Impact of Locally Available Recycled Concrete Aggregate on Concrete's Mechanical and Durability Properties

Robert Bušić, Ivana Miličević, Larisa Šargač

***Abstract*—**The construction industry generates a large amount of waste, which poses a challenge for disposal and often requires significant areas for landfill. Therefore, recycling construction waste has become imperative. This study focuses on investigating the use of locally available recycled concrete as a substitute for traditional aggregates and analyzing the impact of this change on the mechanical and durability properties of concrete. The research begins with the crushing of locally available waste concrete, followed by sieving and sorting the aggregate into different fractions. Four concrete mix designs were created, with one serving as a reference mixture without recycled aggregate, while the remaining three mixes included recycled aggregate in varying proportions. The experimental part includes testing the key properties of concrete in both fresh and hardened states, including slump and flow tests, compressive strength, static modulus of elasticity and shrinkage of the concrete, with the aim of assessing the impact of locally available recycled aggregate on concrete properties. By using experimental testing methods, the results were compared with conventional concrete, providing deeper insights into the potential advantages and disadvantages of using locally available recycled concrete in various construction projects.

***Keywords*—**Concrete, durability, recycled aggregate, sustainability.

I. Introduction

CONCRETE is the most widely used construction material in the world, playing a crucial role in the development of infrastructure and urbanization. The construction sector generates large amounts of waste worldwide, with some studies indicating that it accounts for approximately 30% of total waste [1]. Significant efforts have been made to reduce construction waste volumes and promote sustainable practices in construction, such as recycling, material reuse, and source waste reduction. Recycling waste has become a key focus in modern society, aiming to reduce the negative impact on the environment and natural resources [2]. In the construction industry, recycled concrete represents a solution for sustainable construction, as it allows for the reuse of waste materials as a substitute of natural aggregate in conventional concrete. The construction sector consumes large amounts of materials derived from natural resources. In Croatia, construction waste is defined as waste generated during the construction, reconstruction, demolition, and maintenance of buildings [3]. Excavated materials are also considered waste, although they can be reused during construction. In the European Union and worldwide, there is a recognized need for improved management of construction waste to reduce its negative impact on the environment and society. Consequently, various strategies are being developed and implemented to reduce construction waste volumes, promote reuse, recycling, and energy recovery [4]. To ensure sustainable waste management, it is essential to consider human health protection and environmental preservation, with principles set forth by the Waste Management Act [3]. Construction waste generated from building new structures and demolishing old ones has significantly increased in recent years, leading to major environmental issues in many countries, primarily due to uncontrolled disposal in illegal dumpsites [5]. The debris from demolished structures can be reduced to suitable sizes and used as aggregate in the production of new concrete.

It is known that the quality of recycled aggregate is lower than that of natural aggregate [6]. Recycled aggregate often contains impurities, has a lower bulk density, and exhibits increased water absorption [7]. These characteristics are due to the adhered mortar that remains on the stone after crushing [8]. As a result, more water needs to be added to fresh concrete, and bleeding of the concrete is commonly observed [9]. Hardened concrete made with recycled aggregate generally has lower compressive strength, a lower modulus of elasticity, and higher shrinkage [10]. Recycling is an important process that enables the reuse of materials and reduction of waste. Through organized collection and processing, new products can be created, reducing the negative impact on the environment. The recycling process of concrete not only addresses the issue of disposing of large quantities of material but also reduces the disadvantage of raw materials and the need for natural resources [11]. Therefore, it is essential to pay close attention to the design of the concrete mix and mixing technology. Excessive water absorption by the aggregate negatively impacts concrete strength, which, along with workability, can also affect the durability properties of the concrete.

To date, numerous studies have been conducted on the impact of recycled concrete on the properties of fresh and hardened concrete. Nevertheless, the topic and research presented in this paper are considered justified due to the

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specific characteristics of local sources of construction waste and their significance for sustainable construction practices in a regional context. The properties of recycled concrete depend greatly on local waste sources, including composition, age, and types of materials used, which means that results obtained in other regions are not necessarily applicable to local conditions. This research contributes to understanding how locally available recycled aggregate affects key concrete properties, such as compressive strength, modulus of elasticity, and durability. Such an approach offers practical value for regional construction projects, allowing designers and contractors to apply more sustainable construction solutions tailored to local resources and standards. Through literature analysis and experimental research, the study provides insight into the potential application of locally available recycled concrete in the construction industry and offers recommendations for further development and implementation of this sustainable technology. The main objective of the research is based on assessing the potential of locally available recycled concrete as a substitute for traditional aggregates in concrete mixtures. The impact of different proportions of recycled aggregate on the mechanical and durability properties of concrete, including compressive strength, static modulus of elasticity, and shrinkage, was investigated. Furthermore, the properties of concrete with recycled aggregate were compared to those of conventional concrete to determine the advantages and disadvantages of using recycled concrete in relation to standard concrete mixtures.

