Advances in Science and Technology
Research Journal

Advances in Science and Technology Research Journal, 18(6), 465–475
https://doi.org/10.12913/22998624/190252
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.07.26
Accepted: 2024.08.15
Published: 2024.09.08

Comparison of Mechanical Properties of Ad Hoc T-Section Reinforced Concrete Beams Made of Concrete with the Use of Natural and Recycled Aggregate

Barbara Sadowska-Buraczewska[1*], Justyna Kujawska[2]

[1] Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology, Wiejska 45 A, 15-351 Bialystok, Poland

[2] Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka 40B, 20-618 Lublin, Poland

* Corresponding author's e-mail: barbara.sadowska@pb.edu.pl; j.kujawska@pollub.pl

ABSTRACT

Sustainable construction represents a pivotal aspect of contemporary engineering endeavors, which are directed towards the minimization of the detrimental impact of the construction sector on the environment. This is achieved through the efficient utilization of resources and the reduction of waste generation. The study presented an analysis of the mechanical properties of ad hoc reinforced concrete beams made of concrete with recycled and natural aggregate. The objective of this study was to assess the potential of recycled aggregates as a substitute for natural aggregates in reinforced concrete structures, with the aim of contributing to the sustainable development of construction. The experiments compared the behavior of reinforced concrete beams with the same degree of reinforcement but differing in the type of aggregate. The results demonstrated that recycled aggregate beams exhibited lower stiffness and higher deformation under load compared to natural aggregate beams, particularly at loads close to the breaking force. Nevertheless, similar failure modes and cracking patterns were observed in both types of beams, indicating that concrete with recycled aggregate could be employed effectively in specific structural applications.

Keywords: reinforced concrete beams, recycled aggregate, natural aggregate, mechanical properties, sustainable construction

INTRODUCTION

Modern structural engineering is confronted with the dual challenges of ensuring the sustainability of its structures and demonstrating environmental responsibility. The utilization of emerging technologies and materials, such as the incorporation of recycled aggregates, represents a pivotal area of research with the objective of reducing the environmental impact of construction. The utilization of recycled materials not only reduces the necessity for natural raw materials, but also minimizes the quantity of waste that is landfilled. The annual production of concrete worldwide is estimated to reach 25 billion tons, resulting in the generation of considerable quantities of construction waste that represents a significant obstacle to sustainable development. In the context of global demand for building materials, it is projected that primary aggregate production will increase to approximately 60 billion tons by 2030 (1). Consequently, there will be an increase in the utilization of aggregates derived from natural sources. Conversely, the issue of the demolition of old buildings and the subsequent development of cities must also be considered. The process of demolition results in a significant amount of construction and demolition debris worldwide, leading to a gradual detrimental effect on the ecosystem. Globally, construction and demolition waste is the most substantial waste category, accounting for approximately 30 to 40% of the overall solid waste. In Europe, demolition waste accounts for 36% of the total solid waste production, amounting to 800 Mt/year. France and Germany are the countries with the highest levels of production, with 227 and 207 Mt/year, respectively (2). Consequently, the recycling of construction and demolition waste is becoming a pivotal strategy in the field of sustainable resource management. Concrete derived from recycled aggregate, sourced through the reclamation of concrete structures, serves as a viable substitute for conventional concrete, consequently diminishing the utilization of natural resources and influencing environmental preservation. The creation of an optimal concrete mixture necessitates considering a multitude of technological, financial and ecological variables (3, 4).

In order to meet the construction requirements, it is necessary that the durability of concretes created using recycled materials be equivalent to that of traditional concretes (5). Studies show that recycled concrete exhibits diminished compressive, bending, and tensile strength compared to natural aggregate (6, 7). Sagheer et al. (2023), demonstrated that natural aggregate beams exhibit enhanced torsional capacity and greater ductility in response to torsional loading than recycled concrete beams. Nevertheless, the overall failure modes and cracking patterns observed in both cases are comparable, indicating that recycled aggregate concrete may offer a viable alternative to natural aggregate in structural applications (8). Khan et al. (2023) demonstrated that the shear strength of recycled concrete beams composed of 50% coarse recycled aggregate is diminished compared to beams constructed with pristine aggregate at specific shear span-to-depth ratios, yet is equivalent at alternative ratios (9). Consequently, it is imperative to meticulously plan concrete mixes, duly considering the variables pertaining to their intrinsic properties and intended applications (10, 11).

It is important to note that a significant challenge in the production of concrete from recycled materials is the financial aspect. In order for recycled materials to be cost-effective, they must be cheaper than natural materials. This is exemplified by the production of concrete with the addition of fly ash (12). One of the primary factors influencing the heightened expenses of alternative concretes is the potential requirement to enlarge the dimensions of certain structural elements, leading to a subsequent rise in the overall expenditure on the materials utilized (13, 14).

