CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF CIVIL ENGINEERING

DEPARTMENT OF ARCHITECTURAL ENGINEERING

HABILITATION THESIS

RECYCLED MATERIALS IN BUILDING STRUCTURES: EXPERIMENTAL AND ENVIRONMENTAL EVALUATION

RECYKLOVANÉ MATERIÁLY VE STAVEBNÍCH KONSTRUKCÍCH: EXPERIMENTÁLNÍ A ENVIRONMENTÁLNÍ VYHODNOCENÍ

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Abstract:

This thesis deals with Sustainable Development goal 12 which is focused on the efficient use of natural resources, and reducing waste generation through prevention, reduction, recycling, and reuse. First, the literature research related to research problems is presented. Furthermore, the possible use of separated materials from construction and demolition waste is described. The Thesis is mostly focused on waste concrete and masonry, due to their highest representation in construction and demolition waste. Life cycle assessment as one of the key questions of sustainability and circularity is discussed. The possibilities of the use of secondary raw materials without suitable utilization and the question of their durability are also studied. In conclusion, the possible issues for further research are described.

Keywords: Construction and Demolition Waste; Recycled Materials; Recycled Aggregate, Recycled Aggregate Concrete, Life Cycled Assessment,

Abstrakt

Tato práce se zabývá cílem udržitelného rozvoje 12, který je zaměřen na efektivní využívání přírodních zdrojů a snižování produkce odpadů prostřednictvím prevence, recyklace a opětovného použití. Nejprve je uvedena rešerše související s řešenými výzkumnými otázkami. Dále je popsáno možné využití oddělených druhotných materiálů ze stavebních a demoličních odpadů. Práce je více zaměřena na využití odpadního betonu a zdiva, a to především z důvodu jejich nejvyššího zastoupení ve stavebním a demoličním odpadu. Je diskutováno hodnocení životního cyklu jako jedna z klíčových otázek udržitelnosti a oběhového hospodářství. Studovány jsou také možnosti využití druhotných surovin, které zatím nemají vhodné využití a dále jsou řešeny otázky jejich trvanlivosti. V závěru jsou nastíněny možné výzkumné otázky pro následující výzkum.

Klíčová slova: Stavební a demoliční odpad, Recyklované materiály, Recyklované kamenivo, Beton s recyklovaným kamenivem, Hodnocení životního cyklu.

Declaration

I hereby declare that this habilitation thesis is my own work. For chapters that have been teamwork, the individual shares are determined. All sources and other materials used have been quoted in the list of references.

In Prague on 28.06.2022 ....

Acknowledgement

First of all, I would like to thank my team at University Centre for Energy Efficient Buildings, especially Kristina Fořtová, Jan Pešta, Diana Mariaková, Jakub Řepka, Tomáš Vlach, and Zuzana Jirkalová, for their perfectly done work on research projects on which I have been the responsible leader of the research part.

I must also thank the head of the department of architectural engineering and my former supervisor Petr Hájek for his helpful comments and friendly approach. Furthermore, my thank belongs to colleagues from the Department of Architectural Engineering and University Centre for Energy Efficient Buildings, especially, Antonín Lupíšek, Martin Volf, Jan Tywoniak, and Jiří Pazderka.

I also need to thank my partners form practice from company AZS Holding especially Jan Otýs and Petra Kaldová, for their support to bring the results of our research to practice.

I would also like to thank great project support from my colleagues at University Centre for Energy Efficient Buildings especially Kateřina Mrkvičková, Karolína Tomešová and Kristina Reist.

Finally, I want to thank all my family members – especially my husband Pavel, for his support, constructive criticism, and inspiring comments.

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Abbreviations

CDW	Construction and Demolition Waste
NA	Natural Aggregate
RA	Recycled Aggregate
RCA	Recycled Concrete Aggregate
fRCA	Fine Recycled Concrete Aggregate
RMA	Recycled Masonry Aggregate
fRMA	Fine Recycled Masonry Aggregate
RAC	Recycled Aggregate Concrete
RCAC	Recycled Concrete Aggregate Concrete
fRCAC	Fine Recycled Concrete Aggregate Concrete
RMAC	Recycled Masonry Aggregate Concrete
fRMAC	Fine Recycled Masonry Aggregate Concrete
LCA	Life Cycle Assessment
LCI	Life Cycled Inventory
LCIA	Life Cycle Impact Assessment
FU	Functional Unit
ADP	Depletion Abiotic and Biotic Resources Potential
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
POCP	Photochemistry ozone creation potential
ODP	Ozone layer depletion
EoL	End of Life
ITZ	Interfacial Transition Zone
SCM	Supplementary Cement Materials
TSMA	Two-stage mixing Approach

1 General Introduction

1.1 Background

Today, society is focused to meet Sustainable Development Goals (SDG) [1]. 17 goals were defined that are "*vital for a recovery that leads to greener, more inclusive economies and stronger, more resilient societies.* This thesis primarily deals with the "*SDG 12 Ensure sustainable consumption and production patterns',* which is focused to implementation of the 10-year framework of Programmes on Sustainable Consumption and production patterns. The objectives relevant to the construction industry are as follows:

- 12.1 to achieve by 2030 the sustainable management and efficient use of natural resources,
- 12.2 substantially reduce waste generation through prevention, reduction, recycling, and reuse;
- 12.6 encourages companies to adopt sustainable practices and integrate sustainability information into their reporting cycle.

This could be achieved through solving two main issues that exist nowadays:

The first is related to the past – there are many buildings at the end of the life cycle. These buildings were built at a time when long lifespan was not considered, and these buildings no longer meet the requirements for today. For these reasons, in the context of a circular economy, the main goal is to find a way to maximize reuse or recycle materials from these buildings.

The second one is in connection with the future – there is still the traditional approach to structural design, which is focused only on the required parameters, which correspond to standards requirements. Evaluation of the performance quality is limited to the construction stage or to the construction guarantee period. However, the new conceptual approach to structural design is an integrated life cycle design (ILCD), which represents a multiparametric design of structures. The main objective of the ILCD is optimized performance parameters from a wide spectrum of sustainability criteria throughout the entire life cycle and its extension. The new fundamental imperatives of circularity are not only dealing with the reuse and recycling of waste materials, but also with thinking about the future in architecture engineering. To design more durable structures with long service life, which are, moreover, demountable for better possible repair or reuse. The recycling of new structures is supposed to be the last possible way of recycling them.

The main goals of this thesis are related to the first one in which the SDG 12 could be achieved through:

- Optimization of the demolition and recycling process, which enables the reuse and recycling of secondary materials produced during the construction and demolition process.

- Motivation of producers to return the materials separated during construction and demolition process, which will be possible to achieve by developing of separating and logistic system, and also showing possible environmental and economic savings.
- Optimization of the use of recycled materials by finding possibilities for applications for secondary raw materials whose use is not allowed by standards such as recycled masonry aggregate and fine recycled aggregate.
- Finding answers to doubts to products with secondary raw materials related to its durability, life span and life cycle.

1.2 The scope of the thesis

Due to the findings of the literature review and practice needs, the thesis is dealing with the following problems:

The use of recycled materials in construction industry
(chapter 3 [2])

This chapter presents the results of the project defined by the Czech Standardization Agency and the Ministry of Industry and Trade in the Czech Republic 'Catalogue of Construction Products with Recycled Content from Construction and Demolition Waste'. This project dealt with the determination of the main barriers to the utilization of recycled materials in the construction industry. Furthermore, the possibilities of the use of selected construction materials were stated.

Life cycle assessment of the recycled aggregate concrete
(chapter 4, Appendix A [3], Appendix C [4])

This chapter deals with one of the key questions about the use of recycled materials which is related to their life cycle assessment. In general, there have been doubts about the environmental impact of the use of recycled materials, often related to the unknown efficiency of the recycling process and the lower durability and shorter life span of products containing recycled materials. Furthermore, the consideration of the recycling process in the case of system boundaries has not yet been defined. A comprehensive experimental and environmental study of RAC is presented. Furthermore, the case studies dealing with the life cycled assessment of structural elements designed from RAC are presented in the appendixes.

The use of recycled masonry aggregate and fine fraction of the recycled aggregate
(chapter 5, Appendix B [5])

This chapter presents the results of research projects that deal with the use of the coarse RA from waste masonry and fRA from waste concrete and masonry. These two materials are not allowed to be used as aggregates for concrete by standards. For this reason, they are remaining in recycling centers without suitable utilization. One of the presented studies is focused on the structural use of recycled masonry aggregate. The second is dealt with the experimental evaluation of the possible replacement of the sand with the fRA.

Durability of RAC and its improvement
(Appendix D [6])

This chapter focuses on another key question related to RAC, its durability. Due to the higher porosity of RA compared to natural aggregate, there are doubts about the durability of RAC. In this case study, the improvement of freeze-thaw and carbonation resistance was experimentally verified.

2 State of the art

The state of the art summarized the background information about the issues dealt with in this thesis.

1. Construction and demolition waste - This chapter deals with the basic principles of circular economy, construction and demolition management and evaluating its potential use.
2. Life cycle assessment of recycled materials – this chapter summarises the LCA methodology in general and further is specifically dealing with the LCA of recycled materials, recycled concrete and masonry especially.
3. Recycled aggregate concrete – this chapter summarises the literature review dealing with the possibilities of substitution of natural aggregate with recycled one.
4. Durability of recycled aggregate concrete and its improvement - this chapter summarizes the literature review and basic principles focused on the durability of recycled aggregate concrete and its improvement.

2.1 Construction and demolition waste

2.1.1 Circular economy

The study [7] reviewed various definitions of circular economy (CE). Due to the analysis of review papers, a definition that combines some of the already known and confirmed ones and is complemented by specialists' inputs, which is:

"Circular economy is an economic system that targets zero waste and pollution throughout the lifecycle of materials, from the extraction of the environment to industrial transformation, and to final consumers, applying to all ecosystems involved. Upon its lifetime end, materials return to either an industrial process or, in case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso, and micro levels and exploits to the fullest the sustainability nested concept. The energy sources usedare clean and renewable. The use and consumption are efficient. Government agencies and responsible consumers play an active role in ensuring correct long-term operation."

The fundamental imperatives of the 3Rs (reduce, reuse, and recycle) were associated with CE. Afterward, a new series of imperatives, the 6Rs "reuse, reduce, recycle, redesign, refurbish, and repurpose" were introduced and the last version contains 10 imperatives the 10Rs "refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recovery.

2.1.2 Construction and demolition waste generation

As a result of increasing construction industry, widespread urbanization and the economic condition, the old buildings are being demolished to build new structures. Due to these activities, a huge amount of the CDW is generated all over the world. The amount of CDW represents 25% -30% [8] of the overall waste generation and 850 million tons were generated in the EU per year [9]. The CDW originates from the construction, renovation, and demolition of buildings, bridges, roads, and other structures. The CDW typically contains inert materials such as concrete, bricks, plasters, etc., and also hazardous particulars such as asbestos, particulate matter, etc. [10]. Inert waste is considered to have a priority to be recycled according to the EU Waste Strategy [11]. The highest percentage of construction waste accounts the waste concrete, which is approximately 40%, followed by metals (33%), bituminous (13%) and masonry (7%) [12–14].

2.1.3 Importance of recycling in the construction sector for the transition to the circular economy

Recycling and the use of construction and demolition wastes are one of the principles of sustainable construction and circular economy. The European Commission published an action plan for the circular economy in 2015 [15]. It describes the main principles of the eco-design of products, which start at the very beginning of the product's life. The new products should be designed as easily recyclable, with low carbon dioxide emissions and with a low content of primary raw materials, which leads to a higher utilization of recycled materials.

The construction industry is one of the largest consumers of primary raw materials worldwide and generates almost 30% of all waste. Majority of construction materials whose life cycle is over can be recycled and use as secondary raw material for the production of new construction product. The main prerequisite for high rates of utilization of recycled materials in the construction industry is the selective demolition process. The Regulation (EU) No. 305/2011 of the European Parliament and of the Council [16] is focused on the sustainable use of natural resources which should be achieved by the construction and demolition proposal.

2.1.4 Recycling rates of construction and demolition waste in the European Union

Each country in the European Union (EU) has different conditions for the use of secondary raw materials. The recovery rate of construction and demolition mineral waste in EU countries is shown in Figure 1. In the EU, there are different regions in terms of available primary raw materials. Regions with abundant natural resources are not motivated to use secondary raw materials in construction production due to the wide availability and low cost of primary raw materials, the only motivation would be landfill costs. However, regions with a limited supply of primary raw materials are already highly motivated to prepare materials from CDW for efficient utilization as secondary raw materials. Due to this fact, it is possible to inspire the demolition and recycling process in other localities. However, it is necessary to find the appropriate approach in a given location to increase the efficiency of recycled materials utilization. The Czech Republic is a country with sufficient amount and low prices of natural resources, which mostly leads to the use of low-quality demolition and recycling process and further to the downcycling of construction and demolition wastes.

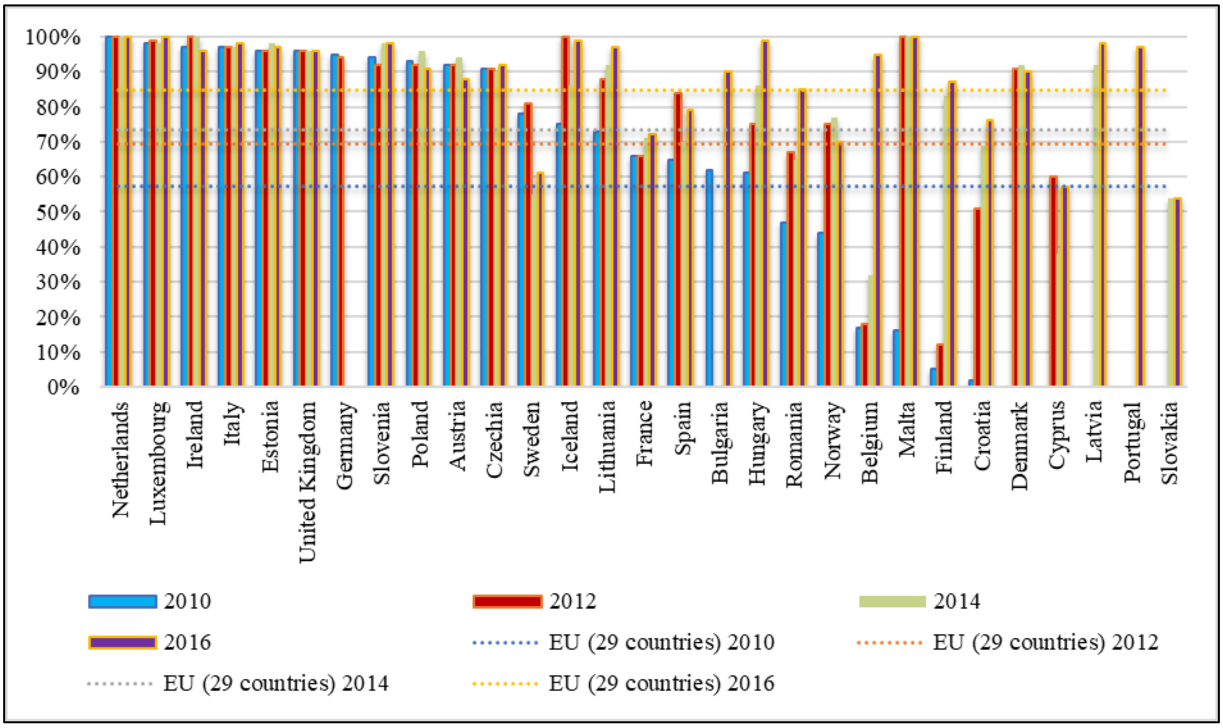


Figure 1 Recovery rate of construction and demolition mineral waste in the EU [17].

2.1.5 Selective demolition

Generally, it could be said that the selective demolition process is essential for the high quality of the recycled materials from the building site. Additionally, it will also be necessary to optimize the recycling process at demolition sites to reduce the transportation of waste materials. Without a solution to efficiently process the demolition and recycling, unsorted CDW will continue to be regarded one of the main contributors to damaging the natural environment due to unsorted landfills, illegal disposal, and mixed contamination. However, if CDW is processed properly, the positive environmental impact of using recycled CDW is clearly satisfied, due to the decreasing consumption of primary recourses and the decrease in landfilling.

Today, the demolition process has been very simple in general; due to the lack of motivation to separate the waste materials, the demolition process has been simplified to minimize financial and time requirements. Therefore, the different construction materials have been mixed during the demolition process. Selective demolition improves quality, but also costs associated with demolition. However, the positive motivation has been coming from producers of construction products over the last few years due to the taking back of construction materials that are separated during the construction and demolition process. The recommended process for selective demolition is defined in (3.4).

2.1.6 Concrete and masonry waste vs natural aggregate production

The consumption of natural aggregate (NA) grows each year by approximately 5% and has reached almost 40 billion tons worldwide each year [18]. In general, CDW generation exceeds 3 billion tons worldwide annually, of which waste concrete is the main topic, ranging between 40 and 85%, which is 63% on average, depending on the locality. The differences are caused by the different construction and material habits in the locality and also by various evaluations of which materials belong to CDW. If it is considered that the amount of concrete waste is 1.89 billion tons worldwide annually (63% of total CDW), and the aggregate production is 40 billion tons worldwide annually, it is possible to cover less than 5% of aggregate needs. Similarly, in the case of the Czech Republic, the ratio of natural aggregate extracted for the construction industry is 4.5%. The amount of concrete waste reported is 3.2 million tonnes per year (2020). That is a relatively small amount, because only the waste received in a landfill or recycling centre is counted, not the material processed at the demolition site. The amount of CDW reported decreases annually, which means that the amount of CDW that is deposited in landfills and recycling centers decreases. In contrast, the extraction of primary raw materials for the construction industry is still growing and is almost 71 million tons (2020) [19]. In addition, there are about 1.4 million tons of masonry and ceramic waste. According to the information of recycling centres, this waste material mostly remains in the recycling centres, or is used as a deposit of waste as technological material to make landfills safe. However, this material could also cover the natural aggregate needs and grow up replacement potential from 4.5% to 6% (see Figure 2).

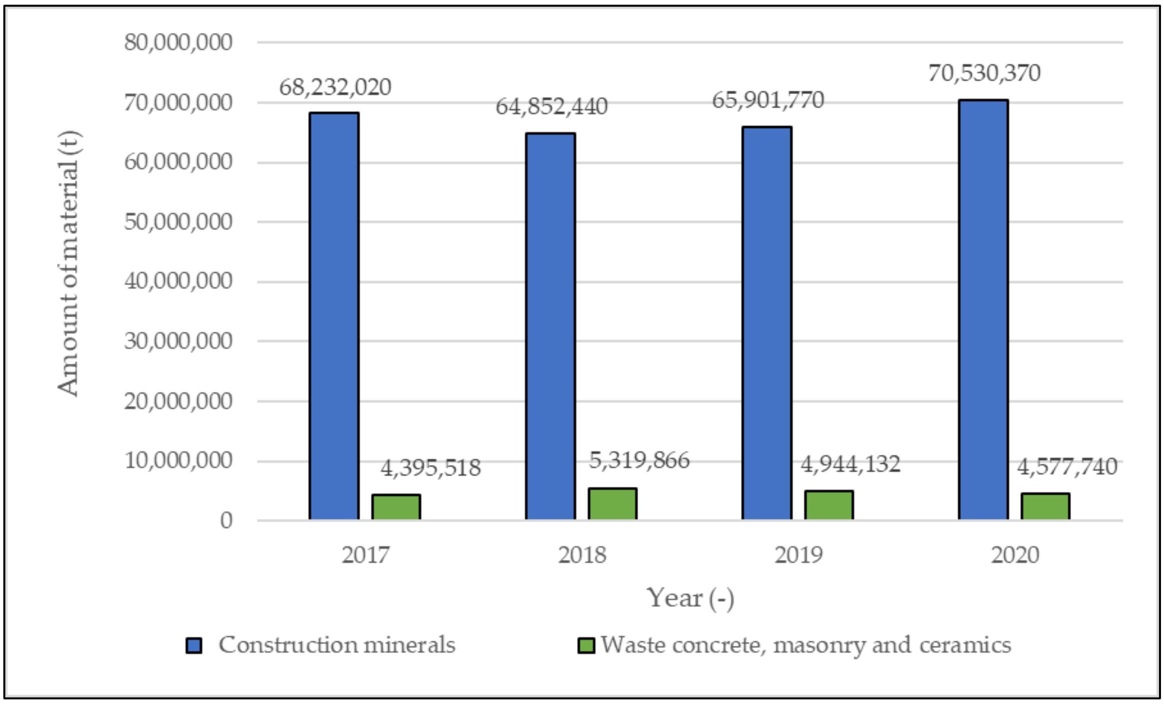


Figure 2 Comparison of the amount of construction minerals needs and waste concrete, masonry and ceramics for the Czech Republic [19].

2.1.7 Recycling of concrete and masonry waste

Concrete is the composite material consists of aggregate (crushed natural aggregate, mined natural aggregate, recycled aggregate) that occupies about 55-80% of the volume of concrete, cement, and water. Furthermore, mineral admixture, such as granulated blast furnace slag, fly ash, silica fume, etc., or superplasticisers to improve the properties of concrete are added in some cases [20]. Furthermore, masonry waste usually contains red clay bricks, mortars, aggregate particles with attached cement mortar, aerated concrete, and contaminants (glass, plastics, paper, textile, soil, etc.) [5]. The amount of contaminants could be reduced by the selective demolition and sophisticated recycling procedure.

The aggregate manufacturing process differs according to the type of aggregate. The mined aggregate (gravel and sand) takes less energy than the crushed aggregate, due to the lower number of manufacturing processes. Usually, the recycling process includes stockpiling, presizing, sorting, screening, removal of contaminants, crushing and sieving to the fraction [18,21]. However, recycling technologies have been developed to separate the attached mortar from the RCA particles, due to their negative effect on the properties of the RCA. On the one hand, these methods lead to better properties of RCA and consequently achieve better properties of RAC. On the other hand, the environmental impact increases due to more complex recycling technology (based on mechanical treatments, thermomechanical treatments, and chemical treatments), and characterization of limits for a recycling process in terms of its environmental benefits is still missing [22,23]. In the case of waste masonry, multistage crushing and sorting techniques have been developed to separate as many contaminants as possible.

2.1.8 Ordinary recycling process of recycled aggregate

Ordinary recycling processes contain only mechanical treating such as crushing, screening, and sorting [24]. At first, the primary sorting of waste materials is mostly done by workers. This procedure is more suitable if the sorting is performed firstly on the demolition sites using a selective demolition process. Furthermore, the fragments of concrete structures are precrushed by the hydraulic demolition shears, and steel bars are removed using a magnetic separator. The lightweight unwanted impurities such as paper, textiles, wood, and plastics, whose amount is dependent on the demolition process, are removed by air or water, respectively. Finally, the crushed concrete particles are sieved into the required fractions. Thus, particles larger than 20 mm can be crushed again in a secondary crusher, such as an impact or rotary crusher. Secondary crushing can be repeated if necessary. Generally, on the one hand, the number of crushing cycles leads to a better quality of RCA due to the higher number of separation processes. On the other hand, it influences the shape and content of the fine particles in RCA. In the case of fine RCA, it was found that the use of various types of crushers, such as jaw crushers, and, impact crushers and furthermore, different crushing settings did not have a significant influence on the particle size distribution of fRCA [25–27]. However, differences in the amount of finest particles have been observed for multiple crushing, where more crushing steps have led to a higher content of the finest [28,29]. Furthermore, rotation speed affects the WA of fRCA [30].

2.1.9 Improvement of recycled aggregate properties by production process

RA negatively influences the properties of concrete, mainly due to cement mortar attached to the aggregate surface. These lead to worse mechanical properties due to the interfacial transition zone (ITZ) and worse durability that is caused by the higher porosity and water absorption (WA) of RAC. This could be eliminated by an improved recycling process, such as the thermomechanical process in which the attached mortar is separated from the aggregate surface during thermal and subsequent mechanical adjustments. However, it has been reported that this treatment technology affects energy and carbon footprints [31]. The energy consumption of the thermomechanical recycling process was found to be between 36 and 62 times higher than the ordinary recycling process. Related to that, the carbon footprint also increases depending on the energy source. In addition, another thermal treatment method is the use of microwaves which weakens the adhered mortar for easier removal [32].

Furthermore, presoaking RCA in acids to remove the adhered mortar has been verified many times [24]. However, the use of acids in higher concentrations endangers the environment because of the huge amount of water needed to wash of treated RCA. For compensation for these disadvantages, acid acetic as a possible solution was studied [33] because it is safer, cleaner, and cheaper. Although the treating by acids affects the shape of the particles, which is also caused by the removal of cement paste [27,28], the effects that were demonstrated were slight [27,34]. Furthermore, the durability of concrete could be weakened by chemical treatment.

In conclusion, according to the presented results, the thermomechanical treatments, and chemical treatments have more disadvantages than advantages. For these reasons, the multistage recycling process seems to be the best solution, and the negative effect of RA on concrete properties with minimizing environmental impact could be reached in the next steps of concrete production. For example, it could be reached by reducing cement with supplementary cement materials (SCM) or using superplasticizers, the other possibilities are advanced mixing designs such as the Equivalent Mortar Volume (EMV) method [35], Particle Packing Method (PPM) [36] and response surface method [37] or by modified mixing procedures such as two stage mixing approach (TSMA) [38].

2.2 *Life cycle assessment of recycled materials*

2.2.1 Life cycle assessment methodology

The methodology used to assess the environmental aspects of a given material is known as Life Cycle Assessment (LCA), and has been regulated since 1996 under the International Standard Organization (ISO). LCA application includes the complete life cycle of the product, process or activity, that is, the extraction and processing of raw materials, manufacturing, transportation and distribution, use, maintenance, recycling, reuse and final disposal [39]. The LCA methodology is defined in ISO standards CSN EN ISO 14040 and 14044.

The life cycle analysis is consisted into four stages:

1. Goal and scope definition

2. Creating the life cycle inventory (LCI)
3. Assessing the environmental impact (LCIA)
4. Interpretation of results

Goal and scope definition

In the assessment, the object is clearly specified in the first stage of LCA. It must be defined in its function, planned scope, purpose, and use of study.

- **Functional unit** - It is defined according to CSN EN 15804 + A1 and CSN EN ISO 14040 and determined the quantified performance of a product system for use as a reference unit. The primary purpose of the functional unit is to provide a reference by which material flows (input and output data) of the LCA results of construction products and any other information are normalized to produce data expressed on a common basis. The functional unit necessarily needs to be comparable. It could be one tonne, one cubic meter, one square meter, or one structural element with the same properties for the same functionality.
- **System boundary** - It is defined according to the CSN EN ISO 14040 and CSN EN 15643-1 set of criteria that specify which unit processes are part of a product system. The system boundary defines what is included and what is not included in the assessment. The system boundaries must be fixed. It is necessary to determine the depth and extent of the assessment.

  The generally known system boundaries are:

- Cradle to gate – containing extraction of the raw material and production phases.
- Cradle to grave – containing extraction of the raw material, production, construction, use and end-of-life phases.
- Cradle to cradle – containing extraction of the raw material, production, construction, use, end-of-life phases, and recycling.