II. Materials and Methods

A. Materials and Mixture Design

To produce recycled aggregate concrete, cement CEM II/B-M (S-LL) 42.5 N from the local cement factory Našice, Croatia was used as a binder material, with a specific gravity of 3.11 g/cm^3 which complies with the requirement of European Standards EN 197-1:2002 [12]. Tap water from the public water supply system, which is in accordance with EN 1008:2002 [13], was used as the mixing water of mixture. In order to achieve the desirable properties of concrete in fresh state, superplasticizer (SP) Energy FM500 in the amount of 0,375% of the cement weight was used as chemical admixtures. SP is in compliance with EN 934-1 [14] and EN 934-2 [15]. Natural sand and crushed stone with nominal sizes of 0–1, 0–4, 4–8, and 8–16 mm with specific gravities of 2.62, 2.79, 2.85, and 2.83 g/cm^3 were used as a fine (FA) and coarse aggregate (CA). The grading curves of the aggregates are shown in Fig. 1. Graphical representation of the granulometric curves provided adequately conveys the necessary information about the particle size distribution of the aggregates. Recycled Concrete Aggregate (RCA) with specific gravity of 2.61 g/cm^3 was used as a replacement material for natural crushed stone. The recycled aggregate was obtained through mechanical crushing with an impact hammer (Fig. 2), then further reduced to smaller fractions using a mobile crusher (Fig. 3). In this form, recycled aggregate was transported to the laboratory of the Faculty of Civil Engineering and Architecture Osijek. The aggregate was first sieved, and the necessary amount of material was then collected from each sieve to replace a designated fraction or percentage of the natural crushed stone. This method was chosen as the most adequate approach because it allows for precise control over the particle size distribution within the concrete mix, ensuring that the recycled aggregate closely matches the gradation of the natural crushed stone it replaces. By sieving and selecting specific fractions, the variability inherent in recycled materials is minimized, enhancing consistency in the concrete's mechanical properties.

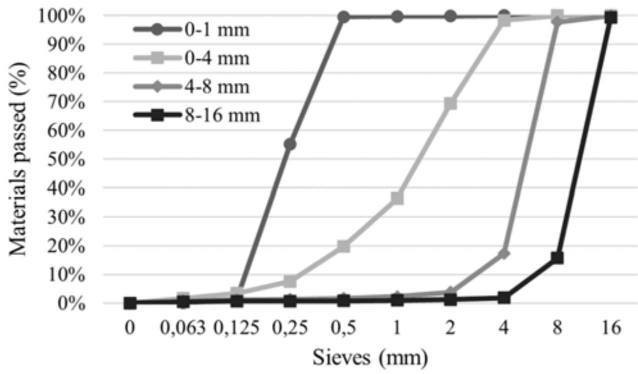


Fig. 1 Granulometric curves of fine and coarse aggregate

Fig. 2 Demolition concrete processing and aggregate crushing

Fig. 3 Recycled concrete aggregate (RCA)

For the purposes of this research, four mixtures were prepared, each with a different proportion of recycled concrete as a replacement for natural crushed aggregate (0-4, 4-8 and 8-16 mm). Table I shows the composition of components for each mixture. For the reference concrete mixture, the percentage share of particular aggregate fractions of 0-1, 0-4, 4-8 and 8-16 mm was 15%, 35%, 20%, and 30% of total amount of aggregate volume, respectively. In addition to the reference mixture, three additional mixtures with recycled aggregate were prepared. The RCA-1 mixture was made by replacing 10% of the volume of natural crushed aggregate (fraction 8-16 mm) with recycled aggregate. The RCA-2 mixture was created by substituting 10% of the volume of natural crushed aggregate (fraction 4-8 mm) with recycled aggregate. The RCA-3 mixture was produced by replacing 85% of the volume of natural crushed aggregate (in the 0-4 mm, 4-8 mm, and 8-16 mm fractions) with recycled aggregate, leaving only 15% natural sand alongside the recycled concrete.

