Journal of Building Material Science | Volume 08 | Issue 02 | April 2026

BILINGUAL PUBLISHING GROUP

Journal of Building Material Science
https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Mechanical Performance and Sustainability Potential of Concrete Containing Construction and Demolition Waste Recycled Aggregates

Mariya Zahran Ahmed Al Rawahi [1], *Kiran Kumar Poloju* [1*], *Amira Al Shareqi* [1], *Nagarju Kola* [2]

[1] *Department of Civil and Mechanical Engineering, Middle East College, Muscat 124, Oman*
[2] *National Institute of Technology Puducherry, Karaikal 609609, India*

ABSTRACT

The construction sector is a major contributor to global carbon emissions and the extinction of resources owing to the heavy use of natural aggregates and production of construction and demolition waste (CDW). The paper examines the viability of using recycled aggregates in the form of CDW as substitutes (0, 10, 30 and 50) of natural coarse aggregates in M25 structural concrete. Experimental testing comprised workability, density, water absorption and compressive strength after 7 and 28 days, which was backed by statistical analysis at 95% confidence level. The findings have shown that the workability reduces with high content of CDW because of augmented water absorption. Internal curing effect enhanced the 10% replacement with the highest compressive strength (31.52 MPa), which was up by 3.5% compared to control. The 30% replacement was found to give similar strength (29.82 MPa) with no statistically significant difference whereas the 50% replacement was found to allow significant reduction as a result of increasing porosity and reducing interfacial transition zones. The replacement level was positively correlated with water absorption, which means that pore connectivity was high. The sustainability analysis indicated possible CO_2 cuts between 6–10% on 30% replacement. The results confirm that at least 30% CDW recycled mixes can be used safely in the structural concrete without affecting the performance, which is in line with the principles of the circular economy and sustainable construction practices.

Keywords: Recycled Aggregate Concrete; Construction Demolition Waste (CDW); Sustainable Construction; Compressive Strength; Circular Economy; Recycled Aggregates

*CORRESPONDING AUTHOR:
Kiran Kumar Poloju, Department of Civil and Mechanical Engineering, Middle East College, Muscat 124, Oman;
Email: p.kirankumar102@gmail.com

ARTICLE INFO
Received: 5 March 2026 | Revised: 24 March 2026 | Accepted: 8 April 2026 | Published Online: 3 June 2026
DOI: https://doi.org/10.30564/jbms.v8i2.13264

CITATION
Al Rawahi, M.Z., Poloju, K.K., Al Shareqi, A., et al., 2026. Mechanical Performance and Sustainability Potential of Concrete Containing Construction and Demolition Waste Recycled Aggregates. Journal of Building Material Science. 8(2): 41–57.
DOI: https://doi.org/10.30564/jbms.v8i2.13264

1. Introduction

1.1. The Global Construction and Energy Transition

The construction industry is a central part of globalization into sustainable and low-carbon infrastructure systems. The energy-based CO_2 emission of buildings and construction activities contributes to climate change and resource depletion in the world by nearly 37% of the total energy-based emissions [1]. Concrete is the most popular construction material in the world, and the volume of aggregates that form its composition is a range of 60–80% [2–4]. The high rates of urbanization and infrastructure development have caused a significant rise in the demand of the natural aggregates resulting in a worsening of the environment caused by quarrying and resource extraction [5]. Simultaneously, the construction sector produces colossal volumes of construction and demolition waste (CDW), almost a third to a half of the total production of solid wastes in the world [6,7]. The recycling of CDW into recycled concrete aggregates (RCA) is a useful approach to minimizing landfill disposal and saving on natural resources [8]. The studies have shown that recycled aggregate concrete can also have similar mechanical performance to conventional concrete provided that the replacement levels are adopted [9–12]. The latest development in sustainable concrete technology also emphasizes the importance of recycled aggregates in environmental effects mitigation and promoting circular construction processes [13–17]. Other current research has focused on the advanced mix design techniques and performance optimization techniques to improve the mechanical and durability properties of recycled aggregate concrete [18–22]. Moreover, the digital design and machine learning are also used to enhance recycled aggregate concrete mixtures to achieve better sustainability and performance results [23–26]. More recent studies prove that recycled aggregate concrete can have a considerable negative effect on the environment and still save structures by applying optimization mix designs and processing approaches [27–31]. Aggregates form about 60–80% of the concrete mass, which implies that the natural aggregate demand has increased at a high rate with urbanization and infrastructural growth [32]. Large-scale mining of natural aggregates in quarries and riverbeds leads to environmental degradation, loss of biodiversity, disruption of groundwater, as well as high consumption of energy in mining and transporting the aggregates [33]. Meanwhile, the construction sector produces vast amounts of construction and demolition waste (CDW) that constitute almost 30–40% of all solid waste in the world [34]. The disposal of CDW in an inappropriate manner leads to landfill congestion, environmental pollution, and inefficient use of resources. To address such issues the construction industry has started embracing the concept of the circular economy that will reduce the levels of waste and ensure the maximal efficiency of the resource. Recycling CDW to produce recycled concrete aggregates (RCA) to use as new concrete is one of the possible opportunities. This plan will help eliminate reliance on virgin aggregates and at the same time deflect garbage off landfills [5,6]. Life-cycle assessment analyses have also shown that recycled aggregated concrete may help to lower considerably environmental effects, energy usage and carbon emissions as far as construction materials are concerned.

1.2. Sustainable Concrete with Recycled Aggregates

Recycled aggregates that are derived and produced out of crushed CDW have developed into a possible alternative to natural aggregates in the production of concrete. Much research has indicated that recycled aggregate concrete can attain the same performance in the mechanical properties as the traditional concrete, if proper replacement levels and mix design approaches have been embraced [7,8]. Nevertheless, the characteristics of recycled aggregates are quite different as compared to natural aggregates because of adhered mortar, which enhances porosity, water absorption and surface roughness [9,10]. The characteristics determine the workability of recycled aggregate concrete, the formation of strength, and the durability performance. The techniques that have been explored to enhance the performance of recycled aggregate concrete have been in the form of fiber reinforcement, nano-modification, carbonation treatment and use of additional cementitious materials like fly ash, slag and rice husk ash [11–13]. These methods will minimize the microstructure and improve bonding of the cement matrix. However, deciding the best amount of recycled aggregates to replace with to ensure structural performance with maximum benefits on the environment is a major concern in sustainable concrete studies.

1.3. Effects of Microstructures and Interfacial Transition Zone (ITZ)

Interfacial transition zone (ITZ) between aggregates and cement paste massively controls the performance of recycled aggregate concrete. In traditional concrete, there is only one ITZ between natural aggregates and cement matrix. Recycled aggregates, in contrast, bring in a dual ITZ system, which is made up of interfaces between old mortar, recycles aggregates and newly formed cement paste [14]. The microarchitecture of this type tends to lead to the creation of greater porosity and microcracking in the ITZ, which may cause a decrease in bond strength and an increase in its permeability [15]. Recent microstructural investigations on the use of advanced characterization methods have shown that ITZ properties can be greatly enhanced with proper treatment of recycled aggregates. Carbonation curing, nano-silica modification, and graphene oxide treatment are some of the methods that have been demonstrated to densify the ITZ and enhance mechanical performance [16–18]. The role of ITZ microstructure is thus important in order to optimize the performance of recycled aggregate concrete.

1.4. Durability Considerations

The other factor that is significant and affects the practical use of recycled aggregate concrete is durability performance. Recycled aggregate concrete (RAC) systems can accelerate the uptake of water, permeability and chloride diffusion due to the porous nature of adhered mortar [19]. These properties can influence the long-term survivability in hostile conditions like the marine or freeze-thaw conditions. Nevertheless, various reports have shown that use of supplementary cementitious materials and advanced treatment of aggregates may achieve a remarkable enhancement in durability performances by regulating the pore structure and minimizing transport properties [20–22]. The significance of these improvements is especially concerned with the fact that recycled aggregate concrete can be used to address the structural performance requirements of the modern infrastructure systems.