The utilization of conventional materials, such as recycled aggregates in concrete, is beneficial to the environment only if their intended use addresses environmental concerns. Otherwise, they may compromise the longevity and final quality of the concrete. It is of paramount importance to optimize concrete mixes with recycled ingredients in order to enhance their properties and extend their lifespan (15). The idea of article is simple and not new, but gives the useful information concerning performance of that type of beams. This study provides valuable insights into the use of recycled aggregates in reinforced concrete structures, contributing to the field of sustainable construction. It highlights the importance of exploring alternative materials to minimize environmental impact while maintaining structural integrity.

In addition to the ecological benefits, it is also important to understand the impact of concretes with recycled materials on the mechanical properties and durability of concrete. These materials may exhibit differences in structural properties when compared to their natural counterparts, which is the subject of intense scientific research. The predominant body of academic literature has directed its attention towards examining the distinct influence of various characteristics of recycled concrete. Nevertheless, a deficiency in scholarly inquiry exists regarding the overall consequences arising from the utilization of recycled aggregates in the production of recycled concrete (16). Despite certain limitations, these solutions present new avenues for the construction industry, offering the potential to produce high-quality structural concrete as a viable alternative to traditional methods.

The aim of this study was to assess the impact of utilizing different types of aggregates on the mechanical characteristics and longevity of reinforced concrete beams. A comparison was made between the mechanical properties and durability of beams constructed with concrete incorporating recycled aggregate from demolished concrete structures and those made with natural aggregate. Additionally, the objective of the study was to recognize any potential technical and practical obstacles linked to the use of recycled aggregate in producing reinforced concrete. The results of this study may contribute to the progress of more environmentally friendly construction techniques and improve the understanding and application of recycled materials in construction.

MATERIALS AND METHODS

Experimental program

The sample preparation process entailed a series of specific activities. In the initial phase of the process, secondary aggregate was procured. Subsequently, samples were produced from recycled concrete using the aforementioned aggregate. A schematic representation of the production of the mixtures is presented in Figure 1. The subsequent stage involved the fabrication of reinforced concrete beams with a T-section.

Material properties

Cement

The concrete samples were manufactured using CEMEX CEM I 42.5 portland cement. The characteristics of this cement are shown in Table 1 (17).

Aggregate

The aggregate used for testing the concrete mix is:

- Fine aggregate: natural sand with a particle size 0–2 mm,
- Coarse aggregate: recycled aggregate with a particle size of 2–8 mm.

The properties of these aggregates are detailed in Table 2. Recycled aggregates conform to the standards PN-EN 13242 and PN-EN 12620, meeting specific quality requirements that permit their use in certain construction applications (18, 19). Furthermore, fine fractions of recycled aggregate that meet the criteria of the PN-EN 12620 standard are suitable for use in the production of structural concrete. Recycled aggregate was obtained from a prefabrication plant. Sieve analysis was not performed. The aggregate meets the requirements for concrete aggregates. Table 3 shows the quantities of ingredients used for concrete with natural aggregate and recycled aggregate. These aggregates are also applicable in other areas where material quality is crucial to ensure the durability and reliability of the final product (19).

Water

The water used in the process was derived from the Białystok water supply system and

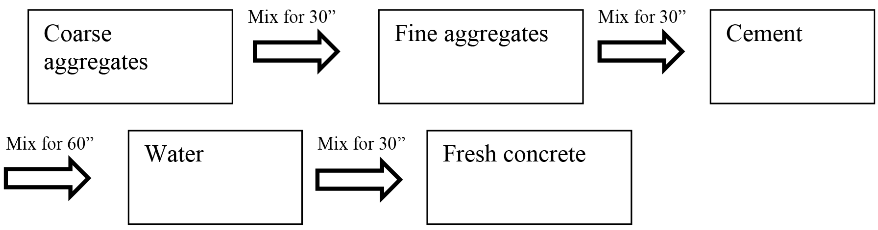

Figure 1. Scheme for the production of concrete mixtures

Table 1. The properties of CEM I 42.5 R cement

Feature	Value	Requirements
Beginning of binding (min)	167	≥60
End of binding (min)	213	
Water demand (%)	27.4	
Volume constancy (mm)	1.2	≤10
Specific surface area (cm^2/g)	3659	
Compressive strength (MPa):		
After 2 days	26.1	≥20
After 28 days	55	≥42.5 and ≤62.5
Chemical analysis (%):		
SO_3	2.97	≤4
Cl	0.068	≤0.10
Insoluble residue (%)	1.63	≤5
Loss on ignition	2.9	≤5
Specific density (g/cm^3)	3.12	

Table 2. The properties of the aggregates used in the concrete mix

Properties of recycled aggregate	Values	Properties of sand	Values
Sand grain content	FI5	Grain size	G_F 85
Resistance to shredding (LA%)	LA30	Dust content	f_3
Bulk density (Mg/m^3)	2.50±0.1	Bulk density (Mg/m^3)	2.65±0.1
Water absorption (%)	≤4	Water absorption (%)	≤0.8
Frost resistance	F4		

met the quality standards, as defined in PN-EN 1008:2004 (20).

Mix design

A series of trials were conducted with the objective of identifying the optimal proportions of the mix design, based on the outcomes of experimental investigations and the material properties. The mix design proportions are shown in Table 3.