TABLE I
MIX PROPORTIONS (KG/M^3)

Materials	R	RCA-1	RCA-2	RCA-3
CEM II/B-M (S-LL) 42.5 N	300	300	300	300
tap water	150	150	150	150
SP (%m_c)	1.13	1.13	1.13	1.13
sand 0-1 mm	286	286	286	286
NCA (0-4 mm)	710	710	710	0
NCA (4-8 mm)	415	415	207	0
NCA (8-16 mm)	618	411	618	0
RCA (0-4 mm)	0	0	0	690
RCA (4-8 mm)	0	0	193	386
RCA (8-16 mm)	0	190	0	570

NCA - natural crushed aggregate; SP – superplasticizer.

B. Mixing Procedure and Curing Conditions

For the purpose of concrete mixing, a laboratory mixer with a maximum capacity of 50 liters was used. The concrete mixing process begins by mixing the saturated surface dry aggregate for 2 minutes. Recycled aggregate has a higher water absorption capacity than natural aggregate, due to the pores in the mortar attached to the recycled aggregate. Excessive water absorption can reduce workability; therefore, a method of pre-soaking recycled aggregate in water is used before mixing the concrete components. Cement and two-thirds of the water are then added to the mixed aggregate, followed by mixing for 4 minutes. In the final step, the remaining water and superplasticizer are added, and mixing continues for an additional 4 minutes. After completing the mixing of the concrete, tests on the fresh concrete are conducted as described in Section II *C*, followed by the placement of the concrete into cylindrical, cubic, and prismatic moulds. The concrete samples are removed from the moulds 24 hours after placement and then cured in water tank until testing age.

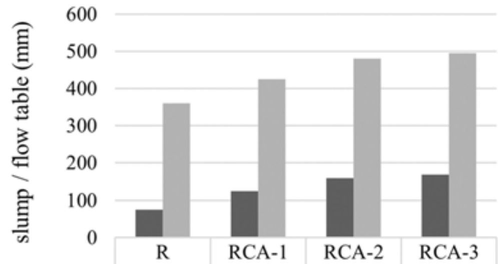
C. Test Methods

Tests were conducted on the designed concrete mixes in both fresh and hardened states. For each mixture, tests on consistency by slump test and flow-table test were performed in accordance with EN 12350-2 [16] and EN 12350-5 [17], respectively. The compressive strength was determined in accordance with EN 12390-3 [18]. Cube specimens with dimensions of 150×150×150 mm were prepared for testing. After curing in water for 7, 14, and 28 days, the specimens were removed, surface-dried, and placed in the testing machine. The load was applied gradually at a constant rate until failure, and the maximum load was recorded. The compressive strength was calculated by dividing the maximum load by the surface area of the specimen. The static modulus of elasticity was determined on concrete cylinder specimen ϕ150×300 mm in accordance with EN 12390-13 [19]. The specimens were first cured under standard conditions for 28 days. Before testing, the cylinders were capped to ensure a uniform load distribution. Axial compression was applied using a hydraulic testing machine, and the deformation was recorded using strain gauges or displacement sensors attached to the specimen. The modulus of elasticity was calculated as the slope of the stress-strain curve within the elastic range, ensuring no cracking or plastic deformation occurred during the test. Drying shrinkage tests were conducted following the EN 12390-16 [20]. Three prism specimens, measuring 100 × 100 × 400 mm, were prepared for each concrete mixture. The specimens were demoulded 24 hours after casting and then stored in a chamber maintained at 20 ± 4 ˚C and 70 ± 5% relative humidity. Length changes were recorded using a length comparator at 7-day intervals until the specimens reached 70 days of age.

III. RESULTS AND DISCUSSION

A. Fresh State Properties

Test results of the fresh state properties are shown in Fig. 4. Based on the consistency test results, the reference mixture (R) is classified as S2 in the slump test and F2 in the flow table test, indicating moderate consistency. The RCA-1 mixture falls into class S3 in the slump test and F3 in the flow table test, showing a higher level of consistency compared to the reference mixture. The RCA-2 mixture reaches class S4 in the slump test and remains in class F3 in the flow table test, indicating even greater consistency. Finally, the RCA-3 mixture is also in class S4 in the slump test but moves up to class F4 in the flow table test, achieving the highest level of consistency among all mixtures. Compared to the reference mixture, RCA-1, RCA-2, and RCA-3 mixtures show increases in consistency of 67%, 113%, and 127% in the slump test, and 18%, 33%, and 38% in the flow table test, respectively. These results indicate a clear correlation between the presence of recycled aggregate and the increase in mixture consistency. All three mixtures containing recycled aggregate exhibit higher consistency than the reference mixture. This increased consistency can be attributed to the characteristic porosity of the recycled aggregate, which allows for greater water absorption. During mixing, the water absorbed by the recycled aggregate can gradually be released back into the mixture, enhancing the overall workability and flow of the concrete. Consequently, mixtures containing various proportions of recycled aggregate display higher values in the slump and flow table tests compared to the reference mixture.