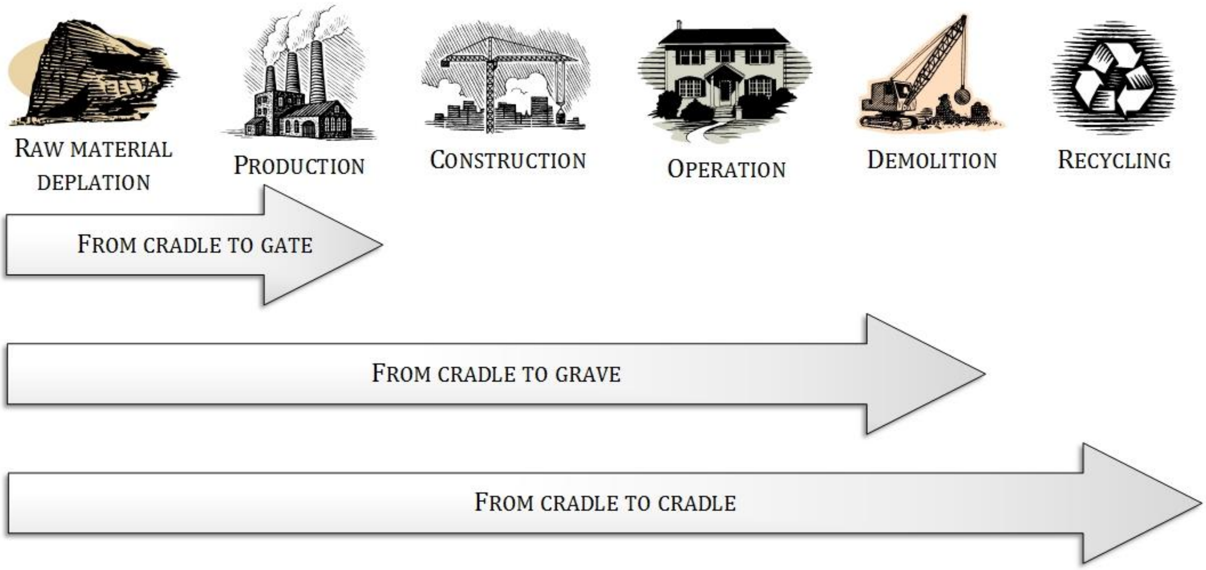


Figure 3 The different Life Cycle Assessment concepts [40]

Life cycle inventory (LCI)

The second stage of LCA is collecting data for calculations of relevant inputs and outputs of the product system. Inputs and outputs include the use of resources, emissions to air, water, soil, and waste generation associated with the system. For LCI is compiled process diagram which includes all phases of product LCA. Each of the defined phases can be composite from additional processes and combined with the production of different types of raw materials in the material production phase and their transportation.

All units of the product life cycle process are collected from data on natural resources, material and energy consumption, emissions, and waste. These data can be specific or general. The specific data are given by companies in each locality. The general data are collected in databases, which are national, local, or global, and also academic, industrial, or commercial.

Life cycle impact assessment (LCIA)

The third phase of LCA is impact assessment, where the potential environmental impacts are evaluated by model. The main aim of the LCIA is to find a relation between inputs and outputs. The inputs are for example natural resources, fossil fuels, water, etc. and the outputs are for example emissions and energy. In this stage, selection of impact categories, category indicators, characterization models, classification, and characterization are usually done. Impact categories describe the impact caused by the product or product system specified in the goal and scope phase.

Most studies have assessed RA and RAC in the following six environmental categories (ADP, AP, EP, GWP, ODP, and POCP) where the baseline method of CML is usually used to quantify these impact categories [18,41–45].

Interpretation of results

This fourth phase is the last one of LCA. The main issues of this phase are:

- identification of significant environmental issues,
- evaluation of the results with the aim of establishing their reliability,
- conclusion and recommendation.

2.2.2 Life cycle assessment of aggregate

Aggregates are the most used component of concrete (around 80%), so the consumption of natural aggregates (NA) has increased with the rapidly increasing production and utilization of concrete. With the decreasing amount of available natural sand, extraction could be more damaging, leading to serious ecological and economic problems. The extraction of river sand causes environmental damage worldwide, such as altering the course of water, eroding the shoreline, changing wave behaviour, local fauna and flora ecosystems, and creating dead-end diversions and pits [25,46]. For these reasons, the positive environmental impact of the substitution of natural aggregates into concrete are clearly seen. However, from the point of view of natural and recycled aggregate LCA, it was observed that the energy consumption and global warming potential were about 20% higher for crushed RCA than for NA [41], and in addition, the energy used for the production of RCA was almost three times higher than for river NA production and more than two times higher than for crushed NA production [42]. The functional unit was 1 tonne of NA or RA, respectively, and the system boundaries include the crushing of the aggregate, the transportation of the mobile plant to the demolition site, and the landfill of recycling waste. On the contrary [42], in another study, it was found that RA production creates about 20% fewer emissions than the mining of NA. The functional unit was 1 tonne of NA or RA, respectively. For these compared studies, local inventory data were used.

2.2.3 Life cycle assessment of recycled concrete

Life cycle assessment (LCA) is the decision-making tool that is mostly used for comparison of a few solutions and in which the FU, system boundary, and input data must be defined correctly. These various parameters greatly influence the results of LCA. Many research studies have been published on LCA of recycling, recycled materials, recycled aggregate and recycled aggregate concrete. However, due to the high variance of goal and scope, functional unit, boundaries, changeable inventory allocation, uncertain data quality, specific geographic location, and various mix designs of RAC, it is doubtful whether these results are comparable. Specifically, different techniques of preparation of NA, various types and distances of transportation, and several principles of compensation for the worse characteristics of RAC such as the higher amount of cement, the addition of mineral additives or a deeper concrete cover in reinforcement concrete [18,47]. For incompatibilities between results and due to these discrepancies, the results of previous studies are not comparable and could only be considered only as case studies [18].

Generally, it has been verified many times that the highest environmental impact of concrete has been found for cement production followed by transportation [18]. Cement, whose production is currently the largest single industrial emitter of CO_2 and causes almost 8% (2.8 Gtons/y) of global CO_2 emissions [48], is responsible for 74% to 81% of total CO_2 emissions of concrete [49]. The influence of different transport distances has been evaluated many times [41,50]. From the point of view of the extraction of natural aggregate, has been observed that the environmental impacts of aggregate production are rather tiny compared to the contributions of cement production and transportation. In addition, in some studies, the utilization of fRA is not recommended to use as a substitute for the natural sand due to the diversity of the properties of RAC in the context of little or no impact on reducing the environmental footprint [51–53]. However, on the other hand, the production of natural aggregates is related to energy consumption and emits CO_2, NO_x, and other air pollutants. The production of 1 t of natural aggregates (river sand and crushed stone) was presented to be responsible for 23–33 kg of $CO_{2\text{-eq}}$ emissions. In contrast, when fRCA is used a significant amount of energy and emissions emitted by the aggregate manufacturer are reduced, where the production of 1 t of fRCA from CDW generates 12 kg of $CO_{2\text{-eq}}$.[54]. The life cycle of concrete structures is shown in Figure 4.

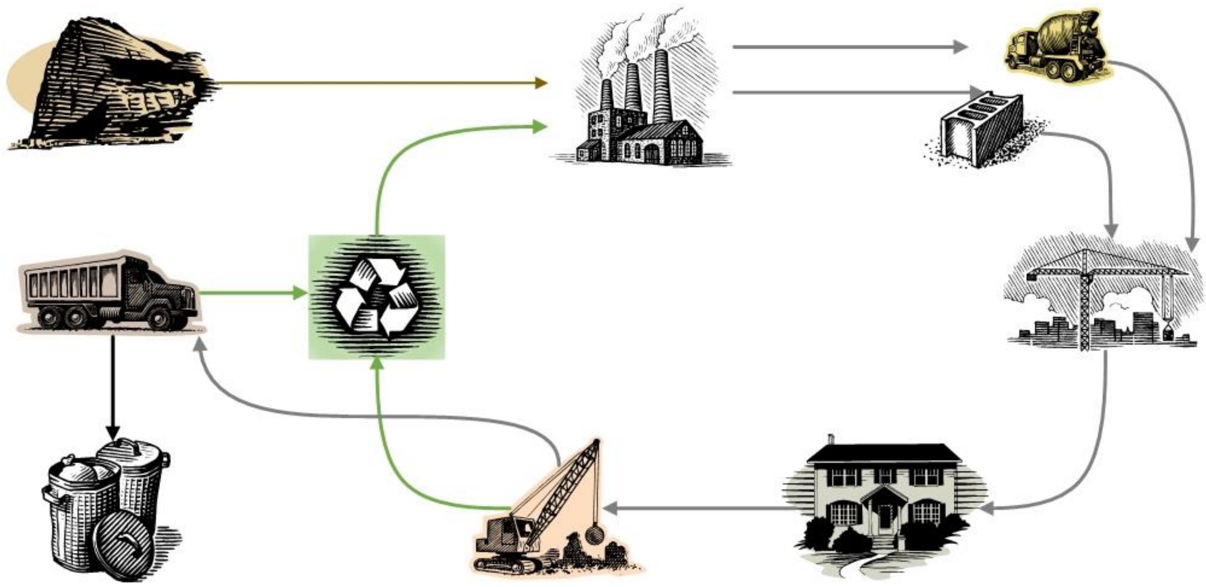


Figure 4 Life cycle assessment of concrete structures [40]

<u>Functional unit of RAC</u>

In previous studies [55], various functional units have been established to provide a baseline for quantifying inputs and outputs and to allow comparison of the product's LCA. In most of the first published studies dealing with LCA of RAC, the FU of RAC was considered per 1 cubic meter of concrete. For this approach, concretes with similar properties, especially mechanical properties and durability, must be assessed [41,56,57]. The decrease in properties was compensated by adding more cement [41] or the replacement ratio of recycled aggregate in concrete up to 30% with no significant decline in concrete properties is the other approach [58]. However, the decrease in greenhouse emissions for this approach in comparison with a conventional solution is only 1%.

Subsequently, two main trends have been taken into account on how to approach the FU. First, the concrete structure made of RAC with the same dimensions but with a different service life [59–61]. For this approach, it is necessary to consider under which conditions the concrete structures will be used. For conditions with high risks of chlorides and carbonation, the service life of RAC for structural use can be shorter than for the conventional solution. In these cases, the comparison of RAC and NAC is not correct due to the more often necessary repairs of RAC structures during their life span. RAC may be unfairly assessed as less environmentally friendly in these cases. For this reason, the second correct approach can also be considered, where the improvement of RAC structural elements for longer service life is taken into account. This could be done, for example, with a thicker cover of concrete to protect reinforcement.

System boundaries

The determination of the system boundaries of recycled materials seems to be a very important question. Similarly to the determination of the functional unit, determining the boundary of the system brings a lot of discrepancies [55]. Since if the boundary of the cradle-to-gate system is chosen and the construction, use, and end-of-life phase is not considered, the possible shorter service life caused by the lower durability of RAC is not taken into account [18,62]. Furthermore, if the use phase is not counted, the benefit in the form of absorbed CO_2, where the potential is equivalent to 13–48% carbon emission throughout the concrete life cycle [56]. However, when the cradle-to-gate system boundary is used, the production of recycled material is considered at the beginning of the new life cycle; however, this is also partially the final stage of the previous life cycle. For this reason, in some studies, the recycling process is recommended considered as the end-of-life phase of the previous life cycle. In this case, the environmental impact of the origin material has been found to decrease by approximately about 15% compared to landfilling [63]. In the case of recycled materials, the evaluation through the whole life cycle cradle to grave or cradle-to-cradle which shows a closed-loop system is recommended [43,56,64,65] (see Figure 5) However, in this consideration, it is assumed that the properties of material are not change during the product life and the material can be used in the same application. Furthermore, a product can be recycled repeatedly. For this reason, it is necessary to correctly define the functional unit, taking into account the worse functionality caused by worse mechanical properties and durability in this case. The other possible approach for reused and recycled materials is the cut-off rule (see Figure 5), where recycling is included in the second life cycle of the material.

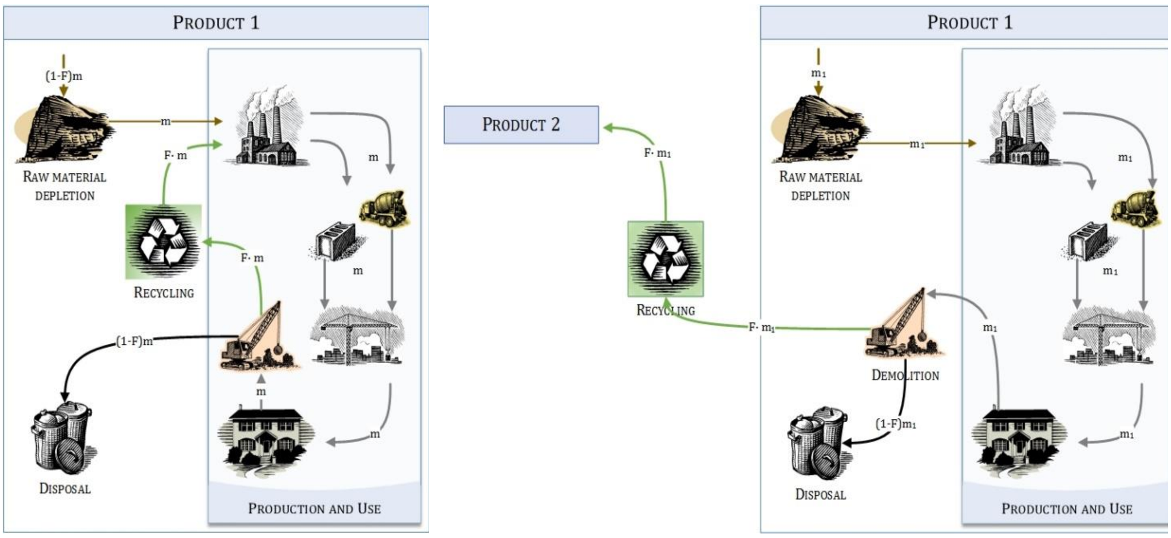


Figure 5 Close-loop system and cut-off rule system of considerations of recycling [40]

Life cycle inventory

The LCI are mostly used databases which usually contain general data. For this reason, recycling processes may not be taken into account properly as they vary according to local habits. In some previous investigations, specific data has been collected and used. The different recycling processes and collected data cause further inconsistency in comparison studies dealing with LCA of RAC. Furthermore, the allocation of emissions must be associated with defined system boundaries.

The categories which have been considered relevant for concrete production, are [42,44]:

- Depletion abiotic and biotic resources potential (ADP)
- Global warming potential (GWP)
- Photochemistry ozone creation potential (POCP)
- Ozone layer depletion (ODP)
- Acidification potential (AP)
- Eutrophication potential (EP)

2.2.4 Life cycle assessment of recycled materials

Except for the LCA of recycled aggregate concrete (Chapter 2.2), there have been published that reported about the other recycled materials in the construction industry. This chapter summarizes the results of the environmental assessment of building materials and products published so far by LCA.

LCA of recycled PVC windows frames

The environmental impacts of recycling PVC window frames have been presented [66]. The study deals with two types of recycled materials, production and consumer, from which white and non-white frits and powder are produced. The results suggest that significant environmental impact savings can be achieved by using PVC from recycled frame waste compared to using primary PVC. The recycling of consumer PVC waste leads to higher savings than that of production waste, mainly due to positive "credits" for metal recycling. For example, replacing the original PVC from consumer waste saved approximately 2 t of $CO_{2\,eq}$ / t PVC, while the production waste PVC will save 1.8 t of $CO_{2\,eq}$ / t of PVC. The results are sensitive to transport distances and truck load. For instance, the global warming potential (GWP) of non-white PVC frit increases 1.7 times as the transport distance increases from 100 to 500 km and the factor of truck load decreases from 0.7 to 0.2. Metal recycling credits affect environmental savings by adding credits for pure aluminium, it saves 54 times more $CO_{2\,eq}$ / t of recycled PVC compared to credits for recycled aluminium.

LCA of used of waste glass and recycled glass wool for thermal insulation

The LCA results of the use of recycled materials on production of glass wool shows that glass wool can be made from up to 80% recycled glass (58% on average). In the case of using waste glass, a lower temperature is required for melting, leading to savings in energy needed for melting and thus savings in CO_2 emissions. Between 1993 and 2010, there was a 19% reduction in CO_2 emissions. In addition, glass wool insulation is recyclable: If a waste management plan is well defined, then at the end of its life cycle, recycled waste wool can be used for new insulation. Already, 75% of the glass wool from production is recycled (up to 100% in some cases) [67].

LCA of recycled gypsum

The study [68] is devoted to comparing the environmental impacts of the use of natural gypsum and gypsum obtained by recycling gypsum boards. From the results obtained for the average indicators for each type of gypsum, it can be observed that in all impact indicators except mineral extraction, natural gypsum had a greater impact compared to recycled gypsum. The highest difference was evaluated in the category of ionizing radiation, where there was a decrease of 87.82% for gypsum from gypsum board waste. Furthermore, it is important to note that recycled gypsum powder has the lowest impact in all categories analysed, 67.57% lower than gypsum plasterboard. Due to the potential for global warming for every single type of gypsum, there is a 40-45% savings in CO_2 emissions compared to the production of natural gypsum. Another significant positive secondary effect of gypsum recycling can be seen in the reduction of energy consumption to gypsum landfilling. A decrease of almost 60% can be observed, which is correlated with the effort to reduce the energy consumption of the construction sector. Similar results were published in another study [69] where an assessment of the environmental impact of gypsum waste recycling on an industrial scale shows mostly positive impacts, compared to the results for natural gypsum and gypsum obtained as a by-product of coal-fired power plants. The calculations for recycled gypsum showed the best results in the following five (out of seven) impact categories: GWP, AP, POCP, transformation of land use and land use (total).

2.3 Recycled Aggregate Concrete

2.3.1 Requirements in standards

In general, international standards allow the use of RCA in concrete depending on the desired concrete strength and the exposition class. The acceptable content of recycled aggregates depends on their properties, such as composition, dry density, water absorption, and percentage of contaminants. In the European Standard (valid for example in the Czech Republic, Germany, Portugal, etc.), the acceptable substitution level of NA by RCA is 50% for exposure classes without environmental risks, and 30% for exposure classes with a low level or without environment risks such as corrosion and freezing, respectively. The density, water absorption, and content of contaminants must be determined. Similar regulations are also in Italy, where, however, the maximum concrete strength class is limited to C30/37. On the contrary, in Brazil, up to 20% of RA is allowed in structural concrete of any strength class. However, there are some limitations to aggregate properties, such as WA up to 7%, and contaminants content lower than 1%.

In contrast, RCA, which contains more than 70% of concrete particles, is possible according to standards [70,71] possible to use as a partial replacement of coarse natural aggregate in certain applications. The use of recycled masonry aggregate (RMA), which contain more than 50% of brick particles, fine RCA, and RMA, originated from concrete or masonry from CDW has not been defined as a partial replacement of aggregate for concrete in Czech standards yet.

2.3.2 Properties of recycled concrete aggregate

Recycled concrete aggregate is a composite material that contains more than 90% of natural aggregate particles that is partially covered with adhered cement mortar. Furthermore, it could contain a small amount of red clay brick, mortar fragments, glass, etc. These materials should not exceed 10%, and the content of contaminants must be up to 0.2%. The quality on the RCA is dependent of demolition and recycling process, including the method, speed, and number of crushing steps [23,25,29,72,73]. Furthermore, the properties of RCA depend on the type and size of the natural aggregate in the parent concrete, the strength of the parent concrete. Problems related to RCA are a highly angular and irregular shape; and a porous and rough particle structure [74–76]. However, the largest complication is the presence of cement mortar, whose volume of in RCA varies between 25% and 60% depending on aggregate sizes. This material is inhomogeneous, more porous, less dense and has a weak ITZ, which is the zone between mortar and aggregate [77]. Furthermore, the weaker ITZ between cement mortar and original NA, whose thickness is about 40–50 μm seems to be essential in decreasing the bond strength between recycled concrete aggregate and fresh concrete [78]. Moreover, during the crushing process, tiny cracks in RCA are developed.

To allow usage for more sophisticated applications, possible ways to improve the quality of RCA have been evaluated by removing old cement mortar from RCA particles and cleaning the material from various impurities in order to achieve properties comparable to NA. Multistage mechanical process, thermal or chemical treatment, separation using microwaves, or a combination of these processes have been tested as possibilities to remove mortar [22]. On the one hand, these processes could improve the quality of RCA and provide opportunities for further use of cement paste. On the other hand, it would be more economically and environmentally demanding. In conclusion, optimization of processes and usage is necessary for a meaningful solution to the utilization of RAC, especially considering the possibilities of practical use in the concrete industry. Many studies on the properties of RCA have been published, which have been reviewed [24,79,80].

The properties of coarse RCA and its use in concrete mixture

There are still doubts about the utilization of recycled concrete aggregate due to its significant heterogeneity, which causes a lack of consensus on the method of mixing design. However, in the case of coarse RCA as a replacement for aggregate in concrete, the investigation can be clearly concluded by many previously done investigations. It is generally known that the cement mortar contained in RCA that is mostly attached to the aggregate surface causes higher porosity and consequently high water absorption and, moreover, weakened the mechanical properties of RCA concrete (RCAC) by multiple ITZ [46,81–84].

Higher water absorption must be compensated by additional water in the concrete mixture to achieve the workability of fresh concrete. Measurement methods of WA are clearly defined by standards (for example EN 1097-6) and furthermore, the methods of calculation of additional mixing water have been presented many times [81]. Due to these findings, more water must be added to the former concrete to achieve the required workability. There are a few ways to get there. One way is to pre-saturate the aggregate [85–87], a further way is to immerse RCA for 30 days in water [88], and the third way is the two-stage mixing approach (TSMA) [38]. The saturation level of recycled aggregate could affect the mechanical properties of concrete since, at higher saturation levels the mechanical bonding between the cement paste and the recycled aggregate becomes weaker [89,90].

The compressive strength of RAC is influenced by the replacement rate of RCA and its quality and composition [91,92]. Furthermore, the decrease in compressive strength depends on the presence of two ITZ, which is normally between the aggregate and the new cement mortar, but in the RAC it is also between the old mortar and new cement mortar [38,93,94]. According to previous studies, the maximum replacement ratio of coarse fractions without a significant decline in properties is 30%. These correspond to most of the standards and specifications worldwide where the limit level of RCA substitution is approximately 30% in structural elements [24].

The properties of fine RCA and its use in concrete mixture

fRCA came from the multiple crushing of waste concrete from CDW [95–98] and from the pre-cast industry [99]. It is made up of NA particles and old cement paste, mostly attached to the aggregate surface. The decline in mechanical properties related to the old cement mortar. This leads to higher porosity and, consequently, to higher water absorption and more ITZ. Furthermore, for the fine fraction of fRCA, which is highly represented in fRCA, a higher specific surface area was found [46]. The number of crushing processes and the rotary speed influence the properties of fRCA. The multistage crushing technique leads to a higher content of fines. On the one hand, the fine content (particles finer than 75 μm) of the aggregate has a larger surface area, which leads to a higher water consumption. On the other hand, the fine content would fill pores between larger particles for a better aggregate skeleton of the concrete mixture [100]. The size of particles between 125 – 500 μm shows high content of cement mortar [25]. This could lead to better mechanical and permeability properties of concrete.

In contrast to the use of the coarse fraction for RCA as a replacement for aggregate in concrete, where the investigation has been clearly concluded with the description of all negative effects. These aspects are, for example, high porosity and, consequently, high water absorption and more ITZ whose negatively influence the properties of fresh and hardened concrete and durability [46,81–84]. The determination of the utilization of fRA is inconsistent. As written many times before in previous studies, the use of RA negatively influences the workability of concrete due to its higher water absorption, which consequently leads to a negative effect on mechanical properties, mostly the compressive strength as the key material property of concrete. In the case of fRA, utilization is more complicated because the way of measuring water absorption has not been clearly developed, where the differences between various evaluation methods are huge, and the absorbability of fRA during concrete manufacturing is also not known. Due to these facts, the use of fRA in concrete is quite challenging. For what, standards around the world respond by essentially not allowing the use of fRA (< 4 mm), contrary to a coarse fraction, as a possible substitution of natural aggregate in concrete.

fRCAs are currently used in low-grade applications, such as a filling material for geosynthetic reinforced structures and soil stabilization, as a substitute material for natural sand in cementitious renderings and masonry mortars [101–108], and road constructions [46]. The maximum replacement rate of sand by fine RCA in concrete mixtures without significant effect on compressive and flexural strength is up to 30% [46,74]. On the contrary, the modulus of elasticity also decreases for concretes with lower replacement ratios.

2.3.3 The properties of recycled masonry aggregate

RMA originated from waste masonry and the main constituents are red clay bricks, ceramics, mortars, and plaster, and in very often cases also waste concrete with aggregate particles and cement mortar. RMA is more porous compared to natural aggregate, and its water absorption is higher. Naturally, the higher porosity and water absorption are caused by the very porous constituents. The possibilities of using RMA are mainly related to the properties and composition of recycled aggregate. The main barriers to the utilization of RMA are their high water absorption, which negatively influences the workability of fresh concrete, and unwanted impurities, which could degrade the mechanical properties of concrete [109]. The water absorption is up to 25 times higher compared to natural aggregate [110–113].

The properties of coarse RMA in concrete mixture.

The workability of fresh concrete with partial replacement of natural gravel by RMA is influenced by its higher water absorption. Workability could be improved by pre-soaked RMA or by adding additional water to the concrete mixture during the mixing process. The workability and the effective connection of water and cement influenced the compressive strength of concrete [114]. Contrary to coarse RCA, a 30% reduction in compressive strength of concrete was found containing a coarse RMA replacement rate [111]. However, no significant changes have been found in compressive strength of concrete containing coarse RMA with a replacement rate of 15%. The compressive strength of concrete with complete replacement of coarse natural aggregate by RMA decreases by up to 35% [110].

The properties of fine RMA in concrete mixture.

Generally, the porosity and water absorption of fRMA are higher compared to those of fRCA [115–118]. The main characteristics of fRMA responsible for concrete properties were presented in many studies of the use of fine RMA as partial or complete replacement of sand [110,119,120]. Similarly, with fRCA, the higher water absorption is caused by the higher porosity of the materials and the larger specific surface area, and also the compensation of higher WA is the same. The maximal replacement ratio of natural sand by fRMA has not been reported yet.

2.3.4 Structural use of recycled aggregate concrete

Although very intensive investigation worldwide has been done on the possible utilization of RA as a partial or complete replacement of NA in concrete, its current applications are limited to low utilities, such as landscaping and pavements [121]. fRCAs are currently used in low-grade applications, such as a filling material for geosynthetic reinforced structures and soil stabilization, as a substitute material for natural sand in cementitious renderings and masonry mortars [101–108], and road constructions [46]. From a research point of view, the most frequently evaluated structural element made by RAC is the beam. Tosič [122] reviewed 217 experimental results and created a database on flexural and shear strength of reinforced recycled aggregate concrete beams. However, it was found that the prediction models defined in Eurocode 2 are not entirely adequate for RCA, mostly for the shear strength, while for flexural strength it fits. However, it has been verified many times that the highest decrease of all properties is observed in the modulus of elasticity, where the decrease is already evident for the low level of substitution. Furthermore, carbonation resistance is also one of the most affected properties due to the high porosity of RCA. For these reasons, the question is whether it is efficient to find solutions on how to replace NA in structural elements with specific requirements, in the context of the fact that the amount of waste concrete that could be recycled can replace only 5% of aggregate needs. Maybe the better way is to find structural applications where high-quality concrete is not necessary.