Subsequently, the concrete mixture was compacted using a vibrating table in order to achieve the optimal consistency. The concrete surface was meticulously trowelled in order to ensure uniformity and smoothness. A significant factor influencing the quality of the final product was the condition of the concrete molds. The molds were meticulously cleaned and coated with a thin layer of release agent, which prevented the mixture from adhering to the molds.

Proper concrete curing was performed according to the guidelines of the PN-EN 12390-2 [2/2001] standard. This involved storing the concrete in water at a temperature of 20±2 °C after removal from the molds (21).

Beam test

Two series of reinforced concrete beams (comprising three elements in each series) were subjected to examination, each series exhibiting the same degree of reinforcement but differing characteristics of the concretes. The beam load scheme on the test bench is depicted in Figure 2.

The beams are marked with the following symbols:

- T1-REC – reinforced concrete T-beam made on recycled aggregates series 1,
- T2-REC reinforced concrete T-beam made on recycled aggregates series 2,
- T3-REC reinforced concrete T-beam made on recycled aggregates series 3,
- T1-N reinforced concrete T-beam made on natural aggregates series 1,
- T2-N reinforced concrete T-beam made on natural aggregates series 2,
- T3-N reinforced concrete T-beam made on natural aggregates series 3.

The objective of tests carried out on beams is to assess their mechanical properties in terms of deflection, deformation and strength.

Preparation of reinforced concrete T-beams

The primary focus of this study was a reinforced concrete T-beam with a length of 110 cm. Figure 3 depicts a diagram of a reinforced concrete beam reinforced by two bars with a diameter of Ø8 at the top and bottom, and smooth steel bars with a diameter of Ø3 were used as stirrups. The main

Table 3. The properties of the concrete mix

Components	Mix with recycled aggregate (kg/m^3)	Mixture with natural aggregate (kg/m^3)
Cement CEM I 42,5 R	350	350
Fine aggregate – sand (0–2.0 mm)	637	637
Coarse aggregate (2.0–4.0 mm)	-	354.9
Coarse aggregate (4.0–8.0 mm)	-	828.1
Coarse recycled aggregate (2.0–4.0 mm)	354.9	-
Coarse recycled aggregate (4.0–8.0 mm)	828.1	-
Water	178	178
Water cement indicator	0.51	0.51
Bulk density	2348	2348

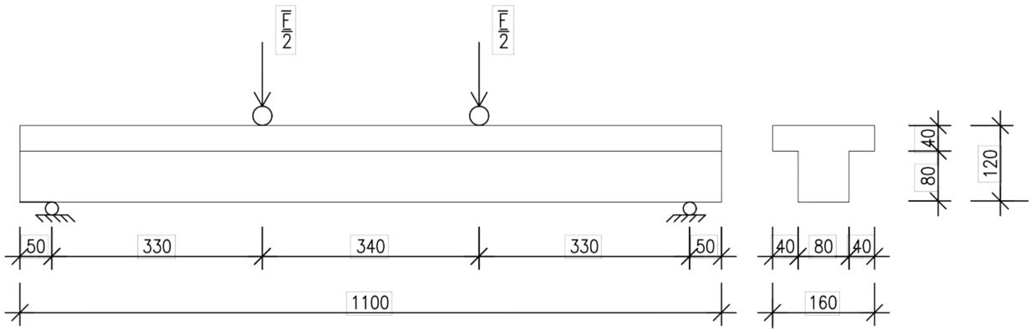

Figure 2. Diagram of a beam on a test bench under temporary load with a cross-section (T-section)

reinforcement consists of BSt 500S steel, with a yield strength of Re = 500 MPa, as per the Technical Approval ITB AT-15-4648/2006. In addition, the stirrups were fastened using knotted wire tied to the reinforcing bars at four corners. In order to ensure a distance of one centimeter between the bottom reinforcement cover and the mold, polystyrene spacers were placed on the mold (21).

Ad hoc tests of reinforced concrete T-beams

After the beam was placed on the test bench and the deflection sensors were installed, the distances between the upper and lower beams were measured. The load was then gradually increased to 5 kN and decreased to 0 kN, with the distances between the specimens recorded over three cycles. The aforementioned values were employed as input data for the purpose of reading deformations, deformations, and crack checks during the load force change every 5 kN. Furthermore, the tensile strength has been validated. Although concrete is not typically designed to carry pure tension, it is important to be aware of its strength in order to assess the load at which cracks will appear.

During the ad hoc tests, the values of concrete deformations for the beams were recorded at three points, as illustrated in Figure 4. The deformation values were recorded at regular intervals, commencing with an increase of the loading force by 5 kN in accordance with the planned schedule of loading the beams. In order to measure the deformations, an instrument designated the "Demec Meter" was employed, the diagram of which is depicted in Figure 4.

