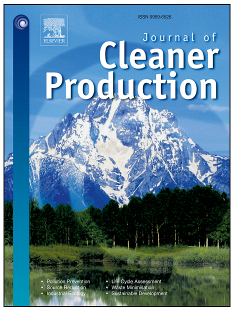

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ENVIRONMENTAL ASSESSMENT OF GREEN CONCRETES FOR STRUCTURAL USE

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Abstract

This paper presents a comparative environmental assessment of several different green **concrete mixes** for structural use. Four green **concrete mixes** were compared with a conventional **concrete mix**: recycled aggregate concrete with a cement binder, high-volume fly ash concrete with natural and recycled aggregates, and alkali activated fly ash concrete with natural aggregates. All five **concrete mixes** were designed and experimentally verified to have equal compressive strength and workability. An attributional life cycle assessment, **based on the scenario which included construction practice, transport distances, and materials available in Serbia**, was performed. When treating fly ash impacts, three allocation procedures were compared: ‘no allocation’, economic, and mass allocation, with mass allocation giving unreasonably high impacts of fly ash. Normalization and aggregation of indicators was performed and the impact of each **concrete mix** was expressed through a global sustainability indicator. A sensitivity analysis was also performed to evaluate the influence of possibly different carbonation resistance and long-term deformational behavior **on the functional unit**. **In this specific case study, regardless of the choice of the functional unit,** the best overall environmental performance was shown by the alkali activated fly ash concrete **mix** with natural aggregates and the high-volume fly ash recycled aggregate concrete **mix**. The worst performance was shown by the recycled aggregate concrete **mix** with a cement binder.

Key words

Green concrete; Fly ash; Recycled concrete aggregate; Alkali activation; Life Cycle Assessment; Environmental performance.

1. Introduction

Over the past few decades, the development of energy and resource efficient technologies and products became a primary goal in a generally accepted principle around the world – sustainable development. The construction industry is no exception to this rule. It is responsible for 50% of the consumption of natural raw materials, 40% of the total energy consumption and almost half of the total industrial waste generation (Oikonomou, 2005). Concrete is the most widely used construction material today. It is estimated that roughly 25 billion tons of concrete are produced globally each year, or over 3.8 tons per person per year (WBCSD, 2009). Twice as much concrete is used in the construction industry worldwide than all the other construction materials combined.

The specific amount of harmful impacts embodied in a concrete unit is, in comparison to other construction materials, relatively small. However, due to the high global production and utilization, the total environmental impact of concrete is still significant: large consumption of natural resources (mineral resources for cement and concrete and fossil fuels in particular), large emissions of greenhouse gasses, primarily CO_2 from cement production and a large amount of generated waste.

So far, a lot of effort has been put into finding sustainable solutions for concrete as a structural material. Two major trends can be outlined: (1) replacement of natural aggregates with recycled ones and (2) partial replacement of cement with supplementary cementitious materials (e.g. fly ash (FA), blast furnace slag, silica fume etc.) or complete replacement of cement with alkali activated binders and, of course, any combination of these possibilities. Demolished concrete can be recycled, although not into its original constituent materials or original whole form. Rather, concrete is crushed into aggregate called recycled concrete aggregate (RCA) for use in new applications. If it fulfills certain quality requirements, RCA can be used as a partial or full replacement of natural aggregate (NA) in new structural concrete – recycled aggregate concrete (RAC). When made with the same mix proportions, RAC exhibits lower mechanical properties such as compressive, tensile strength, and modulus of elasticity (Rahal, 2007; R. V. Silva et al., 2015a; R. V Silva et al., 2015) and higher shrinkage and creep than corresponding NAC (Domingo-Cabo et al., 2009; R. V. Silva et al., 2015b). The exact value of this decrease/increase depends on various factors: RCA quality, replacement ratio, mixing procedure, use of admixtures, additions, etc.

Approximately one ton of the greenhouse gas CO_2 is released for each ton of Portland cement clinker produced (Bilodeau and Malhotra, 2000), originating from the combustion of carbon-based fuels and the calcination of limestone. Today, there is a general trend of replacing high amounts of Portland cement with FA in concrete. Concrete that contains more than 35% of FA in the total cementitious materials mass is usually called high-volume fly ash concrete (HVFAC). Owing to the pozzolanic activity of FA, this type of concrete can have similar mechanical properties as Portland cement concrete if produced with a low water-tocementitiuos materials ratio and the use of a superplasticizer (Bouzoubaâ and Fournier, 2003; Poon et al., 2000).

At the end of this ’cement replacement’ line stands alkali activated concrete in which the cement binder is completely replaced by alkali activated materials rich in silicon and aluminium. Different natural and waste materials are activated with alkaline solutions, usually with a combination of sodium hydroxide and sodium silicate solutions. According to (Davidovits, 2015), currently two types of low-calcium FA based materials are in the research focus: (1) alkali activated fly ash concrete (**AAFAC**) which uses caustic sodium hydroxide and usually needs curing at elevated temperatures and (2) slag/FA based geopolymer concrete which uses non-caustic silicate solution and is capable of hardening at ambient temperature. With both types it is possible to obtain adequate mechanical properties for structural concrete (Davidovits, 2015; Glasby et al., 2015; Rangan, 2009). High-calcium FA can also be used, but it is much less reactive in alkali activated systems than low-calcium FA and therefore better suited for cement replacement in binary and ternary systems (Winnefeld et al., 2010). However, there is published research on alkali activated high-calcium FA concrete with NA and RCA aggregate where relatively good concrete properties were obtained (Nuaklong et al., 2016).

All of these efforts aim at the same environmental improvements: preservation of natural resources, lowering of CO_2 emissions, and decreasing the amount of generated waste. With RCA, there is also a potential for reducing transportation burdens, since concrete can often be recycled on demolition sites or close to urban areas where it will be reused.

A concrete with a simultaneous replacement of cement and natural aggregates has the largest potential for a decrease of environmental impact, if engineering properties required for structural use can be obtained. In this work, four ’green’ **concrete mixes**, with experimentally verified equal compressive strengths, were environmentally assessed and compared with a corresponding conventional **concrete mix** (NAC). These were recycled aggregate concrete with a cement binder (RAC), high-volume fly ash concrete with natural (NAC_FA) and recycled aggregates (RAC_FA) and alkali activated fly ash concrete with natural aggregates (NAC_AAFA). In all **concrete mixes** only low-calcium FA was used. The reason for such a choice lies in the fact that blast furnace slag is scarce in Serbia while vast amounts of low-calcium FA are generated at coal-fired power plants—6 million tons obtained per year, while 200 million tons is being currently deposited in the landfills. Moreover, only 2.7% of the total FA generation in Serbia is currently utilized by the construction industry (Dragaš et al., 2016).

2. Background

In order to introduce a new material or technology into the construction practice, its performance at all levels (including cost) should be competitive to materials or technologies already existing on the market. Along with its technical performance, the environmental performance of a construction material should also be assessed.

A lot of research was dedicated to mechanical and durability related properties of so-called green concretes. However, their environmental performance was substantially less investigated although it was, in fact, the driving force behind the introduction of green concretes (Celik et al., 2015; Davidovits, 2015; Fawer et al., 1999; Habert et al., 2011; Jiménez et al., 2015; Knoeri et al., 2013; Marinković et al., 2010; McLellan et al., 2011; Teixeira et al., 2016; Turk et al., 2015; Turner and Collins, 2013; Van Den Heede and De Belie, 2014; Weil et al., 2009, 2006). Replacing virgin materials and cement with by-products or waste, with or without alkali activation, does not necessarily and directly lead to better environmental performance in the course of the concrete's life cycle. Any environmental assessment should be performed using a comprehensive, scientific-based approach, where all energy and material flows within system boundaries and in the course of the concrete’s life cycle are clear and transparent.

For that purpose, the well recognized and standardized methodology – Life cycle assessment (LCA) is usually applied. It allows for evaluating the environmental impacts of processes and products during their life cycle. LCA is used according to the ISO 14040 standard (ISO, 2006), which provides a framework, terminology and methodological phases of the assessment: (1) goal and scope definition (including the system boundaries and functional unit (FU) definition), (2) creating the life cycle inventory (LCI), (3) assessing the environmental impact (LCIA), and (4) interpreting the results. Beside these four mandatory steps, normalization, grouping, weighting, and additional LCIA data quality analyses are optional steps within the LCIA phase.

Whenever dealing with multi-functional processes, some type of allocation (partitioning the input and/or output flows of a process to the product system under study) must be applied. For green concretes this is especially important when calculating the impacts of by-products from other industries or recycling impacts. ISO 14040 (ISO, 2006) recommends a three-step procedure with regard to allocation. As a first step, allocation should be avoided where possible by dividing the process into subprocesses or by expanding the system boundaries to include all the additional functions of the co-products. System expansion is not the same as the commonly applied substitution method, but it was proven to be conceptually equivalent at the process level (Tillman et al., 1994). As a second step, when allocation cannot be avoided, it must be done in a way that reflects an underlying, causal, physical relationship—usually mass allocation. The third step is about ‘other relationships’ such as market value—economic allocation. If system expansion for some reasons is not acceptable, the question remains what type of allocation to use—mass or economic. Chen et al. (2010) tested mass and economic allocation in the case of FA used as a substitute for cement in concrete. The authors concluded that mass allocation induced large impacts of FA, higher than those of ordinary cement, which can discourage the cement and concrete industry to use this by-product. On the other hand, economic allocation, although unstable because of potential market prices fluctuations, induced much lower impacts of FA. It supports the fact that FA is primarily waste and therefore should not have an environmental impact similar to that of the main product. Van Den Heede and De Belie (2012) recommended economic allocation to ensure an enduring use of FA as a cement-replacing material.

Having all this in mind, it is obvious that there are many possible options when applying LCA. It is hard to compare the results of previous research in this area since they differ in many aspects. On the material level, various compositions of green concretes were analyzed, with different replacement ratios of virgin materials with by-products and waste, different alkali activators were used, etc. On the LCA level, different system boundaries are possible, different approaches to LCI modeling, different choices of FU, etc. **Beside the commonly used FU equal to 1 m^3 of concrete, the FU extended to include strength and durability requirements was applied by some researchers (Garcia-Segura et al., 2014, De Schepper et al., 2014, Van Den Heede and De Belie, 2014). A thorough analysis of an equivalent functional unit for RAC was conducted in (Dobbelaere et al., 2016). Based on the analysis of material properties, authors showed that, depending on the particular serviceability and ultimate state, the equivalent functional unit was higher for RAC than for corresponding NAC, if the same mix design was applied for both concretes.**

Assuming that the goal of the LCA study is the comparison of conventional and green concrete’s environmental performance, the results of the assessment mostly depend on the system boundaries, or the way of dealing with multi-functional processes – whether an attributional or consequential approach to inventory data modelling is chosen.