1.5. Energy and Carbon Cutting Potential

Energy and climate-wise, the use of recycled aggregates in lieu of natural aggregates gives great advantages to the environment. Recycled aggregates are usually produced with a lower energy requirement than natural aggregates, especially where the source of CDW is close to the destination [23]. As a result, recycled aggregate concrete is able to provide solutions to the reductions in embodied energy and carbon release linked to construction materials. In addition, recent studies have also emphasized the possibilities of the digital optimization tools and machine learning methods to develop sustainable concrete mixtures balancing mechanical behavior, durability, and environmental effects [24–26]. These strategies are useful in making low-carbon construction materials that can be in line with the energy transition efforts across the world.

1.6. Research Objective

Although a good amount of research has been conducted on the topic of recycled aggregate concrete, it is not clear that the number of its replacement levels can be maximized to ensure the structural performance and the highest level of sustainability. Consequently, the current research is experimental research on the mechanical and durability behavior of concrete that involves the use of CDW aggregates in lieu of natural coarse aggregates on a partial basis.

This study has the aims and objectives:

1. To find out the workability properties of recycled aggregate concrete mixtures.
2. To determine density and water uptake characteristics relating to the addition of CDW.
3. To establish the development in compressive strength at 7 and 28 days.
4. To analyze microstructural behavior according to mechanism of ITZ that is reported in literature.
5. To determine the most suitable level of CDW replacement in the use of structural concrete.

The research is relevant to the design of low-carbon and circular construction materials because this paper will show that it is possible to use recycled aggregates to create structural concrete.

New studies also affirm that recycled aggregate concrete is structurally viable in the application of infrastructure development. Recent publishing studies have shown an increase in the processing, durability performance, and microstructure of RAC systems using recycled aggregates [35–38].

The existing literature has shown that RAC is capable of similar strength, although most of them are not statistically proven or they do not incorporate sustainability metrics [12,14]. Besides, the inconsistency of recycled aggregates and ITZ behavior is not addressed fully [9,11]. New developments are directed at nano-modification and artificial intelligence (AI)-based mix optimization, but there are few practical experimental studies of structural-grade concrete that are carried out [39].

1.7. Novelty of This Research

This is unlike earlier research that has either examined the mechanical performance or sustainability in isolation, where the current research incorporates experimental validation, statistical significance (95% confidence analysis of variance (ANOVA)), and reduction in carbon to determine an optimal replacement level in structural applications. This is research that has not been carried out before and has the following novelty such as

(i) Experimental verification of aggregates of CDW-based in M25 structural concrete at controlled levels of replacement,
(ii) Statistical confirmation (ANOVA) guarantees structural integrity to 30% replacement.
(iii) Mechanical performance interpreted coupled with sustainability (carbon reduction),
(iv) The identification of an optimal threshold of replacement whereby there is a compromise between the strength and environmental desirability.

1.8. Research Gap

Despite the existence of several studies on recycled aggregate concrete, there are still no combined experimental-statistical-sustainability models that set the best replacement rates of structural use. The paper fills this gap by integrating mechanical tests, statistical testing and analysis of carbon impact.

2. Materials and Methods

2.1. Cement

Ordinary Portland Cement of 53 grade was used as binder material. The cement met the requirements of the standard requirements of structural concrete use. The cement properties, which include fineness, specific gravity, and compressive strength, meet the requirements of the standards in use. The common properties of OPC that are applicable in this study are listed in **Table 1**.

Table 1. Properties of cement.

Property	Value
Specific Gravity	3.15
Initial Setting Time	35 min
Final Setting Time	480 min
28-day Compressive Strength	53 MPa

2.2. Fine Aggregate

The fine aggregate was made of natural river sand. Sand was clean, well-graded and had no organic impurities. The sand fulfilled the Zone II grading standards as shown in **Table 2**.

Table 2. Properties of fine aggregates.

Property	Value
Specific Gravity	2.63
Water Absorption	1.2%
Fineness Modulus	2.65

2.3. Natural Coarse Aggregates

The conventional coarse aggregates were crushed stone aggregates whose nominal maximum size was 20 mm. The properties of coarse aggregate are shown in **Table 3**.

Table 3. Properties of coarse aggregate.

Property	Value
Specific Gravity	2.70
Water Absorption	0.5%
Bulk Density	1,550 kg/m^3

2.4. Recycled Aggregates (CDW)

Aggregates were recycled using the construction and demolition waste that was gathered in the form of demolished concrete structures. The processing steps include manual extraction of contaminants (steel, plastics and wood), crushing in mechanical crusher, sizing to acquire the target size fraction and removal of dust particles. The mortar is adhered to recycled aggregates, hence it plays a big role in influencing the physical properties of recycled aggregates, as shown in **Table 4**.

Table 4. Properties of CDW.

Property	Value
Specific Gravity	2.35
Water Absorption	4.8%
Bulk Density	1,350 kg/m^3

Recycled concrete aggregates (RCA) compositional chemistry relies mainly on the parent concrete and the quantity of applied mortar on the surface of the aggregates. RCA, as indicated in **Table 5**, generally has greater values of calcium oxide (CaO) and loss on ignition (LOI) because of remaining cement paste, and has great quantities of silica (SiO_2) because of natural aggregates. These compositional properties affect hydration kinetics, interfacial transition zone (ITZ) behavior and long-term durability performance of recycled concrete aggregate. An increase in CaO level would help achieve secondary hydration and internal curing effect and also the higher the LOI the greater the porosity and water absorption capacity. Recent studies of aggregates based on CDW have also reported similar compositional trends [16,19,20].

Table 5. Recycled Concrete Aggregates (RCA/CDW) chemical composition.

Oxide Component	Typical Range (%)	Mean Value (%)	Source/Origin	Influence on Concrete Behavior
SiO_2 (Silicon Dioxide)	45–65	~55	Natural aggregates + adhered mortar	Contributes to strength and stability; affects pozzolanic interactions
CaO (Calcium Oxide)	15–30	~22	Residual cement paste	Influences hydration and secondary C–S–H formation
Al_2O_3 (Aluminum Oxide)	4–10	~7	Cement phases (C_3A, C_4AF)	Affects setting time and sulfate reactions
Fe_2O_3 (Iron Oxide)	2–6	~4	Cement and natural aggregates	Minor role in hydration; contributes to density
MgO (Magnesium Oxide)	1–4	~2	Dolomitic aggregates	May influence long-term expansion if excessive
SO_3 (Sulfur Trioxide)	0.5–2.5	~1.5	Gypsum residues	Affects setting and potential sulfate attack
Na_2O + K_2O (Alkalis)	0.5–2.0	~1.2	Cement paste residues	Influences alkali–silica reaction (ASR) risk
Loss on Ignition (LOI)	3–12	~7	Unhydrated cement + organic impurities	Indicates adhered mortar and porosity
Chlorides (Cl^-)	0.01–0.10	~0.05	Contaminants (marine/exposure)	Critical for reinforcement corrosion risk

Porous mortar adhered surface and internal microcracks formed during crushing are considered the main factors contributing to increased water absorption of recycled aggregates. Physical characteristics of recycled aggregates compared to natural aggregates are given by the fact that they contain adhered mortar and microstructural damage during the crushing procedures. The latter properties usually lead to increased water absorption, reduced density and porosity compared to natural aggregates [40–43].