Deflection measurement

Deflections were measured using displacement sensors placed at three specific locations, as shown in Figure 5:
- L – above the left support
- P – above the right support
- Ś – at the centre of the beam span

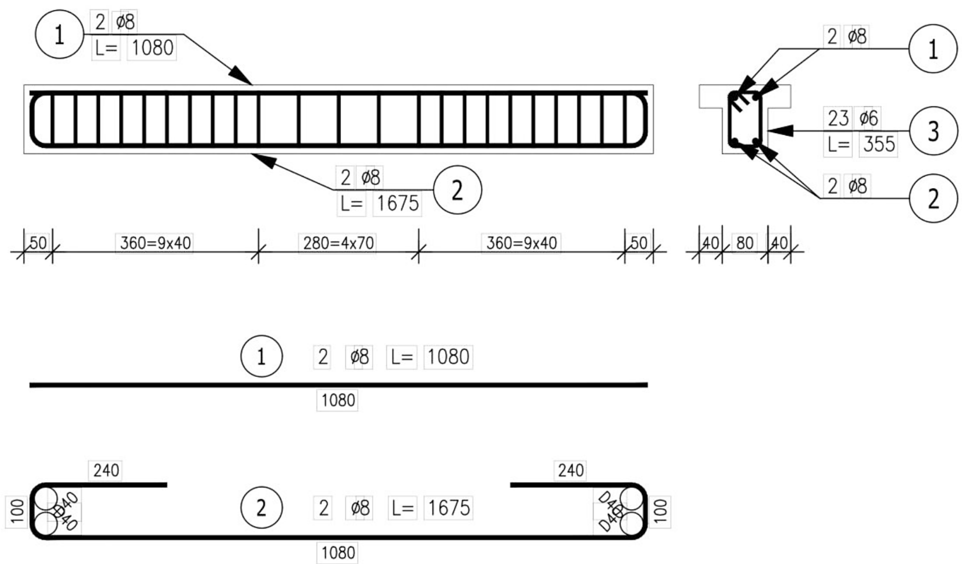

Figure 3. Scheme of T-section beams with reinforcement

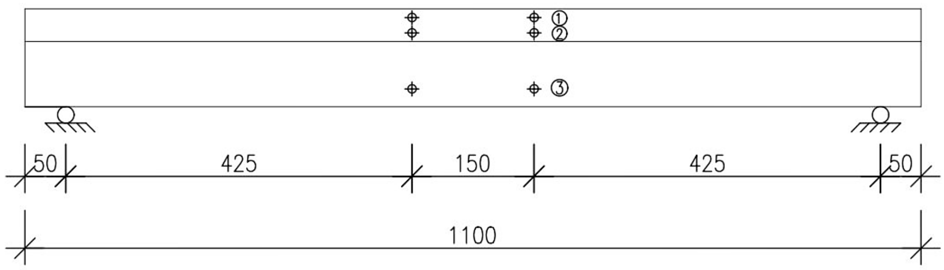

Figure 4. Beam diagram with bases for measuring concrete deformations at cross-section height

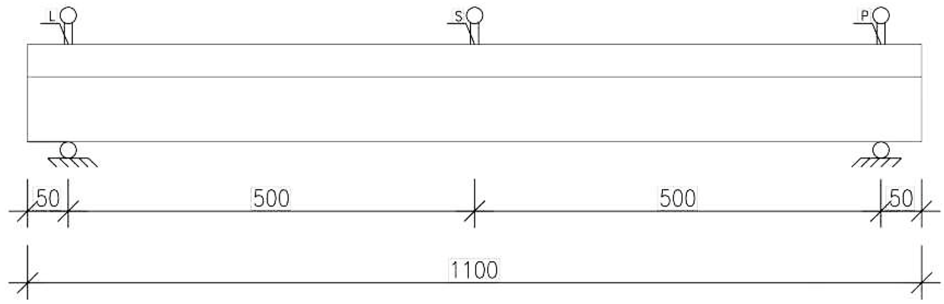

Figure 5. Beam diagram with deflection measurement points: L – left support, S – middle support, P – right support

Before starting the measurements, the sensors were calibrated to zero at a 5 kN load. Measurements were then taken with each 5 kN increment until the beam failed. The observations were made in parallel with the deflection measurements.

RESULTS

Relative strain measurement is a fundamental parameter that enables the understanding and prediction of the behavior of materials under load, which is essential for the creation of durable and safe structures. Tables 4–6 present the results of the relative deformation analysis of the tested beams.

For all beams, both on recycled and natural aggregates, it can be observed that the relative deformation increases along with force (Table 4). Nevertheless, the beams constructed with recycled aggregate generally exhibit higher deformation values than their counterparts constructed with natural aggregate at the same forces, which suggests that the recycled aggregate beams have lower stiffness. As the forces applied approached the destructive force (35 kN), the beams with recycled aggregate exhibited significantly higher deformations (0.84–0.88‰) than the beams with natural aggregate (0.42–0.50‰). At low forces (5–10 kN), the deformation values of beams with recycled and natural aggregate are similar, which may indicate similar initial mechanical properties. The deformation of beams with recycled aggregate increases significantly at destructive forces, reaching values of 1.38‰ to 1.89‰. These values are significantly higher than for the beams with natural aggregate (0.39–0.40‰).

