radiation, human health [kBq U235 eq.]	3.502	3.961	3.653	4.562
Land Use [Pt]	76.81	85.06	78.98	91.05
Ozone depletion [kg CFC-11 eq.]	1.42E-07	1.63E-07	1.5E-07	1.747E-07
Particulate matter [Disease incidences]	1.61E-06	1.73E-06	1.62E-06	1.919E-06
Photochemical ozone formation, human health [kg NMVOC eq.]	0.123	0.141	0.129	0.151
Resource use, fossils [MJ]	422.69	448.01	422.40	520.26
Resource use, mineral and metals [kg Sb eq.]	1.45E-05	1.64E-05	1.52E-05	1.583E-05
Water use [m³ world equiv.]	229.19	260.76	240.56	282.25

4.2.1 Alternative LCA

In this chapter, alternative assessment was concluded.

During concrete recycling process, steel reinforcement is acquired from the parental concrete, and it can be recycled and used again. This fact may be considered as a benefit for concrete mixtures with fRCA. This factor was not considered in the first LCA. Data considering this benefit were taken from Environmental footprint 3.0 database.

Table 11 - LCIA results for alternative LCA

Impact category indicators	**HPC_REF**	**HPC_1**	**HPC_2**	**HPC_3**
Acidification [Mole of H+ eq.]	0.130	0.144	0.133	0.161
Climate Change - total [kg CO2 eq.]	71.40	77.39	72.36	85.24
Ecotoxicity, freshwater - total [CTUe]	836.71	959.41	882.37	1037.44
Eutrophication, freshwater [kg P eq.]	0.00077	0.00088	0.00081	0.00094
Eutrophication, marine [kg N eq.]	0.042	0.048	0.044	0.051
Human toxicity, cancer - total [CTUh]	1.08E-08	1.09E-08	1.05E-08	1.228E-08
Ionising radiation, human health [kBq U235 eq.]	3.502	3.989	3.670	4.573
Land Use [Pt]	76.81	85.59	79.30	91.26
Ozone depletion [kg CFC-11 eq.]	1.42E-07	1.63E-07	1.5E-07	1.747E-07
Particulate matter [Disease incidences]	1.61E-06	1.59E-06	1.54E-06	1.86E-06
Photochemical ozone formation, human health [kg NMVOC eq.]	0.123	0.140	0.129	0.151
Resource use, fossils [MJ]	422.69	425.68	408.76	510.94
Resource use, mineral and metals [kg Sb eq.]	1.45E-05	9.82E-06	1.11E-05	1.307E-05
Water use [m³ world equiv.]	229.19	260.27	240.26	282.05

4.3 Interpretation of results

In this chapter, data obtained from LCIA were normalized and weighed. Normalized and weighed data were obtained by using the data file from Environmental footprint 3.0 method.

The process of normalization uses indicator data for larger areas. The results of individual impact categories can be compared with indicator data for example for Europe or the whole world. By normalization, we get a dimensionless figure expressing the indicator impact's share for the whole area. The normalized category results can be added up within the system. That means we can obtain a single value for each system and compare them with each other easily.

The purpose of weighing is to emphasize the importance of some categories. Weighing is done by multiplication by the weighing coefficient.

Table 12 - Normalized and weighed impact category results

Impact category indicators	**HPC_REF**	**HPC_1**	**HPC_2**	**HPC_3**
Acidification	0.00014	0.00016	0.00015	0.00018
Climate Change - total	0.00186	0.00208	0.00192	0.00224
Ecotoxicity, freshwater - total	0.00038	0.00043	0.00040	0.00047
Eutrophication, freshwater	1.34E-05	1.53E-05	1.41E-05	1.64E-05
Eutrophication, marine	6.3428E-05	7.24E-05	6.65E-05	7.75E-05
Eutrophication, terrestrial	9.5647E-05	0.000109	0.00010	0.000117
Human toxicity, cancer - total	1.3669E-05	1.51E-05	1.41E-05	1.61E-05
Human toxicity, non-cancer - total	8.3191E-05	9.37E-05	8.65E-05	0.00010
Ionising radiation, human health	4.1573E-05	4.7E-05	4.34E-05	5.42E-05
Land Use	7.4418E-06	8.24E-06	7.65E-06	8.82E-06
Ozone depletion	1.6694E-07	1.92E-07	1.76E-07	2.06E-07
Particulate matter	0.00024	0.00026	0.00024	0.00029
Photochemical ozone formation, human health	0.00015	0.00017	0.00015	0.00018
Resource use, fossils	0.00054	0.00057	0.00054	0.00067
Resource use, mineral and metals	1.7225E-05	1.95E-05	1.8E-05	1.88E-05
Water use	0.00170	0.00193	0.00178	0.00209
Sum of impacts	**0.00534**	**0.00599**	**0.00554**	**0.00673**