Recycled aggregates have a great sensitivity to the variability of their source, such as the varied adhered mortar content, contamination, and crushing. Recent research has emphasized that inconsistency in recycled aggregate properties has a great effect on the performance of strength and durability [13]. In this experiment, processing (manual segregation, crushing, sieving) was done strictly in order to reduce variability. Nevertheless, it is also admitted that large-scale applications demand standard quality control processes, such as grading, water absorption levels, and contamination elimination as suggested by Prasittisopin et al. [19].

In this study, no direct chemical characterization (e.g., X-ray fluorescence (XRF) analysis) was performed; thus, the given composition is founded on the proven information on similar sources of recycled aggregates.

2.5. Mix Design

It has been established in the past that between 20% and 40% of recycled aggregate substitutions have given an average mechanical performance of structural concrete [28,30]. Concrete mixtures were tailored to the M25 grade concrete that is normally utilized in the structure like residential buildings and reinforced concrete buildings. The proportion of mix was used in this research, which was Cement: Fine Aggregate: Coarse Aggregate = 1:1:2, Water-cement ratio = 0.50. The recycled aggregates were used as substitutes for the natural coarse aggregates at four replacement levels, as shown in **Table 6**.

Table 6. Different replacement levels of CDW.

Mix ID	CDW Replacement
CM	0%
C10	10%
C30	30%
C50	50%

These levels of replacement were chosen in order to test the performance of the recycled aggregate concrete at low levels of replacement through to relatively high levels of replacement. Past research has shown that a recycled aggregate replacement of 20–40% normally results in satisfactory mechanical performance of structural concrete [29]. But the increased replacement level can have a significant effect on the durability performance because there will be more porosity and permeability [30,31].

2.6. Specimen Preparation

A laboratory concrete mixer was used to mix concrete materials so that there was even distribution. The mixing process involved exposure of cement and aggregates to dry mixing and then water was slowly added until a uniform mixture was achieved. Concrete on the steel molds was then added freshly and compacted by application of mechanical vibration to remove air trapped and provide correct compaction. The specimen that was prepared to undergo testing consists of a cube specimen: 150 mm × 150 mm × 150 mm. These specimens were subject to a compressive strength test. The specimens were covered with casing to ensure that they do not lose moisture and left to dry for 24 h. All specimens were then demolded and kept in water tanks at room temperature till the testing ages of 7 and 28 days. These are the curing periods that are normally utilized to assess early age and typical design compressive strengths of concrete [32].

The specimens were dried under controlled laboratory conditions with a temperature of 25 ± 2 degrees with relative humidity around 60–70%. The environmental conditions were controlled to make sure that the hydration was constant and there was less variation in test results since relative humidity can greatly affect the moisture transportation, strength building, and durability behavior of concrete.

2.7. Testing Procedures

2.7.1. Workability

The slump test was used to determine fresh concrete workability. Another parameter that affects the concrete placement, compaction and finishing properties is workability. Recycled aggregates normally lower the workability as they become rough in nature and have high water absorption capacity [33].

2.7.2. Density Measurement

Density of concrete was established post-curing by weighing the hardened concrete specimens and then dividing the weight of the specimen by the volume of the specimen to establish the density. The data obtained as density measurements gives a useful insight on internal porosity and compactness of concrete mixtures.

2.7.3. Water Absorption Test

Water absorption tests were also performed in order to test the porosity properties of the concrete mixtures. An increase in water uptake is normally a sign of a higher pore connectivity and durability issues [34]. The porosity of mortar bonded by adherents causes recycled aggregates to have a higher water absorption because the material has inner microcracks [35].

2.7.4. Compressive Strength Test

A universal compression testing machine was used to do compressive strength tests.

The most significant mechanical property of concrete is compressive strength, which defines the structural load-bearing capacity of concrete [36].

The experimental findings are given as the mean values of three specimens, with the corresponding standard deviations to explain the variation in the recycled aggregate properties.

3. Results and Discussion

3.1. Workability

The fact that all the experimental results include standard deviation gives the idea of the variability of recycled aggregate concrete which is necessarily determined by the heterogeneity of the construction and demolition waste. The variability is within acceptable levels, which implies that there is uniform material behavior at various levels of replacement.

The subsequent rise in water absorption and the subsequent decrease in density can also be explained by the increased LOI and CaO content of adhered mortar with the recycled aggregates (**Table 6**).

The slump values were low as replacement level of CDW increased, as shown in **Table 7** and **Figure 1**. It may be explained by the increased water absorption capacity of recycled aggregates and irregular surface texture which leads to a decrease in workability. Adhered mortar is common in recycled aggregates, and this consumes more water in concrete mixtures and adds to their surface area. Consequently, this causes the absorption of additional mixing water by recycled aggregates and the resulting low amount of free water to lubricate the particles. The results of the reduction in slump as the recycled aggregate content increases are in agreement with those of past researchers. It is the rough surface texture and larger water absorption capacity of recycled aggregates that raise inside friction and decrease the free water available to the aggregates to be mixed with [37].

3.2. Density

Recycled aggregate replacement levels had minimal effect on the decrease in the density of concrete, as shown in **Table 8** and **Figure 2**. The reason for this is mainly because the specific gravity of the recycled aggregates is lower than that of the natural aggregates. In recycled aggregates, there are remnants of mortar that cannot be removed from the original aggregate particles. The density and porosity of the adhered layer of mortar are lower than those of natural aggregates. In turn, when the recycled aggregates are increased, the total concrete density decreases marginally. The decrease in density of recycled aggregate concrete mixtures may be explained by the fact that the specific gravity of adhered mortar deposited on the recycled aggregates is lower [38–40].

Table 7. Slump values of concrete mixtures with varying contents of construction and demolition waste (CDW).

Mix	CDW (%)	Slump (mm)	Standard Deviation (±mm)
CM	0	85	±2.1
C10	10	78	±2.5
C30	30	70	±3.0
C50	50	62	±3.6

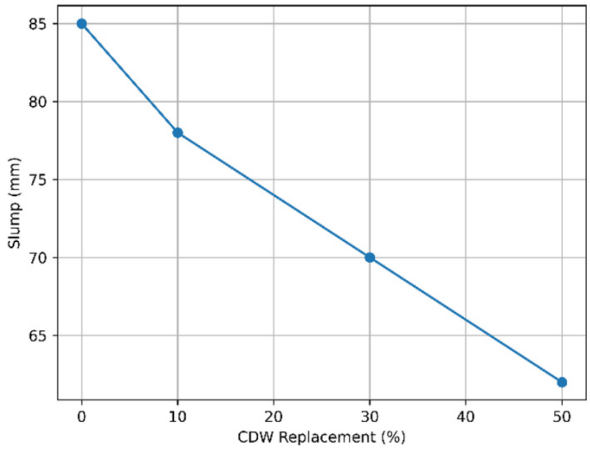

Figure 1. Slump dependence on CDW replacement demonstrated decreasing workability owing to the consumption of more water by recycled aggregates.

Table 8. Density of hardened concrete at different levels of CDW replacement.

Mix	Density (kg/m^3)
CM	2,420
C10	2,395
C30	2,368
C50	2,325

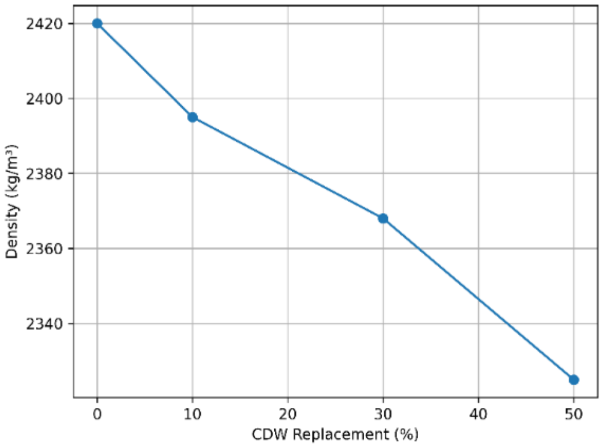

Figure 2. Distribution of density of the recycled aggregate concrete which shows decrease in unit weight due to adhered mortar.