2.4 Durability of recycled aggregate concrete and its improvement

The durability is one of the most discussed properties of RAC, due to its higher porosity and water absorption. The durability properties of concrete are essential for its usage in structural applications. Concrete structures are very often exposed to the effect of the environment. The durability properties of concrete, especially freeze-thaw resistance and carbonation could be negatively influenced by higher porosity and water absorption of RA and attached cement mortar in the case of RCA.

2.4.1 Freeze-thaw resistance of RAC

Generally, it was found that the freeze-thaw resistance decreases with the increasing replacement ratio [123] and is linearly correlated with the porosity and water absorption capacity [124]. Higher capillary water absorption causes the worse freeze-thaw resistance

[125], due to the water content in the porous system. The freezing process causes the pressure inside the pores of the concrete to increase with an increase in the volume of water, which can lead to local cracks. However, on the contrary, the higher porosity of the RA could provide better hydraulic pressure dissipation [6,126]. Furthermore, concrete with RMA has been found better frost resistant than concrete with RCA [126]. However, this phenomenon needs to be verified. The RAC freeze-thaw resistance is closely related to water absorption and very often influences the future use of concrete structural elements in environments. For internal utilization, the worse freeze-thaw resistance does not lead to more complications. However, for external structures which are in contact with the ground, the worse freeze-thaw resistance could cause an essential complication for future use.

2.4.2 Carbonation resistance of RAC

Concrete carbonation can be described as a physical–chemical process taking place on the surface of the concrete in reaction to atmospheric CO_2. The permeability, moisture content, cement content and water/cement ratio, mineral additions, aggregate type, and porosity of concrete are responsible for the resistance to carbonation of concrete. Furthermore, concrete carbonation is influenced by CO_2 content, relative humidity, and ambient temperature of the environment [127,128]. The resistance to concrete carbonation is an essential knowledge for the future use of reinforced concrete because it is necessary to protect reinforcement bars against corrosion. Concrete provides the passive coating of steel bars and can be destroyed by carbonation and chloride ingress. The corrosion of steel bars is negatively influenced by the RA in the concrete, depending on the level of RA, which decreases with an increasing amount of RA in the concrete. Furthermore, carbonation starts earlier in RAC compared to NAC [97,128–138]. The majority of world standard defines that the maximal replacement rate of coarse fraction in concrete is 30%, which correlates with general global findings that there are no significant changes for a concrete with the replacement rate of up to 30% [132,137]. Furthermore, the masonry content in RA worsens the resistance to carbonation resistance of concrete, leading to the an increase in the carbonation depth with increasing replacement rate of RMA [127]. On the contrary, the worse resistance to carbonation of RAC can bring environmental benefits due to the larger amount of atmospheric CO_2 in concrete [28,29].

2.4.3 Improvement of the RAC properties in general

In general, there are a few methods to improve the characteristics of fresh and hardened RAC. First, RAC characteristics can be positively influenced by the mixing process, for example, to compensate the absorbability of RA with additional water, added during mixing of concrete [120] or before mixing by presoaking the RA for 24 h [115]. Presoaking of RCA to compensate its absorbability (determined according to the water absorption test) using the two-stage mixing approach [141] positively influences the concrete mix which achieves greater compressive strength and durability [142–144]. The reason for this is that the water in the porous RA affects the internal healing effect. In this way, water is gradually released to further hydrate cement [144–146]. Furthermore, the possibilities for treating RA rather than pre-water treatment are carbonation, lime carbonation and immersion of acetic acid [147], bio-deposition treatment [148] or impregnation by cement paste, limewater or diluted water glass [149]. Additionally, carbon treatment could be used to separate the attached mortars and reduce the ITZ [150–152].

2.4.4 Improvement of the durability of RAC

First, the durability of the RAC could be improved by adding mineral admixtures [153] such as the optimal amount of fly ash, metakaolin, silica fume, or ground-granulated blast furnace slag [37,154–159] which are able to fill pores and therefore improve the microstructure [160]. Furthermore, the density and strength of the concrete could be enhanced by the ability of mineral admixtures to react with $Ca(OH)_2$ to form an additional C–S–H gel. However, when the cement is partially replaced by mineral additives, the pH of concrete is reduced, which leads to worsening of carbonation resistance [127]. However, low calcium bentonite has been confirmed as a potential partial replacement for Portland cement with a positive influence on the mechanical properties and durability of RAC [161]. Another possibility is the use of superplasticizers leading to crystal growth, which causes a denser concrete structure, which may reduce the depth of RAC carbonation at an early age, as described [162], but fortunately this effect weakens over time. Third, the other way to reduce the carbonation depth is by lowering the w/c ratio [127]. In addition, the durability of the RAC could be improved by adding fibers, such as Nano-SiO_2 or Basalt fibers [157,163]. Finally, the freeze–thaw resistance and carbonation resistance, which are the essential characteristics of RAC used for external reinforcement wall, decrease as a result of the higher porosity and water absorption capacity of RA. Therefore, in this investigation, the crystalline admixture, whose ability to improve freezing–thawing and carbonation resistances was verified in a previous study [6], was used.

3 Catalogue of Construction Products with Recycled Content from Construction and Demolition Waste [2,164]

This chapter is based on the conference paper of co-authors Tereza Pavlů, Jan Pešta, Martin Volf and Antonín Lupíšek.

Author's contribution: conceptualization, methodology, investigation, resources, writing (overall contribution 85%)

3.1 Motivation and objective

The main objective of the present project made for the Czech government was to create a catalogue of construction products and materials which contain recycled content from construction and demolition waste. The motivation for the work was to support a higher utilization of construction products with the content of secondary raw materials in the Czech Republic. It was designed for architects, designers, civil engineers, construction contractors and public and private investors. The catalogue provides an overview of products with recycled content, a list of valid requirements on the utilization of recycled materials listed in standards and legislation. Examples of good practice are presented to break the existing psychologic barriers to the use of secondary raw materials in the Czech construction industry. This contribution summarizes the findings in the field of the recycling of construction and demolition waste and its further use as produced secondary raw materials in the construction industry.

3.2 Methods

The creation of the Catalogue of Construction Products with Recycled Content from Construction and Demolition Waste started summarizing of the available information on the construction and demolition waste from the national statistics. It was followed by a broad literature study of available standards, existing legislative documents and regulation and communication with companies and searching for good examples from construction practice. In collaboration with the Ministry of Industry and Trade and the Czech Standardization Agency were organized several round tables, in the early stages of the work to collect ideas and requirements of different stakeholders from the construction and recycling industry and in the final stages of the project to get feedback on form of the deliverables so that they are practical to use in the daily life.

3.3 Statistics of recycled materials with potential use in construction products

The amounts and recovery rates of each material type in construction and demolition waste divided according to European Waste Catalogue are reported by the Czech Statistical Office on a yearly basis [12,14] – see Figure 6. The concrete, masonry and ceramics make almost 50% share. The recycling rate of these materials is around 60% and around 30% is downcycled and used for landscaping and earth works. The second largest category are metals, which make approximately one third of the construction and demolition wastes. Metals are separated during demolition and recycling process and are collected as raw materials for the production of new metals. Almost 13% share has bituminous mixtures, coal tar and tarred products with recycling rates of more than 90%. They are mostly used as primary materials in road structures. Other material categories such as wood, glass, plastics, insulations, gypsum and other materials represent less than 2% each and their recycling rates have not been reported in detail.

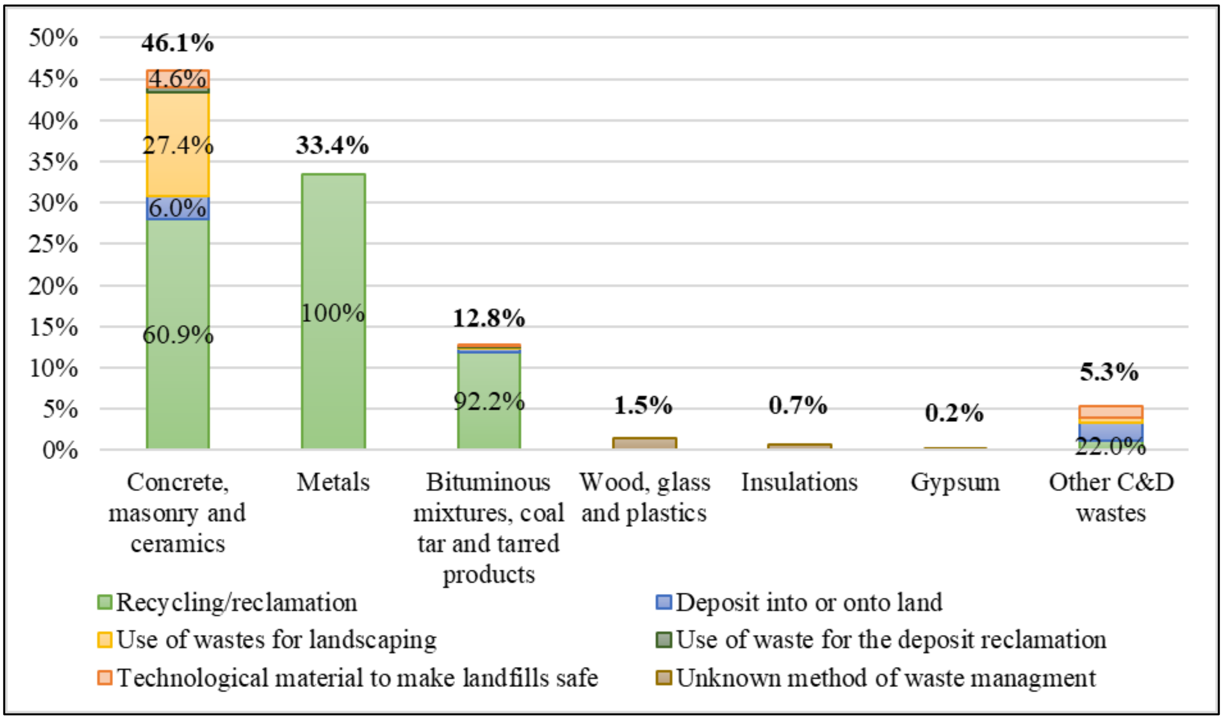


Figure 6: The weight percentage of material categories in construction and demolition waste and their further use [12,14].

3.4 Process of selective demolition

The selective demolition counts the following steps:

1. The pre-demolition audit – the process where types and amounts of different materials are specified, and the process of demolition is stated
2. The furniture, equipment, sanitary, separable floor surfaces, and other wastes are removed from the building.
3. The demountable structures and components such as partitions, doors, windows, lightweight building envelopes, roof cover, roof structure, metal structures etc. are removed. Consequently, these structural elements should be divided into individual parts according to materials. For example, the windows, should be separated into glass, plastic frames, metals, etc.
4. The ETICS is removed from walls by machine technique.
5. Load bearing structures (skeleton or wall structure), which are mostly from the concrete or masonry, are demolished by machine technique.

6. Foundation structures, which are mostly from the concrete, is demolished by machine technique. The concrete from this structure is usually strongly contaminated by soil, with required sophisticated recycling technology.

3.5 Potential use for recycled materials

3.5.1 Concrete, masonry and ceramics

The potential use of recycled concrete, masonry and ceramics is related to their original use in structures and the quality of demolition and recycling process. There are possibilities to reuse or recycle these materials for new construction products, but there are some limitations and barriers in the utilization.

The original use of waste concrete originating from buildings or transportation structures influences the possible quality of utilization (see Table 1). The main barriers are high availability and low cost of natural resources, uncertainty of the quality of the recycled material and its influence on the properties of new products.

Table 1: The waste concrete – main risks to reuse or recycling and its possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Concrete from foundation structures and floors	Unwanted impurities, soil content	Backfilling Landscaping
Reinforced concrete from structural elements from buildings or transportation structures	The quality and properties of recycled aggregate Limitations of the utilization are defined by standards The possibility of unwanted impurities	Gravel replacement (foundation structures, interior structures) [39,49,165] Sand replacement [25,75] Cement replacement [166,167] Mineral admixture
Concrete sludge	Separation of materials (aggregate, water, cement slurry)	Aggregate replacement

Waste masonry originating from buildings shall contain only red bricks, ceramic blocks and mortars. However, it is usually contaminated by other materials such as ceramic, glass, plastic, wood etc. which limits possibilities of further use (Table 2). The main barriers to their reuse and recycling are high availability and low cost of natural resources, uncertainty of the quality of recycled material and its influence on the properties of new products.

Table 2: The waste masonry and ceramics – main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Red bricks	Difficult demolition process	Reuse as a brick
Crushed bricks	Worse properties than natural materials The use is not allowed by standards	Gravel replacement (precast wall block) [110,119] Sand replacement [110,120]
Milled bricks	Difficult separation during the demolition process	Clay (e.g. for courts)

Specification	The main risks to reuse and recycling	Possibilities of utilization
Mixed masonry waste	Contamination by unwanted impurities due to low-quality demolition and recycling process (paper, plastics, wood, glass, etc.) The use is not allowed by standards Worse properties than natural materials	Backfilling Landscaping Gravel replacement (precast wall block) [168,169] Sand replacement [170]
Brick and ceramic powder	Contamination by unwanted impurities due to low-quality demolition and recycling process (paper, plastics, wood, glass, etc.)	Cement replacement [171,172] Mineral admixture

3.5.2 Metals

Metals have a high potential of recycling due to high prices of metal waste. Metals are separated from construction and demolition waste and are collected in special centers and further used as raw material for the production of new metal elements (Table 3). The recycling rate of metals is almost 100%.

Table 3: The waste metals – main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Structural elements	Contamination by unwanted impurities due tolow-quality demolition and recycling process	Metal elements
Steel reinforcement	Insufficient separation from concrete	
Aluminum profiles	Contamination by unwanted impurities due to low-quality demolition and recycling process	Aluminum profiles

3.5.3 Bituminous mixtures, coal tar and tarred products

The possibilities of the utilization recycled asphalt are due to their original use and the quality of the recycling process. Options for recycling are in Table 4. It has to be guaranteed that the reclaimed asphalt is free of contamination for its recovery or recycling as a construction material.

Table 4: The waste bituminous mixtures, coal tar and tarred products – main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Aggregates for unbound and hydraulically bound materials	Contamination by fuels and oils	Civil engineering work and road construction
Bituminous mixtures	Contamination by fuels and oils	Reclaimed asphalt

3.5.4 Wood, glass and plastics

The potential use of recycled wood, glass and plastics depends on their original use in structure and the quality of dismantling process. Options for reuse and recycling together with limitations and barriers in Table 5.

The waste wood from timber structures can be contaminated by chemicals for protection of wood against biological degradation. This contamination influences future utilization. The wood panels federation define the amount of chemicals contained in wood. This wood is enabled to use as raw material for wood panels production [173].

The waste materials from windows can be separated during the demolition process and used as raw material for the production of new products. Materials coming from dismantling windows are flat glass, aluminum, plastics, wood and steel. The flat glass is clear and valuable material without impurities and with high potential of close-loop recycling without influence of the quality of new products. Plastic frames are produced from unplasticized polyvinyl chloride (PVC-U) which is after dismantling 100% recyclable. PVC from old windows can be recycled at least seven times without having any impact on the quality or weather resistance characteristics [174] or it can be added the new plastic window frames [175].

Table 5: Wood, glass and plastics – main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Wood (timber structures, timber frames)	Biological degradation The necessity of selective demolition process (deconstruction)	Reuse as a structural element Wood panels [173]
Flat glass (windows, envelopes)	The necessity of dismantling of windows components	Secondary raw material for the flat glass production [176]
Plastic frames (windows)	The necessity of dismantling of windows components	Secondary raw material for the plastic frames production [175]

3.5.5 Thermal and acoustic insulations

The potential use of recycled insulations is related to the type of insulation and its original use in structure (Table 6). It is easier to dismantle and recycle insulation on which are no additional layers such as plasters, adhesives, etc. Nowadays, the recycling of waste arising during production of insulations is efficient and is normally carried out. The recovery rate of this waste material is approximately 75% for glass insulation [177]. It is also possible and efficient to recycle waste insulation arising during the construction process of large buildings and complexes. However, it is not efficient to recycle insulations from demolition waste due to potential contamination of unwanted impurities and thus very demanding recycling.

Table 6: The waste insulations, main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Expanded polystyrene	Hazardous substances	Light-weight concrete
Mineral wool	The necessity of selective demolition process (deconstruction)	Reuse as a secondary raw material for the mineral wool production

3.5.6 Gypsum plasterboards

The potential use of recycled gypsum plasterboards is related to its original use in structure (Table 7). Nowadays, the recycling of waste arising during production of plasterboards is efficient and is normally used. It is also possible and efficient to recycle waste plasterboards arising during the construction process, which is not contaminated of unwanted impurities such as plasters, synthetic paints, etc. High motivation for recycling of gypsum plasterboards is complicated landfilling due to the production of the toxic gas H_2S during landfilling in inert landfills [178].

Table 7: The waste gypsum, main risks to reuse or recycling and their possible utilization.

Specification	The main risks to reuse and recycling	Possibilities of utilization
Gypsum (Plasterboards)	The necessity of selective demolition process (dismantling of plasterboards) High availability and low cost of raw material Contamination of unwanted materials (plasters, synthetic paints, etc.) Inefficient refundability	Plasterboards [179] Gypsum for cement production [180]

3.6 Construction products with recycled content

There are construction products and materials with recycled materials content which are normally used in the building industry. On one hand, some of these materials are possible to use in the same way as conventional materials. On the other hand, other materials have limitations of utilization which are defined in standards or have to be determined by producers. Examples of construction products with recycled materials content are in Table 8.

Table 8: Examples of construction products with recycled materials content.

Construction product	Possible utilization	Maximum content of recycled materials content
Recycled mixed aggregate	Backfilling Landscaping	Up to 100%
Recycled concrete aggregate	Aggregates for bituminous mixtures	The maximum content of recycled aggregate it is not defined by standards.

Construction product	Possible utilization	Maximum content of recycled materials content
	Aggregates for unbound and hydraulically bound materials	
Recycled aggregate concrete	Concretes of defined exposure classes	Up to 50% of coarse fraction of recycled concrete aggregate
Precast concrete elements	Precast concrete elements Same ways as conventional concrete	Up to 20% of recycled concrete aggregate with defined origin
Concrete blocks for walls with recycled (concrete, masonry or mixed) aggregate	Same ways as conventional products Limitations of utilization must be determined	The maximum content of recycled aggregate it is not defined by standards.
Metals	Same ways as conventional products	Up to 95%
Reclaimed Asphalt	Bituminous mixtures	Up to 100%
Wood panel	Same ways as conventional products	The maximum content of recycled aggregate it is not specified by standards.
Windows with PVC-U profiles	Same ways as conventional products	Up to 100% Approx. 30%
Mineral wool (stone)	Same ways as conventional products	Not specified amount of waste from production
Mineral wool (glass)	Same ways as conventional products	Up to 80% of waste glass Approx. 50% of waste glass
Expanded polystyrene	Same ways as conventional products	Not specified amount of waste from production
Gypsum plaster boards	Same ways as conventional products	Up to 10% of waste gypsum from production

3.7 Conclusion

The recovery rate of waste materials from construction and demolition waste depends on the quality of the demolition and recycling process. Waste materials which are dismantled during the demolition process have a high potential for utilization as secondary raw materials for production of new construction elements. Nevertheless, there are many materials which are contaminated by unwanted impurities or chemicals. This mostly leads to complicated and non-efficient recycling. For this reason, it is very important to optimize the demolition and recycling processes to obtain high quality secondary raw materials which will be technical, ecologically and economically comparable with primary raw materials.

4 A Comprehensive Study of the Use of Recycled Aggregate Concrete for Building Foundation Structures: Experimental and Environmental Evaluation

This chapter is based on the research of team Tereza Pavlů, Jan Pešta, Kristina Fořtová, Jakub Řepka under the leadership of Tereza Pavlů.

Author's contribution: conceptualization, methodology, investigation, resources, discussion of the results, writing (overall contribution 65%)

4.1 Introduction of the study

This study focuses on the comprehensive evaluation of the use of recycled aggregate concrete in concrete structures. The reported investigation is to find the impact of the recycling procedure, the aggregate replacement ratio, and the concrete strength class on the properties of concrete and consequently on the environment to find the optimal way to recycle concrete waste. In this investigation, two types of recycled concrete aggregate prepared by different production processes are used as aggregate for concrete. Furthermore, four groups of concrete with different amounts of cement, water-to-cement ratio, and replacement ratio were manufactured and their suitability for foundation structural elements was evaluated. The elements were designed to take into account the properties of the concrete from which were proposed due to the variability of properties of recycled aggregate concrete. This was approached due to the comparability of single variants using the LCA method. Finally, the environmental impact of each solution was evaluated, discussed, and compared with each other and also with previous studies.

4.2 Materials and methods

4.2.1 Materials

<u>Recycled concrete aggregate</u>

Generally, the quality of RA is influenced by the demolition process, used recycling technique such as separation process used crushing method, and number of crushing stages, properties of parent concrete. These aspects influence the amount of unwanted impurities in the RCA such as soil, dust, clay, the amount of cement mortar contained in the RCA, and finally the number of cracks that developed by crushing. According to the previous studies, higher water absorption and lower density of RA have been identified. Higher water absorption influences the effective water-cement ratio and has a negative impact on the workability of the concrete mix. For this reason, the determination of the properties of recycled aggregate is necessary before its use for concrete. In the previous studies, the water absorption of coarse RA from waste concrete ranges between 0.5% and 14.75%, and the dry density of coarse RA ranges from 1900 to 2700 kg/m^3 [109]. The dry densities of fRCA have been between 1630 and 2560 kg/m^3 and WA vary between 2.38% and 19.3% [25,76,81,137,181–186]. Furthermore, the use of fRCA is mainly related to doubts due to the finest content, which influences the effective water-to-cement ratio and properties of fresh and hardened concrete. Furthermore, if the basic recycling process is used, it could contain contaminants such as soil, dust, and clay. It was found [187] that RCA containing clay obtained the worse properties of concrete. The clay covers the particles of RA and make a barrier between RCA and new cement paste. Moreover, the mixing water is absorbed by clay, so it is necessary to increase the water-cement ratio to achieve the same workability. This may be eliminated by the multi-stage recycling process.

In this study, the RA was derived from waste concrete and was prepared from demolition waste in a recycling centre in the Czech Republic. Two different recycling processes were used to prepare RA: Recycled aggregate type 1 (RA 1) was prepared by a one-stage crushing process and recycled aggregate type 2 (RA 2) was prepared by a multi-stage crushing process. In both, the reinforced concrete is pre-crushed by the hydraulic shears and afterwards, the steel reinforcement is separated by a magnetic separator. All crushing stages were performed by the jaw crusher which is part of a mobile recycling plant powered by diesel. In the first stage, the crushing of the concrete fragments was carried out in fractions of 0/4, 4/8, 8/16 and 16/128 mm. In the second step, the fraction 16/128 mm is crushed again and sieved to fractions 0/4, 4/8 and 8/16 mm (see Figure 8). RA 1, which was carried out during the one-stage recycling process, contains the amount of unwanted impurities such as soil and dust. RA 2 performs a two-stage crushing process that contains only crushed concrete due to the separation of unwanted impurities during the first stage of recycling. Due to properties and composition, RA can be classified for instance onto class A according to the Czech European standard [70]. The results of the RA properties correspond to the results of previous studies. The properties of manufactured RA are summarised in Table 9.

Table 9. Physical properties of used aggregates.

Types of recycled aggregate	Grading (mm)	Content of finest particles	Oven-dried particle density		Water absorption capacity		Saturation level
		f (%)	ϱRD (kg/m^3)	σ	WA24 (%)	σ	(%)
Natural aggregate (NA)	0/4	0.3	2570	81	1.0	0.0	0.0
	4/8	0.3	2530	12	1.7	0.3	0.0
	8/16	0.4	2540	12	1.9	0.2	0.0
Recycled concrete aggregate (RA1)	0/4	3.6	2220	80	6.9	0.5	2.5
	4/8	0.3	2380	320	7.0	0.2	4.5
	8/16	0.0	2420	150	9.0	0.4	4.5
Recycled concrete aggregate (RA2)	0/4	1.0	2430	60	3.6	0.8	1.6
	4/8	0.3	2420	150	7.0	0.3	2.5
	8/16	0.1	2420	320	6.0	0.3	3.7

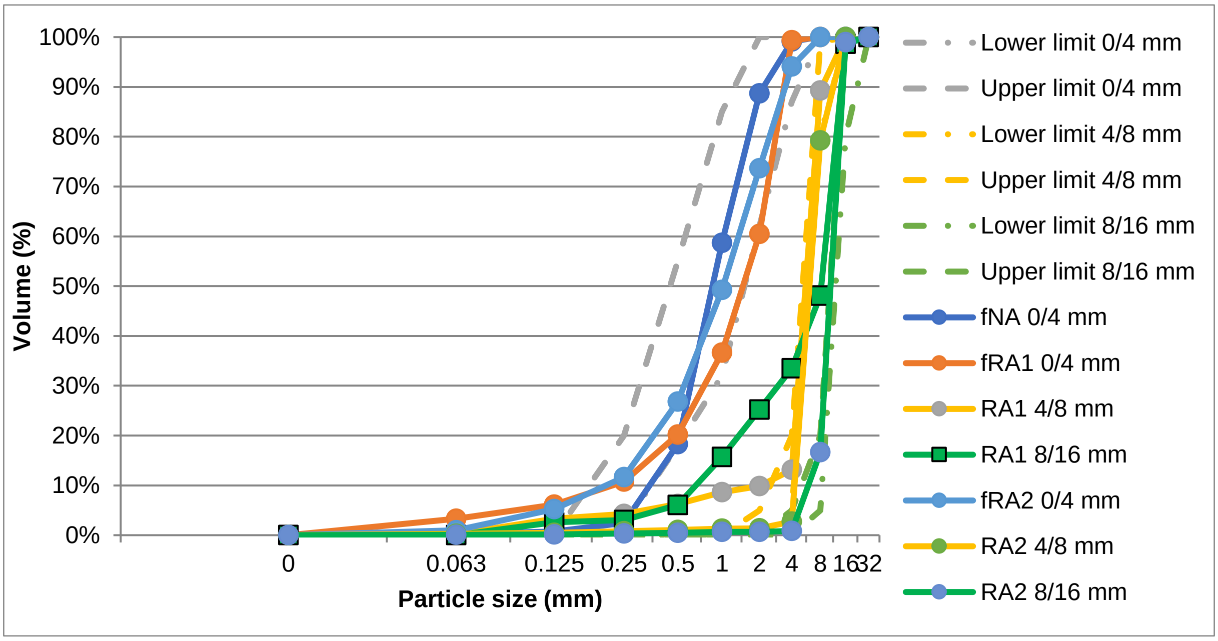


Figure 7 The sieving curves of recycled aggregate from waste concrete

The result of sieving curves shows that the RA1 manufactured by the one-stage crushing process did not meet the requirements of lower and upper limits defined in EN 12620, due to the high fines content on all fractions of RA1. On the contrary, the RA2 manufacturing through a two-stage crushing process was kept within limits. The sieving curves were used for the design of concrete mixtures. For this reason, the high amount of fine particles in RA1 was taken into account for the mixture design.