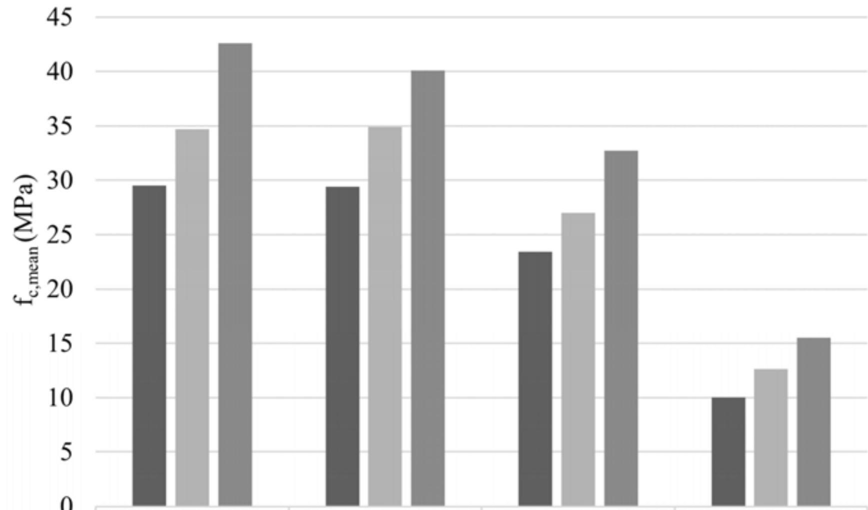


	R	RCA-1	RCA-2	RCA-3
slump test (mm)	75	125	160	170
flow table test (mm)	360	425	480	495

Fig. 4 Workability of fresh concrete

B. Hardened State Properties

Test results of the compressive strength test is shown in Fig. 5. The RCA-1 mixture, which contains only 10% recycled aggregate in the 8-16 mm fraction, shows results very close to the reference mixture. After 28 days, the compressive strength of RCA-1 is 40.08 MPa, which is only 5.92% lower than the reference mixture. This mixture also meets the C25/30 concrete class, indicating that adding a small percentage of recycled aggregate in the coarser fraction does not significantly impact overall compressive strength. This result can be explained by the fact that the coarser fraction of aggregate has a lesser effect on concrete porosity, as it does not contain as many micropores that would affect strength. On the other hand, the RCA-2 mixture, in which 10% of the fine aggregate in the 4-8 mm fraction was replaced with recycled aggregate, shows a 23.15% lower strength than the reference mixture, although it still meets the C25/30 class with a compressive strength of 32.74 MPa. These results suggest that replacing finer fractions of natural aggregate with recycled aggregate leads to a greater reduction in compressive strength due to the increase in overall concrete porosity. The fine fractions of recycled aggregate may contain more adhered mortar and microstructural imperfections, which reduce the final strength. In the RCA-3 mixture, where almost 85% of the natural aggregate was replaced with recycled aggregate, the compressive strength after 28 days is 15.49 MPa, which is as much as 63.64% lower than the reference mixture. This mixture does not meet the C25/30 class but only reaches the C12/15 class, which is unsuitable for load-bearing concrete elements but may serve as subgrade concrete in construction projects. This drastic drop in strength is the result of the high proportion of recycled aggregate, whose porosity and presence of old mortar significantly reduce the cohesion and strength of the concrete. In relative terms, the increase in compressive strength over time within each mixture also varies. The reference mixture shows the highest relative increase in strength over time, while the mixtures with recycled aggregate, especially RCA-3, show a lower relative increase. This suggests that recycled aggregate slows down the cement hydration process, thus reducing the final strength.



	R	RCA-1	RCA-2	RCA-3
fc,7	29.52	29.40	23.42	10.03
fc, 14	34.69	34.89	27.02	12.63
fc, 28	42.60	40.08	32.74	15.49

Fig. 5 Compressive strength of concrete mixtures at different ages (7, 14, and 28 days)

The modulus of elasticity test results (Fig. 6) indicates a decrease in concrete stiffness as the proportion of recycled aggregate increases. The reference mixture (R) has the highest modulus of elasticity, which is due to the presence of natural aggregate that provides greater stiffness. The RCA-1 mixture, with 10% recycled aggregate in the coarser fraction, shows only a slightly lower modulus of elasticity. In the RCA-2 mixture, where the finer aggregate was replaced, the modulus of elasticity drops to 30.912 MPa, suggesting that finer fractions of recycled aggregate, due to the presence of old mortar, increase porosity and reduce stiffness. The greatest decrease is observed in RCA-3, where 85% of the aggregate is recycled material, with a modulus of 19.633 MPa, indicating high porosity and reduced stiffness due to the high recycled aggregate content.