This is especially true when comparing recycled and conventional concrete. In LCA studies where a consequential approach with system expansion (understood as substitution) is applied, results are usually beneficial for RAC. For instance, Knoeri et al. (2013) showed that RAC environmental impacts were reduced to 70% of the conventional concrete impacts. Turk et al. (2015) obtained similar results: impacts were reduced to 88% and 65% of the corresponding conventional concrete’s impacts in the case of RAC and RAC_FA, respectively. However, the main reasons for such improvements in environmental behavior were avoided burdens: avoided waste landfilling and avoided iron production if iron scrap as a co-product of recycling was recovered. These avoided impacts were therefore attributed only to the product that receives waste, i.e. green concrete.

In attributional LCA studies where allocation is used instead of system expansion with substitution, results are not so beneficial for RAC. The credits from recycling or utilization of by-products in concrete are accounted for only on the level of different waste management scenarios comparison, not on the level of the product’s life cycles comparison. With this approach, at best, for low cement increase in RAC, impacts of RAC and the corresponding conventional concrete are similar (Marinković et al., 2010; Weil et al., 2006). Specially, according to Jiménez et al. (2015), if a mix proportioning method called ‘equivalent mortar volume method’, proposed by Fathifazl et al. (2009), is used in RAC design, the RAC impacts are lower than those of the corresponding conventional concrete, even with an attributional approach.

The second main source of discrepancy in obtained results are different replacement percentages of coarse NA with RCA in previously mentioned studies. They range from 30% (Turk et al., 2015), 45% (Knoeri et al., 2013) to 100% in (Marinković et al., 2010).

LCA studies performed on the environmental evaluation of HVFAC with natural aggregates showed that replacement of cement with FA reduced the environmental impacts of concrete

(Celik et al., 2015; Teixeira et al., 2016; Van Den Heede and De Belie, 2014). However, this was possible if the standardized k-value concept (EN 206-1, 2000), which limits the amount of active FA and strength of concrete, was not followed (Van Den Heede and De Belie, 2014). As expected, the exact value of reduction depended on the system boundaries and chosen FU. The results of research performed so far on LCA of AAFAC are contradictory. This is mostly the consequence of different LCI data used for alkali activators (Davidovits, 2015). Habert et al. (2011) reported that AAFA concrete had a slightly lower impact on global warming and higher other environmental impacts than ordinary Portland cement concrete. Turner and Collins (2013) came to a similar conclusion regarding the global warming potential. This was probably the result of a misinterpretation of Fawer's data on LCI of sodium silicate (Fawer et al., 1999). Other research was dedicated mostly to the calculation of the global warming potential (McLellan et al., 2011; Weil et al., 2009; Yang et al., 2013) and showed a significant reduction of this impact category in the case of AAFA concretes. The exact value of the reduction again depended on the system boundaries, whether transportation and heat curing were included, the activator type, etc.

3. Objectives

The main aim of this work was to bring in a single environmental LCA several different green **concrete mixes** that utilize FA and RCA as substitutes for natural resources. Therefore, the objectives were to determine the appropriate functional unit for **concrete mixes** with possible different performances, to identify the life cycle phases with major impacts, to quantify and compare these impacts for different **concrete mixes**, and finally, to recommend the best option and/or improvements within the analyzed **concrete mixes**.

4. Methodology

Comparative environmental assessment of five different **concrete mixes** was performed using LCA according to ISO 14040 (ISO, 2006). **Concrete mixes are intended for the application in precast structural elements. AAFA concretes must be cured at elevated temperatures and therefore they are not suited for in-situ applications.** Beside the mandatory steps, normalization and aggregation was also performed**. Assessment was carried out according to the scenario typical for Serbia, which included: specific concrete mixes, transport distances and localy available materials (specifically RCA and FA). Regarding exposure conditions, carbonation-induced steel corrosion was assumed and a service life of 50 years. An attributional LCI modeling approach was adopted.** All five **concrete mixes** were designed and experimentally verified to have the same compressive strength and workability. In the following, firstly, the tests of concrete properties are described.

4.1 Tests of concrete properties

An experimental program was carried out to obtain the mix proportions of five different concrete types, so that all of them have equal 28-day compressive strength and workability:

NAC – natural aggregate concrete made entirely with river aggregate and a cement binder;

NAC_FA – natural aggregate concrete with 35% replacement of cement with FA;

NAC_AAFA – alkali activated fly ash natural aggregate concrete;

RAC – recycled aggregate concrete with natural fine and recycled coarse aggregate (100% replacement ratio) and a cement binder;

RAC_FA – recycled aggregate concrete with 35% replacement of cement with FA.

Coarse RCA was obtained from a demolished reinforced concrete structure which had been exposed to weather conditions for more than thirty years. The crushing of the demolished concrete was performed in a mobile recycling plant, while natural aggregate was river sand and gravel from the Morava River (Serbia). NA was used in saturated, surface-dry condition while RCA was used in oven-dried condition. For easier control of RCA absorption and concrete workability, in concrete mixtures containing RCA an additional water amount was calculated on the basis of the water absorption of RCA after 30 minutes. Basic properties of recycled and natural aggregates are shown in Table 1, while their particle size distribution is presented in Figures 1 and 2. **Water absorption of RCA after 24 h varied from 3.7% to 4.6%, and oven-dried density varied from 2309 kg/m^3 to 2370 kg/m^3, depending on the particle size. With these properties, RCA can be classified for instance, as belonging to between classes A3 and B1 according to the classification proposed in (Silva et al., 2014). Since the loss of the concrete's compressive strength with these RCA classes can be significant (5% - 30%), lower quality of RCA would not be recommended for structural applications. Hence applied RCA can be considered as a representative for the class of RCA that could be used for the structural elements made of RAC.**

Low-calcium FA was obtained from the coal-fired power plant 'Nikola Tesla B' (TENT) in Obrenovac, Serbia, while blended Portland cement CEM II/A-M (S-L) 42.5R was used. This type of cement has additions (ground slag and limestone) up to 20% of the total mass. The chemical composition and physical properties of FA and cement are presented in Table 2, together with requirements of EN 450-1 (2012) for FA use in concrete. According to the standard ASTM-C618-12a (2012) it was classified as class F. However, the molar silicon/aluminium (Si/Al) ratio of FA was 2.9, i.e., considerably higher than recommended for the application in concretes for structural use (Davidovits, 1999), and the CaO content was also relatively high for class F. **The FA and cement particle size distribution is presented in Figure 3. Applied FA had particle size distribution as fine as cement had thus enabling high pozzolanic reactivity in concrete mixes that contained FA and best possible properties.**

For FA activation, a combination of sodium hydroxide solution (NaOH) and sodium silicate solution (Na_2SiO_3) was chosen as the alkali activator (AA). The chemical composition of the sodium silicate solution was Na_2O = 14.7%, SiO_2 = 28.08% and H_2O = 57.22% by mass.

A series of laboratory tests were carried out to obtain the target compressive strength (40 MPa) and target workability (slump equal to 15 ± 3 cm) for all **concrete mixes**. Concrete specimens were cast in 100 mm cube steel moulds, and the concrete was compacted using a vibrating table. After finishing, the specimens (except those of NAC_AAFA) were covered with wet fabric and stored in the casting room at a temperature of 20 ± 2°C. They were demoulded after 24 h and kept in a water tank until testing.

AAFA concrete needs curing at elevated temperature. NAC_AAFA samples were, after casting, compacting, and sealing in a plastic membrane, cured for 6 h at a constant temperature of 80°C. This heating regime was selected as a typical curing procedure in precast concrete plants in Serbia. After curing, the samples were stored at laboratory conditions, a temperature of 20 ± 2°C and approximately 50% relative humidity until testing.

The proportioning of the concrete mixtures was based on the absolute volume method. Firstly, laboratory tests with various mix proportions of NAC and RAC were performed to obtain these target values. Eight NAC mixes and eight RAC mixes with different free water-to-cement ratios were designed for a target slump (this ratio refers to the free water content, excluding the amount of additional water). For each concrete mix compressive strength was tested on three samples. Based on average values, a relationship between concrete compressive strength and cement-to-free water ratio (m_c/m_w) was established for NAC and RAC and shown in Figure 4. Using this relationship, the free water-to-cement ratio (m_w/m_c) was determined on the basis of required compressive strength equal to 40 MPa for both **concrete mixes**. Mix proportions and obtained properties of NAC and RAC **mixes** are presented in Table 3, where m_w/m_c is designated as w/c.

For NAC_FA **concrete mixes** no such relationship was established, but trial mixtures with various water-to-cementitious materials ratios were tested until the desired compressive strength and workability were obtained (Dragaš et al., 2016). This was found as a simpler approach since several parameters affect the concrete properties. The results are presented in Table 4, where the designation of a particular mixture includes the cement (C) amount, the FA (F) amount and water-to-cementitious materials ratio. It was determined in previous works (Dragaš et al., 2016; Kou and Poon, 2012) that replacing not only a part of cement, but also a part of aggregate with FA had a beneficial effect on the concrete compressive strength, especially on the early-age strength. In the first attempt (C192F192_055), 50% of cement was replaced with FA and in the second attempt (C192F346_036), an extra amount of FA was added at the expense of the fine aggregate amount and that resulted in a higher compressive strength of concrete. The maximum aggregate content that could be replaced was determined on the basis of the required aggregate mixture particle size distribution according to EN 12620 (2010). The effect of water-to-cementitious materials ratio was tested, firstly by changing the water content (C192F346_037, C192F346_034, and C192F346_030) and then by changing the FA content (C200F200_049, C200F250_043, C200F300_039, C200F350_036, and C200F400_033). Based on these results, with minor changes in the constituents' amounts, a final mixture was selected and tested. It is designated as NAC_FA and presented in the last, shaded row of Table 4.