3.3. Water Absorption

The values of water absorption were found to increase as the replacement levels of the CDW increased, as shown in **Table 9** and **Figure 3**. The greatest absorption of water was in the 50% mix. The porous nature of recycled aggregates could explain such behavior. In a recycled aggregate, microcracks are formed as a result of crushing. Such microcracks enhance the connectivity of the pores and water penetration in the concrete matrix. The mortar layer covered over the recycled aggregates is also adhered with capillary pores that enhance higher absorption of water [41]. The fact that water absorption is increasing with the increasing amount of CDW shows that there is high internal porosity in the concrete matrix. This is normally attributed to the porous character of adhered mortar in the recycled aggregates [42–44].

Table 9. Recycled aggregate concrete water absorption characteristics.

Mix	Water Absorption (%)
CM	2.1
C10	2.6
C30	3.4
C50	4.2

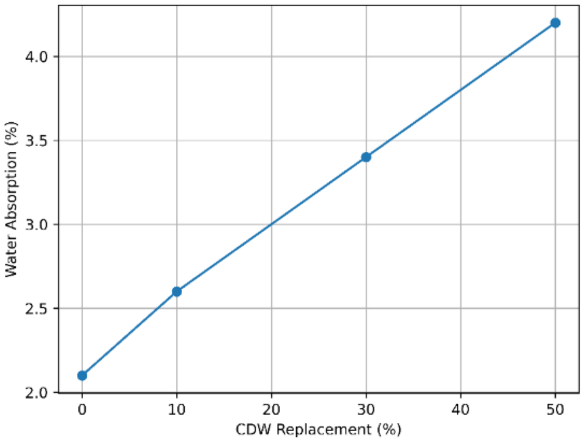

Figure 3. Recycled aggregate concrete properties of water absorption that shows higher porosity of concrete with higher percentage of CDW.

3.4. Compressive Strength

3.4.1. Seven-Day Compressive Strength

The compression strength test outcomes of the lower age prove that there is no negative impact on the hydration and strength development when replacement level of recycled aggregates is low. The concrete with 10% replacement rate of CDW demonstrated similar compressive strength as the control mixture and thus it was seen that even low amounts of recycled aggregates can be successfully used without affecting their early mechanical properties. The 30% replacement blend displayed a marginally low strength, which can be explained by the greater porosity of the recycled aggregates because of the stuck mortar. The same trends have been seen by other previous lead studies on recycled aggregate concrete, indicating that a moderate level of such replacement will lead to slight strength degradation of the material owing to weaker interfacial bonding in the matrix [45]. Nonetheless, the 50% replacement mixture showed pronounced decrease in compressive strength which is mainly related to greater pore connectivity and lower aggregate paste bonding. The large quantities of recycled aggregate content augment the volume of adhered mortar and microcracks through crushing processes and therefore decrease the effective load-bearing capacity of the concrete matrix. The results are shown in **Table 10** and **Figure 4**.

Table 10. Development of compressive strength of concrete mixtures at 7 and 28 days.

Mix	7-Day (MPa)	28-Day (MPa)	SD (±)
CM	20.79	30.45	±1.10
C10	21.35	31.52	±1.25
C30	19.84	29.82	±1.30
C50	17.62	26.33	±1.50

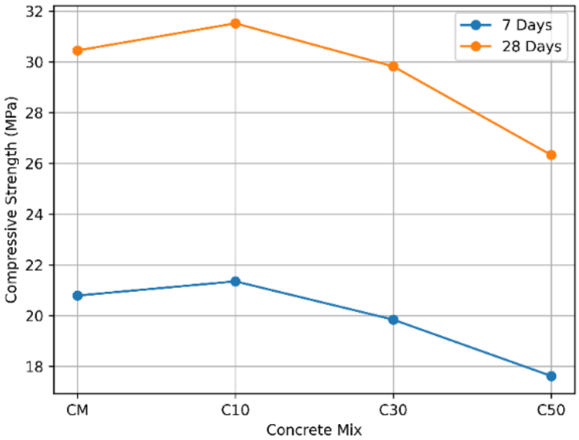

Figure 4. Comparison between compressive strength development of recycled aggregate concrete on 7 and 28 days.

The obtained results on compressive strength of the obtained samples have a high consistency with the recent experimental studies on recycled aggregate concrete (RAC). Investigations by Akbarimehr et al. [45] have indicated that no less than 30% recycled aggregate substitute does not decrease structural-grade compressive strength and remains above considerable deterioration [12]. Correspondingly, Chen et al. [46] showed that it is possible to improve the mechanical performance of optimised RAC mixtures because of enhanced ITZ properties [11]. Moreover, the contemporary investigation by Liu et al. [47] proves that RAC with fixed replacement rates (20–40%) has a steady mechanical behavior since porosity and hydration are balanced [22]. The current work is congruent with these data sets, which proves the fact that the 30% replacement of CDW makes the best mechanical-sustainability compromise.

Discussion of Compressive Strength (ITZ Explanation)

Recycled aggregate concrete mechanical performance will be determined by the dual ITZ system, in which the stress transfer and crack propagation will be governed by the interaction of old mortar, recycled aggregates, and new cement paste. Current research has shown that ITZ property has a great impact on strength and durability [9,11,48].

It has been shown that, using artificial intelligence methods, optimized recycled aggregate concrete mixtures can be produced that predict strength and durability with minimal effort on experiments [49,50].

3.4.2. Twenty-Eight Days Compressive Strength

At the age of 28, the compressive strength values of the mixture show that the 10% CDW replacement mixture had a slightly higher compressive strength than the control concrete. This can be explained by the internal curing effect that the recycled aggregates offer. Recycled aggregates have a greater water absorption capability and thus during mixing, they can hold water and slowly discharge it during hydration and therefore increase cement hydration and further C–S–H formation. The compressive strength of the 30% replacement mixture was similar to that of the control mix, which shows that moderate level of recycled aggregate incorporation does not have significant impact on the structural performance. The results are in line with a number of experimental studies that show acceptable mechanical performance of recycled aggregate replacement level of up to about 30–40% [51]. On the contrary, the 50% replacement blend had a significant decrease in compressive strength, which is explainable by a higher level of porosity and weaker interfacial transition zones. High levels of recycled aggregate add various ITZ regions and microstructural defects that lower good stress transfer at the cement matrix. These findings suggest that 30% CDW replacement is a good compromise between mechanical performance and sustainability advantages; hence, it is suitable for structural concrete application.

The compressive strength values measured in this paper are in agreement with earlier studies that have determined that with moderate quantities of recycled aggregates, the same compressive strength of normal concrete could be achieved [52,53].

- **Hydration Effect and Internal Curing Effect**

The increased compressive strength at low levels of replacement of the recycled aggregates can be explained by the ability of the recycled aggregates to offer internal curing. Recycled aggregates have a greater water holding capacity and thus, they are able to hold mixing water and release it slowly during cement hydration. This reaction facilitates the hydration responses and further development of more calcium silicate hydrate (C–S–H) in the cement mix. Enhanced hydration helps in densification of the microstructure as well as partially offsets the adverse consequences of a higher porosity of recycled aggregates. Recent research also says that the methods used to optimize recycled aggregate concrete mixtures are artificial intelligence and machine learning methods that can help find the best amounts of replacement and mix ratios to enhance mechanical performance of concrete mixtures [54–56].