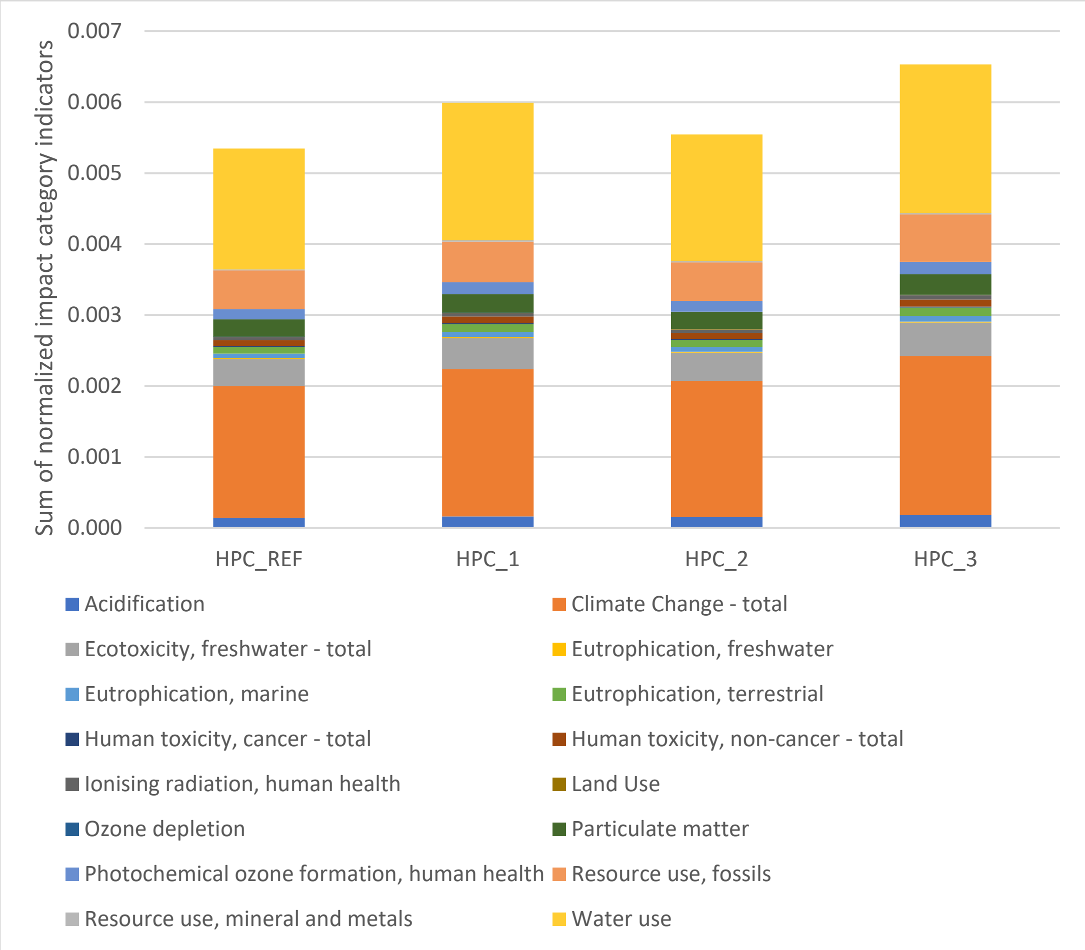

Figure 23 - Normalized and weighed impact category results in graph

Table 12 contains normalized and weighed results for each column. At the bottom line, the sum of impacts is calculated. Figure 23 shows the same results in the graph. The results show that the column made of HPC_REF mixture has the smallest environmental impact, followed by the column made of HPC_2, HPC_1 and HPC_3 mixture. The reason for this result must be the noticeable decrease in strength of all mixtures containing fRCA. Among mixtures containing fRCA, HPC_2 mixture shows the best results. HPC_2 mixture contained fRCA replacement of the coarsest aggregate fraction (0.6/1.2 mm) and the strength of this mixture did not decrease so significantly like the strength of mixtures HPC_1 and HPC_3. On the other hand, HPC_3 mixture, the mixture with the quartz powder replacement, shows the worst results. This result is also influenced by the necessity of using additional energy for an extra crusher to get the fine fRCA replacement.