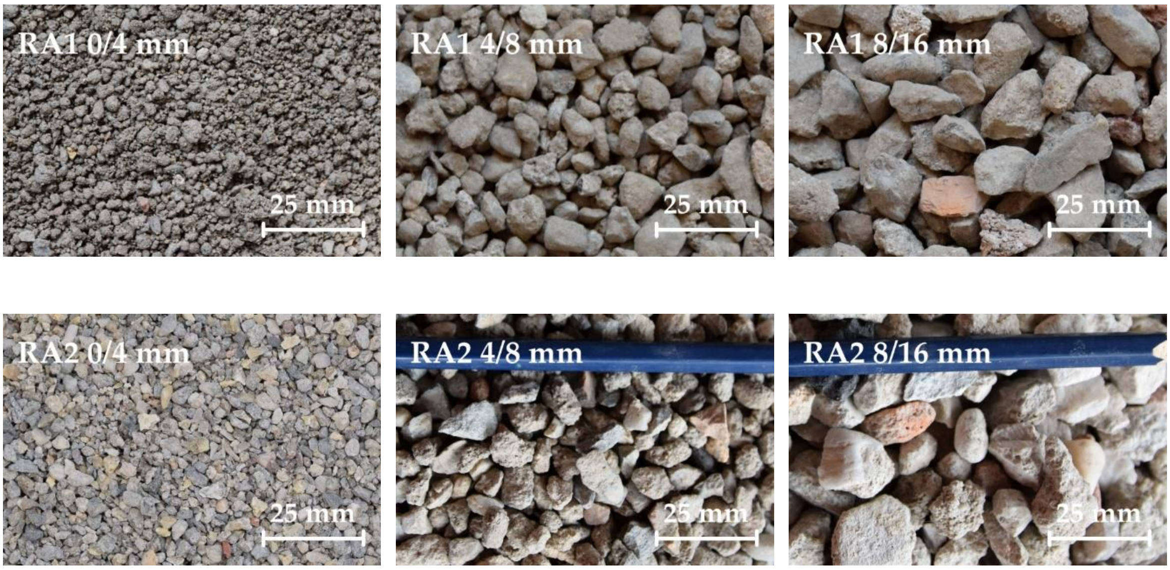


Figure 8 The recycled aggregate from waste concrete

Concrete mixtures

The RAC mixtures and NAC mixtures were designed for comparison to optimize the use of RA for the same structural use. One type of NA, different types of RA (fRA1, RA1, fRA2, RA2) were used in various replacement ratios. The mixtures are considered with increasing grade where the lowest is labelled I and contains 240 kg/m^3 of CEM I 42.5 R, and an effective water-to-cement ratio of 1.0; mixtures labelled II contain 260 kg/m^3 of CEM I 42.5 R, and an effective water-to-cement ratio of 0.65. mixtures labelled III contain 300 kg/m^3 of CEM I 42.5 R, an effective water-to-cement ratio of 0.55, and mixtures labelled IV contain 320 kg/m^3 of CEM I 42.5 R, and an effective water-to-cement ratio of 0.50 is considered as the highest-grade concrete. The replacement ratio of the coarse fraction was 30% (C30), 50% (C50) and 100% (C100), the full or partial replacement of natural sand by fRA is labelled by F. The considered exposition classes were X0 and XC1 according to the Czech European Standard [70]. The mixtures were optimized using the Bolomey particle size distribution curve. The mixing procedure used in this study was similar to the two-stage mixing approach performed by Tam [38]. In the first stage, the RA was inserted into a part of the water (the water estimated to be absorbed) and mixed for a period of 10 min, and consequently, the remaining constituents were placed. Additional water was calculated according to the water absorption capacity of fRA and RA and the current levels of aggregate saturation before mixing. The composition of the concrete mixtures per cubic meter is shown in Table 10.

4.2.1 Concrete properties evaluation methodology

The basic physical properties of concretes with various mix proportions of NA and RA were tested in the laboratory. Density and water absorption by immersion were examined. The mechanical properties of were tested on Controls MCC8 50-C8422/M according to the following standards: compressive strength – EN 12390-3 (2003), flexural strength EN 12390-5 (2009); static modulus of elasticity EN 12390-13 (2014); dynamic modulus of elasticity EN 12504-4 (2005) are performed to obtain these target values. For each concrete mix, three samples are tested.

The water absorption capacity by immersion, which describes the behaviour of the material especially in terms of open pore structure, was obtained in a cubic specimen 100 × 100 × 100 mm^3. The samples were immersed in a water chamber and, after stabilizing the weight, dried in an oven at 105 ± 2 ° C as long as their weight stabilized throughout. The capillary water absorption of concrete specimen of size 100 × 100 × 100 mm^3 with time was determined by conditioning the samples at 105°C in oven until their weight stabilization. The stabilized samples were placed on a support device by exposing one of the surfaces to water. The changes in mass of the samples were observed at 0, 1, 10, 30, 60 minutes, 2, 4, 24, 36, 72 hours. Measurement is carried out for 72 hours or until the weight stabilizes. The slope of the line obtained by plotting absorption against the square root of time gives the sorptivity of the concrete according to ASTM C1585-20.

Table 10 Concrete mixtures of NAC and RAC, per cubic meter

	CEM (kg/m³)	WATER (kg/m³)	NA (0/4) (kg/m³)	NA (4/8) (kg/m³)	NA (8/16) (kg/m³)	RCA (0/4) (kg/m³)	RCA (4/8) (kg/m³)	RCA (8/16) (kg/m³)	W/C (-)	EFF. W/C (-)	RR (%)
NAC I	240	240	755	530	554	0	0	0	1.00	1.00	0
RAC I C100 RA1	240	250	440	0	0	0	247	1102	1.04	1.00	75
RAC I C100 RA2	240	248	0	0	0	0	133	1060	1.03	1.00	100
RAC I C100F RA1	240	282	608	0	0	471	522	526	1.18	1.00	63
RAC I C100F RA2	240	271	248	0	0	411	346	553	1.13	1.00	84
NAC II	260	169	736	533	570	0	0	0	0.65	0.65	0
RAC II C30 RA1	260	201	632	0	656	0	485	0	0.77	0.65	27
RAC II C30 RA2	260	184	632	0	656	0	485	0	0.71	0.65	27
RAC II C50 RA1	260	206	611	0	311	0	506	283	0.79	0.65	46
RAC II C50 RA2	260	206	611	0	311	0	506	283	0.79	0.65	46
RAC II C100 RA1	260	179	415	0	0	0	239	1134	0.69	0.65	77
RAC II C100 RA2	260	211	588	0	0	0	526	538	0.81	0.65	64
RAC II C100F RA1	260	177	0	0	0	444	132	1094	0.68	0.65	100
RAC II C100F RA2	260	200	221	0	0	418	346	567	0.77	0.65	86
NAC III	300	165	700	538	601	0	0	0	0.55	0.55	0
RAC III C30 RA1	300	200	615	0	674	0	485	615	0.67	0.55	55
RAC III C30 RA2	300	183	615	0	674	0	485	615	0.65	0.55	55
RAC III C100 RA1	300	175	364	0	0	0	225	1198	0.58	0.55	82
RAC III C100 RA2	300	208	549	0	0	0	533	564	0.69	0.55	75
RAC III C100F RA1	300	174	0	0	0	390	131	1163	0.69	0.55	100
RAC III C100F RA2	300	196	169	0	0	433	347	593	0.69	0.55	89
NAC IV	320	160	681	541	616	0	0	0	0.50	0.50	0
RAC IV C100 RA1	320	170	339	0	0	0	217	1230	0.53	0.50	81
RAC IV C100 RA2	320	204	529	0	0	0	537	577	0.64	0.50	68
RAC IV C100F RA1	320	169	0	0	0	363	130	1198	0.53	0.50	100

	CEM (kg/m³)	WATER (kg/m³)	NA (0/4) (kg/m³)	NA (4/8) (kg/m³)	NA (8/16) (kg/m³)	RCA (0/4) (kg/m³)	RCA (4/8) (kg/m³)	RCA (8/16) (kg/m³)	W/C (-)	EFF. W/C (-)	RR (%)
RAC IV C100F RA2	320	191	143	0	0	440	348	606	0.60	0.50	91

Table 11 Properties of concrete mixtures and foundation elements with NAC and RAC

Type of concrete	Density	Water abs. by immersion	Capillary water abs.	Compressive str.	Flexural str.	Static elastic modulus	Strength class acc EN 1992-1-1	Flexural str. acc EN 1992-1-1	Volume of element
	(kg/m³)	(%)	(kg/m²)	(MPa)	(MPa)	(GPa)	(-)	(MPa)	(m³)
NAC I	2199	7.6	14.440	15.0	4.5	22.7	C8/10	-	-
RAC I C100 RA 1	1864	16.9	26.267	8.6	2.3	9.8	-	-	-
RAC I C100 RA 2	1949	15.2	19.393	11.0	2.5	12.2	C8/10	-	-
RAC I C100 F RA 1	1777	20.5	30.657	6.7	2.1	8.1	-	-	-
RAC I C100 F RA 2	1983	16.1	13.133	11.8	3	13.6	C8/10	-	-
NAC II	2284	5.5	5.967	37.8	5.6	30.1	C25/30	1.8	3.96
RAC II C30 RA 1	2143	7.6	5.760	21.9	4.1	23.6	C12/15	1.1	5.06
RAC II C30 RA 2	2199	5.6	5.433	32.4	5.6	28.9	C25/30	1.8	3.96
RAC II C50 RA 1	2023	13.4	5.763	22.1	3.8	18	C16/20	1.3	4.62
RAC II C50 RA 2	2168	6.1	6.500	33.5	5	25.4	C25/30	1.8	3.96
RAC II C100 RA 1	1977	15	15.593	15.2	3.6	14.2	C8/10	-	-
RAC II C100 RA 2	2054	11.8	8.413	22.3	3.3	-	C16/20	1.3	4.62
RAC II C100 F RA 1	1881	18.3	20.947	13.6	3.2	11.9	C8/10	-	-
RAC II C100 F RA 2	2100	12.5	3.733	27.4	3.9	21.6	C20/25	1.5	4.4
NAC III	2277	5.4	4.653	46.3	7.3	33.2	C30/37	2.0	3.74
RAC III C30 RA 1	2141	9.4	-	24.9	4.7	22.7	C16/20	1.3	4.62
RAC III C30 RA 2	2200	6.7	5.067	32.4	5.4	28.5	C25/30	1.8	3.96
RAC III C100 RA 1	2006	14.3	12.533	21.9	4.2	13.8	C12/15	1.3	5.06
RAC III C100 RA 2	2109	11	4.867	32.0	4.0	21.1	C25/30	1.8	3.96

Type of concrete	Density	Water abs. by immersion	Capillary water abs.	Compressive str.	Flexural str.	Static elastic modulus	Strength class acc EN 1992-1-1	Flexural str. acc EN 1992-1-1	Volume of element
	(kg/m^3)	(%)	(kg/m^2)	(MPa)	(MPa)	(GPa)	(-)	(MPa)	(m^3)
RAC III C100 F RA 1	1903	17.6	18.427	16.8	3.5	-	C12/15	1.1	5.06
RAC III C100 F RA 2	2104	12.3	3.167	32.4	4.6	22.6	C20/25	1.5	4.4
NAC IV	2317	4.8	3.320	56.5	8.2	35.7	C35/45	2.2	3.52
RAC IV C100 RA 1	2005	13.9	7.533	23.6	4.5	14.5	C16/20	1.3	4.62
RAC IV C100 RA 2	2127	10.6	3.627	30.5	3.6	23.5	C25/30	1.8	3,96
RAC IV C100 F RA 1	1933	17.6	9.567	18.7	3.6	12.9	C12/15	1.1	5.06
RAC IV C100 F RA 2	2106	12.1	3.267	35.4	5.3	23.5	C25/30	1.8	3.96

- means that mixture cannot be used for the considered construction element

4.3 *Methods*

Due to the suitable characteristics of concrete, it is the most widely used material for foundation structures. Furthermore, the foundation structures usually consume a large volume of materials, because it is necessary to carry the load from building to the subsoil. Given these facts, the foundation structures have been one of the structures that represented the highest environmental impact in almost every impact category analysed by LCA [188–190].

4.3.1 Foundation structural element

Based on the properties of the mixtures, the foundation structural elements were designed to carry an equal load under the same geological conditions and had the same effective loading area [m^2]. The element is designed from plain concrete without reinforcement. The elements made of concretes were designed to maintain the same utility properties which led to a greater element height. It followed that for the same utility properties, the structural element with the lower strength class had a larger volume, which means that a larger amount of concrete must be used to obtain the same utility properties. The volume of concrete elements for the foundations is shown in Table 11. These volumes were used as reference flows for environmental assessment.

The height of the foundation structure is design by following equation:

$$h \geq \frac{a}{0.85}\sqrt{\frac{3\sigma}{f_{ctd}}}$$

where h is height of the foundation structure; a is ½ width of the foundation structure; 0,85 is coefficient of shear, σ is stress in the foundation joint; and f_{ctd} is flexural strength of concrete according to the target strength class,

4.3.2 Environmental assessment

The environmental assessment of RAC for structural use and its comparison with NAC have been published [42,44,191,49,192,193,79,41,194,43,195,62,196]. To compare the environmental impact of several new concrete mixtures with recycled aggregates, a holistic approach should be used considering a whole product system. Therefore, LCA was selected as the most suitable method for this purpose, similar to the case of concrete structural elements [197]. This method was performed following the ISO 14040:2006 [198]. According to these requirements, LCA consists of four main parts: the definition of the goal and scope, LCI, LCIA and life cycle interpretation [199].

Goal and scope definition, functional unit and system boundaries

The primary goal of this study was to determine the concrete mixture with the lowest environmental impact in the comparison, where the mixtures are used for the same function in the building of foundation structures. The secondary goal is to describe the influence of the type of recycled aggregate on the environmental impact of the concrete mixture, or concrete strength class classification, respectively.

In this study, compared foundation structures were designed to have the same function. Therefore, the compared functional unit was one foundation structural element with an equal load and an equal effective loading area. As compensation for the lower strength class, the higher element heigh was designed and a larger volume of concrete had to be used for the same utility properties of the structure. The referential flows of the concrete mixtures that were needed to reach defined FU are different and are described as a calculated volume in Table 2. The system boundaries for each concrete mixture were considered cradle-to-grave, so include all life cycle phases production of materials, production of concrete and construction of foundation structure, deconstruction and (including transport on site), deconstruction and end of life (EoL) of the foundation element. The EoL of foundation structures includes deconstruction and transport to landfill as a typical type of removal for construction and demolition waste. The production of primary raw materials includes the excavation and production of RCA as secondary raw materials begins with the unloading of demolition and construction waste in a recycling plant. For the basic scenario, the distances for transport of resources and waste were assumed to be 50 km.

Two types of aggregates were considered: RA 1 from the one-stage recycling process and RA 2 from the two-stage crushing process. The first stage is the same for both types. The CDW is crushed and sieved. In addition, reinforcement steel bars are separated. Through this recycling process, three fractions are produced. Two of them are used for landscaping. The third is RA 1, which can be used as aggregate for concrete, or it can be crushed and sieved again. In this second stage further three fractions are produced and one of them is RA 2 aggregate. The two-stage crushing process helps with the separation of clay particles and therefore RA 2 type is more suitable for concrete.

Life cycle inventory (LCI)

Data for inventory analysis were performed using Gabi 9 software. Concrete production was conducted based on Fiala [200]. Specific data describing production of resources in the Czech republic were preferred but also generic data from GaBi 9 database were used [201]. Data describing the recycling process were provided by the Czech manufacturer of recycled aggregate.

Life cycle impact assessment, normalization and weighing

The environmental assessment was performed according to the Environmental footprint (EF), version 3.0 characterization method. To compare the overall impact of each foundation structure, the results of the impact indicators were normalized and weighted. Normalized results were calculated by relating the results of environmental indicators to global impact. In this step, the results are multiplied by global factors for each category. In this case, normalization was carried out with factors according to EF 3.0 personal equivalents included in Gabi software. The weighing emphasizes a specific value of each category. In this step, the results after normalization are multiplied by factors that are based on the opinion of the scientific community. In this study, the weighing was performed using weighing factors according to EF 3.0, which were also included in Gabi software.

4.4 Results and Discussion

4.4.1 Potential of concrete mixtures for foundation structure element

The results of the basic mechanical and physical properties are shown in Table 11. The target concrete strength class was examined due to the characteristic compressive cube strength according to the Eurocode and ISO 12491. This method of determining the class of concrete is chosen because of the consideration of the number of samples to eliminate their influence. The target strength classes for NAC mixtures were C25/30 (NAC I), C25/30 (NAC II), C30/37 (NAC III), and C35/45 (NAC IV). The target concrete strength classes for RAC mixtures ranged from C8/10 to C25/30 depending on type of used aggregate, replacement ratio of coarse and fine aggregate and target strength class determined by the amount of cement and water-to-cement ratio. The flexural strength used for structural design was considered according to the Eurocode based on the target strength class. The flexural strength verified by experimental measurements was higher than flexural strength used for the calculation in all cases.

According to the European standard EN 206+A2 the lower strength class which is possible used for foundation structures is C12/15 (with characteristic cube compressive strength 15 MPa) and usually the strength class C16/20 (with characteristic cube compressive strength 20 MPa) is used for foundation structures made of plain concrete. Higher strength classes are mostly used for reinforced concrete foundation structures. However, to obtain the clearest possible comparison of structural use, only one type of structural element needs to be chosen. For this reason, it was decided to use the plain concrete foundation structure for environmental comparison even if concretes higher than strength class C20/25 would not be used for this application.

4.4.2 Properties of recycled aggregate concrete

Generally, it has been verified many times that the properties of RAC depend on the quality of RA, especially the water absorption and content of contaminants, the replacement ratio of aggregate, and the concrete grades [24]. In the previous studies, it has been observed that the compressive strength of concrete decreases more intensively for higher concrete grades from the strength class C45/55, where failure planes have occurred through aggregate particles, which shows aggregate as a limiting factor of strength. On the contrary, for the concrete strength class C30/37, failure planes have been observed around the aggregate, so in this case the limiting factor is ITZ [202]. Due to this fact, it could be assumed that, for higher strength classes, the use of RCA reduces compressive strength more expressively and with increasing replacement ratio the influence is growing. On the other hand, in the case of low-strength classes of concrete, where the ITZ is more limiting, the increased replacement ratio should not be essential [24].

Furthermore, it has been observed that the equivalent mortar volume (EMV), which is the total mortar volume considered as the sum of residual and fresh mortar volumes in RCA-containing concrete, could decline the properties, due to the large amount of ITZ. For this reason, the possibility to reduce the amount of cement in the mixture and improve the mechanical properties and durability of concrete was improved [35]. This could also be related to the previous findings that lower strength classes have a lower amount of mortar, which is the probable reason why the decline in properties is lower for the lower strength classes of concrete. Furthermore, as mentioned before, the content of clay in RCA influences the workability of fresh concrete, due to its ability to absorb water and reduce the bond between the RCA and the new cement mortar [187]. Finally, replacement of natural sand by fRCA was also many times verified. The decline in mechanical properties of concretes containing fRCA in a similar way to coarse RCA is related to old cement mortar which leads to higher porosity, consequently higher water absorption, and more. Furthermore, for the finest fraction (0-0.063) of fRCA, which is highly represented in fRCA, a higher specific surface area was found [81].

The results of the properties examined of concrete correspond with the results of previous studies. The results of physical and mechanical properties showed the dependence on the quality of RA, replacement ratio, and the grade considered concrete. The results of the physical and mechanical properties of RCA are discussed in the following chapters.

Physical properties of concrete

It was reviewed [24,43], that the density of RAC decreases and the WA of RCA increases with the replacement of the aggregate in the concrete mixture, due to the higher porosity of RCA. The results of this case study show a decrease in dry density for all tested RAC mixtures tested. The highest decrease was observed for low-grade mixtures with full replacement of fine and coarse aggregate by RA1, where the decrease was up to 25% in comparison with the control mix corresponding with concrete grade. In contrast, the lowest decline was found for mixtures with a replacement rate of 30%. This confirms the results of previous studies, that the density of RAC depends on the replacement rate and quality of the RCA. In the case of WA, the WA of RAC with full replacement of coarse RCA was reported to increase by up to 50% compared with the NAC [43]. However, in this case, study the WA increases many times more. The highest increase of WA was observed for mixtures with full replacement of fine and coarse aggregate by RA1, where the maximal increase is 3.3 times. On the contrary, a lower increase of shown for mixtures containing only 30% of RCA, where the maximal increase is 2%. Furthermore, no mixture with full replacement of aggregate was reached to increase WA only up to 50% as reported in previous studies. The results showed that the WA is dependent on the replacement ratio and quality of RCA and furthermore, the influence of concrete strength class could be observed. The influence of RCA substitution increases with increasing grade concretes (see Figure 9). The results of WA by capillarity show slightly different results compared to WA by immersion, where in the capillary WA decreases with increasing grade of concrete for NAC and RAC in general. Maximum increase, which is up to 4 times, of WA could be observed for mixtures with full replacement of aggregate by RA1, where in comparison concretes containing only coarse fraction of RA and concretes with fRA1 also the negative influence of fRA can be observed. On the contrary, in the case of RA2, the positive effect could be found with the use of fRA2. This could probably be caused with the filling the pores by fines in the concrete skeleton. In conclusion, it is necessary to mention that both of WA negatively influence the durability of concrete.

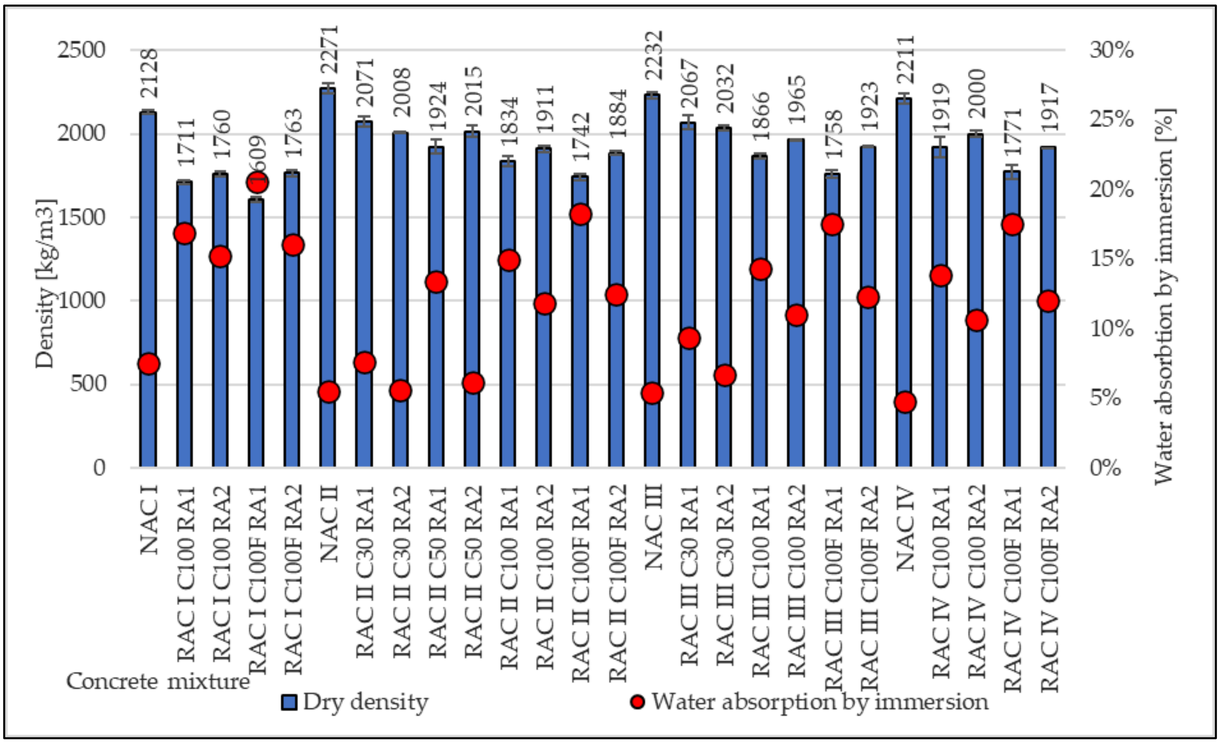


Figure 9 Density and water absorption of NAC and RAC

<u>Mechanical properties of concrete</u>

According to the previous studies [43], the compressive strength decreases up to 25%, flexural strength decreases up to 10% and modulus of elasticity which ranges up to 45% for concretes with full replacement ratio. However, the results of the strengths and modulus of elasticity for RAC mixtures did not correspond with this assumption.

The decline of compressive strength confirmed the results of previous studies that the decline is more appreciable for higher grade concretes. In this case study, the increasing decrease in compressive strength depends on the strength class of concrete strength is shown. From this point of view, the maximal decrease in compressive strength is shown for the RAC IV labelled RAC IV, with a decrease of 67%. On the contrary, the mixture with the same replacement ratio and aggregate type RA1 from mixtures labelled RAC I decreased "only" about 55%. Furthermore, the influence of the aggregate quality is shown. All mixtures manufactured by RA2 achieved better results in comparison with RA1. This shows the negative impact of soil, which could be contained in aggregate manufactured by the one-stage crushing technique. Additionally, when also fRA2 is used in the mixture the compressive strength increases compared to mixtures where only the coarse fraction of RA2 is used. This phenomenon could be caused by the filler effect of fRA, where the finest particles fill the pores and improve the structure of the mixture to be denser, reducing internal stresses, and early propagation of stress [46]. However, this phenomenon is essential for the quality of fRA, which must be composed only of crushed concrete without contaminants, as shown by the negative influence of fRA1. Finally, the influence of replacement rate was also confirmed by this study, in which concretes with only a 30% replacement ratio showed a lower decrease in compressive strength. However, in the case of a 50% replacement ratio, it could be observed that the replacement ratio and the quality of RA have a similar influence.

The result of flexural strength also shows a significant decline. However, in this case the decreasing trend related with growing grade of concrete was not observed. However, the influence of the aggregate quality, replacement rate and, moreover, the improvement by the use of high quality fRA can be seen. In the case of flexural strength, the angular shape and rough surface texture of fRA particles could lead to better interlocking between particles [46]. The highest decrease in flexural strength was measured for mixtures containing only RA1 (fine and coarse fraction), where the maximal decline was 56%. In conclusion, the results of the flexural strength, which was examined by experimental verification, were compared with the flexural strength listed in Eurocode for the corresponding concrete strength class. From this comparison, it was found that although the decline of flexural strength was significant, the examined flexural strength was still higher than in Eurocode (see Figure 12).

In this study, a similar decline in the modulus of elasticity compared to compressive strength was shown. This is slightly different results than is generally reported that the modulus of elasticity is a more affected concrete property [24]. However, the decrease in modulus of elasticity is essential for future use for all properties tested except of concrete with a 30% replacement rate for a coarse fraction where the decrease was only 4%. Similar to the results of compressive and flexural strength, the modulus of elasticity is negatively affected by the low-quality aggregate and substitution level of aggregate. The declines were not significantly influenced by the concrete grade, similar to the flexural strength. However, contrary to both strengths the positive influence of the high-quality fRA was not verified. This phenomenon corresponds with the results of previous studies dealing with replacing natural sand in concrete mixtures, where it has been reported many times that fRA negatively influences the modulus of elasticity for the low replacement ratios. On the contrary to compressive strength where the replacement ratio of up to 30% was defined as usable. For this reason, the use of concrete with fRA is not recommended for structural concretes such as beams [46].

