

SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA

FACULTY OF CIVIL ENGINEERING

Department of Materials Engineering and Physics

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Dissertation Thesis Abstract

**Recycling and use of demolition waste materials for rigid
pavement concrete**

for the award of the academic title of “philosophiae doctor” (PhD)

in the doctorate study programme: D-TS4 Building Technology
in the field of study: Civil Engineering
form of study: full-time

Bratislava 2026

The dissertation Thesis has been prepared at the Department of Materials Engineering and Physics, Faculty of Civil Engineering, Slovak University of Technology in Bratislava

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The dissertation thesis abstract was sent on: 16.04.2026

The dissertation defence will take place on 18.06.2026 at 10:00 in the meeting room of the Department of Materials Engineering and Physics, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Radlinského 11, 810 05 Bratislava.

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1 Abstract

The dissertation research addresses the growing environmental and resource challenges associated with construction and demolition waste, which constitutes 30–40 % of total waste in the European Union. The study focuses on the recycling of CDW into aggregates for cement-based composites, particularly for use in the lower layers of rigid pavements. The main goal is to develop sustainable concrete mixtures that meet technical, durability, and economic requirements while reducing environmental impact. The research investigates three main types of recycled aggregates: recycled concrete aggregate, recycled masonry aggregate, and mixed recycled aggregate, including fine fractions. These materials typically exhibit higher porosity and water absorption than natural aggregates, which may negatively influence concrete properties. Therefore, the study emphasises optimising mix design, including cement content, use of superplasticisers, and fibre reinforcement. The experimental program consisted of four stages. The first stage analysed CDW recycling technologies and environmental impacts using life cycle assessment. Results confirmed that recycled aggregates significantly reduce CO₂ emissions, energy consumption, and landfill use. The second stage involved trial concrete mixtures, identifying optimal compositions and materials. Portland cement CEM II/B-S 42.5 N and a polycarboxylate superplasticizer were found to be the most effective combination. Results showed that concretes with RCA achieved comparable or even higher compressive strength (up to 53.4 MPa) than conventional concrete due to improved bonding and internal curing effects. RMA-based concretes had lower strength but remained suitable for pavement applications. All mixtures met durability requirements, including frost resistance (F100). Increasing cement content from 300 to 350 kg/m³ provided only marginal strength improvement, making the lower dosage more cost-effective. For modification concretes and improving their properties fibre reinforcement was applied. Polypropylene fibres did not improve mechanical properties and increased water demand. Microstructural analyses (SEM, MIP, XRPD, FTIR) confirmed proper hydration processes and absence of harmful components. Economic evaluation showed that recycled aggregate concrete can be 19–37 % cheaper than conventional concrete. The study proves that recycled aggregates are a viable, sustainable alternative to natural materials in road construction. Optimal concrete mixtures with recycled aggregates meet all technical standards, reduce

environmental impact, and offer significant economic benefits, supporting the transition toward circular economy practices in the construction industry.

2 Anotácia

Dizertačný výskum sa zaoberá rastúcimi environmentálnymi a surovinovými výzvami spojenými so stavebným a demolačným odpadom, ktorý predstavuje 30–40 % celkového odpadu v Európskej únii. Štúdia sa zameriava na recykláciu demolačného odpadu na kamenivo pre cementové kompozity, najmä na použitie v spodných vrstvách tuhých vozoviek. Hlavným cieľom je vyvinúť udržateľné betónové zmesi, ktoré spĺňajú technické, trvanlivostné a ekonomické požiadavky pri súčasnom znížení environmentálneho vplyvu. Výskum sa zaoberá tromi hlavnými typmi recyklovaného kameniva: recyklované betónové kamenivo, recyklované murovacie kamenivo a zmiešané recyklované kamenivo, vrátane jemných frakcií. Tieto materiály sa zvyčajne vyznačujú vyššou pórovitosťou a nasiakavosťou v porovnaní s prírodným kamenivom, čo môže negatívne ovplyvniť vlastnosti betónu. Preto sa práca zameriava na optimalizáciu návrhu zmesí, vrátane obsahu cementu, použitia superplastifikátorov a vláknovej výstuže. Experimentálny program pozostával zo štyroch etáp. V prvej etape sa analyzovali technológie recyklácie demolačného odpadu a environmentálne dopady pomocou hodnotenia životného cyklu. Výsledky potvrdili, že recyklované kamenivo výrazne znižuje emisie CO₂, spotrebu energie a potrebu skládkovania. Druhá etapa zahŕňala návrh skúšobných betónových zmesí a identifikáciu optimálnych zložení a materiálov. Ako najefektívnejšia kombinácia sa ukázal portlandský cement CEM II/B-S 42.5 N a polykarboxylátový superplastifikátor. Výsledky ukázali, že betóny s recyklovaným betónovým kamenivom dosiahli porovnateľnú alebo dokonca vyššiu pevnosť v tlaku (až 53,4 MPa) ako konvenčný betón, a to vďaka lepšej súdržnosti a efektu vnútorného ošetrovania. Betóny na báze recyklovaného murovacieho kameniva vykazovali nižšiu pevnosť, no zostali vhodné pre použitie v konštrukciách vozoviek. Všetky zmesi spĺňali požiadavky na trvanlivosť vrátane mrazuvzdornosti (F100). Zvýšenie obsahu cementu z 300 na 350 kg/m³ prinieslo len minimálne zlepšenie pevnosti, čo robí nižšie dávkovanie ekonomicky výhodnejším. Na modifikáciu betónov a zlepšenie ich vlastností bola použitá vláknová výstuž. Polypropylénové vlákna nezlepšili mechanické vlastnosti a zvýšili potrebu vody. Mikroštruktúrne analýzy (SEM, MIP, XRPD, FTIR) potvrdili správny priebeh hydratačných procesov a neprítomnosť škodlivých zložiek. Ekonomické hodnotenie