- **The interfacial Transition Zone (ITZ) is located between the two surfaces**

ITZ is a material in the interface that has a significant effect on mechanical properties of recycled aggregate concrete. The ITZ weds the natural aggregates and cement paste in traditional concrete. Nevertheless, recycled aggregates have a more complicated microstructure as they contain adhered mortar. These interfaces are usually more porous than natural aggregate concrete [57,58], like the old mortar-new mortar interface and new mortar recycles aggregate interface. This two-way ITZ system has a great impact of stress transfer in the concrete matrix. More detailed microstructural studies have shown that the ITZ area tends to be more porous than bulk cement paste [59]. With moderate replacement levels the rough surface texture of recycled aggregates may enhance mechanical interlocking and increase bonding between particles of the aggregate and cement paste. But, when the replacement is high, there will be more porosity in the ITZ region, which causes low bond strength and low values of compressive strength. Extensive microstructural studies have indicated that nano-modification and carbonation treatment are capable of increasing the interfacial bonding properties between recycled aggregates and cement paste to a great degree [59]. Adhering to the mortar on recycled aggregates causes the appearance of several interfacial transition zones (ITZs) such as the previous mortar-aggregate interface and the new one that is formed between mortar and recycled aggregate. The porosity and density of microcracks of these ITZ zones are usually higher than those of conventional concrete, which may decrease the bond strength and augment permeability. Interfacial transition zone (ITZ) in recycled aggregate concrete is a very important factor affecting mechanical performance and durability. The presence of bonded mortar forms a complex multi-stage interface composed of old mortar, renewed material aggregate, and newly composed cement paste [60]. Recent reports have shown that the use of sophisticated treatment techniques like nano-modification and curing can help to significantly enhance the ITZ microstructure and bond strength of recycled aggregate concrete systems [61,62].

The micro-structure of recycled aggregate concrete is controlled by the development of several interfacial transition zones (ITZ) between recycled aggregates and cement paste. Recycled aggregates, as opposed to traditional concrete, have adhered to mortar, which introduces a dual ITZ structure, of an old mortar-aggregate interface and a new mortar cement paste interface. These interfaces are usually more porous and more microcracking than the natural aggregate concrete. Moderate replacement levels result in a rough surface texture of recycled aggregates that improves mechanical interlocking in the cement matrix, whereas too much replacement can lead to an increase in pore connectivity and a decrease in bond strength. This mechanism is based on earlier microstructural studies of recycled aggregate concrete [2,3,16,37,43–46].

3.5. Statistical Analysis

The statistical analysis performed on ANOVA was to assess the significance of the compressive strength difference between the various levels of replacement. It was observed in the analysis that compressive strength value of control mix, and 10% replacement mix, and 30% replacement mix have no statistically significant difference at a 95% confidence level. Nevertheless, replacement mixture of 50% proved to reduce the strength significantly in a statistically significant way. These results show that recycled replacement up to 30% of aggregate replacement can indeed be successfully incorporated into structural concrete without detrimental effects on the mechanical performance.

3.6. Industrial Practical Engineering Implications

The results of the research have significant consequences in terms of sustainable construction.

1. Natural aggregates could be replaced with recycling to as high as 30%, without much loss of strength.
2. Circular economic principles in construction can be achieved by the use of CDW aggregates.
3. Even moderate levels of replacement can enhance hydration by curing internally.
4. Quality control in the process of recycled aggregates is required to ensure stability of performance. Hence, recycled aggregate concrete can be successfully employed in such applications as structural concrete, pavement construction, precast elements and non-structural components.

4. Sustainability Implications

Recycled aggregates have also aided in sustainable construction by lowering environmental effects brought about by the extraction of natural aggregates and disposal of waste. Recycled aggregate concrete has been demonstrated to help reduce resource use and landfill waste by a large percentage and help achieve the principles of the circular economy in construction in a life-cycle assessment study [57–60]. The estimated CO_2 reduction table is shown in **Table 11**.

Table 11. Details of CO_2 Reduction.

Replacement Level	Natural Aggregate Reduction	Estimated CO_2 Reduction
10%	Low	3–5%
30%	Moderate	8–12%
50%	High	15–18%

Life-cycle assessment research findings affirm that recycled aggregate concrete has the potential to lower the embodied carbon emissions by around 10–15% based on the level of replacement and state of transportation [24,63–65].

Use of recycled aggregates instead of natural aggregates decreases the emission that comes with the extraction, crushing and transportation of aggregates. Life-cycle analysis shows that recycled concrete aggregates may obtain a variety of carbon savings between 5–15% based on the level of replacement as well as the distance of transportation.

Recycled Aggregate Concrete Carbon Footprint Calculation

In terms of carbon, recycled aggregate concrete has proven to be able to have reductions in its embodied emissions relative to conventional concrete, as shown in **Table 12**. Recent research also shows that embodied carbon emissions can be decreased by 5–15% by using recycled aggregates instead of natural aggregates based on replacement level and transportation distance [66,67]. Further studies have indicated that further sustainability performance of recycled aggregate concrete can be achieved through optimization of recycling process and better aggregate treatment procedures [68,69]. In this study, the carbon footprint of concrete mixtures was estimated by a simplified embodied carbon approach given by the following form:

$$\text{co}_2 = \sum (m_i \times EF_i)$$

where: m_i = mass of material (kg/m^3);

EF_i: emitted material factor (kg CO_2/kg).

Table 12. Emission factors mentioned in the literature.

Material	Emission Factor (kg CO_2/kg)
Cement	0.90
Natural aggregates	0.005
Recycled aggregates	0.002
Water	0.0003

With these factors, the estimated quantity of embodied carbon reduction of recycled aggregate concrete mixtures may be estimated as indicated in **Table 13**.

Table 13. Carbon footprint reduction with CDW aggregate replacement estimation.

CDW Replacement Level	Natural Aggregate Reduction	Emission Factor (kg CO_2/kg)
0%	Baseline	0%
10%	Low	2–4%
30%	Moderate	6–10%
50%	High	10–15%

The findings suggest that the recycled aggregates can be used in place of natural aggregates in part without leading to significant emissions of embodied carbon. The highest environmental benefits are at higher replacement levels, but mechanical performance also must not be ignored when the optimal replacement ratios are set. The 30% CDW replacement rate in this research showed good balance between structural performance and environmental benefits, which have similar compressive strength and could cut carbon emissions due to aggregate production. Such results prove the incorporation of recycled aggregates into the construction material of low carbon, which leads to the development of the circuit of resource use and the creation of infrastructure that is energy efficient.

5. Conclusions

The paper assessed the viability of using the construction and demolition waste aggregates as a partial substitute for natural coarse aggregates in structural concrete. Resting on the outcomes of the experiment, the following conclusions may be made:

1. The workability reduces as CDW replacement increases, as water absorption increases and aggregates morphology becomes angular.

2. The concrete density reduces slightly with the level of recycled aggregate since the specific gravity of adhered mortar reduces.
3. Water uptake is also high at high replacement values, which means that it is more porous and subject to durability.
4. The compressive strength of the 10% CDW replacement mixture was the highest (31.52 MPa at 28 days), a fact that was slightly higher than the control mixture.
5. Compressive strength of concrete with 30% CDW aggregates was equivalent to that of standard concrete; thus, it can be used in structural construction.
6. The high levels of replacement (50) led to a decrease in strength because of higher connectivity of the pores and the reduced interfacial transition zones.
7. The use of recycled aggregates to substitute natural aggregates can minimize the environmental effects linked to quarrying and disposal of CDW, and this practice will lead to circular construction.

In general, the findings demonstrate that the aggregates of CDW can be safely used as a natural coarse substitute for structural concrete up to 30% without affecting the mechanical performance of concrete and enhancing the environmental sustainability. The results show that structural concrete applications of recycled aggregates which can be obtained using construction and demolition waste can be successfully employed in infrastructure development. Alternative future studies ought to concentrate on enhancing the durability performance of recycle aggregate concrete by enhancing the aggregate treatment and using additional cementitious materials.