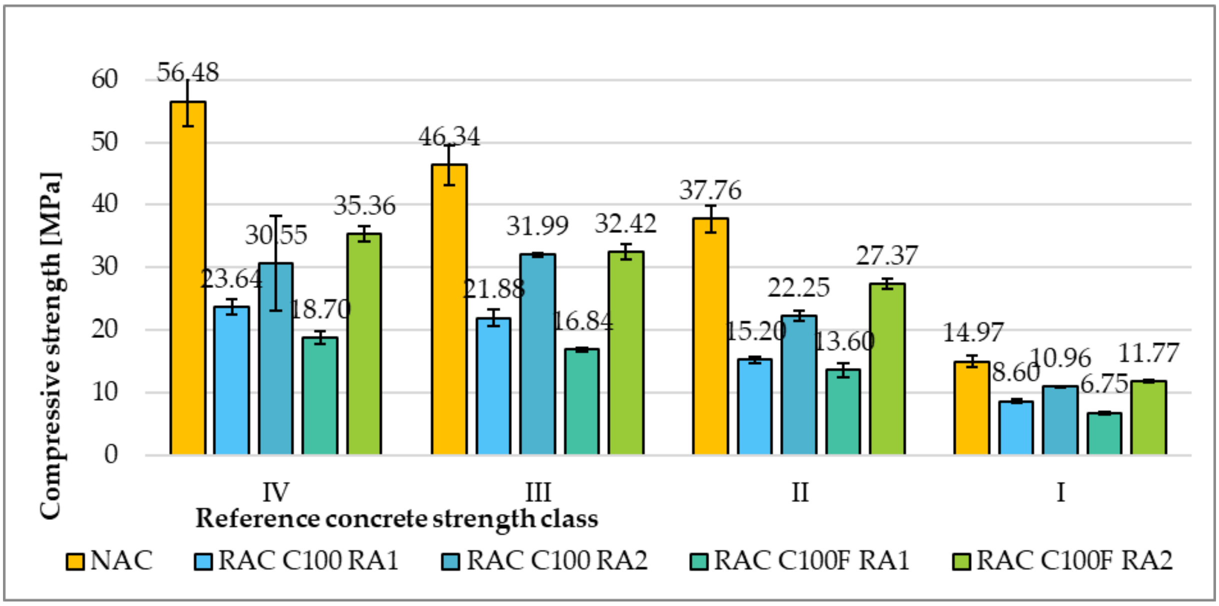


Figure 10 Compressive strength of NAC and RAC for mixtures with full replacement of coarse aggregate

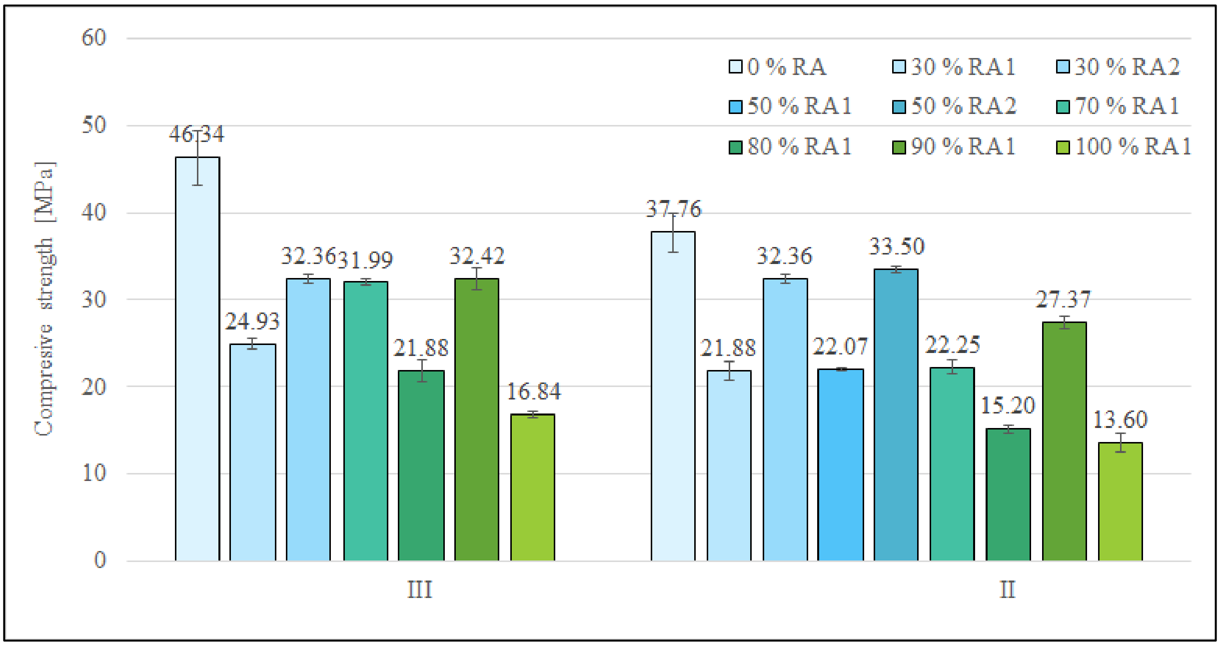


Figure 11 Compressive strength of NAC and RAC for mixtures with partial replacement of coarse aggregate

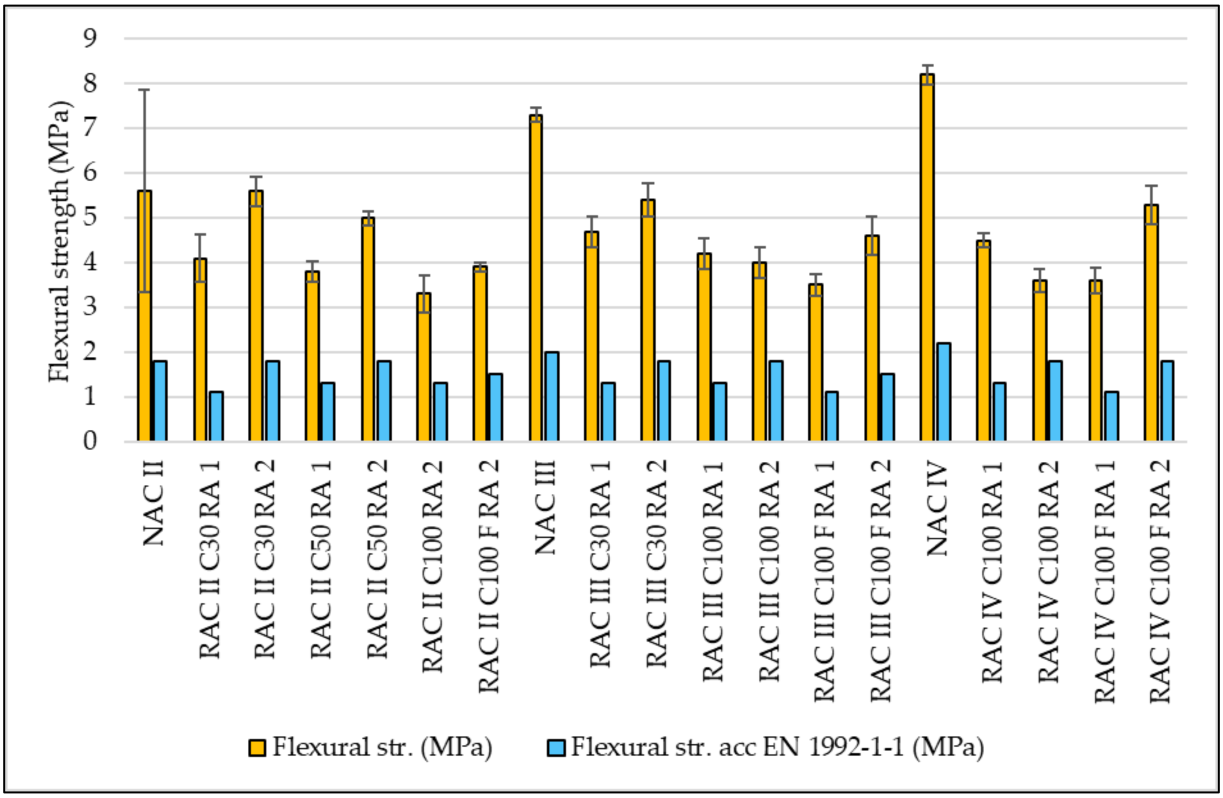


Figure 12 Examined flexural strength, and flexural strength of NAC and RAC used for mixtures for design foundation structural element

4.4.3 Life cycle assessment of foundation structure

Life cycle inventory

The LCI is the second stage of LCA, where the data for calculations of relevant inputs and outputs of the product system are collected. Inputs and outputs include the use of resources, emissions to air, water, soil, and waste generation associated with the system. In the case of water consumption, the higher consumer is cement production followed by landfilling of construction waste. During the recycling process, poorer quality recycled aggregate is also produced as a by-product, which is not suitable for concrete. However, this type of aggregate is suitable to use as a replacement for NA for backfilling or landscaping. For this reason, the excavation of primary resources is avoided and so water demand for this excavation is reduced. Therefore, the consumption of water is lower for foundation structures with recycled aggregates.

The demand for energy resources reflects the properties of the concrete when the concrete's higher strength classes are used in lower volume. For this reason, fewer materials need to be transported. The RA 2 concretes, due to their high quality, have a smaller volume than RA 1, therefore RA 2 concretes have a lower demand for crude oil for transport.

Similarly, the recycling process affects hard coal demand. Hard coal reduction is caused by recycling coal, which is avoided by steel scrap. The more construction and demolition waste is recycled, the more steel scrap is separated and recycled and so more demand for hard coal is avoided. A significant flow is the CDW, which is needed to produce enough aggregates to form a foundation structure. The production of 1 t of RA 2 processes more CDW than the production of 1 t of RA 1 type. **Figure 13** shows the amount of construction and demolition waste for each foundation structure as the main input into the production system. Unsurprisingly, an almost linear dependence of the mass of used recycled materials by the replacement ratio of aggregate in the concrete mixture is shown. Furthermore, the concrete mixtures in which RA 2 was used show higher use of recycled materials, due to the fact that more materials need to be recycled to produce high-quality RA.

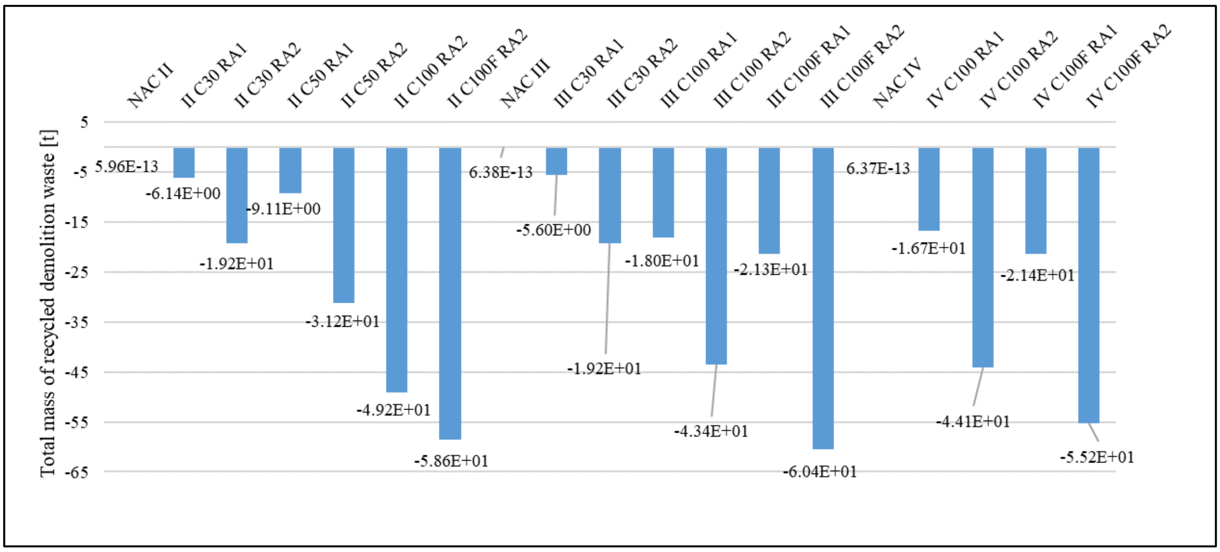


Figure 13 Demolition waste consumption for building concrete foundation element (t)

Contribution of recycled aggregate to impact on Climate Change

In previous studies, the environmental impact in the Climate Change category is mainly associated with production of cement. On the contrary, the production of recycled aggregate can beneficially affect the total impact of foundation element, as it is presented in Figure 14 In this figure, the contribution of RA and cement in Climate Change category is described and related to total results of each foundation element. The contribution of RA 1 is rather insignificant in comparison with RA 2. This is affected by the lower amount of processed CDW in the one-stage recycling process. On the other hand, a larger amount of CDW is consumed in the production of RA 2 as shown in Figure 13. The impact of recycling process of CDW is beneficial due to considering benefits of recycling of steel scrap from CDW and reuse of other fractions of RA as a replacement of primary aggregate. This phenomenon is also described in [4] (Appendix C).

The impact of the cement and aggregate was relatively related to the impacts of individual concrete. The results show the almost linear dependence on the replacement ratio of aggregate in concrete mixture separately for individual types of RA. Furthermore, the higher influence of cement is shown for concrete with higher quality RA (RA 2).

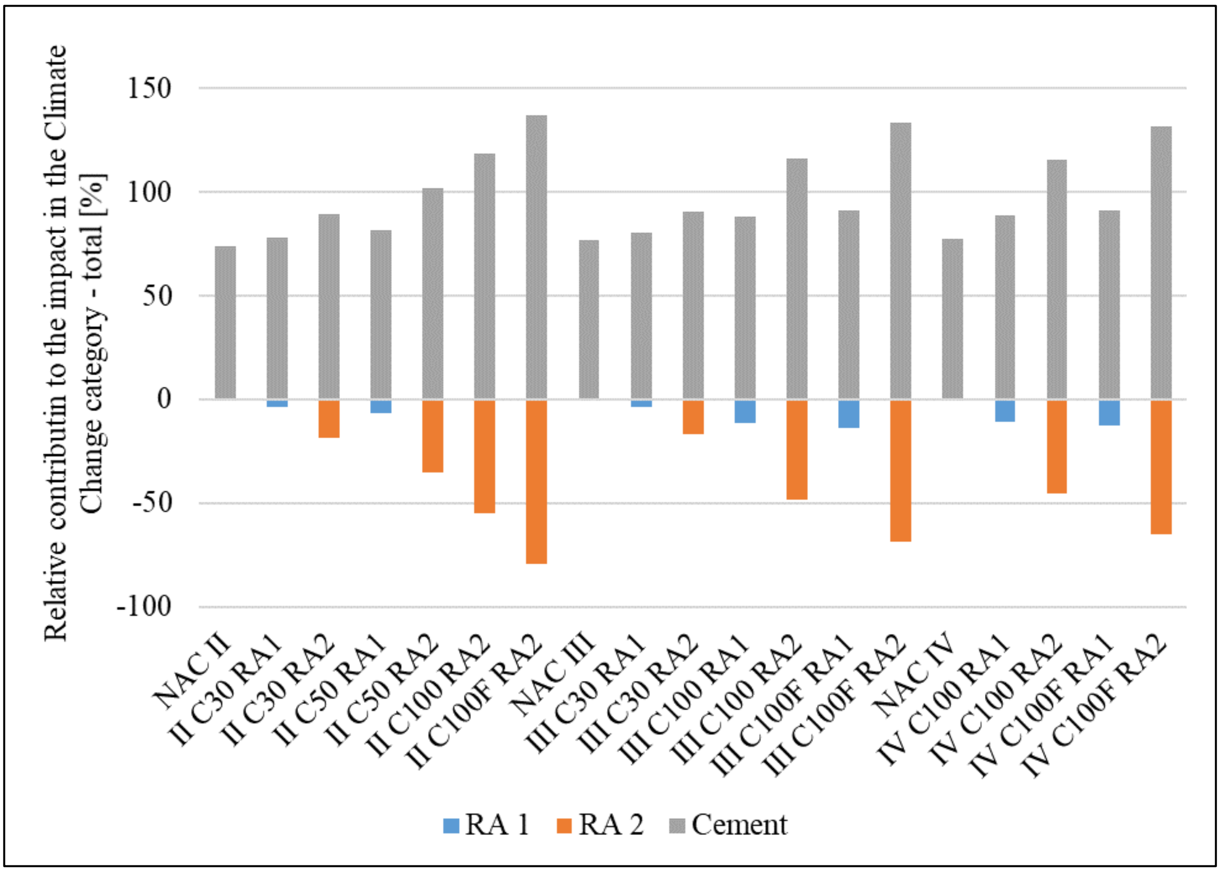


Figure 14 Summarized results of impact indicators after normalization and weighting (according to EF 3.0 personal equivalents), NAC II (50 km) is 100%

Beneficial impact of recycling process

The influence of benefits associated with aggregate and steel scrap recycling is presented in Figure 15. Both types of benefits are higher for mixtures containing a higher amount of RA. Additionally, the use of a two-stage crushing process, in which more CDW is consumed, leads to a more beneficial contribution in comparison with the production of RA 1. In the case of credits for steel recycling and credits for aggregate, the most beneficial impact was reached by foundation RAC III C100F RA 2. However, in the total results, the most beneficial impact was found for RAC II C100F RA2 where a lower amount of cement than in RAC III C100F RA 2 was used.

In conclusion, the result confirmed the results presented above, showing that the positive effect of replacing NA in concrete with RA is shown for concretes with a high replacement ratio [58]. Concrete with a replacement ratio of 30% showed a higher total impact than reference concretes for the lower quality aggregate and slightly lower total impact for the higher quality aggregate.

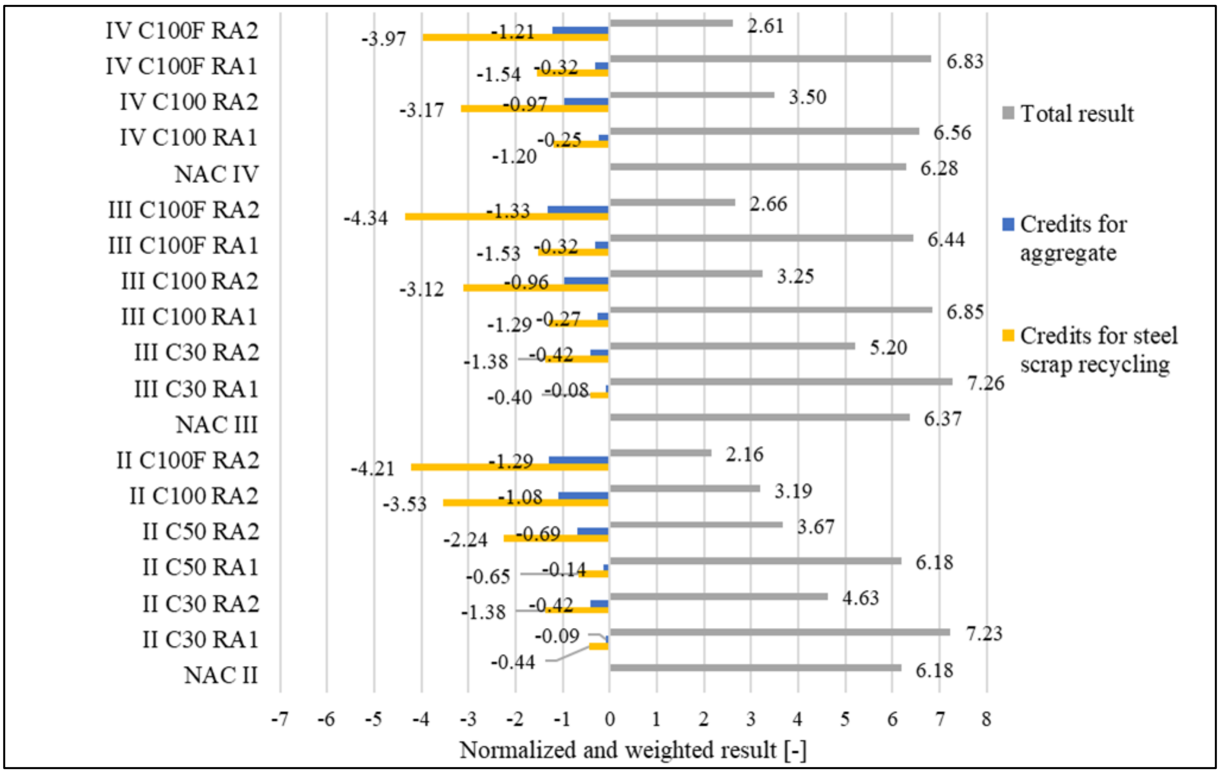


Figure 15 Normalized and weighted results associated with credits for use of aggregates and steel scrap recycling, normalization and weighing according to PEF 3.0 (person equivalents), total result represents the sum of all environmental benefits and burdens of foundation structures

Contribution of transport

As reported in previous studies, the transportation of materials is the process with the second highest impact from concrete production [18], due to the energy and emissions related to diesel production and consumption. Furthermore, concrete is a material with high mass by volume, so its transportation is costly. For these reasons, the use of recycled materials at the demolition site such as partial replacement of primary materials, leads to the reduction of environmental burdens. In the case of aggregate, the NA could be replaced by RA for backfilling and landscaping or the high-quality one as a partial replacement of aggregate in concrete.

The increase of the normalized and weighted impact related to the transportation and landfilling of unused materials are shown in **Figure 16**. The results show the clear benefit of utilization of the materials on the demolition site. The increase of the impact associated with the transportation and landfilling is dependent on the increasing amount of RA in concrete. Furthermore, the impact is greater for concretes containing lower-quality aggregate RA1.

The decrease of the normalized and weighted impact related to the transportation to a shorter distance is shown in **Figure 17**. The reference scenario is considered as a transport distance of 50 km, and the modified scenario is considered as a transport distance of 25 km. The results show a linear decrease for all evaluated concretes which is 8%.

These results also confirmed the lower impacts related to the use of higher quality RA in general.

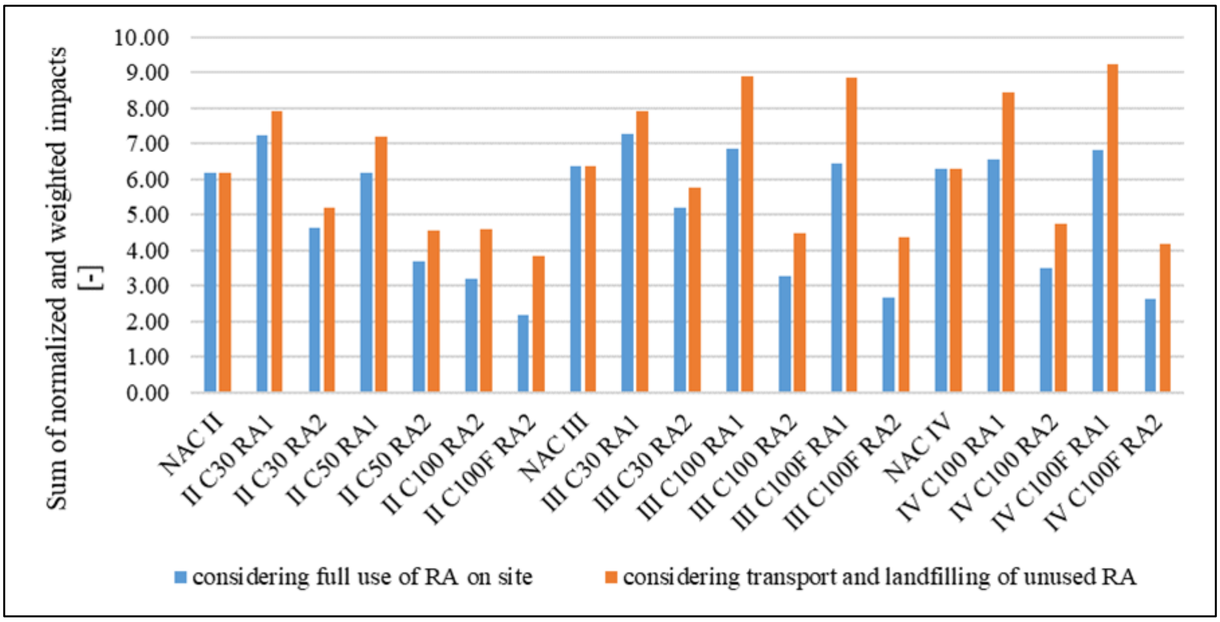


Figure 16 Summarized results of impact indicators after normalization and weighting for two scenarios considering full use of RA on the demolition site and transport and landfilling of unused RA

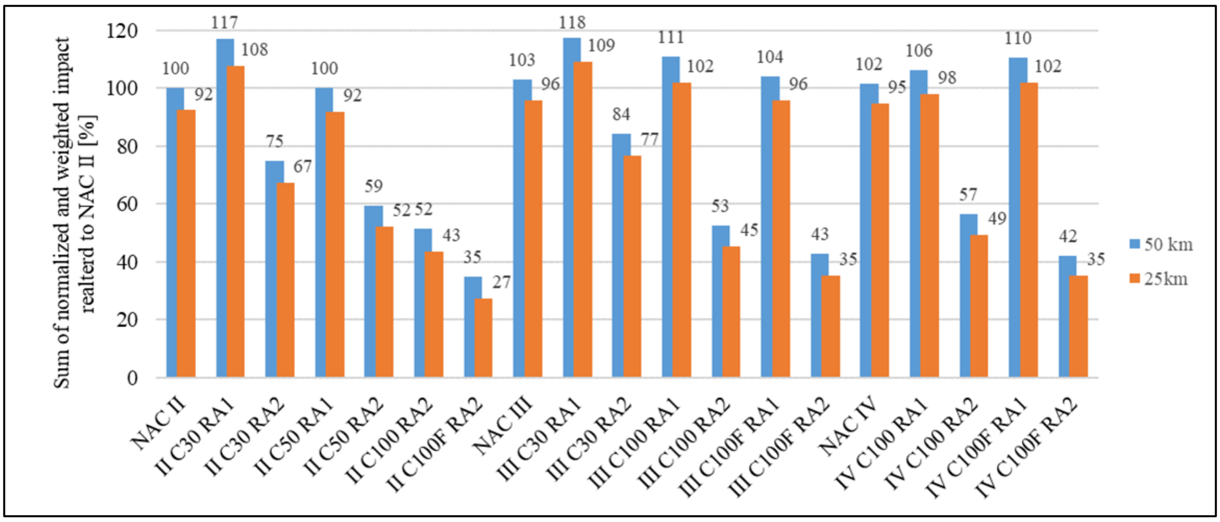


Figure 17 Summarized results of impact indicators after normalization and weighting for two scenarios considering distance 50 and 25 km (according to EF 3.0 personal equivalents), NAC II (50 km) is 100%

4.5 Conclusion of the study

This study focused on the comprehensive approach to comparing RAC from different points of view. The influence of the recycling procedure was investigated by different numbers of crushing processes. The effect of the concrete grade and the rate of replacement was also observed. Furthermore, the possibility of replacing natural sand with fRA was verified.

Finally, the environmental assessment of the concrete mixtures was performed through the designed foundation structural element.