ukázalo, že betón s recyklovaným kamenivom môže byť o 19–37 % lacnejší ako konvenčný betón. Štúdia dokazuje, že recyklované kamenivo predstavuje realizovateľnú a udržateľnú alternatívu k prírodným materiálom v cestnom staviteľstve. Optimálne betónové zmesi s recyklovaným kamenivom spĺňajú všetky technické normy, znižujú environmentálny dopad a prinášajú významné ekonomické výhody, čím podporujú prechod na princípy obehového hospodárstva v stavebníctve.

3 Introduction

The construction industry is one of the largest consumers of natural resources worldwide and, at the same time, one of the major producers of waste. Construction and demolition waste (CDW) arises from the demolition of buildings, renovation of infrastructure, reconstruction of transport networks, industrial activities, and emergency events. According to available statistical data, CDW represents the largest waste stream in the European Union, accounting for approximately 30–40 % of the total waste generated annually [1]. Similar trends have been reported in North America and Asia, where rapid urbanisation and infrastructure renewal have led to a continuous increase in CDW volumes [2]. Traditionally, CDW has been disposed of in landfills, causing long-term environmental burdens, occupation of land, and loss of potentially valuable secondary raw materials. At the same time, the demand for natural aggregates for concrete production continues to grow, resulting in depletion of natural resources, destruction of landscapes, increased energy consumption, and higher greenhouse gas emissions. These issues have intensified the search for sustainable alternatives in construction materials engineering.

The recycling of CDW into aggregates suitable for cement composites represents a key strategy within the framework of sustainable development and the circular economy. Recycled aggregates enable partial or full replacement of natural aggregates, reduce landfill demand, and decrease the environmental footprint of concrete production. However, recycled aggregates generally exhibit higher porosity, higher water absorption, and more heterogeneous composition compared to natural aggregates, which may negatively influence the properties of concrete.

This dissertation thesis focuses on the systematic investigation of the use of recycled aggregates derived from CDW in cement-based composites intended primarily for road construction. The research is oriented towards practical applications, particularly the lower layers of rigid pavements, where large material

volumes are required and where the use of recycled aggregates can bring significant environmental and economic benefits. The originality of the presented research lies in the comprehensive comparison of different types of recycled aggregates, including recycled concrete aggregates (RCA), recycled masonry aggregates (RMA), and mixed recycled aggregates (MRA), as well as in the inclusion of fine recycled fractions that are rarely applied in practice. The dissertation also evaluates the influence of cement content, fibre reinforcement, and slag-rich cement on the performance of recycled-aggregate concrete. The thesis aims to bridge the gap between laboratory research and practical application by proposing concrete compositions that meet technical, durability, and regulatory requirements while contributing to sustainable construction practices.

4 Background of the research

Construction and demolition waste (CDW) consists mainly of concrete, masonry, asphalt, wood, metals, glass, and plastics. European legislation promotes waste prevention and recycling, setting a mandatory target of at least 70 % recycling of non-hazardous CDW by weight [3]. Achieving this target requires not only effective waste-management systems but also the development of technologies and materials capable of utilising recycled components. Numerous studies confirm that recycling CDW significantly reduces landfill use and conserves natural aggregate resources [4]. Moreover, recycled aggregates generally exhibit lower embodied energy and reduced CO₂ emissions compared with natural aggregates, particularly when locally sourced recycling facilities are used [5]. Despite these advantages, the application of recycled aggregates in concrete remains limited because of concerns regarding variability, durability, and long-term performance. Therefore, extensive experimental verification is necessary before recycled aggregates can be widely adopted in structural and road concretes.

Recycled aggregates are commonly classified based on their origin. Recycled concrete aggregates originate from crushed concrete elements and consist of natural aggregate particles covered with adhered cement mortar. This adhered mortar increases porosity and water absorption, which can negatively affect concrete properties [6]. Recycled masonry aggregates are produced from ceramic bricks and tiles. They are characterized by lower density, higher water absorption, and lower strength compared to RCA. Mixed recycled aggregates represent heterogeneous

mixtures obtained from uncontrolled demolition processes and may include concrete, masonry, asphalt, and minor contaminants.