In the Figure 23 we can also see the most significant categories affecting the total environmental impact – climate change, water use, fossil resource use, freshwater ecotoxicity and particulate matter are the 5 categories with the biggest impact.

Another view on the results shows how much the materials used for the HPC mixtures contribute to the most significant impact categories. In the Figure 24, contributions to climate change category are shown. Cement has clearly the biggest influence on the climate change category in each mixture. The influence of extra crushing electricity needed for HPC_3 can be seen in the Figure 24, too.

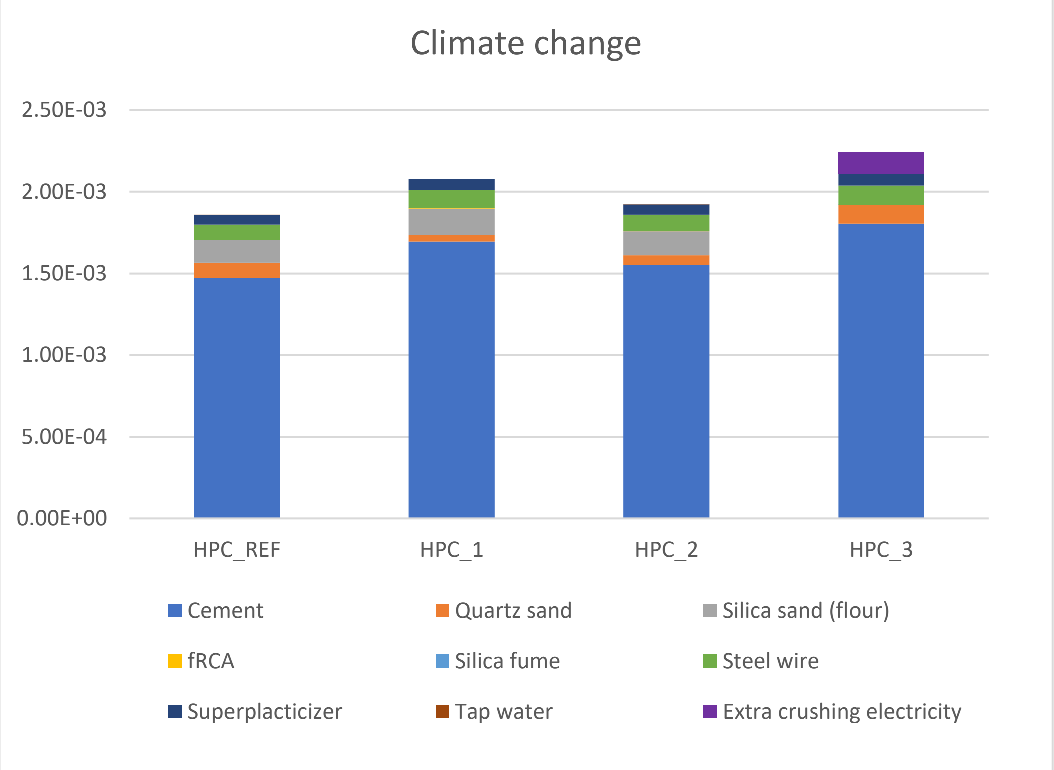

Figure 24 - Contributions of materials to climate change impact category

Next, Figure 25 shows the contributions of the materials to the water use category. Surprisingly, the use of plasticizer is linked to almost 100 % of the water use impact. Apparently, producing superplasticizer is a complicated process requiring a high amount of water. Extra crushing electricity needed for HPC_3 mixture also has a negligible impact on the water use category, and it is barely seen in the graph.