From the presented results, the following conclusions could be written:

1. The recycling procedure and especially the number of crushing processes essentially influence the quality of RA. When the RA is manufactured by the two-stage crushing procedure the quality of RA is much higher than from the one-stage crushing procedure, in which a number of contaminants such as soil and clay remain. Furthermore, by using of a two-stage crushing procedure, the high-quality fRA is produced to improve the properties of concrete when it is used as a replacement for natural sand. Furthermore, the environmental impact of higher quality RA was evaluated as lower than that of lower quality RA.
2. The decrease of the density and increase of the water absorption by immersion and by capillarity shows higher differences in comparison with the control mixes that it is reported in previous studies. This could negatively affect the durability of concrete.
3. Only the compressive strength is significantly influenced by concrete grade, where it was confirmed the results of previous studies that the influence growing with increasing concrete strength class. However, the decline of compressive strength was higher than in previous studies and varied up to 64%, similarly with modulus of elasticity.
4. The decline of flexural strength was also observed; however, the measured values from experimental verification were still higher in comparison with the defined flexural strength in Eurocode. For this reason, the foundation structure could be designed from the stated values corresponding to the concrete strength class.
5. The LCA of foundation structures designed from the NAC and RAC, which meets the requirements on structural concrete, confirmed that the highest impact to the concrete has cement production followed by transportation. The negative impact of cement production can be reduced by replacing NA in concrete by high-quality RA.

In conclusion, the physical and mechanical properties of concrete with higher-quality aggregate reached better performance. Although, the two-stage crushing procedure is more complex procedure with higher energy consumption, the positive effect of the high-quality aggregate was confirmed in all studied categories. Furthermore, in these cases of the utilization recycled aggregate at demolition site, the higher-quality aggregate is possible to use as a partial or full replacement of aggregate for concrete – for foundation structural element for new building, for instance. Moreover, lower quality recycled aggregate can be used for backfilling and landscaping. The positive impact of recycling without transportation and landfilling has been confirmed.

5 Design of Performance Based Concrete Using Sand Reclaimed from Construction and Demolition Waste – Comparative Study of Czechia and India

This chapter is based on the research of team Tereza Pavlů, Kristina Fořtová, Namratha V Khanapur, Diana Mariaková, Bhavna Tripathi, Tarush Chandra and Petr Hájek with international cooperation with School of Civil and Chemical Engineering, Manipal University Jaipur, India; under the leadership of experimental part Tereza Pavlů.

Author’s contribution: conceptualization, methodology, investigation, resources, discussion of the results, writing (overall contribution 60%)

5.1 Introduction of the study

The main goal of this study is to evaluate possibilities to use a sand for the substitution in concrete in two different regions using the same research approach. As mentioned in previous studies, the influence of the recycling technology and properties of the parent concrete on fRA is essential for its future use. For these reasons, the basic material properties of fRA and fRAC were examined and compared to find differences in this investigation.

5.2 Recycling of CDW in the Czech Republic and India

In the case of the Czech Republic, the use of recycled aggregate from construction and demolition waste became increasingly desirable over the last few years. The main reason is the decreasing amount of available natural resources, which is mostly caused by mining closure which does not allow the opening of new or expansion of existing quarries, which is caused by an increasing price of natural aggregate, however secondary also due to the pressure to be more circular. Demolition and construction companies are increasingly approaching the sorting of individual waste, such as waste concrete and masonry, for on-site use, especially for landscaping. This approach is not ideal, but it is satisfactory in many respects, especially if landscaping is necessary on site. For this reason, the amount of mineral CDW (concrete, bricks, ceramics, etc.) reported as received in a landfill or in a recycling center is relatively small, 4.6 million tonnes per year (2020), which is approximately 450 kg per person, and year-on-year has a declining trend. This means that the amount of CDW reported in landfills and recycling centers decreases. On the contrary, the extraction of primary raw materials for the construction industry is still growing and is almost 71 million tons, which is 6,700 million kg per person per year (2020). For comparison, in 2015 it was 6,400 million kg. As can be seen in these statistics compiled annually by the Czech Statistical Office [19], even if we use the most recycled aggregates from waste, we cannot cover all the needs of construction aggregates. In the case of the use of concrete and masonry waste, we are around 4% of coverage, in the case of maximum use of unsorted waste (under the ideal assumption that they will be started to sort), it can cover around 7%. From the point of view of the requirements of the Czech standard, which corresponds with the EN standard, it is possible to partially replace the coarse fraction in concrete with a coarse fraction of RCA, containing more than 90% of the waste concrete and natural aggregate. The maximum replacement rate is 30% for selected classes of concrete, mostly without any environmental burdens. This corresponds to the many times published results of the worldwide investigation that the replacement of coarse fractions by up to 30% does not significantly influence the properties of concrete [24]. However, the use of a fine fraction of RCA or RMA in general is not allowed by a standard because of the problematic quality assurance and determination of water absorption. For all these reasons, it is becoming more and more important to optimize demolition and recycling technology to get as many quality materials as possible, which will stop landfilling, because such a price of raw material is not worth landfilling.

In India, the management and reuse of CDW is a prime concern. A study conducted by Building Material and Technology Promotion Council (BMTPC), New Delhi in the year 2018 indicates that the quantity of CDW in India varies from 12-15 to 25-30 million tonnes per year (BMTPC, 2018). The report mentions that the estimated quantity of CDW from new construction is approximately 40-60 kg/m2 of the built-up area and that from the demolition of constructed structures is around 300-500 kg/m2 of the built-up area. In order to tackle the problem of CDW recycling plants are set up in a few cities in India. There are four operational recycling plants in India [203], first operational large-scale CDW recycling facility was set up in Burari, New Delhi in 2009, followed by another plant in East Kidwai Nagar, New Delhi, and one in Ahmedabad, Gujarat. Most of the other cities have not set up CDW recycling facilities despite having CDW management rules issued by the Ministry of Environment, Forest and Climate Change published by the Central Pollution and Control Board [204] As per the guidelines, all construction projects and facilities that generate more than 20 tons of CDW in a day or 300 tons in a month are identified as bulk CDW generators and are required to implement a waste management plan. From the point of view of the requirements of the Indian standards with the latest revision of guidelines in 201Ithe use of RCA as coarse fraction has been permitted up to 50%, 25%, and 100%, respectively, for plain cement concrete, reinforced concrete, and lean concrete with compressive strength less than 15 MPa [205]. Similarly, the use of fRCA is allowed up to 25%, 20%, and 100%, respectively, for plain cement concrete, reinforced concrete with compressive strength less than 25 MPa, and lean concrete with compressive strength less than 15 MPa. On the contrary, the use of RA is not permitted either as coarse or as fine aggregate for the production of plain cement concrete and reinforced concrete. RA is allowed to be used as coarse aggregate in lean concrete (<15 MPa compressive strength 15 MPa) only.

5.3 Materials and Methods

In total, 13 concrete mixtures (7 in the Czech part and 6 in India part) were prepared and tested to verify the possible replacement of natural sand by fRA. Two concrete strength classes were chosen for comparison: the concrete class with compressive strength 20 MPa for plain concrete and the concrete class with compressive strength 30 MPa for structural (reinforcement) concrete. Natural river sand and crushed stone sand (India) in these mixtures were replaced by fine recycled aggregate (fRA) originating from construction and demolition waste (CDW) from waste concrete (fRCA) (both) and waste masonry (fRMA)(Czechia). The coarse natural aggregate was used for all the concrete mixtures. The basic physical properties (density, water absorption), mechanical properties (compressive strength, tensile strength, and modulus of elasticity), and durability (freeze-thaw resistance and carbonation resistance) of concrete were verified and compared.

5.3.1 Fine recycled aggregate

As described above, the measurement method of fRA's density and water absorption has not yet been established, leading to the high differences between published results. Previous studies have found that the dry density of fRMA between 2000 and 2500 kg/m^3 and WA ranges from 12% to 15% [113,115,119,120]. The dry densities of fRCA have been between 1630 and 2560 kg/m^3 and WA vary between 2.38% and 19.3% [25,76,81,137,181–186]. For comparison, the presented values of the densities of natural fine aggregate varied between 2530 and 2720 kg/m^3 and WA for natural fine aggregate range between 0.15 and 4.1%. In conclusion, fRMA and fRCA have a lower density than natural sand [46]. Furthermore, the evaluation methodology for the determination of the WA of fRA has not been established, which differs from the coarse RA, where the methodology for the evaluation of the property has been clearly defined. This leads to the unclear and non-comparable results presented in available literature where the measured values differ by up to 60% when tested by different operators and methods. The fRA does not absorb its capacity during mixing. As has been published in previous studies, it was estimated that it ranges between 49 and 89% [81]. For this reason, the determination of the effective water-to-cement ratio, which influences the workability and, consequently, the mechanical properties of the RAC become complicated.

This study presents possibilities of replacing the whole fine fraction of natural sand (fNA) with fine recycled aggregate (fRA). The Czech team uses coarse NA (fractions 4-8 and 8-16 mm) and natural mined sand, two types of fRCA and one type of fRMA (fractions 0-4 mm). A type of fRCA1 and fRMA were prepared by a Czech recycling company, the origin of these aggregates was building structures and the aggregate was washed during the recycling process. The other type of fRCA2 was prepared in the laboratory by crushing waste concrete originating from floor structures. For comparison, the India team used one type of coarse NA (fractions 4.75-10 and 10-20 mm), two types of fNA, natural river sand (fNA2) and crushed stone sand (CSS), and one type of fRA (fractions 0-4.75 mm). fRCA was obtained by crushing waste concrete obtained from precast plant set-up for a bridge construction project in Jaipur, India, and was crushed in laboratory. In this research only the fine fraction of RA (0-4 mm) was used in this research (see Figure 18), the coarse fractions were not replaced and remain NA for all the mixtures. The main component of fRCA was waste concrete (natural aggregate particles and old cement mortar), and fRMA mainly contains waste masonry (red brick, aerated concrete, and plaster). All tested properties of fRA differ from those of fNA, especially WA, which is higher and ranges from 3.6 to 8.9% for f RA, while the value for fNA is 1.0% and CSS is 2.8%. This evaluation shows slightly lower WA of fRMA compared to the results of previous studies [25,76,81,137,181–186], which is probably caused by an inconsistent method of measuring fRA WA. The results of fRA WA confirm the conclusions of many previous studies, such as the influence of WA by the parent concrete and recycling technology [81]. The lower WA was measured for fRCA1 that originated from normal strength concrete and was washed during the recycling procedure, so it is assumed that the content of cement mortar was low. In contrast, the higher WA was measured for fRCA3, which originated from high-strength concrete, so the high amount of cement mortar in concrete is assumed. Furthermore, the different WA measurement evaluation procedures were used.

The oven dried particle density of fRA ranges from 2220 kg/m^3 to 2430 kg/m^3 which was lower compared to NA with decline up to 14%, which corresponds with the results of previous studies [25,76,81,137,181–186]. Furthermore, RA contains more fine particles and has different granulometry compared to NA and does not meet the requirements of the Standard [71] (see Figure 19, Figure 20).

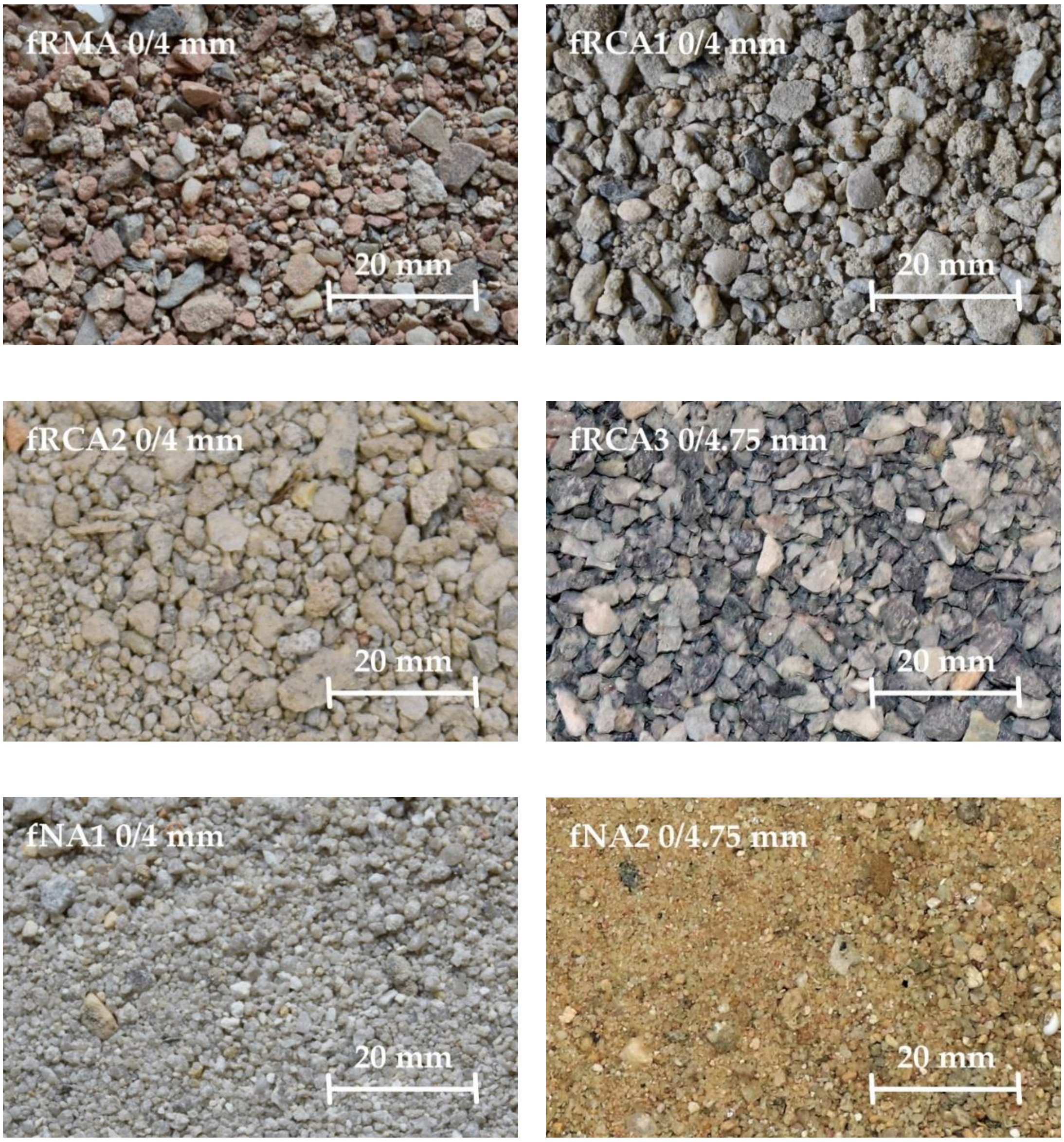


Figure 18. NA and RA used in concrete mixtures

The selected properties of RA, which are of the greatest importance in terms of recipe design, were tested according to the requirements of the valid Czech European standard [71]. The basic properties of the three NA fractions and the fine fractions of all RA are given in **Table 12**. The Standards used for examination of the aggregate are listed in **Table 13**.

Table 12. Physical properties of particular fractions of used aggregates.

Types of recycled aggregate	Grading (mm)	Content of finest particles	Oven-dried particle density		Water absorption capacity		Saturation level
		f (%)	ϱRD (kg/m³)	σ	WA_{24} (%)	σ	(%)
Natural aggregate	0–4	0.3	2570	81	1.0	0.0	0.0
	4–8	0.3	2530	12	1.7	0.3	0.0

Types of recycled aggregate	Grading (mm)	Content of finest particles	Oven-dried particle density		Water absorption capacity		Saturation level
		f (%)	ϱRD (kg/m^3)	σ	WA_{24} (%)	σ	(%)
(NA1)	8–16	0.4	2540	12	1.9	0.2	0.0
Natural	0-4.75	0.0	2581	23	0.81	0.00	0.0
aggregate	4.75-10	0.0	2670	11	0.45	0.01	0.0
(NA2)	10-20	0.0	2690	06	0.45	0.05	0.0
Crushed stone sand (CSS)	0-4.75	0.0	2596	83	2.78	0.18	0.0
Fine recycled masonry aggregate (fRMA)	0–4	1.0	2320	130	6.6	0.8	4.7
Fine recycled concrete aggregate (fRCA1)	0-4	0.6	2430	60	3.6	0.8	1.6
Fine recycled concrete aggregate (fRCA2)	0–4	2.0	2220	80	6.9	0.5	2.5
Fine recycled concrete aggregate (fRCA3)	0-4.75	0.0	2052	12	8.90	0.15	0.0

Table 13 The overview of test methods for aggregates.

Tests/ Standards	The Czech team	The Indian team
Specific gravity/ dry density	EN 1097-6	BIS (1963)
Water absorption of aggregates	EN 1097-6	BIS (1963)
Particle size distribution	EN 933-1	BIS (1963)

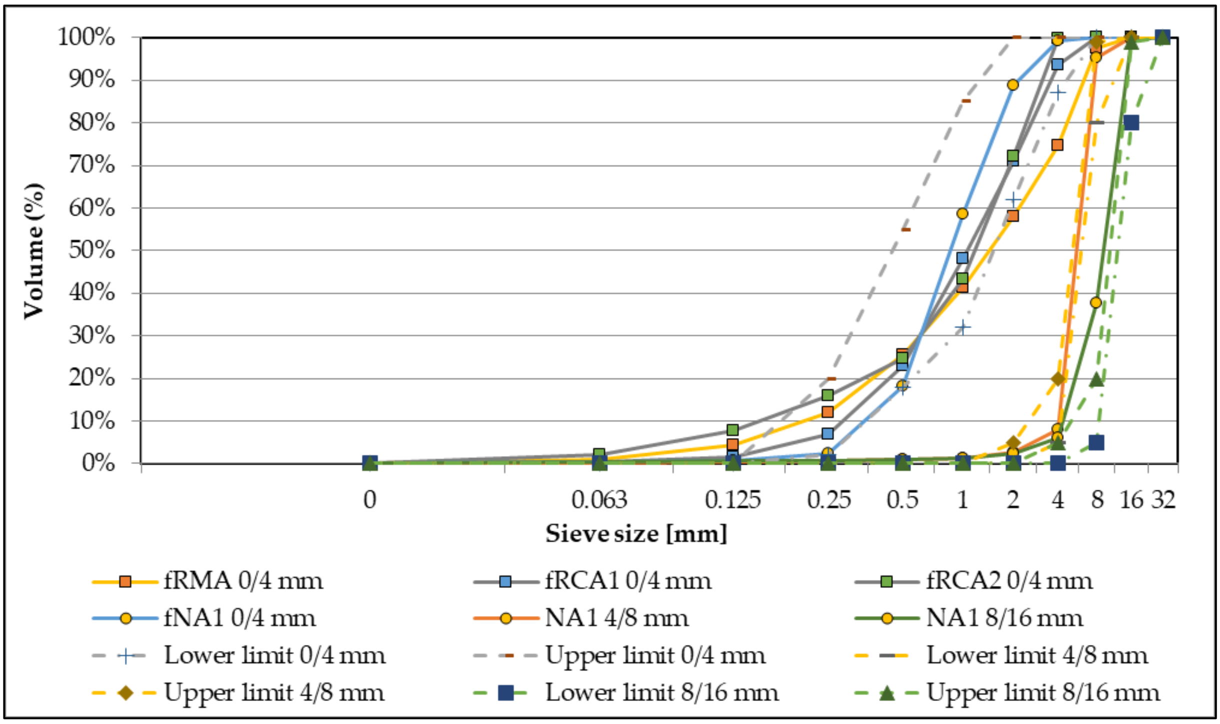


Figure 19. Sieving curves of the Czech team for 3 fractions of natural aggregate and fine fractions of 3 types of recycled aggregate with limits defined in the standard EN 12620 used in concrete mixtures.

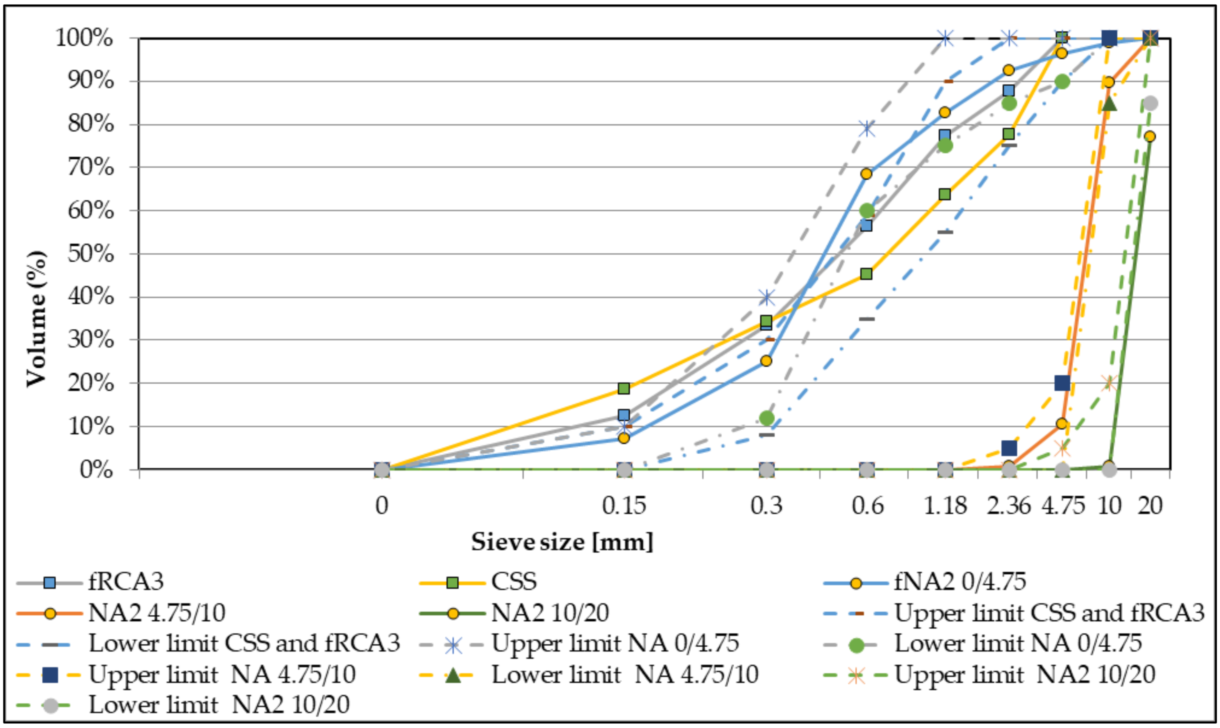


Figure 20. Sieving curves of the Indian team for 3 fractions of natural aggregate, crushed stone sand and fine fraction of recycled concrete aggregate with limits defined in the standard BIS (1963) used in concrete mixtures.

5.4 Recycled aggregate concrete mixtures

Laboratory measurements were performed on 13 concrete mixtures. The amount of cement CEM I 42.5 R was 260 kg/m^3 for the mixtures labelled I and III, 300 kg/m^3 for II and 320 kg/m^3 for IV. The water-to-cement ratio ranges from 0.55 to 0.78 and is listed below (**Table 14**). The mixtures were optimized using the Bolomey particle size distribution curve. The mixing procedure used in this study was similar to the procedure performed by Evangelista and de Brito where the two-stage mixing technique was used and where the fRA were inserted into a part of the water (2/3 of the required mixing water, plus the water estimated to be absorbed) and mixed during a period of 10 min, in the first stage and consequently the remaining constituents were placed [46]. In the case of this study, the fRAs were mixed with part of the water (water estimated to be absorbed) for 10 min, and after this stage the remaining constituents and the mixing water were added to the concrete mixture. The additional water was calculated according to the water absorption capacity of fRA and current levels of aggregate saturation before mixing. The effective water-to-cement ratio was estimated as 0.65 for compressive strengths of 20 MPa and 0,55 for 30 MPa reversal. in the Czech part of the study. In the case of the Indian part, the effective water-to-cement ratio was estimated as 0.50 for compressive strengths of 20 MPa and 0,45 for 30 MPa resp and superplasticizers were used to improve the workability of fresh concrete.

Six control mixtures of conventional concrete (NAC IA, NAC IIA, NAC IB, NAC IIB, CSSC IB and CSSC IIB), three mixtures of strength class corresponding compressive strengths 20 MPa and three mixtures of 30 MPa resp. with only NA up to a particle size of 16 mm were produced. In these mixtures three types of fNA were used: 1) mined sand by Czech team; 2) river sand and 3) crushed stone sand by Indian team. For comparison, in further 7 mixtures for both concrete classes the fNA was fully replaced by the different types of fRA: 1) fRCA 1, fRCA 2 and fRMA by Czech team and 2) fRCA 3 by Indian team. The concrete mixture was prepared in a pan mixer by adding superplasticizer during mixing to obtain the desired workable concrete. The specimens were cured for 28 days before the test. The mixture proportions are given in the **Table 14**.

At the age of 28 days, physical and mechanical properties were tested according to valid Czech and Indian standards. Furthermore, durability (freeze-thaw resistance and accelerated aging due to CO_2) and long-term strength development (at the ages of 90, 180 and 360 days) were tested. Samples of dimensions 100 × 100 × 400 mm, 150 × 150 × 150 mm and 100 × 100 × 100 mm were used for testing.

Table 14. Concrete mix proportion, per cubic meter.

Concrete mixture	Cement	Water mixing/ additional	w/c ratio	SP	Natural Aggregate		Recycled aggregate
					Fine	Coarse	Fine
	(kg/m^3)	(kg/m^3)	(-)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
NAC IA	260	169 + 0	0.65	-	709	1130	0
fRMAC IA	260	169 + 18	0.72	-	0	766	971
fRCAC1 IA	260	169 + 17	0.71	-	0	949	843
fRCAC2 IA	260	169 + 34	0.78	-	0	946	773

Concrete mixture	Cement	Water mixing/ additional	w/c ratio	SP	Natural Aggregate		Recycled aggregate
					Fine	Coarse	Fine
	(kg/m3)	(kg/m3)	(-)	(kg/m3)	(kg/m3)	(kg/m3)	(kg/m3)
NAC IB	260	130 + 12	0.55	2.3	813	1266	0
CSSC IB	260	130 + 28	0.61	3.1	813	1266	0
fRCAC3 IB	260	130 + 78	0.80	0.3	0	1266	813
NAC IIA	300	165 + 0	0.55	-	671	1167	0
fRMAC IIA	300	165 + 17	0.61	-	0	822	920
fRCAC1 IIA	300	165 +16	0.60	-	0	994	800
NAC IIB	320	144 + 12	0.49	1.6	779	1213	0
CSSC IIB	320	144 + 27	0.53	3.2	779	1213	0
fRCAC3 IIB	320	144 + 75	0.68	0.3	0	1213	779

5.5 Evaluation methodology

The physical, mechanical and durability properties were examined by both teams. The dimensions of specimen and testing standards used in the experimental work are shown in **Table 15.** Testing procedures were designed to be similar as much as possible with the respect to regional habits. However, the test procedures and their differences are described below. At the age of 28 days, physical and mechanical properties were tested according to valid Czech and Indian standards. Furthermore, durability (freeze-thaw resistance and accelerated ageing due to CO_2) and long-term strength development (at the ages of 90, 180, and 360 days) were tested.

Table 15**.** The overview of test methods for concrete samples.