Previous research has demonstrated that concretes containing recycled aggregates generally exhibit lower compressive strength and modulus of elasticity compared to conventional concrete, particularly at high replacement ratios [7]. However, for non-critical structural applications and road construction, the achieved properties are often sufficient. The use of chemical admixtures, optimized grading curves, and fibre reinforcement can significantly improve the mechanical performance and durability of recycled aggregate concrete [8]. Fine recycled aggregates, although challenging, offer significant potential for sustainable material development when properly incorporated into mix designs. Fig. 1 demonstrates cross-sectional cutting of recycled-aggregate concrete and recycled aggregates of various type for its manufacturing.



Figure 1: Cross section of concrete on recycled aggregate

5 Objectives and research scope

The objective of the work is the development and analysis of sustainable cement concrete compositions based on recycled aggregates of different types for road construction, particularly for the lower layers of rigid pavements, with guaranteed strength and durability.

The research was carried out within the framework of a grant project of the Slovak Government Office entitled “Scholarships for excellent researchers threatened by the war conflict in Ukraine”, number 09103-03-V01-00141, under “Component 9: Effective management and strengthening of funding for research, development and innovation”, reform/investment – “Reform 3: Excellent science”.

6 Materials

Portland cement CEM II/B-S 32.5 R, containing 21 wt% blast-furnace slag

(Považská cementarėň Inc., Slovakia), was used for the trial concrete series (Stage II). Portland cement CEM II/B-S 42.5 N, containing 21 wt% blast-furnace slag (Považská cementarėň Inc., Slovakia), was used for the main concrete series (Stage III). Cement CEM III/A 32.5 N, with a blast-furnace slag content of 65 wt% (CRH Cement Multicem, Germany), was used for the additional series with dispersed fibre reinforcement (Stage IV). The polycarboxylate-type superplasticisers Soudal Soudaplast (Soudal, Czechia) and Berament HT28 (BetonRacio Ltd., Slovakia) were applied in an amount of 1.2 % by mass of cement, in accordance with the manufacturers' recommendations. The main characteristics of Soudal Soudaplast are a density of 1,050 kg/m³ at 20 °C and pH 6; the corresponding values for Berament HT28 are 1,080 kg/m³ and pH 6.

Four types of coarse aggregate in the 8/16 mm size fraction were used in the experiments: river gravel (RG), recycled concrete aggregate (RCA), recycled masonry aggregate (RMA), and mixed recycled aggregate (MRA). The composition based on river gravel and quartz sand was used as the basic reference mixture against which the experimental concretes were compared. The RCA consisted of extracted granite gravel and crushed concrete with a low content of adhered cement-sand matrix. The RMA consisted of crushed brickwork and ceramic and porcelain stoneware tiles, with a small amount of glass and aerated concrete. The MRA contained 35.3 % cement-sand matrix, 29.8 % granite bonded to the cement-sand matrix, 24.7 % pure granite, 9.0 % bricks and ceramic tiles, 0.8 % asphalt concrete, and 0.4 % steel wire. Three types of fine aggregate in the 0/4 mm size fraction were used for concrete production: quartz sand, fine recycled concrete aggregate (RCA-f), and fine recycled masonry aggregate (RMA-f). Fig. 2 illustrates types of recycled aggregates used for concrete production.

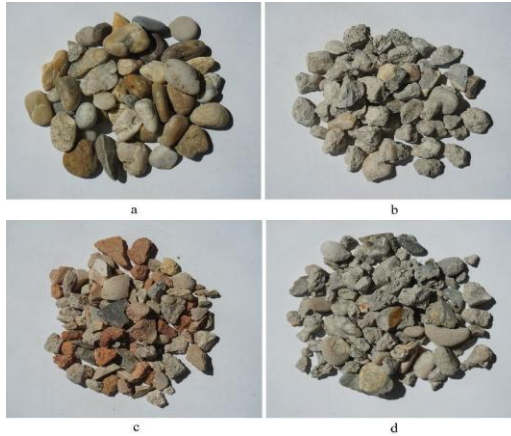


Figure 2: Coarse aggregates for the production of concretes: (a) river gravel, (b) recycled concrete aggregate, (c) recycled masonry aggregate, and (d) mixed recycled aggregate

For the additional experimental phase conducted in the fourth stage of the research, aimed at obtaining recycled-aggregate concretes with improved properties (primarily flexural strength), mixtures with dispersed fibre reinforcement were produced. Three types of fibre were used: polypropylene fibre EGIBI PP 34 $\mu\text{m}/12$ mm, polypropylene fibre BeneSteel 55, and alkali-resistant glass fibre ANTI-CRAK HP 12.