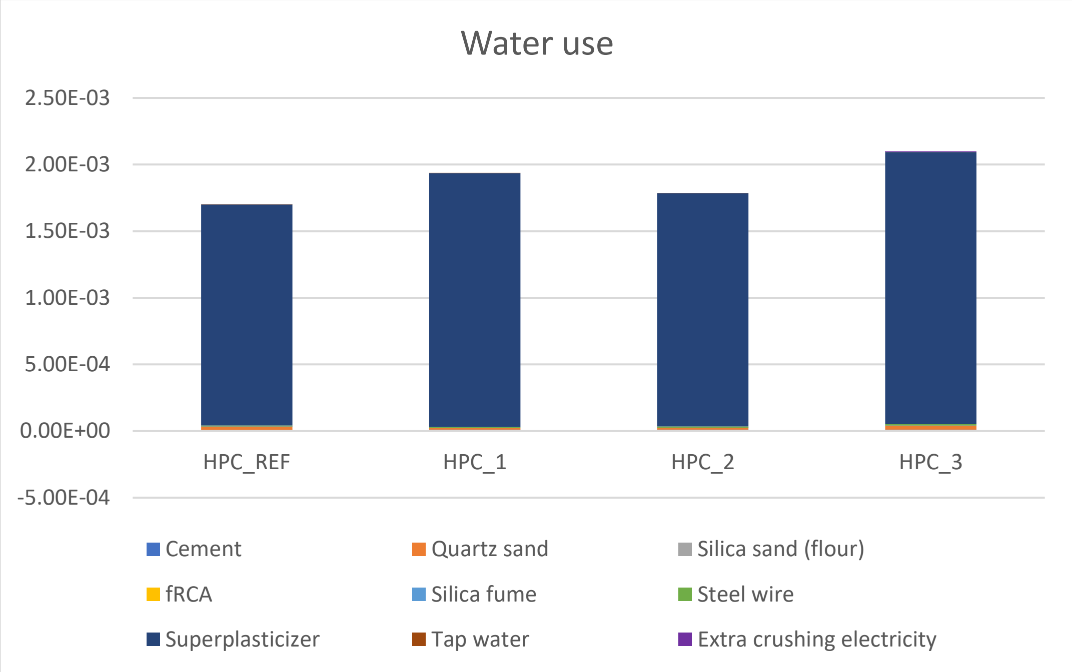

Figure 25 - Contributions of materials to water use impact category

Except for the water use category, cement is a material with the biggest contribution to the most other categories. Altogether, cement production also results in the biggest share of the environmental impact of concrete, followed by transportation and aggregate production.

As said, the system boundaries were set as cradle to gate, which means only the production stage of the concrete mixtures was considered in the LCA. Transportation of fresh concrete is not considered as well as processes during the life stage and end-of-life stage. It must be mentioned that the mixture with the highest strength (HPC_REF) would require the least volume of concrete, therefore transportation of this mixture would also have the smallest environmental impact.

4.3.1 Alternative LCA results

Table 13 and Figure 26 contain normalized and weighed results for the alternative assessment described in the chapter 4.2.1. Because in the alternative assessment reusing of reinforcement acquired from the parental concrete is considered, HPC mixtures containing fRCA show slightly better results compared to the previous assessment.

Table 13 - Normalized and weighed impact category results – alternative LCA

Impact category indicators	**HPC_REF**	**HPC_1**	**HPC_2**	**HPC_3**
Acidification	0.00014	0.00016	0.00015	0.00018
Climate Change - total	0.00186	0.00201	0.00188	0.00222
Ecotoxicity, freshwater - total	0.00038	0.00043	0.00040	0.00047
Eutrophication, freshwater	1.3401E-05	1.53E-05	1.41E-05	1.637E-05
Eutrophication, marine	6.3428E-05	7.23E-05	6.64E-05	7.749E-05
Eutrophication, terrestrial	9.5647E-05	0.000109	0.0001	0.000117
Human toxicity, cancer - total	1.3669E-05	1.37E-05	1.32E-05	1.548E-05
Human toxicity, non-cancer - total	8.3191E-05	9.02E-05	8.43E-05	9.936E-05
Ionising radiation, human health	4.1573E-05	4.74E-05	4.36E-05	5.429E-05
Land Use	7.4418E-06	8.29E-06	7.68E-06	8.842E-06
Ozone depletion	1.6694E-07	1.92E-07	1.76E-07	2.055E-07
Particulate matter	0.00024	0.00024	0.00023	0.00028
Photochemical ozone formation, human health	0.00015	0.00016	0.00015	0.00018
Resource use, fossils	0.00054	0.00054	0.00052	0.00065
Resource use, mineral and metals	1.7225E-05	1.16E-05	1.32E-05	1.551E-05
Water use	0.00170	0.00193	0.00178	0.00209
Sum of impacts	**0.00534**	**0.00585**	**0.00546**	**0.00668**