Tests	**Curing Period**		**The Czech team**	
	Standards	**Standards**	**Specimen size**	**Specimen size**
	[days]		[mm]	
Compressive strength	7, 28, 90, 180, 360	EN 12390-3 (2003)	150 × 150 × 150	Compressive strength
Flexural strength	28	EN 12390-5 (2009)	100 × 100 × 400	Flexural strength
Static modulus of elasticity	28	EN 12390-13 (2014)	100 × 100 × 400	Static modulus of elasticity
Dynamic modulus of elasticity	28	EN 12504-4 (2005)	100 × 100 × 400	Dynamic modulus of elasticity
Carbonation	28	Inspired by ČSN EN 12390-12	100 × 100 × 200	Carbonation
Freeze-thaw resistance	28	ČSN 73 1322 (1969)	100 × 100 × 400	Freeze-thaw resistance
Water absorption by immersion	28	Usual procedure of examination	100 × 100 × 100	Water absorption by immersion
Sorptivity	28	Inspired by ASTM C1585-20	100 × 100 × aprox. 200	Sorptivity

5.6 Results and Discussion

In this chapter, the results of physical, mechanical and durability properties found in this investigation are presented and compared for both research groups.

5.6.1 Physical properties

As reported in previous studies [165,206], the absorption of concrete fundamentally influences its durability. For this reason, immersion-based water absorption and capillary water absorption were evaluated to determine its impact on durability properties. The porosity of concrete and, consequently, the proportion of water with fRCA increased with the increasing replacement rate of fRCA [207,208]. Furthermore, the density of concrete was indicated. The density of RAC was lower than that of NAC and the maximum decline was 10%. In general, the water absorption of fRA concrete by immersion was found to be higher than that of the control mixtures, which corresponds to previous studies [132,137]. As was concluded in many previous studies, water absorption is higher due to the presence of old mortar in fRCA and porous materials in fRMAC absorb more water than natural sand, resulting in higher water absorption of fRA concretes. Slight differences between the control and fRAC mixtures developed by the Czech Republic and India can be observed. The maximum increase of water absorption by immersion for mixture was FRCAC3 IB, manufactured by the Indian team, which was almost 2.5 times higher than the reference mixture. In the case of the Czech team, the maximum increase of 85% was expected, the fRMAC, due to the high porous materials contained in the fRMA, such as red bricks, mortars, aerated concrete, etc. The water absorption by immersion of the fCRAC mixtures increases between 30% and 50%, which is slightly higher than the values presented in previous studies, where water absorption by immersion has been reported to increase from 15% [207,209] to 46% [132] for concrete with the complete substitution of natural sand by fRCA in concrete. The dry density and water absorption of different mixtures are shown in **Table 16** and **Figure 21**.

However, previous studies reported that the most significant increase was found for capillary absorption, which increased from 46% to 95% for 100% fRCAC [138]. This was not confirmed in this study. The capillary water absorption measured by both teams was lower than that of the control concretes. The only increase was found for fRMAC IA, which was 44%; on the opposite the lower decrease was measured for fRMAC IIA with a decrease of more than 60%. This decrease may be due to the filling of pores present in the concrete by the products of hydration of unhydrated cement present in the fRCA and, moreover, the water contained soaked in the concrete after curing, due to the high WA of the fRA.

Table 16. Average values of results of physical properties of concrete, including standard deviation.

Recycled concrete mixture	Dry density		Water absorption by immersion		Capillary water absorption	
Designation	**(kg/m³)**	**σ**	**(%)**	**σ**	**(kg/m²)**	**σ**
NAC IA	2301	18	5.89	0.35	2.31	0.30
fRMAC IA	2181	14	10.89	0.38	3.34	0.75
fRCAC1 IA	2276	11	7.68	0.25	1.98	0.22
fRCAC2 IA	2250	6	8.34	0.78	2.17	0.29
NAC IB	2373	5	6.30	0,66	3.83	0.05
CSSC IB	2391	74	8.80	2,88	4.53	0.25
fRCAC3 IB	2332	26	14.60	0,57	3.00	0.62
NAC IIA	2324	13	5.03	1.11	1.17	0.14
fRMAC IIA	2191	12	10.30	0.32	0.45	0.08
fRCAC1 IIA	2278	5	7.70	0.06	0.76	0.44
NAC IIB	2380	14	6.90	0,59	3.33	0.45
CSSC IIB	2193	11	8.30	0,87	1.93	0.48
fRCAC3 IIB	2188	21	13.20	0,31	1.70	0.36

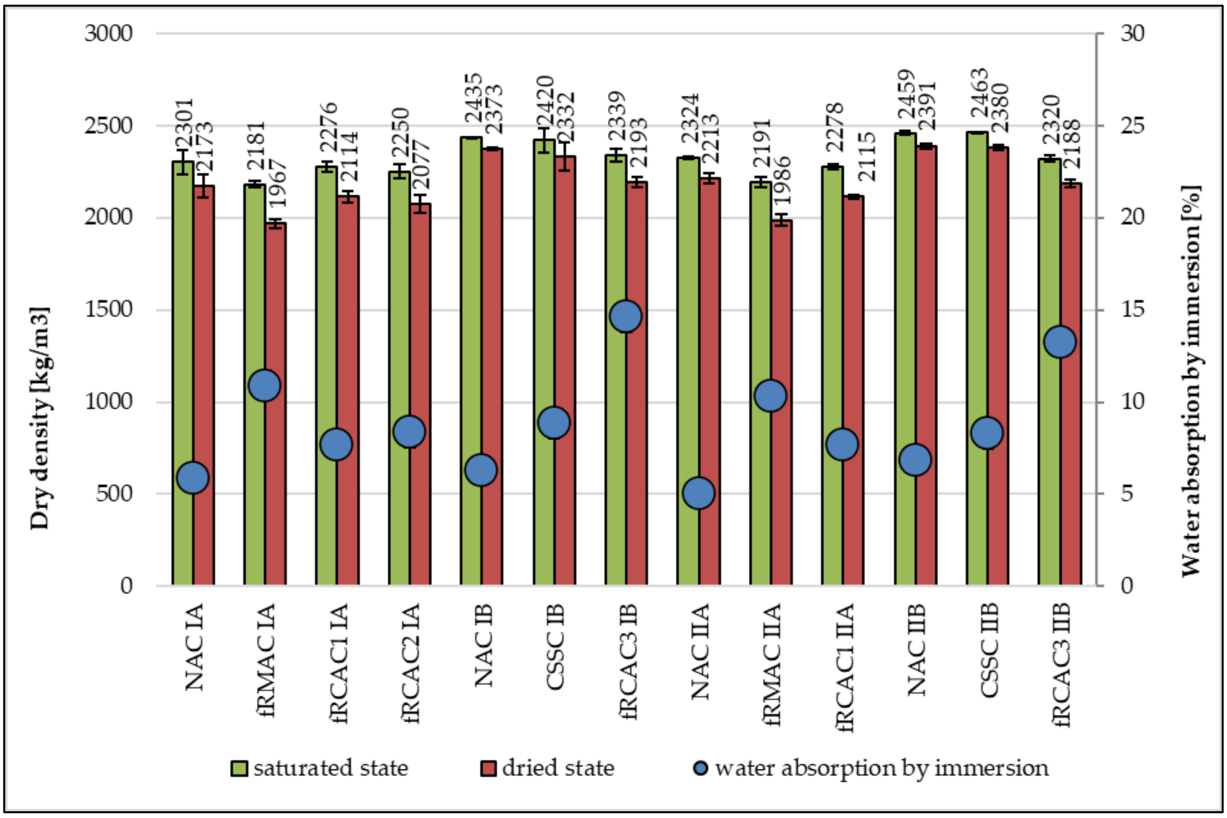


Figure 21 Physical properties of concrete mixtures – saturated surface dry density, oven dry density and water absorption by immersion

5.6.2 Mechanical properties

The compressive strength, flexural strength and modulus of elasticity were evaluated at age 28 days. The comparison of the results between two research groups is shown in **Table 17**. The results of individual properties are discussed in following chapters.

Table 17. Average values of results of mechanical properties of concrete teste at age of 28 days, including standard deviation.

Recycled concrete mixture	Compressive strength		Flexural strength		Static modulus of elasticity		Dynamic modulus of elasticity	
Designation	**(MPa)**	**σ**	**(MPa)**	**σ**	**(GPa)**	**σ**	**(GPa)**	**σ**
NAC IA	33.2	2.5	6.2	0.2	36.7 [1)]	1.4	38.2 [1)]	1.8
fRMAC IA	30.0	2.2	5.5	0.4	22.4 [1)]	1.0	27.3 [1)]	1.4
fRCAC1 IA	34.4	1.7	5.8	0.3	29.6 [1)]	0.4	34.5 [1)]	0.7
fRCAC2 IA	36.7	2.9	5.7	0.1	31.8 [1)]	1.2	35.4 [1)]	1.7
NAC IB	25.3	1.1	3.9	0.5	30.7 [2)]	0.0	41.2 [2)]	0.0
CSSC IB	30.5	0.7	4.3	0.7	24.4 [2)]	0.0	26.6 [2)]	0.0
FRCAC3 IB	22.5	1.2	6.5	0.6	25.3 [2)]	0.0	26.4 [2)]	0.0
NAC IIA	44.9	0.9	7.6	0.9	35.9 [1)]	0.5	38.2 [1)]	0.8
fRMAC IIA	38.0	0.9	6.8	0.6	25.3 [1)]	0.2	30.0 [1)]	0.9
fRCAC1 IIA	42.9	0.8	6.5	0.4	31.4 [1)]	1.0	35.7 [1)]	0.6
NAC IIB	35.8	0.6	4.3	0.1	33.2 [2)]	0.0	44.5 [2)]	0.0
CSSC IIB	35.8	0.9	5.3	1.1	29.3 [2)]	0.0	29.7 [2)]	0.0
FRCAC3 IIB	25.3	0.9	5.5	0.4	25.6 [2)]	0.0	32.6 [2)]	0.0

[1)] *Examined on prismatic specimen 100 × 100 × 400 mm³*

[2)] *Examined on cylindric specimen of 150 mm diameter and 300 mm length*

Compressive strength

The results of compressive strength, which is the key material property of concrete, of fine recycled concrete aggregate concrete (fRCAC) differ from previous studies: it has been found to be higher [74], the similar or lower [74,185,210–212] compared to reference concrete with only NA. As a maximum decrease in compressive strength was found, 6.7%, 11.1%, 31.3%, and 50% were found for the substitution of fine natural aggregates 10%, 30%, 50%, and 100% in concrete mixture, respectively. On the other hand, the maximum increase for concrete with 50% replacement rate was 16%. Generally, it could be said that the compressive strength is rather sensitive to the high replacement level of fRCA (100%), regardless of the strength class of concrete, mostly due to its inaccurately measured water absorption and unknown rate of water during the mixing procedure. For this reason, additional water is used to compensate for these two factors, leading to the unknown effective water-to-cement ratio, which is only estimated in the case of fRAC. Despite these, the compressive strength could be positively affected by the filler effect of fRA, where the finest particles fill the pores and make the structure of the mixture denser, reduce internal stresses, and early propagation of stress. Moreover, the positive influence on mechanical properties could have an additional internal cure caused by the water absorbed in the aggregate. Furthermore, the angular shape and rough surface texture of fRA particles could lead to better interlocking between particles [46].

Similarly with the previous studies, heterogeneous results were found. On the one hand, the compressive strength of concrete containing fRCA1 and 2 is higher than the control mixtures for lower concrete strength classes, with maximum increase equal to 10%. On the contrary, the compressive strength of the mixture with fRCA1 in the higher strength class slightly decreases (4%). Furthermore, the compressive strength of both fRCA3-containing mixtures decreases compared to both control mixes, and furthermore, the decline is greater compared to the fRCA1 and fRCA2 mixtures. At 28 days, the strength of concrete FRCAC3 IB was observed to decrease maximally with respect to two controls by 11% with respect to NAC IB and 26% with respect to CSSC IB. The strength of FRCAC3 IIB concrete was found to reduce by 29%, respectively, compared to control NAC IIB and 29%, respectively, with respect to CSSC IIB. The compressive strength of both concrete strength classes with fRMA slightly decreases (10% and 15%, respectively) compared to the control mix. Furthermore, of development the compressive strength over time shows the higher rise of fRAC than control concrete (see **Figure 22**).

The decrease in strength and differences between each mixture is probably caused by the presence of an undefined amount of adhered mortar and the amount of additional water to compensate for the higher water absorption and the ability of fRA to soak water during mixing. As previously written, the amount of cement mortar is influenced by the parent concrete and the recycling procedure [81]. In this case, it is assumed that in fRCA1 and fRMA the content of fines was reduced by washing. In contrast, fRCA3 originated from high strength concrete, so the high amount of cement paste is assumed in parent concrete and consequently the high fine content. In this case, the study confirms previous studies in which the negative effect of lack of knowledge about fine particles and its influence on the effective water-to-cement ratio was described many times [46]. As the maximum replacement rate in the case of compressive strength was stated 30% [3,74,75,137,213,214].

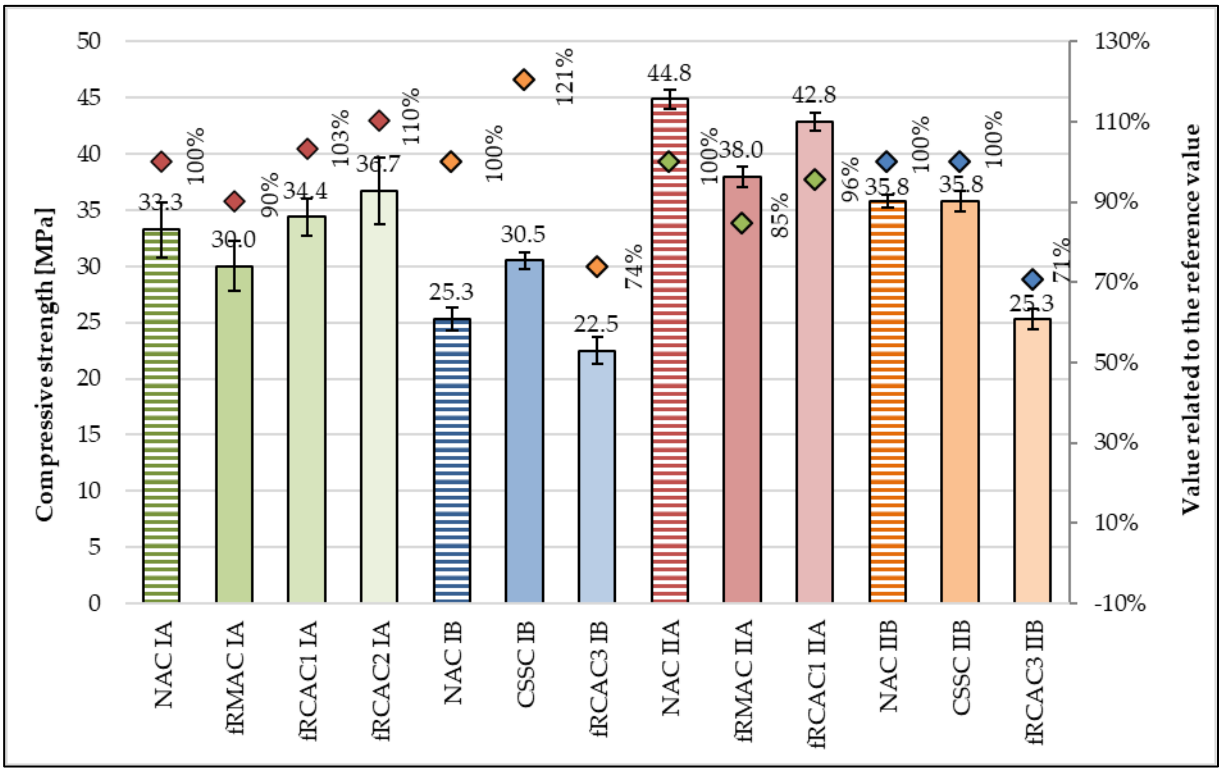


Figure 22. Comparison of compressive strength of concrete containing fNA, fRCA, and fRMA with respect to control mixtures.

Flexural strength

The flexural strength of fRCA concrete/mortar was observed to decrease with increasing fRCA in previous studies [105,143]. The maximum reduction in tensile strength was 33% for concrete with a replacement ratio. A decrease in tensile strength was reported with increasing natural fine aggregates with fRCA and with the increasing of water-to-cement ratio [215]. In contrast, the flexural strength of the mortar at 28 days was found to be higher than the control by 13.7% [29]. The higher strength is attributed to the better interlocking of the fRCA with the paste due to the presence of the the uneven surfaces of fRCA. As the maximum replacement rate in the case of flexural strength was stated 20% [144]. The flexural strength decreases for all examined mixtures. The decrease in properties of the fRAC I mixtures ranged from 6% to 11%, and the reduction for the fRAC II mixtures was between 11% and 15%. Interestingly, in the case of flexural strength, fRMAC achieved lower declines than both fRCACs. On the contrary, the strength of FRCAC3 IB was observed to increase by 67% and 51% compared to NAC IB and CSSC IB respectively. The strength of fRCAC3 IIB was observed to increase by 28% and 4% compared to NAC IIB and CSSC IIB respectively (see **Figure 23**).

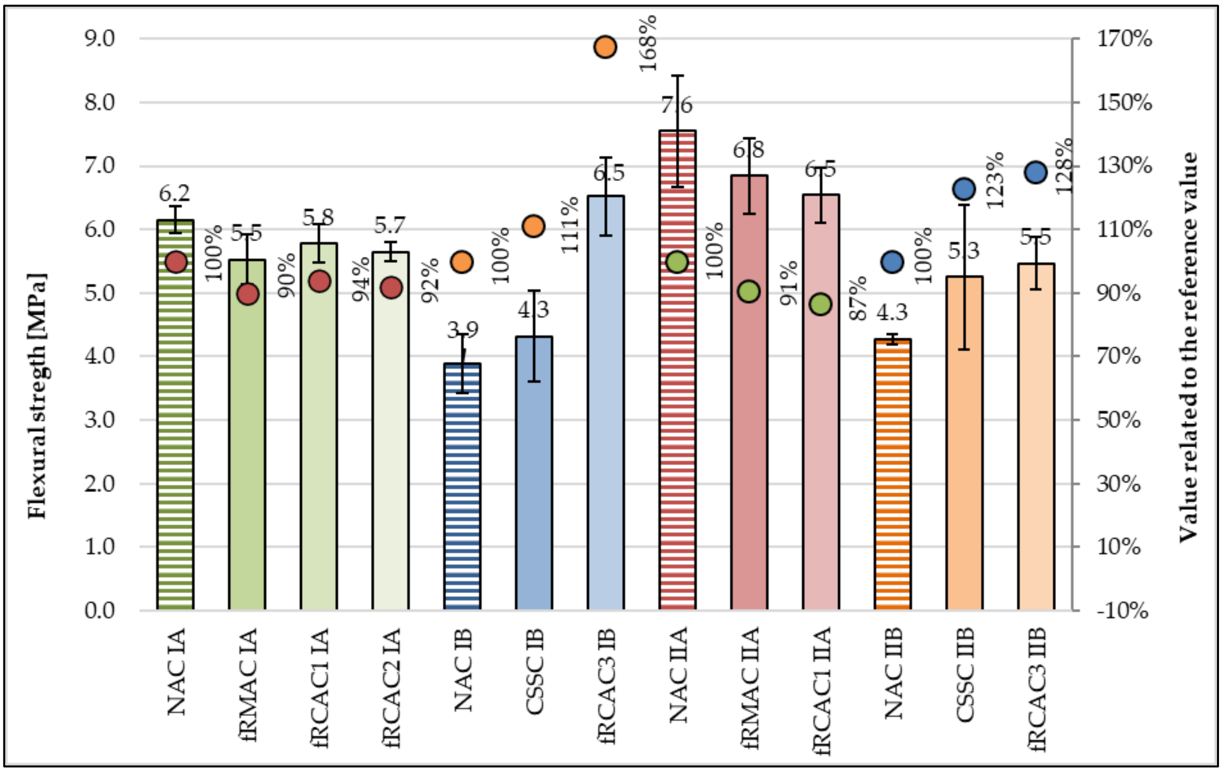


Figure 23. Comparison of flrxural strength of concrete containing fNA, fRCA, and fRMA with respect to control mixtures.

Modulus of Elasticity

The static modulus of elasticity is the key characteristic of the material for the behavior of reinforced concrete structural elements, because of its lower deflection of beams and slabs, for example. Similar to the general results of concrete containing coarse RA, the highest degradation of properties was found for the modulus of elasticity. The reductions of the static modulus of concretes where natural sand was replaced by fRA range between 9.5% and 17% [145,185]. Wang et al. [216] described that concrete with coarse NA and 100% fRCA had an elastic modulus that decreased by 5.6–13.5%. Furthermore, a significant decline in modulus of elasticity has been reported for low substitution levels (<30%) [217,218]. This study confirmed that the decrease in static modulus of elasticity ranges from 13% to 39% with respect to fRAC I, to 13% and 30% with respect to fRAC II, respectively. The dynamic modulus of elasticity declines was slightly lower and varied between 10% and 28% for fRAC I and between 6% and 21% for fRAC I. The lower both modulus of elasticity and both concrete strength concrete classes were measured for mixture with fRMA. The dynamic modulus of elasticity of FRCAC3 IB was found to decrease by 36% compared to NAC IB and CSSC IB. The dynamic modulus of elasticity of FRCAC3 IIB was found to decrease by 23% compared to NAC IIB and was observed to increase by 10% in regards to CSSC IIB. The static modulus of elasticity of FRCAC3 IB was observed to decrease by 18% with respect to NAC IB and was found similar to CSSC IB and the static modulus of concrete FRCAC3 IIB was observed to decrease by 22% and 12% with respect to NAC IIB and CSSC IIB respectively. The decrease may be due to the loss of mortar stiffness due to the presence of adhered mortar. Similar findings were observed in [219]. The results of the dynamic and static modulus of elasticity of both research groups are shown in **Figure 24**. and **Figure 25**.

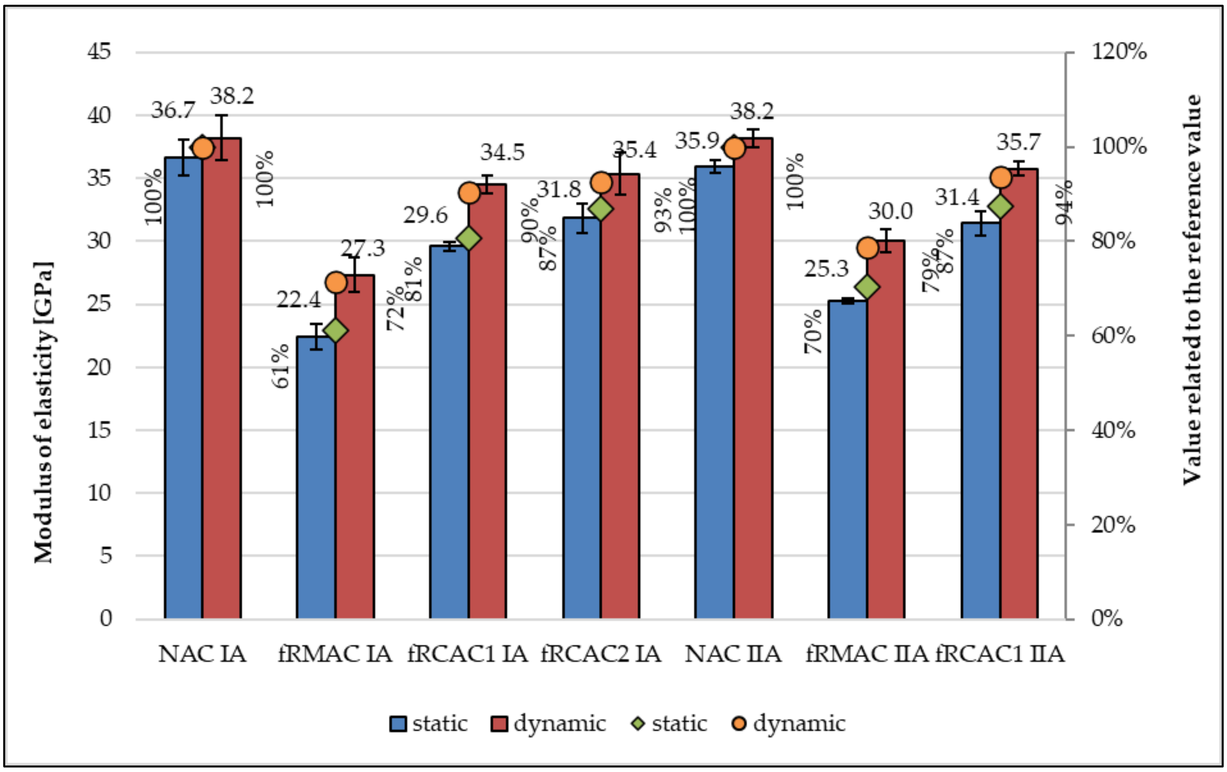


Figure 24. Comparison of static and dynamic modulus of elasticity for concrete mixtures prepared by the Czech team.

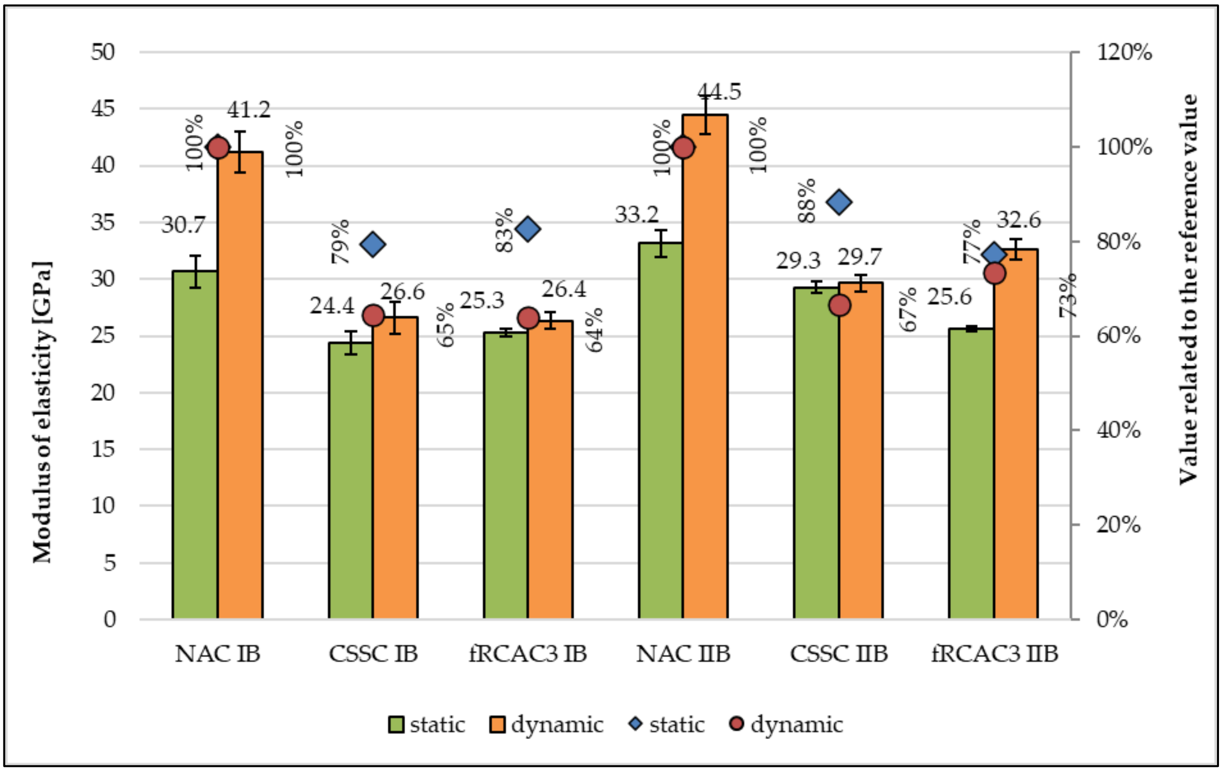


Figure 25. Comparison of static and dynamic modulus of elasticity for concrete mixtures prepared by the Indian team.