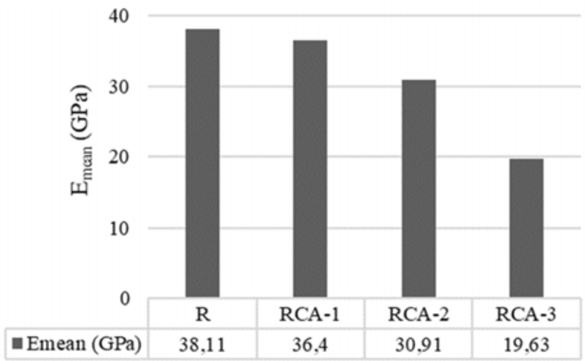


Fig. 6 Mean modulus of elasticity (E_{mean}) of concrete mixtures

The drying shrinkage test results shown in Fig. 7 indicate that concrete shrinkage increases over time for all mixtures, but with varying intensity depending on the proportion of recycled aggregate. The reference mixture and the RCA-1 mixture exhibit relatively low shrinkage. This similarity suggests that adding a small percentage of recycled aggregate in coarser fractions has an almost negligible impact on shrinkage. The RCA-2 mixture, however, shows somewhat higher shrinkage values, which can be attributed to the finer fractions of recycled aggregate that contain more porous old mortar, increasing overall porosity and the concrete's susceptibility to drying. In the RCA-3 mixture, where almost 85% of the natural aggregate was replaced with recycled aggregate, the highest shrinkage was observed, reaching a final value of 0.607 mm/m after 70 days. This significantly higher value compared to the other mixtures indicates high porosity and low resistance to drying, caused by the large proportion of recycled aggregate. The old mortar in the recycled aggregate retains and releases water during drying, leading to greater concrete shrinkage. Overall, the results clearly show a correlation between the proportion of recycled aggregate and increased drying shrinkage, with higher recycled aggregate content leading to greater shrinkage due to increased porosity and the presence of old mortar.

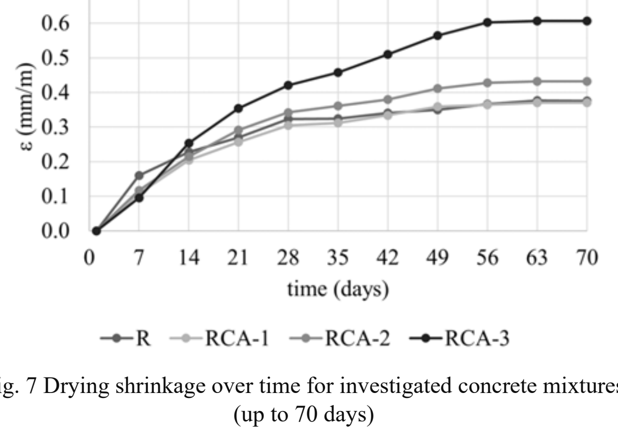


Fig. 7 Drying shrinkage over time for investigated concrete mixtures (up to 70 days)

IV. Conclusion

This study demonstrates that incorporating RCA affects both the fresh and hardened properties of concrete. In the fresh state, RCA enhances the mixture's workability, as seen in increased slump and flow values, due to the recycled aggregate's porosity, which absorbs and gradually releases water. In the hardened state, higher RCA content leads to reductions in compressive strength and modulus of elasticity. While the RCA-1 mixture (10% RCA) performs similarly to the reference and meets the C25/30 strength class, RCA-2 and RCA-3 show significant decreases in strength and stiffness, with RCA-3 (85% RCA) meeting only the C12/15 class. These reductions result from increased porosity and the presence of old mortar, which weaken cohesion. Drying shrinkage results show that higher RCA content increases shrinkage, further impacting durability. This is due to RCA's high water absorption and old mortar content, which increase porosity.

Future work should focus on improving the performance of locally available RCA in concrete applications. Research should explore methods such as pre-treating locally sourced recycled aggregates, using supplementary cementitious materials, or optimizing RCA replacement ratios to enhance concrete properties. Long-term studies on durability, including freeze-thaw resistance and chemical resilience, are recommended to better understand and maximize the potential of locally available RCA in sustainable concrete mixes.

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