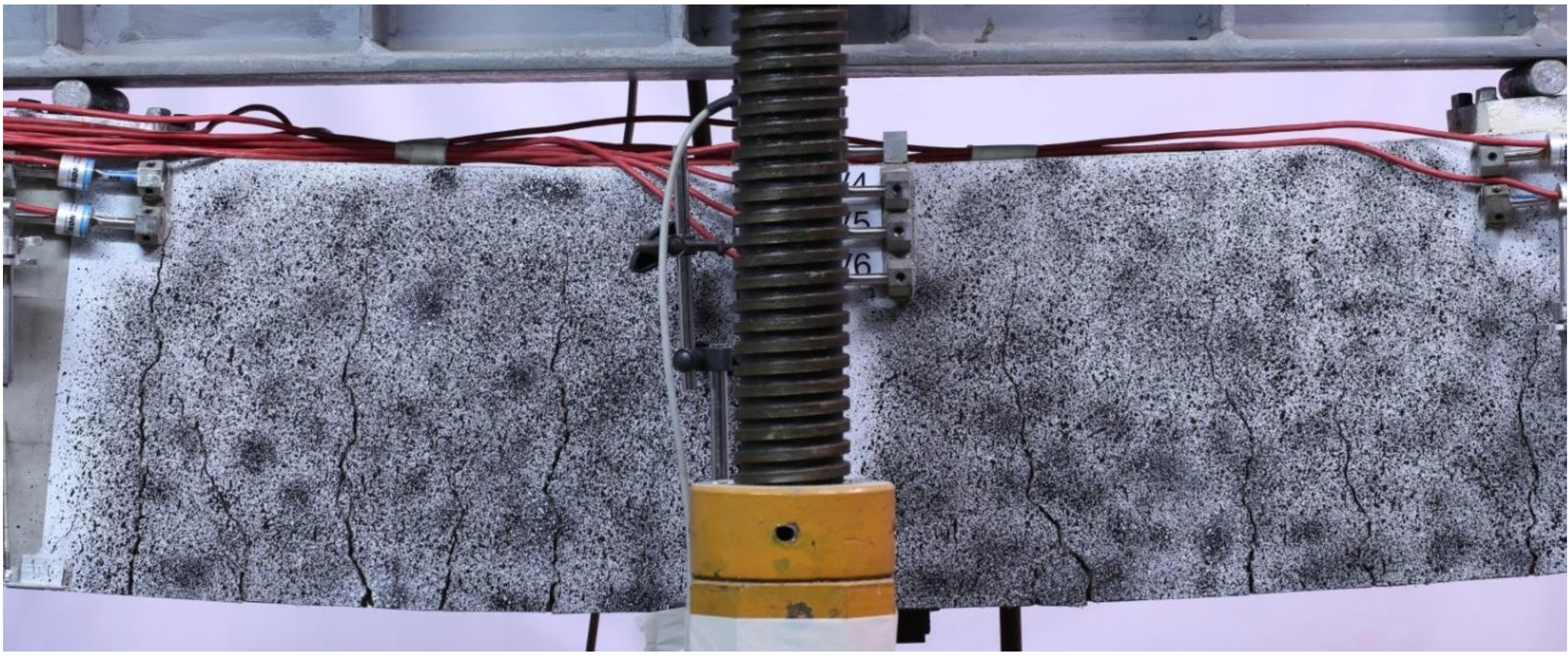
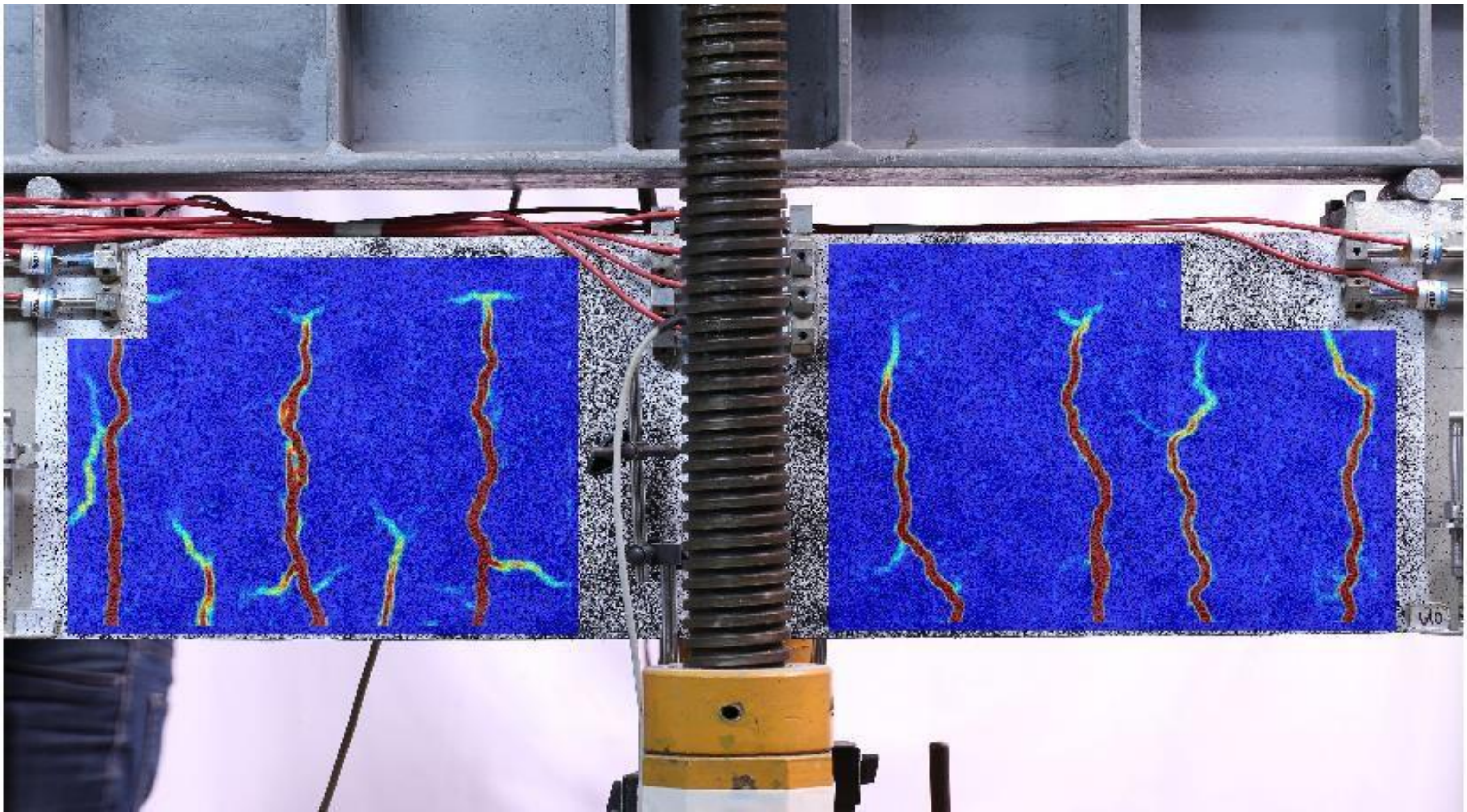
UNIVERSITY OF BELGRADE
FACULTY OF CIVIL ENGINEERING
Chair for Materials and Structures



CONCRETE STRUCTURES RESEARCH TEAM



CONCRETE STRUCTURES RESEARCH TEAM

RESEARCH

At the University of Belgrade's Faculty of Civil Engineering (FCE) our research team headed by prof. Snežana Marinković is working on advancing knowledge in a variety of different fields related to concrete and reinforced concrete structures. Our research is conducted under a number of research projects and is a part of our younger member's PhDs. The subjects range from investigations into the sustainability and durability of concrete composites with new material components to traditional research of reinforced concrete structures.

- Use of recycled materials in concrete and reinforced concrete structures
- Replacement of cement by industrial by-products
- Life-Cycle Assessment of concrete and concrete structures
- Design and analysis of reinforced concrete structures

THE TEAM

The permanent staff of our research team consists of one full professor, one associate professor, 3 assistant professor and 1 assistant with additional PhD and undergraduate students involved in temporary research activities.