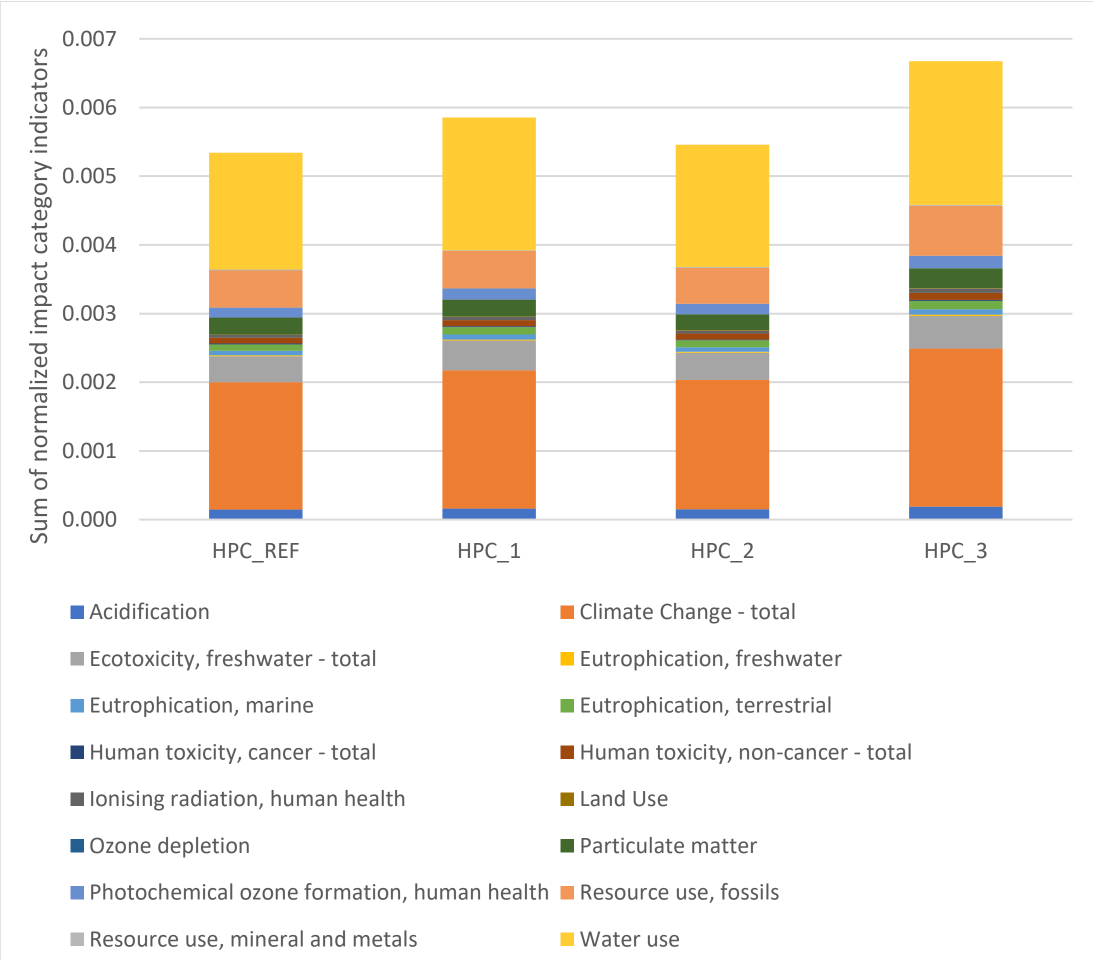

Figure 26 - Normalized and weighed impact category results in a graph - alternative LCA

However, the reference mixture HPC_REF still shows the best results – the smallest environmental impact. Even though the reference mixture still shows the best result, it is obvious that reusing the reinforcement is a good way of environmental impact reduction.

5 Conclusions

Recycling seems to be a good way of establishing more sustainable production in many industry sectors. The construction industry is an industry with the highest amount of waste produced, mostly concrete waste. Therefore, the construction industry should not overlook the possibility of using recycled concrete aggregate in concrete production.

This thesis aimed to research the possibility of using fine recycled concrete aggregate in HPC. The preparation and experimental verification of the samples was described in the first part of the thesis. The samples made from each mixture were tested for compressive and flexural strength, shrinkage, and dynamic modulus of elasticity. The results of the tests showed the strength decrease (both flexural and compressive) of all mixtures containing fRCA. On the other hand, the positive property of the mixtures containing fRCA was lower shrinkage.