6. Limitations of the Study and Future Research

Although the findings of this study are very valuable, there are some limitations. Experimentation on compressive strength was only performed, but other durability characteristics like chloride penetration, carbonation, and freeze thaw resistance had not been studied. Moreover, microstructural explanations (scanning electron microscopy (SEM), X-ray diffraction (XRD)) were not proved experimentally but on literature basis. The following areas are the key areas that should be involved in future research:

1. Durability Evaluation: The diffusion of chloride and carbonation and the interaction of both should be studied in detail to evaluate long-term performance. The high permeability of RAC can be attributed to the fact that it is mostly more porous and intricate at the ITZ [9,11], but treatment can enhance durability [12,57].
2. Microstructural Characterization: With the evolution of microelectronics, many materials are currently analyzed with microscopes, electron microscopy, or other methods because of the need to study material properties at the atomic level. To measure the behavior of ITZ, pore structure, and connectivity of cracks, experimental studies on SEM, XRD, and micro-computed tomography (Micro-CT) are required in order to correlate them with mechanical and durability performance.
3. Application is AI-Based Mix Optimization: The implementation of machine learning can be applied to optimize the mix design, to predict the performance, and to save on experimentation effort, especially in light of variable recycled aggregates [70–72].
4. Life-Cycle Assessment (LCA):

    The durability-based service life prediction should be combined with complete LCA in future research to determine the long term environmental benefits. Embodied carbon can be lowered by about 10–15% through RAC depending on the level of replacement [73–75]. The quality control and standardization used must be thoroughly detailed, including a description of the quality assurance measures employed to guarantee adherence to International Organization for Standardization (ISO) 9001 principles. Life-cycle assessment research findings affirm that recycled aggregate concrete has the potential of lowering the embodied carbon emissions by around 10–15% based on the level of replacement and state of transportation [24,72–75].

5. Standardization and Quality Control: The quality control and standardization involved should be well-described, with an outline of the quality controls in place to ensure the compliance with ISO

9001 principles. Studies must be done on the establishment of standard processing procedures and quality classification systems of the recycled aggregates to provide similar performance [13,19].

It has been shown that, using artificial intelligence methods, optimized recycled aggregate concrete mixtures can be produced that predict strength and durability with minimal effort on experiments [71,72].

In general, the future work must approach it in an integrated manner that incorporates durability, microstructure, optimization of AI, and assessment of sustainability in order to allow reliable large-scale use of recycled aggregate concrete.

Author Contributions

Conceptualization, M.Z.A.A.R. and K.K.P.; methodology, M.Z.A.A.R., K.K.P., A.A.S. and N.K.; validation, M.Z.A.A.R.; formal analysis, M.Z.A.A.R., K.K.P., and N.K.; investigation, M.Z.A.A.R., K.K.P., A.A.S. and N.K.; resources, M.Z.A.A.R., K.K.P. and A.A.S.; data curation, M.Z.A.A.R., K.K.P. and N.K.; writing—original draft preparation, M.Z.A.A.R.; writing—review and editing, K.K.P., A.A.S. and N.K.; visualization, M.Z.A.A.R. and K.K.P.; supervision, K.K.P.; project administration, M.Z.A.A.R. and K.K.P. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] de Andrade Salgado, F., de Andrade Silva, F., 2022. Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review. Journal of Building Engineering. 52, 104452. DOI: https://doi.org/10.1016/j.jobe.2022.104452

[2] Bahraq, A.A., Jose, J., Shameem, M., et al., 2022. A review on treatment techniques to improve the durability of recycled aggregate concrete: Enhancement mechanisms, performance and cost analysis. Journal of Building Engineering. 55, 104713. DOI: https://doi.org/10.1016/j.jobe.2022.104713

[3] Lu, Z., Tan, Q., Lin, J., et al., 2022. Properties investigation of recycled aggregates and concrete modified by accelerated carbonation through increased temperature. Construction and Building Materials. 341, 127813. DOI: https://doi.org/10.1016/j.conbuildmat.2022.127813

[4] Wang, J., Che, Z., Zhang, K., et al., 2023. Performance of recycled aggregate concrete with supplementary cementitious materials (fly ash, GBFS, silica fume, and metakaolin): Mechanical properties, pore structure, and water absorption. Construction and Building Materials. 368, 130455. DOI: https://doi.org/10.1016/j.conbuildmat.2023.130455

[5] Gao, S., Guo, J., Zhu, Y., et al., 2023. Study on the influence of the properties of interfacial transition zones on the performance of recycled aggregate concrete. Construction and Building Materials. 408, 133592. DOI: https://doi.org/10.1016/j.conbuildmat.2023.133592

[6] Lu, D., Wang, D., Wang, Y., et al., 2023. Nano-engineering the interfacial transition zone between recycled concrete aggregates and fresh paste with graphene oxide. Construction and Building Materials. 384, 131244. DOI: https://doi.org/10.1016/j.conbuildmat.2023.131244

[7] Poloju, K.K., Annadurai, S., Manchiryal, R.K., et al., 2023. Analysis of rheological characteristic studies of fly-ash-based geopolymer concrete. Buildings. 13(3), 811. DOI: https://doi.org/10.3390/buildings13030811

[8] Sun, H., Luo, L., Yuan, H., et al., 2023. Experimental evaluation of mechanical properties and microstructure for recycled aggregate concrete collaboratively modified with nano-silica and mixed fibers. Con-

struction and Building Materials. 403, 133125. DOI: https://doi.org/10.1016/j.conbuildmat.2023.133125

[9] Chen, Q., Zhang, J., Wang, Z., et al., 2024. A review of the interfacial transition zones in concrete: Identification, physical characteristics, and mechanical properties. Engineering Fracture Mechanics. 300, 109979. DOI: https://doi.org/10.1016/j.engfracmech.2024.109979

[10] Xu, L., Wang, J., Huang, R., et al., 2024. Investigations on micro-mechanical properties of the ITZs between recycled aggregates and recycled cement paste. Construction and Building Materials. 450, 138640. DOI: https://doi.org/10.1016/j.conbuildmat.2024.138640

[11] Lu, C., Yu, Q., Wei, J., et al., 2024. Influence of interface transition zones (ITZ) and pore structure on the compressive strength of recycled aggregate concrete. Construction and Building Materials. 456, 139299. DOI: https://doi.org/10.1016/j.conbuildmat.2024.139299

[12] Farooq, M.U., Hameed, R., Tahir, M., et al., 2023. Mechanical and durability performance of 100% recycled aggregate concrete pavers made by compression casting. Journal of Building Engineering. 73, 106729. DOI: https://doi.org/10.1016/j.jobe.2023.106729

[13] Dacić, A., Fenyvesi, O., Abed, M., 2024. An innovative approach for evaluating the quality of recycled concrete aggregate mixes. Buildings. 14(2), 471. DOI: https://doi.org/10.3390/buildings14020471

[14] Lu, L., 2024. Optimal replacement ratio of recycled concrete aggregate balancing mechanical performance with sustainability: A review. Buildings. 14(7), 2204. DOI: https://doi.org/10.3390/buildings14072204

[15] Brencich, A., Dubesti, A., Ali Akbari Hamed, F., 2024. Structural concrete from 100% recycled aggregates. Applied Sciences. 14(24), 11709. DOI: https://doi.org/10.3390/app142411709

[16] Luo, H., Aguiar, J., Wan, X., et al., 2024. Application of aggregates from construction and demolition wastes in concrete: Review. Sustainability. 16(10), 4277. DOI: https://doi.org/10.3390/su16104277