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- Associate Prof. Ivan Ignjatović, PhD, Faculty of Civil Engineering, University of Belgrade, (Tel. +381 11 3218 546, e-mail: ivani@imk.grf.bg.ac.rs)
- Assistant Prof. Jelena Dragaš, PhD, Faculty of Civil Engineering, University of Belgrade, (Tel. +381 11 3218 547, e-mail: jelenad@imk.grf.bg.ac.rs)
- Assistant Prof. Nikola Tošić, PhD, Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya (UPC) since 2020. Before that, Faculty of Civil Engineering, University of Belgrade (Assistant Prof.) 2013-2020. (Tel. +34 674 722 774e-mail: nikola.tosic@upc.edu)
- Assistant Prof. Vedran Carević, PhD, Faculty of Civil Engineering, University of Belgrade, (Tel. +381 11 3218 573, e-mail: vedran@imk.grf.bg.ac.rs)
- Assistant Andrija Radović, MSc CE, Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, (Tel. +381 65 8432 885, e-mail: andrija.radovic@pr.ac.rs)

Use of Recycled Materials in Concrete and Reinforced Concrete Structures

Background

Among all human activities, the building industry has one of the largest environmental impacts: 40% of the raw stone, gravel and sand consumption; 25% of virgin wood; 40 % of total energy and 16 % of annual water consumption. This means an annual consumption of 10 to 11 billion tons of aggregate and 3.6 billion tons of cement.

On the one hand, the concrete industry's needs for aggregate lead very often to uncontrolled exploitation of river gravel changing the river ecosystem and habitats. On the other hand, use of crushed aggregate brings an increase in green-house gas (CO_2) emission from the overall process of concrete production due to various phases of aggregate production such as mining, processing of stone pieces and transport.

Recycled Concrete Aggregate (RCA)

Recycled concrete aggregates are obtained by recycling of concrete demolition waste. They are produced by a crushing and sieving process in concrete recycling plants. The products are aggregates which consist of original natural aggregates with some residual cement paste attached to them. Due to this residual cement paste RCA properties differ from natural aggregate properties. Mainly the density of RCA is up to 10% lower and water absorption is much higher - it can range from 3.5% to 13%.

Demolition of concrete structures

Recycled concrete aggregates are commonly used in lower quality product applications such as back-fills and road sub-base and base, where they compete favorably with natural aggregates in many local markets today. However, only a small amount of RCA is used today for higher quality product applications such as structural concrete. Such utilization of RCA, combined with large consumption of natural resources, growing generation of waste and urban area extension raises many difficulties and as a consequence, society is facing huge challenges.

Recycled concrete aggregates (above), river gravel (below)

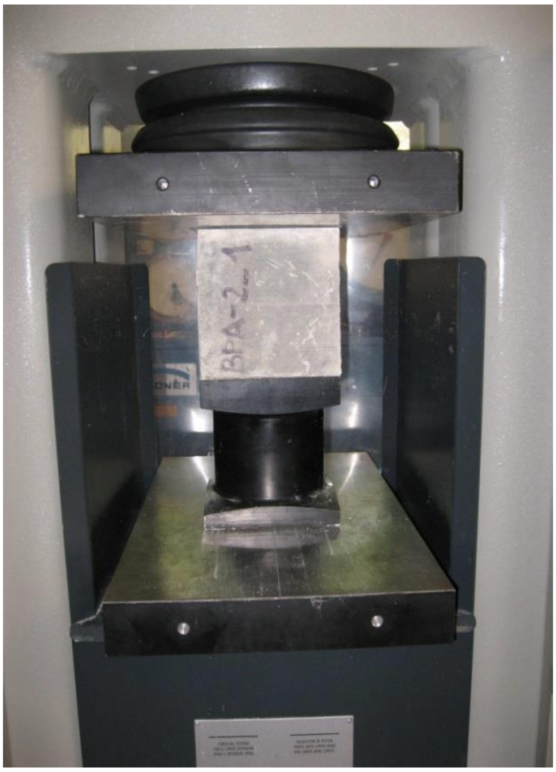
<u>Research at FCE Belgrade</u>

At FCE Belgrade, our research team has been investigating various aspects relating to recycled aggregate concrete (RAC) for several years, supported by a series of research projects.

Most importantly the mixture proportioning of RAC has been mastered, enabling the production of RAC comparable in strength and workability to natural aggregate concrete (NAC). The increased water absorption of RCA requires the use of additional water in the mixture. Our approach is to target equal compressive strength and slump after 30 minutes for both RAC and NAC. In our mixtures we only use coarse recycled aggregates as the fine recycled aggregates tend to show extremely high water absorption.

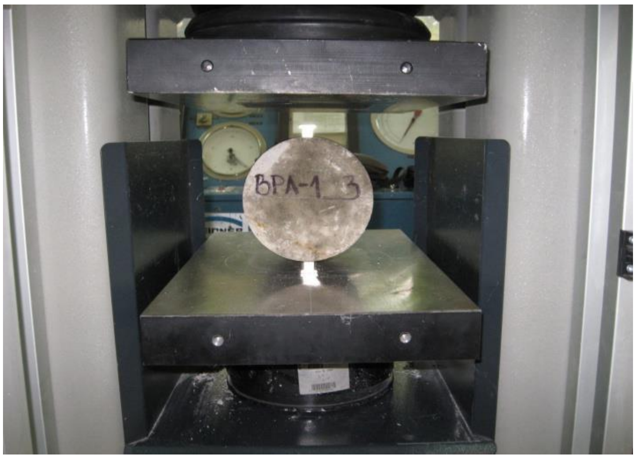
Preparation of RAC and testing workability

Our facilities are fully equipped for testing various mechanical and durability properties of concrete such as compressive strength, tensile splitting and flexural strength, modulus of elasticity, creep and shrinkage, as well as carbonation, chloride penetration and water permeability.



Testing of compressive strength (left) and modulus of elasticity (right)

We have successfully conducted a series of experiments on RAC beams testing their ultimate strength in bending and shear. Another experimental programme investigating the long-term behaviour of RAC beams under sustained loading is currently underway. A number of journal and conference papers have been published as well as a magisterial and doctoral thesis.



Testing of tensile splitting (left) and flexural strength (right)

All this research has endowed us with knowledge and confidence going forward and continuing our work on promoting the use of recycled materials in concrete and making concrete greener.

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Testing of creep (left) and accelerated carbonation (right)

Testing of RAC beams in bending (left) and shear (right)


Testing the long-term behaviour of RAC beams (left and right)

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Chloride migration coefficient (NT492)—testing equipment

Climate chamber with a pool system for testing the freeze-thaw resistance of concrete

Reinforcement corrosion determination using the linear polarization resistance (LPR) method

Replacement of Cement by Industrial By-products

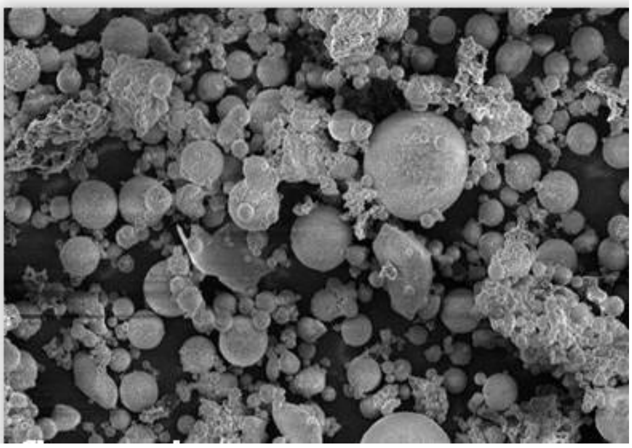
Background

Among all human activities, the building industry has one of the largest environmental impacts: 40% of the raw stone, gravel and sand consumption; 25% of virgin wood; 40 % of total energy and 16 % of annual water consumption. This means an annual consumption of 10 to 11 billion tons of aggregate and 3.6 billion tons of cement.