5. Methods of research

Concrete mixtures were designed with cement contents of 300 kg/m^3 and 350 kg/m^3 and with minimal consistency corresponding to road-concrete requirements. Before testing, the samples were cured in a special chamber at a relative humidity of $(90 \pm 5) \%$ and tested at the ages of 3 and 28 days. The experimental programme included the determination of density, water absorption, compressive strength, flexural strength, frost resistance, impact resistance, and thermophysical properties. Advanced analytical methods such as SEM, MIP, XRPD, FTIR, and thermal analysis were used to study microstructural characteristics. A more detailed description of the test methodology is provided below.

6. Research results

Stage I. Recycling technology and environmental assessment

The first stage of the dissertation research analyses technologies for the

dismantling, sorting, and processing of construction and demolition waste (CDW) aimed at obtaining homogeneous and high-quality recycled aggregates (RA). Due to the high cost of demolition, the correct selection of dismantling technologies is essential for reducing expenses, improving material separation, and maximizing the reuse of secondary raw materials. The environmental assessment was performed using a life cycle assessment approach in accordance with EN 15804:2012. Environmental impact indicators were evaluated for 1 m³ of C25/30 concrete using data from the ÖKOBAUDAT database [9]. The results demonstrate that the secondary use stage (D1) provides a positive environmental effect, reducing CO₂ emissions, resource consumption, and overall environmental impact compared to natural aggregates. The use of recycled aggregates therefore offers both environmental and economic benefits and supports sustainable development in construction.

Stage II. Trial composition investigation

At the second stage of the dissertation research, a trial experimental programme was conducted to develop and compare concrete mixtures based on natural and recycled aggregates in order to determine optimal compositions for rigid-pavement bases. The mixtures were designed using different types of coarse and fine aggregate, two cement classes, and two superplasticiser additives. In total, four series of compositions were developed, differing in cement content, aggregate type, and admixture. The study compared concretes based on river gravel (reference compositions), recycled concrete aggregate (RCA), and recycled masonry aggregate (RMA) as coarse aggregates, as well as quartz sand, fine recycled concrete aggregate (RCA-f), and fine recycled masonry aggregate (RMA-f). Cement contents of 300 kg/m³ and 350 kg/m³ were selected to evaluate the influence of cement dosage on concrete properties. Portland cements CEM II/B-S 32.5 R and CEM II/B-S 42.5 N were used, while the effect of the polycarboxylate superplasticisers Soudal Soudaplast and Berament HT28 was also investigated.

Based on the trial results, Portland cement CEM II/B-S 42.5 N and the superplasticizer Berament HT28 were identified as the most effective combination for concretes with recycled aggregates. All tested recycled aggregate concretes demonstrated sufficient mechanical properties for use in the lower layers of rigid pavements.

Stage III. Performance of optimal concretes on recycled aggregates

This stage presents an extensive experimental investigation of the optimised concrete mixtures incorporating various types and sizes of recycled aggregate, building on the results of the previous trial stage. Specifically, the mixtures used recycled concrete aggregate (RCA) and recycled masonry aggregate (RMA) in comparison with traditional natural aggregates such as river gravel and quartz sand. Ten optimal concrete mixtures were formulated and tested, divided into two series according to cement content: Series A with 300 kg/m³ and Series B with 350 kg/m³. The primary objective was to assess their suitability for use in the lower layers of rigid pavements through a comprehensive analysis of fresh-state properties, hardened-state characteristics, microstructure, durability, and cost. The compositions are presented in Table 1.

Table 1: Compositions of the optimal concrete mixtures

Label	Cement, [kg]	Coarse aggregate,		Fine aggregate,		Additive, [kg]	Water, [l]	w/c	Stiffness of the mixture
		Type	[kg]	Type	[kg]				
1A	300	RG	1,252			3.6	124	0.41	S1
2A		RCA	1,122	quartz	762		138	0.46	S1
3A		RMA	982				175	0.58	S1
4A		RCA	1,070	RCA-f	755		168	0.56	S1
5A		RMA	803	RMA-f	765		229	0.76	S1
1B	350	RG	1,233			4.2	136	0.39	S1
2B		RCA	1,112	quartz	727		141	0.40	S1
3B		RMA	968				183	0.52	S1
4B		RCA	992	RCA-f	752		166	0.47	S1
5B		RMA	789	RMA-f	704		232	0.66	S1

* the specified amount of raw materials is given for the production of 1 m³ of concrete mixture

To achieve the target consistency (S1 stiffness, corresponding to a cone slump of 1–2 cm), the required w/c ratio of the overall mixture increased in direct relation to the porosity and water absorption of the aggregates. Mixes containing RMA, especially those incorporating fine ceramic aggregate (RMA-f), demanded the highest w/c ratios. However, a critical recalculation accounting for water absorbed by the porous coarse aggregates revealed a significantly lower effective w/c ratio for the cement-sand

matrix itself. For instance, RCA-based mixes had an effective matrix w/c as low as 0.22–0.24, indicating that the additional water primarily saturated the aggregate rather than weakening the binding paste, which positively influenced subsequent hydration and strength development. The mechanical characteristics of the concretes at 28 days are presented in Table 2.