Owing to RAC and NAC_FA test results, only two trial mixtures for RAC_FA were needed, Table 5. In the first attempt (C192F346_033), neither strength nor slump were adequate, which was corrected with a different natural/recycled aggregate ratio and lower superplasticizer amount. Final mixture is designated as RAC_FA and presented in the last, shaded row of Table 5.

To obtain an optimal mix design of AAFAC, tests on pastes with varying SiO_2/Na_2O ratios in the range 0.87–1.64, were first performed (Dragaš et al., 2014), Table 6. This variation was achieved with a combination of 10M or 16M NaOH solution (M – molarity is the mass of NaOH solids in a solution expressed in terms of moles) and a Na_2SiO_3 solution with different moduli n ($Na_2SiO_3/NaOH$ = 2, 3.5, 5, and 10). All paste samples had an AA to FA mass ratio (AA/FA) equal to 0.6 since it was not possible to activate FA with a smaller amount of AA. The reason for the uncommonly high needed amount of AA was probably an unfavorable Si/Al ratio in the used FA. Based on the paste test results of compressive strength and having in mind both cost and environmental effects, activators containing a 10M or 16M NaOH and Na_2SiO_3 solution with the modulus n equal to 10 (except for one mixture with this modulus equal to 3.5) were chosen for the evaluation of concrete properties. To estimate the influence of additional water on workability and compressive strength of AAFAC, the water content was also varied, Table 7. Finally, concrete mixture C_1 (NAC_AAFA) in the first, shaded row of Table 7 was chosen, for its compressive strength and workability.

With selected concrete mixtures, both target design requirements were fulfilled. The 28-day compressive strength of all **concrete mixes** is somewhat over 40 MPa, with a maximum difference of 4.0 % when compared with NAC **mix**. However, slightly larger cement amount (about 3%), i.e., slightly smaller free water-to-cement ratio, was applied in RAC **mix** to reach similar compressive strength as NAC. **The first idea was to produce all concrete mixes without adding superplasticizer to avoid its effect and enable fair comparison**. **For that reason, RAC mix contained slightely larger cement amount compared with the NAC mix.** However, concrete mixtures with a high content of FA (NAC_FA and RAC_FA) were very dry and stiff in the fresh state and it was necessary to add a certain amount of superplasticizer to obtain a desired workability. It was noticed also that small changes of the superplasticizer content resulted in a significant change of concretes’ workability. **Therefore,**

the five tested concrete mixes were not five environmentally optimal ones (with the lowest possible cement content) but five possible mixes, which all fulfill same requirements regarding strength and workability.

4.2 Goal, scope and functional unit

This specific case study is performed with a goal of comparing the environmental impact of the life cycle of five different **mixes** of structural concrete as defined in the previous section. **In order to enable comparison of the entire life cycles of different concrete types, a FU should be chosen to provide the same performance of the structures that are made of them, throughout their whole life cycle.** Same structural performance means that serviceability limit states (including short and long-term behavior), ultimate limit states (strength) and the service life (durability) of the concrete structural element are equal, regardless of the concrete that it is made of. **Therefore it was firstly necessary to determine if different analyzed concrete mixes cause different serviceability and durability performance of the structure. Similar load carrying capacity was provided with the same compressive strength.**

Most of the research including comparison of NAC properties to green concrete properties was based on the same mix design (meaning a simple replacement of cement or natural aggregate with FA and/or RCA by weight, where the amount was corrected only for different densities). This approach does not lead to equal 28-day compressive strength, neither for FA concretes nor for RAC or their combinations. In this study, different **concrete mixes** with same compressive strengths and accordingly adjusted mix designs were compared. When needed, as in the following, only research data that complied with that requirement were considered. This significantly reduced the available test database on the properties and behavior of structural elements made of green concretes.

For all analyzed concrete types, previous research has shown that the behavior of structural elements under short-term loading is very similar to that of the corresponding NAC. The deflection, cracking load and crack pattern, yield load, flexural and shear capacity of beams made of NAC_FA (Arezoumandi et al., 2014; Rao et al., 2011; Yoo et al., 2015), NAC_AAFA (Sumajouw et al., 2007; Yost et al., 2013a, 2013b), RAC (Ajdukiewicz and Kliszczewicz, 2007; Choi et al., 2012; Gonzalez-Fonteboa and Martınez-Abella, 2007; Han et al., 2001; Ignjatović et al., 2013), and RAC_FA (Sadati et al., 2016) were very similar to those of the corresponding NAC beams, if the beams were made of concretes with similar compressive strength. The same conclusion was valid for RAC slabs and seismic behavior of RAC frames (Reis et al., 2015; Schubert et al., 2012; Xiao et al., 2006).

Regarding the long-term behavior there is very limited data and it is almost exclusively related to the behavior of RAC beams under sustained loads (Ajdukiewicz and Kliszczewicz, 2011; Choi and Yun, 2013; Knaack and Kurama, 2015a). Because RAC usually has a lower modulus of elasticity and larger shrinkage and creep strains compared with the corresponding NAC (Domingo-Cabo et al., 2009; Knaack and Kurama, 2015b; Limbachiya et al., 2000), RAC beams exhibit larger deflections under sustained loads. Based on this limited research data, deflection increase can be up to 20–25% if beams are made of concretes with similar compressive strength. To the best of the authors' knowledge, no previous research has been conducted on the long-term behavior of structural elements made of other green concretes analyzed in this study. So it was assumed that their behavior was similar to the long-term behavior of corresponding NAC. This assumption was made on the basis of available research data on creep on the material level of NAC_FA (Dragaš et al., 2016), NAC_AAFA (Hardjito et al., 2004; Rangan, 2009), and RAC_FA (Kou and Poon, 2012). In this area there was also very limited test data, since most of the research referred to the comparison of concretes with different compressive strengths.

Regarding durability-related properties, a service life of 50 years and XC1 exposure class according to European standard EN 1992-1-1 (2004) were considered. The XC1 exposure class is related to an indoor environment with low air humidity (common conditions in building structures), i.e., only carbonation-induced steel corrosion is taken into account. This practically means that the carbonation depth should stay smaller than the reinforcement cover in the course of 50 years of service life, for all analyzed concrete **mixes**. Otherwise, maintenance and eventual repair caused by the carbonation-induced steel depassivation and corrosion onset will not be equal for different concretes.

Carbonation is a slow, mostly diffusion-controlled process which starts from the concrete surface and slowly penetrates into the interior of concrete. Its rate and extent are controlled physically by gas permeability (porosity of concrete) and chemically by the reserve of alkalinity in the cement paste. Also, carbonation is affected by the curing and exposure conditions (CO_2 concentration, humidity, temperature of the natural environment, etc.) (Pacheco Torgal et al., 2012).

Most of the research data on concrete carbonation are based on accelerated carbonation tests and measuring the carbonated (non-carbonated) part by a phenolphthalein indicator test. Although there are concerns about the capability of such a test to reproduce realistic environmental conditions and chemical processes within concrete (Bernal et al., 2013; Van Den Heede and De Belie, 2014), this is still the major source of information. There is also research (Lye et al., 2015) showing that similar carbonation resistance is obtained under accelerated and natural CO_2 exposures in the case of HVFAC.

When produced with equal compressive strength, RAC exhibits similar or slightly lower carbonation resistance than NAC (Levy and Helene, 2004; Limbachiya et al., 2012; R. V. Silva et al., 2015c). On the other hand, most of the research has shown that replacing cement with FA in NAC increased the carbonation depth, with the increase being larger for a larger

FA content. According to an extensive study by Lye et al. (2015) this was also true in the case of equal 28-day compressive strength. Lower carbonation resistance of FA concretes is explained by the effect of the reduction of calcium hydroxide consumed in the pozzolanic reaction dominating over the process of pore refinement caused by blocking capillary pores with new formed C-S-H (Sim and Park, 2011). The largest increase in the carbonation depth was however reported in RAC_FA concretes. Even in the case of similar compressive strengths, the carbonation depth of RAC_FA was almost twice as large as the carbonation depth of corresponding NAC for a 35% replacement ratio of cement (Kou and Poon, 2012; Limbachiya et al., 2012).

In AAFA concretes, carbonation is understood as the reaction of sodium hydroxide with CO_2 forming sodium carbonate hydrates. According to previous research (Law et al., 2014; Sufian Badar et al., 2014), this results in only a minimal reduction of the initial pH to approximately 11. This pH value should be sufficient to protect reinforcement from depassivation in carbonated AAFAC and consequently, this type of concrete should mitigate the risk of carbonation-induced corrosion.

From previous analysis it was concluded that structural elements made of RAC may have larger long-term deflections and structural elements made of RAC_FA and possibly of NAC_FA may have lower carbonation resistance than corresponding NAC elements. **Proper modeling of different structural behavior for all analyzed concrete mixes at this state-of-the-knowledge is hardly possible – simple extrapolation of material properties on the structural behaviour is not correct. So the following estimation, as a simplification based on evaluated test results on the beams, is made.** Deflection of a structural element under lateral loading (v) is related to its height (h) through the following relationship:

$$v \sim 1/h^3 \qquad (1)$$

If RAC beams exhibit 20–30% larger long-term deflections than corresponding NAC beams, from equation (1) it can be solved that they should have a 5–10% larger height to maintain the same deformational level. On the other hand, to provide for the same carbonation resistance, the reinforcement cover should be increased for the possible larger carbonation depth. Since the order of magnitude of such enlargement is several centimeters, again a 5–10% (beams-slabs) larger height of the element is needed to provide for the same duration of service life (durability).

For these reasons, two scenarios with different FU were considered:

Scenario 1 – a functional unit of 1 m^3 was assumed for all analyzed **concrete mixes (FU based only on the strength requirements)** and

Scenario 2 – a functional unit of 1.1 m^3 was assumed for RAC, NAC_FA and RAC_FA, and 1.0 m^3 for the other **concrete mixes (FU includes strength, serviceability and durability requirements).**

4.3 System boundaries and LCI

Since the goal of the study was to estimate and compare the absolute impacts of different concrete life cycles at a given point in time, an attributional data modeling approach was chosen. A consequential approach (also called change-oriented approach) was found not to fit well with the goal, because this type of approach is intended to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a certain decision, i.e., the results are intended to represent the net environmental impacts of the change caused by this decision (Ekvall and Andrae, 2006; Ekvall and Weidema, 2004; Pelletier et al., 2015).