Cement production is also a significant source of CO_2 emissions, accounting for approximately 7% of global CO_2 emissions from industry. Emissions from the cement manufacture vary worldwide from 0.73 to 0.99 kg of CO_2 for each kilogram of cement produced. Another consequence of the energy-intensiveness of cement production is its relatively high cost – it is the most expensive constituent of concrete.

Supplementary Cementitious Materials in Concrete

Cement is by far the largest contributor to all environmental impacts of concrete in general. The most available supplementary cementitious material worldwide and in Serbia in particular, is fly ash. Fly ash is a by-product from the coal power industry. It is the inorganic residues contained in the coal which are melted in the coal power plant and trapped through exhaust gas. Fly ash has a round shape and contain principally silicium, iron and aluminium.

Coal powered plant (left) and fly ash particles under SE microscopy (right)

The U.S. produces roughly 131 million tons of fly ash each year, China and India 300 million tons. In Serbia, there are six coal-burning power plants which cover about 70% of the country’s electric energy needs (EPS, 2010). During 2010, about 40 million tons of coal was exploited and transported from Kolubara and Kostolac mines. But these processes have a major environmental consequence – 6 million tons of fly ash obtained per year. Fly ash from six power plants in Serbia is classified as class F.

A lot of research has been done on cement substitution with fly ash – both complete and partial substitution.

Alkali-activated Fly Ash Concrete (AAFAC)

In alkali-activated fly ash concretes there is no cement in the binder. These concretes are produced through a polimerization of fly ash particles. The process is started by “activating” the fly ash using strong alkali (sodium hydroxide - NaOH and sodium silicate – water glass) with pH values of over 13 and a certain amount of water. The resulting alumino-silicate structure resembles zeolites. This polymerization process requires significantly less time than the hydration of cement but requires care at elevated temperatures.

Alkali solutions (left) and alkali-activated fly ash binder paste (right)

The mechanical properties of AAFAC are highly dependent on the chemical composition and particle size distribution of fly ash.

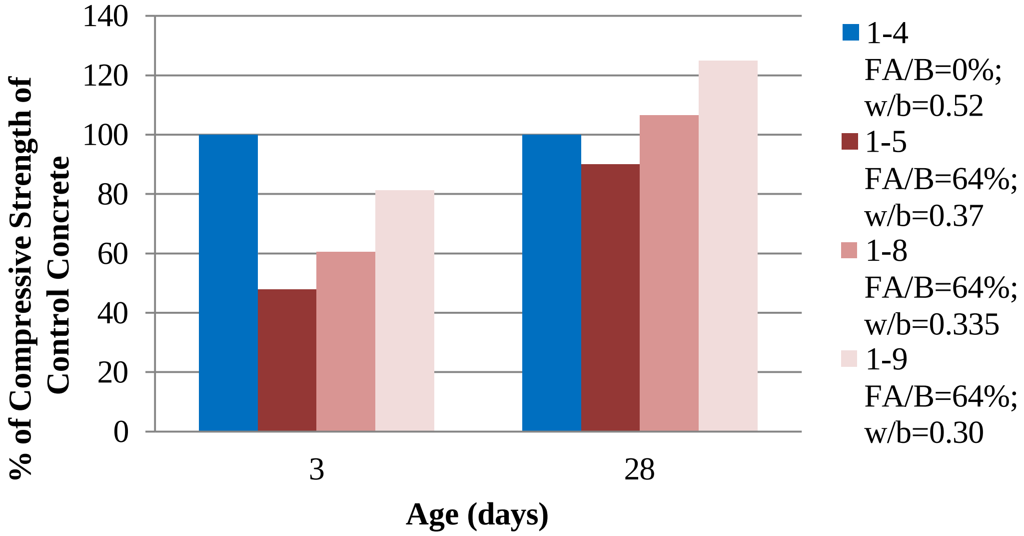

AAFAC workability (left) and cast cubic specimens (right)

High-volume Fly Ash Concrete (HVFAC)

An alternative to AAFAC is the production of concrete in which at least 50% of cement is replaced by fly ash – high volume fly ash concrete (HVFAC). HVFAC is also defined as concrete containing more than 30% fly ash by mass of total binder (cement and fly ash) material, FA/B > 30%. The chemical reactions in HVFAC are identical to those in ordinary concrete i.e. hydration of cement, but with the added pozzolanic effect of fly ash.

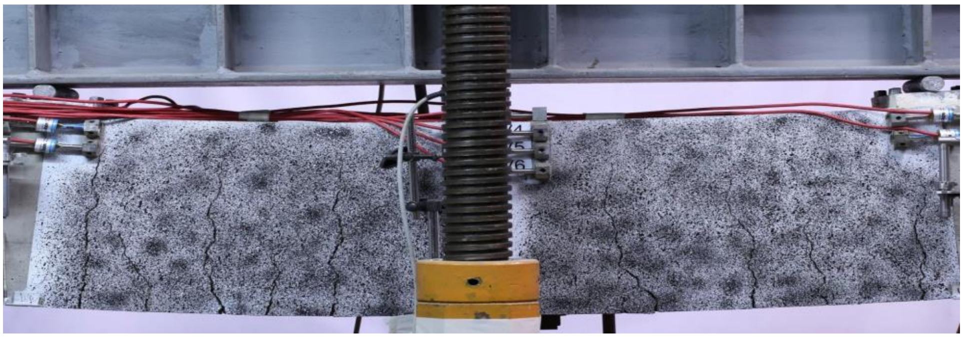
Our research has shown that high percentages of cement replacement are possible while obtaining comparable mechanical properties as Ordinary Portland cement concrete with good workability due to the packing effect of fine fly ash particles and small additions of superplasticizers.

HVFAC workability - slump (left) and flow (right)