Table 2: Physico-mechanical characteristics of the studied concretes at the age of 28 days

Label	Density [kg/m ³]	Water absorption by volume, [%]	Water absorption by mass, [%]	Compressive strength, [MPa]	Flexural strength, [MPa]	Frost resistance	Impact resistance, [J/cm ²]
1A	2,460	6.2	2.6	48.0	3.61	F100	1.93
2A	2,340	7.6	3.4	49.2	3.77	F100	1.98
3A	2,240	9.7	4.5	41.6	3.18	F100	2.40
4A	2,290	7.8	3.4	35.5	3.37	F100	2.01
5A	2,060	13.9	7.2	27.1	2.82	F100	2.52
1B	2,470	5.6	2.3	50.2	3.62	F100	1.90
2B	2,360	7.6	3.4	53.4	3.84	F100	1.90
3B	2,240	8.7	3.0	42.7	3.35	F100	2.49
4B	2,250	7.7	3.0	39.8	3.57	F100	1.94
5B	2,040	12.4	5.7	27.7	2.89	F100	2.73

The physical and mechanical properties of the concretes showed clear dependencies on aggregate type. Density decreased with increasing aggregate porosity, with the reference mixes using dense river gravel achieving the highest values (2460 kg/m³) and the RMA-based mixes the lowest (2040–2240 kg/m³). Consequently, water absorption was highest for the more porous RMA-based concretes. In terms of mechanical performance, a standout result was that concrete made with RCA and quartz sand (Mixes 2A/2B) not only matched but slightly exceeded the compressive and flexural strength of the natural-aggregate reference concrete. This is attributed to the rough surface texture of RCA, which improved bonding with the cement matrix, in contrast to the smoother river gravel, and to the beneficial effect of internal curing from the absorbed water. The 28-day compressive strength of the RCA concretes reached up to 53.4 MPa. While RMA-based concretes exhibited lower compressive strength, their values (27.1 – 42.7 MPa) remained sufficient for the intended application and were better than some previous studies had indicated. Notably, increasing the cement dosage from 300 kg/m³ to 350 kg/m³ resulted in only marginal improvements in compressive strength (2 – 12 %), which calls into question the cost-effectiveness of the higher cement content. Flexural-strength behaviour followed the same trend as compressive strength. Graphs in Fig. 3 demonstrates compressive and flexural strength of concrete series 1A – 5A, 1B – 5B at

the ages of 3 and 28 days.

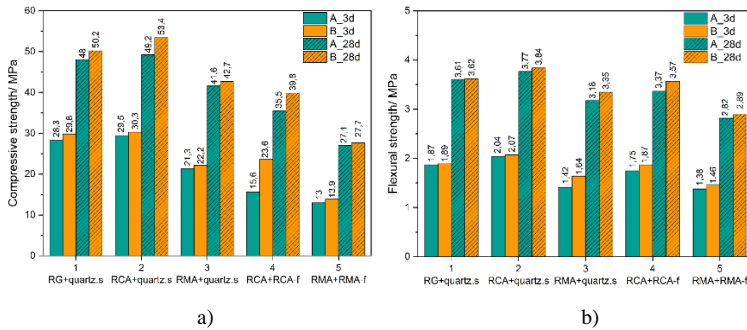


Figure 3: (a) compressive strength and (b) flexural strength of concretes at the ages of 3 and 28 days

Microstructural and chemical analyses provided insight into the underlying reasons for the performance differences. Mercury intrusion porosimetry (MIP) confirmed a direct link between aggregate type and pore structure, with total porosity increasing from the reference mixes to RCA and further to RMA-based mixes. Pore classification and its influence on strength followed established models. Scanning electron microscopy (SEM) images revealed the presence of standard hydration products such as C-S-H, portlandite, and ettringite, and highlighted the interfacial transition zone, showing good bonding for RCA and some areas for improvement in the RMA mixes. Complementary techniques (XRPD, FTIR, and TG/DTG/DSC) verified the expected chemical composition, confirmed the absence of harmful inclusions, and demonstrated the normal progression of cement hydration, including the decomposition of phases such as ettringite, C-S-H, portlandite, and calcium carbonate over specific temperature ranges.

In conclusion, the research demonstrates that concretes utilising recycled aggregates are technically viable and economically advantageous for road-base construction. Recycled concrete aggregate combined with quartz sand emerged as the most effective overall, providing enhanced mechanical performance. Recycled masonry aggregate proved optimal for applications requiring high impact resistance. The study found that a cement dosage of 300 kg/m³ is more than adequate, as a higher dosage yielded negligible benefits. The research also confirmed that while a high overall mix w/c is needed for workability with porous aggregates, the effective w/c

ratio of the cement-sand matrix remains low, mitigating the typical adverse effect of excess water on strength. Crucially, all tested compositions met or exceeded the relevant standards for strength and durability, validating the sustainable and practical use of recycled aggregates in the lower layers of rigid pavements.