[17] Zhang, P., Sun, X., Wang, F., et al., 2023. Mechanical properties and durability of geopolymer recycled aggregate concrete: A review. Polymers. 15(3), 615. DOI: https://doi.org/10.3390/polym15030615

[18] Su, Y., Yao, Y., Wang, Y., et al., 2023. Modification of recycled concrete aggregate and its use in concrete: An overview of research progress. Materials. 16(22), 7144. DOI: https://doi.org/10.3390/ma16227144

[19] Prasittisopin, L., Tuvayanond, W., Kang, T.H.-K., et al., 2025. Concrete mix design of recycled concrete aggregate (RCA): Analysis of review papers, characteristics, research trends, and underexplored topics. Resources. 14(2), 21. DOI: https://doi.org/10.3390/resources14020021

[20] Bai, J., Ge, C., Liang, J., Xu, J., 2025. Recycled aggregate: A solution to sustainable concrete. Materials. 18(12), 2706. DOI: https://doi.org/10.3390/ma18122706

[21] Bardan, M., Czarnecki, L., 2025. Green recycled aggregate in concrete: Feasibility study. Materials. 18(3), 488. DOI: https://doi.org/10.3390/ma18030488

[22] Zhang, L., Li, X., Li, C., et al., 2024. Mechanical Properties of Fully Recycled Aggregate Concrete Reinforced with Steel Fiber and Polypropylene Fiber. Materials. 17(5), 1156. DOI: https://doi.org/10.3390/ma17051156

[23] Poloju, K.K., Srinivasu, K., 2022. Influence of GGBS and concentration of sodium hydroxide on strength behavior of geopolymer mortar. Materials Today: Proceedings. 65(2), 702–706. DOI: https://doi.org/10.1016/j.matpr.2022.03.276

[24] Vasquez-Cabrera, A., Montes, M.V., Llatas, C., 2025. The incorporation of recycled aggregate concrete as a strategy to enhance the circular performance of residential building structures in Spain. Applied Sciences. 15(6), 3265. DOI: https://doi.org/10.3390/app15063265

[25] Bakharev, T., 2005. Durability of geopolymer materials in sodium and magnesium sulfate solutions. Cement and Concrete Research. 35(6), 1233–1246. DOI: https://doi.org/10.1016/j.cemconres.2004.09.002

[26] Duxson, P., Fernández-Jiménez, A., Provis, J.L., et al., 2007. Geopolymer technology: The current state of the art. Journal of Materials Science. 42, 2917–2933. DOI: https://doi.org/10.1007/s10853-006-0637-z

[27] Hardjito, D., Wallah, S.E., Sumajouw, D.M.J., et al., 2004. On the development of fly ash-based geopolymer concrete. ACI Materials Journal. 101(6), 467–472.

[28] Nath, P., Sarker, P.K., 2014. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials. 66, 163–171. DOI: https://doi.org/10.1016/j.conbuildmat.2014.05.080

[29] Silva, R.V., de Brito, J., Dhir, R.K., 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials. 65, 201–217. DOI: https://doi.org/10.1016/j.conbuildmat.2014.04.117

[30] Poon, C.S., Shui, Z.H., Lam, L., et al., 2004. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cement and Concrete Research. 34(1), 31–36. DOI: https://doi.org/10.1016/S0008-8846(03)00186-8

[31] Tam, V.W.Y., Gao, X.F., Tam, C.M., et al., 2008. New approach in measuring water absorption of recycled aggregates. Construction and Building Materials. 22(3), 364–369. DOI: https://doi.org/10.1016/j.conbuildmat.2006.08.009

[32] Djerbi Tegguer, A., 2012. Determining the water absorption of recycled aggregates utilizing hydrostatic weighing approach. Construction and Building Materials. 27(1), 112–116. DOI: https://doi.org/10.1016/j.conbuildmat.2011.08.018

[33] Khatib, J.M., 2005. Properties of concrete incorporating fine recycled aggregate. Cement and Concrete Research. 35(4), 763–769. DOI: https://doi.org/10.1016/j.cemconres.2004.06.017

[34] Evangelista, L., de Brito, J., 2007. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cement and Concrete Composites. 29(5), 397–401. DOI: https://doi.org/10.1016/j.cemconcomp.2006.12.004

[35] Kou, S.C., Poon, C.S., 2009. Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. Cement and Concrete Composites. 31(9), 622–627. DOI: https://doi.org/10.1016/j.cemconcomp.2009.06.005

[36] Kou, S.C., Poon, C.S., 2012. Enhancing the durability properties of concrete prepared with coarse recycled aggregate. Construction and Building Materials. 35, 69–76. DOI: https://doi.org/10.1016/j.conbuildmat.2012.02.032

[37] Tam, V.W.Y., Tam, C.M., Le, K.N., 2007. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resources, Conservation and Recycling. 50(1), 82–101. DOI: https://doi.org/10.1016/j.resconrec.2006.05.012

[38] Boccaccini, A.R., Rossetti, M., Roether, J.A., et al., 2009. Development of titania coatings on glass foams. Construction and Building Materials. 23(7), 2554–2558. DOI: https://doi.org/10.1016/j.conbuildmat.2009.02.019

[39] Marinković, S., Radonjanin, V., Malešev, M., et al., 2010. Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management. 30(11), 2255–2264. DOI: https://doi.org/10.1016/j.wasman.2010.04.012

[40] Xiao, J., Li, W., Sun, Z., et al., 2013. Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation. Cement and Concrete Composites. 37, 276–292. DOI: https://doi.org/10.1016/j.cemconcomp.2013.01.006

[41] Poloju, K.K., Al Ajmi, Z., Annadurai, S., et al., 2025. Experimental study on acid resistance of geopolymer concrete incorporating fly ash and GGBS: Towards low-carbon and sustainable construction. Buildings. 15(21), 4012. DOI: https://doi.org/10.3390/buildings15214012

[42] Ruan, S., Qiu, J., Yang, E.-H., et al., 2018. Fiber-reinforced reactive magnesia-based tensile strain-hardening composites. Cement and Concrete Composites. 89, 52–61. DOI: https://doi.org/10.1016/j.cemconcomp.2018.03.002

[43] Andreu, G., Miren, E., 2014. Experimental analysis of properties of high performance recycled aggregate concrete. Construction and Building Materials. 52, 227–235. DOI: https://doi.org/10.1016/j.conbuildmat.2013.11.054

[44] Bravo, M., de Brito, J., Pontes, J., et al., 2015. Durability performance of concrete with recycled aggregates from construction and demolition waste plants. Construction and Building Materials. 77, 357–369. DOI: https://doi.org/10.1016/j.conbuildmat.2014.12.103

[45] Akbarimehr, D., Eslami, A., Nasiri, A., et al., 2024. Performance study of sustainable concrete containing recycled aggregates from non-selected construction and demolition waste. Sustainability. 16(7), 2601. DOI: https://doi.org/10.3390/su16072601

[46] Chen, Y., Liu, X., Ye, P., et al., 2024. Mechanical properties of recycled aggregate concrete reinforced with steel fibers under triaxial loading. Journal of Building Engineering. 92, 109541. DOI: https://doi.org/10.1016/j.jobe.2024.109541

[47] Liu, H., Shi, N., Yu, Z., et al., 2025. Influence of size and content of recycled aggregate on mechanical properties of concrete. Buildings. 15(17), 3009. DOI: https://doi.org/10.3390/buildings15173009

[48] Zhang, S., Ji, Y., Hao, X., 2025. Interfacial damage mechanisms and performance prediction in recycled aggregate concrete. Coatings. 15(4), 441. DOI: https://doi.org/10.3390/coatings15040441