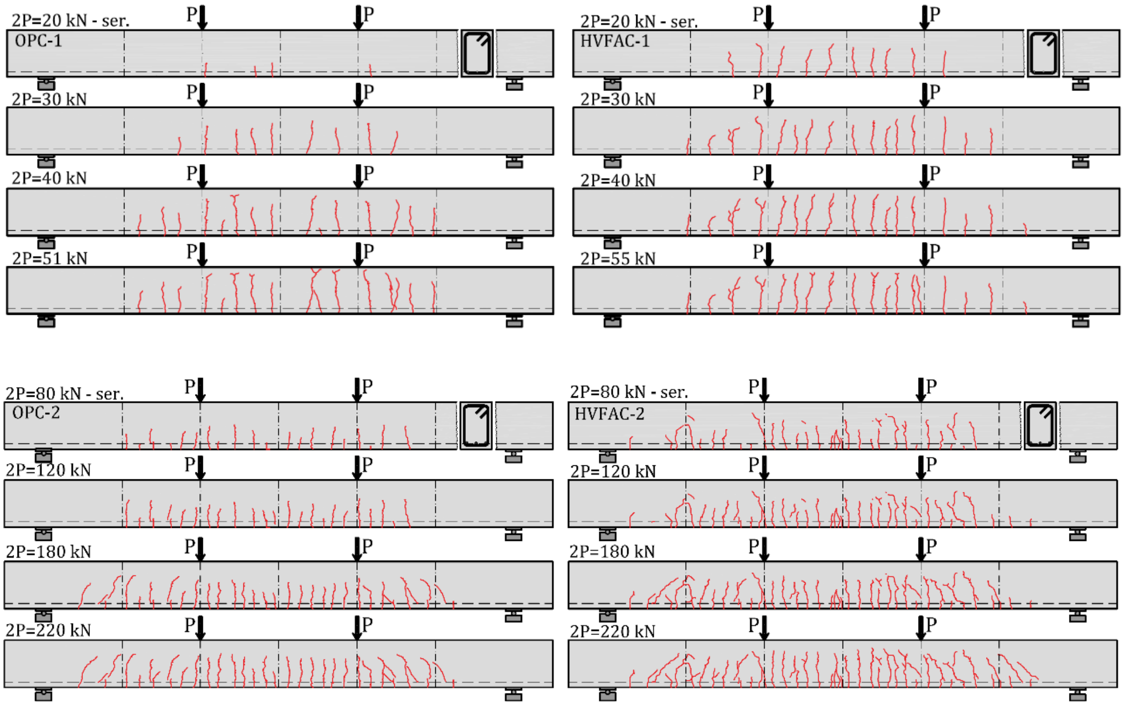


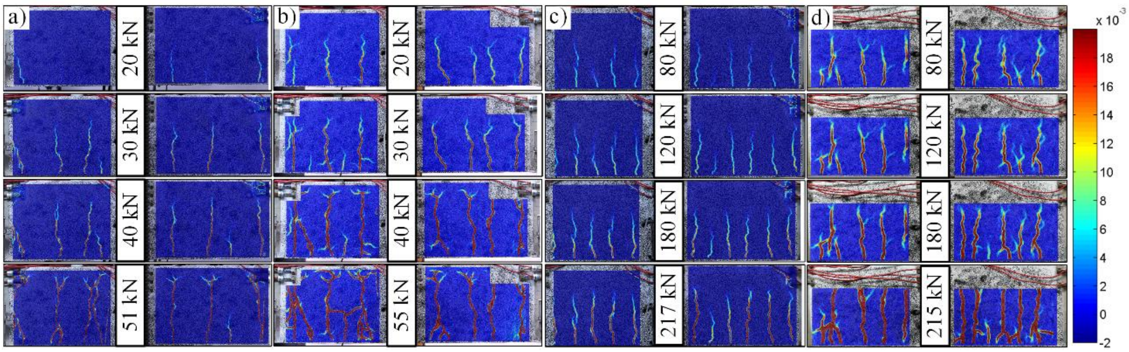
Compressive strength of HVFAC compared to Ordinary Portland cement concrete

The added benefit of HVFAC is the decrease in concrete production costs since fly ash, a waste material, is used in large quantities.

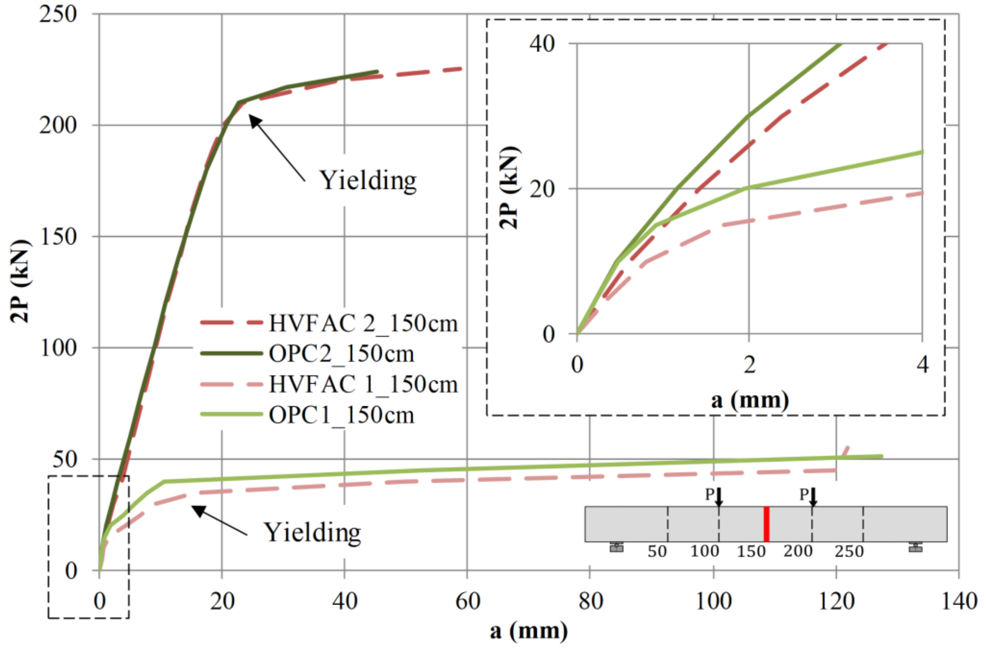


Cracks in the middle part of the HVFAC beam in four-point bending test

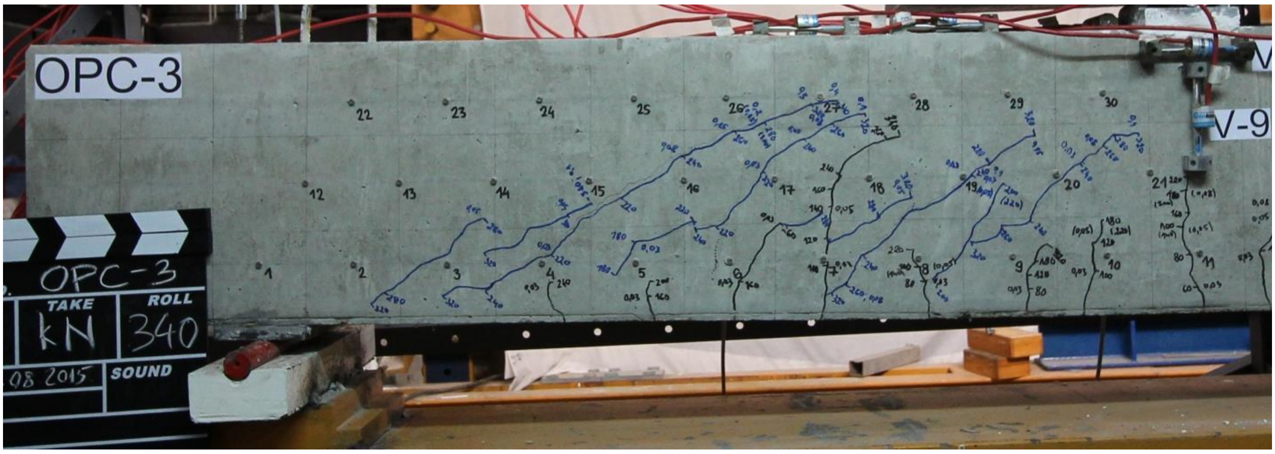




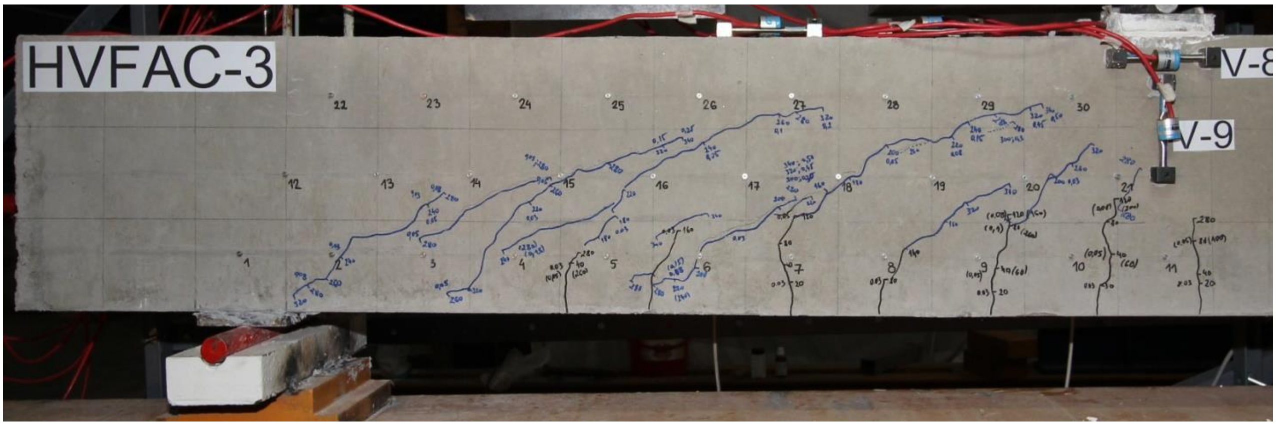
Cracks measured with DIC system in the middle part of the HVFAC beam in four-point bending test