The largest differences in deformations are observed when measuring the values for the bottom indexes (Table 6). It can be observed that recycled aggregate beams exhibit significantly higher deformation values (e.g. 9.56–10.78‰ at 35 kN) in comparison to natural aggregate beams (0.86–1.28‰ at the same force). This indicates a significantly reduced structural resistance under higher loads.

The analysis of variance (ANOVA) comparing the deformations of concrete beams made with recycled and natural aggregates revealed a p-value of less than 0.05. This indicates that there are statistically significant differences in the maximum deformations between the two types of aggregate.

The results indicate that beams made from recycled aggregates exhibit lower stiffness and a greater tendency to deform compared to those made from natural aggregates. This may indicate that the recycled aggregate used in the construction of the beams is of a lower quality or that the

Table 4. Concrete deformation values (approx. 1 cm from the top edge of the shelf) for beams on recycled aggregate

Strength (kN)	Relative strain ε (‰)						One-way ANOVA. Factor analyzed: coarse content
	T1-REC	T2-REC	T3-REC	T1-N	T2-N	T3-N	
0	0	0	0	0	0	0	F = 5.734 p = 0.029
5	0.08	0.06	0.06	0.07	0.06	0.06	
10	0.18	0.14	0.16	0.16	0.15	0.15	
15	0.26	0.20	0.24	0.19	0.21	0.22	
20	0.34	0.28	0.34	0.24	0.25	0.28	
25	0.41	0.36	0.41	0.30	0.32	0.35	
30	0.46	0.41	0.49	0.35	0.38	0.41	
35*	0.84	0.88	0.87	0.42	0.47	0.50	
40				0.58	0.60	0.54	

Note: *close to destructive power.

Table 5. Experimental deformation values of concrete (approx. 1 cm from the bottom edge of the shelf) on recycled aggregate

Strength (kN)	Relative strain ε (‰)						One-way ANOVA. Factor analyzed: coarse content
	T1-REC	T2-REC	T3-REC	T1-N	T2-N	T3-N	
0	0	0	0	0	0	0	F = 4.625 p = 0.030
5	0.07	0.03	0.05	0.04	0.05	0.04	
10	0.12	0.05	0.09	0.09	0.10	0.09	
15	0.18	0.12	0.15	0.14	0.17	0.15	
20	0.27	0.18	0.17	0.21	0.22	0.20	
25	0.36	0.24	0.24	0.28	0.29	0.25	
30	0.46	0.37	0.37	0.32	0.34	0.32	
35*	1.38	1.89	1.66	0.40	0.39	0.39	
40				0.59	0.55	0.60	

Note: *close to destructive power.

Table 6. Experimental values of concrete deformation for bottom repairers on recycled aggregate

Force (kN)	Relative strain ε (‰)						One-way ANOVA. Factor analyzed: coarse content
	T1-REC	T2-REC	T3-REC	T1-N	T2-N	T3-N	
0	0	0	0	0	0	0	F = 5.713 p = 0.019
5	0.11	0.18	0.10	0.07	0.06	0.07	
10	0.42	0.45	0.47	0.12	0.13	0.14	
15	0.64	0.69	0.69	0.19	0.21	0.21	
20	1.19	1.19	1.17	0.23	0.26	0.27	
25	1.55	1.59	1.58	0.40	0.59	0.62	
30	2.67	2.88	2.17	0.55	0.61	0.67	
35*	9.56	10.78	8.12	0.86	1.28	1.1	
40				1.14	1.65	1.67	

Note: *close to destructive power.

beams have a lower load-carrying capacity. The beams constructed from recycled aggregates are more susceptible to elevated loads, particularly when the loads approach the destructive force. This is evidenced by the significantly greater deformations observed in these beams compared to those constructed from natural aggregates.

The results suggest that recycled material may behave differently under high loads, which could significantly impact the design and use of recycled aggregate in concrete structures. Despite their increased susceptibility to deformation, recycled aggregates can still be advantageous in structures with reduced stress. Table 7 shows the deflection values of reinforced concrete beams made with recycled and natural aggregates under the load force F.

In the initial loading phase (up to 20 kN), the beams made of recycled aggregates and natural aggregates exhibit relatively low deflection values, which increase as the load increases. The deflections exhibited by beams made from recycled aggregates are slightly higher than those exhibited by the beams made from natural aggregates. This may indicate that the recycled material has a lower stiffness.

At loads of 25 kN and 30 kN, the discrepancies in deflections between recycled and natural aggregates become more pronounced. The deflections of the beams on recycled aggregates are found to be significantly higher, reaching values that are up to 100% higher than those on natural aggregates. This may be indicative of a diminished strength of recycled composites in comparison to natural composites.

The deflection of beams on recycled aggregate exhibits a marked increase at a load of 35 kN, which is considered to be close to the destructive force. For instance, a T2-REC beam exhibits a deflection of 14.75 mm, which is considerably higher than any beam deflection on natural aggregate for the same force. This implies that the structural integrity of the beams on recycled aggregate may be less robust in the vicinity of destructive forces.

The results of the experiments demonstrate that the reinforced concrete beams manufactured using recycled aggregates exhibit reduced stiffness and diminished resistance to elevated loads in comparison to the beams produced using natural aggregates.