Stage IV. Modified concrete compositions

This stage investigated two key modifications of concrete mixtures incorporating recycled aggregates: the addition of dispersed fibre reinforcement and the use of non-separated, heterogeneous mixed recycled aggregate (MRA). The aim was to enhance selected mechanical properties, primarily flexural strength, and to assess the feasibility of utilising more complex, unprocessed recycled materials in road-pavement concrete.

Influence of Fibre Reinforcement on RA Concrete Properties

A supplementary series of concretes was developed incorporating three types of fibre: polypropylene microfibre (EGIBI PP), polypropylene macrofibre (BeneSteel 55), and alkali-resistant glass fibre (ANTI-CRAK HP). These were added to three base compositions containing different aggregates: natural river gravel, recycled concrete aggregate (RCA) with quartz sand, and RCA with fine RCA (RCA-f). All mixtures used a high-slag cement (CEM III/A) at a dosage of 300 kg/m³ and were designed for S1 consistency.

The inclusion of fibre significantly affected the fresh concrete's water demand. The large polypropylene macrofibre (BeneSteel 55) substantially increased the water required to achieve the target workability, elevating the water-cement (w/c) ratio by 13 – 15%. In contrast, the microfibre and glass fibre had a minimal impact on water demand, increasing it by only 0 – 7 %. Consequently, the density of the hardened concrete was most reduced (by 1 – 5 %) in mixtures containing the BeneSteel fibre.

Mechanical testing at 28 days revealed a distinct performance difference among the fibres. Both polypropylene fibres failed to improve compressive strength and even caused a slight reduction (0.3 – 5 %), a result primarily attributed to the associated increase in the w/c ratio. The macrofibre (BeneSteel 55) also reduced flexural strength by 5 – 6 %. The microfibre provided only a marginal increase in flexural strength (1 – 4 %). In contrast, the alkali-resistant glass fibre was the only type to enhance both compressive and flexural strength, increasing them by 4 – 12 % and by up to 9 %, respectively. While technically effective for boosting performance, its use warrants an

assessment of economic feasibility. All fibre-reinforced mixtures demonstrated excellent durability, achieving a frost-resistance grade of at least F100. The research concluded that, for stiff concretes made with recycled aggregates, the tested polypropylene fibres were ineffective, whereas alkali-resistant glass fibre presents a viable option for performance enhancement.

Influence of Aggregate Homogeneity (Mixed Recycled Aggregates) on Concrete Characteristics

This phase evaluated the performance of concrete made with non-separated, heterogeneous mixed recycled aggregate (MRA), directly comparing it with concretes made with natural river gravel, RCA, and RMA. All mixtures used CEM II/B-S cement at 300 kg/m³.

The critical finding was that concrete produced with MRA exhibited mechanical properties equivalent to those of the reference concrete made with natural river gravel, achieving a 28-day compressive strength of 48.1 MPa and a flexural strength of 3.6 MPa. This confirms that the excess mixing water was primarily absorbed by the porous MRA and did not weaken the cementitious matrix. Furthermore, MRA concrete demonstrated superior impact resistance (2.20 J/cm²), 15 % higher than the reference mix, benefiting from the energy-dissipating characteristics of the ceramic and porous constituents within the MRA. All mixes, including those with MRA, satisfied the frost-resistance requirement of F100.

This study conclusively validates the technical viability of using unprocessed mixed recycled aggregates from construction and demolition waste to produce concrete suitable for road-base layers. This approach offers substantial environmental and economic benefits by utilising a low-cost, widely available secondary material, thereby conserving natural resources and diverting waste from landfills.

7. Conclusions

The following conclusions were drawn from the research:

- During this research, the life cycle of buildings and structures was assessed, including the demand for materials and energy resources at each stage. The potential recycling of construction waste resulting from the dismantling of such structures was considered the final stage of a structure's life cycle. Recycling and reuse of construction

waste lead to a number of benefits: waste reduction; lower emissions into the atmosphere and hydrosphere; lower energy and water consumption; reduced use of natural resources; reduced anthropogenic impact on the environment; economic benefits; and the possibility of reclaiming construction-waste landfills.