Load–deflection curves for different type of concretes and reinforcement ratios



Crack pattern in shear spam of Ordinary Portland cement beam in four-point bending test



Crack pattern in shear spam of High volume fly ash concrete beam in four-point bending test

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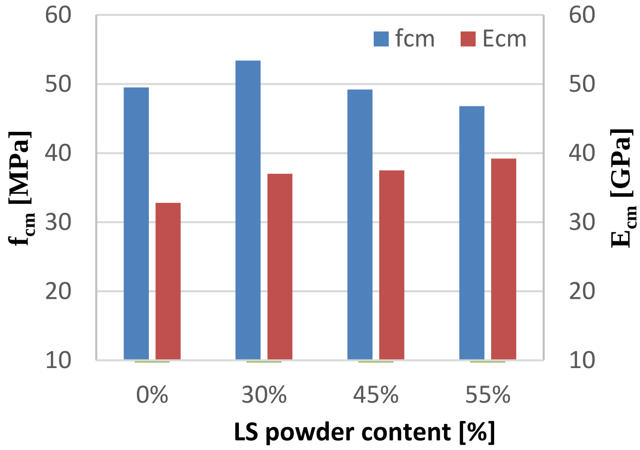
Concrete with Reduced Cement and High Limestone Powder Content

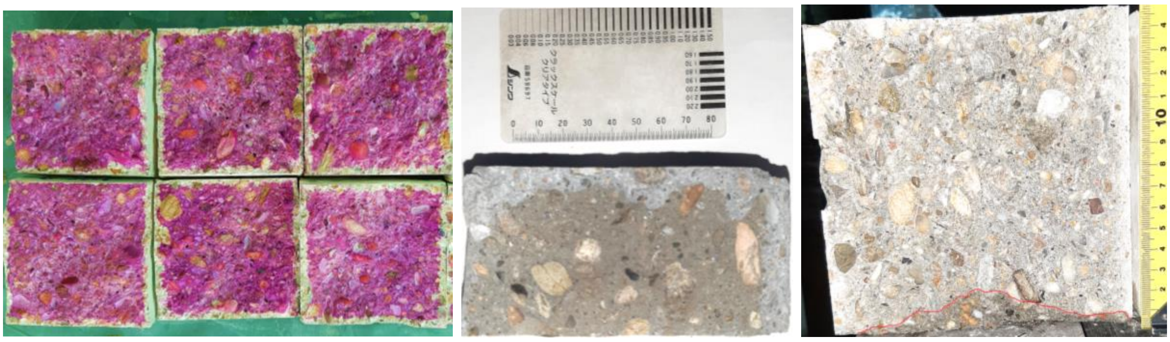
The limited availability and relatively high cost of certain SCMs have driven a growing demand for alternative materials to substitute cement. In this context, the application of locally available and environmentally preferential materials, such as limestone (LS) powder, could offer a sustainable solution.

Our experimental investigations have demonstrated that incorporating LS powder enhances the particle packing of concrete mixtures. This improvement enables the achievement of comparable workability and mechanical properties of LS powder concrete and OPC concrete, even when more than 50% of the cement is replaced by LS powder.



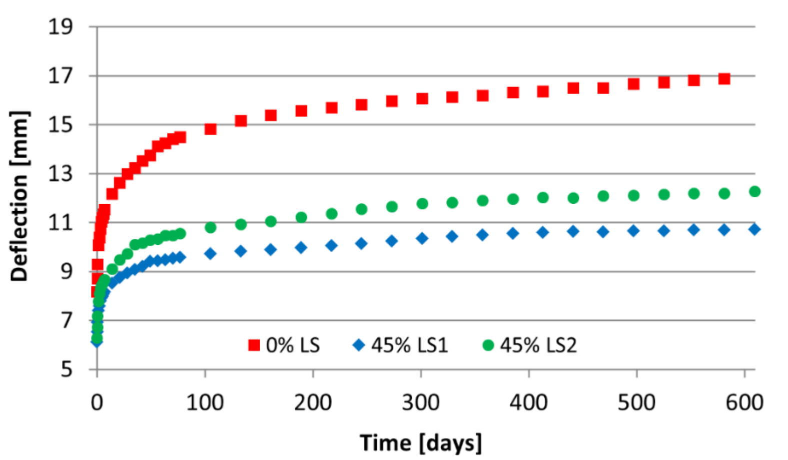
Compressive strength and modulus of elasticity of LS powder concrete and OPC concrete

In addition to workability and mechanical properties, we conducted the tests on durability-related aspects, including carbonation resistance, chloride ingress, resistance to freeze-thaw cycles, and water penetration depth.



Carbonation, chloride ingress and water penetration test of LS powder concrete

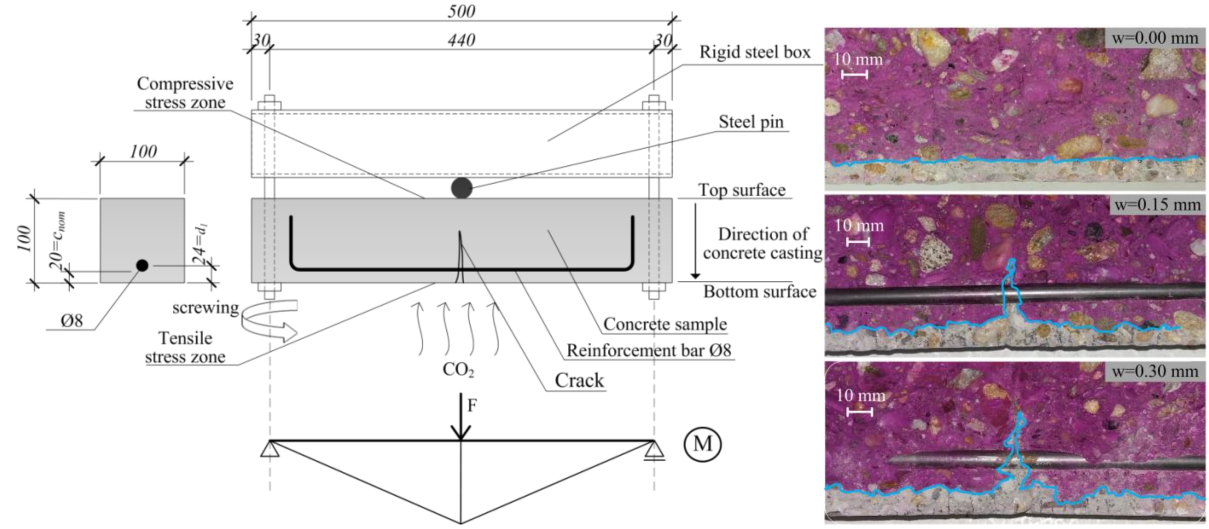
Finally, the long-term behavior of LS powder reinforced concrete beams under sustained loads is tested. Lower creep and shrinkage, as well as deflections of beams made of LS powder concrete, were observed, compared to OPC concrete.



Time-deflection curves for different type of concretes

Durability of different concrete types

The use of RCA or FA for the production of new concrete greatly affects the physical and mechanical properties of concrete. In order to ensure the sustainable application of these green alternatives, the durability properties of RAC and HVFAC should also be tested. The durability of concrete is defined by its resistance to the action of harmful agents from the external environment that lead to various types of damage (deterioration mechanisms). Deterioration mechanisms can affect the concrete structure (freeze/thaw with or without de-icing agents, alkali-silicate reaction and sulphate action) or can cause reinforcement corrosion (carbonation and chloride penetration). The main reason for the deterioration of reinforced concrete (RC) structures is the corrosion of steel reinforcement. Carbonation-induced corrosion has been reported as a major durability problem in urban conditions, considering a large number of buildings that are exposed to a CO2-rich environment. In this regard, research focused on RAC and HVFAC carbonation resistance was conducted. An experimental programme was carried out from 2017 to 2020, at the Faculty of Civil Engineering, University of Belgrade. For the purpose of this research, three concrete mixtures were prepared and tested: reference ordinary Portland cement concrete with NA (NAC), concrete with 100% replacement of coarse NA with RCA (RAC) and concrete with 50% of class F FA in total cementitious materials mass (HVFAC). Deterioration processes and their transport mechanisms were studied and tested almost exclusively on uncracked concrete samples. Possibly the most important factor that affects the carbonation process is the appearance of cracks in RC structures. With relatively low tensile strength of concrete, the cracking of structural elements is almost inevitable due to different action effects. For that reason, the analysis of crack width on carbonation depth and prediction models was one of the main objectives of this research. For that reason, the analysis of crack width on carbonation depth and prediction models was one of the main objectives of this research. Samples with different crack width (0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm and 0.30 mm) and reference samples without cracks were made and tested.