[49] Neupane, R.P., Imjai, T., Makul, N., et al., 2025. Use of recycled aggregate concrete in structural members: A review focused on Southeast Asia. Journal of Asian Architecture and Building Engineering. 24(3), 1197–1220. DOI: https://doi.org/10.1080/13467581.2023.2270029

[50] Yousheng, D., Keqin, Z., Yunbo, F., et al., 2023. Analysis and optimization of design parameters for recy-

cled concrete modified with nano-$CaCO_3$ considering environmental and economic and mechanical properties. Journal of Materials Cycles and Waste Management. 25, 3651–3663. DOI: https://doi.org/10.1007/s10163-023-01785-7

[51] Zeng, L., Geng, Y., Li, T., et al., 2024. Effect of ZrO_2-TiO_2 co-doping on the structure, alkali resistance and mechanical properties of basalt fibers. Construction and Building Materials. 438, 137312. DOI: https://doi.org/10.1016/j.conbuildmat.2024.137312

[52] Liu, C., Zhang, W., Liu, H., et al., 2022. Recycled aggregate concrete with the incorporation of rice husk ash: Mechanical properties and microstructure. Construction and Building Materials. 351, 128934. DOI: https://doi.org/10.1016/j.conbuildmat.2022.128934

[53] Al-Naghi, A.A.A., Alashker, Y., Salmi, A., et al., 2025. Durability and strength development of recycled aggregate concrete with binary, ternary, and multi-blended SCMs under hot-water curing. Case Studies in Construction Materials. 23, e05457. DOI: https://doi.org/10.1016/j.cscm.2025.e05457

[54] Silva, Y.F., Burbano-Garcia, C., Rueda, E.J., et al., 2025. Short- and long-term mechanical and durability performance of concrete with copper slag and recycled coarse aggregate under magnesium sulfate attack. Applied Sciences. 15(15), 8329. DOI: https://doi.org/10.3390/app15158329

[55] Poloju, K.K., Srinivasu, K., 2021. Impact of GGBS and strength ratio on mechanical properties of geopolymer concrete under ambient curing and oven curing. Materials Today: Proceedings. 42(2), 962–968. DOI: https://doi.org/10.1016/j.matpr.2020.11.934

[56] Wei, D., Zhu, P., Yan, X., et al., 2022. Potential evaluation of waste recycled aggregate concrete for structural concrete aggregate from freeze-thaw environment. Construction and Building Materials. 321, 126291. DOI: https://doi.org/10.1016/j.conbuildmat.2021.126291

[57] Yu, Q., Tang, J., Wang, G., et al., 2026. Enhancement of mechanical properties and strengthening mechanism of fully recycled aggregate concrete via calcium-based composite mineralization. International Journal of Concrete Structures and Materials. 20, 5. DOI: https://doi.org/10.1186/s40069-025-00882-1

[58] Dafedar, M.M.M., Rao, B.K., Pai, B.H.V., et al., 2025. Viability of using 100% of recycled concrete aggregates for durable solid masonry blocks. Emergent Materials. 8, 6017–6037. DOI: https://doi.org/10.1007/s42247-025-01194-6

[59] Jaji, M.B., van Zijl, G.P.A.G., Babafemi, A.J., 2024. Durability and pore structure of metakaolin-based 3D printed geopolymer concrete. Construction and Building Materials. 422, 135847. DOI: https://doi.org/10.1016/j.conbuildmat.2024.135847

[60] Panghal, H., Chaudhary, S., Kumar, A., 2025. Enhancing sustainable concrete performance: Dual treatment of recycled coarse aggregates for improved strength and durability. European Journal of Environmental and Civil Engineering. 29(15), 3225–3256. DOI: https://doi.org/10.1080/19648189.2025.2515490

[61] Akbulut, Z.F., Guler, S., Yavuz, D., et al., 2025. Toward sustainable construction: A critical review of recycled aggregate concrete properties and future opportunities. Case Studies in Construction Materials. 23, e05133. DOI: https://doi.org/10.1016/j.cscm.2025.e05133

[62] Zheng, Y., Li, Q., Zhou, L., et al., 2025. Lifecycle assessment and lifecycle cost analysis of sustainable concrete incorporating recycled aggregates. Sustainability. 17(5), 1779. DOI: https://doi.org/10.3390/su17051779

[63] Zhao, Z., Liu, Y., Lu, Y., et al., 2024. Prediction of properties of recycled aggregate concrete using machine learning models: A critical review. Journal of Building Engineering. 90, 109516. DOI: https://doi.org/10.1016/j.jobe.2024.109516

[64] Neupane, R.P., Devi, N.R., Imjai, T., et al., 2025. Cutting-edge techniques and environmental insights in recycled concrete aggregate production: A comprehensive review. Resources, Conservation & Recycling Advances. 25, 200241. DOI: https://doi.org/10.1016/j.rcradv.2024.200241

[65] Jagadesh, P., Karthik, K., Kalaivani, P., et al., 2024. Examining the influence of recycled aggregates on the fresh and mechanical characteristics of high-strength concrete: A comprehensive review. Sustainability. 16(20), 9052. DOI: https://doi.org/10.3390/su16209052

[66] Liu, K., Fu, K., Sang, Y., et al., 2024. Frost resistance of recycled aggregate concrete: A critical review. Journal of Building Engineering. 90, 109450. DOI: https://doi.org/10.1016/j.jobe.2024.109450

[67] Peiris, D., Gunasekara, C., Law, D.W., et al., 2025. Impact of treatment methods on recycled concrete aggregate performance: A comprehensive review. Environmental Science and Pollution Research. 32, 14405–14438. DOI: https://doi.org/10.1007/s11356-025-36497-y

[68] Gao, S., Ji, Y., Liu, A., et al., 2024. The adsorption and diffusion behavior of chloride in recycled aggregate concrete incorporated with calcined LDHs. Cement and Concrete Composites. 148, 105452. DOI:

https://doi.org/10.1016/j.cemconcomp.2024.105452

[69] Liu, K., Alam, M.S., Zhu, J., et al., 2021. Prediction of carbonation depth for recycled aggregate concrete using ANN hybridized with swarm intelligence algorithms. Construction and Building Materials. 301, 124382. DOI: https://doi.org/10.1016/j.conbuildmat.2021.124382

[70] Jin, L., Dong, T., Fan, T., et al., 2022. Prediction of the chloride diffusivity of recycled aggregate concrete using artificial neural network. Materials Today Communications. 32, 104137. DOI: https://doi.org/10.1016/j.mtcomm.2022.104137

[71] Liu, K., Dai, Z., Zhang, R., et al., 2022. Prediction of the sulfate resistance for recycled aggregate concrete based on ensemble learning algorithms. Construction and Building Materials. 317, 125917. DOI: https://doi.org/10.1016/j.conbuildmat.2021.125917

[72] Ebid, A.M., Ulloa, N., Onyelowe, K.C., et al., 2024. Multiple AI predictive models for compressive strength of recycled aggregate concrete. Cogent Engineering. 11(1). DOI: https://doi.org/10.1080/23311916.2024.2385621

[73] Golafshani, E.M., Kim, T., Behnood, A., et al., 2024. Sustainable mix design of recycled aggregate concrete using artificial intelligence. Journal of Cleaner Production. 442, 140994. DOI: https://doi.org/10.1016/j.jclepro.2024.140994

[74] Joseph, H.S., Pachiappan, T., Avudaiappan, S., et al., 2023. A comprehensive review on recycling of construction demolition waste in concrete. Sustainability. 15(6), 4932. DOI: https://doi.org/10.3390/su15064932

[75] Xiang, W., Wan, D., Zhou, W., et al., 2024. Direct and indirect photodegradation mechanism of ractopamine in aquatic environment. Journal of Hazardous Materials. 480, 136082. DOI: https://doi.org/10.1016/j.jhazmat.2024.136082