In accordance with the goal of the study, system boundaries were chosen and shown in Figure 5. In the phase ‘Concrete’, steam curing at a concrete plant was included for alkali activated concrete. Transport to construction site, construction, and use phases were omitted from the assessment since similar impacts were expected for all **concrete mixes** (Scenarios 1 and 2). End-of-life was assumed to be comparable (part of the waste was disposed of in landfills and part was recycled), so it was omitted as well. This assumption was somewhat beneficial for green concretes since it is not proven yet that they can be recycled back into new RCA, but they certainly can be recycled into aggregates for low-value applications.

In resolving multifunctional problems (in this case study, open-loop recycling and treating of FA as by-product), allocation was applied. The system expansion with substitution method was not used since it can lead to double counting of avoided burdens in attributional LCA, i.e., same loads can be subtracted from multiple products, depending on the goal of the study (Chen et al., 2010; Vogtländer et al., 2001).

Recycling is a multi-functional process in a way that it is a waste management service for the product that is recycled and a part of a raw material production for the product that receives the recycled material. Recycling of concrete from one product life cycle (NAC) to another (RAC) is a case of an open-loop recycling and it should be somehow allocated between these products. Although there are more refined approaches (Allacker et al., 2014), a relatively simple but not uncommon approach was adopted in this study (Vogtländer et al., 2001): demolition and separation were allocated to the NAC life cycle, while the recycling process itself was allocated to the RAC life cycle, Figure 6.

Fly ash is no longer considered as merely waste but as a useful by-product (European Union, 2008). As such, it carries a part of the environmental load of the electricity production in the coal-fired power plant (primary process – main product), beside the load from its own treatment prior to the utilization in concrete (secondary process – by-product). In the power plant TENT, the secondary process includes only transport from the electromagnetic separator to the storage silo which is a pneumatic process powered by electricity.

For the calculation of the part of the environmental load of the primary process which should be allocated to FA, three types of allocation were considered:

‘No allocation’ – FA was considered as waste; only impacts from the secondary process were included;

‘Mass allocation’ – impacts of the primary process were allocated between the main product and by-product according to the ratio of their masses. The mass allocation coefficient C_m can then be calculated as (Chen et al., 2010):

$$C_m = \frac{m_{byproduct}}{m_{mainproduct} + m_{byproduct}} \qquad (2)$$

where $m_{byproduct}$ is FA mass and $m_{mainproduct}$ is electricity ’mass’;

’Economic allocation’ – impacts of the primary process were allocated between the main product and by-product according to the ratio of their prices. The economic allocation coefficient C_e can then be calculated as (Chen et al., 2010):

$$C_e = \frac{(€ \cdot m)_{byproduct}}{(€ \cdot m)_{mainproduct} + (€ \cdot m)_{byproduct}} \qquad (3)$$

where € is the price per unit of material, and m is a mass of material produced during the process.

For the production of 1 kWh of electricity, 1.290 kg of coal is consumed, while 0.194 kg of FA and 0.013 of bottom ash is generated in TENT. ‘Mass’ of the electricity (main product) is calculated as the mass of equivalent coal:

$$m_{mainproduct} = 1.290 - 0.194 - 0.013 = 1.084 kg \quad (4)$$

and the mass allocation coefficient $C_{m,FA}$ is:

$$C_{m,FA} = \frac{0.194}{1.084 + 0.194} = 0.152 \quad (5)$$

The cost of FA and industrial electricity in Serbia is 3.5 €/ton and 0.05 €/kWh, respectively. The economic allocation coefficient $C_{e,FA}$ is then:

$$C_{e,FA} = \frac{0.194 \cdot \frac{3.5}{1000}}{1 \cdot 0.05 + 0.194 \cdot \frac{3.5}{1000}} = 0.013 \quad (6)$$

With the allocation coefficients $C_{m,FA}$ and $C_{e,FA}$, the impacts of electricity production were allocated to FA production in the ‘mass allocation’ and ‘economic allocation’ case, respectively.

Life cycle inventory (LCI) data for the aggregate, cement and concrete production, as well as for the FA treatment, were obtained from local Serbian suppliers whose products were used for concrete mixes (Marinković et al., 2008). The data on energy demand and emissions for the cement production were obtained from Lafarge Cement Plant, Beočin, Serbia. LCI data for the natural (river), recycled aggregate and concrete production were calculated based on the information about technology processes and used energy obtained from their manufacturers. Basically, this is about 0.015 MJ of diesel per kg of river aggregate and 0.024 MJ of diesel per kg of recycled aggregate, for the production without separation. Separation was included in the concrete production, where about 20 MJ of electricity per m^3 of concrete is consumed. For steam curing, about 600 MJ of natural gas (15 m^3) is spent per m^3 of concrete in a precast concrete plant. Similar data were reported by other researchers (Kawai et al., 2005).

Emission and resource data for diesel and natural gas production and distribution, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) production and transport that couldn't be collected for local conditions were taken from the Ecoinvent V2.0 database (Dones et al., 2007; Spielmann et al., 2007; Zah and Hischier, 2007), Table 8. Impacts of the superplasticizer production were neglected since its mass was lower than 0.15 % of the concrete mass.

Transport distances and types were estimated as typical for a construction site located in the capital of Serbia, Belgrade and presented in Table 9. Recycling is performed in a mobile recycling plant at the demolition site close to Belgrade (20 km). A larger transport distance for RCA was deemed unacceptable in industrial practice, mostly because of the cost efficiency in comparison with natural river aggregate. **Since Serbia has only mobile recycling plants, it was assumed that a mobile recycling plant has to be transported from somewhere in Serbia to the demolition site close to Belgrade (200 km distance as a worst case scenario).**

4.4 Life cycle impact assessment

The impact category indicators included in this work were global warming potential (GWP), ozone layer depletion potential (ODP), eutrophication potential (EP), acidification potential (AP), and photochemical oxidant creation potential (POCP). They were calculated using the CML baseline methodology (Guinée et al., 2002). Besides, abiotic depletion of fossil fuels potential (ADP_FF) was calculated using the cumulative energy demand method. For the ADP_FF calculations, the following heating values of fossil fuels were used: 19.1 MJ/kg of hard coal, 8.8 MJ/kg of soft coal, 42.0 MJ/kg of diesel, and 39.0 MJ/m^3 of natural gas. An original Excel-based software was used for the life cycle inventory and the life cycle impact calculations.

4.4.1 Normalization and aggregation

Calculated indicators are expressed in different units and their absolute values vary significantly. In order to enable aggregation and calculation of a single sustainability indicator, normalization is performed using the Diaz-Balteiro equation (Díaz-Balteiro and Romero, 2004). This equation, in the case of a ‘less is better’ indicator type, can be formulated as:

$$\overline{I_i} = \frac{I_i - I_{i*}}{I_i^* - I_{i*}} \qquad (7)$$

where $\bar{I}_i$ is the normalized value of i-th indicator, I_{i*} and I_i^* are the worst and the best value (minimum) of the i-th indicator, respectively. In this way, indicator’s values are converted into dimensionless values ranging from 0 (worst value) to 1 (best value) (Teixeira et al., 2016).

Now, a global sustainability indicator SI can be calculated by the aggregation of n normalized indicator’s values (Teixeira et al., 2016):

$$SI = \sum_{i=1}^{n} w_i \overline{I_i} \qquad (8)$$

where w_i are the weights representing the relative importance of the i-th indicator for the overall environmental performance. The ‘most sustainable’ product is then the product with the maximum SI value. It should be noted that according to ISO 14040 (ISO, 2006) there is no scientific way to reduce LCA results to a single overall score or number, hence weights are usually determined by a panel of experts expressing the societal preference.

In this study two different sets of weights were used and compared: (1) all six calculated indicators are equally important, i.e., the weight of each is equal to 1/6 = 0.1667 and (2) the most important indicator is GWP and weights suggested by the US Environmental Protection Agency Science Advisory Board (Mateus et al., 2013) were used for SI calculation. These weights are shown in Table 10.

4.4.2 Sensitivity analysis

As already explained, in order to evaluate the influence of different carbonation resistance and long-term deformational behavior of structural elements made of different concrete **mixes**, two scenarios (Scenarios 1 and 2) were tested and compared. **Comparison of these two scenarios was performed to test the sensitivity of the impacts' results on the choice of FU – to determine how important is whether a simple FU (including only strength requirements) or an improved FU (including also serviceability and durability requirements) is applied.**

No sensitivity analysis regarding other parameters and assumptions that can affect results (quality of RCA, chemical composition and fineness of FA, transport distances, exposure conditions and duration of service life) was performed. These limitations should be kept in mind.

5. Results and interpretation

LCI data per 1 kg of constituent materials, 1 m^3 of concrete (including curing) and 1 ton-kilometer (tkm) of transport are shown in Table 11.

Calculated impact indicators in the 'no allocation', **'economic allocation' and 'mass allocation'** case and for Scenario 1 are shown in Figures 7, 8, and 9. Impact indicators of green **concrete mixes** are presented as a percentage of the NAC **mix** impact indicators. Results significantly depend on the allocation type. Large amounts of airborne pollutants are emitted from coal-fired power plants in the process of electricity production and even a small allocation coefficient can strongly affect the FA impact indicators.

This is especially the case with 'mass allocation' because a relatively large mass of FA is generated during electricity production. In this case all impacts of FA concretes (no matter whether alkali activated or not) are significantly higher than impacts of NAC and RAC with no FA. Similar conclusions have been made by other researchers (Chen et al., 2010; Tillman et al., 1994) regarding the FA environmental impact when used as mineral addition or cement replacement in concrete.

Since 'mass allocation' results in unreasonably high FA impacts, only the results obtained with 'economic allocation' are presented in the following text.

Absolute values of impact indicators of analyzed **concrete mixes** in Scenario 2 are presented in Table 12, while Figure 10 shows these indicators relative to the NAC indicators. This scenario is less favorable for RAC, NAC_FA, and RAC_FA than Scenario 1, but more realistic in the authors' opinion. While in Scenario 1 impact indicators of NAC and RAC are practically equal, in Scenario 2 all indicators of RAC are slightly higher (up to 13%) than NAC indicators. The main reason for this increase is a larger cement amount in RAC. In Scenario 2, the cement content in RAC is 14% higher than in NAC due to the larger FU. FA concretes with natural and recycled aggregates (NAC_FA and RAC_FA) perform better than NAC except in the case of EP and AP, where their impact is slightly higher. This, however, is due to the allocation procedure, since in the 'no allocation' case all impacts of FA concretes are lower than those of NAC for both scenarios. Alkali activated concrete NAC_AAFA is superior regarding GWP, AP, and POCP, while for ADP_FF and ODP it presents the worst option. The single reason for much higher ADP_FF of alkali activated concrete is the large energy consumption for concrete curing at elevated temperatures. On the other hand, high ODP originates from the alkali activators' production.