The ANOVA test results on deflection data for beams with recycled and natural aggregates show a p-value of less than 0.05. This indicates a statistically significant difference in the average deflections between beams made with recycled aggregates and those made with natural aggregates.

Cracking in reinforced concrete structures is a complex phenomenon influenced by numerous factors. Observing cracks is crucial, as their presence can signal a reduction in the structure's load-bearing capacity, potentially leading to concrete failure. The measurement of crack width and nature is of paramount importance in the assessment of the safety of structures. Initially, cracks appeared at a force of approximately 30% of the critical load, with the beam on recycled aggregate exhibiting a force of 10 kN and the beam on natural aggregate exhibiting a force of 15 kN. The initial vertical cracks appeared in the central region of the beams, where a constant bending moment was present. As the load increased, the cracks exhibited both an increase in length and width. In addition, the number of cracks increased, and oblique cracks also appeared, originating in the zones between the points of application of forces and supports.

Table 7. Experimental values of beam deflections on recycled aggregate in the middle of the span

Force (kN)	Deflection (mm)						One-way ANOVA. Factor analyzed: coarse content
	T1-REC	T2-REC	T3-REC	T1-N	T2-N	T3-N	F = 6.63 p = 0.0133
0	0	0	0	0	0	0	
5	0.19	0.21	0.25	0.17	0.22	0.19	
10	0.87	0.93	0.96	0.37	0.43	0.40	
15	1.87	1.61	1.70	0.67	0.81	0.74	
20	2.76	2.54	2.43	1.07	1.12	1.09	
25	3.59	3.64	3.76	1.85	1.98	1.91	
30	5.45	4.95	4.95	2.15	2.30	2.22	
35*	12.13	14.75	10.27	2.71	3.22	2.96	
40				3.16	4.11	4.02	

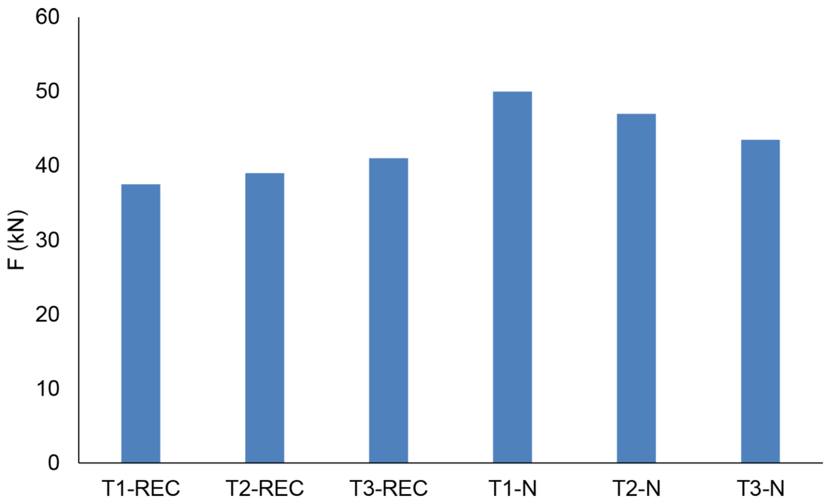

Figure 6. Destructive force of the beams under test

The average breaking force for beams on recycled aggregate is found to be lower than for the beams on natural aggregate (Figure 6). This indicates that recycled aggregate may exhibit reduced strength in terms of destructive power compared to natural aggregate.

DISCUSSION

The results offer several key insights into the mechanical properties of concrete beams made with recycled aggregate compared to those made with natural aggregate. Firstly, significantly higher deformation values are observed in the recycled aggregate beams, especially at loads approaching the ultimate load. Higher deformation values in beams with recycled aggregate, especially at loads close to the ultimate load, have also been demonstrated in the work of other researchers (22-24). Choi et al. (2013) demonstrated that incorporating recycled aggregates increases the deflection of reinforced concrete beams in both short-term and long-term behavior (25).

The research demonstrated that beams made from recycled aggregates exhibited twice the deflection values at a force of 10 kN compared to beams made from natural aggregates. These higher deflection values indicate lower stiffness in the recycled material (6). Wardah et al. (2023) found that beams with a higher percentage of recycled aggregate show greater deflection, especially under near-failure loads (26). The results indicate a lower quality of the structural material or a lower load-bearing capacity, which is crucial for the design of concrete structures.

Despite the differences in beam properties, the overall behavior of recycled aggregate beams is similar to that of natural aggregate beams in terms of failure modes and cracking patterns. This suggests that recycled aggregate beams can be used as a partial replacement for natural aggregate in structural concrete (7).

The findings indicated a necessity for further investigation into the optimization of recycled aggregate concrete compositions with the objective of enhancing their mechanical properties and expanding their applicability in more challenging applications. In particular, this research should focus on analyzing the impact of different recycling aggregate treatment processes on the structural properties and on identifying potential avenues for improvement. Furthermore, it is essential to ascertain the extent to which variations in chemical composition between natural and recycled aggregates influence the outcomes of deformation and deflection. This can facilitate a more comprehensive comprehension and utilization of these materials in engineering applications.