In the second part of the thesis, the LCA method was used to compare each mixture´s environmental impact. A column was chosen as a functional unit to include different strengths of the mixtures in the assessment. This column was designed with different cross-section areas in order to carry a specific load. Different volumes of the columns represented different strengths of the mixtures. For example, column made from reference mixture had smaller cross-section, because the compressive strength of this mixture was higher. Therefore, the least amount of concrete was needed for this column.

The concrete with the best result was the reference mixture with only natural aggregate. The reason for that was the relatively noticeable strength decrease of concrete mixtures containing fRCA. For 1 m^3, the environmental impact results would be obviously better for concretes with fRCA, but this result would not be reflecting the decreased strengths. The reference mixture showed the best results in almost all impact categories. Even the alternative assessment which included reusing the reinforcement acquired from parental concrete showed the same results. Therefore, it could be said that the replacement of the natural aggregate by fRCA fractions used in HPC_1, HPC_2 and HPC_3 is not suitable.

The properties of HPC are very sensitive to aggregate replacements, which can significantly decrease material´s strength. The strength decrease is then reflected in the environmental impact of the concrete. The properties of HPC containing fRCA could be possibly improved by using a different type of fRCA – different fractions or fraction combinations, levels of replacement, fRCA of different origin or produced by different recycling process.

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7 The list of the tables

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10 Annexes

Quantities	EU-28: Ce	DE: Dried	DE: Silica s	CZ: recyklac	GLO: mark	EU-28: Rei	RER: polyc	CZ: Tap wa	CZ: Electri	Reinforc
EF 3.0 Acidification [Mole of H+ eq.]	0.001505	4.52E-05	0.000316	2.45E-05	1.96E-05	0.001209	0.004153	1.46E-07	0.001304	-6,10631
EF 3.0 Climate Change - total [kg CO2 eq.]	0.844467	0.037853	0.240257	0.0022385	0.003159	0.465355	1.184921	8.82E-05	0.563272	-0,03758
EF 3.0 Ecotoxicity, freshwater - total [CTUe]	1.372001	0.065157	0.952646	0.0328537	0.044651	2.397141	373.2461	0.004764	3.507785	0,01031
EF 3.0 Eutrophication, freshwater [kg P eq.]	2.03E-07	3.41E-08	8.31E-07	-1.44E-08	3.23E-07	1.11E-06	0.000386	1.16E-08	1.74E-06	-2,16598
EF 3.0 Eutrophication, marine [kg N eq.]	0.000506	2.07E-05	0.000109	1.43E-05	7.13E-06	0.000287	0.000695	8.45E-08	0.000263	-7,97166
EF 3.0 Human toxicity, cancer - total [CTUh]	9.28E-11	5.48E-12	4.23E-11	-1.51E-12	1.78E-12	1.53E-10	1.04E-09	7.21E-14	7.05E-11	-1,77847
EF 3.0 Ionising radiation, human health [kBq U235	0.023176	0.000576	0.020127	-0.000474	0.000227	0.12714	0.238056	4.19E-06	0.089491	0,00042
EF 3.0 Land Use [Pt]	0.355096	0.054888	1.282413	0.0037607	0.04011	1.870011	2.33579	0.000175	3.429954	0,00817
EF 3.0 Ozone depletion [kg CFC-11 eq.]	6.93E-13	1.07E-13	3.96E-12	-2.73E-15	6.13E-10	3.85E-12	7.34E-08	3.75E-16	4.78E-12	-2,82025
EF 3.0 Particulate matter [Disease incidences]	1.75E-08	1.02E-09	4.62E-09	-9.59E-10	2.98E-10	1.57E-08	6.13E-08	2.88E-12	9.93E-09	-2,16914
EF 3.0 Photochemical ozone formation, human he	0.001467	5.60E-05	0.000275	4.32E-05	2.18E-05	0.001065	0.002634	1.20E-07	0.000719	-1,78601
EF 3.0 Resource use, fossils [MJ]	2.743919	0.610825	3.195053	0.0240674	0.04723	7.302472	27.97064	0.001261	9.538327	-0,34181
EF 3.0 Resource use, mineral and metals [kg Sb ec	1.81E-08	1.29E-09	8.66E-08	-2.25E-09	1.12E-08	9.80E-08	5.57E-06	3.38E-12	4.18E-08	-1,01491
EF 3.0 Water use [m³ world equiv.]	0.018259	0.035801	0.00441	-3.14E-05	0.000315	0.120102	119.4829	0.001802	0.008994	-0,00743