Tables 13 and 14 show which **unit processes** are the major contributors to GWP and ADP_FF in Scenario 2. As already well known, cement is by far the largest contributor to GWP for non-alkali activated concretes, Table 13. The contribution of aggregate and concrete production is practically negligible (up to 2%), while the contribution of transport and FA production is similar (8–12%). For alkali activated **concrete mix**, concrete production (i.e., curing) and alkali activator production have the largest, but similar shares in GWP (32–33%). Again, aggregate production is negligible, and transport and FA production contributions range from 15% to 19%. In the case of ADP_FF, transport has a larger share (up to 25%), but otherwise the distribution among **unit processes** is similar as in GWP, Table 14. Similar conclusions are valid for other impact indicators of non-alkali activated **concrete mixes**. However, a major contributor to ODP and EP of alkali activated **concrete mix** is the alkali activator production.

When normalized, impact categories can be presented together in a 'radar' diagram showing in that way the so-called 'sustainable profile'. This type of presentation enables an easier understanding of the complete environmental profile of the particular concrete. Figure 11 shows such sustainable profiles of all analyzed **concrete mixes** for Scenarios 1 and 2. Normalized values of each impact indicator and for each **concrete mix** were calculated using Equation 7. As already explained, the worst value of the normalized indicator is equal to 0, while the best is equal to 1, meaning the larger the profile area, the better the environmental (sustainable) performance. In Figure 11, the area of the referent NAC and NAC_AAFA profiles are shaded. Then it can easily be seen that alkali activated concrete is better in GWP, AP, and POCP, while non-alkali activated concretes are better in ADP_FF, ODP and EP. While in Scenario 1 sustainable profiles of NAC and RAC are similar, in Scenario 2 the NAC sustainable profile is evidently better than that of RAC. Also, NAC_FA and RAC_FA profiles ‘shrank’ in Scenario 2 compared with Scenario 1.

Finally, the aggregation results are presented in Table 15. Sustainability indicators (SI) were calculated according to Equation 8 for each **concrete mix** and both scenarios. When using the ‘EPA’ weights, NAC_AAFA showed the best overall environmental performance (the highest *SI*), while the worst belonged to RAC, regardless of the scenario. When using ‘equal’ weights, the best and the worst environmental performance belonged to RAC_FA and RAC, respectively, regardless of the scenario. **So, in this study, impacts’ results in terms of best and worst overall environmental performance were not sensitive on the FU choice, but on the choice of weights.** This sensitivity on the choice of weights was obtained because the ‘EPA’ weights give a relatively high preference to GWP, which made the results of alkali activated **concrete mix** practically unattainable.

It is also interesting to exclude alkali activated **concrete mix**, i.e., to compare **concrete mixes** suitable not only for precast but also for in-situ applications (NAC, NAC_FA, RAC and RAC_FA). Sustainable profiles for that case are shown in Figure 12, where only the area of the NAC profile is shaded. The change from Scenario 1 to Scenario 2 is now clearer, giving a much better environmental performance of NAC in Scenario 2. In this scenario, all normalized impact indicators of RAC were equal to 0. However, regardless of the scenario and type of weights used, RAC_FA had the best environmental performance, while RAC had the worst, Table 16.

6. Conclusion

The LCA case study presented here **included five specific concrete mixes** and was mostly based on the construction practice, transport distances and materials available in Serbia. The concretes were made partially from waste: FA complying to EN 450-1 (2012) requirements and RCA, which was clean, without any impurities and with water absorption lower than 5%. **The carbonation induced steel corrosion and a service life of 50 years were assumed. An attributional approach in LCI modeling with allocation was applied. The following conclusions, valid only for this set of assumptions and applied methodology, are drawn:** Two types of allocation procedures were tested and compared with the 'no allocation' case. If mass allocation is applied, the FA **concrete mixes** environmental burdens become higher than the burdens of **concrete mix** with blended cement (several times) and this can certainly discourage producers from implementing this material as cement clinker replacement. That's why economic allocation is recommended since it results in much lower impacts of FA, which is appropriate for waste, which FA in fact is. This is also recognized by the standard EN 15804 (2012) which recommends economic allocation when the difference in revenue from the co-products is more than 25%; in the case of electricity and FA as co-products, this is certainly fulfilled.

Possible lower carbonation resistance and higher long-term deflections in the course of 50 years of service life were taken into account by introducing two scenarios with different FUs. **The FU in Scenario 1 was equal to 1 m^3 of concrete and included only strength requirements. In Scenario 2, FU included strength, serviceability and durability requirements and for NAC_FA, RAC and RAC_FA was assumed to be 1.1 m^3, while for other concrete mixes it was kept equal to 1 m^3.** For the aggregation of normalized indicators' results and sustainability indicator calculation, two different sets of weights were used: 'equal' and 'EPA' weights.

Impacts' results in terms of best and worst overall environmental performance were not sensitive to the FU choice, but to the choice of weights.

Recycled aggregate **concrete mix** with a cement binder (RAC) showed the worst overall environmental performance in both scenarios and for both weight sets used. If better environmental performance is to be expected, RAC should be designed with the same cement amount as NAC; the water-to-cement ratio should be decreased and workability problems solved with the aid of a superplasticizer.

Alkali activated **concrete mix** with natural aggregates (NAC_AAFA), despite the uncommonly high amount of alkali activator that had to be used, showed the best overall environmental performance in both scenarios, if 'EPA' weights were applied. It had the best sustainability indicator value. If no preference was given to GWP ('equal' weights), FA **concrete mix** with recycled aggregates (RAC_FA) became the best option. However, AAFA concretes have limited application only to precast concrete structures because curing at a temperature of 80°C is practically impossible in-situ at large scale. Besides, high caustic sodium hydroxide, which is needed for the alkali activation, is user-hostile and can present a problem in the industrial practice. In order to improve the environmental and cost efficiency and extend applicability, a partial replacement of FA with blast furnace slag is recommended, i.e., slag/fly ash geopolymer concrete is recommended.

When comparing only concretes suited for all applications, FA **concrete mixes** (NAC_FA and RAC_FA) had a better environmental performance than NAC and RAC in both scenarios and for both weight sets. Even with a larger FU, FA recycled aggregate **concrete mix** (RAC_FA) proved to have the best sustainability indicator. Besides, only 47% (39% if water is excluded) of this concrete is made of natural resources, while 53% (61% if water is excluded) is made of waste – RCA and FA.

Based on the results of this case study, RAC with FA is to be recommended for in-situ applications. For precast structural applications, both NAC_AAFA and RAC_FA can be recommended, depending on what particular impact category is preferred. Conclusions are not to be generalized – for other assumed scenarios or different approach in LCI modelling results may be different.

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Table 1. Oven-dry density and absorption of aggregates

	Oven-dry density (kg/m^3)	Absorption 24h (%)
Natural aggregate		
0-4 mm river sand	2573	1.20
4-8 mm river gravel	2548	1.24
8-16 mm river gravel	2591	1.04
Recycled aggregate		
4-8 mm	2309	4.60
8-16 mm	2370	3.70

Table 2. Chemical and physical properties of cement and fly ash

Property	CEM II 42.5R	Fly ash	EN 450-1:2012
SiO_2 (%)	21.04	58.24	-
Al_2O_3 (%)	5.33	20.23	-
Fe_2O_3 (%)	2.37	5.33	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	83.80	min 70 (%)
TiO_2 (%)	-	0.45	-
CaO (%)	60.43	7.62	-
MgO (%)	2.43	2.01	max 4 (%)
P_2O_5 (%)	-	0.00	max 5 (%)
SO_3 (%)	3.55	2.21	max 3 (%)
Na_2O (%)	0.22	0.52	max 5 (%)
K_2O (%)	0.70	1.51	-
MnO (%)	-	0.03	-
LOI (%)	3.53	2.10	max 5 (%)
Fineness (>45 µm, %)	-	11.71	max 12 (%)
Specific gravity (kg/m^3)	3040	2075	-

Table 3. Mix proportions and properties of NAC and RAC

Concrete mixture	Cement	Water	w/c[1]	Natural aggregate		Recycled aggregate	Super plasticiz.	Density (hardened)	Compress. strength, 28 days	Slump
				Fine	Coarse	Coarse				
	(kg/m^3)	(kg/m^3)	-	(kg/m^3)		(kg/m^3)	(kg/m^3)	(kg/m^3)	(MPa)	(cm)
NAC	302	180	0.596	619	1203	-	-	2384	40.5	19
RAC	312	180+40[2]	0.580	597	-	1106	-	2320	42.1	16

[1] free water-to-cement ratio

[2] additional water amount

Table 4. Trial NAC_FA mixtures

Concrete mixture	Cement	Fly ash	Water	w/cm[1)]	Aggregate		Super plasticiz.	Density (hardened)	Compress. strength, 28 days	Slump
					Fine	Coarse				
	(kg/m^3)	(kg/m^3)	(kg/m^3)	-	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(MPa)	(cm)
C384F0_055	384	0	212	0.55	683	985	0	2388	41.2	5.5
C192F192_055	192	192	212	0.55	650	937	0	2307	31.0	6.0
C192F346_039	192	346	212	0.39	452	937	1.9	2273	36.1	16.8
C384F0_052	384	0	201	0.52	758	1015	0	2401	50.7	4.2
C192F346_037	192	346	201	0.37	524	969	1.9	2310	45.7	14.8
C192F346_034	192	346	180	0.34	524	1026	2.6	2315	54.0	1.5
C192F346_030	192	346	161	0.30	524	1076	3.7	2365	63.3	18.0
C200F200_049	200	200	195	0.49	811	810	0	2303	34.2	12.7
C200F250_043	200	250	195	0.43	749	810	1.0	2295	38.2	14.8
C200F300_039	200	300	195	0.39	687	810	1.2	2244	36.7	2.8
C200F350_036	200	350	195	0.36	625	810	2.2	2268	42.0	3.3
C200F400_033	200	400	195	0.33	563	810	2.4	2255	40.2	70.0[2)]
NAC_FA	192	346	195	0.36	625	810	2.5	2257	42.0	15.0