Experimental setup for testing the effect of cracks on concrete carbonation resistance

Life-Cycle Assessment of Concrete and Concrete Structures

Background

Concrete is very durable construction material that can last for hundred years in some applications. The specific amount of harmful impacts embodied in concrete unit is, in comparison with other construction materials, relatively small. However, due to the high global production and utilization of concrete, final negative environmental impact of concrete structures is significant:
- large consumption of natural resources;
- large consumption of energy (mostly for cement production and reinforcement steel production; in addition, for operation and maintenance of buildings and other structures; finally for transportation, construction, demolition and recycling at smaller extent);
- large emissions of greenhouse gasses, primarily CO_2 which is responsible for climate change and originates mostly from the cement production and energy consumption; at smaller extent, emissions of SO_2 which is responsible for acidification and mostly originates from transportation phase;
- large amount of produced construction and demolition waste.

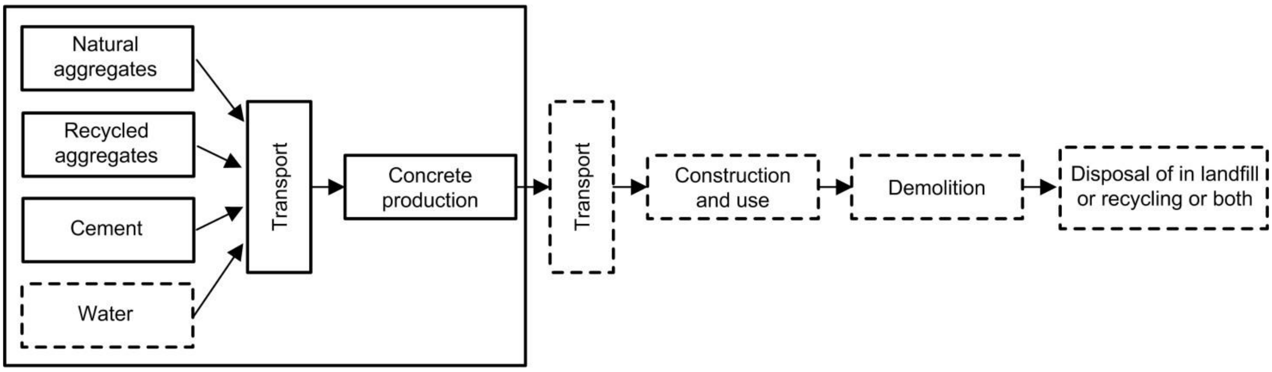
Therefore, concrete has a significant impact on the environment because of its enormous production and utilization. That is why the environmental assessment of concrete is of great importance in the lieu of the efforts towards the sustainable society. There are many methodologies for evaluating the environmental loads of processes and products during their life cycle, but the most acknowledged (ISO standards 14040 – 14043) is Life cycle assessment (LCA).

Research at FCE Belgrade

Numerous studies are performed with the aim to assess the environmental impact of different green concretes. Here the comparison between the environmental impacts of natural (NAC) and recycled (RAC) aggregate concrete production in Serbia is shown.

-LCI data are collected from Serbian suppliers and manufacturers. Emission data for diesel production and transportation, natural gas distribution and transport that couldn't be collected for local conditions were taken from Ecoinvent data base.

-LCIA is performed using original excel-based software made for life cycle inventory and life cycle impacts calculation and commonly for 'cradle-to-gate'part of the life cycle.



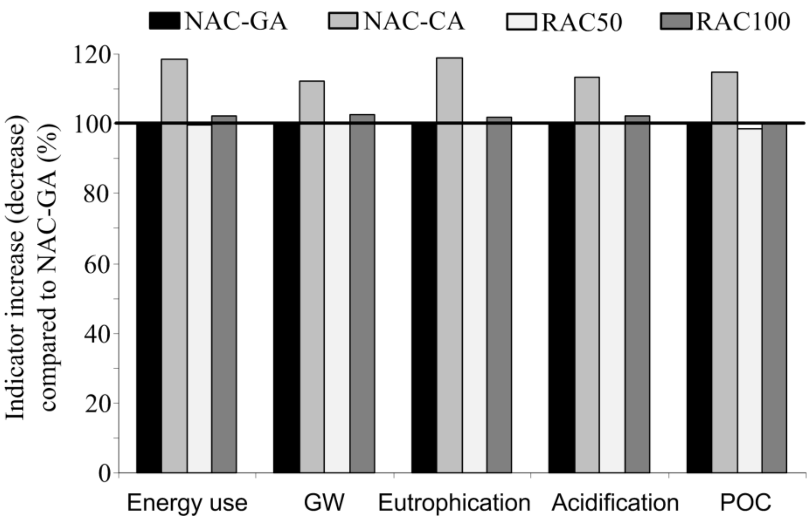
-Results are interpreted for concrete with different aggregate types and the contribution of various stages in the concrete life cycle to environmental impacts is analyzed.

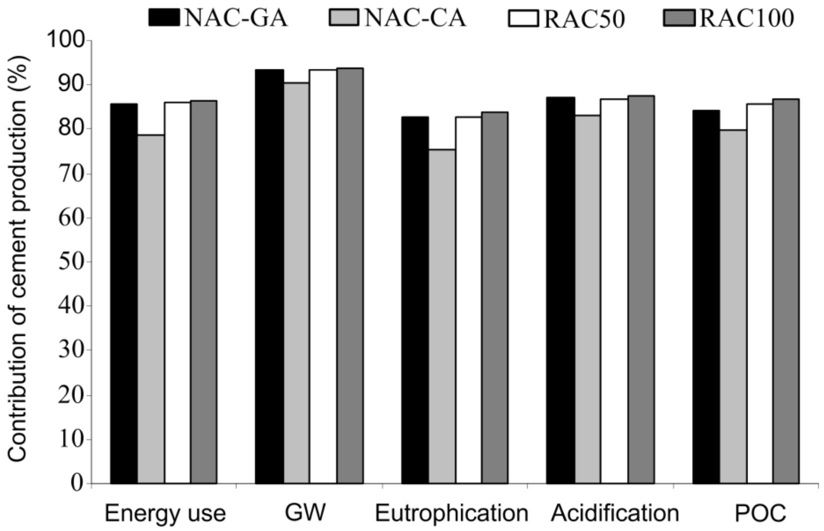
NAC-GA natural aggregate concrete with gravel aggregate

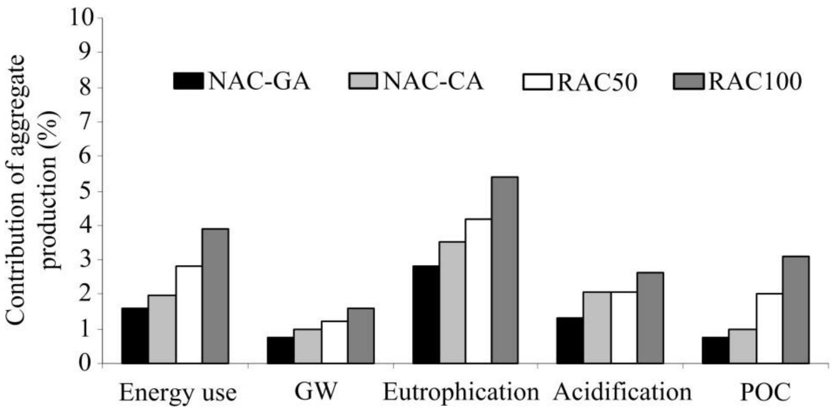
NAC-CA natural aggregate concrete with crushed aggregate