Annex 1 – Environmental footprint data from Environmental footprint 3.0 database for materials, electricity, and reinforcement reusage benefit

	EU-28: Ceme	DE: Dried	DE: Silica s	CZ: recyklac	GLO: mark	EU-28: Rei	RER: polyc	CZ: Tap wa	CZ: Electri	Reinforc
EF 3.0	3.56E-05	2.45E-06	1.33E-05	7.19E-08	3.16E-07	3.29E-05	0.001161	2.13E-08	3.52E-05	-2,06785
EF 3.0 Acidification	1.68E-06	5.04E-08	3.53E-07	2.74E-08	2.18E-08	1.35E-06	4.63E-06	1.63E-10	1.46E-06	-6,81292
EF 3.0 Climate Change - total	2.20E-05	9.85E-07	6.25E-06	5.82E-08	8.22E-08	1.21E-05	3.08E-05	2.30E-09	1.47E-05	-9,77867
EF 3.0 Ecotoxicity, freshwater - total	6.17E-07	2.93E-08	4.29E-07	1.48E-08	2.01E-08	1.08E-06	0.000168	2.14E-09	1.58E-06	4,64165
EF 3.0 Eutrophication, freshwater	3.54E-09	5.94E-10	1.45E-08	-2.52E-10	5.62E-09	1.94E-08	6.73E-06	2.01E-10	3.03E-08	-3,77431
EF 3.0 Eutrophication, marine	7.66E-07	3.14E-08	1.66E-07	2.16E-08	1.08E-08	4.34E-07	1.05E-06	1.28E-10	3.98E-07	-1,20726
EF 3.0 Eutrophication, terrestrial	1.16E-06	4.78E-08	2.43E-07	3.34E-08	1.61E-08	6.45E-07	1.46E-06	9.21E-11	5.71E-07	5,63637
EF 3.0 Human toxicity, cancer - total	1.17E-07	6.90E-09	5.33E-08	-1.90E-09	2.25E-09	1.93E-07	1.32E-06	9.08E-11	8.88E-08	-2,24157
EF 3.0 Human toxicity, non-cancer - to	9.32E-07	2.09E-08	1.50E-07	-1.04E-08	3.18E-09	1.38E-06	2.44E-06	5.72E-10	3.43E-07	-5,34456
EF 3.0 Ionising radiation, human healt	2.75E-07	6.83E-09	2.39E-07	-5.62E-09	2.69E-09	1.51E-06	2.83E-06	4.98E-11	1.06E-06	5,01902
EF 3.0 Land Use	3.44E-08	5.32E-09	1.24E-07	3.64E-10	3.89E-09	1.81E-07	2.26E-07	1.69E-11	3.32E-07	7,92221
EF 3.0 Ozone depletion	8.15E-13	1.26E-13	4.66E-12	-3.21E-15	7.21E-10	4.53E-12	8.63E-08	4.41E-16	5.63E-12	-3,31713
EF 3.0 Particulate matter	2.64E-06	1.54E-07	6.95E-07	-1.44E-07	4.48E-08	2.37E-06	9.23E-06	4.34E-10	1.49E-06	-3,26435
EF 3.0 Photochemical ozone formatio	1.73E-06	6.59E-08	3.24E-07	5.09E-08	2.57E-08	1.25E-06	3.10E-06	1.41E-10	8.46E-07	-2,10267
EF 3.0 Resource use, fossils	3.51E-06	7.82E-07	4.09E-06	3.08E-08	6.05E-08	9.35E-06	3.58E-05	1.61E-09	1.22E-05	-4,37491
EF 3.0 Resource use, mineral and meta	2.14E-08	1.53E-09	1.03E-07	-2.67E-09	1.33E-08	1.16E-07	6.60E-06	4.01E-12	4.96E-08	-1,20405
EF 3.0 Water use	1.35E-07	2.66E-07	3.27E-08	-2.33E-10	2.34E-09	8.91E-07	0.000887	1.34E-08	6.67E-08	-5,51472

Annex 2 – Normalized and weighed environmental footprint data from Environmental footprint 3.0 database for materials, electricity, and reinforcement reusage benefit