1) water-to-cementitious material ratio

2) flow value

Table 5. Trial RAC_FA mixtures

Concrete mixture	Cement	Fly ash	Water	w/cm1)	Aggregate		Super plasticiz.	Density (hardened)	Compress. strength, 28 days	Slump
					Fine (natural)	Coarse (recycled)				
	(kg/m^3)	(kg/m^3)	(kg/m^3)	-	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(MPa)	(cm)
C312F0_058 (RAC)	312	0	180+40 2)	0.58	597	1106	0	2320	42.1	16.0
C192F346_033	192	346	180+45 2)	0.33	501	900	2.5		37.0	35.0
RAC_FA	192	346	180+38 2)	0.33	637	779	1.1	2203	40.5	14.7

1) water-to-cementitious material ratio

2) additional water amount

Table 6. Mix proportions and properties of alkali activated pastes

Paste mixture	AA/FA	NaOH	Na_2SiO_3/ NaOH	Na_2O/FA	SiO_2/Na_2O	Compress. strength, 28 days
	(-)	(M)	(-)	(%)	(-)	(MPa)
P_1	0.6	10	2.0	10.72	1.04	57.1
P_2			3.5	10.09	1.30	49.2
P_3			5.0	9.77	1.44	55.3
P_4			10.0	9.34	1.64	59.7
P_5		16	2.0	12.86	0.87	NA
P_6			3.5	11.51	1.14	53.9
P_7			5.0	10.84	1.30	58.8
P_8			10.0	9.92	1.54	65.4

Table 7. Trial NAC_AAFA mixtures

Concrete mixture	Fly ash	Water	Aggregate		NaOH solution	Na_2SiO_3 solution	SiO_2/Na_2O	Density (hardened)	Compress. strength, 28 days	Slump
			Fine	Coarse						
	(kg/m^3)	(kg/m^3)	(kg/m^3)		(kg/m^3)	(kg/m^3)	(-)	(kg/m^3)	(MPa)	(cm)
C_1 (NAC_AAFA)	400	0	682	948	21.8	218.2	1.64	2311	40.7	18.3
C_2	400	10	672	969	21.8	218.2	1.64	2293	34.3	23.3
C_3	400	20	661	953	21.8	218.2	1.64	2275	37.2	25.3
C_4	400	28	670	966	21.8	218.2	1.64	2281	30.5	28.0
C_5	400	0	689	994	21.8	218.2	1.54	2279	43.6	13.2
C_6	400	28	656	949	53.3	186.7	1.14	2270	36.3	26.5

Table 8. Sources of LCI data

Type of data	Source (file name in Ecoinvent V2.0)	Geography
Energy		
Coal mining and distribution	Ecoinvent (hard coal, at regional storage/kg/EEU)	EU average
Diesel production, distribution, and usage	Ecoinvent (diesel, at regional storage/kg/RER) (diesel, burned in building machine/MJ/GLO)	EU average
Natural gas production, distribution, and usage	Ecoinvent (natural gas, high pressure, at consumer/MJ/RER) (natural gas, burned in industrial furnace >100kW/MJ/RER)	EU average
Electricity	Ecoinvent (electricity mix/kWh/CS)	Serbia
Concrete components		
Cement production	Industry	Serbia
Fly ash treatement	Industry	Serbia
River and recycled aggregates production	Industry	Serbia
Sodium hydroxide production	Ecoinvent (sodium hydroxide, 50% in H_2O, mercury cell, at plant/kg/RER)	EU average
Sodium silicate production	Ecoinvent (sodium silicate, hydrothermal liquor, 48% in H_2O, at plant/kg/RER)	EU average
Concrete production	Industry	Serbia
Transport		
Road and river	Ecoinvent (transport, lorry 16-32t, EURO3/tkm/RER) (transport, barge/tkm/RER)	EU average

Table 9. Transport distances and types

Material	Route		Transport distance (km)	Transport type
	From	To		
River aggregate	Place of extraction	Concrete plant	100 x 2	Barge 10000 t
Recycled aggregate	Recycling plant[1]	Concrete plant	20 x 2	Truck 16–32 t
Cement	Cement factory	Concrete plant	100 x 2	Truck 16–32 t
Fly ash	Power plant	Concrete plant	50 x 2	Truck 16–32 t
Sodium hydroxide	Factory	Concrete plant	25 x 2	Truck 16–32 t
Sodium silicate	Factory	Concrete plant	15 x 2	Truck 16–32 t
Mobile recycling plant [2]		Demolition site	200	Truck 16–32 t

1) Recycling is performed in a mobile plant at the demolition site

2) For each campaign of 2500 t the mobile plant (20 t) is transported 200 km

Table 10. ‘EPA’ weights (Mateus et al., 2013)

Indicator	Weight (%)
ADP_FF	12
GWP	38
ODP	12
EP	12
AP	12
POCP	14

Table 11. LCI data per 1 kg of constituent material, 1 m^3 of concrete, and 1 ton-kilometer (tkm) of transport

	Cement (kg)	Fly ash (kg)			Aggregate (kg)		NaOH (kg)	Na_2SiO_3 (kg)	Concrete (m^3)	Curing (m^3)	Transport (tkm)	
		No allocation	Mass allocation	Economic allocation	Natural	Recycled	active substance	active substance			Lorry 16–32 t	Barge
Fossil fuels												
diesel (kg)	1.484E-03	2.828E-05	2.833E-03	2.757E-04	3.898E-04	6.499E-04	4.115E-02	4.297E-02	2.002E-02	8.129E-02	5.426E-02	1.111E-02
gas (m^3)	4.577E-03	9.366E-05	9.382E-03	9.131E-04	2.959E-05	4.934E-05	9.357E-02	9.878E-02	6.630E-02	1.788E+01	8.769E-03	1.694E-03
soft coal (kg)	1.223E-01	7.419E-03	7.432E-01	7.233E-02	1.739E-05	2.900E-05	3.590E-01	1.820E-01	5.252E+00	1.770E-01	4.890E-03	2.050E-03
hard coal (kg)	1.555E-01	5.661E-05	5.671E-03	5.520E-04	2.422E-05	4.039E-05	2.089E-01	1.154E-01	4.008E-02	1.796E-01	7.275E-03	2.369E-03
Emissions (g)												
CO_2	7.394E+02	6.489E+00	6.501E+02	6.327E+01	1.085E+00	1.771E+00	6.637E+02	3.447E+02	4.594E+03	3.582E+04	1.549E+02	3.697E+01
CO	3.757E+00	1.244E-03	1.246E-01	1.213E-02	4.397E-03	6.620E-03	2.403E-01	1.435E-01	8.808E-01	2.847E+00	4.199E-01	3.549E-02
CH_4	9.985E-01	3.095E-03	3.100E-01	3.017E-02	5.499E-05	9.094E-04	1.728E+00	1.230E+00	2.191E+00	9.252E+01	3.146E-01	5.279E-02
C_2H_4	5.198E-05	1.040E-07	1.041E-05	1.013E-06	1.104E-06	2.055E-06	5.803E-04	7.562E-04	7.359E-05	1.719E-03	2.528E-04	5.336E-05
CFC-11	1.991E-12	2.945E-15	2.950E-13	2.872E-14	4.129E-15	6.751E-14	4.156E-10	4.853E-10	2.085E-12	1.521E-11	2.333E-11	2.276E-13
CFC-113	8.122E-11	6.884E-14	1.965E-12	6.711E-13	3.100E-13	6.192E-12	3.764E-08	4.502E-08	4.873E-11	6.260E-10	2.172E-09	1.144E-11
CFC-114	1.164E-06	5.190E-09	5.200E-07	5.061E-08	5.064E-10	1.441E-09	1.032E-05	5.326E-06	3.674E-06	5.512E-06	3.022E-07	6.671E-08
SO_x	2.104E+00	7.540E-02	7.554E+00	7.352E-01	3.677E-04	1.274E-03	2.877E+00	1.628E+00	5.338E+01	1.386E+01	3.049E-01	5.286E-02
NO_x	3.495E+00	1.132E-01	1.134E+01	1.103E+00	1.507E-02	2.227E-02	1.128E+00	6.238E-01	8.011E+01	1.934E+01	1.283E+00	5.034E-01
N_2O	6.269E-04	3.111E-05	3.116E-03	3.033E-04	4.139E-05	6.727E-05	1.140E-02	6.318E-03	2.202E-02	3.565E-01	5.808E-03	3.278E-03
NH_3	1.283E-03	4.615E-07	4.623E-05	4.499E-06	9.679E-06	1.819E-05	2.434E-02	1.133E-02	3.267E-04	1.536E-02	2.277E-03	6.160E-04
NMVOC	6.461E-03	1.299E-04	1.302E-02	1.267E-03	1.775E-03	2.639E-03	1.342E-01	1.250E-01	9.198E-02	9.189E+00	1.569E-01	5.073E-02
HCl	9.841E-03	5.654E-04	5.664E-02	5.513E-03	1.249E-06	3.906E-06	5.962E-02	3.030E-02	4.003E-01	2.912E-02	8.775E-04	3.626E-04
N (water)	1.468E-04	6.788E-06	6.800E-04	6.618E-05	1.469E-06	2.861E-06	1.068E-02	5.272E-03	4.805E-03	3.971E-03	3.834E-04	1.080E-04
PO_4^{-3} (groundwater)	2.336E-01	5.442E-03	5.451E-01	5.305E-02	2.152E-05	1.671E-04	2.815E+00	1.534E+00	3.852E+00	1.579E+00	5.248E-02	1.832E-02
P (air, water, ground)	3.940E-06	1.081E-07	1.083E-05	1.054E-06	5.874E-07	1.178E-06	5.987E-04	2.920E-04	7.654E-05	4.228E-03	1.659E-04	3.818E-05

Table 12. Indicators' results per FU in Scenario 2

	Unit	NAC	NAC_FA	NAC_AAFA	RAC	RAC_FA
ADP_FF	MJ-eq.	1.765E+03	1.662E+03	2.466E+03	1.956E+03	1.663E+03
GWP	g CO_2-eq.	2.604E+05	2.168E+05	1.342E+05	2.929E+05	2.161E+05
ODP	g CFC-11-eq.	3.390E-04	2.678E-04	5.947E-04	3.822E-04	2.674E-04
EP	g PO_4^{3-}-eq.	2.700E+02	2.821E+02	3.285E+02	2.933E+02	2.757E+02
AP	g SO_2-eq.	1.730E+03	1.893E+03	1.198E+03	1.899E+03	1.867E+03
POCP	g C_2H_4-eq.	8.748E+01	8.101E+01	4.835E+01	9.489E+01	7.898E+01