- As part of the study, technologies for the dismantling of buildings and structures were analysed. It was found that effective methods for processing construction waste have been developed, enabling maximum recovery of high-quality secondary concrete aggregates.
- During the research, five effective and optimised concrete compositions based on recycled aggregates were developed: river gravel and quartz sand; recycled concrete aggregate and quartz sand; recycled masonry aggregate and quartz sand; recycled concrete aggregate of coarse and fine size; and recycled masonry aggregate of coarse and fine size. An optimal cement type and superplasticiser were identified. In addition to coarse recycled aggregates, fine recycled aggregates were also used, thereby maximising the use of secondary materials.
- The concretes under investigation were tested for mechanical characteristics at 3 and 28 days, namely density, water absorption, frost resistance, compressive strength, flexural strength, impact resistance, and thermophysical properties. The tests showed that concrete based on recycled aggregates has the necessary strength characteristics for use in the construction of the lower layers of rigid pavements. According to STN 73 6102 and STN 73 6101, concretes for the lower layers of rigid pavements must have a frost-resistance grade of at least F25 or F50, depending on regional environmental conditions, and flexural strength of at least 1 MPa or 1.2 MPa, depending on the road category. All developed recycled-aggregate concrete compositions fully satisfied the requirements of the relevant regulations for the construction of the lower layers of rigid pavements.
- It was established that the optimal concrete based on recycled concrete aggregate and quartz sand achieved approximately 2 % higher compressive strength at 28 days than the concrete based solely on natural aggregates, namely river gravel and quartz sand.
- To determine the structural properties of the developed concretes, the following analyses were carried out: FTIR, TG/DTG/DSC, XRPD, MIP, and SEM. The analyses confirmed the absence of deleterious inclusions that could promote corrosion or pose risks to human health and supported the adequacy of sample preparation, as indicated by

processes involving calcium hydroxide and calcium carbonates. XRPD provided information on the mineralogy of the concrete components. MIP demonstrated the relationship between the type of fine aggregate and pore-size distribution in concrete. SEM observations confirmed the presence of C-S-H phases, ettringite, and other cement-hydration products.

- The prices of the prototype concretes were calculated, and the cost of concretes made with recycled aggregates was found to be 19 – 37 % lower than that of conventional concrete, confirming the economic feasibility of using recycled aggregates in concrete production.
- During the study, it was found that the optimal concrete compositions were those containing 300 kg of cement per m³ of concrete mixture and 1.2 % superplasticiser by mass of cement. Increasing the cement content to 350 kg per m³ of mixture did not lead to a significant increase in strength.
- Experiments were conducted on modifying recycled-aggregate concrete by adding fibres of different types as dispersed reinforcement. These concretes did not show a sufficient increase in mechanical properties; moreover, coarse polypropylene fibre reduced compressive and flexural strength because it increased the w/c ratio. Thus, the use of fibre as dispersed reinforcement in concretes on recycled aggregates was not efficient from an economic point of view.
- Experiments were also carried out on the production of concrete based on secondary aggregates with a heterogeneous structure, namely mixed recycled aggregate. The results showed no significant deterioration in the strength characteristics of concrete when mixed recycled aggregate was used instead of homogeneous recycled concrete aggregate. This confirms the suitability of such aggregate for concrete production, especially in view of its widespread availability and economic benefits.

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9 Publishing activities

V3 Vedecký výstup publikačnej činnosti z časopisu

V3_01 Artem Chystiakov, O. A. Q Ziada, S. A. Ahmed et al. Experimental Investigation of 3D-Printed Structures from Wood-Based Polymer Composites, 17 November 2025, PREPRINT (Version 1) available at Research Square, <https://doi.org/10.21203/rs.3.rs-7997275/v1>. (Accepted for publication on 24.02.2026). ADC

V3_02 KROVIAKOV, Sergii - CHYSTIAKOV, Artem. Properties of concrete and fiber-reinforced concrete for bases of road clothes based on secondary

aggregates with heterogeneous composition. In *Modern Construction and Architecture*. No. 7 (2024), s. 99-108. ISSN 2786-6696. V databáze: DOI: 10.31650/2786-6696-2024-7-99-108. ADE

V3_03 KROVIAKOV, Sergii - CHYSTIAKOV, Artem. Strength of concrete for bases of road clothes on different types of secondary gravel and sand. In *Modern Construction and Architecture*. No. 5 (2023), s. 79-89. ISSN 2786-6696. V databáze: DOI: 10.31650/2786-6696-2023-5-79-89. ADE

V3_04 KROVIAKOV, Sergii - CHYSTIAKOV, Artem. Vykorystannya vtorynnykh zapovnyuvachiv dlya betoniv osnovy dorozhn'oho odyahu = The use of secondary aggregates for concrete pavement bases. In *Nauka ta budivnytstvo* [elektronický zdroj]. Vol. 38, no. 4 (2023), online, s. 34-40. ISSN 2313-6669. V databáze: DOI: 10.33644/2313-6679-4-2023-5. ADE

V3_05 KROVIAKOV, Sergii; CHYSTIAKOV, Artem; BERSHADSKYI, Anton; SHEVCHENKO, Tetyana. Concretes on secondary crushed stone as a promising material for the rigid pavement base. *Bulletin of Odessa State Academy of Civil Engineering and Architecture*, no. 87 (2022), online, p. 85–91. DOI: 10.31650/2415-377X-2022-87-85-91. ADE

V3_06 NEPOMYASHCHY, Alexander; VYROVOY, Valeriy; CHISTYAKOV, Artem.aedrovich. Frost resistance of cement-sand and concrete beams during unilateral freezing. In *Croatian Regional Development Journal*. Vol. 2, Issue 1 (2021), online, pp 73-84. e-ISSN: 2718-4978. V databáze: DOI: 10.2478/crdj-2021-0009. ADE