Recycled cement research indicates the differences in the chemical composition of natural and recycled aggregates could significantly affect the results of the study. Recycled aggregates often contain remnants of old cement paste from the previous concrete structure. This can alter the aggregate's properties, such as increasing its porosity and water absorption, which can affect the overall mix design and concrete performance. Higher water absorption in recycled aggregates can lead to a weaker aggregate-cement bond and thus lower strength and durability (27). Zhang et al. demonstrated a less robust interfacial region existing between fresh cement mortars and reused aggregates (28). Omary et al. noted significant micro-cracks in the cement paste adhering to the aged coarse-recycled aggregates (29). The scholars highlighted that this occurrence was primarily linked to the crushing procedure, greatly influencing the characteristics of the produced concretes.

Recycled aggregates might contain impurities or contaminants that are not present in natural aggregates. These can include materials like gypsum, plaster, wood, or metal fragments, which can adversely affect the hydration process and the mechanical properties of the concrete. The chemical composition of recycled aggregates can be more variable than that of natural aggregates due to the diverse sources of the recycled material (30). This variability can lead to inconsistencies in the concrete's performance, making it challenging to predict its behavior under load. Recycled aggregates might have different levels of reactive silica or other components that can contribute to alkali-aggregate reactions. These reactions can cause expansion and cracking in the concrete over time, affecting its long-term durability. The variability in the composition of recycled cements highlights the need for more research to produce cements of very high quality.

It can be postulated that in response to the growing social demand for environmental responsibility, recycled aggregate will increasingly be used as an integral component of structural concrete. Ongoing technological advancements in the construction industry are expected to reduce waste and increase the proportion of recycled materials used in concrete production.

CONCLUSIONS

Despite exhibiting lower stiffness and greater deformations compared to natural aggregate, particularly at loads approaching the destructive force, concrete with recycled aggregate can be effectively utilized in reinforced concrete structures. The results indicate that it can be used under specific structural conditions, which could contribute to the promotion of more sustainable construction.

The occurrence of similar failure modes and cracking patterns in beams made with both types of aggregates suggests that recycled aggregate concrete can be a viable alternative to virgin aggregate, provided it is properly designed and applied.

Although recycled aggregate has the effect of reducing some of the mechanical properties of concrete, appropriate treatment and selection of components can minimize these differences, thus enabling a wide application of this material in construction practice.

Using recycled aggregate in concrete is not only environmentally beneficial, as it reduces the necessity for natural raw materials and minimizes waste, but also represents an essential step towards more sustainable construction. In response to the growing public demand for green solutions, recycled aggregate can be a valuable component of structural concrete, thereby supporting the development of sustainable construction technologies.

Acknowledgments

The research leading to these results has received funding WZ/WB-IIL/6/2023.

REFERENCES

1. Han S., Zhao S., Lu D., Wang D. Performance Improvement of recycled concrete aggregates and their potential applications in infrastructure: A Review. Buildings 2023,13(6). https://doi.org/10.3390/buildings13061411.
2. Eurostat 2024f. Recycling rate of municipal waste. Available from: https://ec.europa.eu/eurostat/databrowser/view/sdg_11_60/default/table.
3. Xiao J., Wang C., Ding T., Akbarnezhad A. A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. J Clean Prod. 2018, 199, 868–81. https://doi:10.1016/j.jclepro.2018.07.210.
4. Fediuk R.S., Ibragimov R.A., Lesovik V.S., Pak A.A., Krylov V.V, Poleschuk M.M., et al. Processing equipment for grinding of building powders. IOP Conf Ser Mater Sci Eng. 2018, 327 (4). https://doi:10.1088/1757-899x/327/4/042029 .
5. Xiao J,. Zhang K., Akbarnezhad A. Variability of stress-strain relationship for recycled aggregate concrete under uniaxial compression loading. J Clean Prod. 2018, 181, 753–71. https://10.1016/j.jclepro.2018.01.247.
6. Wanas A.H., AL- Kaabi J.J.F., Mushatat H.A. Evaluation of shear behavior of prepared recycled concrete aggregate concrete deep beam. Period Eng Nat Sci. 2023, 11(2), 297. http://dx.doi.org/10.21533/pen.v11i2.3539.
7. Dawood M. H., Al-Asadi A.K. Mechanical properties and flexural behaviour of reinforced concrete beams containing recycled concrete aggregate. Sci Rev Eng Environ Sci. 2022;31(4):259–69. https://

doi.org/10.22630/srees.4250.