Table 13. Contribution of various **unit processes** to GWP (%), Scenario 2

	CEM II	NA+RCA	FA	Activator[1]	Concrete	Transport
NAC	88.2	0.8	-	-	1.8	9.3
NAC_FA	74.1	0.8	11.2	-	2.1	11.7
NAC_AAFA	-	1.3	19.1	32.6	31.7	15.2
RAC	89.1	1.0	-	-	1.6	8.3
RAC_FA	74.3	1.1	11.3	-	2.1	11.2

[1] $NaOH+Na_2SiO_3$

Table 14. Contribution of various **unit processes** to ADP_FF (%), Scenario 2

	CEM II	NA+RCA	FA	Activator[1]	Concrete	Transport
NAC	73.4	1.9	-	-	2.9	21.9
NAC_FA	54.5	1.7	15.9	-	3.0	24.9
NAC_AAFA	-	1.2	11.3	43.7	30.7	13.2
RAC	75.2	2.5	-	-	2.6	19.7
RAC_FA	54.4	2.3	15.9	-	3.0	24.3

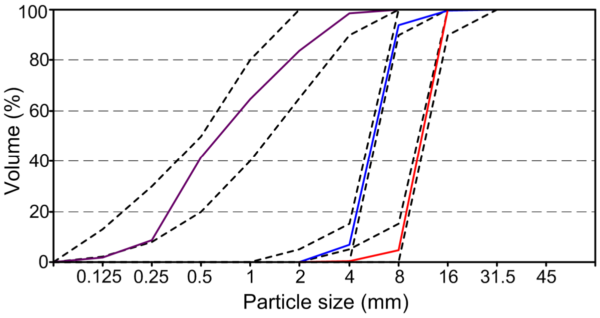
[1] $NaOH+Na_2SiO_3$

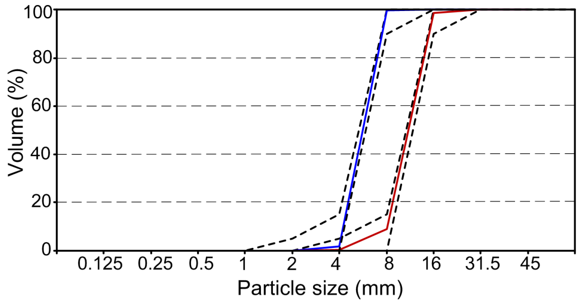
Table 15. Sustainability indicators for both scenarios and both weight sets

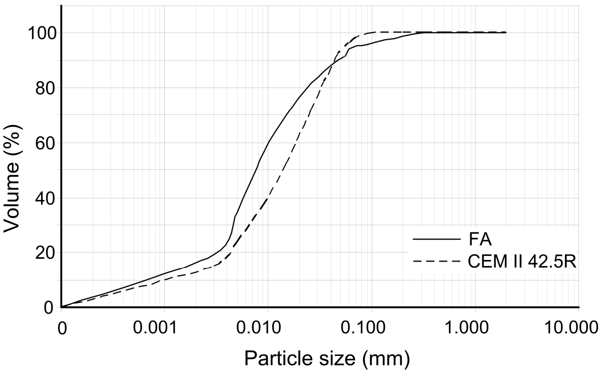
Concrete type	SI 'EPA' weights Scenario 1	SI 'EPA' weights Scenario 2	Concrete type	SI 'Equal' weights Scenario 1	SI 'Equal' weights Scenario 2
NAC_AAFA	0.640	0.640	RAC_FA	0.662	0.629
RAC_FA	0.622	0.585	NAC_FA	0.634	0.596
NAC_FA	0.599	0.560	NAC_AAFA	0.500	0.500
NAC	0.287	0.447	NAC	0.382	0.543
RAC	0.269	0.226	RAC	0.373	0.314

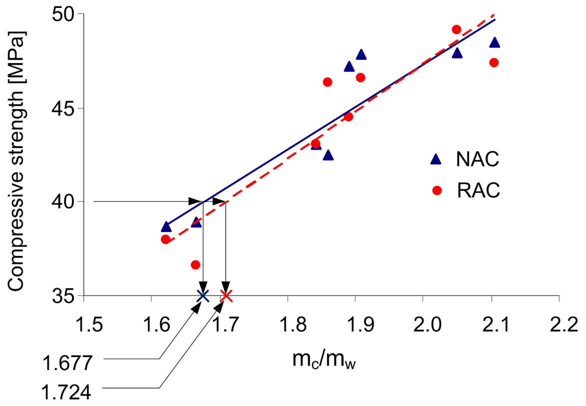
Table 16. Sustainability indicators for both scenarios and both weight sets, ‘in-situ’ concretes

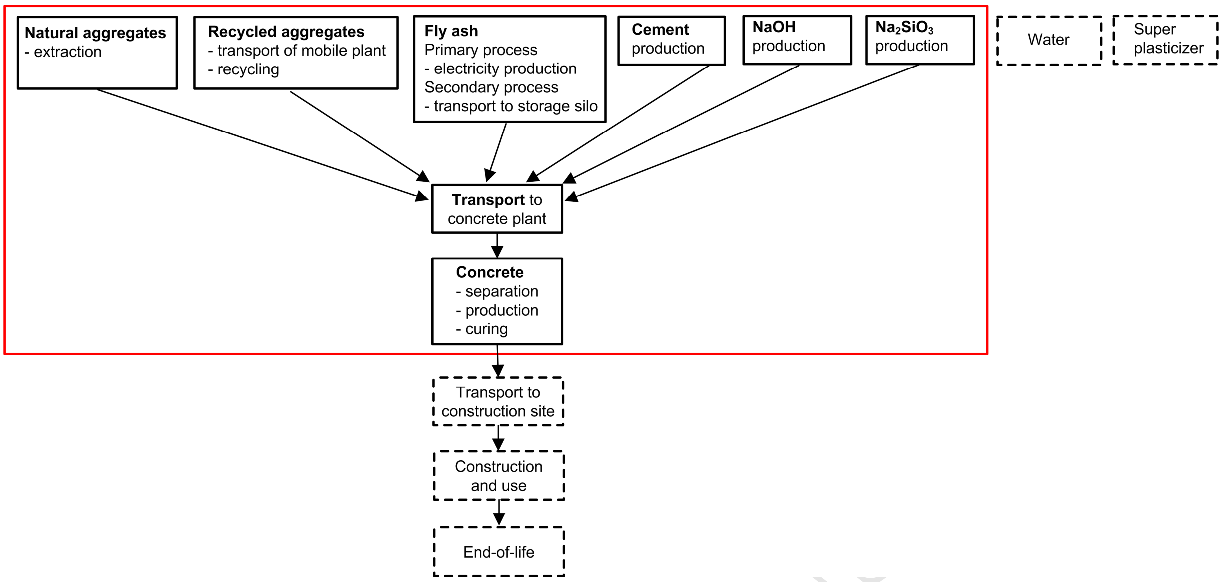
Concrete type	SI		Concrete type	SI	
	‘EPA’ weights			‘Equal’ weights	
	Scenario 1	Scenario 2		Scenario 1	Scenario 2
RAC_FA	0.999	0.872	RAC_FA	0.999	0.823
NAC_FA	0.845	0.800	NAC_FA	0.791	0.730
NAC	0.080	0.589	NAC	0.079	0.653
RAC	0.023	0.000	RAC	0.030	0.000

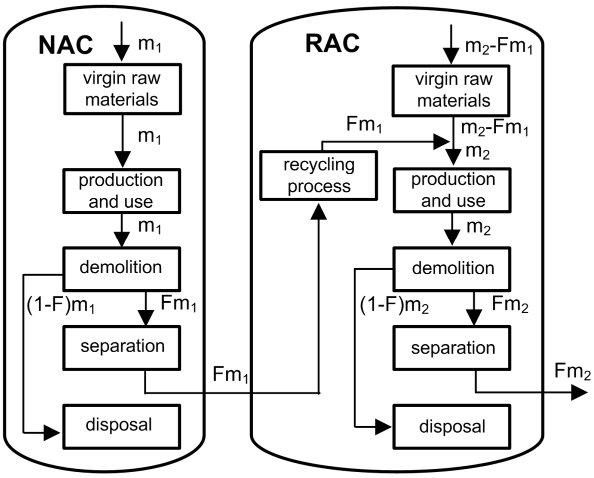

100
80
60
40
20
0
Volume (%)
0.125
0.25
0.5
1
2
4
8
16
31.5
45
Particle size (mm)

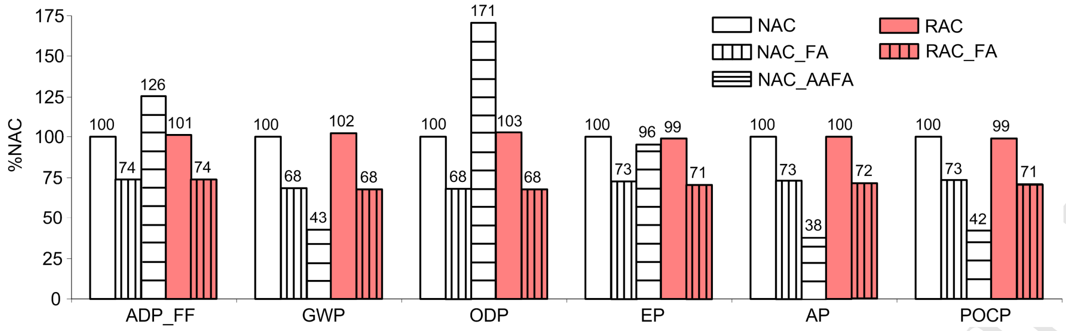

100
80
60
40
20
0
Volume (%)
0.125
0.25
0.5
1
2
4
8
16
31.5
45
Particle size (mm)


Volume (%)
100
80
60
40
20
0
0
0.001
0.010
0.100
1.000
10.000
Particle size (mm)
FA
CEM II 42.5R


Compressive strength [MPa]
50
45
40
35
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
m_c/m_w
▲ NAC
● RAC
1.677
1.724