5.6.3 Durability

Durability is the key characteristic of the material in the case of the exposition class of concrete utilization and its structural use. The most important factor that affects durability is concrete permeability, which is studied by the oxygen and water permeability test, water absorption by immersion, and capillarity [132,138,207,220–224]. In this study, the freeze-thaw resistance and carbonation of concrete containing fRA was verified. The summarized results of the durability are shown in **Table 18**.

Table 18. Frost resistance coefficient determined from the flexural strength after freezing and thawing cycles and carbonation depth of concrete mixtures.

Recycled concrete mixture	Fexural strength + σ				frost resistance coefficient	Freeze-thaw resistance	Indicator increase of carbonation depth compared to NAC
Designation	0 cycles		100 cycles		(-)	Cycles	(mm)
NAC IA	6.15	± 0.22	6.87	± 0.20	1.12	100	2.78 1)
fRMAC IA	5.53	± 0.39	5.85	± 0.40	1.06	100	7.10 1)

Recycled concrete mixture	Fexural strength + σ				frost resistance coefficient	Freeze-thaw resistance	Indicator increase of carbonation depth compared to NAC
Designation	0 cycles		100 cycles		(-)	Cycles	(mm)
fRCAC1 IA	5.78	± 0.30	6.57	± 0.26	1.14	100	4.51 1)
fRCAC2 IA	5.65	± 0.14	6.22	± 0.27	1.10	100	1.68 1)
NAC IB	3.89	±0.46	3.44	±0.36	0.88	100	11.00 2)
CSSC IB	4.32	±0.72	3.35	±0.09	0.78	100	11.83 2)
fRCA3 IB	6.52	±0.61	3.15	±0.14	0.48	-	14.50 2)
NAC IIA	7.55	± 0.87	7.80	± 0.12	1.03	100	0.77 1)
fRMAC IIA	6.84	± 0.60	6.78	± 0.00	0.99	100	1.71 1)
fRCAC1 IIA	6.54	± 0.44	6.73	± 0.10	1.03	100	0.57 1)
NAC IIB	4.27	±0.08	4.00	±0.15	0.94	100	5.17 2)
CSSC IIB	5.25	±1.14	4.78	±0.64	0.91	100	5.50 2)
fRCA3 IIB	5.47	±0.41	3.36	±0.32	0.61	-	11.70 2)

1) *Examined on prismatic specimen 100 × 100 × 200* m^3
2) *Examined on specimen size 50 × 50 × 100* mm^3*, longitudinal sides coated with epoxy paint*

The frost resistance coefficient was determined from the flexural strength before and after freezing and thawing cycles the same way as for the dynamic modulus of elasticity.

Freeze-thaw resistance

In the case of freeze-thaw resistance, the positive effect of fRA in the mixture has been found. This phenomenon is caused by the higher porosity of the fRCA, which can provide better hydraulic pressure dissipation. However, the negative influence of the freezing and thawing could be observed, due to the less resistant mortar, however, without loss of mechanical properties [143,144,225]. This investigation achieved the same results; the freeze-thaw resistance of all examined fRA concretes was similar to or slightly better than reference concretes in the case of flexural strength, which was measured before and after freezing and thawing. In the case of the dynamic modulus of elasticity, a slight decline of the frost resistance coefficient can be observed with the maximal decrease of the frost resistance coefficient of about 13%. However, all mixtures tested meet the requirements defined in the Czech national standard, where the frost resistance coefficient must not decrease by more than 25%. Additionally, the weight and dimensions of the fRCA concrete subjected to freeze-thaw cycles of 100 numbers were not significantly affected. The test procedure implemented by the Indian team was slightly different from that of the Czech team, due to other testing equipment. However, the results achieved are similar. The samples were tested for flexural strength and the flexural strength of FRCAC3 IB was observed to be similar to the controls. The strength of fRCA3 II was observed to decrease by 16% and 30% with respect to NAC IIB and CSSC IIB, respectively (see **Table 18** and **Figure 26**.) The dynamic modulus of elasticity of FRCA concrete was compared after 100 cycles with the control (see **Table 19** and **Figure 26**). In a study [143] the incorporation of FRCA in concrete was not found to make a significant difference in the freeze-thaw resistance of concrete.

Table 19. Dynamic modulus of elasticity measured by ultrasonic method and frost resistance coefficient determined from the dynamic modulus of elasticity after freezing and thawing cycles

Recycled concrete mixture	Dynamic modulus of elasticity (GPa) + frost resistance coefficient (-)									Freeze-thaw resistance
Designation	0 cycles	25 cycles		50 cycles		75 cycles		100 cycles		Cycles
NAC IA	37.6	36.4	0.97	36.5	0.97	35.8	0.95	36.9	0.98	100
fRMAC IA	19.7	17.0	0.86	18.4	0.94	17.6	0.89	19.3	0.98	100
fRCAC1 IA	35.1	32.3	0.92	30.9	0.88	32.4	0.92	31.3	0.89	100
fRCAC2 IA	37.3	34.3	0.92	33.3	0.89	33.2	0.89	33.1	0.89	100
NAC IIA	29.31	-	-	-	-	-	-	25.9	0.89	100
CSS I	27.88	-	-	-	-	-	-	27.7	1.00	100
fRCA3 I	23.89	-	-	-	-	-	-	30.7	1.29	100
NAC IIA	40.4	37.0	0.92	36.0	0.89	37.4	0.93	35.1	0.87	100
fRMAC IIA	31.6	28.4	0.90	25.9	0.82	29.8	0.94	28.0	0.88	100
fRCAC1 IIA	35.2	29.6	0.84	34.5	0.98	33.4	0.95	31.1	0.88	100
NAC IIB	25.37	-	-	-	-	-	-	21.1	0.83	100
CSS II	18.91	-	-	-	-	-	-	24.4	1.29	100
fRCA3 II	24.84	-	-	-	-	-	-	22.5	0.91	100

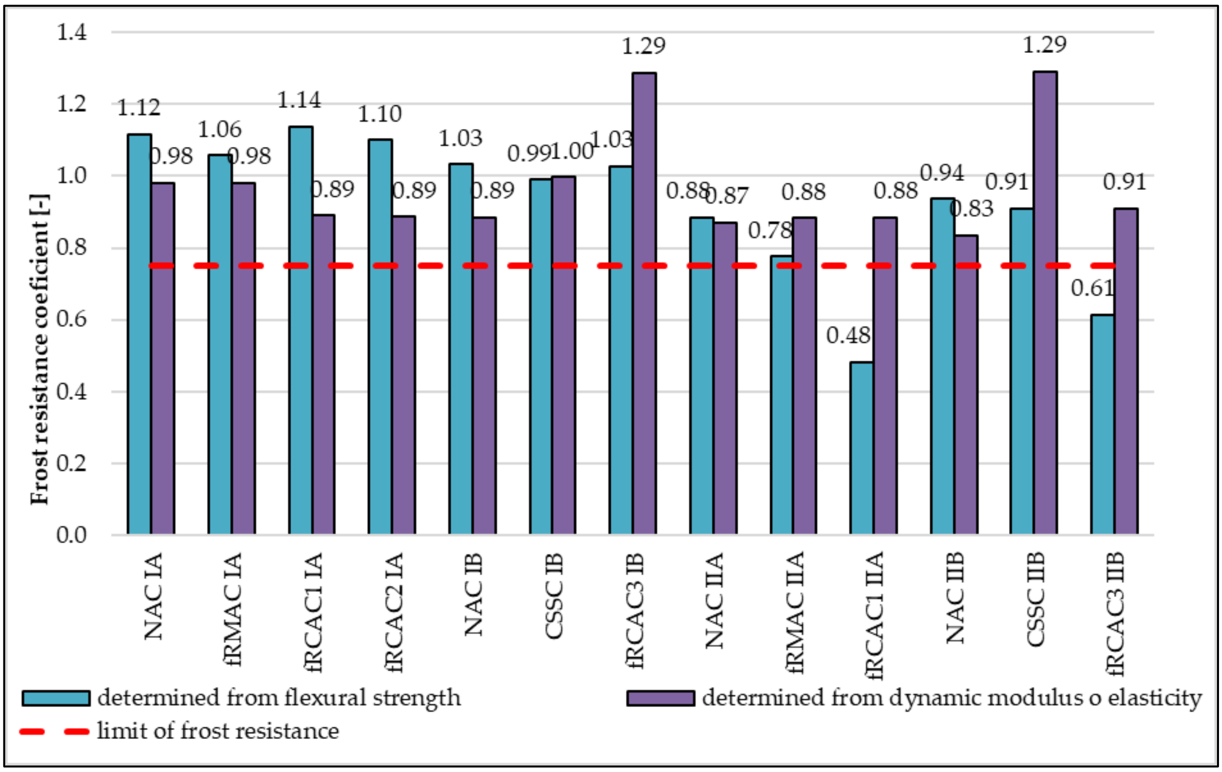
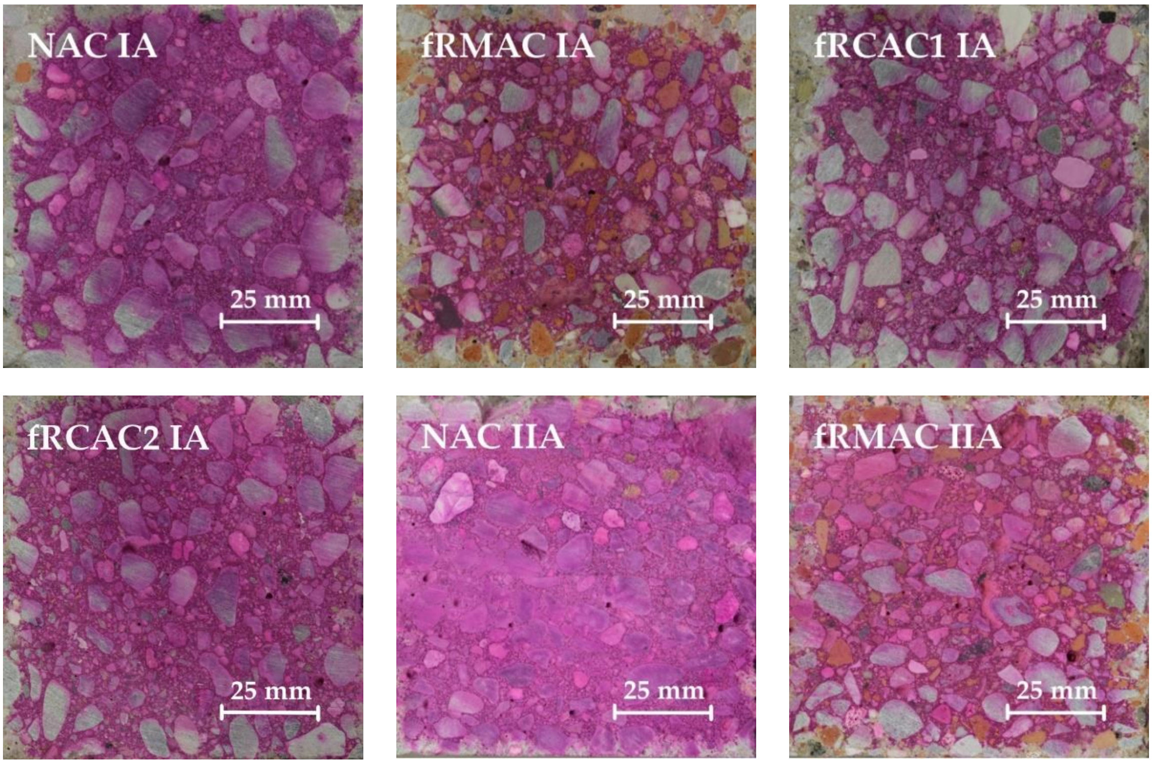


Figure 26. Comparison of flexural strength and dynamic modulus of elasticity of concrete containing fNA, fRCA, and fRMA after freeze-thaw cycles.

Carbonation resistance

The carbonation resistance of concrete is an essential property in the case of structural reinforcement elements. Carbonation depth determines the concrete protective cover of the steel reinforcement bar. The poorest carbonation resistance could cause higher consumption of the concrete to achieve the same service life of reinforced concrete structural elements [226]. In previous studies, the importance of using a reasonable amount of water was mentioned as essential for the carbonation resistance to carbonation of fRA concretes, especially when the amount of RFA exceeds 40%. The higher amount of water unexpectedly was reported to have not improved the porosity of concrete, but rather worsened the carbonation resistance of the fRAC. The optimal effective water-to-cement ratio was found to be essential for adequate resistance to carbonation of concrete [137,227]. This was also confirmed by this investigation. The mixtures with a lower estimated effective water-to-cement ratio achieved better carbonation resistance and, moreover, a higher amount of cement in the mixture. The mixtures containing fRMA show a deeper penetration of CO_2 into the concrete, probably caused by the high porous fRMA. The increase in carbonation depth is 155% for fRMAC IA and 123% for fRMAC IIA. On the contrary, fRCAC achieves more favorable results in carbonation resistance, where only one mixture (fRCAC 1 I) increased carbonation depth. However, from the point of view of the results evaluated in previous studies carried out by the same research group [6,126], the negative influence of fRA is significantly lower than the impact of coarse RA.



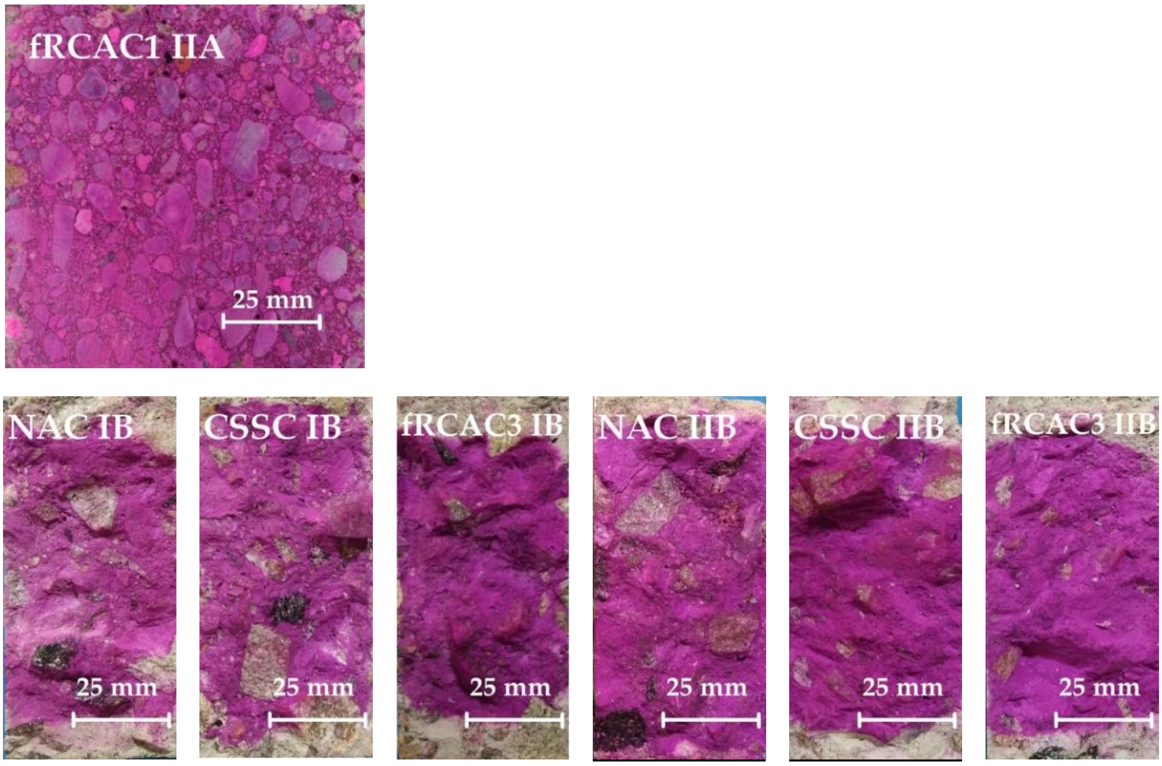


Figure 27. Carbonation depth of NAC and RAC.

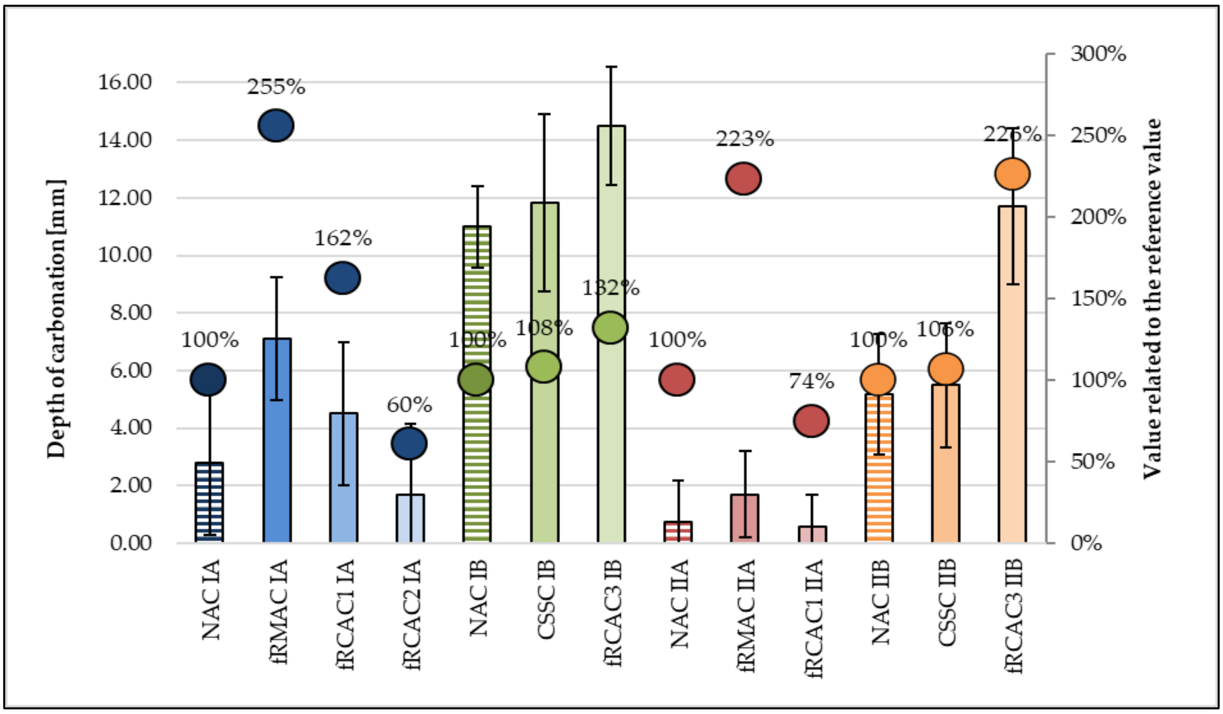


Figure 28. Comparison of carbonation depths of concrete containing fNA, fRCA, and fRMA with control mixtures.

The depth of carbonation of FRCAC3 IB and FRCAC3 IIB concrete after 28 days of exposure of samples to CO_2 was found to increase compared to controls. FRCAC3 IB was found to have higher depth of carbonation by 32% and 23% compared to

NAC IB and CSSC IB. A significant increase in depth was observed in FRCAC3 IIB with respect to NAC IIB and CSSC IIB by 126% and 112%, respectively. The increase in carbonation depth is attributed to the presence of more pores in the fRCA concrete. Similar observations were found by [132,138,221]. The depth of carbonation of all mixes is given in the (**Figure 27** and Figure 28).

5.7 Conclusions of the study

In this study, the experimental verification of the possibilities of replacing natural sand in concrete mixture by fine recycled aggregate. Basically, the basic material properties of fRA were examined. Additionally, the physical, mechanical, and durability properties of concrete containing fRA were verified and discussed. The comparison of the properties between two different regions was done. It is generally known that mechanical properties and durability decrease with replacement of natural sand by fRA, as a maximum substitution level was stated to be 30%. The quality of fRA concrete is negatively influenced by the higher porosity and water absorption of the concrete, which is not easy to determine, so the effective water-to-cement ratio is not clearly known, which was also shown in this study in general. The final conclusions that have been reached, mostly confirming results reported in previous studies, can be summarized in the following points.

- The density of fRA and consequently that of fRAC decrease slightly compared to that of the natural sand and control mix, respectively. Water absorption of fRA and consequently of fRAC increases significantly compared to the natural sand control and the control mix, respectively. On the contrary, the capillary water absorption decreases.
- The compressive strength shows mostly a slight decline; however, from the point of view that natural sand was fully replaced, the decline of this key material property is not essential for future use of this material. The same is possible to report about flexural strength.
- In the case of modulus of elasticity, the highest decline in properties was found, which corresponds to previous studies, that modulus of elasticity is the most affected mechanical property of concrete with replacement of natural aggregate by recycled aggregate in general. The static modulus of elasticity is the key characteristic of the material for the behaviour of reinforced concrete structural elements, due to its lower deflection of beams and slabs. For this reason, it is not recommended to use concrete with full replacement of natural sand for reinforcement concrete structures.
- In contrast, durability properties did not worsen significantly with fRA. The freeze-thaw resistance is completely satisfactory, and, furthermore, the carbonation resistance is slightly affected but not essentially in terms of structural use, but not essentially in terms of structural use, due to the fact that the coating of concrete which covers steel bars is usually 35 mm. However, due to the significant decline of modulus of elasticity, does not allow use of fRAC for reinforcement concrete structures.

The novelty of this study was the comparison of the properties of fRA and fRAC in different regions according to SDG 17. The main objective of this study was to evaluate the substitution possibilities of concrete sand in two different regions with the same research approach. Overall, this work represents efforts in direction of attaining a resource savings and thus addressing the SDG 12. As mentioned in previous studies, the influence of recycling technology and properties of the parent concrete properties on fRA is essential for its future use. For this reason, the basic material properties of fRA and fRAC were examined and compared to find differences in this investigation. Although minor differences in material properties were found, from the authors' point of view, they were not substantial enough to prevent the use of reclaimed sand from construction and demolition waste in each country. Furthermore, it was found that according to local standards, availability of material and results of this investigation, it will be more suitable to use fRAC with full replacement of sand for plain concrete structural elements such as foundation structures, cement and concrete screed, etc.

6 General conclusion

This thesis dealt with the possibility of transitioning to a circular economy in the construction sector. From the literature research, experimental evaluation, environmental assessment, and requirements of practice were found that the amount of mineral CDW remaining in the landfills or recycling centres covers approximately 5% of NA needs. For this reason, it becomes necessary to combine primary and secondary raw materials in optimal ways to balance their use and reduce the consumption of primary sources. This corresponds to the fact that due to the decline of properties, it is possible to replace maximally 30% in the case of RCA and 15% in the case of RMA.

Several studies are discussing how to prepare CDW more suitable for further utilization. Generally, it could be said that the selective demolition process is essential for the high quality of recycled materials from the building and demolition site. It was found that if recycled materials are used to produce new materials the energy needs, and emission production are reduced. Without solving how to efficiently process demolition and recycling, the unsorted CDW will continue to be regarded as one of the main contributors to damaging the natural environment, due to unsorted landfills, illegal dumping, and mixed contamination. Concrete and masonry waste has been identified as the most represented waste in CDW that could be recycled to replace NA.

NA is used not only as an aggregate for concrete but also for backfilling, landscaping, etc. Poorer quality RA, which is not suitable to use as concrete aggregate, is possible to use in the same way. The ideal solution is to use it at the demolition site if it is in accordance with the new construction to eliminate transportation costs and emissions. This is due to the fact, that transportation is one of the most emitters in general, essential for further reducing energy and emissions. However, if the CDW is processed properly, the positive environmental impact of using recycled CDW is clearly met, because of the decrease in the consumption of primary recourses and the decrease of landfilling.

In summary, it will be important to transfer the recycling of concrete and masonry waste to the construction site, to reduce emissions related to the transportation of huge amounts of material. Furthermore, the manufacturer will be necessary to recover materials from construction and demolition sites. And finally, to find the way to use types of aggregate that are not allowed to use according to standards in practice.

The conclusions presented in this thesis are mostly related to the past. Due to the fact, that recycling is related with materials at the end of their first life cycle. In the future, it will be necessary to improve the architectural design approach, making structures and structural elements demountable, more durable, and repairable. This will meet the requirements of circular economy and eco-design, respectively. However, nowadays there is also the pressure to reduce the embodied energies and emissions relating mostly to high-performance structural materials. For this reason, it will be necessary to balance these two aspects in the future.

7 References

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8 Appendix A

Environmental Assessment of Two Use Cycles of Recycled Aggregate Concrete

This scientific paper is based on the research of Tereza Pavlů, under supervision of Vladimír Kočí and Petr Hájek

Author's contribution: conceptualization, methodology, investigation, resources, discussion of the results, writing (overall contribution 70%)

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https://doi.org/10.3390/su11216185

9 Appendix B

The Utilization of Recycled Masonry Aggregate and Recycled EPS for Concrete Blocks for Mortarless Masonry

This scientific paper is based on the research of Tereza Pavlů, Kristina Fořtová, Jakub Diviš and supervision by Petr Hájek under leadership of experimental evaluation by Tereza Pavlů

Author’s contribution: conceptualization, methodology, investigation, resources, discussion of the results, writing (overall contribution 60%)

Number of citations 06/2022 (overall / excluding autocitations)

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- Scopus 15 / 13
- Google scholar 16 / 13

https://doi.org/10.3390/ma12121923

10 Appendix C

Sustainable Masonry Made from Recycled Aggregates: LCA Case Study

This scientific paper is based on the research of Jan Pešta, Tereza Pavlů, Kristina Fořtová, and supervision by Vladimír Kočí under leadership of experimental evaluation by Tereza Pavlů and Environmental assessment by Jan Pešta

Author’s contribution: conceptualization, methodology, investigation, resources, discussion of the experimental results, writing (overall contribution 30%)

Number of citations 06/2022 (overall / excluding autocitations)

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- Scopus 11 / 10
- Google scholar 16 / 14

https://doi.org/10.3390/su12041581

11 Appendix D

Improvement of the Durability of Recycled Masonry Aggregate Concrete

This scientific paper is based on the research of Tereza Pavlů, Kristina Fořtová, Diana Mariaková, Jakub Řepka and supervision by Jiří Pazderka under leadership of experimental evaluation by Tereza Pavlů.

Author's contribution: conceptualization, methodology, investigation, resources, discussion of the experimental results, writing (overall contribution 60%)

Number of citations 06/2022 (overall / excluding autocitations)

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- Scopus 2 / 2
- Google scholar 2 / 1

https://doi.org/10.3390/ma13235486