V2 Vedecký výstup publikačnej činnosti ako časť editovanej knihy alebo zborníka

V2_01 CHYSTIAKOV, Artem - KROVIAKOV, Sergii - BERSHADSKYI, Anton - MEDVEĎ, Igor - SLANÝ, Michal. Sustainable effect of using recycled aggregates for road concrete production. In *Sustainability in energy and buildings 2024: conference proceedings* [elektronický zdroj]. 1. vyd. Cham : Springer Nature, 2025, online, s. 177-188. ISBN 978-981-96-5068-2. V databáze: DOI: 10.1007/978-981-96-5069-9_16 ; SCOPUS: 2-s2.0-105019648502. AFC

- V2_02 CHYSTIAKOV, Artem - MEDVEĎ, Igor - SLANÝ, Michal. Mechanical and structural properties of cement concretes on recycled aggregates. In *Clay Minerals and Selected Industrial Minerals in Material Science, Applications, and Environmental Technology : Book of Abstracts*. 1. vyd. Bratislava : Slovak Clay Group, 2025, online, s. 8. ISBN 978-80-972367-9-3. BFB
- V2_03 CHYSTIAKOV, Artem. Peculiarities of Ph.D. studying programs in Slovakia. In *Materialy XXX Mizhnarodnoi naukovo-metodychnoi konferentsiyi "Upravlinnya yakistyu pidhotovky fakhivtsiv"*, častina 1. 1. vyd. Odesa : Odeska deržavna akademija budivnictva ta architekturi, 2025, S. 170. ISSN 2412-1932. BFA
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- V2_05 CHYSTIAKOV, Artem - TOCIK, Martin. Determination optimal compositions for concrete on mixed recycled aggregates. In *Advances in Architectural, Civil and Environmental Engineering (AACEE 2025) : 35th Annual PhD Student Conference on Applied Mathematics, Building Technology, Geodesy and Cartography, Landscaping, Theory and Environmental Technology of Buildings, Theory and Structures of Buildings, Theory and Structures of Civil Engineering Works, Water Resources Engineering. November 5th 2025, Bratislava, Slovakia*. 1. vyd. Bratislava : Spektrum STU, 2025, online, s.47-54. ISBN 978-80-227-5555-9. AFD
- V2_06 KÁZSMÉR, Michal - CHYSTIAKOV, Artem. Návrh experimentu drevo-plastového kompozitného nosníka tlačeného na 3D tlačiarňi. In *Advances in Architectural, Civil and Environmental Engineering (AACEE 2025) : 35th Annual PhD Student Conference on Applied Mathematics, Building Technology, Geodesy and Cartography, Landscaping, Theory and Environmental Technology of Buildings, Theory and Structures of Buildings, Theory and Structures of Civil Engineering Works, Water Resources Engineering. November 5th 2025, Bratislava, Slovakia*. 1. vyd. Bratislava : Spektrum STU, 2025, online, s. 343-350. ISBN 978-80-227-5555-9. AFD

- V2_07 CHYSTIAKOV, Artem - KROVIKOV, Sergii - IHNATENKO, Andrii - MEDVEĎ, Igor. Use of secondary aggregates for concrete production. In *Juniorstav 2024* [elektronický zdroj] : *proceedings of the 26th International Scientific Conference of Civil Engineering. Brno, ČR, 25. 1. 2024.* 1. vyd. Brno : ECON publishing, 2024, online, [8] s. ISBN 978-80-86433-83-7. V databáze: DOI: 10.13164/juniorstav.2024.24091. AFC
- V2_08 CHYSTIAKOV, Artem. Using of mixed recycled aggregates for concrete production. In *Advances in Architectural, Civil and Environmental Engineering (AACEE 2024) : 34th Annual PhD Student Conference on Applied Mathematics, Building Technology, Geodesy and Cartography, Landscaping, Theory and Environmental Technology of Buildings, Theory and Structures of Buildings, Theory and Structures of Civil Engineering Works, Water Resources Engineering. October 23rd 2024, Bratislava, Slovakia.* 1. vyd. Bratislava : Spektrum STU, 2024, online, s. 62-69. ISBN 978-80-227-5461-3. AFD
- V2_09 CHYSTIAKOV, Artem - BODIAK, Kyrylo. Methodology for concrete research based on secondary aggregates. In *Advances in Architectural, Civil and Environmental Engineering (ACEE 2023) [elektronický zdroj] : 33rd Annual PhD Student Conference on Applied Mathematics, Building Technology, Geodesy and Cartography, Landscaping, Theory and Environmental Technology of Buildings, Theory and Structures of Buildings, Theory and Structures of Civil Engineering Works, Water Resources Engineering. October 25th 2023, Bratislava, Slovakia.* 1. vyd. Bratislava : Spektrum STU, 2023, CD-ROM, s. 70-76. ISBN 978-80-227-5378-4. AFD