Natural aggregates
- extraction
Recycled aggregates
- transport of mobile plant
- recycling
Fly ash
Primary process
- electricity production
Secondary process
- transport to storage silo
Cement production
NaOH production
Na_2SiO_3 production
Water
Super plasticizer
Transport to concrete plant
Concrete
- separation
- production
- curing
Transport to construction site
Construction and use
End-of-life


NAC
m1
virgin raw materials
m1
production and use
m1
demolition
(1-F)m1
Fm1
separation
disposal
Fm1
RAC
m2-Fm1
virgin raw materials
Fm1
m2-Fm1
m2
recycling process
production and use
m2
demolition
(1-F)m2
Fm2
separation
Fm2
disposal


%NAC
175
150
125
100
75
50
25
0
ADP_FF
GWP
ODP
EP
AP
POCP
NAC
NAC_FA
NAC_AAFA
RAC
RAC_FA
100
74
126
101
74
100
68
43
102
68
100
68
171
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100
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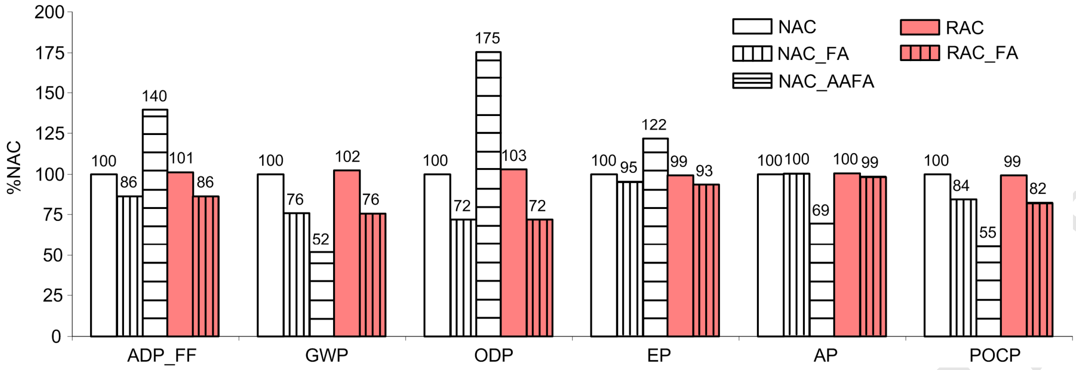
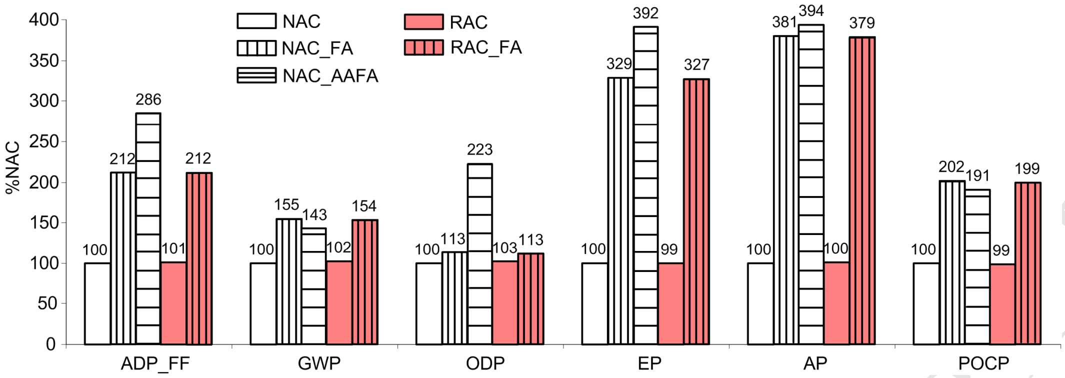
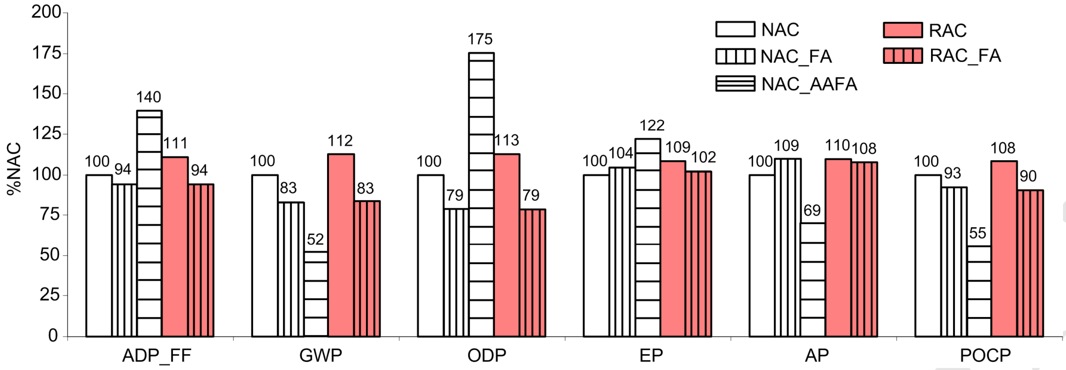
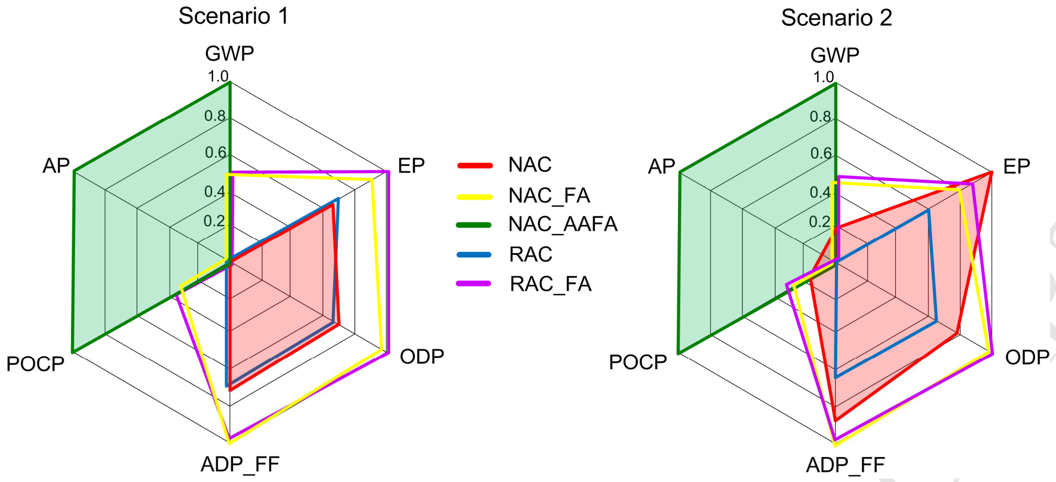
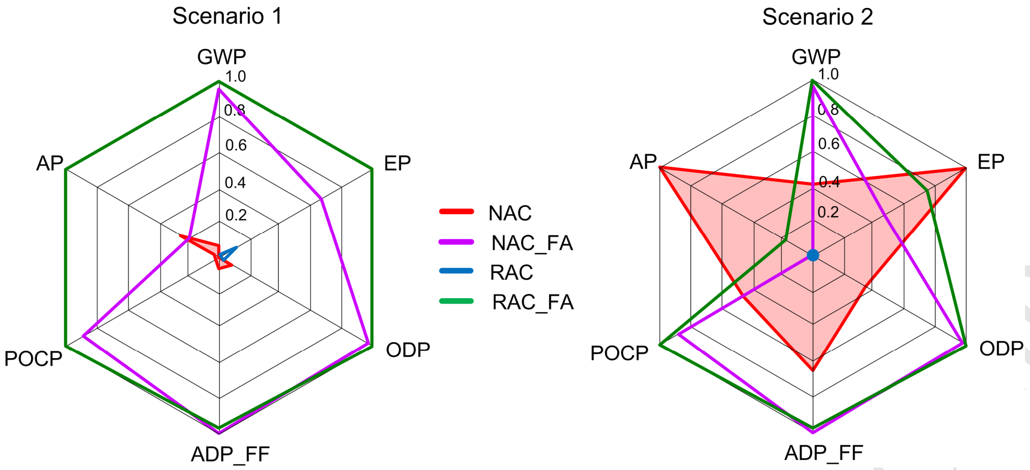
72
100
73
42
99
71


200
175
150
125
100
75
50
25
0
%NAC
NAC
NAC_FA
NAC_AAFA
RAC
RAC_FA
100
86
140
101
86
100
76
52
102
76
100
72
175
103
72
100
95
122
99
93
100
100
69
100
99
100
84
55
99
82
ADP_FF
GWP
ODP
EP
AP
POCP


NAC
NAC_FA
NAC_AAFA
RAC
RAC_FA
%NAC
400
350
300
250
200
150
100
50
0
ADP_FF
GWP
ODP
EP
AP
POCP
100
212
286
101
212
100
155
143
102
154
100
113
223
103
113
100
329
392
99
327
100
381
394
100
379
100
202
191
99
199


%NAC
0
25
50
75
100
125
150
175
200
NAC
NAC_FA
NAC_AAFA
RAC
RAC_FA
ADP_FF
100
94
140
111
94
GWP
100
83
52
112
83
ODP
100
79
175
113
79
EP
100
104
122
109
102
AP
100
109
69
110
108
POCP
100
93
55
108
90


Scenario 1
GWP
1.0
0.8
0.6
0.4
0.2
EP
ODP
ADP_FF
POCP
AP
NAC
NAC_FA
NAC_AAFA
RAC
RAC_FA
Scenario 2
GWP
1.0
0.8
0.6
0.4
0.2
EP
ODP
ADP_FF
POCP
AP


Scenario 1
GWP
1.0
0.8
0.6
0.4
0.2
EP
ODP
ADP_FF
POCP
AP
NAC
NAC_FA
RAC
RAC_FA
Scenario 2
GWP
1.0
0.8
0.6
0.4
0.2
EP
ODP
ADP_FF
POCP
AP

Highlights:

- Four green concretes were assessed using LCA and compared with conventional concrete
- NAC, RAC, HVFAC with natural aggregates and with RCA, and AAFAC were studied
- LCA on the level of concrete life cycles was performed for specific scenarios
- The best overall environmental performance was shown by AAFAC and HVFAC with RCA
- The worst overall environmental performance was shown by RAC with a cement binder