RAC50 recycled aggregate concrete with 50% replacement of coarse natural aggregate with recycled aggregate

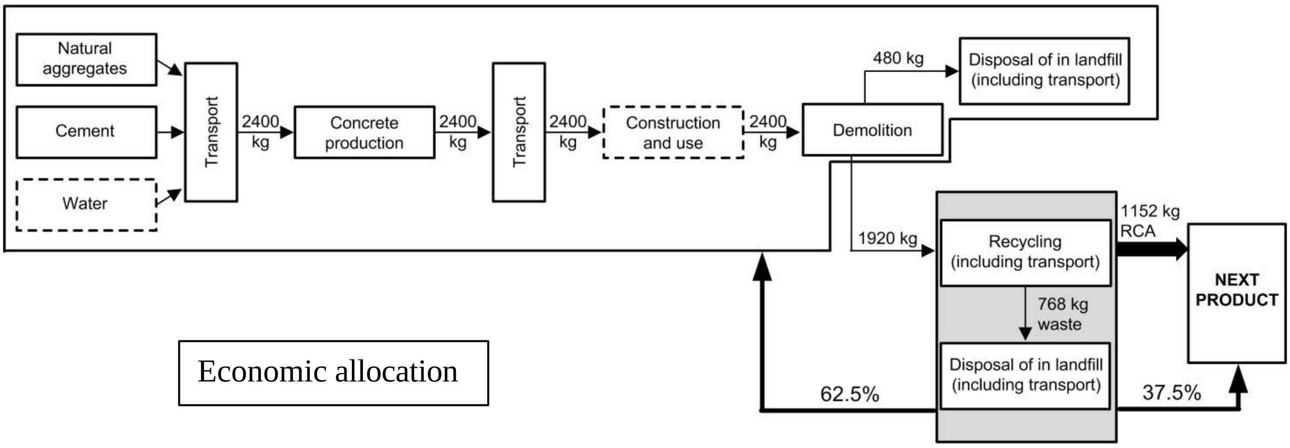
RAC50 recycled aggregate concrete with 100% replacement of coarse natural aggregate with recycled aggregate

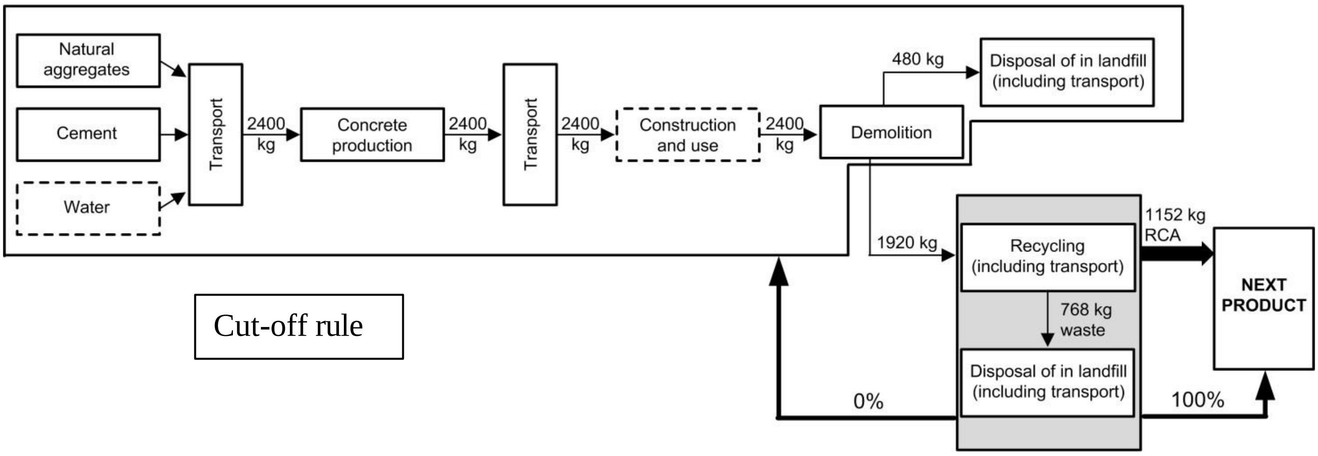




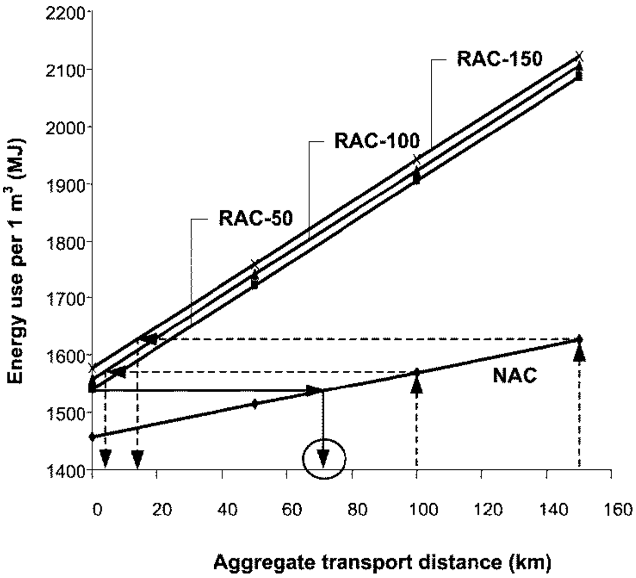


-In the case of concrete recycling, different allocation procedures (such as economic allocation and cut-off rule) are analyzed.





-Comparing NAC and RAC, limit transport distances of natural aggregates are determined.



Desing and Analysis of Reinforced Concrete Structures

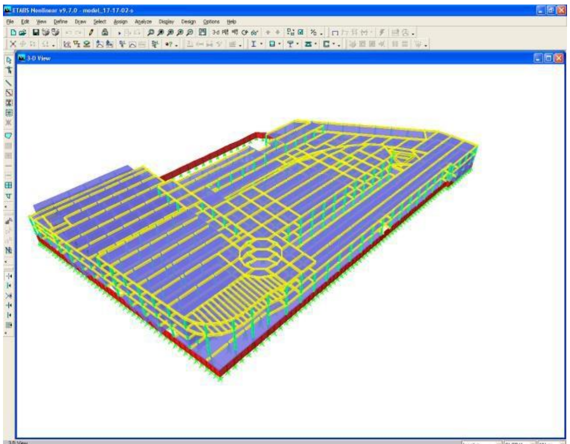
Background

As structural engineers, an integral part of what we do in the Concrete Structures Research Team is the design and analysis of reinforced concrete structures. These activities can range from the design of complex buildings and industrial projects, reviews, peer-reviews, independent calculations, to finite element modelling of experimental research. Our Team can also offer expertise in all stages of construction and service together with the solutions for the end-of-life.

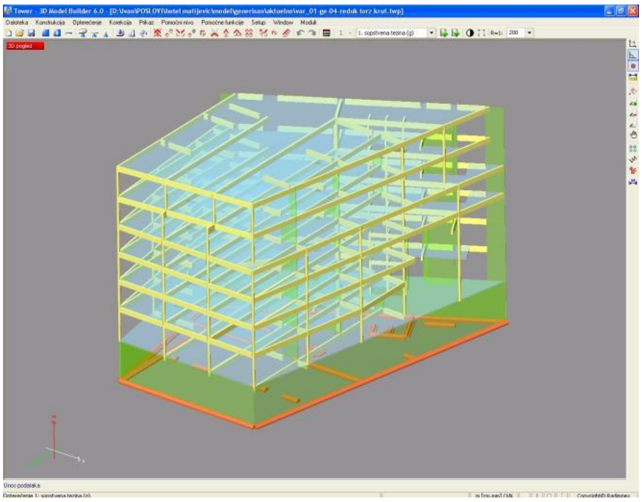
Design of Reinforced Concrete Structures

Members of our team have been lead designers as well as participants in numerous projects. They have designed various types of reinforced concrete structures: commercial and residential buildings, shopping malls and industrial projects. All of our team's members are proficient in using different design codes, e.g. Eurocode 2 (EN 1992), ACI, AASHTO. Analyses are carried out in programmes such as ETABS, SAP2000, and Tower.