8. Sagheer A.M., Tabsh S.W. Shear strength of concrete beams without stirrups made with recycled coarse aggregate. Buildings 2023, 13(1). https://doi.org/10.3390/buildings13010075.
9. Khan, AuR., Fareed, S., Khalid F. Behaviour of Reinforced recycled aggregate concrete beams subjected to torsional loading. In: Building for the Future: Durable, Sustainable, Resilient fib Symposium 2023 Lecture Notes in Civil Engineering 2023.
10. Abbas A., Fathifazl G., Isgor O.B., Razaqpur A.G., Fournier B., Foo S. Durability of recycled aggregate concrete designed with equivalent mortar volume method. Cem Concr Compos 2009, 31(8), 555–63. http://dx.doi.org/10.1016/j.cemconcomp.2009.02.012
11. Fediuk R., Ali Mosaberpanah M.A., Lesovi V. Development of fiber reinforced self-compacting concrete (FRSCC): Towards an efficient utilization of quaternary composite binders and fibers. Adv Concr Constr. 2020, 9(4), 387–95. https://doi.org/10.12989/acc.2020.9.4.387
12. O'Donnell B.T., Ives C.J., Mohiuddin O.A., Bunnell B.A. Beyond the present constraints that prevent a wide spread of tissue engineering and regenerative medicine approaches. Front Bioeng Biotechnol. 2019, 7(May), 1–12. https://doi.org/10.3389/fbioe.2019.00095.
13. Wijayasundara M., Mendis P., Crawford R.H. Methodology for the integrated assessment on the use of recycled concrete aggregate replacing natural aggregate in structural concrete. J Clean Prod 2017, 166, 321–34. http://dx.doi.org/10.1016/j.jclepro.2017.08.001.
14. Chernysheva N., Lesovik V., Fediuk R., Vatin N. Improvement of performances of the gypsum-cement fiber reinforced composite (GCFRC). Materials (Basel). 2020, 13(17). https://doi.org/10.3390/ma13173847. https://doi.org/10.3390/ma13173847.
15. Fediuk R.S., Ibragimov R.A., Lesovik V.S., Akopian A.K., Teleshev A.A., Khankhabaev L.R., et al. Application of cementitious composites in mechanical engineering. IOP Conf Ser Mater Sci Eng. 2018, 327(3). http://doi:10.1088/1757-899X/327/3/032021
16. Makul N., Fediuk R., Amran M., Zeyad A.M., Klyuev S., Chulkova I., et al. Design strategy for recycled aggregate concrete: A review of status and future perspectives. Crystals 2021, 11(6). 11(6), 695. http://doi:10.3390/cryst11060695
17. https://www.cemex.pl/documents/46481509/60021021/Parametry_CEM_I_42-5-R-Chelm.pdf/.
18. PN-EN 13242+A1:2010. Aggregates for unbound and hydraulically bound materials used in buildings and road construction.
19. PN-EN 12620+A1:2010. Aggregate for concrete.
20. PN-EN 1008:2004 . Mixing water for concrete. Specification of sampling, testing and assessment of suitability of mixing water for concrete, including water recovered from concrete production processes.
21. PN-EN 12390-2:2019-07. Testing hardened concrete – Part 2: Making and curing specimens for strength tests.
22. El-Sadany R.A., Al-Tersawy S.H., Sallam H.E.D.M. Effect of GFRP and steel reinforcement bars on the flexural behavior of RC beams containing recycled aggregate. Frat ed Integrita Strutt. 2022, 16(61), 294–307. http:// doi:10.3221/IGF-ESIS.61.20.
23. Ftnan A.H., Makki R.F. Behavior of recycled aggregate concrete beams strengthened with FRP. Kufa J Eng. 2022, 13(4), 13–24. https://doi.org/10.30572/2018/KJE/130402.
24. Sryh L., Forth J. Long-Term flexural behaviour of cracked reinforced concrete beams with recycled aggregate. Int J Concr Struct Mater. 2022, 16(1). https://doi.org/10.1186/s40069-022-00512-0
25. Choi W.C., Yun H. Do. Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate. Mater Des. 2013, 51, 742–50. http://dx.doi.org/10.1016/j.matdes.2013.04.044.
26. Wardeh, G., Ghorbel, E., Tayeh B. Influence of recycled aggregates on the flexural and shear behavior of reinforced concrete elements: experimental and numerical study. In: Design and Modeling of Mechanical Systems - V CMSM 2021 Lecture Notes in Mechanical Engineering. 2023.
27. Khelafi A., Kaid N., Soltani R., Kerdal D.E, Khelafi H. Elaboration of recycled concrete sand aggregates-based mortars: An alternative recycling process. Constr Build Mater. 2023, 398 (132333). https://doi.org/10.1016/j.conbuildmat.2023.132333.
28. Zhang J., Shi C., Li Y., Pan X., Poon C.S., Xie Z. Influence of carbonated recycled concrete aggregate on properties of cement mortar. Constr Build Mater. 2015, 98, 1–7. http://dx.doi.org/10.1016/j.conbuildmat.2015.08.087.
29. Omary S., Ghorbel E., Wardeh G. Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties. Constr Build Mater. 2016, 108, 163–74. http://dx.doi.org/10.1016/j.conbuildmat.2016.01.042
30. Piersanti M., Shehata M.H. A study into the alkali-silica reactivity of recycled concrete aggregates and the role of the extent of damage in the source structures: Evaluation, accelerated testing, and preventive measure. Cem Concr Compos. 2022, 129, 104512. https://doi.org/10.1016/j.cemconcomp.2022.104512.