Delta City shopping mall in Belgrade, after completion...



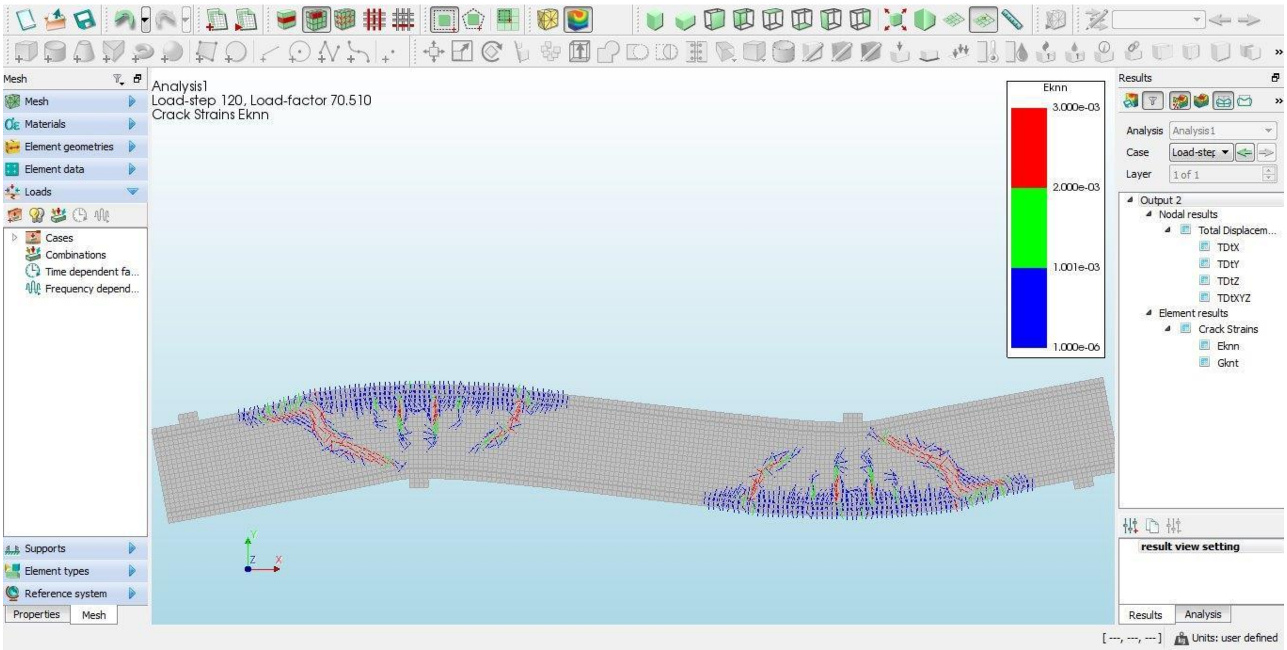
...and during modelling in ETABS



Hotel "Center" in Novi Sad: Tower model (left), completed building (right)

Numerical Modelling of Experimental Research

For more in-depth analysis of exeperimental results carried out on reinforced concrete members, numerical modelling based on the finite element method is used. Our research team has an academic license for one of the leading programmes in this area—DIANA, developed by DIANA FEA, Delft, the Netherlands. Using a comprehensive choice of material models, finite elements and analysis procedures, detailed studies can be performed—ultimate loads on reinforced members and structures, dynamic and transient analyses.



Numerical modelling of reinforced concrete structures in DIANA

Research Projects

2007-2011: COST Action TU 1301 (2014-2017): NORM for Building Materials. COST (European Cooperation in Science and Technology).

2007-2011: COST Action C 25 – Sustainability of Constructions – Integrated Approach to Life-time Structural Engineering, COST (European Cooperation in Science and Technology).

2011-2019: TR 36017 – Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible application. Ministry for Education, Science and Technology, Republic of Serbia.

2015-2016: START – Danube Region Project Fund: “Research of River-Port Sediment and its Potential use in Civil Engineering”.

2014-2016: SCOPES – Recycled aggregate and fly ash concrete: Economic and technologic study – from down cycling to urban ecology. Joint Research Project with ETH Zürich. Swiss National Science Foundation.

2014-2017: COST ACTION TU1301: NORM for building materials – NORM4BUILDING.

2018-2018: Making concrete green – customized concrete structures optimized for long-term loadings. Initiation of International Cooperation with Ruhr University Bochum and Ss. Cyril and Mehtodius University in Skopje. German Research Foundation (DFG).

2018-2019: SPS project 985402 – IMSAFE, Improved Security through Safer Cementation of Hazardous Wastes. NATO Science for Peace and Security Programme.

2018-2019: Energy and Environmentally Efficient Resource Use in the Concrete Construction Industry. Bilateral Research Project with University of Lisbon – Instituto Superior Técnico. 451-03-1924/2016-09/3. Ministry for Education, Science and Technology, Republic of Serbia.

2017-2018: DS-2016-0051 – Fiber reinforced alkali activated composites (properties and selected durability aspects). Multilateral Research Project with Brno University of Technology and Technical University Vienna. Ministry for Education, Science and Technology, Republic of Serbia.

2021-2023: HyCRETE – Hybrid Solution for Improved Green Concrete Performance, Science Fund Republic of Serbia, collaboration with Technical University of Delft, The Nederlands.

2023-2027: CIRCBOOST – Boosting the uptake of circular integrated solutions in construction value chains, HORIZON-CL6-2022-CIRCBIO-02-two-stage, Horizon Europe. 28 partners from 8 countries. https://circboostproject.eu/

Publications:

Journal articles

Dragaš J., Marinković S., Ignjatović I., Tošić N., Koković V.: Flexural behaviour and ultimate bending capacity of high-volume fly ash reinforced concrete beams, Engineering Structures 277, 2023, 115446.

Marinković S., Josa I., Braymand S., Tošić N.: Sustainability assessment of recycled aggregate concrete structures: A critical view on the current state-of-knowledge and practice, Structural Concrete 24(2), 2023, 1956-1979.

Marinković M., Radović A., Carević V. (2023) Carbonation of limestone powder concrete: state-of-the-art overview. Building Materials and Structures. 66, pp.127-139. DOI: https://doi.org/10.5937/GRMK2300005M.

Luković M., Budnik B., Dragaš J., Carević V. Ignjatović I. (2023) Contribution of Strain-Hardening Cementitious Composites (SHCC) to shear resistance in hybrid reinforced concrete beams. Building Materials and Structures. 66, pp.145-155. DOI: 10.5937/GRMK2300006L.

Carević V., Ignjatović I. (2022) Limit values of accelerated carbonation resistance to meet EC2 durability requirements. Building Materials and Structures. 65, pp.1-6. DOI: 10.5937/GRMK2201001C.

Merta I., Poletanović B., Dragaš J., Carević V., Ignjatović I., Komljenović M. (2022) The influence of accelerated carbonation on physical and mechanical properties of hemp-fibre-reinforced alkali-activated fly ash and fly ash/slag mortars. Polymers. 14 (9),1799. DOI: 10.3390/polym14091799.

Radović A., Hafez H., Tošić N., Marinković S., De La Fuente A.: ECO2 framework assessment of limestone powder concrete slabs and columns, Journal of Building Engineering 571, 2022, 104928.

Marinković S., Carević V., Dragaš J. (2021) The role of service life in Life Cycle Assessment of concrete structures. Journal of Cleaner Production. 290, 125610. DOI: 10.1016 /j.jclepro.2020.125610

Josa I., Tošić N., Marinković S., De La Fuente A., Aguado A.: Sustainability-oriented multi-criteria analysis of different continuous flight auger piles, Sustainability 13(14), 2021, 7552.

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